UNITED STATES DEPARTMENT OF AGRICULTURE

BULLETIN No. 681

Also Bulletin 26 of The Engineering Experiment Station
The Pennsylvania State College

Contribution from the Bureau of Chemistry
CARL L. ALSBERG, Chief
and the Engineering Experiment Station of The Pennsylvania State College
R. L. SACKETT, Dean

Washington, D. C. — May 18, 1918

GRAIN-DUST EXPLOSIONS

INVESTIGATION IN THE EXPERIMENTAL ATTRITION MILL AT THE PENNSYLVANIA STATE COLLEGE

By

B. W. DEDRICK, Instructor in Milling Engineering, and R. B. FEHR, Assistant Professor of Mechanical Engineering, The Pennsylvania State College, in collaboration with DAVID J. PRICE, Engineer in Charge, Grain-Dust Explosion Investigations, Bureau of Chemistry, Department of Agriculture

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GRAIN-DUST EXPLOSIONS:

INVESTIGATION IN THE EXPERIMENTAL ATTRITION MILL AT THE PENNSYLVANIA STATE COLLEGE.[1]

By B. W. Dedrick, *Instructor in Milling Engineering*, and R. B. Fehr, *Assistant Professor of Mechanical Engineering, The Pennsylvania State College*, in collaboration with David J. Price, *Engineer in Charge, Grain-Dust Explosion Investigations, Bureau of Chemistry, Department of Agriculture.*

CONTENTS.

OBJECT AND SCOPE OF THE INVESTIGATION.

The great loss of life and property resulting from explosions in coal mines, flour and feed mills, grain elevators, thrashing separators, etc., emphasizes the fact that carbonaceous dusts are very inflammable and that careful laboratory and field investigations should be conducted in order to devise means for combating this great danger. Although Faraday in 1844 suggested that coal dust suspended in air would propagate an explosion, it has been recognized only within the past 30 years that coal dust is explosive without the presence of a combustible gas. And not only coal dust, but many other carbonaceous dusts are now known to be very inflammable and capable of propagating flames. Some idea of the large amount of attention that has been given to the explosibility of dusts can be gained by referring to the bibliography at the end of this bulletin (p. 52) and to that printed in Bureau of Mines Bulletin 20, which deals particularly with coal-dust explosions.

[1] The erection of the mill and the conduct of the experiments were under the charge of B. W. Dedrick and R. B. Fehr, of the Department of Mechanical Engineering, assisted by P. X. Rice, R. E. Campbell, and E. F. Grundhoeffer, instructors in experimental engineering, and C. L. Charles, student assistant.

In June, 1913, an explosion in a feed-grinding plant in Buffalo, N. Y., caused the death of 33 men, injured more than 70 employees, and damaged a great deal of grain and property. Shortly afterwards the Bureau of Chemistry began its work in connection with dust explosions in grain mills, elevators, and industrial plants. During the period in which this study has been carried on a large number of disastrous dust explosions, in which many lives have been lost, large quantities of grain and food products destroyed, and much property damaged, have occurred in grain elevators, feed, cereal, and flour mills, starch factories, sugar refineries, and other industrial plants which handle grain. Several definite causes for these explosions have been established, and effective preventive methods have been developed and tested. At present the United States Department of Agriculture is conducting a special war-emergency campaign for the prevention of dust explosions and fires. Representatives of the department are rendering direct assistance to the millers and grain men of the country in installing devices for preventing explosions and in showing them how to remedy dangerous conditions.

The grain-dust explosion work, as conducted by the Bureau of Chemistry, falls into two general classes:

(1) Dust explosions which occur in grain mills, elevators, and industrial plants during the handling and milling of grains and the manufacture of food products.

(2) Dust explosions which occur in thrashing machines during the operations in the harvest fields.

MILL AND ELEVATOR EXPLOSIONS.

As soon as possible after the occurrence of an explosion in a mill or elevator, the field engineers of the bureau investigate carefully the conditions under which the explosion originated and assist the company to devise and install some means for preventing any more such explosions. During the course of these field investigations it has become apparent that one of the causes for a large number of dust explosions and fires in the cereal and feed mills, particularly in the feed-grinding departments, is the ignition of the dust on the interior of the grinding machine during operation. In many instances the evidence indicated that the explosion and fire originated within the machine, usually in the attrition type of mill. As they were believed to have been caused by sparks from foreign particles or metallic substances entering with the grain, the bureau emphasized the necessity for taking steps to remove these materials from the mill stream before it entered the grinding machines.[1]

[1] Preliminary Report on the Explosibility of Grain Dusts, Cooperative Investigation by Millers Committee, Buffalo, N. Y., under the direction of Dr. George A. Hulett, chief chemist, Bureau of Mines, U. S. Department of the Interior, by David J. Price, engineer in charge, and Harold H. Brown, assistant chemist, Grain-Dust Explosion Investigations, Bureau of Chemistry, U. S. Department of Agriculture Copies no longer obtainable.

Early in the investigation it became obvious that experimental work was necessary to determine the circumstances under which the explosions and fires might originate and to establish definitely the possible causes. Because of the equipment available in connection with its milling course and its convenient location to Eastern mills, The Pennsylvania State College was selected as the best place for an experimental mill. This phase of the dust-explosion work was accordingly assigned to the experimental department of that institution, the experiments being conducted under a cooperative agreement between the Department of Agriculture and The Pennsylvania State College. The materials were furnished by various milling companies at the request of the department. This bulletin gives a description of the equipment of the mill, the manner in which the experiments were carried on, and the results obtained, together with an outline of conditions conducive to explosions in grinding machines and the effect of various preventive devices.

Aside from the relation of explosions and fires to grinding processes in the milling industry, the phase of the grain-dust explosion problem discussed in this bulletin, the department engineers have established a number of additional possible causes, among which may be mentioned: The use of open flames, lanterns, gas jets, etc., defective electrical equipment, frictional electricity produced by friction of pulleys and belts, choke-ups and friction in elevator legs, inefficient methods of dust removal and collection, and the continuance of dust rooms.

Recent investigations by the bureau have revealed the surprising fact that many of the owners and operators of large grain mills and elevators are unfamiliar with the circumstances surrounding grain-dust explosions, as a result of which dangerous conditions are permitted to exist. Recently a fire, originating in a dust explosion at the top of the elevator leg in one of the large grain elevators in the East, destroyed almost 1,000,000 bushels of grain. The present crisis makes it imperative that all known precautionary methods be adopted. The Department of Agriculture is therefore redoubling its efforts, and has arranged to conduct a special emergency campaign throughout the United States, to the end that grain dealers and millers may become familiar with the work already done. The field engineers will assist the millers and operators of grain elevators in the installation of preventive devices already developed by the Bureau of Chemistry.

THRASHING-MACHINE EXPLOSIONS.

The second division of the department's investigations into the matter of grain-dust explosions comprises an extensive study of thrashing-machine explosions, which has been confined largely to the States of Washington, Idaho, and Oregon.[1] During the past season the investigation has been extended to Colorado, Texas and other grain-growing sections.

THE EXPERIMENTAL ATTRITION MILL.

The investigations conducted with the experimental attrition mill were undertaken for (1) the determination of the possible causes of explosions, and (2) the testing of various preventive measures that have been suggested during the progress of the work. The entire scope of the investigation can be seen in the following outline of the various phases of the problem that were touched upon:

1. Sparks emitted by foreign substances.
2. Naked flame.
3. Carbon arc in attrition mill.
4. Carbon arc in dust room.
5. Explosibility of various grains.
6. Static electricity in attrition mill.
7. Static electricity as cause of explosions.
8. Effect of atmospheric humidity.
9. Effect of moisture content of materials.
10. Revolving dampers or fire traps.
11. Relief valve and pipe.

PRINCIPLES UNDERLYING GRAIN-DUST EXPLOSIONS.

On account of the general lack of knowledge concerning the theory of dust explosions it may be advisable to insert at this point a brief summary of the chief facts and principles involved.

It is generally conceded that two main conditions must be present in order that a dust may produce an explosion: (1) Fine, dry dust must be in a state of suspension in an atmosphere containing the proper amount of oxygen. (2) A source of sufficient heat must be brought in contact with the dust.

It should be noted that carbonaceous dusts are not considered capable of igniting spontaneously, for an outside source of heat is required. The following sources of heat have been listed as the probable causes of many of the explosions in milling plants throughout the country:[2]

1. Use of open lights, or naked flames, such as lamps, torches, gas jets, lanterns, candles, and matches.

2. Entrance of foreign material in grinding machines.

3. Electric sparks from motors, fuses, switches, lighting systems.

4. Static electricity produced by friction of pulleys and belts, grinding machines, etc.

As for the first condition, many factors are involved, such as the chemical composition, moisture content, fineness, atmospheric humidity, density or degree of diffusion, and presence of inert gases.

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[1] U. S. Dept. Agr. Bul. 379.

[2] Reference 27, Bibliography.

The Bureau of Chemistry is now conducting laboratory investigations of these factors, and has obtained data on the relative inflammabilities of various grain dusts, as well as on the use of inert gases. Briefly, the conclusions reached thus far are as follows:[1]

1. Most of the carbonaceous dusts have a higher degree of inflammability than Pittsburgh coal dust.

2. An inert gas mixture containing 12 per cent or less of oxygen will prevent a dust explosion from starting or propagating.

In 1913 R. V. Wheeler,[2] chief chemist for the Explosion in Mines Committee, England, published the report of his investigations of the relative inflammabilities of various dusts. He classified dusts as follows:

1. Dusts which ignite and propagate flame readily, the source of heat required for ignition being comparatively small, for example, a lighted match.

2. Dusts which are readily ignited, but which, for the propagation of flame, require a source of heat of large size and high temperature, such as an electric arc, or of long duration, such as the flame of a Bunsen burner.

3. Dusts which do not appear to be capable of propagating flame under any conditions likely to obtain in a factory, because they do not readily form a cloud in air, or are contaminated with a large quantity of incombustible matter, or the material of which they are composed does not burn rapidly enough.

