

EXPLOSIVE PROPERTIES OF SUGAR DUSTS

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by

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DEDICATION

To Mary, whose understanding and assistance
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ABSTRACT

The phenomena of dust explosions were of relatively little importance prior to the turn of the century. However, with the rapid industrial development of the early part of this century, the problem began to become increasingly more important, since these new industries produced and handled finely divided materials which could, under proper conditions, cause dust explosions of such violence that life and property were placed in jeopardy.

This industrialization in this country and in Europe instigated many intense investigations into the problems presented by dust explosions. Most of the investigations up to the present time have been primarily concerned with the problems of prevention and alleviation of explosion hazards from dusty materials. It has been found that explosion hazards exist for nearly all materials which are found in a finely divided or dusty state. In general, these materials fall into three classes; namely, natural carbonaceous materials (sugar, starch, coal, flour, etc.), metallic materials (iron, aluminum, magnesium, etc.), and synthetic carbonaceous materials such as plastic resins, fillers, and molding compounds.

Although much work has been done on preventative measures, there has been very little done on the theoretical or mechanistic aspects of dust explosions. The U. S. Bureau

of Mines has conducted numerous investigations into the dangers existing from dusts, but most of its work has been concerned with testing the relative flammability and explosibility of all types of dusts. These investigations have dealt with ignition temperatures, explosion pressures, and rates of explosions with respect to particle size and dust concentration but have for the most part neglected the theory of the explosions.

This thesis constitutes an attempt to obtain a better understanding of the fundamental nature of dust explosions. It concerns a study of three different sugars; namely, dextrose, sucrose, and raffinose. The use of these sugars made possible a study of dust explosions as affected by the number of carbon atoms in the molecule, the specific surface of the material, and the concentration of the explosive dust cloud.

An attempt has been made in this work to postulate a mechanism for the explosion of sugar dusts. This postulation is based on the explosion mechanisms for hydrocarbon gases.

It was found that the minimum and optimum explosive concentrations of a dust cloud of sugar are functions of the specific surface and the number of carbon atoms in the molecule. The maximum explosion pressure and the initial, average, and maximum rates increase as the specific surface

increases and as the number of carbon atoms in the molecule decreases.

The results of this investigation indicate that there is a "critical point" for dust explosions of any particular dust. This "critical point" is characterized by a "minimum" optimum concentration, a "maximum" optimum explosion pressure, and maxima for the initial, average, and maximum rates. These "critical points" can be obtained from an analysis of the maximum pressure vs. concentration records of dust explosions and also from an analysis of the various rate data and gas analysis data.

It was also indicated that a dust explosion could be analyzed from a theoretical viewpoint by assuming the dust to be a gas. This then permits the application of gas explosion theory to dust explosions. It is then possible to calculate the flame propagation velocity and maximum explosion pressure of a dust explosion from theoretical considerations.

EXPLOSIVE PROPERTIES OF SUGAR DUSTS

INTRODUCTION

The phenomena of dust explosions were of relatively little importance until just before the turn of the century. Prior to this time, industrial plants were of such size and construction that a dust explosion was of a relatively minor nature and could be regarded as little more than a mildly rapid flame propagation. Even these were few in number since there were few industries which used or produced materials in a form which could create a potential explosion hazard. However, with the advent of large scale industrial and commercial processes producing or using materials of a dusty nature, the problem of dust explosions began to constitute a real potential hazard. Around 1900, explosions in flour mills, grain elevators, coal mines, and sugar refineries began to take a startling toll of life and property, and the further mechanization of industry naturally contributed more and more possible dust sources as well as ignition sources in the form of heat, static electricity, and electrical fixtures.

It was originally suspected that the explosions were caused only by carbonaceous dusts, such as starch, coal, wood, sugar, and grain dusts, which were capable of forming

explosive mixtures with air; but this suspicion was proved to be in error when further experience and study revealed that dusts from aluminum, magnesium, titanium, iron and other metals actually constituted a far greater explosion hazard than the carbonaceous materials. The development of the plastics field also contributed many potentially dangerous dusts, since a majority of the materials used in this industry are carbonaceous and easily lend themselves to the formation of an explosive dust-air mixture. In general, it can be said that any oxidizable substance, if it is produced or handled in any form where there is a possibility of the existence of dust, powder, or finely divided material, constitutes a potential dust explosion hazard.

It was estimated in 1945 that there were more than 28,000 plants in the United States that held the possibility of a dust-explosion hazard (1). At the same time it was reported that over a twenty-five year period there occurred 567 dust explosions which resulted in 372 persons killed, 936 injured, and property loss exceeding \$52,000,000. The average annual property loss over this period was \$2,000,000. The figure for the year of 1943 was 4.5 times this figure. This upward trend of losses from dust explosions easily illustrates the need for further investigations into the causes and nature of these phenomena as well as for investi-

gations into the methods of prevention.

There has indeed been a considerable amount of work done in this country and others as to the nature and prevention of dust explosions, but there has been very little done on the study of mechanism or theory of dust explosions. The Bureau of Mines has been responsible for the great majority of work in this country. Most of its work has naturally been directed toward the prevention of dust explosions, but studies have also been made with regard to many of the factors influencing the explosibility of the dusts. These studies have included investigations into the effects of concentration, particle size, ignition source, physical and chemical properties of the dust, and explosion atmosphere.

This thesis constitutes an attempt toward a better understanding of the fundamental nature of dust explosions. It concerns a study of the explosibility of three different sugars; namely, dextrose, sucrose, and raffinose. Sugars were selected rather than other materials because they could be obtained with a high degree of purity and because they represented a series of chemically related substances. Thus, for example, the effect of the number of carbon atoms in a series of sugars as related to explosibility could be studied.

Dust clouds of the sugars mentioned were exploded in a pressure chamber by means of a high voltage arc. From

pressure-time records and gas analysis data in relation to dust concentration and particle size, it was possible to study many of the aspects of the explosions.

HISTORICAL ASPECTS OF DUST EXPLOSIONS

Similarity of Dust Explosions and Gas Explosions

As has been pointed out, the subject of dust explosions had received very little serious consideration prior to the turn of the century. In fact, there seemed to be no consideration that dust alone could explode until a large number of explosions had occurred in mines and industrial plants where no explosive gases were present. It is well established that mixtures of inflammable gases and air will produce an explosion if two basic conditions are satisfied; namely, a suitable mixture of the gases and an ignition source, electrical or thermal, sufficiently intense to ignite the mixture. From this initial ignition the gas molecules in the immediate vicinity of the heat source ignite, and they in turn ignite the gas surrounding them. Hence, a flame propagation results which under proper conditions leads to a rapid increase in pressure. As the proportion of the inflammable gas in either air or oxygen is decreased, a lower limit of explosiveness is reached at which point it can be imagined that the gas molecules are too widely separated to support the flame propagation needed for an explosion. It is therefore not inconceivable to consider the phenomena of dust explosions from a similar viewpoint to that for gases (2).

Indeed, if a dust explosion is to occur, every con-

dition necessary for a gaseous explosion must be satisfied. The dust concentration must exceed a minimum explosive limit, and there must be a suitable ignition source to initiate the explosion and to cause a rapid flame propagation. However, the rate of flame propagation in dust explosions is generally much less than that for gas explosions. In addition to the analogous gas conditions which must be met, there is also the matter of particle size which must be considered for dust explosions. This then means that whereas gaseous explosions are governed primarily by concentration and ignition source, dust explosions are governed by concentration, ignition source, and particle size or specific surface.

Nature of Dust Explosions

Generally speaking, dust explosions can be produced only when an inflammable dust is dispersed and ignited in oxygen, air, or some other gaseous atmosphere which will support the combustion and flame propagation. However, this is not a rigid requirement, since it is possible that dust which has collected on exposed surfaces can contribute to an explosion as well as initiate a combustion process which in turn could create a dust cloud capable of being exploded. This creates a two-fold problem for dust explosions which does not exist for gases, that is, an actual cloud explosion and a stagnant surface combustion, either

of which may initiate or contribute to the other.

The ignition of dust clouds and the intensity of the ensuing explosions are dependent on a wide variety of physical and chemical properties of the dusts. Some of the factors have been mentioned previously, such as particle size, concentration of the cloud, and the intensity and nature of the ignition source. Other physical characteristics influencing the explosions are turbulence in the cloud, initial temperature, initial pressure, and composition of the gaseous atmosphere with respect to oxygen content, inert gas content, and humidity. The effect of initial temperature and pressure is so slight that it can be neglected if the work is carried out under "room conditions." The effect of humidity is quite variable in that in some cases the moisture in the atmosphere might cause the dust particles to agglomerate and thus lessen the explosive probability; on the other hand, the presence of moisture might either enhance the explosion by causing a more rapid oxidation of the particles or deter the explosion by the formation of an insensitive oxide film. For metal dusts no generalization can be made, but for carbonaceous material it can be broadly stated that an increase in humidity tends to dampen the explosion even though violent explosions have been produced under highly humid conditions (3, 4).

The moisture content of the material affects the

explosions in the same general way as humidity except that experiments have shown that actual molecular moisture content lowers the explosibility of a material. This is indicated in Table I by the marked difference between sucrose ($C_{12}H_{22}O_{11}$), which contains no water of hydration, and lactose ($C_{12}H_{22}O_{11} \cdot H_2O$), which contains one molecule of hydration water. Other chemical properties which are of

TABLE I

COMPARATIVE EXPLOSIVE PROPERTIES OF SUGARS AND STARCHES (5)

Material in Dust Cloud	Concentration of Dust in Atmosphere (mg/l)	Maximum Explosion Pressure (psig)	Rates of Pressure Rise (psi/sec)	
			Avg. Rate	Max. Rate
Dextrose	100	19	126	278
	500	43	205	398
Sucrose	100	22	138	362
	500	31	167	526
Levulose	100	20	141	292
	500	45	316	665
Lactose	100	12	89	177
	500	22	82	168
Starch (Corn)	100	23	166	577
	500	43	360	863
Starch (Potato)	100	18	138	361
	500	38	257	722

major importance are ash and volatile matter contents, heat of combustion, and ease of oxidation. The last factor is dependent on the particle size and surface available for oxidation as well as the chemical nature of the material.

In nearly all of the work done on dust explosions the "minimum ignition temperature" has been used as a criterion of the ease of oxidation of the dusts. This temperature is defined as the lowest temperature at which a visible burning or flame propagation will take place and is a function of particle size in that as the material becomes finer, the ignition temperature is lowered. The standard test equipment used for this determination at the U. S. Bureau of Mines is the Godbert-Greenwald inflammability apparatus (6).

The shape of the particles as well as the shape and size of the test container are other factors which affect the explosiveness of the dusts, or more correctly, it could be said that the severity or magnitude of any experimental or accidental dust explosion is a function of the container, building, or structure in which the explosion occurs.

Causes of Dust Explosions

In order to have a dust explosion there must exist a suitable dust-gas mixture which must come in contact with a sufficiently intense heat source to cause ignition. Some of the dust properties affecting explosions have been discussed already, but even if these properties fall within the explosive range there must be an ignition source to initiate or cause an explosion. Elimination of the initiating sources would then naturally prevent all dust explosions except those

caused by static electrical discharge from the particles themselves; however, this means of initiation is of minor if not negligible importance.

The first and most important source of ignition is that provoked by careless smoking and matches. The safety movement of the past few years has somewhat eliminated smoking and the use of matches in and around plants where combustible materials are produced or handled, but the hazard of carelessness still exists. One example of what has happened in the past is cited by Price and Brown (2). A man went to a flour storage bin to see how much flour it contained. He was unable to see because of the dust raised by the incoming flour. It is presumed that he struck a match to see the flour level, and as a result of the momentary carelessness, an explosion occurred which killed the man and severely damaged the building.

The use of open flames and unshielded lights have also been responsible for a great number of explosions. One possible source of an explosion of this type could come about from the use of an acetylene welding torch in a machine shop where a dust cloud of metal grindings was created by sweeping the floor. There are many recorded explosions which were results of a similar, seemingly harmless, practice. Explosions resulting from small-scale fires could be placed in this same general class. A small fire which in itself

may be of a minor nature could become disastrous if allowed to create or come in contact with a cloud of dust. This obviates the necessity of eliminating all possible unnecessary dust collection sources throughout a plant.

The most prevalent source of ignition is probably from electrical causes such as sparks from motors, fuses, switches, short circuits, etc.. In addition to these more or less obvious potential igniters, there exist several others in connection with electric lights. It is possible for an explosion to stem from the breakage of a light bulb in an atmosphere of dust in air and also from the collection of dust on the bulbs themselves. In the latter case, a fire starting on an unshielded light bulb could drop to the floor and set up a chain of events which would rapidly become hazardous.

Another prevalent ignition potential can be found in crushing, grinding, and pulverizing equipment. Sparks from such operations could easily lead to a serious explosion. The major part of this type of ignition could probably be attributed to foreign material in the equipment; however, in the case of metal dusts there is always present the possibility of self-ignition. Again, many safety measures have been adopted to prevent explosions resulting from this type of source.

The final major ignition sources can be included

under static electricity and friction. Friction between some materials can create a static field or generate heat, either of which is capable of causing a dust explosion under suitable conditions. The neutralization of static charges and the dissipation of all possible friction heat has greatly reduced explosions initiated by static electricity and friction.

The elimination and control of all possible ignition sources would immediately reduce the dust explosion hazards in many industrial plants. Safety codes for this control have been published by the National Fire Protection Association (7) and much work on the subject has been done by the U. S. Bureau of Mines.

Prevention of Explosions

As has been pointed out in the previous section, the best means of preventing dust explosions is to eliminate and control all potential ignition sources. Special equipment has been designed for use in dusty industries to eliminate many dust-explosion hazards resulting from mechanical and electrical fixtures. Any charges of static electricity on machinery and drive-belts should be dissipated through the use of ground wires and brushes. Additional preventative measures can be incorporated in a safety program to insure that all workers are aware of the dust explosion hazard and understand the need for care in handling dusty materials.

The removal of all dust accumulation is in many cases difficult to accomplish, but wherever feasible this dust removal should be practiced. In other cases the explosive potential can be reduced by handling the operations, such as grinding, under an inert, gaseous atmosphere so that the formation of an explosive atmosphere becomes improbable. An inert dust, such as fuller's earth, can be used in some cases to accomplish the same dampening effect provided by the use of inert gases.

Other protective measures which could be adopted to lessen the effect of a dust explosion could be separation or isolation of the dust-producing operation, provision of suitable fire-fighting apparatus that would not disturb stagnant dust, and provision of adequate explosion vents in the roofing, walls, and heating and ventilating equipment. The use of vents is only a protective device and should not be misconstrued to be a preventative measure.

Industrial Dust Explosions

It may be generally stated that dust explosions have occurred ever since industrial plants have been producing inflammable dusts. The variety of the types of explosions may best be illustrated by citing a few actual cases as outlined by Price and Brown (2).

A dust explosion occurred in a flour mill in Kansas City, Missouri in 1922 which was of unusual interest because

of the fact that it occurred in a mill equipped with the latest type of machinery and dust-collecting equipment. The evidence available indicated that the explosion occurred in the rolls and was probably caused by sparks from foreign material passing through the rolls. The extent of the explosion was limited and confined to the dust-collecting equipment.

In 1920, an explosion occurred in the finishing department of a Wisconsin aluminum products plant. The explosion developed from a process which put a glossy finish on small aluminum peices by holding them against a rapidly revolving wire brush. Aluminum dust created in the process was drawn away from the polishers into a suction system which discharged into the open air. A heavy piece of steel wire fell into the exhaust pipe and sparks were created which ignited the dust. The initial explosion propagated back through the suction system and went into the polishing room, causing a secondary explosion which was felt two miles from the plant.

A portion of a Brooklyn, New York sugar refinery was destroyed by an explosion in 1917 that resulted in the loss of twelve lives and property damage in excess of \$1,000,000. It was believed that the explosion originated in the sugar pulverizing machinery and that it propagated to the dust clouds present in the storage bins, and then throughout the

other various parts of the plant. The fire which followed the explosion spread rapidly and was unchecked since the sprinkler system was destroyed by the initial explosion.

There are records of other explosions from dusts of starch, rice, wood, sulfur, metal, cork, rubber, plastics, and many others too numerous to mention. Tables II and III give some further indication of the scope of dust explosions in this country. It should be pointed out that these tables include only cases reported to the National Fire Protection Association and exclude dust explosions in mines and military ordnance plants.

TABLE II: DUST EXPLOSIONS IN THE UNITED STATES (7)
(to July 1, 1949)

<u>Material Classification</u>	<u>Number of Explosions</u>	<u>Number Killed</u>	<u>Number Injured</u>	<u>Amount of Losses</u>
Coal Dust	32	28	31	\$ 427,659
Coffee Dust	11	5	13	201,700
Cork Dust	37	6	28	181,190
Cotton Dust	16	6	12	264,070
Feed & Cereal Dusts	108	63	230	8,866,977
Fertilizer Dusts	26	7	20	852,450
Flour Dusts	105	33	88	11,526,545
Grain Dusts	185	124	331	38,318,507
Malt Dust	24	2	18	1,804,500
Metal Dusts	62	68	151	2,247,465
Pitch & Resin Dusts	5	12	47	2,055,300
Plastic Dusts	24	12	45	507,972
Rubber Dust	8	11	2	410,300
Seed & Seed Products Dusts	8	8	5	1,967,000
Starch & Corn Products Dusts	42	146	146	10,493,326
Sugar Dust	26	12	31	1,722,300
Wood Dust	123	29	150	6,717,904
Other Dusts	94	26	118	2,749,815
Totals	936	598	1,466	\$91,314,980

TABLE III: RECORD OF DUST EXPLOSIONS AND CAUSES (7)

<u>Date</u>	<u>Location</u>	<u>Dust</u>	<u>Cause</u>	<u>Damage</u>
Dec., 1926	Chicago, Ill.	Flour	Faulty electric switch	\$150,000
May, 1947	Hutchinson, Kan.	Flour	Pulley friction	200,000
Apr., 1947	Dodge City, Kan.	Flour	Friction spark	450,000
Feb., 1932	Kansas City, Mo.	Grain	Small fire	512,000
July, 1933	Minneapolis, Minn.	Grain	Hot bearing	125,000
May, 1934	Painesville, Ohio	Bronze	Metallic spark	100,000
Mar., 1944	Maywood, Calif.	Magnesium	Grinding	65,000
Apr., 1944	Pemberton, N.J.	Celotex	Spontaneous ignition	338,000
Feb., 1948	Elyria, Ohio	Plastics	Friction or static spark	115,000
Jan., 1945	Fremont, Ohio	Rubber	Electric spark	380,000
Jan., 1924	Pekin, Ill.	Starch	Overheated bearing	750,000
Sept., 1948	Chicago, Ill.	Starch	Fire in dryer	5,000,000
Oct., 1945	Alma, Mich.	Sugar	Clogged dust collector	100,000
Apr., 1945	Pine Bluff, Ark.	Wood	Boiler spark	124,000
Mar., 1945	Ashelot, N.H.	Paper	Motor sparks	75,000
Sept., 1944	Ft. Worth, Tex.	Cotton	Broken light bulb	75,000

PREVIOUS WORK ON DUST EXPLOSIONS

Following a series of disastrous coal dust explosions in the United States in 1907, the U. S. Bureau of Mines in the Department of the Interior began investigations into the causes of dust explosions in mines and industrial plants and to develop means of prevention. The U. S. Department of Agriculture assumed the responsibility for these investigations in 1914 and continued the work until around 1940 when it was transferred back to the Bureau of Mines which has conducted nearly all dust explosion studies done in this country since 1940.

Price and Brown (2) summarized and correlated all of the information available prior to 1922. Their book has become a standard reference on the subject of dust explosions and is rather extensive in the treatment of underlying theories as well as explaining the nature of industries that are prone to dust explosions, the preventative measures generally recommended, the causes of explosions, and historical background of dust explosions. This book also contains a complete and comprehensive bibliography of work done pertaining to dust explosions prior to 1922. Considering the importance of dust explosions, it is difficult to understand the lack of basic research on the subject during the past half century.

In 1935, Edwards and Leinbach (5) published data showing the maximum explosion pressure, the average rate of pressure rise, and the maximum rate of pressure rise for over a hundred agricultural and other dusts. These data were obtained with a modified Clement-Frazer apparatus having a volume of 0.049 cubic feet, in conjunction with a British coal-dust recording type manometer. However, only a few tests were made with each dust and these were for only two concentrations. Some of the results of this work are shown in Table I.

In addition to the work of the U. S. Department of Agriculture, information on natural carbonaceous materials has been obtained by the Underwriters' Laboratories (8) and the Bureau of Mines (3, 9) which deals with explosions of starch dusts. The Underwriters' Laboratories work was primarily concerned with maximum explosion pressures and rates of pressure development in a 20 cubic foot cylindrical explosion chamber approximately 7 feet long by 2 feet in diameter. The Bureau of Mines studied essentially the same factors using the Hartmann explosion-test apparatus which consists essentially of a 2.75 inch inside diameter lucite cylinder 12 inches long, a volume of 0.041 cubic feet. The work of the Bureau of Mines also included information on relative inflammability, ignition temperature, and minimum ignition energy. The results obtained from these separate

investigations are in wide disagreement, a fact which can in large part be attributed to the great difference in size of the test equipment, methods of dust dispersion, ignition, etc..

Dust explosion hazards resulting from metal powders were investigated by the Bureau of Mines in an attempt to obtain information on the extent of the hazards, the number of explosions, and the amount of damage and loss resulting from explosions of metallic dusts. Brown (10, 11) investigated the ignition temperatures, explosive limits, and pressures developed by dusts of aluminum, magnesium, and zinc and correlated existing data to determine the extent of the hazard and the need for measures of prevention and protection from dust explosions. A later work by Hartmann, Nagy, and Brown (6) treats the problem of metallic dust explosion in a more comprehensive manner and deals with many metals not previously studied including powders from atomization, vapor condensation, carbonyl decomposition, milling, reduction, and stamping. The metals studied were aluminum, antimony, iron, magnesium, manganese, silicon, tin, titanium, zinc zirconium, and two alloys of magnesium and aluminum. In addition to the ignition temperatures and pressure data, this work presented information on relative inflammability, minimum cloud density, minimum ignition energy, and effects of inert gases. The equipment used for

explosive testing was the Hartmann apparatus.

The most recent addition to the family of dangerous dusts has been from the plastics industry which thus far has experienced very few major explosions; but where, nevertheless, the potential hazard is a large one. Hartmann and Nagy (12) have investigated the problem and compiled information for plastics of the same type which was collected for metals, as reviewed above. The materials dealt with were representative of all dusts and powders likely to be produced or used in the industry; this included resins from ten different base materials and molding compounds of seven different types as well as primary ingredients for resins and fillers for molding compounds. Their findings indicate that the potential explosion hazard for plastic powders is of the same order of magnitude as that for metal dusts, which puts them, as a class, in a comparable explosive position with the more explosive carbonaceous dusts such as sugar and starch.

In Great Britain the principal worker in the field has been R. V. Wheeler (13, 14) who has done much work on coal dusts as well as on a wide variety of other dusts. Wheeler's general classifications of explosive materials is presented partially in Table IV. Even though some of his work has been revised, the table still holds as a good indication of relative dangers existing from certain dusts.

The classification Wheeler established is:

Class I: Dusts which ignite and readily propagate flame, the heat source required for ignition being small; for example, a match or cigarette.

Class II: Dusts which are readily ignited but which require a large heat source such as an electric arc to cause a flame propagation.

Class III: Dusts which do not appear to be capable of propagating flame under any probable factory conditions; because (a) they do not readily form a cloud in air, (b) they are contaminated with a large quantity of incombustible material, or (c) the material does not burn rapidly enough. The materials are arranged in each class roughly according to their relative potential explosion hazard.

The criteria used to establish this classification were the determination of minimum ignition temperatures and the study of relative ignition temperatures and flame propagation properties of the dusts.

Some of the results of other investigations which have been conducted on dust explosions are listed in Table V and VI which give a further indication of the relative dangers existing from different dusts.

The relative flammability as used in Table VI is defined as the percentage by weight of inert dust (usually calcined fuller's earth) required in a mixture of flammable

TABLE IV: CLASSIFICATION OF EXPLOSIVE DUSTS (13)

<u>Class I</u>	<u>Class II</u>	<u>Class III</u>
Sugar	Copal gum	Tobacco
Dextrine	Leather	Spice milling
Starch	"Dead" cork	Bone meal
Cocoa	Rice (milling)	Lamp black
Rice meal	Sawdust	Retort carbon
Cork	Castor bean	Grain (cleaning)
Soya bean	Paper	Tapioca
Wood flour	Yellow meal	Drug grinding
Malt	Oil cake	Cotton seed
Grain (flour mill)	Grist milling	Charcoal
Distillery meal	Horn meal	Foundry blacking
Cellulose acetate	Shoddy	Brush carbon
Tea	Shellac	Stale coke
Grain (storage)		Bone charcoal
Corn flour		Rag paper
Wheat flour		
Chicory		
Phonograph record		

dust to prevent ignition and flame propagation when the mixture is dispersed into a dust cloud in the presence of a standard source of ignition (12).

In addition to the work on the explosibility of powders and dusts, the U. S. Bureau of Mines has also conducted research into the use of diaphragms and other devices for venting dust explosions (15, 16). These studies were primarily concerned with the possible industrial application of blow-out discs, hinged panels, and glass panes to relieve the pressures developed during an explosion and thus minimize the damages which would result. The materials tested for possible vent closure application included plasticized cloth netting, kraft paper, builders' paper, aluminum foil, steel swinging panels, and many other materials and variations. The information which has been and is still being obtained will furnish important design data for equipment in dust handling industries.