Class 1.	
Sugar.	Grain (flour mill).
Starch.	Maize.
Rice meal and sugar refuse.	Grain (grain storage).
Wood flour.	Rape seed.
Malt.	Corn flour.
Oat husk.	Flour (flour mill).
Class 2.	
Rice milling.	Grist milling.
Castor oil meal.	Corn meal.
Offal grinding (bran).	Mustard.
Class 3.	
Spice milling.	Sack cleaning.
Cotton seed.	Rape seed (Russian).
Cotton seed and soy bean.	Grain cleaning.

Available data show quite conclusively that there is a great similarity between gas and dust explosions. The following extract from an article[3] by H. H. Brown, of the Bureau of Chemistry, is of interest in this connection:

It will be noted that just as high pressures have been observed in coal-dust explosions as in gas explosions. However, the extremely high velocities attained by the flame in certain gas mixtures have not been reported as observed in dust explosions. Such high velocities could not be expected, for even the finest dust particles are many times larger than gas molecules, and so, even in the most dense dust clouds, the particles could not be as close together nor as intimately mixed with the oxygen as are gas molecules. Therefore, the heat of combustion of one dust particle can not be as readily transmitted to the next particle as it can in a mixture of gases. But the finer the dust the more nearly will it approach the size of a gas molecule. Therefore, it

[1] References 36 and 37, Bibliography. [2] Reference 26, Bibliography. [3] Reference 36, Bibliography.

might be expected that the velocity of the flame through a cloud of very fine dust would more nearly approach the velocity attained in gas explosions. As a matter of fact, this is true. Taffanel has brought this out in tests made at the French Experiment Station. Results obtained by the Bureau of Mines lead to the same conclusion.

The rate at which inflammation travels through a gas mixture is dependent upon at least two factors, the inflammability of the gas and the percentage of the gases in the mixture. The rate at which inflammation travels through a dust cloud seems to be dependent upon two similar factors, namely, the inflammability of the dust and the amount of dust in suspension. A third important factor is the fineness of the dust.

It will be seen, therefore, that gas and dust explosions are similar in many ways, and that a gas explosion is only a limited case of a dust explosion.

A thorough knowledge of the nature of dust explosions and of the accompanying phenomena is necessary in order to devise means for the prevention of such explosions and for the stoppage of explosions if by mischance they should start. It is, therefore, necessary to know how dust ignites, the various means by which it may be ignited or inflamed, and the chemical processes that take place. Another important factor to know is the ease with which the dust ignites and propagates a flame. This property we may call the "inflammability" of the dust. The term "explosibility" has also been applied in this connection.

It is important to note that investigations of dust explosions indicate that, in general, two reports are heard, the first being sharp and quick, and the second of a loud, rumbling nature and accompanied by more flame. It is thought that the first report is due to the ignition of a small quantity of fine dust in suspension, and that the resulting concussion is sufficient to disturb the dust that has settled at places farther away, thus forming an additional explosive mixture. The flame from the first explosion furnishes the source of ignition for this newly formed dust mixture, so that the big explosion with its loud roar is propagated throughout the entire dust zone.

APPARATUS USED IN THE INVESTIGATION.

For the purpose of conducting the experiments on grain-dust explosions a small, light frame building (15 by 15 by 24 feet), covered with galvanized iron, was erected by the Department of Mechanical Engineering, Pennsylvania State College (Pl. I). A small dust room was afterwards built at the side of the main structure at the discharge end of the screw conveyor. The grinding floor is elevated about 6 feet above the basement, which is level with the ground.

A 16-inch attrition mill (Pl. II) was installed on a platform 14 inches high, with a removable hopper underneath. Two elevators, one dump bin, a stock hopper over the mill, and a small bin for receiving ground materials were also provided. A screw conveyor 10 feet long was placed 2 feet below the floor to receive the material from the mill, and to carry it to the chop elevator or out into the dust room. The attrition mill, screw conveyor, and elevator are driven by a 15-horsepower direct-current motor, located in the basement.

The elevator legs and feed bin can be seen on the left of figure 1, Plate II. Immediately over the mill hopper are the spouts extending down from the stock bin and elevator. The removable hopper is partially withdrawn from under the mill platform. Above this hopper is one of the steel carbon holders entering the wooden door which has replaced the iron door of the lower part of the hood. In this wooden door is located a peephole, covered with mica, for the purpose of observing any sparks or flashes that may occur within the hood. On the opposite side of the mill (Pl. II, fig. 2) is a similar arrangement of peephole and carbon holder. The rheostat and ammeter for regulating the carbon arc, located on the edge of the hopper of the floor dump, are shown on the right. On the floor back of these instruments can be seen the recently installed relief pipe (R), leading from the hopper to the outside of the building, a distance of 8½ feet.

Plate III, figure 1, shows the dust room, located at the end of the conveyor, and the small door which gives access to the basement of the mill building. A small box (E) was built over the open end of the conveyor for the purpose of inclosing the carbon arc used in Series 4 (p. 14.) A relief pipe extends from this box up through the roof, and is capped by the hood (F).

Figure 1 gives a sectional view of the 16-inch attrition mill which was used for the tests described in this report. The grinding

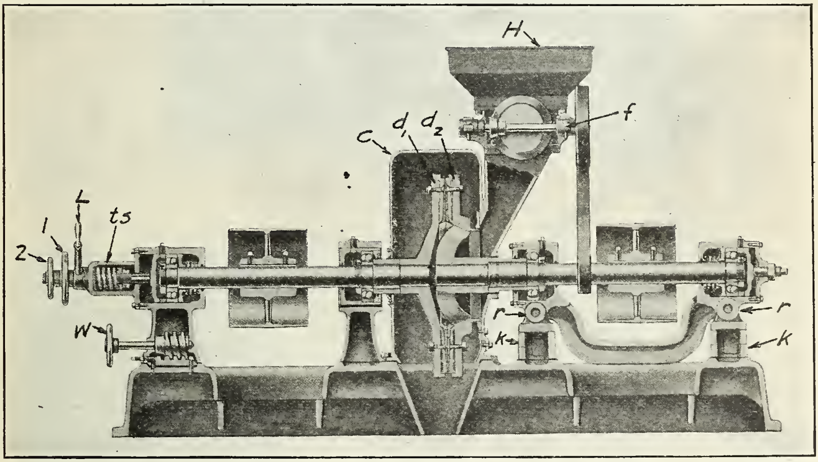

FIG. 1.—Sectional view of ball-bearing attrition mill.

plates or disks (d_1 and d_2) revolve in opposite directions at about 2,200 revolutions per minute. The upper part of the hood or casing (c) inclosing the grinding disks can be readily removed. H is the feeding hopper where the grain is introduced and fed by a "wabbler," which is run by the friction pinion on the shaft (f). Horizontal slides within the hopper regulate the amount of feed. The adjustment of the fineness of grinding is accomplished by handwheels (1 and 2), the latter serving as a locking device. The tension spring (ts) holds the left disk in position, and acts as a safety appliance to allow the disks to separate in case hard substances pass through the mill. L is a quick-release lever for operating the spreading device.

Figure 2 is a diagrammatic view of the removable hopper (h) under the mill, spout (s), single revolving damper (installed for Series 8 and 9), and screw conveyor. The by-pass spout with its valve and peephole (C) was installed for the purpose of observing how far the flame due to an explosion may be propagated without the use of a "check" valve. B is a peephole for observing any flames that may pass the damper.

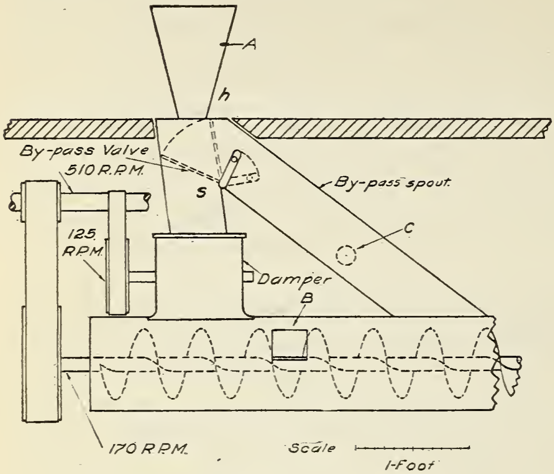

FIG. 2.—Elevation-attrition mill and conveyor. Single damper.

The construction of the single damper can be seen in figure 3, which gives the arrangement when two of these single dampers were

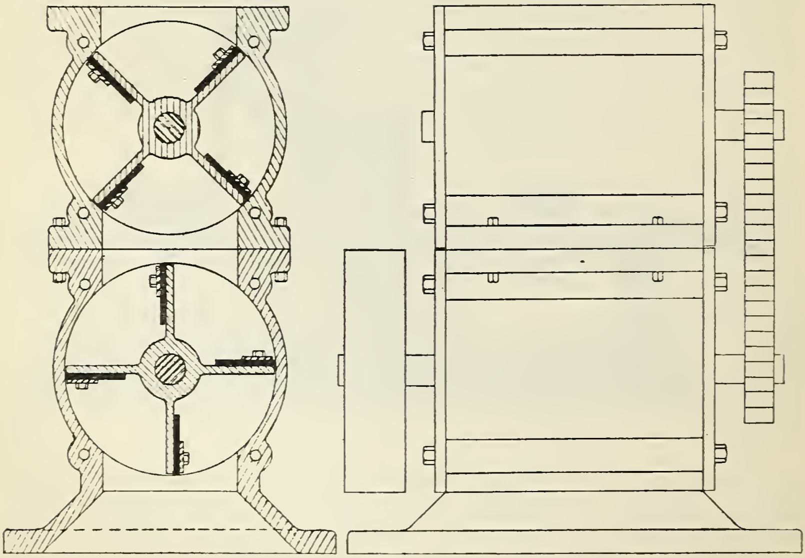

FIG. 3.—Views of double damper.

placed in series, as in Series 11. As can be seen in the sectional view, the paddles or blades with their rubber "wipers," shown in black, are so arranged that there is never a clear path through the damper.

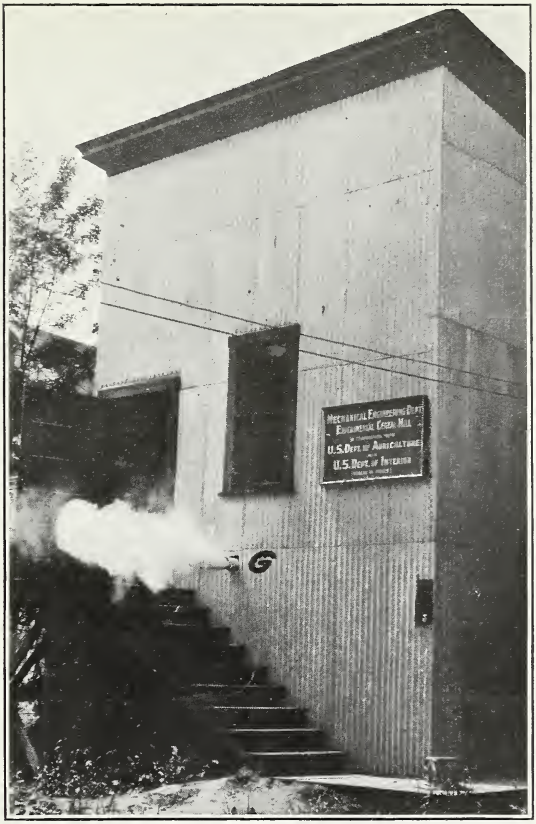

FIG. 1.

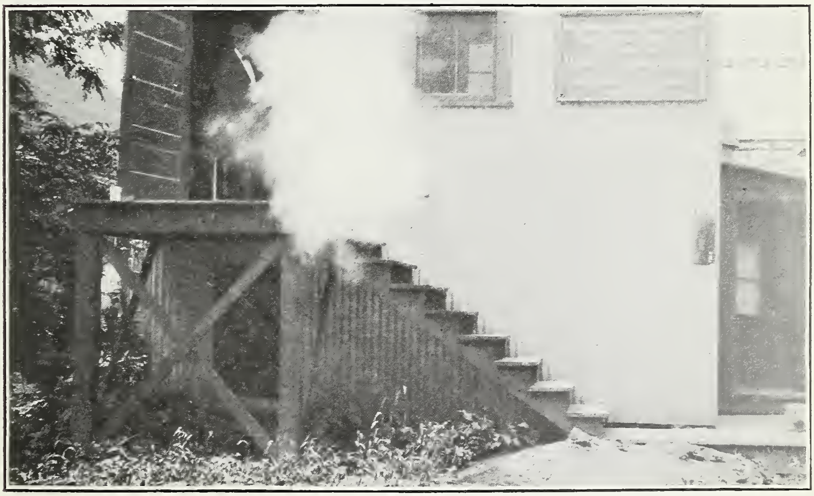

FIG. 2.

EXTERIOR OF EXPERIMENTAL MILL BUILDING.

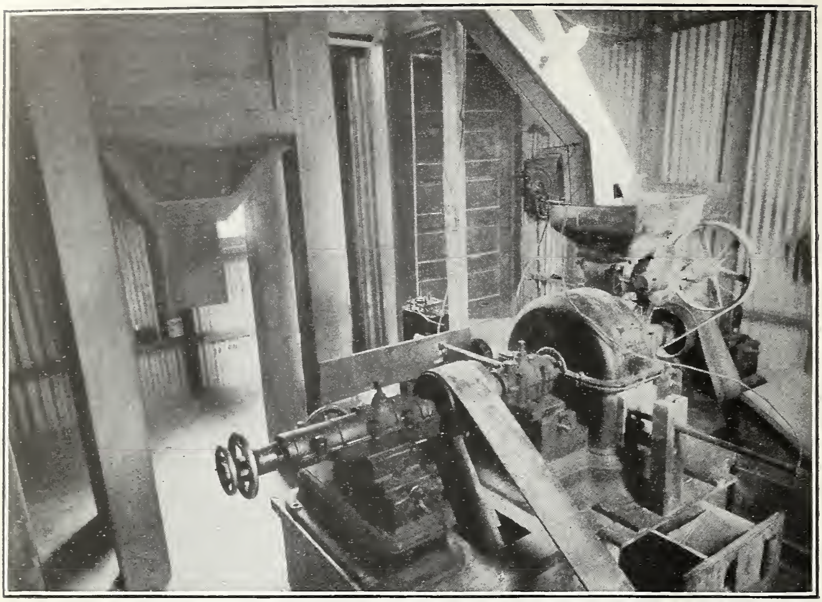

FIG. 1.

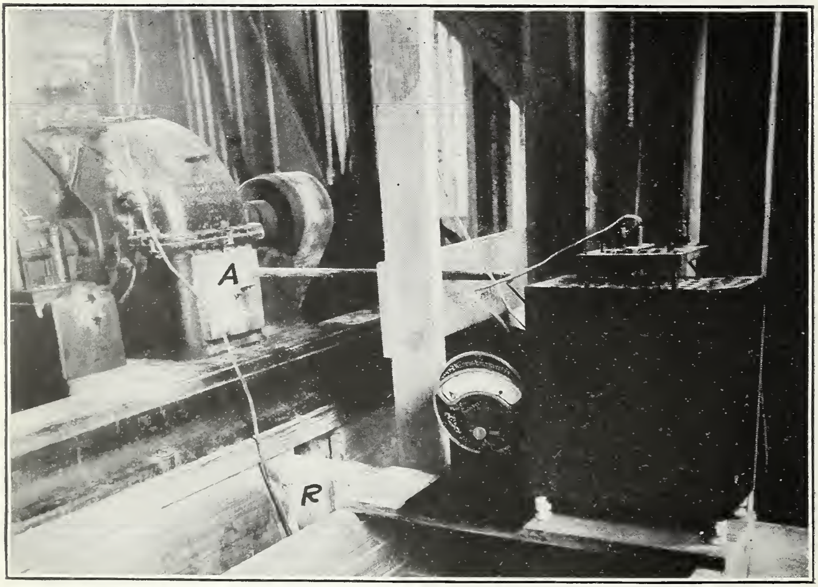

FIG. 2.

INTERIOR OF EXPERIMENTAL MILL BUILDING.

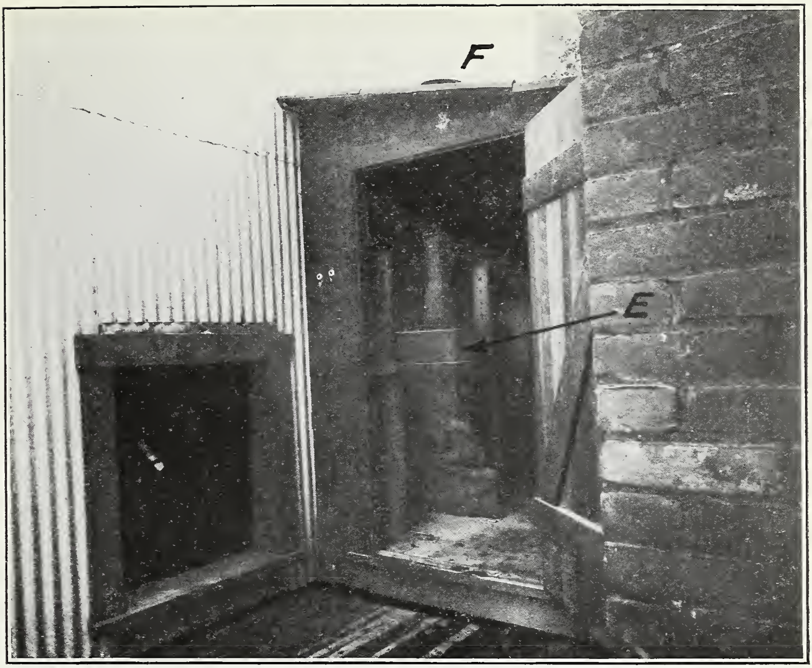

FIG. 1.—DUST ROOM.

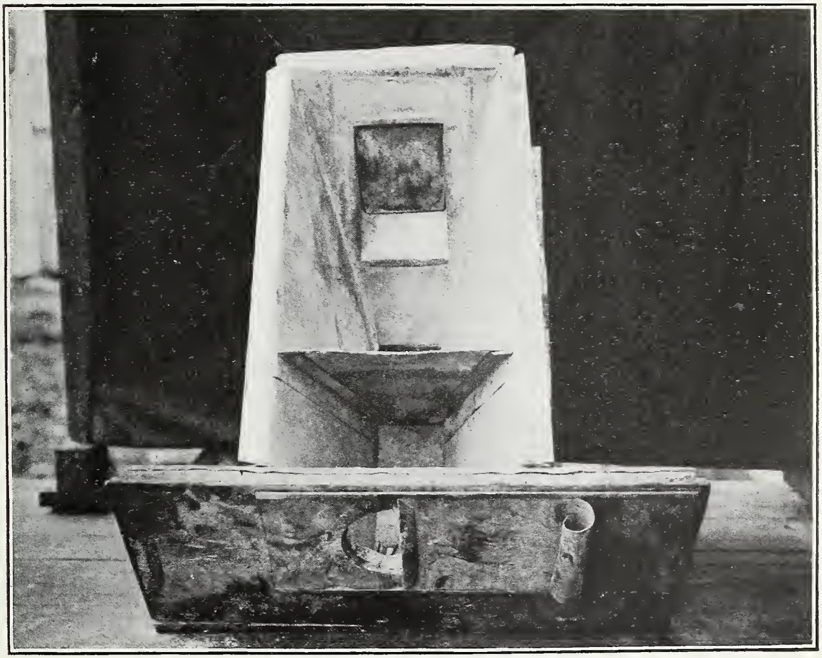

FIG. 2.—REMOVABLE HOPPER.