TABLE V: EXPLOSIVE PROPERTIES OF DUSTS

Material	Ignition Temp. (°C)	Maximum Press. (psig)	Maximum Rate (psi/sec)	Average Rate (psi/sec)	Reference
Starch	470	72	2150	1050	4
Starch	-	75	240	105	8
Starch	480	78	1650	1050	3
Starch	380	51	1590	830	12
Starch	-	43	863	360	5
Aluminum	645	89	5700	2150	4
Aluminum	645	62	5700	2170	8
Magnesium	520	72	4750	4400	4
Magnesium	670	72	4760	1450	6
Hard rubber	350	57	3350	850	4
Sulfur	190	41	1450	600	4
Coal	610	46	780	370	12
Soap	430	60	1300	660	4
Polystyrene	490	44	650	350	12
Phenol resin	580	51	3160	1370	12
Cellulose Acetate	420	68	1740	800	12
Shellac	400	56	2170	850	12
Urea resin	510	65	780	300	12
Sugar (Sucrose)	410	31	526	167	5
Dextrose	-	43	398	205	5
Synt. Rubber	320	59	1870	740	12
Vinyl Acetate	550	49	490	250	12

TABLE VI: RELATIVE FLAMMABILITY OF DUSTS (17)

<u>Material</u>	<u>Relative Flammability</u>
<u>Organic Dusts</u>	
Cellulose acetate resin	90 plus
Polystyrene resin	90 plus
Synthetic-rubber molding compound	90 plus
Lignin resin	90 plus
Phenolic resin	90 plus
Shellac resin	90 plus
Cellulose acetate molding compounds	90 plus
Urea resin	80
Corn and cornstarch	70
Bituminous coal	65
Potato starch	57
Wheat flour	55
Tobacco	20
<u>Metallic Dusts</u>	
Magnesium	90 plus
Zirconium	90 plus
Dow metal	90
Iron	85-90
Aluminum	80
Antimony	65
Manganese	40
Zinc	35
Cadmium	18

THEORY OF DUST EXPLOSIONS

Comparison of Dust Explosions and Gas Explosions

In a gas explosion there are two basic steps, the ignition and the propagation. If an explosive gas mixture comes in contact with an ignition source, a rapid combustion process is initiated which becomes self-sustaining and which spreads throughout the area of the inflammable mixture. There is an optimum concentration for inflammable gas mixtures at which a maximum flame propagation rate occurs and the maximum pressure is developed if the mixture is confined and the combustion process is explosive in nature. From the optimum point, a shift in concentration causes a lessening in the explosive violence until a point is reached where the gas concentration is too low to support explosive combustion or where the concentration becomes too high to support it. At the lower limit, it can be conceived that the gas particles are too far apart to establish the chain reaction needed; at the higher limit, the oxygen content of the gas becomes insufficient to support the reaction.

The nature of dust explosions is much the same as that for gases, and every requirement and feature of gas explosions must apply if there is to be a dust explosion. There is also an upper and lower limit for explosive dust concentrations, and a particular point at which the most

violent explosion will be produced. Morgan (18) has made investigations which have demonstrated that there is an actual upper limit for dusts, but that in most cases it is so great that for all practical purposes it does not exist. In the case of sugar, Beyersdorfer (19) calculated the lowest concentration at which sugar dust would explode to be 17.5 grams per cubic meter and the highest to be 13,500 grams.

As has been previously pointed out there are some factors affecting dust explosions which are not precisely analogous to any affecting gases, the principal one being particle size or surface. In gases, the particles are of molecular dimensions; whereas, for dusts the particles are macroscopic, and the explosions developed become a function of surface and concentration rather than concentration alone if all other factors remain the same.

Flame and Pressure Propagation

An explosion reaction is characterized by the fact that the reaction velocity increases with time until the balance of explosive conditions is offset and the reaction ceases. According to Jost (20) if a pressure-time curve of a bomb explosion takes a course similar to those shown in Figures 6, 7, and 8 the mass conversion velocity increases as the explosion increases. Assuming a spherical combustion chamber it becomes possible to derive formulae which will

give an approximation of the flame velocity or pressure velocity, the two being closely related.

Let us take a spherical bomb of radius R_0 which is ignited in the center at time t_0 ; the initial pressure is P_0 , the maximum pressure is P_e , and up to a certain time t , in which the material consumed has been exploded, the pressure is P . The simplest possible relation between the rise in pressure and conversion α is:

$$\alpha = \frac{P - P_0}{P_e - P_0} = \left[\frac{r_0}{R_0} \right]^3 \quad (1)$$

Jost has shown that this equation is reasonable and valid and can be applied to explosion processes in bombs. Using the pressure-time curve of an explosion along with equation (1), the actual burning velocity can be calculated for a given initial mol ratio of oxygen to combustible material, assuming a spherical flame front. From this equation, the radius r_0 of the sphere occupied by the gas mass burned up to time t can be calculated, and dr_0/dt can be obtained from a diagram of r_0 vs. t . The volume of a spherical shell of radius r_0 and thickness dr_0 is

$$4\pi r_0^2 dr_0$$

As this shell is reached by the flame it is expanded to the greater value r_e and reaches a temperature T and a pressure

P. Its volume is now

$$4\pi r_o^2 dr_o (P_o/P)(T/T_o)$$

Over the time dt , the burning zone has progressed a distance of $V_n dt$, where V_n represents the average flame velocity. If the thickness of the original gas layer is such that the gas progresses through it in the time dt , then

$$4\pi r_o^2 V_n dt = 4\pi r_o^2 dr_o (P_o/P)(T/T_o) \quad (2)$$

Since the compression of the gases has been assumed to be adiabatic

$$T/T_o = (P_o/P)^{1 - 1/k} \quad (3)$$

and the velocity equation becomes

$$V_n = (r_o/r_e)^2 (P_o/P)^{1/k} (dr_o/dt) \quad (4)$$

- V_n - average flame velocity
- r_o - initial sphere radius to contain material burned
- r_e - radius of burned sphere at time t
- P_o - initial pressure
- P - pressure at time t
- t - time
- k - C_p/C_v for gases

This equation has been applied to gaseous explosion processes and gives approximate flame velocities for dusts if it is assumed that the dispersed solid exists as a gas. However, it is applicable only to explosions in closed

vessels whose shape approximates a sphere and does not apply to flame propagation in long tubes or cylinders. Lewis and von Elbe (21) used the method described above to calculate velocities in explosions of ozone-oxygen mixtures and their results are of the same order of magnitude which would be expected with dust explosions.

A comprehensive discussion of flame and pressure propagations resulting from explosions in closed vessels is presented by Jost (20) and Lewis and von Elbe (22).

Explosions in Closed Vessels

When an explosion occurs in a closed container the rate of pressure increase is a function of the size and shape of the vessel. In vessels whose dimensions do not differ widely in any direction, such as a wide, short cylinder, the flame and pressure propagations developed are essentially the same as for spheres, the primary difference being that in the latter stages, the pressure or flame front adapts itself to the shape of the container. The wall effects experienced constitute a possible distortion of the propagation, since they may have a cooling or deactivating effect; or on the other hand, they can have an enhancing effect by virtue of the walls being somewhat coated with dust. The errors involved are in all probability of negligible interest and do not seem to be major contributing or deterring factors.

Mechanistic Considerations

Two Germans, Beyersdorfer (19) and Jaeckel (23, 24), in their work with sugar dusts hypothesized that the explosions occurred in two phases; first, the gasification of the dust; and second, the oxidation of the sugar gases. It was supposed that the gases formed from the sugar were hydrogen, carbon monoxide, and methane which were easily ignited and initiated the explosion. These, in turn, directly ignited the dust. French experimenters, Taffenel and Durr (25) conducted tests on inflammability of coal dusts in which a coal of a known volatile matter content was blown through a heated porcelain tube at 700° C., at which temperature it did not inflame. On analysis of the dust, it was found that the volatile matter content of the coal had decreased; a fact which was considered to demonstrate that the evolution of volatile matter precedes inflammation of dust clouds.

On the other hand, British experimenters (26) conclude that even though volatile matter is released on heating of coals to the ignition temperature, the amount of gas given off in the normal period of contact appears insufficient to form an explosive gas mixture throughout the cloud. The conclusion drawn from this work is that the initiation and propagation of dust explosions in the early stages takes place in the same manner as in the later stages, that is by

rapid oxidation of the dust particles themselves. In this country, the U. S. Bureau of Mines (27) attacked the problem of mechanism from two different aspects, one being to drop a heated ball through a dust cloud and the other being to raise the dust cloud with a blast of hot gas heated to a temperature sufficient to cause ignition of the dust. In both cases, when there was an oxygen containing atmosphere, ignitions were obtained. Using a nitrogen atmosphere, it was possible to analyze the gases given off in the momentary heating of the dusts.

As a result of these two independent investigations, it is evident that it is possible to inflame dust suspensions in air under conditions where the gasification of the dust appears to be so slight that it can not be considered to be an effective factor in causing ignition. An alternate explanation seems to be that the finely divided dust particles are directly attacked by oxygen. The size of the dust particles is an extremely important factor in this relative flammability of dusts.

It is quite true that dust particles in a cloud present a large surface from which there could be a rapid distillation of gases when exposed to a heated surface. However, the volatile content of many potentially dangerous dusts is so low that, coupled with the above argument, it seems to prove that in the ignition of a dust cloud there is

a rapid oxidation of the particles themselves rather than a gasification process which leads to either a gas explosion or a combination gas-dust explosion.

Postulation of an actual explosion mechanism for carbonaceous materials, such as sugar or starch, is extremely difficult, since even the very simplest explosion processes are not well understood or clearly defined. Consider, for example, the reaction between hydrogen and oxygen as outlined by Laidler (28):

- (1) $\text{H}_2 \longrightarrow 2 \text{H}$
- (2) $\text{H} + \text{O}_2 \longrightarrow \text{OH} + \text{O}$
- (3) $\text{O} + \text{H}_2 \longrightarrow \text{OH} + \text{H}$
- (4) $\text{H} + \text{O}_2 \longrightarrow \text{HO}_2$
- (5) $\text{HO}_2 \longrightarrow \text{destruction at surface}$
- (6) $\text{HO}_2 + \text{H}_2 \longrightarrow \text{H}_2\text{O} + \text{OH}$
- (7) $\text{H} \longrightarrow \text{destruction at surface}$
- (8) $\text{OH} \longrightarrow \text{destruction at surface}$

This simple process, as may be seen, involves at least eight possible steps.

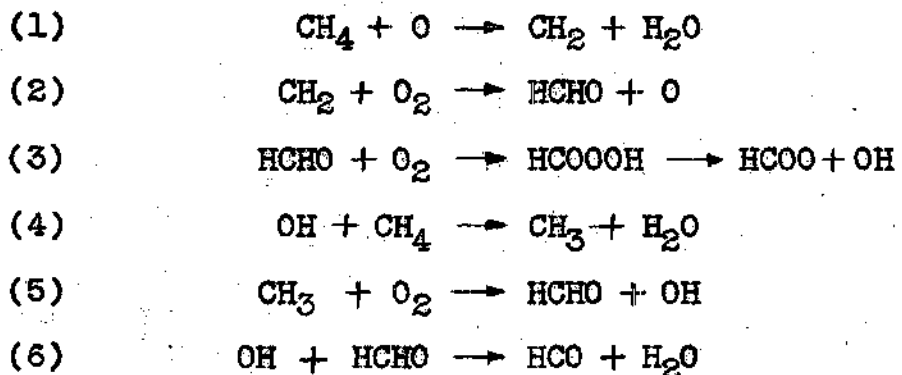
Assuming that the rates of equations (7) and (8) are of negligible importance, the application of a steady-state treatment gives the following expression for the rate of reaction for hydrogen and oxygen combustion. In the following equation, each "K" represents a rate constant, t is time,

and (H_2O) , (M) , and (H_2) represent concentrations of water, inert gases, and hydrogen.

$$\frac{d(H_2O)}{dt} = \frac{K_1 \left[\frac{1.5 K_5 + 2 K_6(H_2)}{K_5 + K_6(H_2)} \right]}{1 - \left[\frac{2 K_2}{K_4(M)} \right] - \left[\frac{K_6(H_2)}{K_5 + K_6(H_2)} \right]} \quad (5)$$

The complexity of this "simple" equation may well serve as an indication of the nature of the mechanism involved in dust explosions where the particle size or surface would also become a contributing factor. For monatomic dusts, such as metals, the above approach could be applied with little difficulty. For polyatomic dusts, the problem becomes more complex.

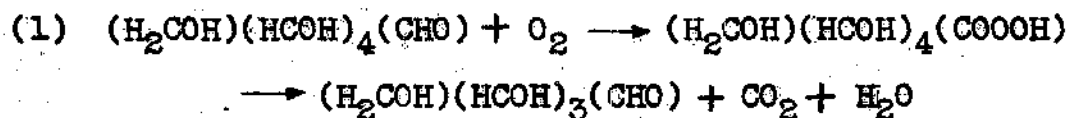
A brief consideration of the mechanism for methane oxidation as outlined by Jost (20) may further indicate the nature of the pattern which would be encountered in analyzing dust explosions of polyatomic molecules. According to Jost, the probable pattern for methane oxidation is:

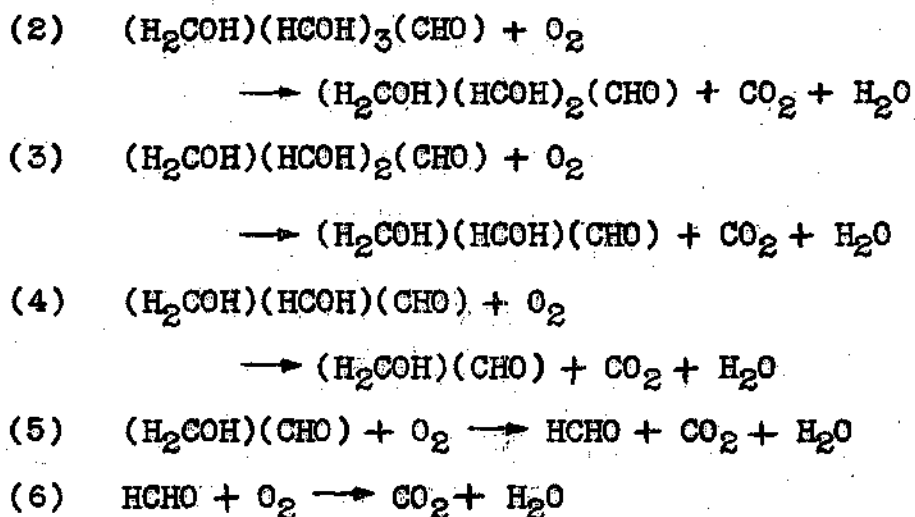


- (7) $\text{HCO} + \text{O}_2 \rightarrow \text{HO}_2 + \text{CO}$
 (8) $\text{HO}_2 + \text{HCHO} \rightarrow \text{H}_2\text{O} + \text{CO} + \text{OH}$
 (9) $\text{OH} \rightarrow \text{destruction at surface}$
 (10) $\text{HO}_2 + \text{HCHO} + \text{O}_2 \rightarrow \text{CO}_2 + 3 \text{OH}$
 (11) $\text{HCHO} + \text{HCO} \rightarrow \text{CH(OH)CHO}$
 (12) $\text{CH(OH)CHO} + \text{O}_2 \rightarrow 2 \text{CO} + \text{H}_2\text{O} + \text{OH}$
 (13) $2 \text{CO} + \text{O}_2 \rightarrow \text{CO}_2$

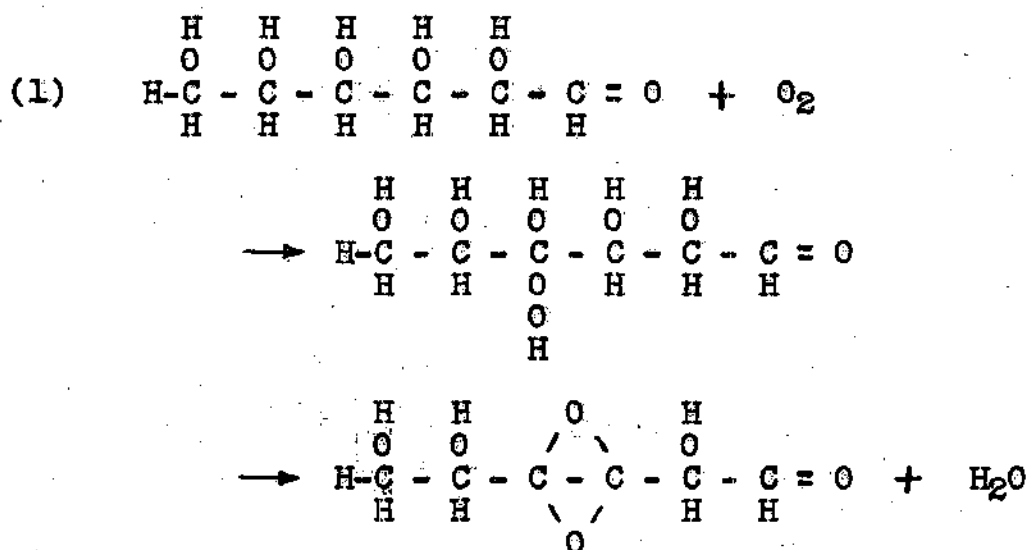
The various radicals which are introduced make this reaction somewhat more complex than the hydrogen-oxygen reaction, and the calculation of the overall reaction rate involves the introduction of twelve individual rate constants whereas the simpler reaction required only six.

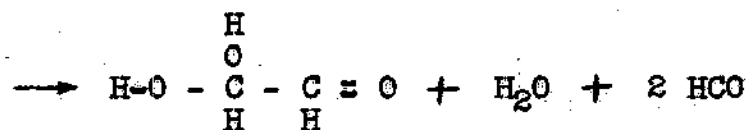
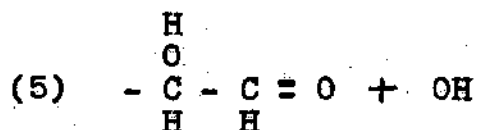
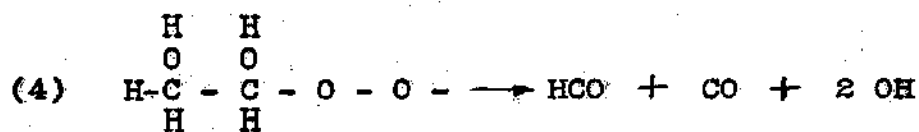
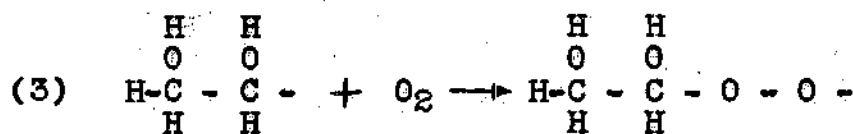
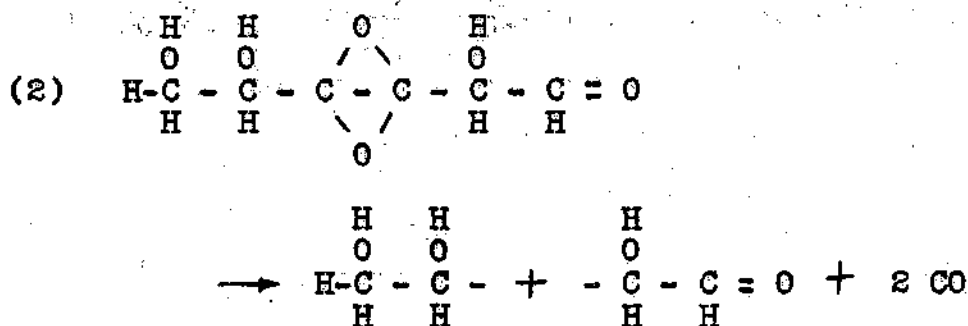
The progression in this manner can now be applied to reactions involving more complex molecules. It can be imagined that the same general mechanism would apply to dust explosions involving sugars and the destruction of the molecule would follow the same pattern. As an example, let us propose a possible mechanism for the combustion of a hexose. From equation (2) above, it can be seen that the chain induction starts from an aldehyde structure. We can then write the very simplest possible mechanism as follows:



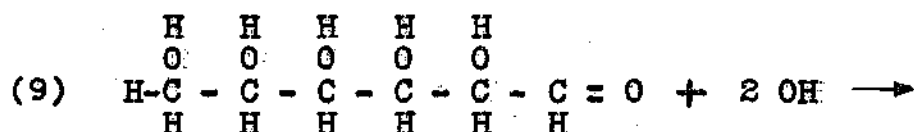


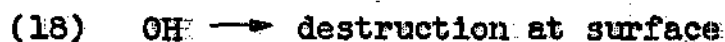
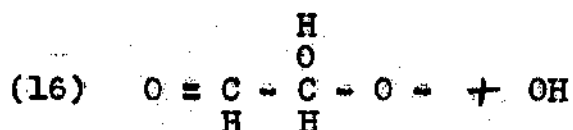
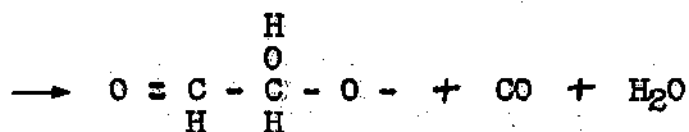
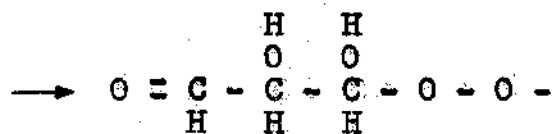
This simple mechanism assumes that the oxidation is a point by point destruction of the aldehyde structure and introduces no proposed chain branching or breaking. A more plausible mechanism would be one in which some chain breaking and/or branching takes place. This should follow from the fact that the mass conversion rates do increase. A more general mechanism would then be:





In addition to being destroyed at the surface, the OH radical could also attack another molecule thereby initiating another chain mechanism. For example:





It should be pointed out that this is an oversimplified mechanism in that it assumes central molecular attack and offers only one highly active radical, OH, where two or more probably exist. However, this mechanism with its variable forms provides a more logical pattern than the one set forth initially and is also more compatible with the mechanistic theory for larger molecules as outlined by Jost (20) and Lewis and von Elbe (22).

EQUIPMENT AND ACCESSORIES

Explosion Chamber

The chamber used for making explosion tests of the dusts was a ten gallon (1.86 cubic feet), cylindrical, pressed steel tank with a hemispherical bottom. The tank walls were one-eighth inch thick and were rated as safe at operating pressures up to 110 psig.. This was considered safe for this work since the maximum pressures recorded for dust explosions of carbonaceous materials of the type to be tested were found to be less than 80 psig.. As an additional safety factor, the tank was equipped with a pressure-relief valve set to open at a pressure of 110 psig.. An opening in the bottom of the tank provided a convenient method of attaching the dust dispersion equipment to the system. The pressure recording devices and the vacuum pump were connected to the system through a $\frac{1}{4}$ inch pipe fastened to the side of the tank.

The top of the tank was fastened in place by means of eight large wing bolts which when tightened gave an airtight gasketed seal between the tank and the removable top. The top was fitted with the electrical leads which connected to the ignition system. The overall schematic diagram of the explosion chamber and test equipment is shown in Figure 1. More detailed descriptions of the test equipment are shown in Figures 2, 3, and 4.

Dispersion Equipment

The dust clouds to be tested were created by causing a blast of air from a small steel bomb (approximately 2 cubic inches) to blow the sample out of a polished brass funnel upwards into the tank. A pressure gauge was attached to this dispersion bomb. This gauge was needed since it was desirable to use the same bomb pressure in all experimental tests. The bomb design is shown in Figure 2b.

The actual dispersion cup was a polished brass funnel (Figure 2a) machined in such a way that a blast of air through a $3/32$ inch hole at the apex of the cone would completely clear the funnel of the dust sample and, at the same time, produce a reasonable uniform cloud. The desired dispersion was obtained by inserting a small brass float which was anchored so that it could rise only $\frac{1}{2}$ inch above the apex of the funnel. The float was attached to one end of a $1/16$ inch diameter brass rod, the other end of which was enlarged so that it would stop the vertical movement when the enlargement reached a perforated brass disc. The float required a pressure of 175-200 pounds for operation, this being the approximate pressure needed to raise the float. Once raised, its position caused the air from the bomb to impinge on the sides of the cone and blow the dust upwards into the tank. It also served as a check valve for the dust sample by keeping it in the funnel and not

allowing it to sift through the small hole and out of the tank.

Before the float control method of dust dispersion was adopted, attempts were made to obtain uniform dispersions with an unanchored float and also with no float at all. Both of these attempts were unsuccessful since neither method permitted the dust to be completely swept from the dispersion cone but only allowed the central core of the sample to be blown into the tank. The dispersion cone and the bomb were separated by an electrically operated magnetic valve which instantaneously released the air from the dispersion bomb, thereby creating the cloud and initiating the explosion.

Ignition System

The ignition system is illustrated in Figure 3. The actual ignitions of the dust clouds were accomplished by use of a high voltage electric spark between two pointed brass electrodes which were held in place in the explosion chamber by insulated copper tubing which was attached to the tank top. The high voltage was obtained by means of a 5000 volt, 150 milliamperes transformer with a 115 volt primary. A voltmeter, variable transformer, and fuse were connected on the primary side of the system to afford a means of controlling the power input. The secondary side contained a small neon tube wired in series so that a bright glow was an indication of spark operation and consequently an indi-

cation that explosive conditions could be produced in the chamber.

Pressure Recording Equipment

A sidearm of $\frac{1}{4}$ inch brass pipe was mounted on the tank as shown in the schematic diagram of Figure 1. Connected to this sidearm were two Bourdon-tube pressure gauges and a small vacuum pump. One of the gauges was of a compound type (0-30 inches of mercury; 0-150 psi) which served as a guide for the removal of air and atmospheric moisture from the tank by the vacuum pump and also as an indicator of the maximum pressures developed by the explosions. The second gauge was fitted with two bamboo pointers which were used to record the explosion pressure on a rotating, soot-blackened cylinder. A ten inch stylus was used for pressures up to 40 pounds and a six inch stylus for pressures above this.

For recording pressures, the tip of the pointer made contact with the blackened drum of a Phipps and Bird high speed kymograph. The instrument consisted primarily of a six inch diameter, six inch high cylinder which was turned at a linear rate of 200 inches per minute by a synchronous motor. The stylus trackings obtained from this drum gave pressure-time records from which the various rate data could be calculated. Sample stylus trackings are shown in Figures 6, 7, and 8.

The operation of the high voltage arc, the solenoid valve, the vacuum pump, and the kymograph were all controlled through a central control system diagrammed in Figure 4.

Surface Measurement Apparatus

The equipment used for measurement of the specific surfaces of the sugar dusts was the Blaine air permeability apparatus (29) illustrated in Figure 5. The apparatus consisted essentially of a brass permeability cell of 1.27 centimeters inside diameter. The bottom of the cell contained a brass disc 1.0 millimeter thick with approximately thirty 1-millimeter holes evenly distributed over its area. The disc fitted snugly into the bottom of the cell.

The plunger was machined to not less than 0.1 millimeter smaller than the inside cell diameter. The plunger was provided with an air vent on one side as indicated in the diagram. The top of the plunger was collared so that when in position there was a distance of 1.5 centimeters between the bottom of the plunger and the perforated disc. This 1.5 centimeter cavity contained the dust to be tested and one filter paper disc on the top and bottom of the sample.

The U-tube manometer was constructed of 9-millimeter outside diameter glass tubing. The top of one arm of the

manometer was connected to the base of the permeability cell. This arm was marked with calibration lines at 1.5, 7.0, and 11.0 centimeters above the midpoint. This arm was also provided with a side outlet 25 to 30 centimeters above the bottom of the manometer. This side arm was for evacuation of the manometer arm connected to the permeability cell.

Auxiliary Equipment

In addition to the equipment described above, this work made use of a set of U. S. Standard screens for size separation and a Fisher Precision Model gas analyzer (30). The gas analysis apparatus contained a potassium hydroxide solution for carbon dioxide absorption, a potassium hydroxide-potassium pyrogallate solution for oxygen absorption, and a fractional combustion unit for oxidation of carbon monoxide to carbon dioxide.