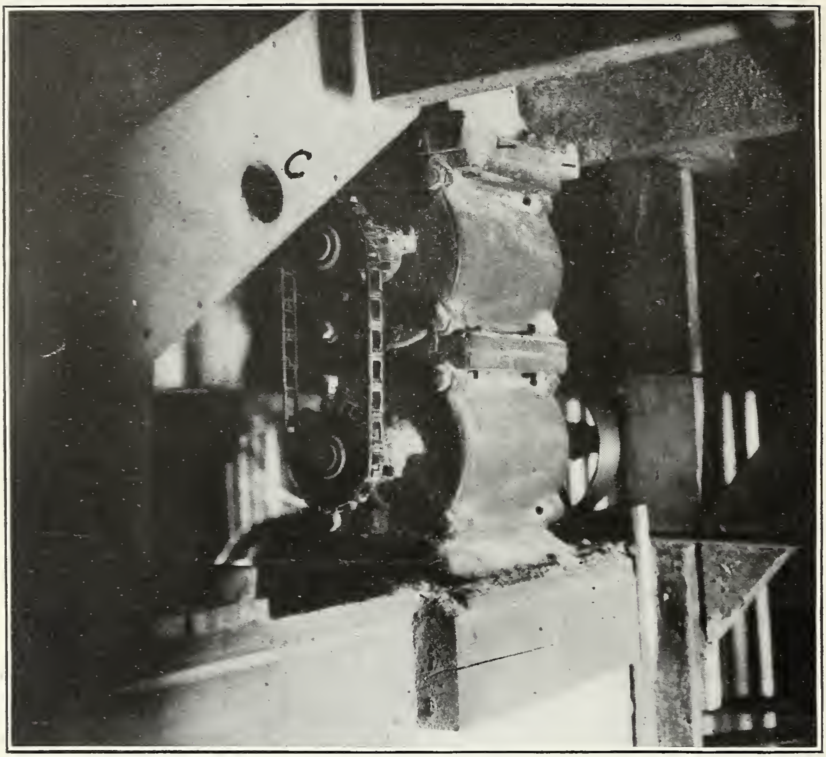

FIG. 1.—DOUBLE DAMPER.

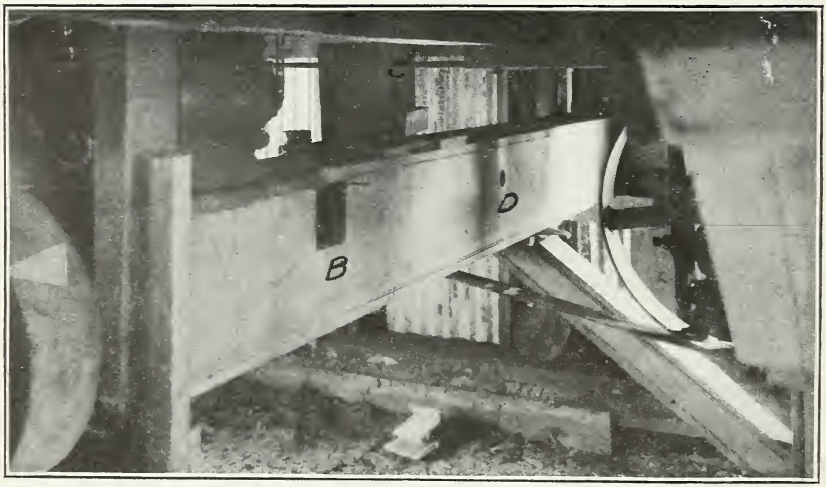

FIG. 2.—INTERIOR OF BASEMENT.

In figure 4, which is a diagrammatic view of the double damper and principal parts of the mill equipment, it is seen that the conveyor was lowered about 10 inches in order to make room for the double damper. Otherwise, the arrangement is practically the same as that in figure 2. The relief valve at A was installed with the relief pipe

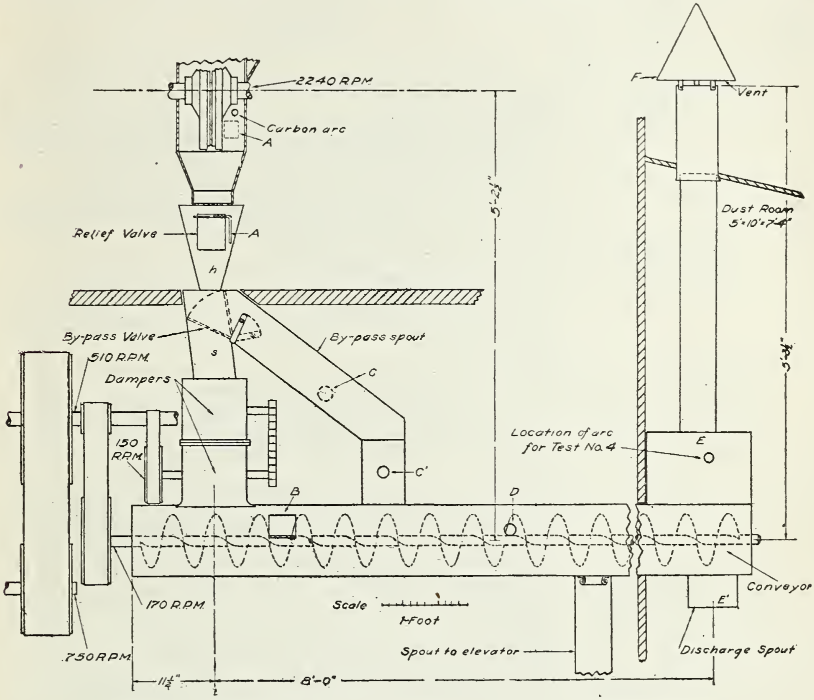

FIG. 4.—Elevation-attrition mill and conveyor. Double damper.

as explained in Series 13 (p. 18). The "spout to elevator," with its slide under the screw conveyor, shows how the ground material could be "recirculated," as stated in several series of tests, by means of the elevator and spouts shown in Plate II, figure 1.

The two dampers were positively connected with each other by means of a chain and sprocket wheels (fig. 3) and were so arranged that they served as a double check for the flame propagated by explosion in the attrition mill. Plate IV gives two views of this double damper from opposite sides, figure 2 of the plate showing also the screw conveyor, peepholes, and spout leading to the boot of the meal or chop elevator.

Plate III, figure 2, shows the removable hopper, with the sheet-iron lining and swinging relief valve as installed for Series 13. This hopper was constructed so as to make a snug fit with the lower part of the hood of the attrition mill. When the hopper is in position under the attrition mill, the relief pipe (R) (Pl. II, fig. 2) can be attached to the stub spout containing the relief valve.

Plate I shows the puffs of smoke, dust, and charred particles that followed a flame issuing from the end (G) of the relief pipe when an explosion occurred in the attrition mill (Series 13).

MATERIALS USED IN THE INVESTIGATION.

DESIGNATION.	NAME.	DESCRIPTION.
A	Fine oat hulls	Oat hulls, finely ground in an attrition mill, millstone, or other grinding mill.
B	Elevator dust	Dust that has settled on machines, beams, etc., in a grain elevator. It is a highly inflammable dust of a very light and fine texture, and composed of floating carbonaceous material of grain, outer skins, together with foreign dust.
C	Oat hulls	The hulls stripped from oats, as in the preparation of oatmeal.
D_1	Flour direct from store.	The interior or endosperm of any grain reduced to a very fine powdery state and free from the branny covering. It is composed mostly of starch, and is highly inflammable when in suspension.
D_2	Flour (oven dried)	Flour dried in an oven at about 150° F.
E	Graham flour	This is wheat which is ground but not bolted. It contains all of the flour, bran, and germy parts.
F	Wheat scourings	A fluffy and inflammable dust taken from dust collectors which are connected to the scouring or brush machines. It consists of foreign materials, such as dirt, smut, and portions of the light, thin, and loose outer skins of the bran.
G	Corn	Shelled corn.
H	Wheat shorts	Composed of the finer portions of bran, germ, and some floury material, separated from flour, in the process of milling.
I	Coarse floor sweepings	A coarser mill dust, settling on floor in immediate vicinity of mill.
J	Fine floor sweepings	The lighter and finer mill dust which settles in the room and outside the immediate vicinity of the attrition mill.
K	Conveyor mixture	A mixture of various materials as obtained from the end of the screw conveyor.
L	No. 2 feed dust	Consists of very fine particles of bran, fuzz, smut dust, and dirt, taken from the dust collector which draws air from the first scourer.
M	No. 1 feed dust	A material taken from the dust collector drawing the air through the second scourer. It consists almost entirely of the outer layers of the bran which have been removed by the scouring action of beaters.
N	Fine oat hull dust	This material is very finely ground oat hulls, brought out by the conveyor in the form of dust.
O	No. 3 elevator dust	Floating dust gathered by hand from the beams and machinery in the elevator.
P	Barley malt sprouts	Consists of barley malt sprouts that have been used as mash material and then dried.
Q	Malt sprouts	Consists of the radicles grown on the barley during the germinating process, and later broken off and dried.
R	Brewers' dried grain	This is the residue from a mash tub in a brewery or distillery, and consists of malt, corn, rice, hops, etc., which have been boiled and then dried.
S	Dried grain	This corresponds to "brewers' dried grain," except that the original mash consists of corn, barley, malt, and the radicles grown on barley during the germinating process, which are later broken off and dried.

EXPERIMENTAL WORK.

The results of the investigation are reported, first, by describing and summarizing briefly each one of the experiments performed, and, second, by discussing each one of the factors mentioned in the scope of the work (p. 12).

PRELIMINARY TESTS.

The experimental mill building at The Pennsylvania State College was completed in the spring of 1915, and the attrition mill, elevators, and conveyor were installed during the early part of the summer. During August several preliminary experiments were made for the primary purpose of ascertaining if explosions would result from the sparks emitted by foreign materials (nails, flint, matches, etc.) when passing between the grinding disks along with the grain.

At first the hood of the attrition mill was removed, so that the sparks emitted could be observed. When a single nail (eightpenny, but clipped to a length of about one-half inch) or small piece of stone was passed through the mill, sparks were, in nearly every case, emitted from different points of the periphery of the disks. Feeding 1 to 2 ounces of these clipped nails, small pieces of flint, or other hard materials, either singly or in combination, resulted in a large number of sparks, as in the case of an emery wheel. These sparks were thrown a distance of from 10 to 16 inches from the periphery of the disks. The sparks were emitted radially when both discs were running, and tangentially when one disk was stationary. When matches were fed into the mill, usually no sparks were emitted from the periphery of the disc, as the rapidly revolving arms of the disk generally ignited the matches before they had fairly entered the eye of the runner.

After making these observations of the sparks produced by foreign materials passing through the attrition mill, the hood was replaced, so that various kinds of grain products could be fed into the mill, with pieces of flint, nails, matches, etc. Three to five quarts of oat hulls, corn, elevator dust, flour, wheat scourings, wheat shorts, and floor sweepings were fed into the mill, at first singly, then in various combinations, with about 2 ounces of foreign materials, a quantity which probably would greatly exceed the amount of such materials finding their way into an attrition mill with the grain during a comparatively long period, under ordinary milling conditions. The disks were set very close in order to grind as fine as or even finer than is usual. Repeated attempts with such materials as flour, dried elevator dust, and dust settlings failed to produce a single explosion. Further efforts were made to obtain explosions by duplicating, as far as possible, the actual conditions obtaining in an attrition mill, by feeding the grain at normal rate until several bagfuls had been passed through. At frequent intervals pieces of nails, flint, etc., were added with the grain, but never was there the slightest evidence of an explosion.

The first explosion in the experimental attrition mill was obtained shortly after the preceding series of runs at the time when J. K. Clement, of the Bureau of Mines, was present to witness the tests. The bottom of the hopper was closed by the slide so as to retain the ground material and not permit any dust to escape except through the hand hole, which was open. When a quantity of elevator dust and ground oat hulls was fed into the mill, a rather dense cloud of dust issued from the hand hole, due to the fan-like action of the grinding disks. Upon placing a gasoline blow torch near this hand hole, the dust ignited and a flame, 6 feet long, shot out toward the wall. The hopper was immediately withdrawn, and about a quart of the same materials thrown into the mill, while the torch was introduced just within the space previously occupied by the hopper. A very thick cloud of dust was blown into the room. Immediately an explosion, or rather a large flame, occurred, followed by a second and more extensive one, covering nearly all the floor area of the dusty side of the building and extending almost to the roof. The door and windows were open. Otherwise, some damage might have resulted. As it was, the arms of the man who handled the torch were burned.

The results of these preliminary experiments (observed by J. K. Clement, B. W. Dedrick, M. P. Helman, J. Weaver, and F. Kline), may be summarized as follows:

1. More than 40 attempts with a total of from 3 to 5 pounds of foreign materials, such as nails, small pieces of stone and flint, and matches, fed along with various kinds of explosive grain products, failed to produce a single explosion.

2. Two attempts with a naked flame were successful in producing explosions.

EXPERIMENTS FROM APRIL 6, 1916, TO OCTOBER 3, 1917.

SERIES 1.

Object.—The object of the test was to determine whether explosions could be obtained by foreign materials capable of emitting sparks when ground, or by an electric arc located near the disks of the attrition mill.

Conditions.—The two removable iron doors of the mill were replaced by wooden doors, provided with peepholes covered with several layers of mica, and drilled for the insertion of iron carbon holders for the electric arc. The position of the arc could be shifted between the shaft and periphery of the disks, but it was soon found that its location did not seem to have any effect on the regularity of the explosions. As a rule, in this and succeeding tests, the arc was located nearer the shaft than the periphery. A rheostat and ammeter were provided for regulating the current (usually 15 to 20 amperes) through the arc. The hopper underneath the grinding disks was put in place, and its hand hole was left open so that the flash due to an explosion could be seen.

Results.—

1. Sparks from foreign materials did not cause an explosion.

2. The electric arc caused four explosions out of six attempts when large handfuls of feed were used.

3. Low rates of feeding did not produce an explosion with the electric arc.

4. Oat hulls, ground or unground, did not ignite, except when mixed with the highly inflammable elevator dust.

5. With elevator dust, when fed by the handful, either alone or with oat hulls, four explosions out of four attempts were obtained.

SERIES 2.

Object.—Same as that of Series 1.

Conditions.—Similar to those of Series 1, except that one of the disks was blocked so as to permit foreign substances, such as nails, to be in longer contact with the revolving disk and thus to give off more sparks. Definite amounts, usually 1 pint, of feed were measured out for the purpose of determining the limits of explosibility of various mixtures.

Results.—

1. In 21 attempts with the electric arc and various grains and mixtures, 16 explosions were obtained.

2. A mixture of 1 part elevator dust to about 8 parts of oat hulls appeared to be the limit of explosibility of these grain products.

3. When there was no opening the explosion was propagated to the outside end of the screw conveyor, as indicated by puffs of smoke (E in Pl. III, fig. 1, and in fig. 4).

4. Blocking one disk appeared to give results not different from those obtained when both disks were running.

5. Other results corroborated those of Series 1.

SERIES 3.

Object.—The primary object was to determine how far the flame was propagated from the source of the explosion.

Conditions.—The conditions of the test were similar to those of Series 2 (one disk being blocked), but the humidity was very high, inasmuch as there was a steady rain during a large part of the test. A 4 by 4 inch hole was cut in the upper part of the horizontal screw conveyor, about 1 foot from the chute leading down from the attrition mill and about 5 feet 4 inches from the shaft of the mill. The various kinds and mixtures of feed were prepared and measured into small paper bags, the contents of one of which were dumped into the feeding hopper at each attempt.

Results.—

1. Out of 39 attempts with the electric arc, 36 explosions occurred, in spite of the very damp atmosphere.

2. Explosions were obtained with elevator dust and oat hulls, and elevator dust, flour, graham flour, wheat scourings, floor sweepings, corn, and various mixtures of these substances.

3. The following classification of the 36 explosions may be made (Pl. III, fig. 1, and text fig. 2):

27 flashes were observed at B (5 feet 4 inches from shaft of mill).

9 flames were observed at E (12 feet 6 inches from shaft of mill).

3 flames were observed at F (17 feet from shaft of mill).

4. During the course of the tests the conveyor continually brought out smoldering lumps of ground products, which could be readily fanned into a red glow.

SERIES 4.

Object.—The object of this series of tests was to attempt to obtain an explosion in the dust room (located outside the building, at the end of the screw conveyor) and to determine if such explosion would propagate the flame back to the mill.

Conditions.—This dust room (5 by 10 feet by 7 feet high) was made as tight as possible, and the door was replaced by a heavy muslin curtain to retain the dust, at the same time permitting free expansion in case of an explosion. The electric arc was located at first in a small box built above the end of the conveyor, and later just outside this box. In both cases the arc was regulated by means of a long wooden pole extending to a safe point outside the building. The duct leading from E to the vent at F was removed (Pl. III, fig. 1). The hopper was placed under the grinding disks, and all holes, including B, were closed, in order to retain the dust as far as possible. Both disks of the attrition mill were run at their normal speed of 2,200 revolutions per minute. The arc was turned on, and various kinds of grain products, which had given explosions in previous tests, were run through the mill as rapidly as possible in order to get a large amount of dust into the dust room. After various grains had been fed for 15 minutes, a blast of burning dust was observed issuing from the outlet in the box above the conveyor. It was evident that the rapidly revolving attrition mill produced enough draft to force its dust out at the conveyor end without the use of a special fan. In fact, the force of the blast was so great that it did not appear possible for the flame to get back to the attrition mill. The flame was extinguished by merely turning off the arc, and then more elevator dust was rapidly fed into the mill, the arc having been turned on again. Within 2 minutes, another heavy blast of flame was observed at the end of the conveyor. In this instance the flame could not be extinguished by turning off the arc, because the wooden box on the end of the conveyor had caught fire. The mill was stopped immediately, and the burning box saved by means of a fire extinguisher. After the arc had been placed just outside this box the mill was run again. Elevator dust and ground oat hulls were fed for 15 minutes, during which time the room became very dense with dust. Although the arc had been burning during this time, no explosion occurred, but, as before, due to the intense heat radiating from the air, the box over the end of the conveyor was again on fire. The mill was stopped, and the fire easily extinguished with a pail of water.

Results.—No explosions were obtained in the dust room by means of an electric arc in this series of tests.

SERIES 5.

Object.—This test was run as a demonstration to Government officials from the Bureau of Mines (G. A. Hulett and J. K. Clement) and from the Bureau of Chemistry (D. J. Price, H. H. Brown, and W. G. Goodenow).

Conditions.—The arc was located near the disks, which were run at their normal speed. Various kinds of grain products (except elevator dust, the supply of which had been exhausted) were fed into the attrition mill.

Results.—Although explosions were readily obtained with flour and wheat scourings, none was obtained with corn, as in Series 3. In fact, the regularity and force of the explosions, none of which caused the flame to extend as far as the end (E) (Pl. III, fig. 1) of the conveyor, were not nearly as great as in Series 3, in spite of the relatively low humidity (49 per cent) of Series 5, as compared with other tests.

SERIES 6 AND 7.

Object.—These experiments were run to determine whether an explosion would result from the discharge of static electricity.

Conditions.—The conditions of testing were similar to those of previous tests with the electric arc. The carbons were replaced by ¾-inch brass balls screwed on the ends of long ¼-inch iron rods, which replaced the ¾-inch iron carbon holders. These ¼-inch rods were inserted through porcelains in the wooden door of the hood, to insure insulation from the metal frame of the machine, and were connected by 15-foot leads to the poles of a small Wimshurst machine.