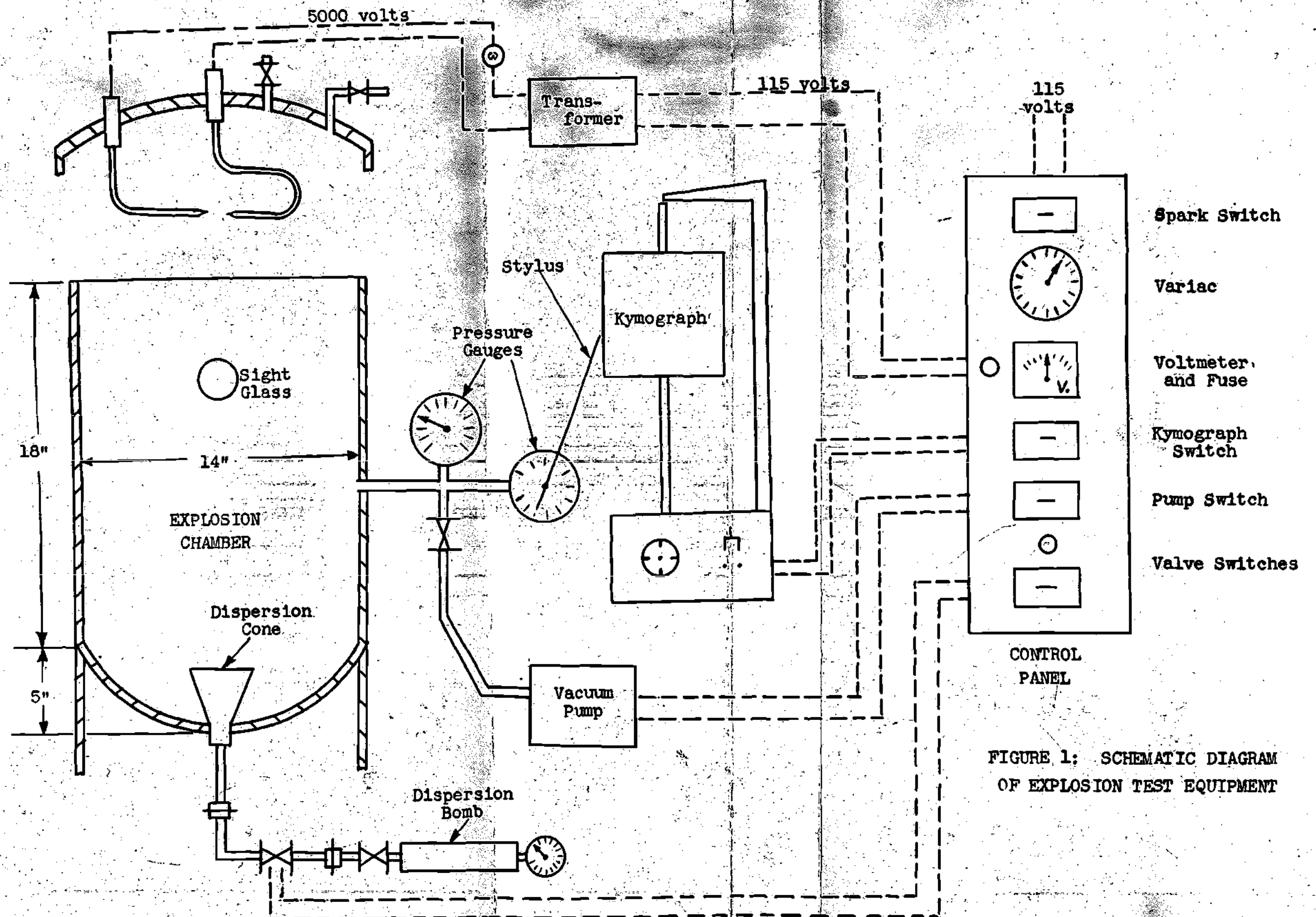
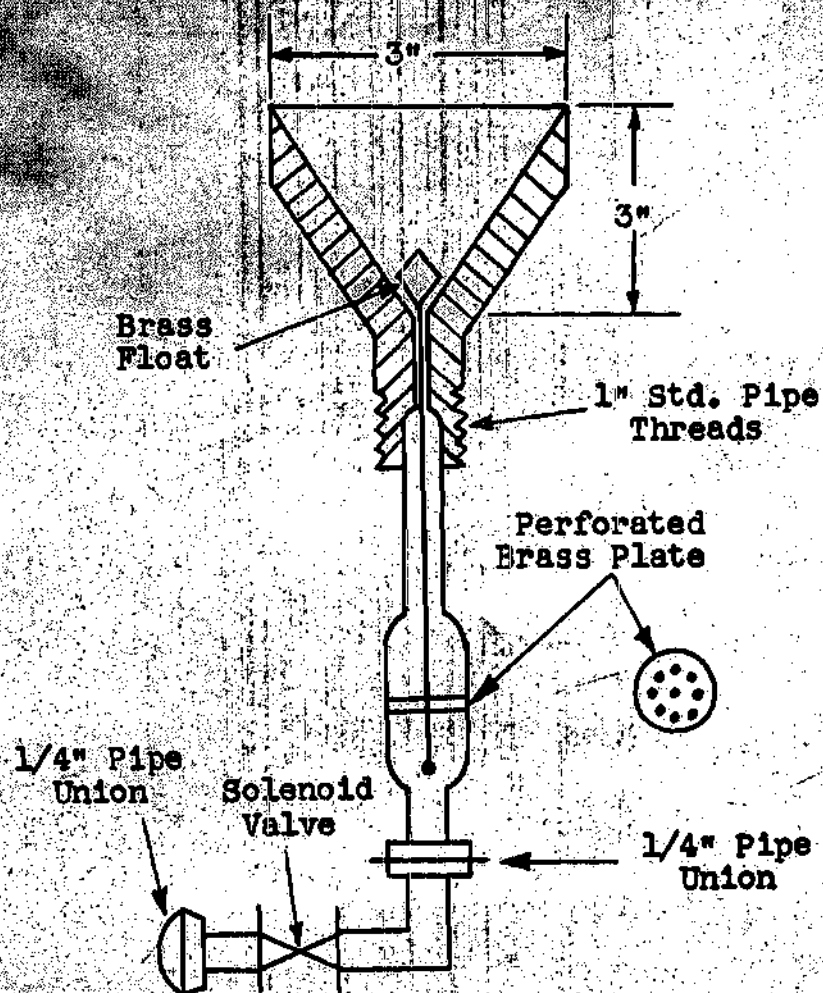
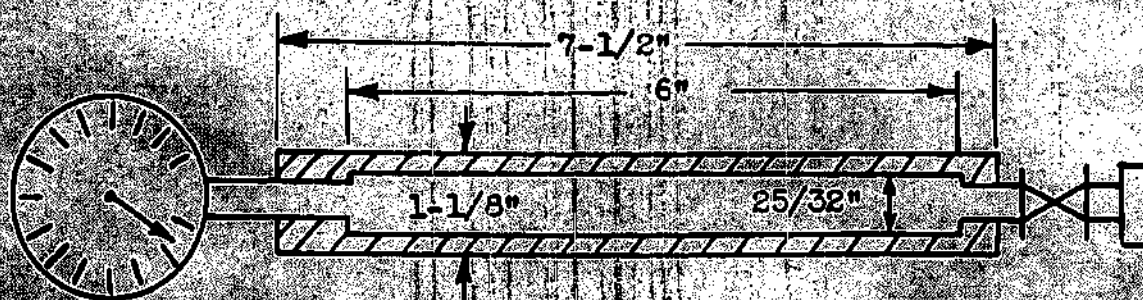


FIGURE 1: SCHEMATIC DIAGRAM
OF EXPLOSION TEST EQUIPMENT



(a)



(b)

FIGURE 2: DISPERSION SYSTEM

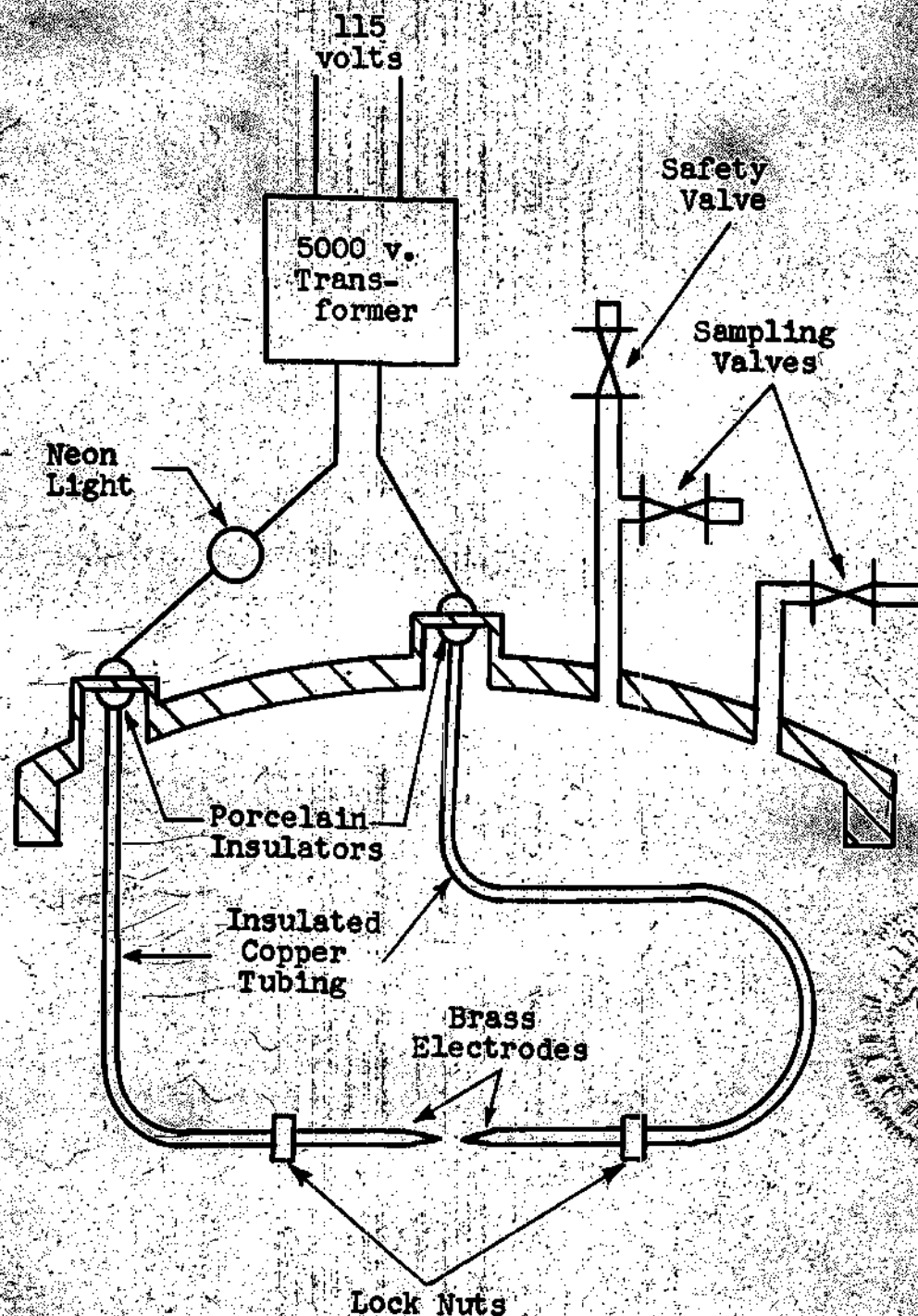


FIGURE 3: IGNITION SYSTEM AND TOP

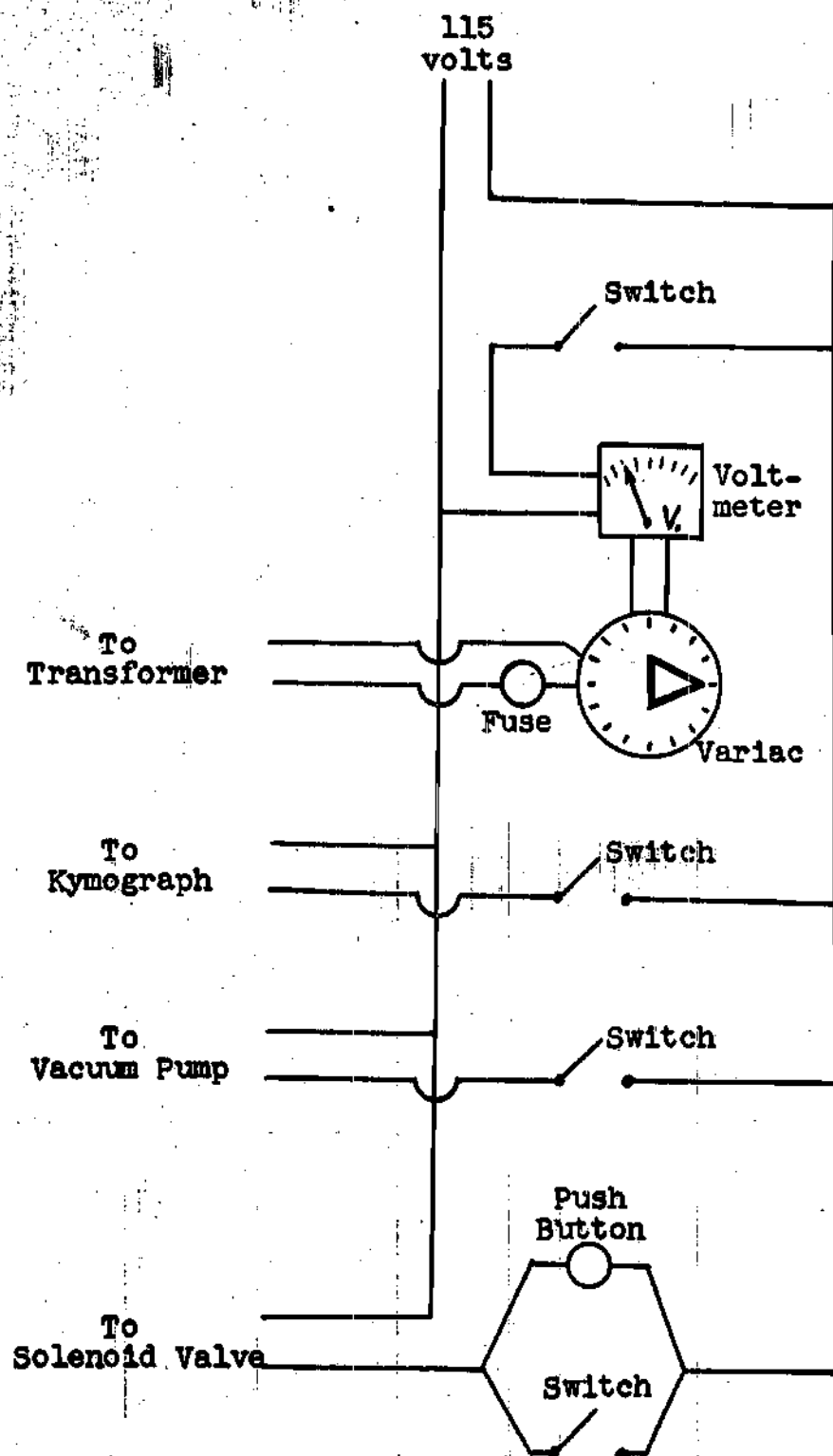


FIGURE 4: ELECTRICAL CONTROL SYSTEM

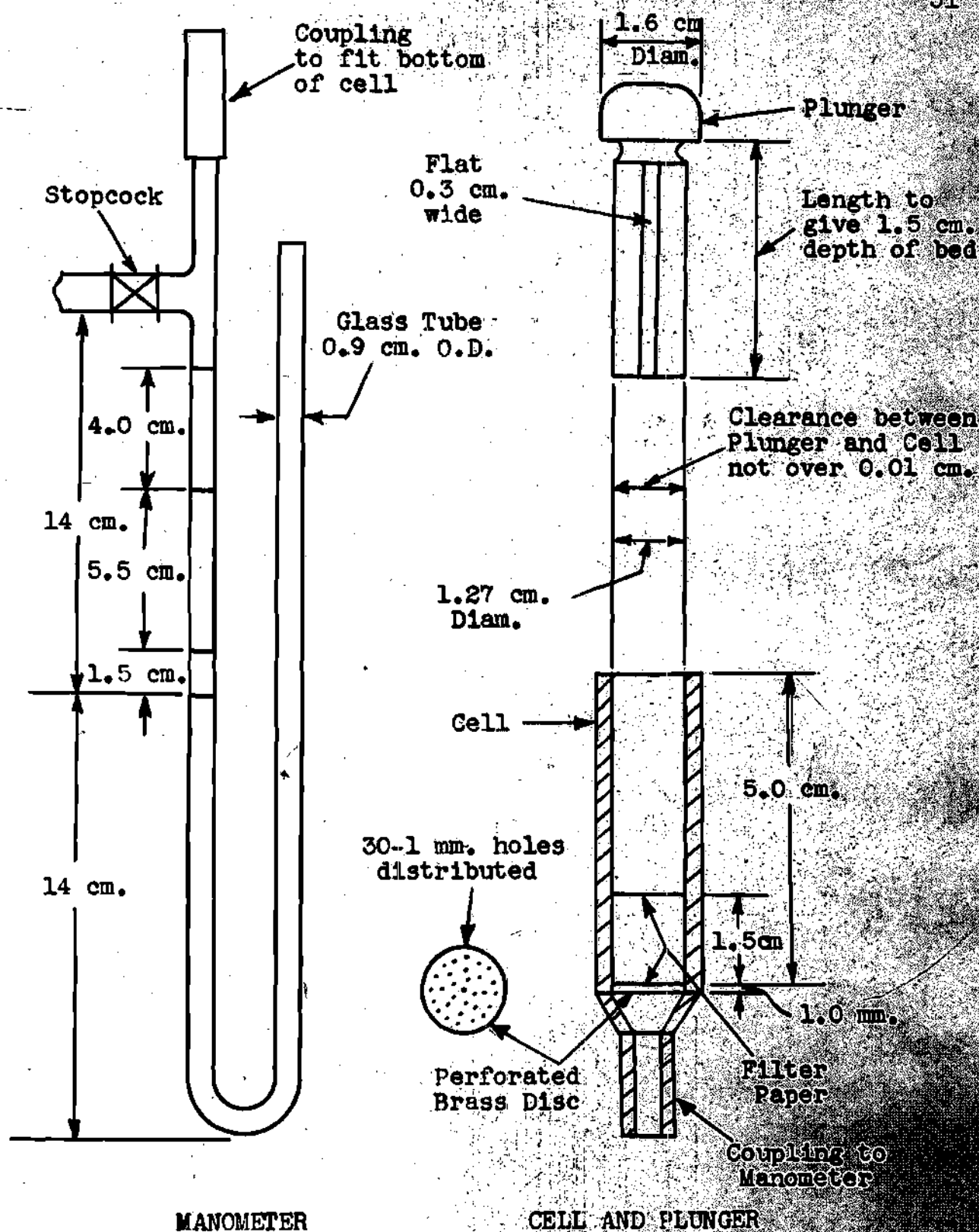


FIGURE 5: BLAINE PERMEABILITY APPARATUS

EXPERIMENTAL PROCEDURE

Preparation of Materials

All of the solid materials used in this work were carefully screened on a standard Ro-Tap machine using a close series of U. S. Standard sieves in order to obtain the maximum number of narrow size fractions, particularly in the range from 140-325 mesh. To obtain the necessary size distribution, the larger size fractions were ground with a mortar and pestle and rescreened until enough material was obtained to give suitable quantities within the size range used for the explosion tests. Since the materials used were somewhat hygroscopic, it was necessary to store the various size fractions to be tested in tightly stoppered bottles to prevent unnecessary absorption of atmospheric moisture. Prior to using the materials they were dried in a moisture oven at 220° F. to further insure a low moisture content.

After drying, a sample of the particular size fraction of the material to be tested was weighed and evenly distributed in the brass dispersion cup. After the electrodes had been set at the proper gap of approximately one-eighth inch, the top was placed on the explosion chamber and the operation of the spark gap tested. If the arc was functioning properly, the top was fastened in place by tightening the eight large wing nuts which forced an

airtight, gasketed seal between the top and the test chamber. The line to the vacuum pump was then opened, and the pump evacuated the chamber to a vacuum of 20 to 25 inches of mercury. After the desired vacuum was reached, the pump was turned off, and air bled slowly into the tank through a drying tube containing calcium chloride. The procedure of evacuating the tank and bleeding air back into the system through a drying tube was followed for each test to insure that the explosions would be carried out in a dry atmosphere. The initial pressure in each case was approximately 1 atmosphere (0 psig).

Operation of Explosion Chamber

At this point the stylus of the pressure recording apparatus was adjusted so that a slight contact would be made at all points on the revolving drum of the kymograph. This drum was covered with a high-gloss paper which had previously been blackened with soot from an acetylene torch. After the recording needle had been properly adjusted, the dispersion bomb was filled with air to a pressure of 275 to 300 psig and the bomb connected to the dispersion system in the bottom of the tank. The pressure range of 275-300 psig was used, since it was found that the best and most readily reproducible dust dispersions were obtained when the initial bomb pressures were within this range. The introduction of this small amount of air to the test chamber caused a negli-

gible increase in the initial tank pressure. The kymograph was then turned on and checked to see that the recording stylus was adjusted properly. The valve connecting the bomb to the solenoid valve was opened, the spark turned on, and the variac adjusted to give a transformer input of 115 volts.

The explosion test was then made by pressing the switch controlling the solenoid. This released the air blast from the bomb through the dispersion cone and thus created a dust cloud which, if explosive, was ignited by the high voltage arc. All equipment was turned off immediately after the explosion. As the explosion progressed, a record was made on the kymograph of pressure vs. time as shown in Figures 6, 7, and 8; the maximum pressure developed was also noted visually. These records afforded a means of calculating the desired initial, average, and maximum rates of pressure rise by determining the slopes at various points on the pressure-time curve. A sample calculation of the initial and maximum rates is shown in Appendix III.

After the explosion was completed, the gaseous explosion products were sampled and analyzed for carbon dioxide, oxygen, hydrogen, and carbon monoxide. The solid residue of the material tested was then weighed; this weight was taken so that it could be used in making a material balance on the explosion process. The recording of the room

temperature completed the data taken for each explosion test. The electrodes, dispersion cup, and explosion chamber were cleaned after each test by washing with water and drying with compressed air. In addition, it was necessary to polish the electrodes after three or four explosion tests had been made.

Method of Particle Surface Measurement

An auxiliary experimental procedure involved the testing of the various size fractions of each sugar to determine their specific surface by the Blaine air permeability method (29). An accurately weighed sample was placed in the permeability cell between two discs of filter paper as shown in Figure 5. The plunger was then depressed so that the collar made contact with the top of the cell. The weight of each sample was such that it would give a porosity of 0.500 with the plunger in the depressed condition. Porosity, in this case, is defined as the ratio of void space to the total volume occupied by the compressed test bed. The permeability cell was attached to the manometer so that an airtight connection was made. The air in one arm of the manometer was slowly evacuated until the liquid was above the highest mark on the calibration scale and the stopcock tightly closed. An electric timer was started as the bottom of the meniscus of manometer liquid reached the second calibration mark and was stopped as the bottom of the meniscus

reached the third mark. The time required for the liquid to fall was recorded to tenths of a second. This time and the equation presented in the following section were used to calculate the specific surface of the sugars. A minimum of three separate tests involving separately prepared beds was used to obtain the average time needed for calculation of specific surface. The calibration of the equipment was made with a standard cement of known surface (U. S. Bureau of Standards, Standards Sample No. 114 f).

EXPERIMENTAL RESULTS

The time-pressure records from the kymograph tracings illustrated in Figures 6, 7, and 8 were transferred to a straight arithmetic grid from which the initial and maximum slopes of the curves could be determined as indicated in Figure 28, Appendix III. These slopes correspond to the initial and maximum rates of pressure increase developed by the explosion tests. The average rates were calculated from the observed maximum pressures and the time required to reach these maxima as taken from the kymograph tracings.

The maximum pressures were then plotted against the dust concentrations at constant specific surface as shown in Figures 9, 10, and 11. The dust concentrations are expressed in grams per cubic meter and were calculated from the known weight of sample in each case and the volume of the test chamber. Constant specific surface was chosen originally as a matter of convenience, but in the course of the investigation it was found that regardless of how a material was prepared, whether through mixing of several widely different particle sizes or the use of a narrow range of particle sizes, the results obtained were substantially the same for any particular material if the specific surfaces were equal. The substantiating data for these findings are not shown by separate tabulation. However, the "D-B" and "R-B" runs which are shown in Tables IX and X

were made partially with material obtained in the range 270-325 mesh by screening and partially with a mixture of two materials, one which was finer than 325 mesh and the other in the range 200-270 mesh. This mixing was necessary to give an adequate supply of the sugar which would have a specific surface comparable to that of the true 270-325 mesh fraction. The rate and gas analysis data were plotted in a manner similar to that used for the maximum pressures. The results are illustrated as follows: initial rates in Figures 12, 13, and 14; average rates in Figures 15, 16, and 17; maximum rates in Figures 18, 19, and 20; and gas analysis data in Figures 21, 22, and 23. The experimental and calculated data for dextrose are presented in Tables VIII and XI, for sucrose in Tables IX and XII, and for raffinose in Tables X and XIII.

In addition to the individual two-dimensional experimental curves, more general three-dimensional diagrams are presented in Figures 24, 25, and 26 which show concentration vs. maximum pressure vs. specific surface for each of the sugars studied.

The specific surface of each sample was determined by means of the Blaine permeability apparatus and the following equation:

$$K = \frac{\rho S_w(1 - e)}{\sqrt{e^3 T/n}} \quad (6)$$

K - constant
e - porosity (0.500)
 ρ - specific gravity
T - time, seconds
n - viscosity of air, poise
(0.0001842 at 80° F.)
S_w - specific surface, cm²/gm

The experimental surface-measurement data are shown
in Table XIV.

DISCUSSION OF RESULTS

Minimum Explosive Concentration

The lower explosive limit for a dust explosion is defined as that point at which there is barely enough material suspended in air to support combustion and propagate flame. The minimum explosive concentrations for dextrose, sucrose, and raffinose are shown in Table VII. For each sugar, the relation between this minimum concentration and specific surface can be represented approximately by an equation of the form

$$\log C_{\min} = a - bS_w$$

where C_{\min} is minimum explosive concentration, S_w is the specific surface of the material, and a and b are constants.

It should be noted that these concentrations are not as sharply defined for dust clouds as they are for gases. These conditions are dependent on the nature of the source of ignition, the physical condition of the material, and the uniformity of the dust dispersion. Since it is difficult to produce and maintain an absolutely uniform cloud, the minimum explosive concentrations are subject to some inaccuracies.