Results.—Under normal conditions this machine was capable of producing a good spark about 3 inches long, but under the conditions of the test, with the long leads, and great leakage, it gave only a very weak spark, hardly more than ½ inch long, between the brass knobs near the disks of the mill. It was, therefore, decided to make use of an induction coil instead of the static machine. By this means a very hot and almost continuous spark 2 inches long could be obtained between the brass knobs. On two different days a total of 20 attempts was made to obtain explosions with various inflammable dusts by means of the spark from an induction coil. The spark gap was varied from ½ to 1¾ inches. No explosions occurred. This negative result, of course, does not indicate that static electricity can not cause an explosion in an attrition mill, but rather that under the particular conditions of the test, the mixtures of air and dust were not sufficiently inflammable to be ignited by the sparks from an induction coil. In order to show that the electric arc, on account of the greater amount and intensity of heat produced, could ignite the same mixtures under the same conditions, the carbons were quickly substituted for the brass knobs, and then within 10 minutes of Series 7, a number of explosions was obtained in Series 8 with the same substances by means of the electric arc.

SERIES 8 AND 9.

Object.—The object of these tests was to note the effect of a single revolving damper in preventing the propagation of explosions occurring in an attrition mill.

Conditions.—The revolving damper was installed as shown in figure 2. The details of this damper may be seen in figure 3, which shows two such dampers in series. The by-pass and butterfly valve were inserted to make certain that the flame would be propagated that far when the damper was off, or out of service.

Results.—

1. Total number of attempts to obtain explosions with arc	73
2. Total number of explosions	57
3. Damper in service during explosion	29
4. Damper out of service during explosion	28
5. Flashes of flame in by-pass (damper off)	11
6. Flashes of flame at end of conveyor (damper on or off)	0
7. Puffs of smoke at end of conveyor (damper off)	21
8. Flashes of flame past damper when in service	6
9. Puffs of smoke at end of conveyor (damper on)	0

SERIES 10.

Object.—To determine whether static electricity was built up during the operation of an attrition mill.

Conditions.—For this purpose a sensitive gold-leaf electroscope was procured from the Department of Physics. The collecting devices consisted of a comb made up of pins and tin foil located near one of the driving belts and of two 5-foot flexible lamp cords with 3-inch pieces of No. 14 bare copper wire soldered to each end. During the tests the casing of the electroscope was grounded by being held in the hand, while the binding part of the gold leaf was connected by the flexible wire lead to the collecting comb, or any part where it was desired to test for static electricity. The attrition mill was run at its normal speed of 2,200 revolutions per minute.

Results.—See Table 10, page 29.

SERIES 11.

Object.—To note the effect of a double damper in preventing the propagation of explosions.

Conditions.—The single damper used in Series 8 and 9 seemed to retard to a marked degree the propagation of explosions occurring in the attrition mill, but did not always prevent the flame from getting past the damper. Consequently, a double damper (figs. 3 and 4 and Pl. IV) was installed, with a view to checking any flame that might pass the first set of revolving paddles. Incidentally the mill was run several hours while oat hulls were fed at as great a rate as possible. The ground oat hulls were conveyed back into the mill in order to produce as much dust as possible. For over an hour the electric arc was turned on, but not a single explosion resulted.

Results.—

1. During the operation of the attrition mill under severe conditions as to rate of feeding and source of ignition no explosion could be obtained with oat hulls during a period of over an hour.

2. Out of six explosions with the dampers in service two flames shot past B and D (fig. 4).

3. In two instances with the dampers in service smoke was observed issuing from the end of the conveyor, but without any force.

SERIES 12.

Object.—Same as that of Series 11.

Conditions.—Similar to those of Series 11, except that the oat hulls used during the preliminary run had been fairly well dried by being spread out in shallow pans, which were then placed on top of radiators for a period of several days. Thus the moisture content was reduced from 9.9 to 3.2 and 5.7 per cent.

Results.—

1. Only one explosion was obtained during the continuous grinding of fine oat hulls.

2. In each of the four explosions with the double damper in service a flame got past the damper and in three cases extended as far as D.

3. In no instance was a flame observed at the end of the conveyor.

4. Smoldering lumps of ground products were found to be very dangerous, in that they set fire to the wooden base of the attrition mill.

On account of the fire hazard involved in these smoldering lumps of grain, special emphasis should be placed on this result of Series 12. During this series of tests it was observed that smoldering lumps, resulting from the explosions, were frequently brought out by the screw conveyor. Some of these lumps happened to be placed on several layers of asbestos paper. After several minutes it was observed that a hole had been burned through the asbestos paper. Even when this smoldering material was buried under several inches of grain it continued to burn, although not as well as when it was spread out in a thin layer and exposed to the atmosphere. That this smoldering material was to be regarded as a great source of danger was very forcibly demonstrated when on the following morning it was discovered that the wooden platform and floor near the removable hopper of the attrition mill had been set on fire, evidently by some smoldering grain that had not been removed after the experiments of the preceding day. This result strongly suggests a greater use of sheet iron, or other noncombustible material, in milling plants.

SERIES 13.

Object.—The object of this experiment was to note the effect of a pressure-relief pipe.

Conditions.—It had been suggested that a means for automatically relieving the pressure, due to an explosion, might aid materially in preventing the propagation of the flame to a dangerous part of the mill. Accordingly, a device (Pl. II, fig. 2, and Pl. I, fig. 1) consisting of a pipe 5 inches in diameter and 8½ feet long, with a rectangular end containing a light sheet-iron relief valve, which remained closed by its method of overhead suspension (fig. 3), was installed. This end of the relief pipe was inserted in the hopper (Pl. III, fig. 2), which had been lined with galvanized iron on account of the many fires that had occurred in the wooden hopper.

Results.—

1. In nearly all of the 14 explosions with the damper in service a flame and puff of smoke were observed at the end of the relief pipe (G), indicating that the relief valve opened properly.

2. In four out of eight instances, however, flames were observed getting past the double damper. although never as far as the conveyor end.

SERIES 14 AND 15.

Object.—The primary object of these last experiments was to determine whether certain grain products, such as oat hulls, containing considerable dust, barley malt sprouts, malt sprouts, brewers' dried grain, and "dried grain," all of which had been recently received from various manufacturers, would give an explosion under severe conditions in an attrition mill. Incidentally, observations were made of the effects due to the relief pipe and double damper.

Results.—

1. By means of the electric arc, explosions were obtained with dusty oat hulls, malt sprouts, barley malt sprouts, brewers' dried grains, and various mixtures (Table 16).

2. Out of 45 explosions with the damper in service, four flames passed the damper, one of them extending as far as the end of the screw conveyor.

3. In all cases of explosions, puffs of smoke were observed at the end (G) of the relief pipe (Pl. I, fig. 1).

TABULAR STATEMENT OF RESULTS OBTAINED AT THE ATTRITION MILL.

TABLE 1.—*Series 1. Explosions with electric arc.*[1]

Time.	Explosion No.	Feed.	Ignition.	Observation of explosion.	Temperature.		Humidity.		Remarks.
					In.	Out.	In.	Out.	
a. m.					°*F.*	°*F.*	*Per ct.*	*Per ct.*	
10.00					55	49		72	Started mill and brought it up to full speed, 2,200 revolutions per minute.
10.05									Started feeding oat hulls.
10.20		Ground oat hulls	Arc	Nothing	57	51			Large handful of feed at each attempt.
10.30		do	do	do	58	51	51		
10.45		do	Stones, nails	Nothing (several attempts)	59	53		47	
11.00	1	Elevator dust	Arc (intermittent)	Flash through hopper handhole; flame 6 feet long.	59	53			
11.15	2	Mixture fine oat hulls and elevator dust.	Arc	Explosion of more force; flame spread more.	59	51	40		
11.30	3	Elevator dust	do	Explosion like that in explosion 2.	59	51	44		
11.32	4	One-fourth oat hulls and sweepings, three-fourths elevator dust.	do	Explosion heaviest of all					
Summary:		6 attempts		4 explosions.					

[1] The arc was located near the shaft and disks, and drew from 15 to 20 amperes.

Date: April 6, 1916.
Weather: Cloudy, but bright; no wind; 51° F.
Observers: R. L. Sackett, B. W. Dedrick, R. B. Fehr, B. J. Culp, H. R. Brown.

TABLE 2.—*Series 2. One disk blocked.*

Time.	Explosion No.	Feed.	Ignition.	Observation of explosion at mill.	Temperature.		Humidity.		Remarks.
					In.	Out.	In.	Out.	
a. m.					*° F.*	*° F.*	*Per ct.*	*Per ct.*	
10.00		Elevator dust	None	Handhole of hopper open	56	53	82		Started mill.
10.10	1	1 pint elevator dust	Arc	Explosion					
10.12		do	Arc (int.)	Nothing					
10.15		do	Flint and nails	do			70		
10.16	2	1 pint 1:1 mixture elevator dust and oat hulls.	Arc	Explosion					
10.20	3	1 pint 1:2 mixture elevator dust and oat hulls.	do	Small flame				87	
10.25	4	do	do	Large flash					
10.30	5	1 pint 1:3 mixture elevator dust and oat hulls.	do	Explosion	58	53	70		
10.35	6	1 pint 1:4 mixture elevator dust and oat hulls.	do	do					
10.38	7	do	do	do					
10.40	8	do	do	do					
10.43	9	1 pint 1:5 mixture elevator dust and oat hulls.	do	Large flash					
10.46	10	1 pint 1:7 mixture elevator dust and oat hulls.	do	do					
10.49		1 pint 1:9 mixture elevator dust and oat hulls.	do	Nothing					
10.50		do	do	do					
10.51		do	do	do					
10.55	11	1 pint elevator dust	Arc (int.)	Very large flame in very dusty room.					
10.58									Handhole of hopper was closed. End of conveyor in outside dust room only opening.
11.00	12	1 pint elevator dust	Arc	Flash	60	53	75		Puff of smoke at end of conveyor.
11.02	13	do	do	Larger flash					Do.
11.07	14	1 pint conveyor product	do	Heavy explosion					Large puff of smoke at end of conveyor.
11.10	15	Same as No. 5	do	do					Do.
11.13	16	Same as No. 10	do	do					Do.
11.15		1 pint oat hulls	do	Nothing					Shut down mill.
Summary:		21 attempts		16 explosions.					

Date: April 13, 1916.
Weather: Cloudy; no wind; 53° F.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, H. R. Brown, R. E. Campbell, H. H. Colbus.

TABLE 3.—*Series 3. Flame propagation.*

Time.	Explosion No.	Feed.	Ignition.	Observations.			Remarks.
				A.	B.	E.	
a. m. 9.25							Started mill. Temperature (inside), 65° F. Humidity (inside), 82 per cent.
9.30	1	1 pint elevator dust	Arc	Puff	Puff	Puff	
9.35							Shut down to repair belt.
9.55							Started again.
10.00	2	1 pint elevator dust	Arc	Very large puff	Flash	Puff	
10.03	3	do	do	Heavy puff	Puff	do	Disks not together.
10.05		do	do	Nothing			Do.
10.06	4	1 pint 1:2 mixture elevator dust and oat hulls.	do	Heavy puff	Puff	Puff	Do.
10.08	5	1 pint 1:7 mixture elevator dust and oat hulls.	do	Puff	Flash	do	Disks together.
10.10	6	1 pint flour	do	Light puff	do	do	
10.12	7	1 pint graham flour	do	Puff	do	Flame	Most violent of any explosion so far.
10.14	8	1 pint flour	do	do	do	do	Very good.
10.16	9	do	do	do	do	Smoke	
10.20	10	do	do	do	do	do	
10.22	11	1 pint 1:1 mixture flour and elevator dust.	do	do	do	do	
10.24	12	1 pint wheat scourings	do	do	do	Much smoke	
10.26	13	do	do	do	do	do	
10.27	14	1 pint corn	do	Set hopper on fire	do	Flame	
10.28	15	do	do	Puff	do	Smoke	
10.30	16	do	do	do	do	Flame	
10.32		do	Flint	Nothing			
10.35		do	Nails	do	Sparks		
10.36	17	1:1 mixture corn and elevator dust	Arc	Puff	Big flame	Big flame	
10.38	18	do	do	Big flare	No flame	No flame	
10.39	19	1:2 mixture corn and elevator dust	do	Puff	Flash	Smoke	
10.45							Steady rain. Temperature (inside), 60° F. Humidity (inside), 97 per cent.
10.50		1:1 mixture corn and elevator dust	Matches	Nothing			
10.52		Elevator dust	do	do			
10.53	20	1:1 mixture corn and elevator dust	Arc	Big puff and flame	Flash	Smoke	
10.55	21	do	do	do	do	Flame	Flame at top of air duct (F).
10.56	22	Corn	do	Puff	do	do	
11.02	23	Flour, corn, and elevator dust	do	do	do	Smoke	

TABLE 3.—*Series 3. Flame propagation*—Continued.

Time.	Explosion No.	Feed.	Ignition.	Observations.			Remarks.
				A.	B.	E.	
a. m.							
11.04		Plain wheat shorts	Arc	Nothing			
11.05	24	1:2 mixture corn and flour	do	Puff	Flash	Smoke	
11.07	25	Flour	do	do	do	do	Outside temperature, 51° F.
11.10		do	do	Nothing			
11.12	26	Coarse floor sweepings	do	Puff	Smoke	Smoke	
11.14	27	do	do	do	do	do	
11.15	28	Fine floor sweepings	do	do	Flash	Big flame	
11.17	29	do	do	do	do	do	Flame at top of air duct (F).
11.19	30	do	Arc (int.)	do	No flash	No flash	
11.20	31	do	do	do	Flash	Big flame	Flame at F.
11.22	32	Coarse sweepings	do	do	Puff	Puff	
11.23	33	Conveyor mixture	Arc	do	Flash	do	
11.24	34	do	do	do	2 flashes	do	
11.25	35	do	do	2 puffs	Flash	do	
11.26	36	do	do	do	do	do	Still raining. Outside temperature, 52° F.
Summary:		43 attempts (39 arc, 4 foreign material).		36 explosions (27 flashes, 9 flames).			

Date: Apr. 14, 1916.
Weather: Steady rain; no wind; 51° F.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, H. R. Brown, R. E. Campbell, H. H. Colbus.

TABLE 4.—*Series 4. Electric arc in dust room (5 by 10 by 7 feet).*

Time.	Observations.	Remarks.
a. m. 9.00		Started mill. Fed corn, flour, floor sweepings. Arc located in box over end of conveyor.
9.15	Blast of burning ground products issuing from outl t of box containing arc	Fed elevator dust. Flame extinguished by turning off the electric current through the arc.
9.18		Fed more elevator dust and turned on arc.
9.20	Blast of flaming dust, which continued when arc was turned off. Wooden box containing arc caught fire.	Fire extinguished by "pyrene." Mill shut down.
9.35	Room dense with dust, but no explosion	Mill started. Arc just outside box, in dust room. Elevator dust fed for 10 minutes.
9.45		Fed ground oat hulls for 5 minutes.
9.50	Fire in box over end of conveyor	Extinguished by water. Mill shut down.
Summary:	No explosion due to electric arc in dust room. Dust from end of conveyor on fire three times.	Wooden box at end of conveyor on fire twice (due to arc).

Date: Apr. 18, 1916.
Weather: Clear; very windy; temperature, 53° F.; humidity, 31 per cent.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, R. E. Campbell.

TABLE 5.—*Series 5. Demonstration for Government officials.*

Time.	Observations.	Remarks.
a. m. 11.00		Started mill, to get it warmed up.
12.00		Started arc.
p. m. 1.30	Explosions readily obtained with flour and with wheat scourings, but none with corn. No indication of flame shooting out of end (E) of conveyor, as in Series 3.	Started demonstration. Fed all the kinds of grain dust previously tried, except elevator dust, the supply of which had become exhausted.
2.15	Fire in hopper, floor and conveyor	Mill shut down.

Date: May 19, 1916.
Weather: Clear; slight breeze; temperature, 67° F.; humidity, 49 per cent.
Observers: G. A. Hulett, J. K. Clement, H. H. Brown, D. J. Price, R. L. Sackett, W. G. Goodenow, B. W. Dedrick, R. B. Fehr, B. J. Culp, H. R. Brown.

TABLE 6.—*Series 6. Preliminary test with induction coil.*

Time.	Feed.	Length of spark.	Observations.	Remarks.
p. m.		*Inches.*		
				Carbons of previous experiments were replaced by $\frac{3}{4}$-inch brass balls connected with an induction coil capable of producing a spark 2 inches long, directly under shaft.
2.20				Started mill.
2.30	1 pint flour	$1\frac{1}{2}$	No explosion.	
	2 pints flour	$1\frac{1}{2}$	do	
	1 pint flour	1	do	
	2 pints flour	1	do	
	1 pint corn	1	do	
	2 pints corn	1	do	
	1 pint wheat scourings	1	do	
	2 pints wheat scourings	1	do	
	1 pint wheat scourings	$1\frac{3}{4}$	do	
	2 pints wheat scourings	$1\frac{3}{4}$	do	
	2 pints floor sweepings	1	do	
	1 pint floor sweepings	1	do	
3.30				Shut down.
Summary:	12 attempts		No explosions	

Date: June 26, 1916.
Weather: Clear; warm; humidity, about 70 to 80 per cent.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, J. Weaver

TABLE 7.—*Series 7. Induction coil.*

Time.	Feed.	Length of spark.	Observations.	Remarks.
a. m.		*Inches.*		
8.15				Started mill. Spark gap located about 6 inches to one side of shaft.
8.30	2 pints corn	1/2	No explosion	
	1 pint flour	1/2	do	
	do	1/2	do	
	1 pint wheat scourings	1/2	do	
	do	1/2	do	
	1 pint fine floor sweepings	1/2	do	
	do	1/2	do	
8.50	1 pint 1:2 mixture elevator dust and oat hulls	1/2	do	
Summary:	8 attempts		No explosions	

Date: June 27, 1916.
Weather: Clear; temperature, 82° F.; humidity, 82 per cent.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, J. Weaver.

TABLE 8.—*Series 8. Revolving damper.*

Time.	Explosion No.	Feed.	Position of damper.	Observations.				Remarks.
				A.	B.	C.	E.	
a. m. 8.15								Started mill.
8.30–8.50								Ran Series 7. Temperature, 82° F.; humidity, 82 per cent.
8.50								Substituted carbons for brass balls. Continuous arc.
9.00	1	Flour	Off	2 puffs	Nothing	Puff	2 puffs	About 1 pint of feed each time.
	2	do	do	Big flash	do	do	Puff	
	3	do	do	do	do	do	do	
	4	do	do	Small flash	do	do	do	
	5	do	On	2 small flashes	do	Nothing	Nothing	
	6	do	do	Small flash	do	do	do	
	7	do	do	Very large flash	do	do	do	Damper stuck.
	8	do	do	2 large flashes	do	do	do	
9.40	9	do	do	do	do	do	do	
	10	do	Off	Large flash	do	Puff	Puff	
	11	1:1 mixture elevator dust and oat hulls.	do	do	do	do	do	
	12	do	On	do	do	Nothing	Nothing	
	13	1:3 mixture elevator dust and oat hulls.	Off	do	do	Puff	Puff	Largest so far in this series.
		do	On	Nothing				
		1:5 mixture elevator dust and oat hulls.	do	do				
	14	Wheat scourings	do	Large flash	**Flash**	Nothing	Nothing	Flame got past damper.
		do	Off	Nothing				3 pints feed.
	15	do	do	Small flash	Nothing	Puff	Nothing	2 pints feed
	16	do	do	Large flash	do	do	do	Do.
	17	do	On	do	do	Flash	do	Do.
	18	Flour	Off	do	do	Puff	do	Do.
	19	do	do	do	do	5 flashes	do	Do.
10.05	20	do	On	do	**Flash**	Nothing	do	Do.