Optimum Explosive Concentration

The optimum explosive concentration is that concentration at which the maximum explosion pressure is developed

from the ignition of a dust cloud. That is, for each specific surface of each sugar there is one particular concentration at which a higher explosion pressure will be developed than would be developed by an explosion of a dust of any other concentration. In Figure 9, a dotted straight line is shown which represents the loci of the optimum concentrations of various specific surfaces of dextrose dust. This "loci of optima" line shows the relationship between specific surface, optimum explosive concentration, and optimum explosion pressure.

The intersection of this line and a line drawn through the origin gives a point whose coordinates may be arbitrarily defined as the "minimum" optimum explosive concentration and the "maximum" optimum explosion pressure. The line drawn through the origin is drawn parallel to the experimental curves.

A construction of this type is reasonable, since for all specific surfaces of dextrose, the maximum pressure vs. concentration curves are parallel, and the optimum explosion pressures and optimum explosive concentrations lie on a straight line. Therefore, as indicated above, the intersection of a line through zero concentration, parallel to the other lines, and a line through the optimum points gives a "minimum" optimum concentration and a "maximum" optimum pressure.

The maximum pressure vs. concentration curves for sucrose and raffinose may be treated in a manner similar to that described for dextrose. This has been done in Figures 10 and 11. The optimum explosive concentrations, optimum explosion pressures, and the calculated "minimum" and "maximum" optima for the sugars studied are shown in Table VII.

If the "minimum" optimum concentrations are plotted against the number of carbon atoms in the sugars, a straight line is obtained. A straight line may also be obtained from a diagram of "maximum" optimum pressure vs. number of carbon atoms in the sugar. These relationships, shown in Figure 27, indicate that the explosibility of sugar dusts is a function of the number of carbon atoms in the molecule or of the length of the carbon chain, assuming that the sugar molecules are linear.

Maximum Pressure

The maximum pressures developed by the explosions of dextrose are shown in Figure 9. The maximum pressure decreases as the specific surface of the material decreases. The "loci of optima" line in Figure 9 represents the loci of optimum explosion pressures for all specific surfaces. The intersection of this line with a line through the origin gives a point which can be taken as the theoretical absolute maximum pressure for the explosion of dextrose dust. This

absolute maximum represents the maximum optimum explosion pressure that any dextrose dust could have regardless of how fine the particles may be. This is true since the line through the origin represents a theoretical dust whose minimum explosive concentration (lower explosive limit) would be zero.

The maximum pressure vs. concentration curves for sucrose and raffinose, as shown in Figures 10 and 11, have been treated in a manner similar to that for dextrose. The absolute "maximum" explosion pressures were found to be 87 psig for dextrose, 70 psig for sucrose, and 50 psig for raffinose; these pressures occur at "minimum" explosive concentrations of 180, 150, and 100 gms/m³, respectively. The data for these theoretical optima or "critical points" are presented in Table VII along with the experimental optima.

When the "maximum" optimum pressures and "minimum" optimum concentrations are plotted against the number of carbon atoms in the sugars, as shown in Figure 27, two straight lines are obtained which relate these "critical points" to molecular structure. Even though each curve is represented by only three points it is felt that the trend is significant, since in each case the points give a good straight line.

The maximum pressures obtained are also presented in three-dimensional form in Figures 24, 25, and 26. From

these pressure vs. concentration vs. specific surface diagrams, a complete picture of the explosive pressure surface can be seen. From these diagrams, it can also be seen that the maximum pressure increases as the specific surface of the material increases. The "pressure peak" which is shown in these figures would continue to increase with an increase in specific surface, approaching an apex in each case which would occur at the "maximum" optimum explosion pressure and the "minimum" optimum explosive concentration. The specific surface of a material which would be represented by this point can not be defined, since as previously discussed, the lower explosive limit of such a material would be at zero concentration.

The following method can be used to calculate an approximate value of the maximum pressure obtained from an explosion of a sugar dust. The method considers the gas analysis, and material and energy balances. For purposes of calculation, the combustion process is assumed to be adiabatic. The nomenclature for the following development is:

V - volume of test chamber (1.86 ft^3)
 V_{std} - standard volume ($359 \text{ ft}^3/\text{mol}$ corrected to test conditions)
 N_G - mols dry gas in test chamber
 N_C - mols carbon oxides in chamber
 N_S - mols sugar burned
 $N_{\text{H}_2\text{O}}$ - mols H_2O formed by combustion
 N_I - mols inert gases after combustion

N_T	- total mols of wet gas in chamber after explosion
n_C	- carbon atoms/mol sugar
n_H	- number of Hydrogen atoms/mol of sugar
F_{H_2O}	- fraction H_2O in gas
F_C	- fraction carbon oxides in gas
F_I	- fraction inerts in gas
C_V	- heat capacity at constant volume
H_C	- heat of combustion
V_{H_2O}	- volume correction for water
T_i	- initial temperature
T_f	- final explosion temperature
P_i	- initial pressure
P_f	- final explosion pressure

The mols of gas in the tank are given by:

$$N_G = V/V_{Std} \quad (7)$$

This is true since the final rest condition within the tank is essentially at atmospheric temperature and pressure. The combustion products of sugars give gaseous explosion products containing carbon dioxide, water, and small amounts of carbon monoxide (1 - 2%). For each molecule of atmospheric oxygen consumed there is one molecule of carbon dioxide formed, neglecting the small amounts of carbon monoxide. Since the hydrogen-oxygen ratio in sugars is the same as in water, only the carbon in the sugars requires atmospheric oxygen. When these gaseous products are cooled to room temperature they reach a rest condition which is substantially at atmospheric pressure since the water vapor condenses and there is present approximately one molecule of carbon oxide gas for each molecule of

oxygen which was consumed. The small amount of carbon monoxide present is the only gas which keeps this final rest pressure from being exactly equal to the initial pressure in the test chamber. The following can be used to obtain the mols of carbon monoxide and carbon dioxide:

$$N_C = N_G(\%CO_2 + \%CO)/100 \quad (8)$$

the mols of sugar exploded,

$$N_S = N_C/n_C \quad (9)$$

the mols of water formed by burning,

$$N_{H_2O} = N_S(n_H/2) \quad (10)$$

the mols of inert gases (nitrogen and remaining oxygen), and the total mols of gas present.

$$N_I = N_G - N_C \quad (11)$$

$$N_T = N_G + N_{H_2O} \quad (12)$$

From equations (8) through (12) the fractional composition of gaseous products of combustion can be obtained.

$$F_{H_2O} = N_{H_2O}/N_T \quad (13)$$

$$F_C = N_C/N_T \quad (14)$$

$$F_I = N_I/N_T \quad (15)$$

Using mean heat capacities at constant volume, the average mean heat capacity can be calculated,

$$(C_V)_{Avg} = F_{H_2O}(C_V)_{H_2O} + F_C(C_V)_{CO_2} + F_I(C_V)_{N_2} \quad (16)$$

and the final explosion temperature can be found.

$$T_f = \frac{N_S(H_C)S}{V(C_V)_{Avg}} - T_1 \quad (17)$$

Using this temperature, the maximum explosion pressure can be calculated from the perfect gas law. A correction factor for water must be included, since the water is present as a vapor at the final explosive condition and is condensed at the final rest condition.

$$V_{H_2O} = N_{H_2O} \times V_{std} \quad (18)$$

Including this correction the pressure is given by

$$P_f = \frac{(V - V_{H_2O})}{V} \cdot \frac{T_f}{T_1} - P_1 \quad (19)$$

This equation gives pressure values from 10 - 20% higher than observed values due to the assumption that the process is adiabatic. A sample calculation of a typical test is shown in Appendix III.

Initial, Average, and Maximum Rates

An explosion of a sugar dust is relatively slow at

the beginning, but as the explosion progresses, this low initial rate gives way to a rapid rise in pressure which continues to increase until the explosion ceases. The initial rate vs. concentration curves for the three sugars are shown in Figures 12, 13, and 14; the average rate vs. concentration in Figures 15, 16, and 17; and the maximum rate vs. concentration in Figures 18, 19, and 20.

The graphical analysis which was applied to the maximum pressure vs. concentration diagrams can also be applied to each of the rate diagrams. However, since the rate curves do not exhibit such sharp maxima or optima as the pressure curves, the analyses of the optimum rates are less reliable than the optimum pressures. The various optima and maxima for the rates are shown in Table VII. It is probable that the optimum rates could also be related to the number of carbon atoms in the sugars, but these analyses have been omitted because of the wide possibility for inaccuracies in determining the optima which would be needed.

Gas Analysis

The gas analysis curves shown in Figures 21, 22, and 23 follow the same general form as the curves for the maximum pressures and for the various rates. As the specific surface of the sample decreases, the amount of material consumed by the explosion becomes less; and as a consequence, the amount of carbon oxides in the gaseous products decreases

and the amount of oxygen remaining increases. The percent of carbon oxides also decreases as the length of the molecular carbon chain is increased.

Similar to the optimum explosion pressure which exists for each specific surface of each sugar, there is also an optimum oxygen concentration and an optimum carbon oxide concentration (carbon oxide being used to include both carbon monoxide and carbon dioxide). These optimum gas concentrations result from the explosion of a particular dust concentration of one specific surface. For oxygen this optimum may be defined as the minimum percent of oxygen obtained from an analysis of the gaseous products of combustion; for carbon oxides it may be defined as the maximum percent obtained. As for the optimum pressures, these optima occur at one specific concentration for each specific surface of each sugar. Straight lines can be drawn through these points as indicated in Figures 21, 22, and 23. These lines intersect the vertical lines drawn through the minimum optimum concentrations for each sugar at 0% oxygen and about 22% carbon oxides. This further substantiates the observations made concerning the optimum explosion pressures and concentrations. In addition, it indicates that these optima would occur at a point where all available oxygen would be consumed by the explosion.

Computation of Pressure Propagation

The velocity of the flame propagation or pressure

propagation can be calculated by the method of Jost as outlined on pages 28 through 31. The basis for this calculation is equation (4).

$$V_n = (r_o/r_e)^2 (P_o/P)^{1/k} (dr_o/dt) \quad (4)$$

- V_n - average flame velocity
- r_o - initial sphere radius to contain material burned
- r_e - radius of burned sphere at time t
- P_o - initial pressure
- P - pressure at time t
- t - time
- k - C_p/C_v for gases

This equation has a probable accuracy of about 10% when applied to the dust explosions studied. A sample calculation of this flame or pressure velocity is shown in Appendix III.

Mathematical Analysis of Time-Pressure Records

The time-pressure rate of an explosion of sugar dust may be determined as follows. Let us suppose that the rate mechanism of the explosion is of the first order and that it is affected by the pressure increase in such a way that

$$dp/dt = ap - \phi(p) \quad (20)$$

where p is the pressure at any time t , a is a constant, and $\phi(p)$ is some function of pressure. The negative sign has been inserted since the pressure increase is assumed to be deterred by a resisting force proportional to the pressure. Various assumptions may be made as to the form of $\phi(p)$, but

it appears from several forms attempted that

$$\phi(p) = bp^2 \quad (21)$$

fits fairly well. We then have

$$dp/dt = ap - bp^2 \quad (22)$$

This is the equation of the logistic and the solution is

$$\frac{p}{p_0} = \frac{1}{1 + e^{-\alpha(t - t_0)}} \quad (23)$$

where p_0 is the maximum explosion pressure, t_0 is the point of inflection of the time-pressure curve, and α is a characteristic constant.

Both t_0 and α may be determined from a logistic-grid plot as was shown by Wilson (31). From several analyses, as shown in Figure 29 of Appendix III, it appears that α has a value of about 0.95 and t_0 a value of about 0.5 for all of the sugars studied at all concentrations and specific surfaces.

Equation (23) can then be applied to all of the sugars studied to obtain an approximation of the actual time-pressure records illustrated in Figures 6, 7, and 8.

CONCLUSIONS

As a result of this study, the following conclusions may be drawn:

(1) The minimum explosive concentration or lower limit of explosibility for sugar dust is a straight line function of the specific surface of the material. This lower limit decreases as the specific surface increases and as the number of carbon atoms in the sugar molecule decreases.

(2) The optimum explosive concentration is a straight line function of the specific surface and decreases as the specific surface increases. The optimum concentration is inversely proportional to the number of carbon atoms in the sugar molecule.

(3) The maximum pressure developed by an explosion of sugar dust is a function of concentration, specific surface, and the number of carbon atoms in the molecule. For any given concentration the maximum explosion pressure increases as the specific surface increases and as the number of carbon atoms decreases. The optimum explosion pressure occurs at a concentration which, generally speaking, is only 100 to 150 gms/m^3 higher than the minimum explosive concentration for each specific surface of each sugar.

(4) The maximum optimum explosion pressure of a sugar dust is inversely proportional to the number of carbon atoms

in the molecule.

(5) The maximum pressure developed by a sugar dust explosion can be calculated theoretically from the gas analysis data and a consideration of material and energy balances.

(6) The initial rate of explosion can be used as a criterion of explosibility. Previously, only the average and maximum rates have been used.

(7) The initial, average, and maximum rates are functions of dust concentration, specific surface, and the number of carbon atoms in the sugar molecule. For any given concentration the rates increase as the specific surface increases and as the number of carbon atoms decreases.

(8) The gas analysis data indicate that the minimum optimum explosive concentration of a particular specific surface of a sugar occurs when the concentration is such that all the available oxygen in the atmosphere is consumed by the combustion of the sugar.

(9) Dust clouds of dextrose are the most hazardous of the sugars studied; sucrose and raffinose follow in order. This means that the dust explosion hazard for sugars is inversely proportional to the number of carbon atoms in the molecule.

(10) The velocity of the pressure or flame propagation of dust explosions in closed vessels can be calcu-

lated from experimental time-pressure records and equation (4).

$$V_n = (r_o/r_e)^2 (p_o/p)^{1/k} (dr_o/dt) \quad (4)$$

V_n - average flame velocity
 r_o - initial sphere radius to contain material burned
 r_e - radius of burned sphere at time t
 p_o - initial pressure
 p - pressure at time t
 t - time
 k - C_p/C_v for gases

(11) The time-pressure relationships of explosions of sugar dusts may be expressed by the following equation:

$$\frac{p}{p_o} = \frac{1}{1 + e^{-\alpha(t - t_o)}} \quad (23)$$

where p is the explosion pressure at time t , p_o is the maximum explosion pressure, t_o is the time at the point of inflection of the time-pressure curve, and α is a characteristic constant based on the slope of the curve when the time-pressure data are plotted on a logistic or autocatalytic grid.

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APPENDIX I
(TABLES)

TABLE VII: CRITICAL POINTS OF EXPLOSIONS OF SUGAR DUSTS

<u>Material</u>	<u>Specific Surface</u> (cm ² /gm)	<u>Minimum Explos. Conc.</u> (gms/m ³)	<u>Optimum Explos. Conc.</u> (gms/m ³)	<u>Optimum Explos. Press.</u> (psig)	<u>Optimum Rates</u> (psi/sec)		
					<u>Init.</u>	<u>Avg.</u>	<u>Max.</u>
Dextrose	1480	300	440	57	17	82	160
	2350	220	400	65	20	90	200
	2930	110	360	68	23	100	220
	4500	20	310	72	27	110	245
Sucrose	1800	320	450	42	12	45	95
	2350	180	320	52	15	65	125
	2950	120	280	56	17	74	160
	3830	40	240	60	22	82	195
Raffinose	2270	500	590	41	7	36	60
	2980	330	470	37	9	42	70
	3700	150	350	33	12	50	90

Calculated Theoretical Optima

			<u>Minimum Optimum Conc.</u> (gms/m ³)	<u>Maximum Optimum Press.</u> (psig)	<u>Maximum Optimum Rates</u> (psi/sec)		
					<u>Init.</u>	<u>Avg.</u>	<u>Max.</u>
Dextrose	-	0	180	87	35	160	300
Sucrose	-	0	150	70	30	130	240
Raffinose	-	0	100	50	17	80	120

TABLE VIII: EXPERIMENTAL DATA, DEXTROSE

Run Number	Sample Weight (grams)	Maximum Pressure (psig)	Solid Residue (grams)	Gas Analysis		
				% CO ₂	% O ₂	% CO
D-A-1	50	63	38	12.1	7.9	2.3
D-A-2	40	67	26.5	14.1	5.9	2.5
D-A-3	40	65	26	13.2	6.0	2.6
D-A-4	35	63	23.5	9.0	10.9	2.6
D-A-5	25	70	10.5	13.9	6.1	2.6
D-A-6	23	68	12.5	9.5	10.9	2.1
D-A-7	20	70	6.5	12.0	7.8	2.5
D-A-8	17.5	73	5	13.1	6.8	2.6
D-A-9	12.5	68	2.5	9.4	10.0	2.3
D-A-10	10	62	2	9.6	10.9	1.9
D-A-11	7	37	2	5.3	15.0	2.0
D-A-12	5	28	1.5	3.8	16.9	1.5
D-A-13	3	15	1.5	2.2	18.2	1.7
D-A-14	2	4	1.5	1.2	18.8	1.2
D-A-15	1	0	1	-	-	-
D-B-1	45	60	34.5	12.7	7.8	2.6
D-B-2	35	62	23	14.1	6.1	2.2
D-B-3	20	68	8	10.4	10.1	2.0
D-B-4	15	65	2.5	13.7	6.0	2.1
D-B-5	10	45	3	7.2	13.3	1.1
D-B-6	9	40	2.5	8.0	12.5	1.1
D-B-7	8	12	2	-	-	-
D-B-8	7	0	7	-	-	-
D-C-1	50	58	38	12.4	7.7	1.0
D-C-2	40	60	28.5	12.1	8.3	0.9
D-C-3	30	62	13.5	15.7	4.4	1.0
D-C-4	25	65	10.5	14.9	5.2	1.9
D-C-5	20	62	7.5	14.2	6.3	1.7
D-C-6	15	55	6.5	11.0	9.2	1.7
D-C-7	13	32	6	5.3	15.0	2.0
D-C-8	12	0	12	-	-	-
D-D-1	50	50	41	10.5	9.9	1.1
D-D-2	40	50	27	11.4	9.3	1.1
D-D-3	30	54	18	12.0	8.6	0.5
D-D-4	25	60	12	12.7	7.7	0.7
D-D-5	20	57	9	11.0	9.7	0.4
D-D-6	18	38	9.5	7.5	12.6	0.4
D-D-7	17	3	-	-	-	-
D-D-8	16	0	16	-	-	-

TABLE IX: EXPERIMENTAL DATA, SUCROSE

Run Number	Sample Weight (grams)	Maximum Pressure (psig)	Solid Residue (grams)	Gas Analysis		
				% CO ₂	% O ₂	% CO
S-A-1	50	50	38	11.7	8.5	2.2
S-A-2	40	53	27.5	9.1	10.5	2.7
S-A-3	30	55	19	9.1	12.1	1.4
S-A-4	20	57	10	11.0	9.7	2.0
S-A-5	15	60	4	11.4	9.6	1.8
S-A-6	10	55	3	11.2	9.3	2.0
S-A-7	7	45	1	6.6	14.2	1.8
S-A-8	6	30	2.5	5.3	15.4	1.5
S-A-9	5	21	1.5	3.2	17.3	1.4
S-A-10	4	16	1	3.6	17.5	1.4
S-A-11	3	4	2.5	1.4	19.5	1.2
S-A-12	2	0	2	-	-	-
S-B-1	50	50	40	8.5	10.9	1.0
S-B-2	50	52	39	10.1	9.6	1.7
S-B-3	40	50	28	10.7	9.0	1.2
S-B-4	30	53	20	11.8	7.9	2.3
S-B-5	20	55	6	12.6	7.3	1.8
S-B-6	15	55	4	9.5	10.0	1.7
S-B-7	10	38	4	7.9	12.5	1.9
S-B-8	9	32	4	4.9	15.2	2.0
S-B-9	8	5	6.5	1.5	19.0	1.3
S-B-10	7	0	7	-	-	-
S-C-1	53	47	40	13.0	7.4	1.2
S-C-2	53	45	39	14.4	6.0	1.4
S-C-3	50	47	37	13.0	7.4	1.3
S-C-4	42	48	30	11.9	9.2	1.8
S-C-5	35	48	21.5	12.0	9.9	1.3
S-C-6	28	48	16	7.6	12.4	1.9
S-C-7	21	50	12	8.6	12.0	1.7
S-C-8	20	50	7	10.6	10.0	1.5
S-C-9	15	53	5.5	9.9	11.3	1.1
S-C-10	13	45	3.5	10.4	10.4	0.8
S-C-11	12	40	3.5	8.6	12.3	1.6
S-C-12	11	31	5.5	5.0	16.2	1.9
S-C-13	10	16	4.5	3.3	17.7	1.1
S-C-14	9	6	7.5	1.3	19.8	1.0
S-C-15	8	0	8	-	-	-
S-D-1	50	38	37	10.5	10.4	1.5
S-D-2	50	37	43	10.1	10.9	1.4

TABLE IX: EXPERIMENTAL DATA, SUCROSE (continued)

Run Number	Sample Weight (grams)	Maximum Pressure (psig)	Solid Residue (grams)	Gas Analysis		
				% CO ₂	% O ₂	% CO
S-D-3	40	43	30	9.6	10.6	1.2
S-D-4	35	38	24	8.5	12.2	1.3
S-D-5	30	40	20	8.7	12.3	1.4
S-D-6	30	40	21	6.9	14.0	1.4
S-D-7	25	42	15	8.0	13.0	1.1
S-D-8	22	45	8	10.5	10.5	1.3
S-D-9	21	40	12.5	8.1	12.7	1.3
S-D-10	20	28	13.5	4.3	16.2	1.1
S-D-11	18	11	15	1.6	19.0	1.2
S-D-12	17	0	17	-	-	-

TABLE X: EXPERIMENTAL DATA, RAFFINOSE

Run Number	Sample Weight (grams)	Maximum Pressure (psig)	Solid Residue (grams)	Gas Analysis		
				% CO ₂	% O ₂	% CO
R-A-1	50	37	38	7.6	13.4	0.3
R-A-2	35	38	26.5	6.3	14.6	0.5
R-A-3	20	39	11	6.0	15.0	0.3
R-A-4	17.5	40	6.5	7.3	13.7	0.2
R-A-5	15	37	6	5.6	15.4	0.4
R-A-6	11	28	5	3.3	17.5	0.4
R-A-7	10	23	4.5	2.9	17.6	0.7
R-A-8	9	5	-	1.1	19.9	0.2
R-A-9	8	0	8	-	-	-
R-B-1	45	35	35	7.6	12.8	0.4
R-B-2	35	35	26	7.3	13.0	0.5
R-B-3	25	37	13	6.4	14.1	0.2
R-B-4	20	32	8.5	7.8	12.4	0.4
R-B-5	19	16	16	2.8	17.9	0.2
R-B-6	18	5	16	1.5	19.4	0.0
R-B-7	17	0	17	-	-	-
R-C-1	50	32	39	7.3	13.5	0.0
R-C-2	35	32	27.5	6.8	14.0	0.0
R-C-3	30	33	22.5	6.4	14.1	0.3
R-C-4	28	23	25	3.0	17.5	0.3
R-C-5	27	15	25	2.0	18.8	0.3
R-C-6	26	0	26	-	-	-
R-D-1	Unable to obtain explosion at any condition.					

TABLE XI: CALCULATED DATA, DEXTROSE

Run Number	Concentration (gms/m ³)	Total Surface (cm ² /m ³)	Maximum Pressure (psig)	Time to Max. Pr. (sec)	Rates of Pr. Rise (psi/sec)		
					Init.	Avg.	Max.
D-A-1	950	428	63	0.66	21.7	83	194
D-A-2	760	342	67	0.63	22.8	107	247
D-A-3	760	342	65	0.61	25.6	107	244
D-A-4	665	299	63	0.76	25.5	84	185
D-A-5	475	214	70	0.63	28.8	111	232
D-A-6	437	197	68	0.61	24.4	112	255
D-A-7	380	171	70	0.60	26.0	108	232
D-A-8	333	150	73	0.65	26.5	112	210
D-A-9	238	107	68	0.81	25.5	85	188
D-A-10	190	86	62	0.80	20.7	78	165
D-A-11	133	60	37	0.76	11.8	43	86
D-A-12	95	43	28	0.76	10.9	37	65
D-A-13	57	26	15	0.57	8.3	26	43
D-A-14	38	17	4	0.29	7.6	14	20
D-A-15	19	9	0	-	-	-	-
D-B-1	855	250	60	0.77	21.7	88	207
D-B-2	665	195	62	0.73	22.4	94	210
D-B-3	380	111	68	0.76	22.3	90	183
D-B-4	285	84	65	0.72	20.4	90	180
D-B-5	190	56	45	0.70	12.7	64	92
D-B-6	171	50	40	0.76	14.1	53	112
D-B-7	152	44	12	-	-	-	-
D-B-8	133	38	0	-	-	-	-
D-C-1	950	223	58	0.72	18.1	81	185
D-C-2	760	179	60	0.67	20.5	90	199
D-C-3	570	134	62	0.71	19.0	86	198
D-C-4	475	112	65	0.66	17.6	98	196
D-C-5	380	89	62	0.70	18.3	88	152
D-C-6	285	67	55	0.74	13.8	74	135
D-C-7	247	58	32	0.77	10.2	42	86
D-C-8	228	54	0	-	-	-	-
D-D-1	950	141	50	0.70	15.0	72	135
D-D-2	760	112	50	0.65	16.7	77	172
D-D-3	570	84	54	0.76	14.7	71	137
D-D-4	475	70	60	0.73	14.4	82	148
D-D-5	380	56	57	0.75	12.7	75	128
D-D-6	342	52	38	0.78	9.1	49	80
D-D-7	323	50	3	-	-	-	-
D-D-8	304	48	0	-	-	-	-

TABLE XII: CALCULATED DATA, SUCROSE

Run Number	Concentration (gms/m ³)	Total Surface (cm ² /m ³)	Maximum Pressure (psig)	Time to Max. Pr. (sec)	Rates of Pr. Rise (psi/sec)		
					Init.	Avg.	Max.
S-A-1	950	364	50	0.75	18.9	67	192
S-A-2	760	291	53	0.84	21.0	62	170
S-A-3	570	218	55	0.59	18.9	93	189
S-A-4	380	145	57	0.79	24.0	72	168
S-A-5	285	109	60	0.82	22.2	73	204
S-A-6	190	73	55	0.84	20.8	66	154
S-A-7	133	51	45	0.65	15.8	69	195
S-A-8	114	44	30	0.74	14.1	40	86
S-A-9	95	36	21	0.86	12.0	24	43
S-A-10	76	29	16	0.91	10.3	18	37
S-A-11	57	22	4	0.93	4.0	4	5
S-A-12	38	15	0	-	-	-	-
S-B-1	950	280	50	0.84	15.2	54	138
S-B-2	950	280	52	-	-	-	-
S-B-3	760	224	50	0.80	14.8	63	146
S-B-4	570	168	53	0.77	15.5	69	134
S-B-5	380	112	55	0.72	15.5	77	178
S-B-6	285	84	55	0.74	14.1	74	148
S-B-7	190	56	38	0.81	13.2	47	91
S-B-8	171	50	32	0.73	11.5	44	76
S-B-9	152	44	5	0.41	5.5	12	36
S-B-10	133	38	0	-	-	-	-
S-C-1	1000	238	47	0.95	11.1	50	112
S-C-2	1000	238	45	0.75	17.1	61	114
S-C-3	950	223	47	0.88	15.0	53	94
S-C-4	798	188	48	0.77	14.1	62	115
S-C-5	665	156	48	0.88	16.4	55	97
S-C-6	532	125	48	0.93	11.7	52	97
S-C-7	399	94	50	0.77	13.5	65	111
S-C-8	380	89	50	0.79	15.0	63	95
S-C-9	285	67	53	0.70	11.5	76	125
S-C-10	247	58	45	0.77	10.7	58	89
S-C-11	228	54	40	0.72	5.4	57	72
S-C-12	209	49	31	0.73	7.2	43	57
S-C-13	190	45	16	0.75	5.7	21	42
S-C-14	171	40	6	0.44	5.0	14	24
S-C-15	152	36	0	-	-	-	-
S-D-1	950	171	38	0.91	9.3	42	88
S-D-2	950	171	37	1.04	11.5	37	82

TABLE XII: CALCULATED DATA, SUCROSE (continued)

Run Number	Concen- tration (gms/m ³)	Total Surface (cm ² /m ³)	Maximum Pressure (psig)	Time to Max. Pr. (sec)	Rates of Pr. Rise (psi/sec)		
					Init.	Avg.	Max.
S-D-3	760	137	43	0.95	7.5	45	86
S-D-4	665	120	38	1.00	9.3	38	74
S-D-5	570	103	40	0.93	10.6	43	79
S-D-6	570	103	40	1.00	13.7	40	73
S-D-7	475	86	42	1.10	11.0	38	93
S-D-8	418	75	45	0.93	8.5	49	95
S-D-9	399	72	40	0.92	11.3	44	86
S-D-10	380	68	28	0.82	8.4	33	72
S-D-11	342	62	11	0.60	5.0	19	27
S-D-12	323	58	0	-	-	-	-

TABLE XIV: SURFACE MEASUREMENT DATA

Sample Number	Material	Size (mesh)	Time (sec)	Specific Surface (cm ² /gm)
Std-1	Standard	-	108.2	3230
Std-2			106.2	3230
Std-3			108.4	3230
D-A-1	Dextrose	325 minus	50.4	4530
D-A-2			49.5	4480
D-A-3			50.3	4510
D-B-1	Dextrose	270 - 325	21.8	2980
D-B-2			21.0	2920
D-B-3			20.5	2890
D-C-1	Dextrose	200 - 270	13.5	2340
D-C-2			14.1	2390
D-C-3			13.4	2330
D-D-1	Dextrose	170 - 200	5.6	1510
D-D-2			5.3	1470
D-D-3			5.4	1480
S-A-1	Sucrose	325 minus	40.0	3930
S-A-2			36.1	3720
S-A-3			38.1	3840
S-B-1	Sucrose	270 - 325	21.1	2850
S-B-2			23.3	2990
S-B-3			23.1	2970
S-C-1	Sucrose	200 - 270	14.4	2360
S-C-2			14.3	2350
S-C-3			14.2	2340
S-D-1	Sucrose	170 - 200	8.6	1820
S-D-2			8.4	1800
S-D-3			8.4	1800
R-A-1	Raffinose	325 minus	30.4	3700
R-A-2			30.4	3700
R-A-3			30.3	3690
R-B-1	Raffinose	270 - 325	20.0	3010
R-B-2			19.3	2950
R-B-3			19.7	2990

TABLE XIV: SURFACE MEASUREMENT DATA (continued)

<u>Sample Number</u>	<u>Material</u>	<u>Size (mesh)</u>	<u>Time (sec)</u>	<u>Specific Surface (cm²/gm)</u>
R-C-1	Raffinose	200 - 270	11.8	2310
R-C-2			11.3	2260
R-C-3			11.1	2240
R-D-1	Raffinose	170 - 200	9.0	2020
R-D-2			8.3	1940
R-D-3			8.8	1990

APPENDIX II
(FIGURES)

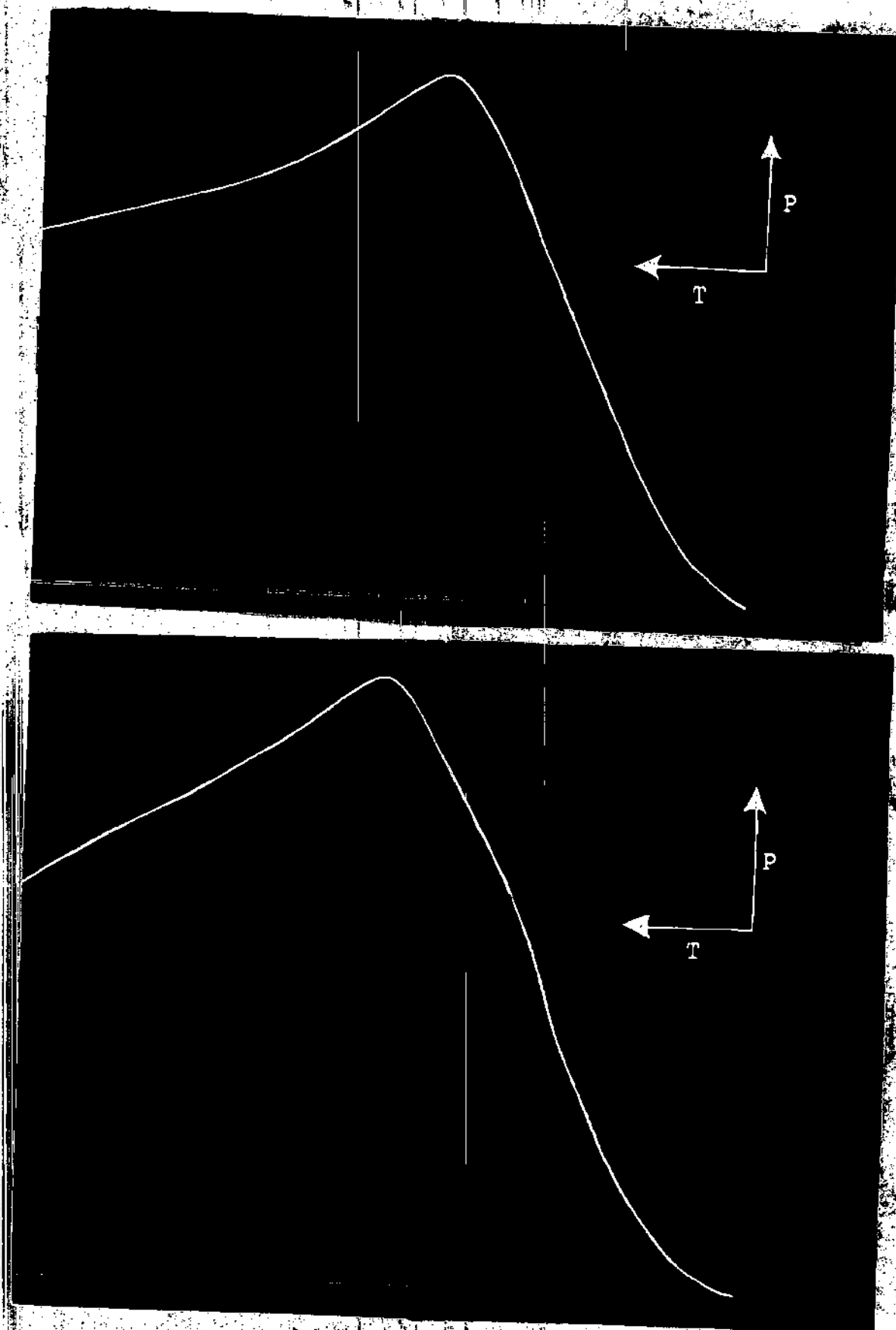


FIGURE 6: TIME-PRESSURE RECORDS, DEXTROSE

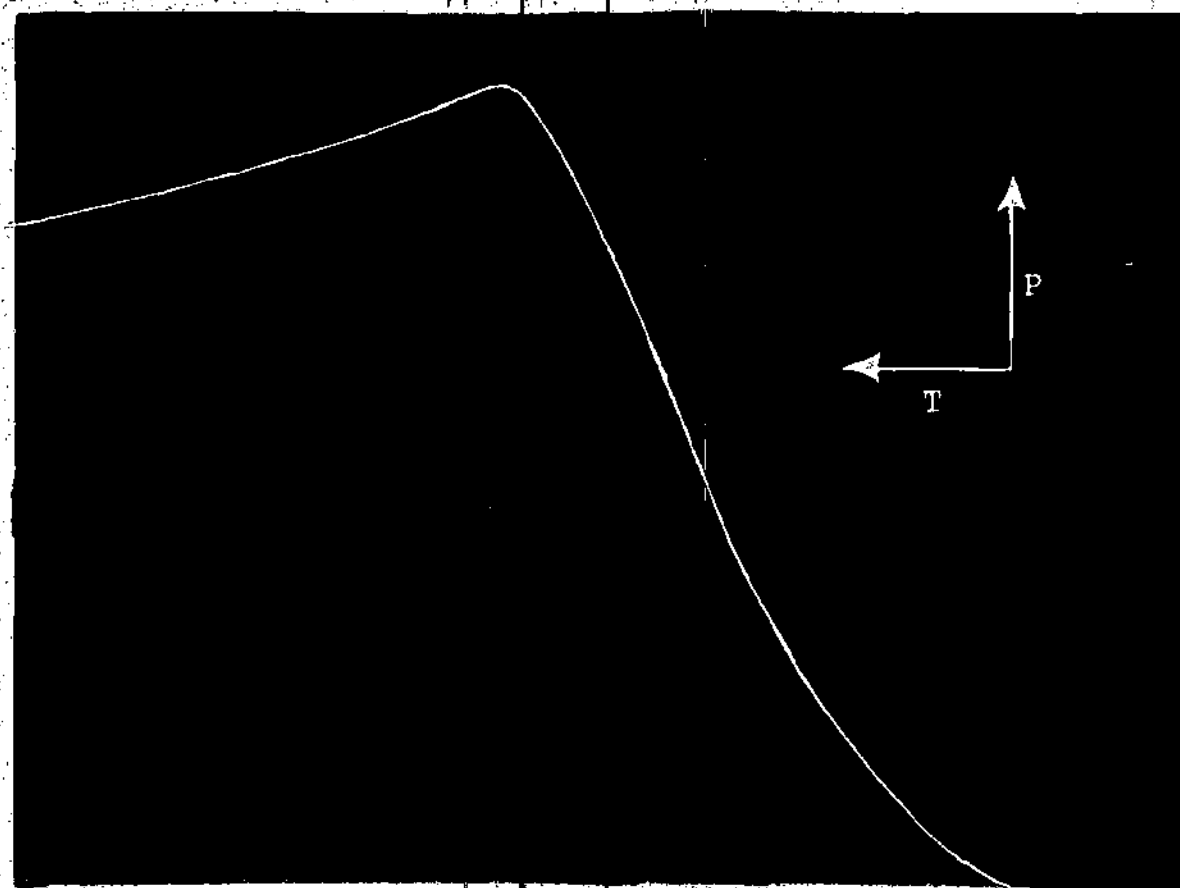
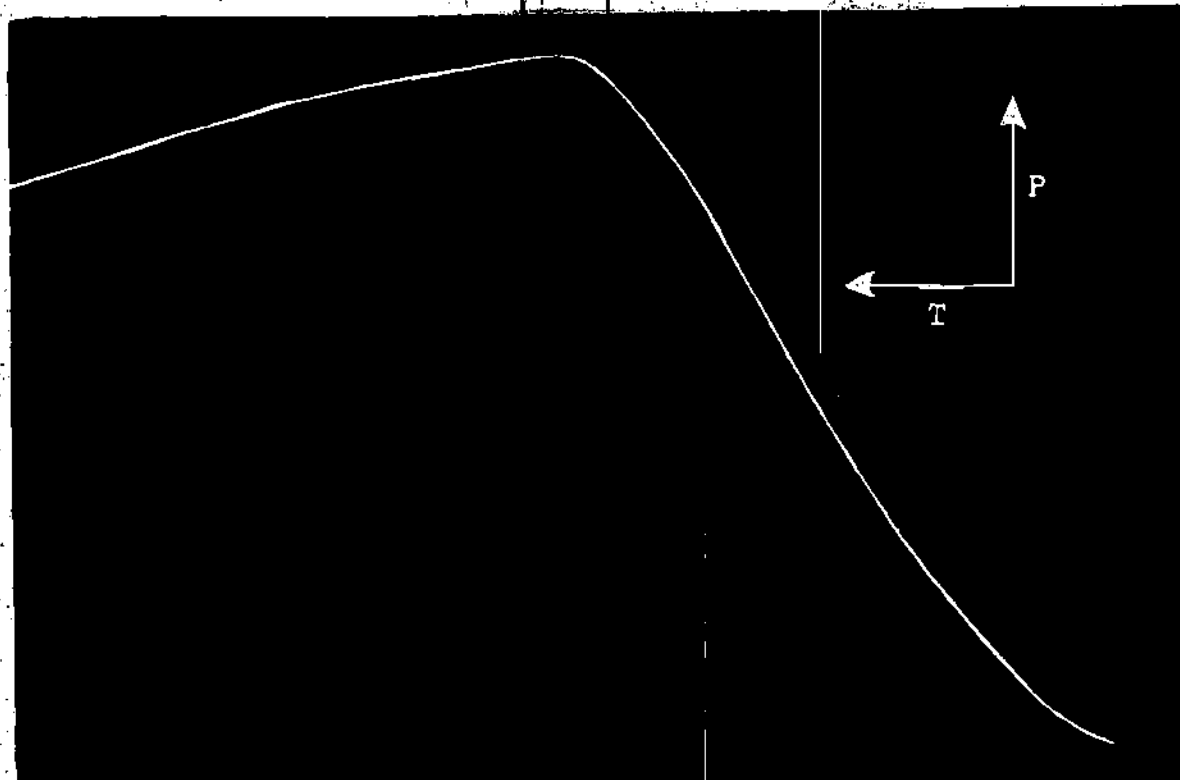


FIGURE 7: TIME-PRESSURE RECORDS, SUCROSE

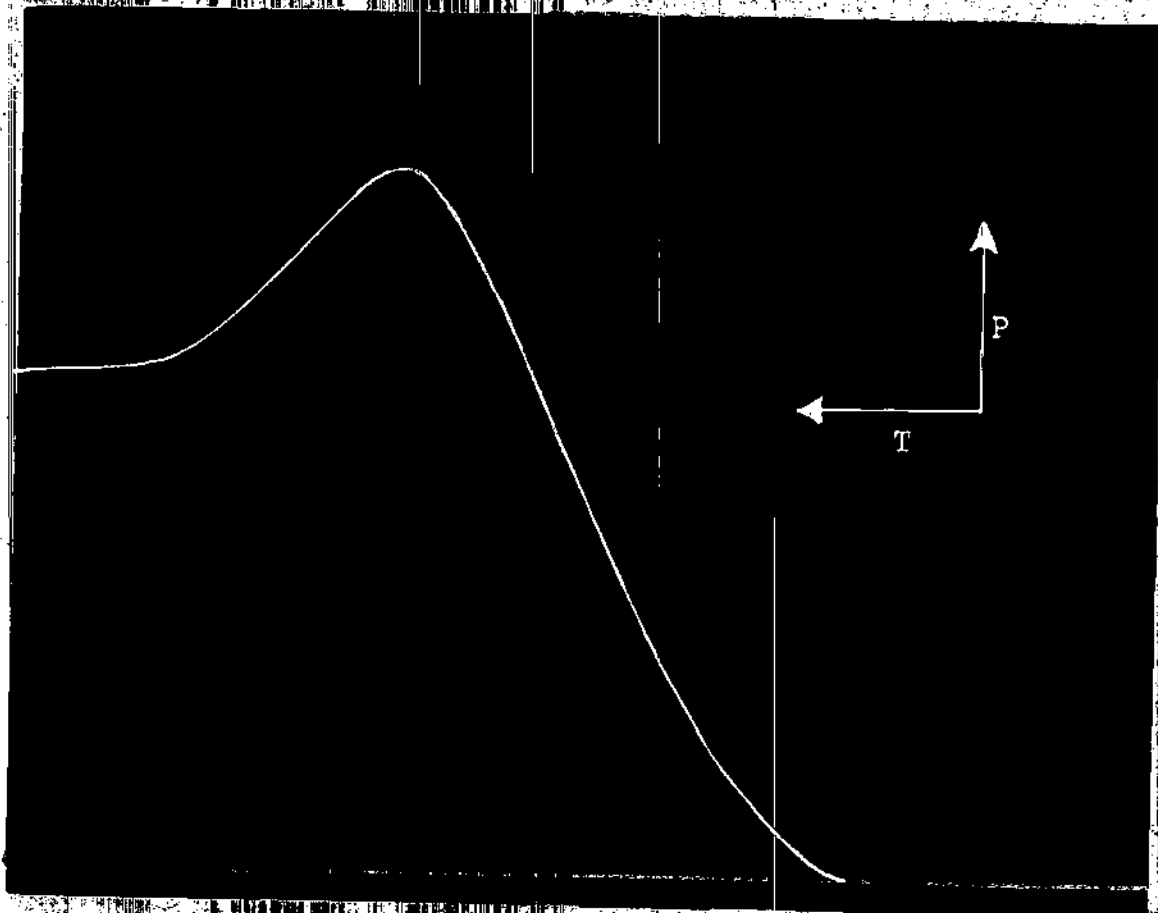
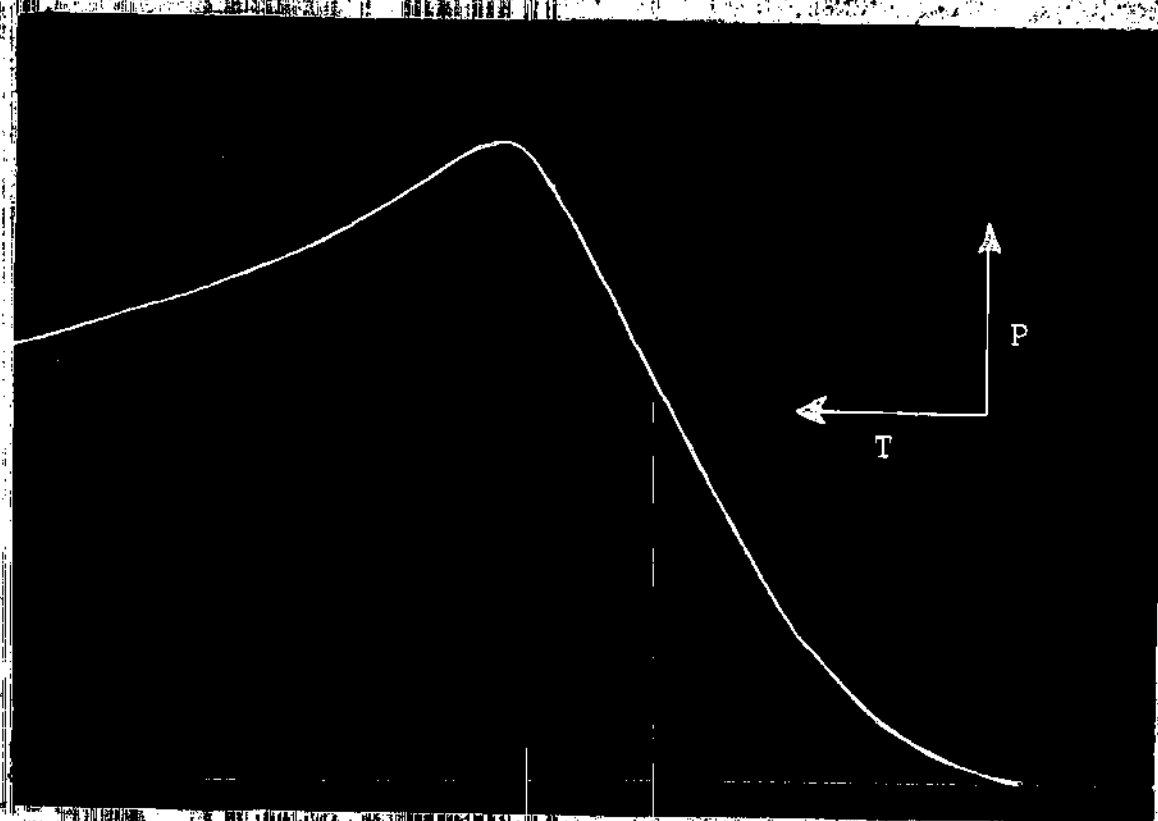


FIGURE 8. TIME-PRESSURE RECORDS, RAFFINOSE

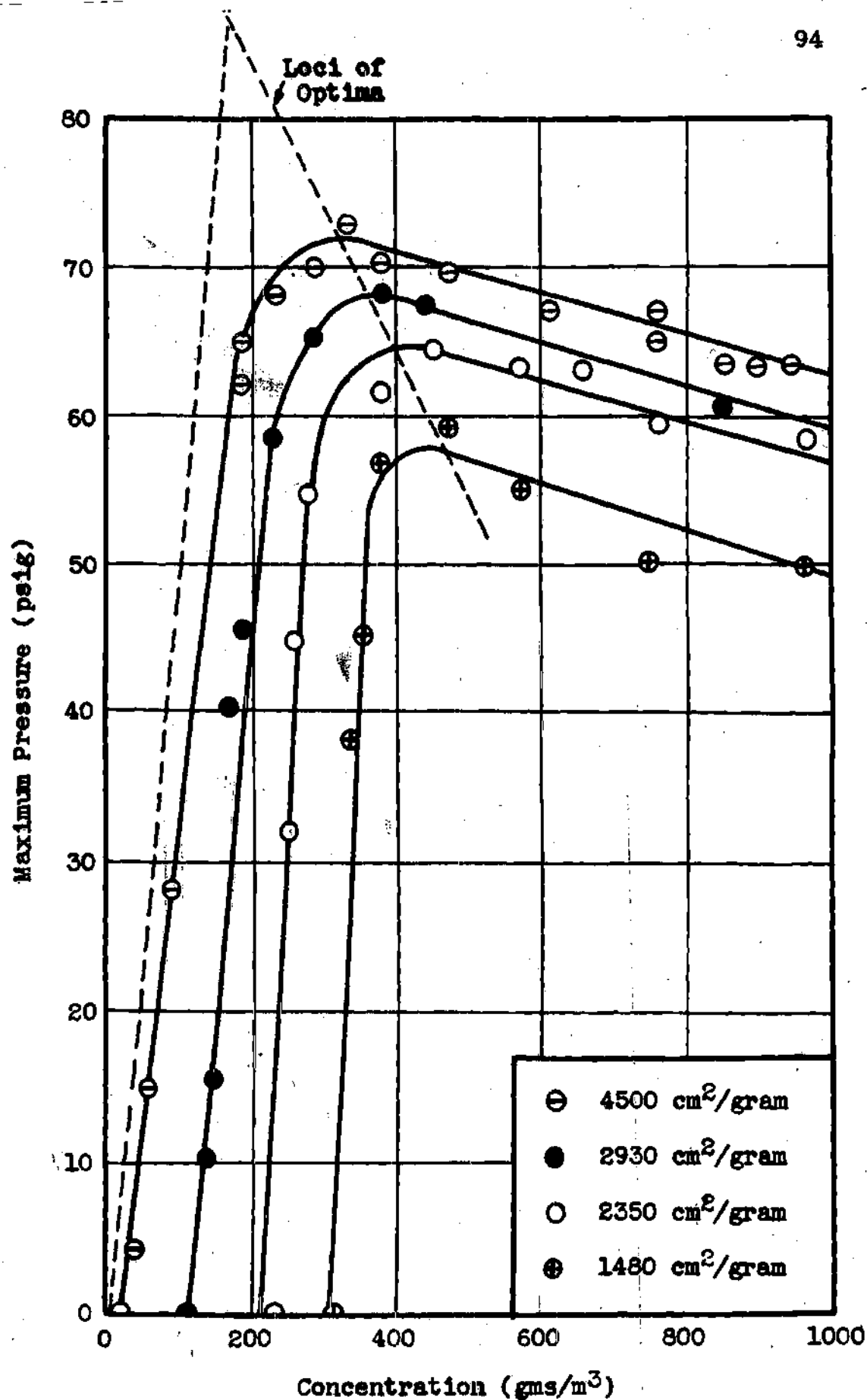


FIGURE 9: MAXIMUM PRESSURE VS. CONCENTRATION, DEXTROSE

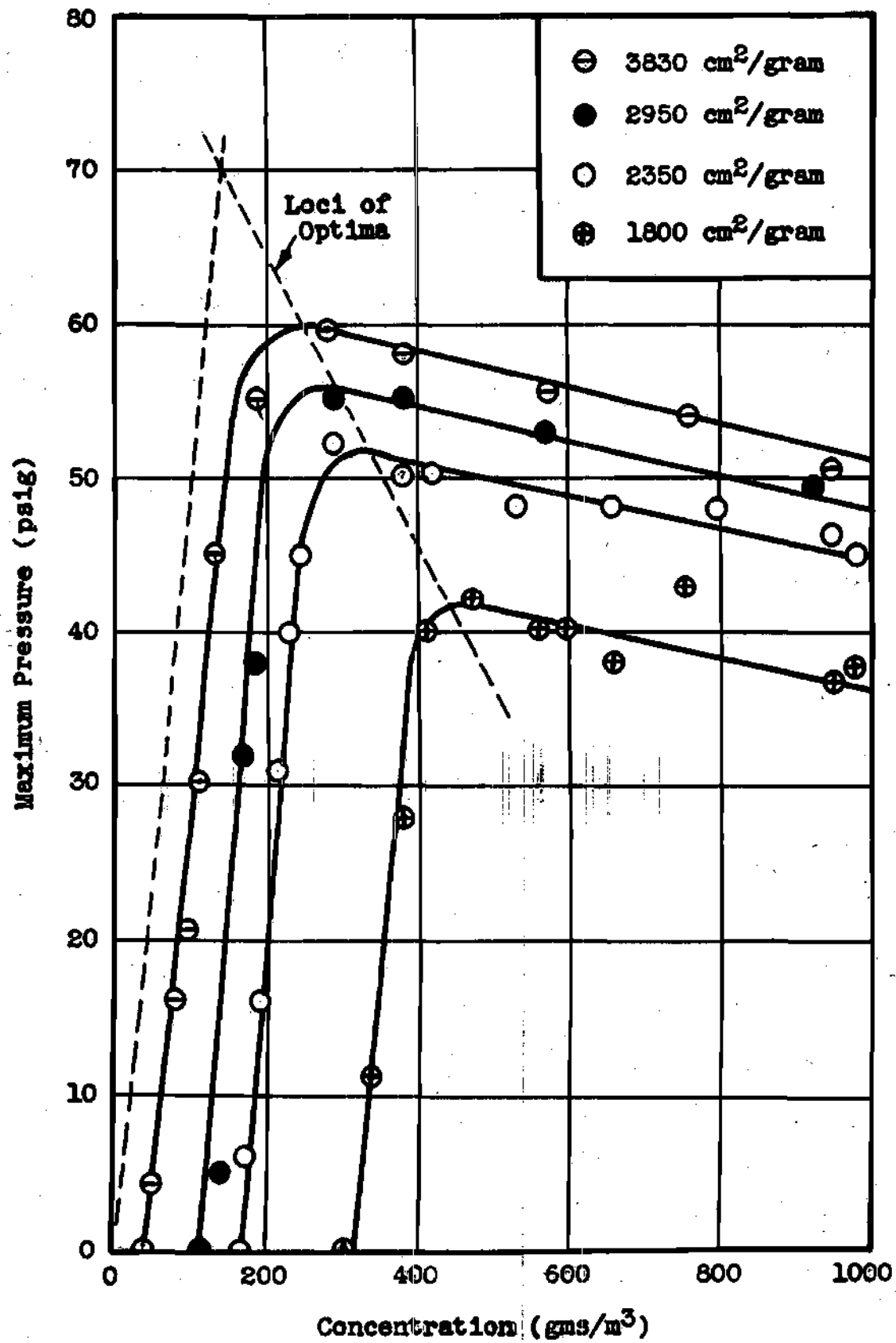


FIGURE 10: MAXIMUM PRESSURE VS. CONCENTRATION, SUCROSE

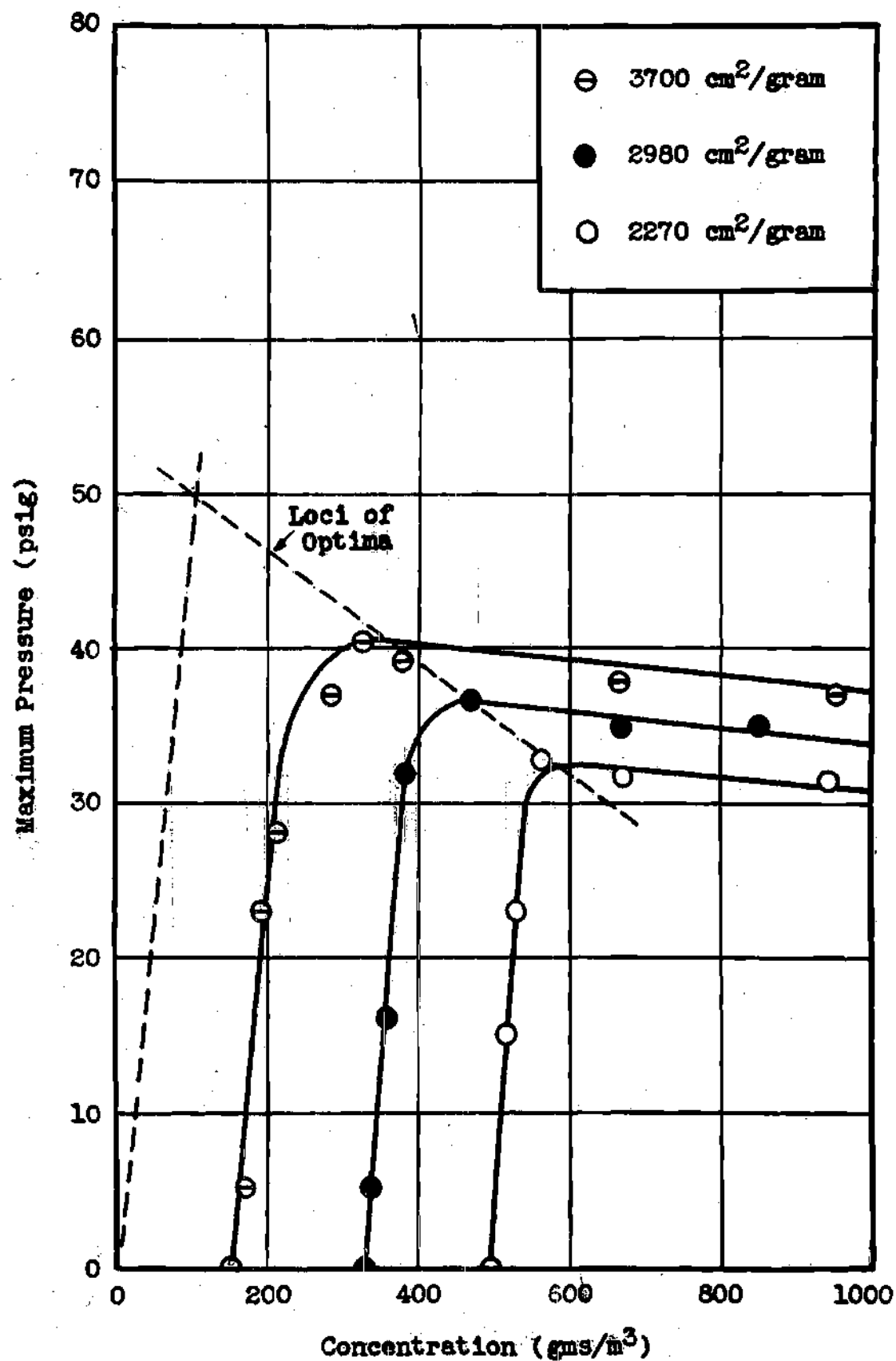


FIGURE 11: MAXIMUM PRESSURE VS. CONCENTRATION, RAFFINOSE

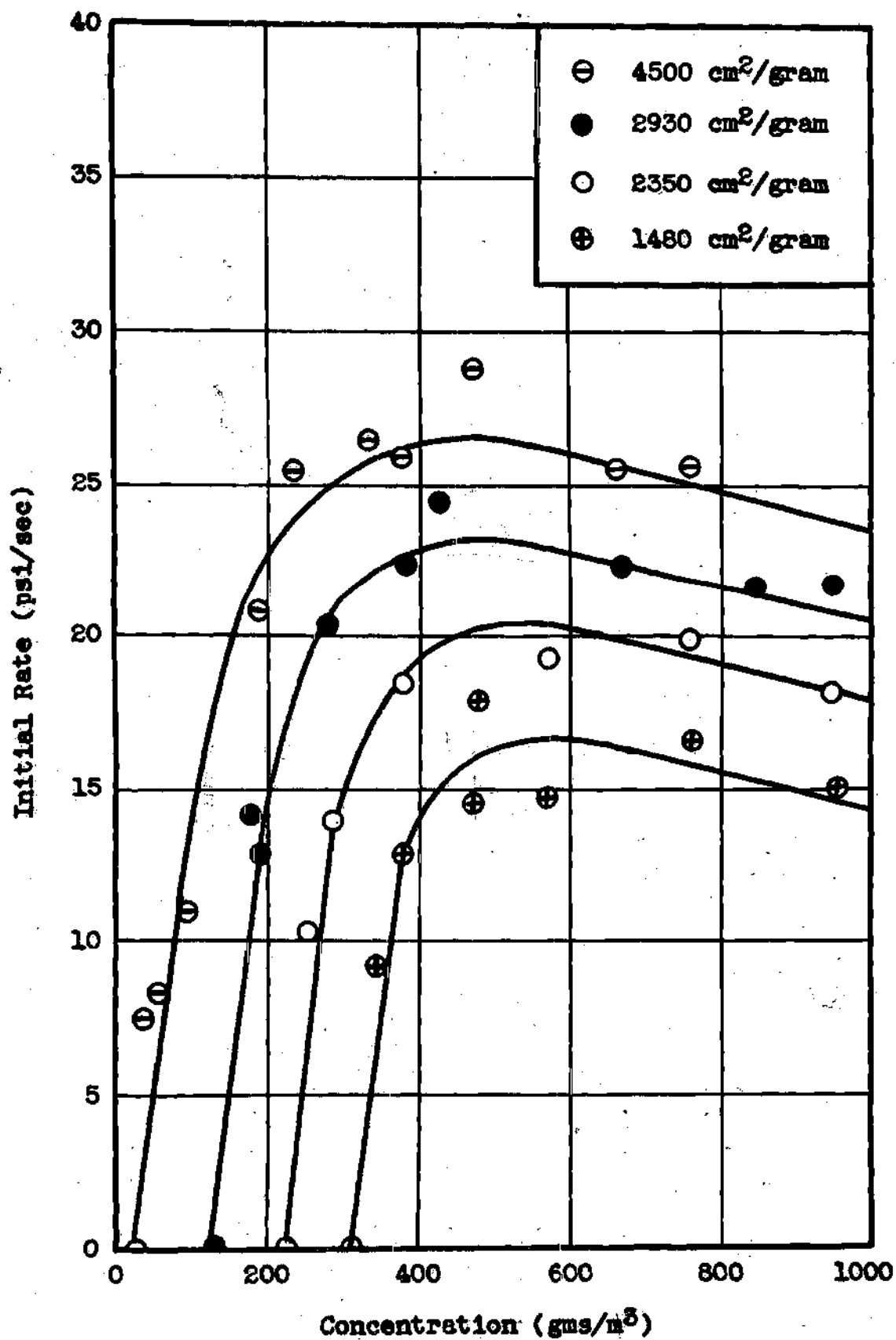


FIGURE 12: INITIAL RATE VS. CONCENTRATION, DEXTROSE

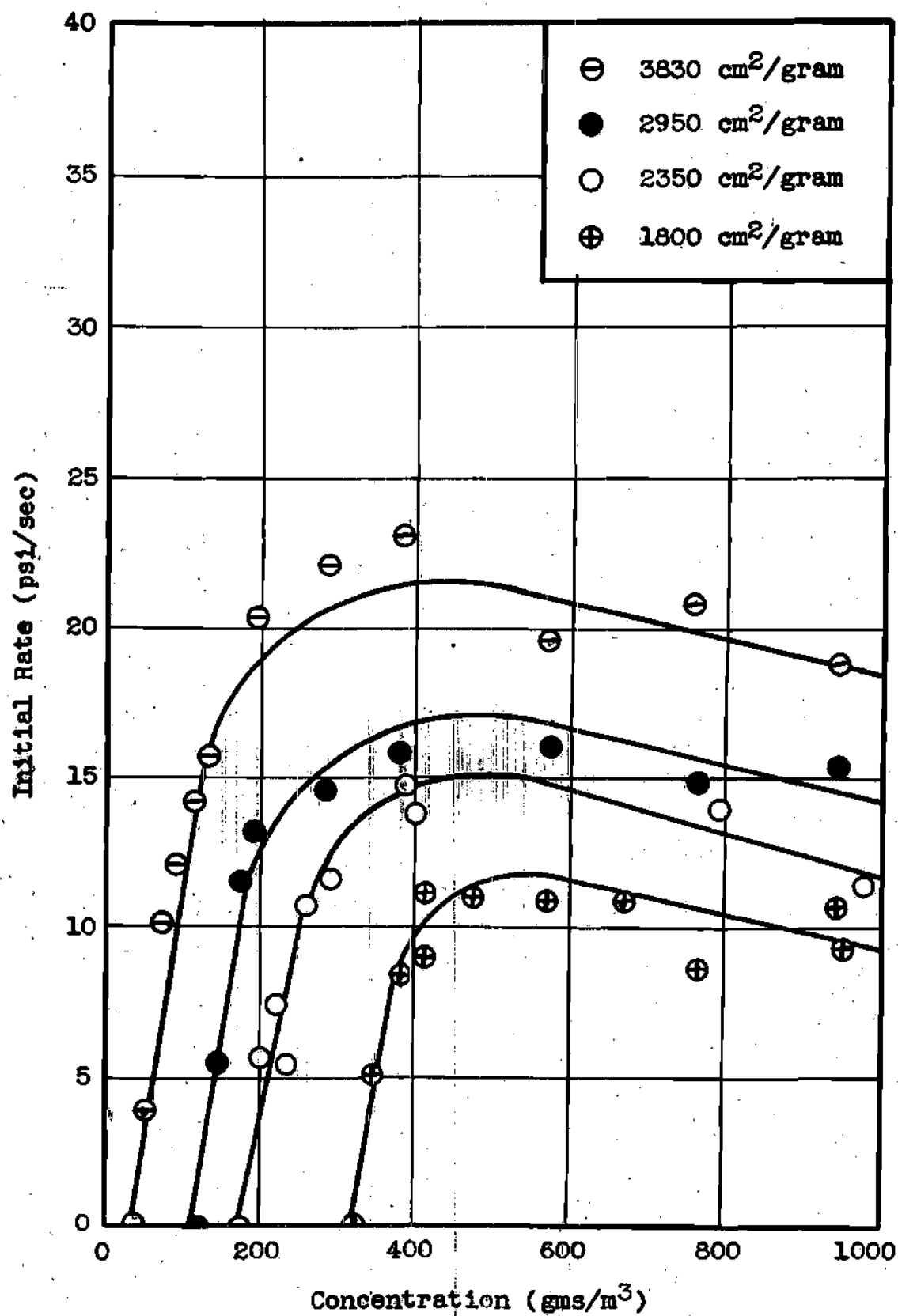


FIGURE 13: INITIAL RATE VS. CONCENTRATION, SUCROSE

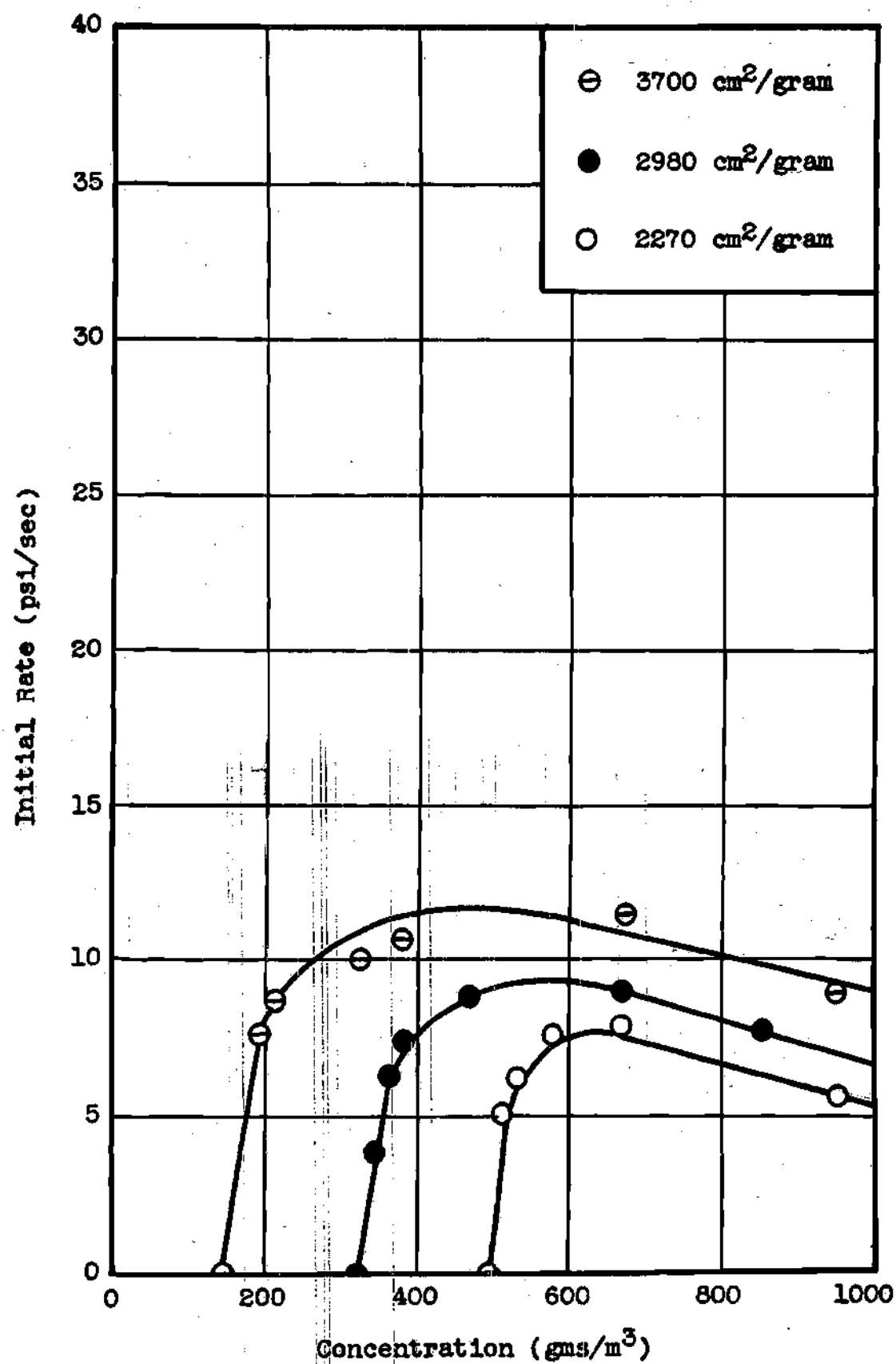


FIGURE 14: INITIAL RATE VS. CONCENTRATION, RAFFINOSE

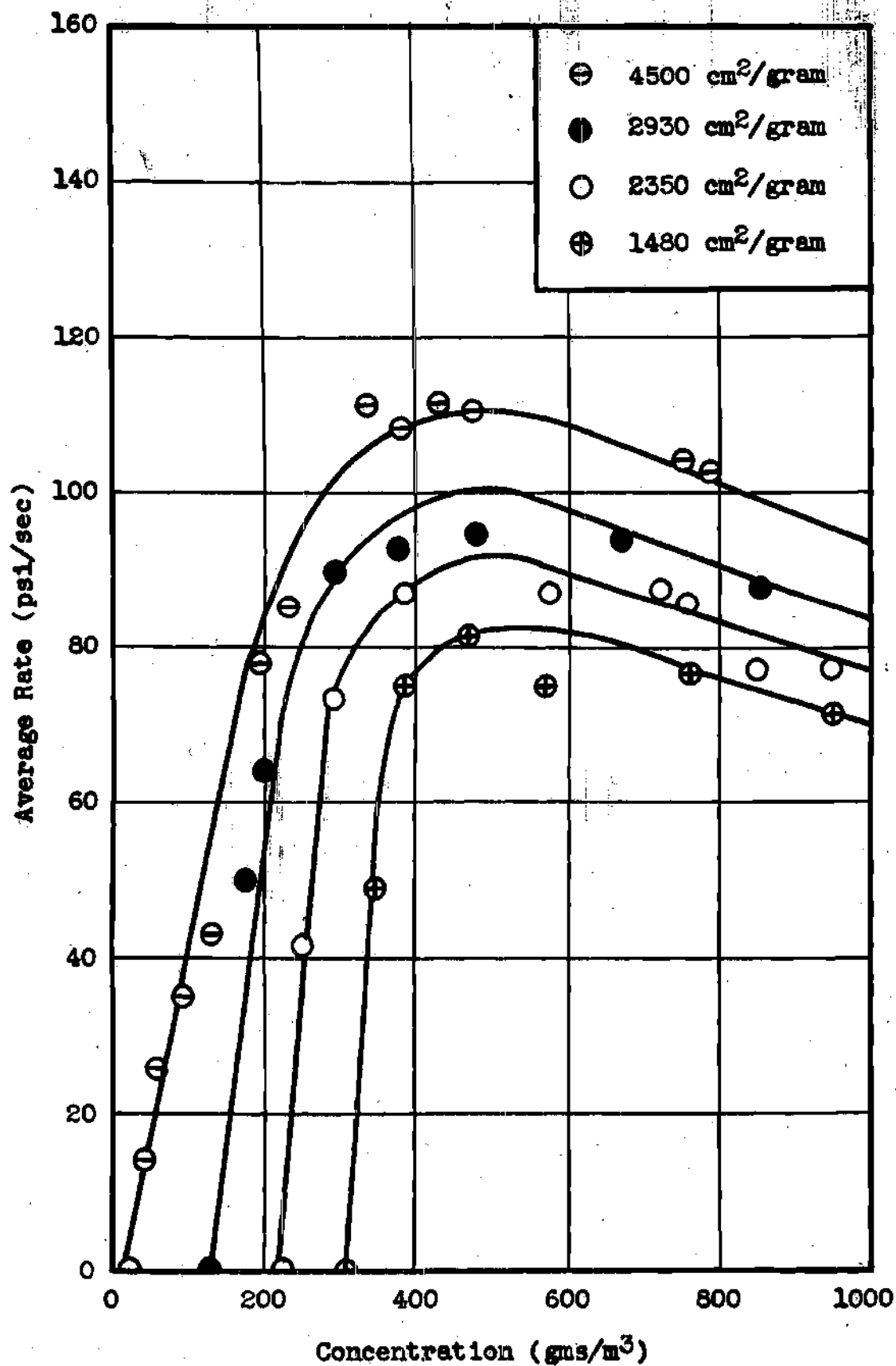


FIGURE 15: AVERAGE RATE VS. CONCENTRATION, DEXTROSE

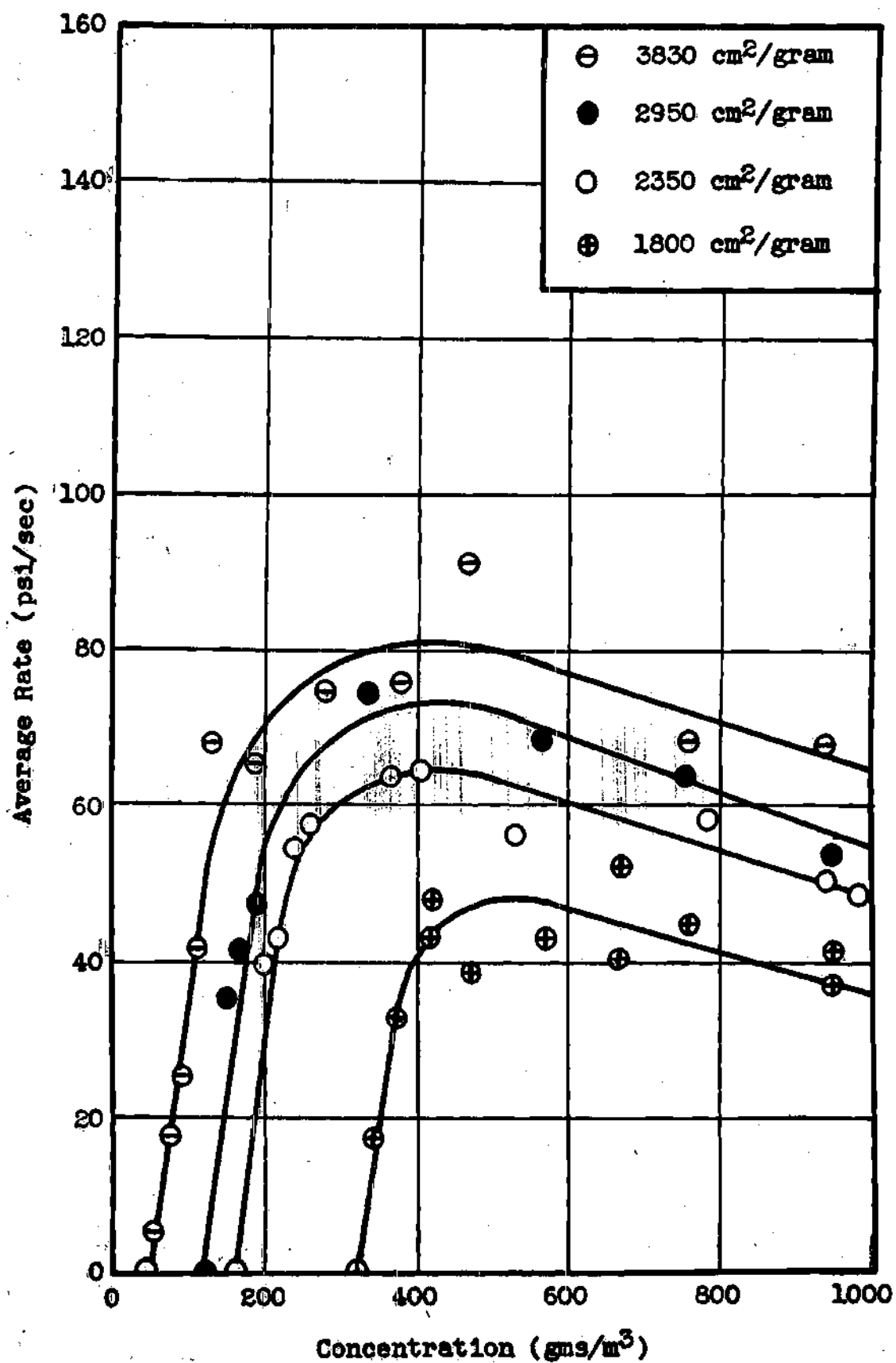


FIGURE 16: AVERAGE RATE VS. CONCENTRATION, SUCROSE

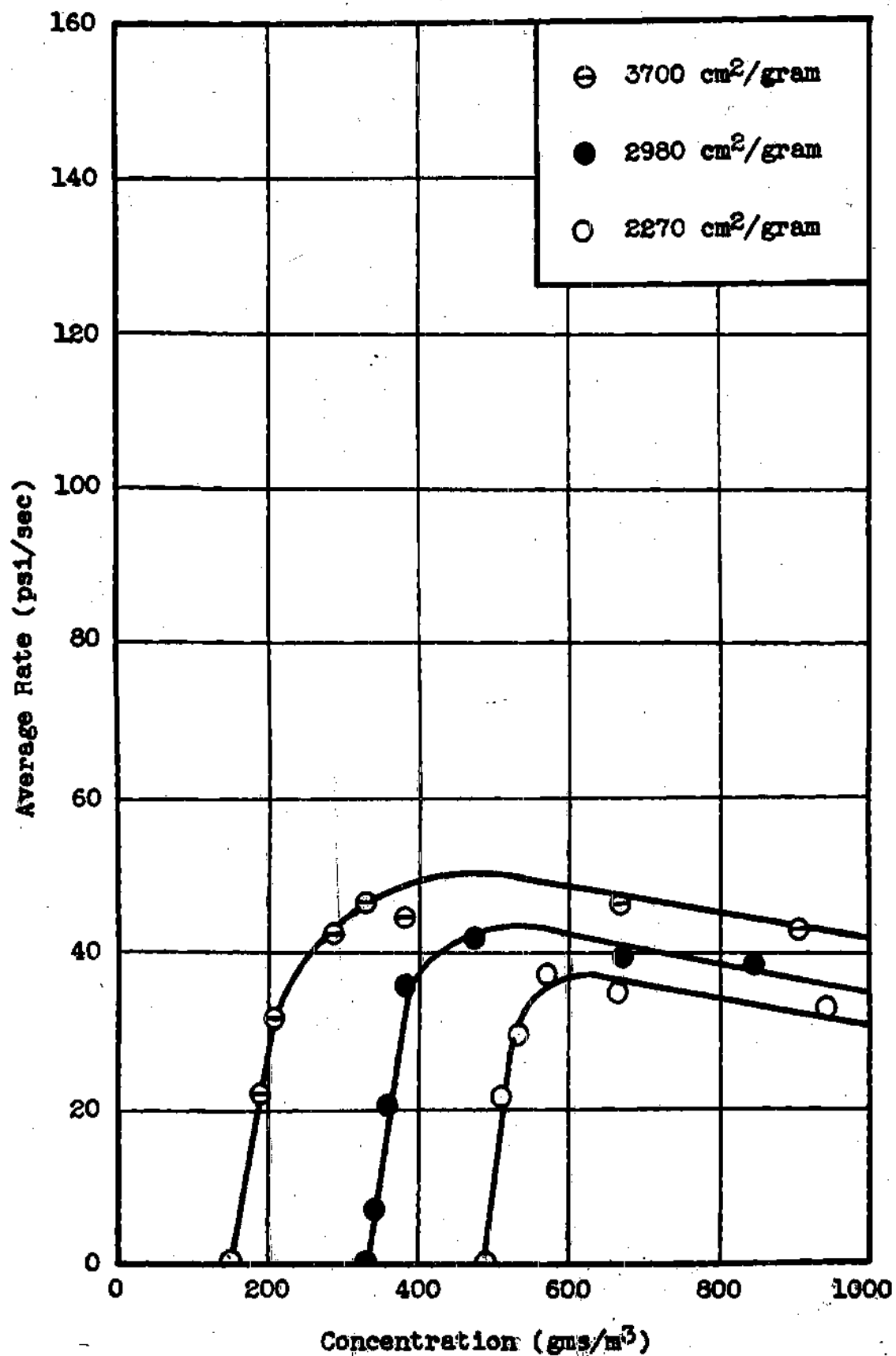


FIGURE 17: AVERAGE RATE VS. CONCENTRATION, RAFFINOSE

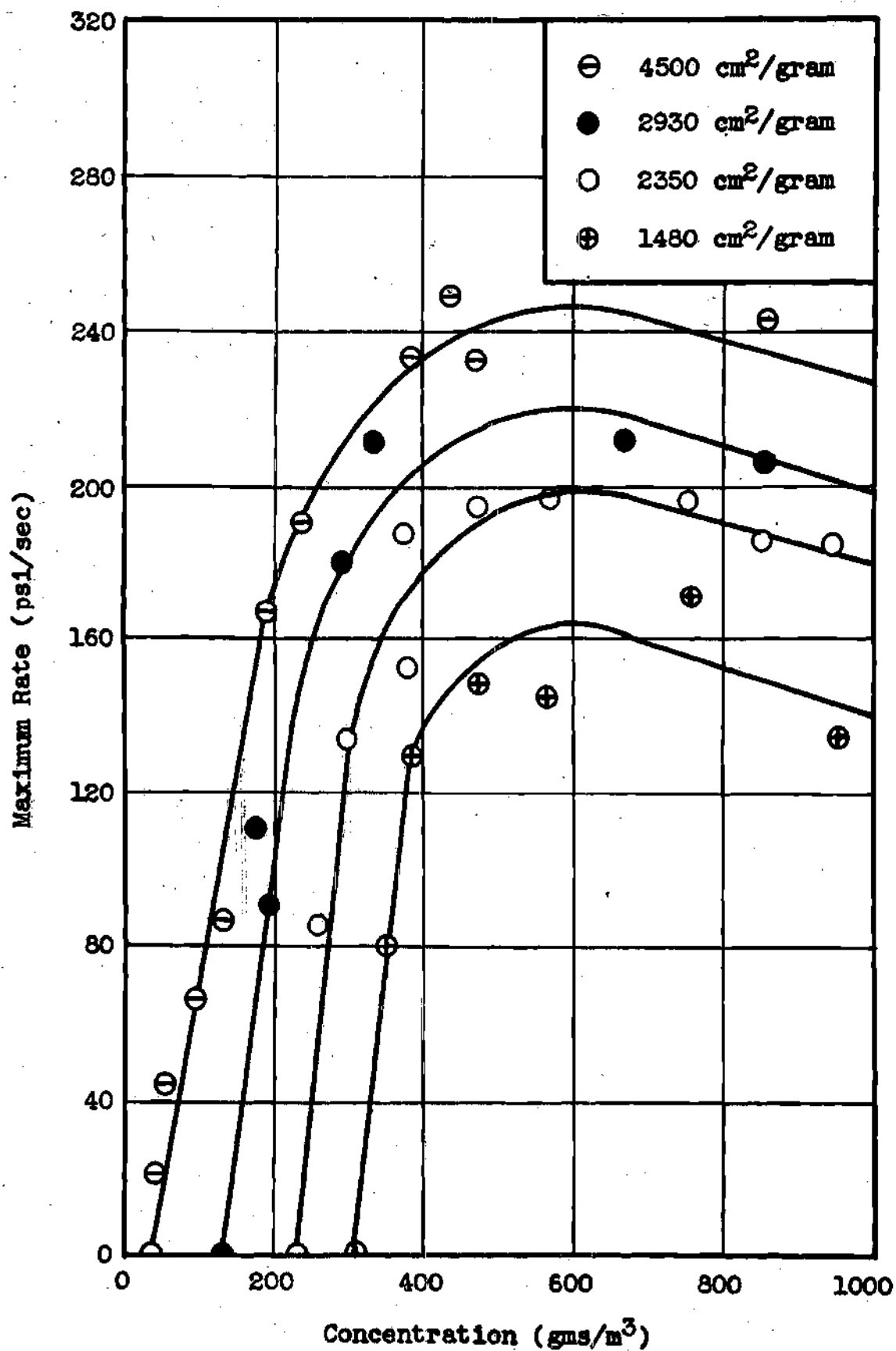


FIGURE 18: MAXIMUM RATE VS. CONCENTRATION, DEXTROSE

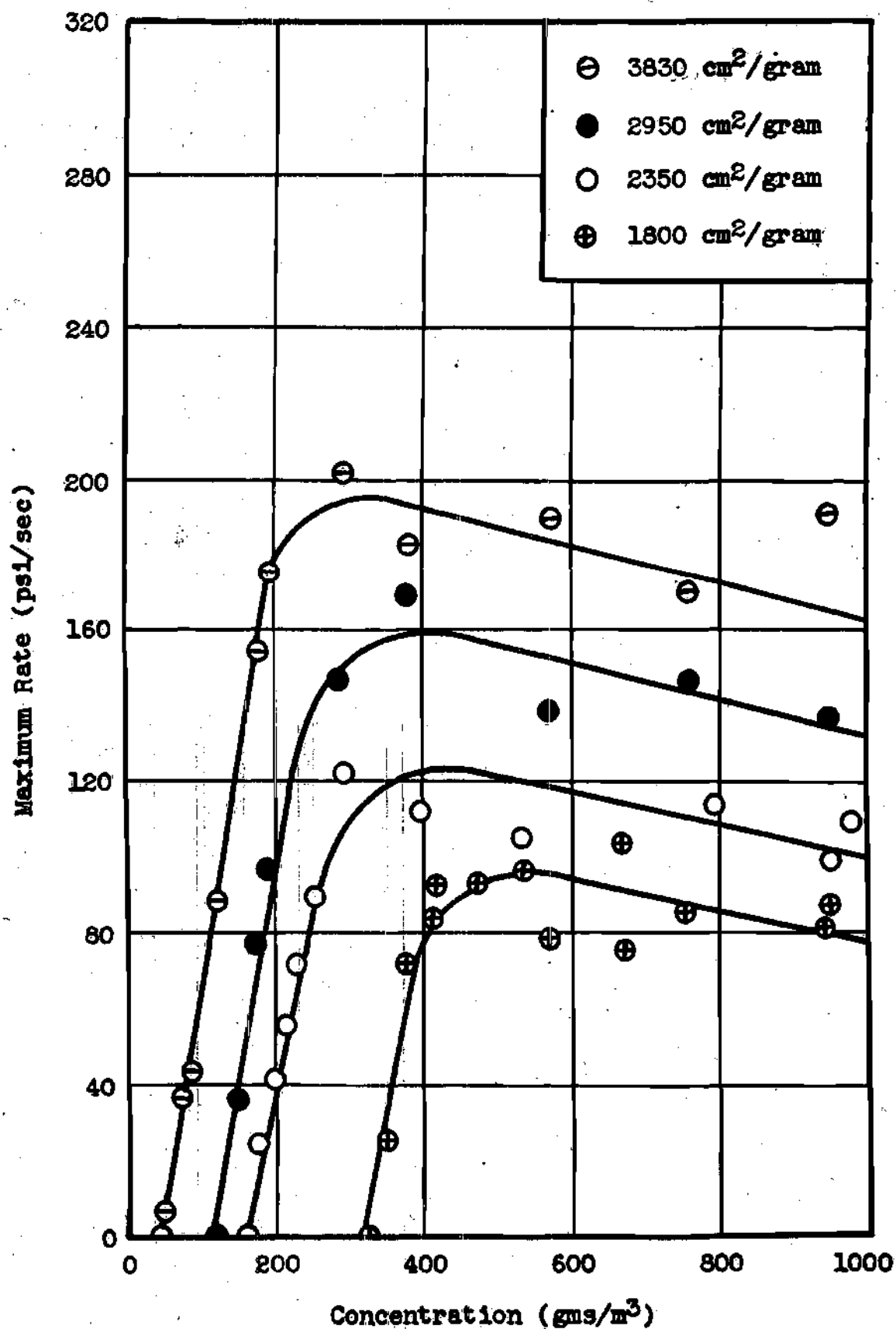


FIGURE 19: MAXIMUM RATE VS. CONCENTRATION, SUCROSE

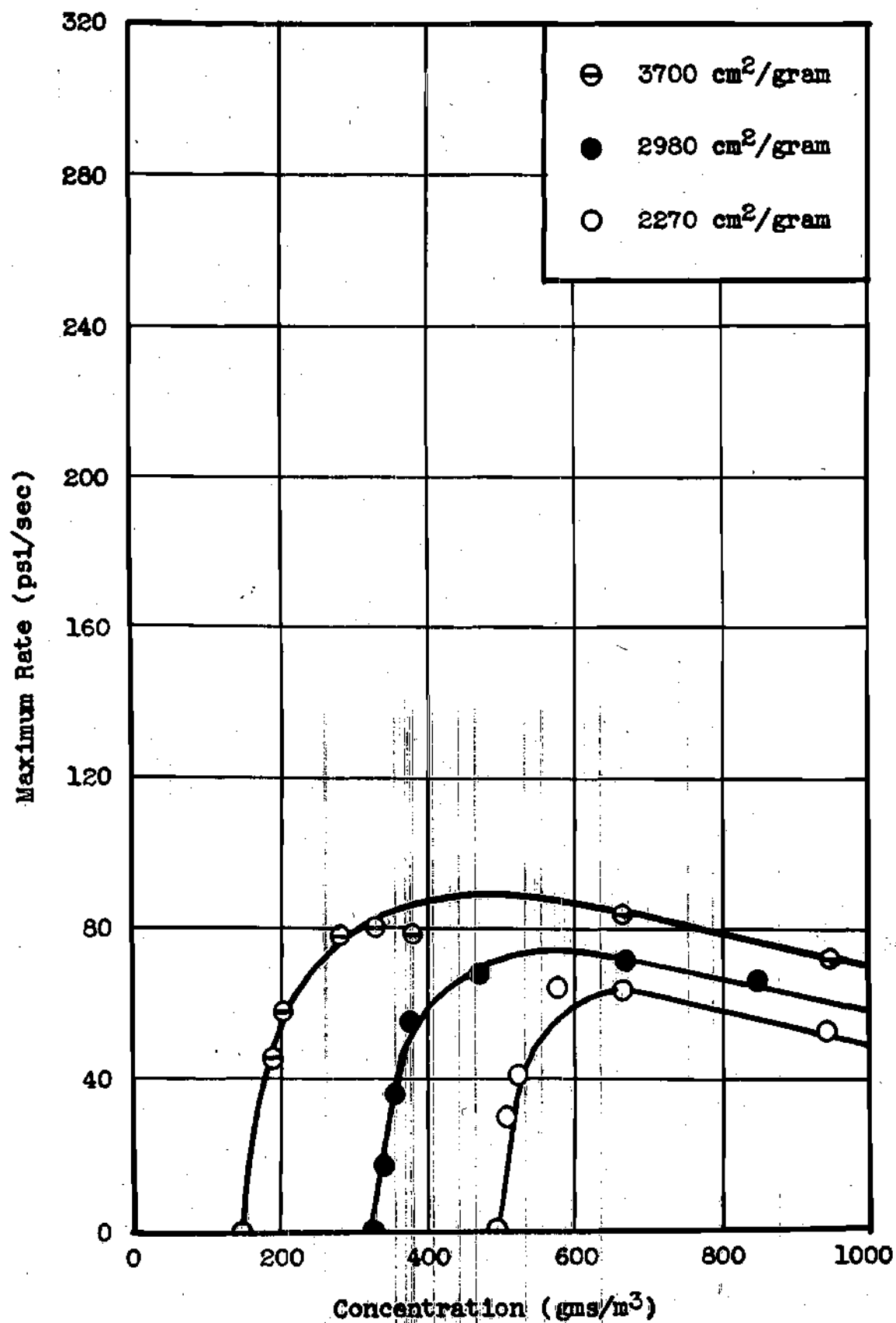


FIGURE 20: MAXIMUM RATE VS. CONCENTRATION, RAFFINOSE

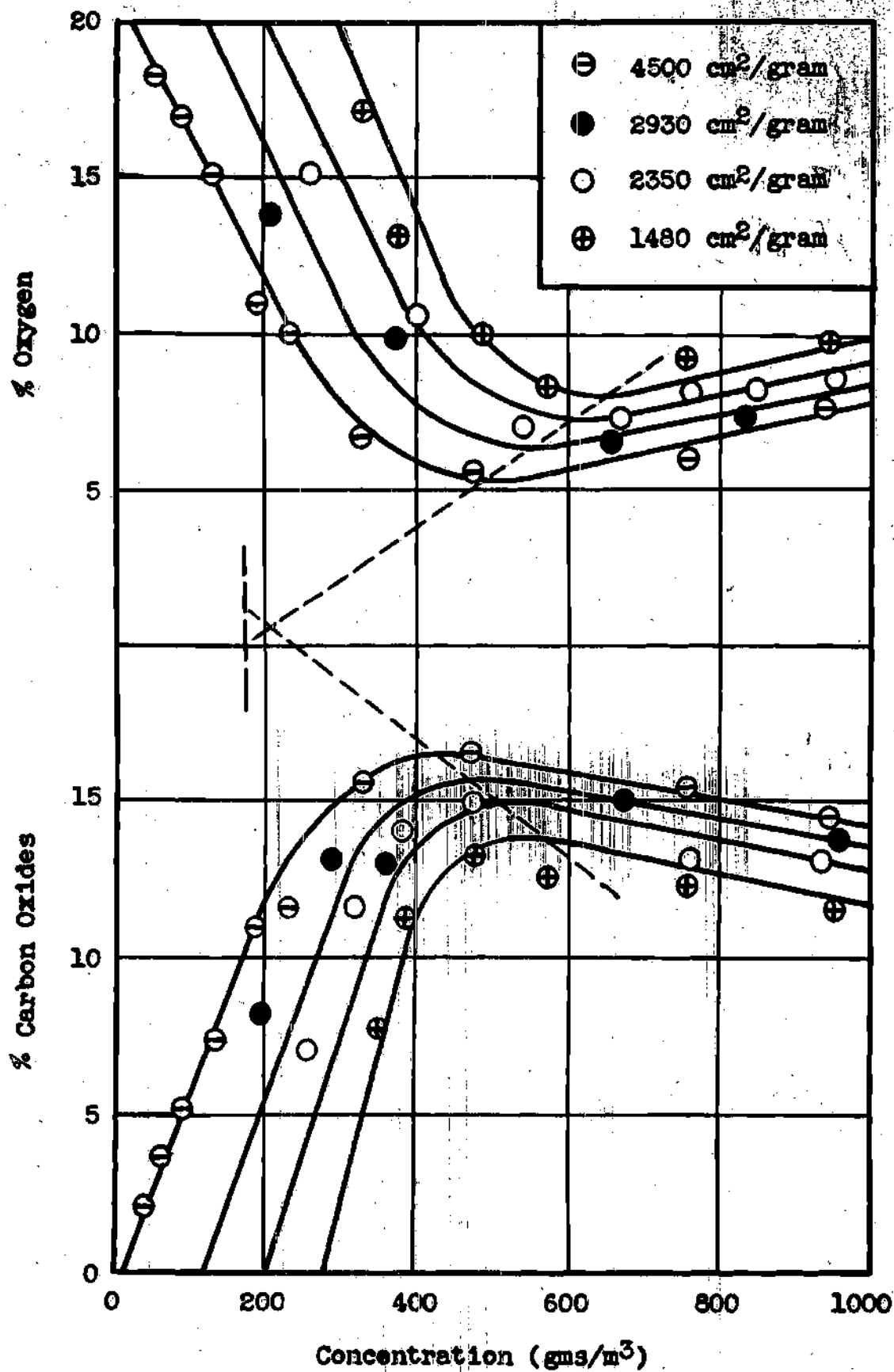


FIGURE 21: GAS ANALYSIS VS. CONCENTRATION, DEXTROSE

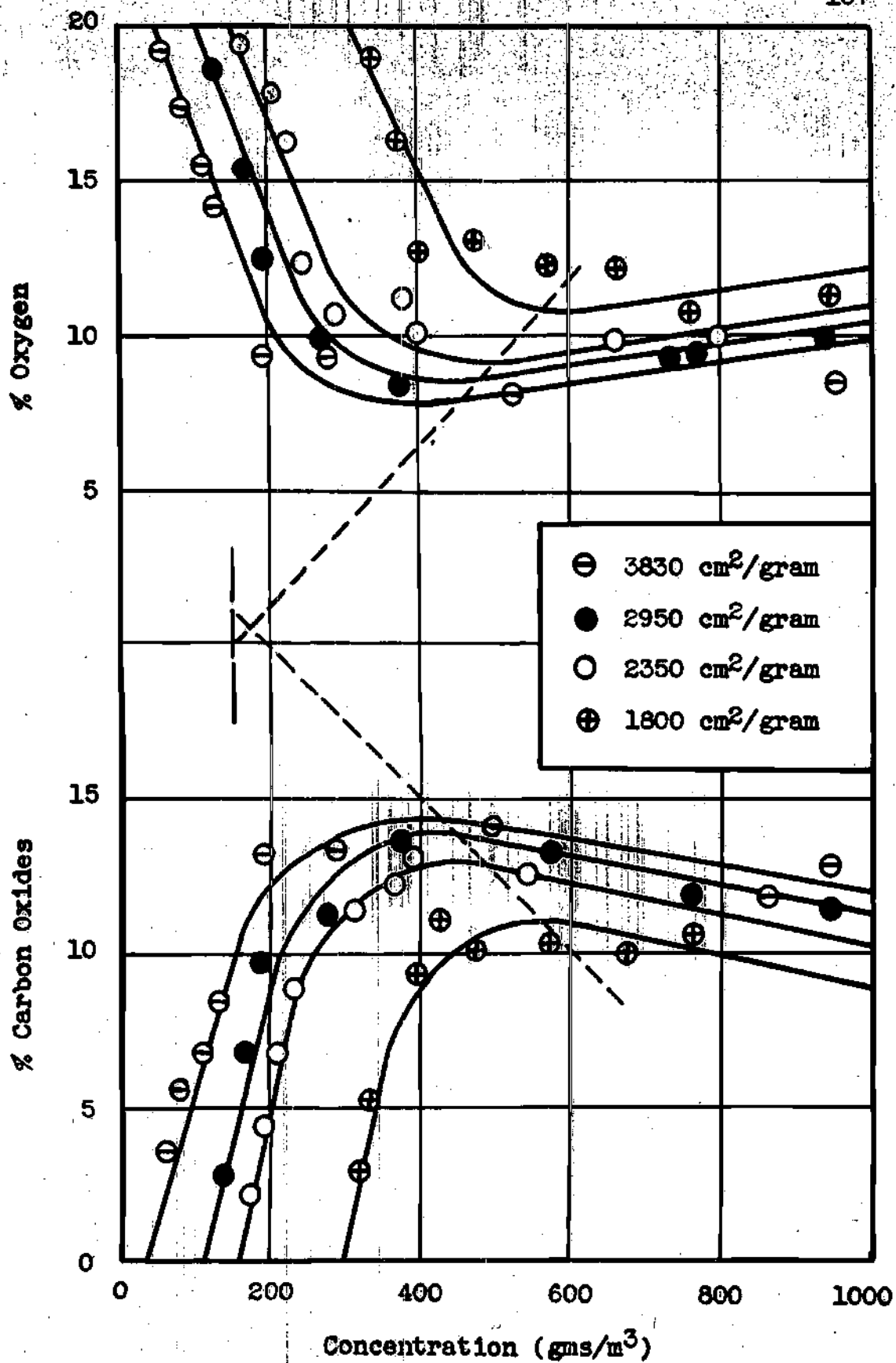


FIGURE 22: GAS ANALYSIS VS. CONCENTRATION, SUCROSE

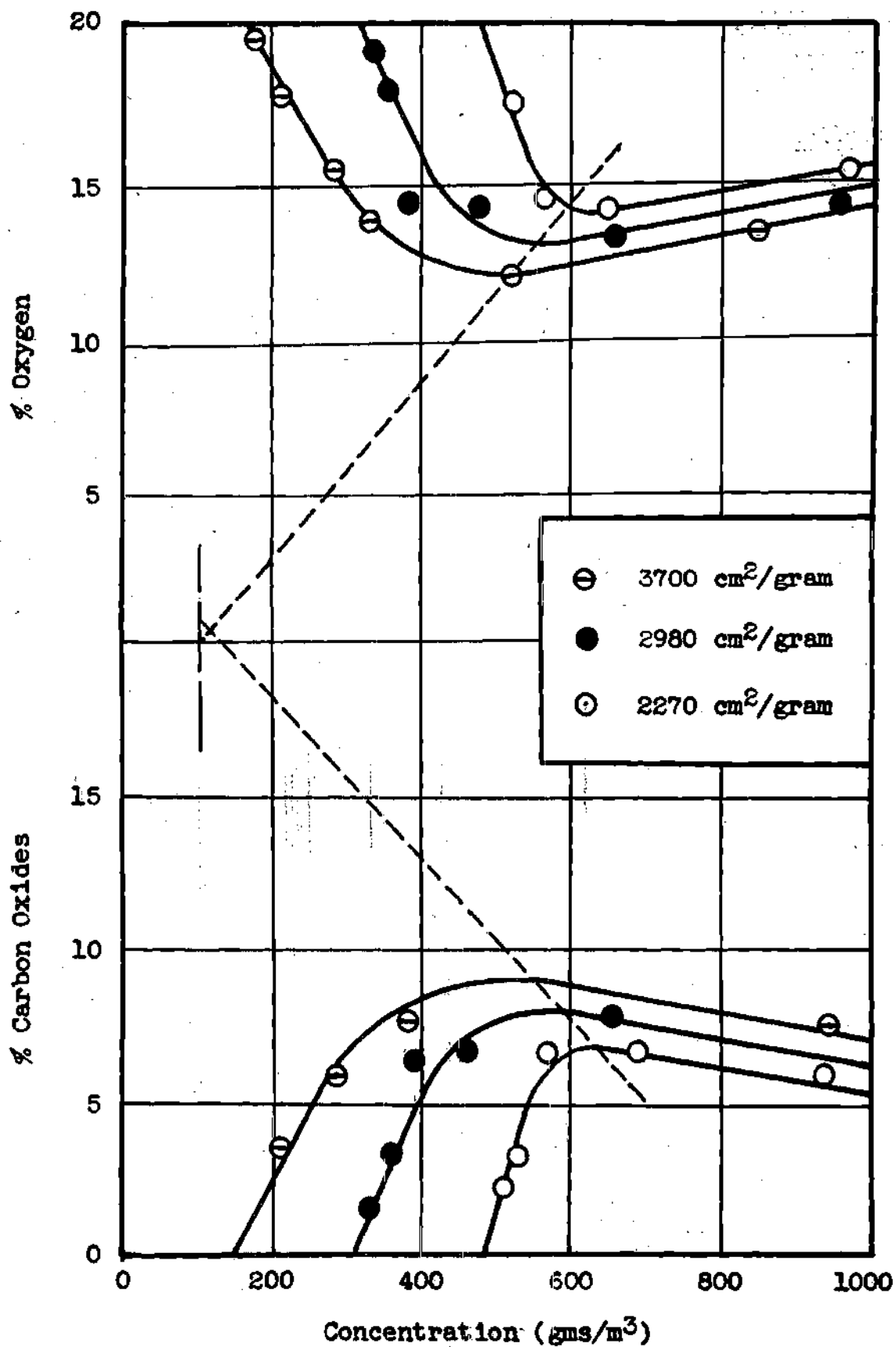


FIGURE 23: GAS ANALYSIS VS. CONCENTRATION, RAFFINOSE

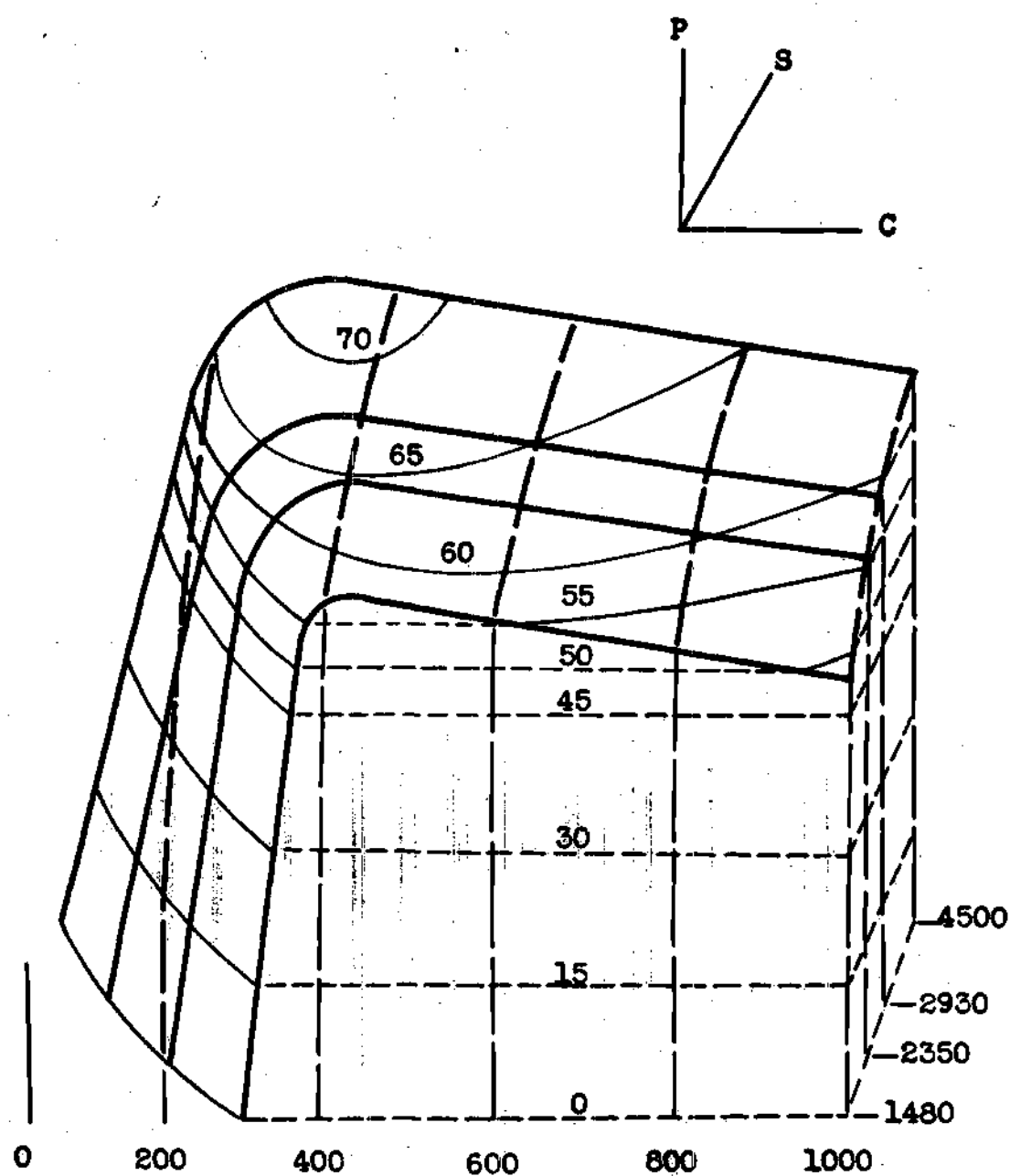


FIGURE 24: PRESSURE VS. CONCENTRATION VS. SURFACE, DEXTROSE

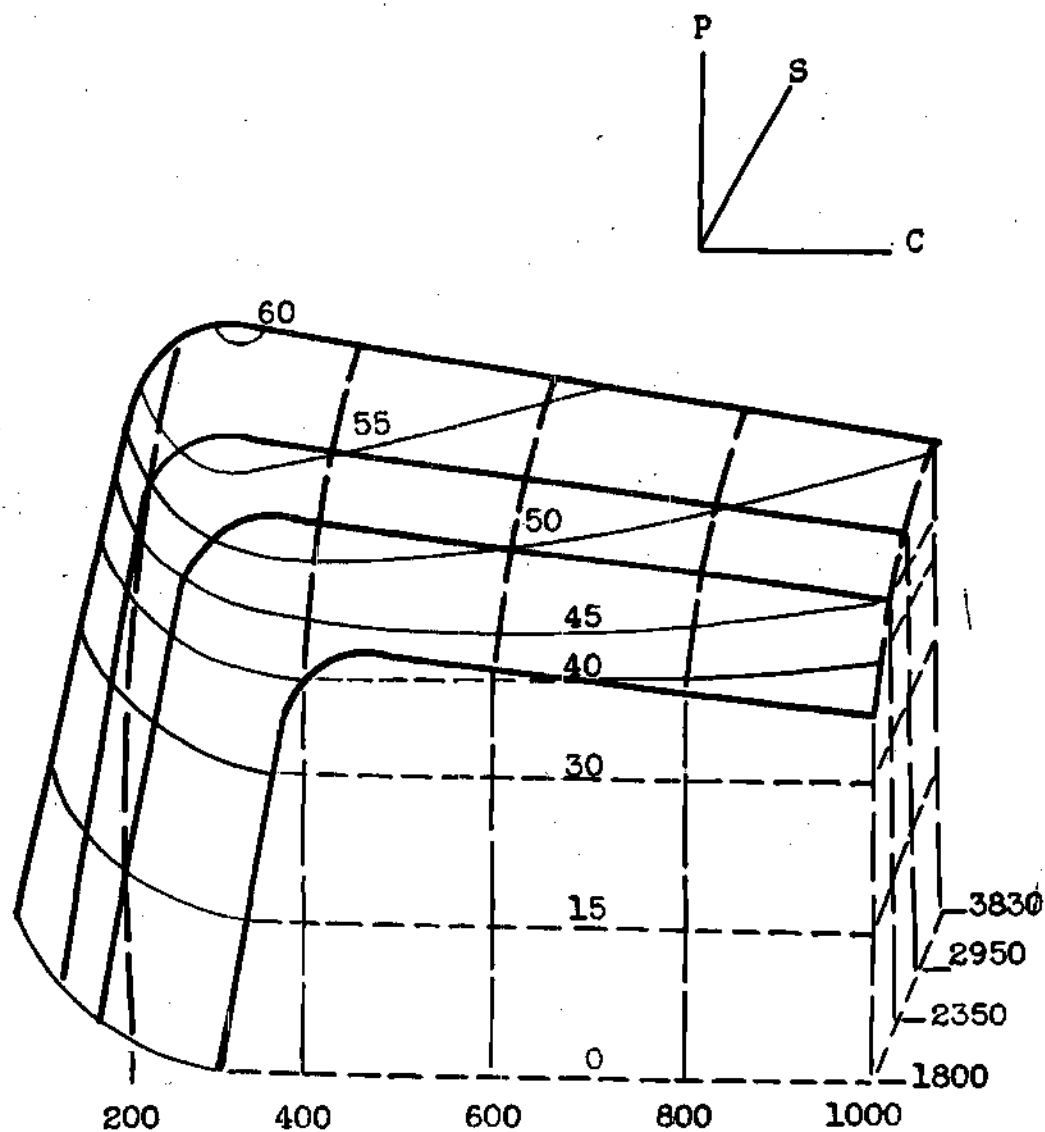


FIGURE 25: PRESSURE VS. CONCENTRATION VS. SURFACE, SUCROSE

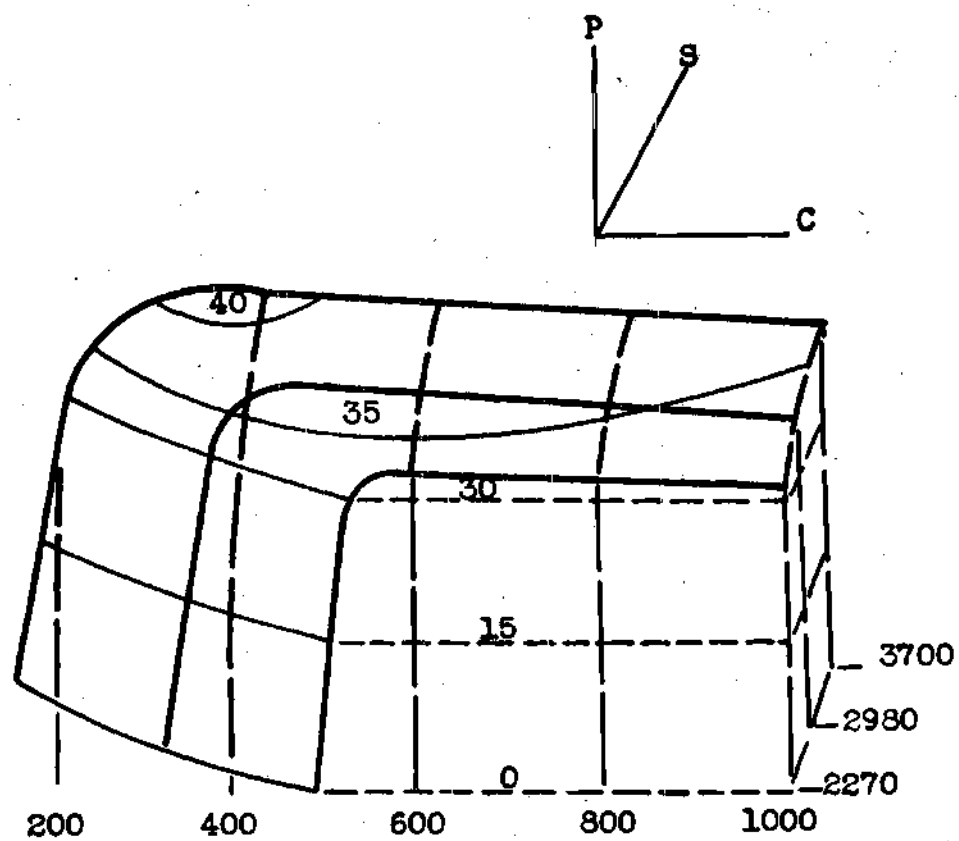


FIGURE 26: PRESSURE VS. CONCENTRATION VS. SURFACE, RAFFINOSE

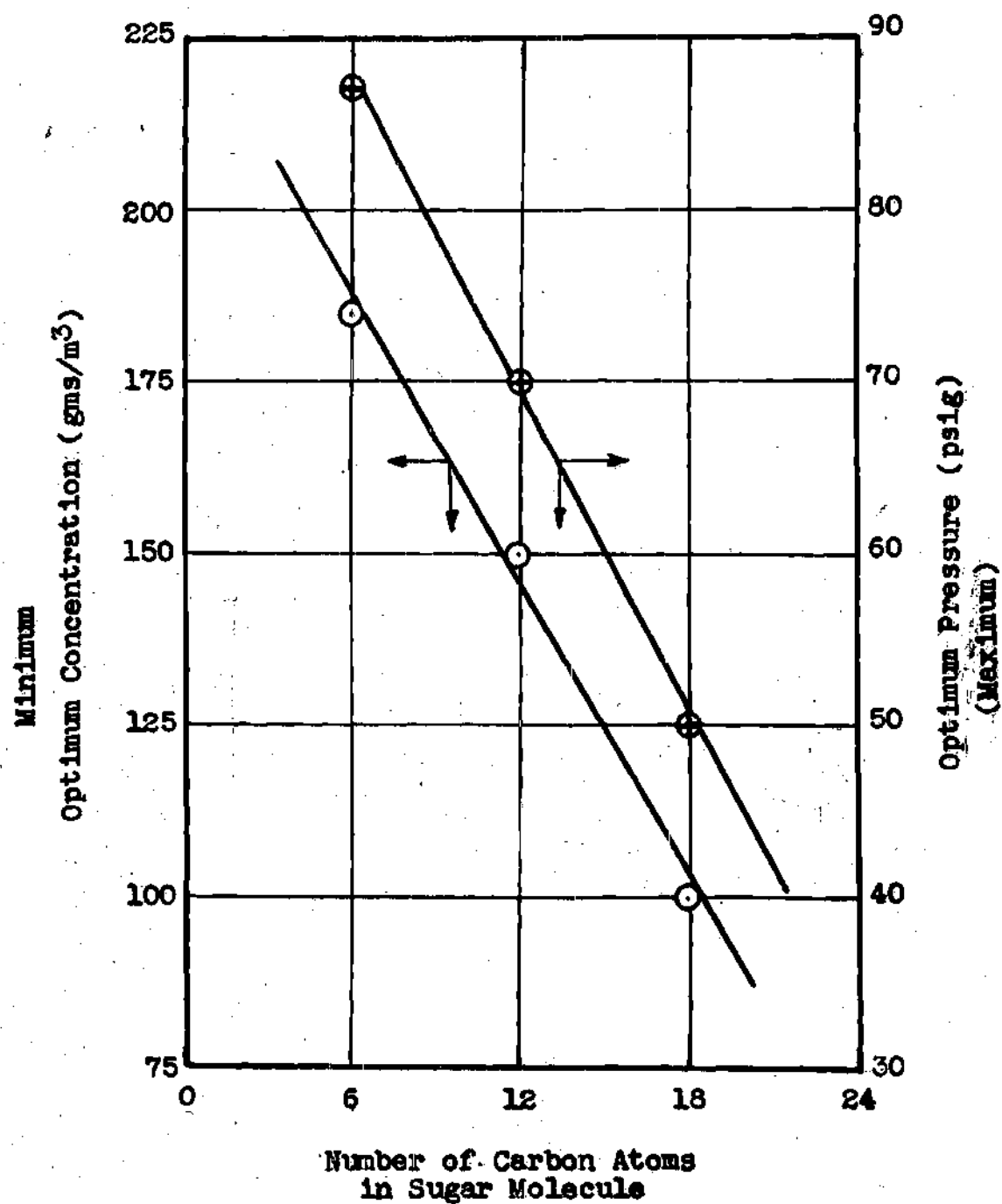


FIGURE 27: RELATION OF NUMBER OF CARBON ATOMS TO OPTIMUM CONCENTRATION AND PRESSURE

APPENDIX III
(CALCULATIONS)

CALCULATIONS

Specific Surface Determination

Calculation based on surface measurement runs Std-1 and D-A-1 and equation (6)

$$K = \frac{\rho S_w(1 - e)}{\sqrt[3]{e^3 T/n}}$$

$$\begin{aligned} \rho (\text{Standard}) &= 3.15 \text{ gms/cm}^3 \\ \rho (\text{Dextrose}) &= 1.544 \text{ gms/cm}^3 \\ e &= 0.500 \text{ (weight of dextrose to give this porosity = 1.47 gms)} \\ n &= 0.0001842 \text{ at } 80^\circ \text{ F.} \\ S_w(\text{Standard}) &= 3230 \text{ cm}^2/\text{gm} \\ T (\text{Standard}) &= 108.2 \text{ seconds} \\ T (\text{Dextrose}) &= 50.4 \text{ seconds} \end{aligned}$$

From Std-1

$$\begin{aligned} K &= \frac{(3.15)(3230)(1-0.500)}{\sqrt[3]{(0.500)^3(108.2)/0.0001842}} \\ &= 18.9 \end{aligned}$$

Then from D-A-1

$$\begin{aligned} S_w &= \frac{K \sqrt[3]{e^3 T/n}}{\rho(1 - e)} \\ &= \frac{18.9 \sqrt[3]{(0.500)^3(50.4)/0.0001842}}{(1.544)(1 - 0.500)} \\ &= 4530 \text{ cm}^2/\text{gm} \end{aligned}$$

An average was taken of three separate calculations of this type for each specific surface of each sugar studied.

Theoretical Maximum Pressure Determination

Calculation based on run D-A-7.

Data: $\%CO_2 = 12.0$
 $\%CO = 2.5$
 $t_1 = 800^\circ F.$
 $P_1 = 740 \text{ mm Hg}$
 $V_{\text{Tank}} = 1.86 \text{ ft}^3$
 $H_c \text{ (Dextrose)} = 673.0 \text{ kg cal/gm mol}$

Heat of combustion from N. A. Lange, Handbook of Chemistry. Handbook Publishers, Inc., Sandusky, Ohio (1941).

The volume of one mol of a perfect gas at the initial conditions is:

$$V_{\text{Std}} = 359(760/740)(540/492) \\ = 405 \text{ ft}^3$$

From equation (7), the number of mols of gas in the explosion chamber is

$$N_G = 1.86/405 = 0.00460 \text{ mols of dry gas}$$

from equation (8)

$$N_C = (0.00460)(12.0 + 2.5)/100 = 0.00067 \text{ mols CO \& CO}_2$$

from equation (9)

$$N_S = 0.00067/6 = 0.000111 \text{ mols dextrose exploded}$$

from equation (10)

$$N_{H_2O} = 0.000111(12/2) = 0.00067 \text{ mols H}_2\text{O}$$

from equation (11)

and the mixture is 35% water vapor in the mixture

$$N_I = 0.00460 - 0.00067 = 0.00393 \text{ mols } O_2 \text{ \& } N_2$$

from equation (12)

$$N_T = 0.00460 + 0.00067 = 0.00527 \text{ total mols of wet gas}$$

from equations (13), (14), and (15)

$$F_{H_2O} = 0.127 \quad F_C = 0.127 \quad F_I = 0.746$$

The following mean heat capacities were taken from

J. H. Perry, Chemical Engineers' Handbook. McGraw-Hill

Book Co., New York (1941).

From equation (16) $P_g = 70 \text{ psia}$

Time = 0.30 sec

$R_g = 83.4 \text{ cm}^3 \text{ (considering tank as sphere)}$

$$(C_v)_{\text{Avg}} = 0.127(0.029) + 0.127(0.035) + 0.746(0.021) \\ = 0.0240 \text{ Btu/ft}^3/\text{°F}$$

From equation (17)

The final theoretical flame temperature can then be obtained

from equation (17)

From equation (17) $(0.000111)(673.0)(1800)$ can be obtained

$$T_f = \frac{(0.000111)(673.0)(1800)}{(1.86)(0.0240)} - 80$$

$$= 2930 \text{ °F}$$

from equation (18)

From the equation $(0.00067)(405)$ can be obtained

$$C_{H_2O} = (0.00067)(405) = 0.28 \text{ ft}^3$$

and the maximum explosion pressure can be calculated by equation (19)

$$P_f = \frac{(1.86 + 0.28)}{1.86} \cdot \frac{3390}{540} \cdot \frac{740}{760} \cdot 14.7$$

$$P_f = 100 \text{ psia} = 85 \text{ psig}$$

$$P_f (\text{observed}) = 70 \text{ psig}$$

$$\% \text{ Error} = \frac{P_f(\text{calc}) - P_f(\text{obs})}{P_f(\text{obs})} \cdot 100$$

$$= \frac{100 - 85}{85} \cdot 100 = 17.7\%$$

Determination of Explosion Velocity

Calculation based on run D-A-7

Data:

$$\begin{aligned} P_e &= 70 \text{ psig} \\ \text{Time} &= 0.60 \text{ sec} \\ R_o &= 23.4 \text{ cm (considering tank as sphere)} \\ r_e &= 15.2 \text{ cm (from graphical integration} \\ &\quad \text{of time vs. radius diagram)} \end{aligned}$$

From these data:

$$(dr_o/dt)_{\text{Avg}} = R_o/t = 39.0 \text{ cm/sec}$$

From equation (20) the average velocity can be obtained directly as r_o R_o

$$\begin{aligned} V_n &= (23.4/15.2)^2 (14.7/84.7)^{0.715} (39) \\ &= 26.8 \text{ cm/sec} \end{aligned}$$

Since the explosion chamber has an actual radius of 7 inches, the expected velocity would be

$$\begin{aligned} V_n (\text{observed}) &= 7 \times 2.54/0.6 \\ &= 29.6 \text{ cm/sec} \end{aligned}$$

Calculation of Initial and Maximum Rates

The initial and maximum rates of pressure increase developed by an explosion of sugar dust can be calculated from the initial and maximum slopes of the time-pressure curve as shown in Figure 28.

Calculation of Theoretical Time-Pressure Relation

Several runs of each of the three sugars were plotted on a logistic grid to determine the constants for the equation discussed on page 71. A sample logistic diagram is shown in Figure 29.

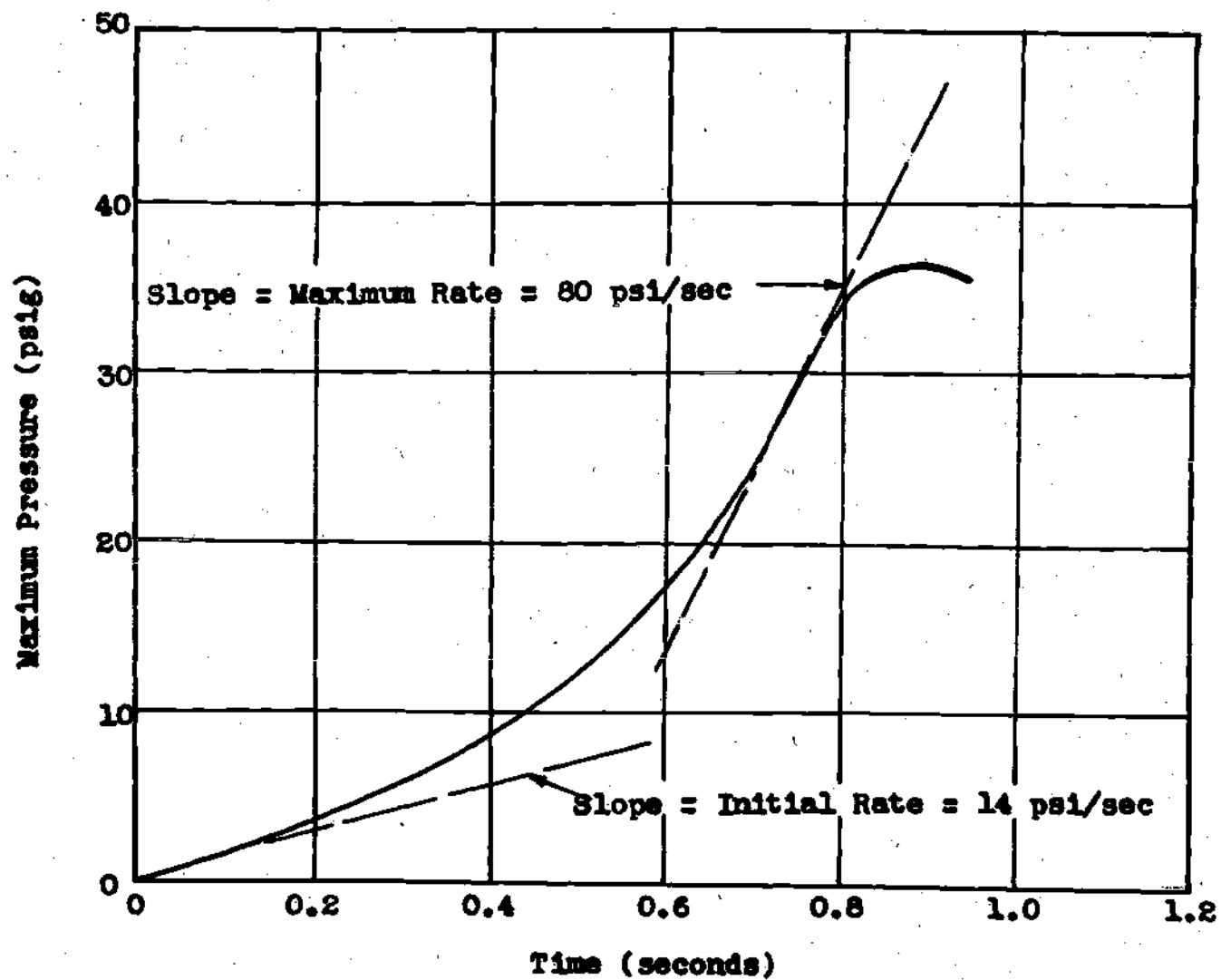


FIGURE 28: SAMPLE CALCULATION OF INITIAL AND MAXIMUM RATES FROM TIME-PRESSURE RECORDS (RUN R-A-4)

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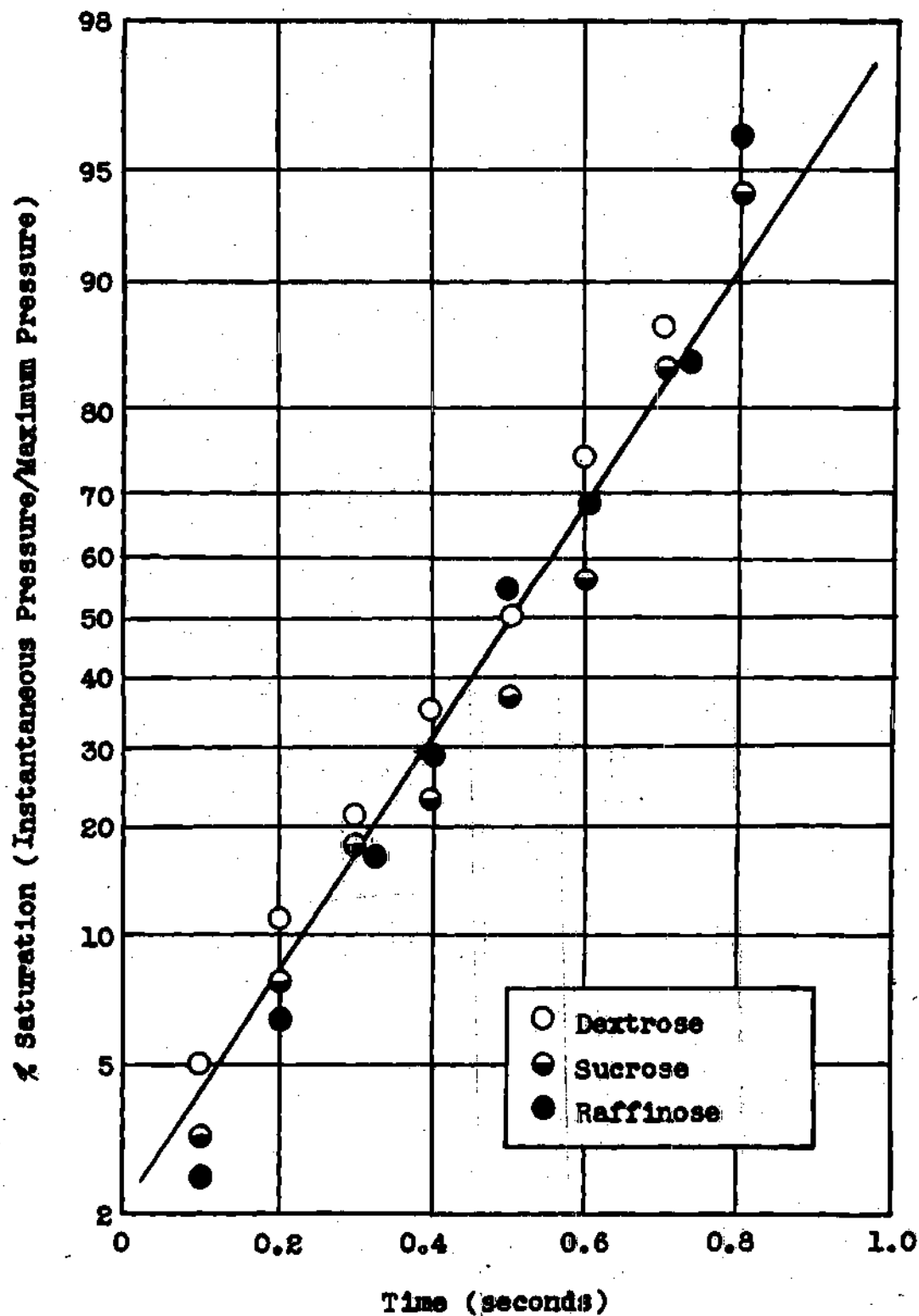


FIGURE 29: LOGISTIC GRID REPRESENTATION OF TIME-PRESSURE RECORDS