								Hopper and floor on fire. Extinguished by "pyrene." Mill shut down. Temperature, 88° F.; humidity, 72 per cent.
p. m. 2.30								Mill started. Temperature, 86° F.; humidity, 87 per cent.
2.35	21	Flour	Off	Flash	Nothing	Flash	Puff	Fire in hopper.
	22	do	On	Small flash	do	Nothing	Nothing	
	23	do	do	Large flash	do	do	do	
2.50	24	do	Off	Flash	do	Puff	Puff	
2.52								Thunderstorm. Mill shut down.
Summary:		27 attempts		24 explosions (13 damper off, 11 damper on).	2 flashes (past damper).	2 flashes (damper off) 11 puffs (damper off).	9 puffs (damper off) No puffs (damper on).	

Date: June 27, 1916.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, F. Kline, J. Weaver.

TABLE 9.—*Series 9. Revolving damper.*

Time.	Explosion No.	Feed.	Position of damper.	Observations. A.	Observations. B.	Observations. C.	Observations. E.	Remarks.
p. m. 2.10								Started mill. Humidity, 63 per cent. Electric arc.
2.30		Flour	Off	Nothing				6 attempts.
2.40	1	do	do	Puff				
	2	1:1 mixture wheat scourings and flour.	do	Big flash	Nothing	Flash	Nothing	
	3	do	do	2 flashes	do	do	do	
	4	do	On	do	do	Nothing	do	
	5	do	do	do	do	do	do	
	6	do	Off	3 flashes	do	3 flashes	Puff	
	7	do	On	2 big flashes	**Sparks**	Nothing	Nothing	
	8	do	do	1 big flash	**Large flash**	do	do	
	9	do	Off	4 flashes	Nothing	2 flames	Puff	
	10	do	do	Flash	do	Puff	do	
	11	do	do	do	do	Big flash	do	
	12	do	On	3 flashes	do	Nothing	Nothing	
	13	do	do	2 flashes	do	do	do	
	14	do	do	Flash	do	do	do	
	15	do	Off	do	do	Puff	Puff	
	16	do	do	do	do	Big flame	do	
	17	do	On	do	do	Nothing	Nothing	
3.10	18	do	do	do	**Flash**	do	do	
								Stopped to extinguish fire in hopper.
3.20	19	Wheat scourings	Off	Flash	Nothing	Flash	Puff	
		do	On	Nothing				4 attempts.
	20	do	Off	Flash	Nothing	3 flashes	Puff	
	21	Flour	On	2 flashes	**Flash**	Nothing	Nothing	
	..	Flour and scourings	Off	Nothing				2 attempts.
	22	do	do	2 flashes	Nothing	Nothing	Puff	
	23	do	On	Flash	do	do	Nothing	
	24	do	do	do				No observations at B, C, and E made.
	25	do	do	Small flash				Do.
	26	do	do	do				Do.
	27	Mixture from conveyor.	do	Large flash	Nothing	Nothing	Nothing	
	28	do	Off	2 small flashes	do	Puff	Puff	
	29	do	do	Flash	do	do	do	

	30	do	do	3 flashes	do	3 flashes	do	
	31	do	On	Large flash		Nothing	Nothing	No observation at B.
	32	do	do	do	Nothing	do	do	
		do	do	Nothing				
3.40	33	do	do	2 large flashes	Nothing	Nothing	Nothing	Mill shut down.
Summary:		46 attempts	15 off, 18 on (during explosion).	33 explosions	4 flashes (damper on)	9 flashes (damper off), 4 puffs (damper off).	12 puffs (damper off), no puffs (damper on).	

Date: June 28, 1916.
Weather: Clear; slight breeze; temperature, 87° F.; humidity, 55 per cent.
Observers: B. W. Dedrick, R. B. Fehr, B. J. Culp, F. Kline, J. Weaver.

TABLE 10.—*Series 10. Static electricity.*

General conditions.			Observations.			Remarks.
Time.	Temperature.	Humidity.	Open belt.	Crossed belt.	Frame of machine.	
p. m.	°*F.*	*Per ct.*				
3.00			Violent deflection of gold leaf when contact was made to comb of pins near belt. Deflection when bare end of lead is held near belt; greater the farther it is from iron pulley.		No deflection when lead is touched to frame.	Apparatus: 5-foot flexible leads with 3-inch bare ends of No. 14 copper wire and sensitive goldleaf electroscope.
3.20	42	54	Deflection, even when hand touches bar end of lead, although not so great.	Same as in case of open belt, but deflections not so great. No effect if hand touches bare end of lead.		Attrition mill runs at normal speed of 2,200 r. p. m.
Summary:						In no case was there enough static electricity to cause a spark to jump from the belt to the knuckle.

Date: March 15, 1917.
Observers: R. B. Fehr, C. A. Nickle.

TABLE 11.—*Series 11. Double damper.*

Time.	Explosion No.	Feed.	Position of damper.	Observations.					Humidity.		Remarks.
				Mill A.	Damper B.	By-pass C'.	Conveyor.				
							D.	E.	In.	Out.	
a. m.									*Per ct.*	*Per ct.*	
7.15											Started mill.
8.30									82		Temperature, 46° F.
8.35		Old oat hulls									Started feeding.
8.45		New oat hulls									Started feeding. Recirculated.
8.50											Turned on arc, 15 to 20 amperes.
9.00										83	
9.15–9.18											Arc off. Static electricity detected on belts by electroscope.
9.20											Temperature of feed at A, 82° F.
9.30									73		
9.46–9.50											Shut down to adjust idler.
9.50–9.55											Arc off.
10.00										76	
10.07–10.10											Fuse out. Shut down.
10.20–11.30											Shut down to align machine and tighten belts.
11.30									77	81	Started to rain. Test discontinued.
p. m.											
1.10										80	Mill started.
1.38	1	Flour	Off	Large flash	Puff	Puff	Puff	Puff			One quart feed. Electric arc.
1.41		do	On	Nothing							
1.44	2	do	do	Puff	Smoke	Nothing	Nothing	Nothing			Flour direct from store, 14.1 per cent moisture.
1.46		do	do	Nothing							
1.47		do	do	do							
1.48	3	do	do	Small puff	Nothing	Nothing	Nothing	Nothing			
1.49	4	do	do	2 puffs	Puff	Puff	Puff	Smoke			

1.51		do	do	Nothing							
1.52	5	do	do	Puff	Nothing	Nothing	Nothing	Nothing			
1.53	6	do	Off	do	Puff	Puff	Puff	Smoke			
1.55	7	do	do	2 puffs	2 puffs	Flash and puff	2 puffs	do			
1.57	8	do	do	Puff	Puff	Puff	Puff	do			
2.02		do	do	Nothing						83	
2.03		do	do	do							
2.04		do	do	do							
2.12	9	do	On	4 puffs	**Long flame**	Flash	**Flash**	Smoke			Flour had been in drying oven, 9.3 per cent moisture.
2.18	10	do	do	Large flame	**Long flame**	do	**Flash**	Nothing			
2.24	11	do	Off	2 flashes	Puff	Smoke	Puff	Puff			
2.30		do	do	Nothing					61		
2.33–2.35		Conveyor	do	do							Three attempts. Ground products from conveyor.
2.38–2.40		Wheat scourings	do	do							Three attempts.
2.42–2.45		No. 2 feed dust	do	do							Five attempts.
2.49–2.52		No. 1 feed dust	do	do							Four attempts.
2.54–2.55		Fine oat hulls	do	do							Two attempts.
2.56		1:3 mixture elevator dust and oat hulls.	do	do					58	83	
3.00											Static electricity detected on belts of machine.
Summary.		37 attempts		11 explosions (5 with damper off, 6 with damper on).	2 flashes (damper on) 1 puff (damper on).	3 flashes (damper on) 4 puffs (damper on).	2 flashes (damper on) 1 puff (damper on).	2 smokes (damper on).			

Date: May 4, 1917.
Weather: Clear; slight breeze; temperature, 41° F.
Observers: B. W. Dedrick, R. B. Fehr, P. X. Rice, R. E. Campbell, V. C. George, J. Weaver, R. P. Lewis, J. A. Spanogle, J. O. Reed, A. Kerstetter.

TABLE 12.—*Series 12. Demonstration.*

Time.	Explosion No.	Feed.	Position of damper.	Observations.					Humidity.		Remarks.
				Mill A.	Damper B.	By-pass C′.	Conveyor.		In.	Out.	
							D.	E.			
									Per ct.	*Per ct.*	
a. m. 8.15											Temperature outside, 58° F.; humidity, 61 per cent.
8.25											Started mill.
8.40		Dried oat hulls									Started feeding. Arc on continuously. Recirculated.
9.15									44	60	
10.30									44	48	
11.15									44	48	
11.30	1	Fine dust (oat hulls) from conveyor.		Small flame							
11.34	2	do		do							
11.42											Nailed peepholes shut, thus jarring conveyor.
11.45	3			Small puff, followed by a 3-foot flame.							Probably due to dust stirred up by sweeping in vicinity of hopper.
p. m. 1.55		Fine oat hulls from morning's grinding.		Nothing							2 attempts.
2.00		Fine oat hulls from morning's grinding (1 quart).	Off	Large flash	Nothing	Flash	Puff	Smoke	46	49	
2.06		do	On	Nothing							9 attempts.
2.20											Collected everything in system.
2.26–2.27		Flour from series 11		Nothing							3 attempts. 14.1 percent moisture.
2.30		Dry flour		do					49	48	3 attempts. 10.2 per cent moisture.
2.35	5	Mixture dry flour and No. 2 feed dust.	On	2 puffs	**Flash**	Nothing	Nothing	Nothing			
2.37	6	No. 3 elevator dust	do	Large flash	**Flash**	do	**Flash**	Smoke			
2.39		No. 1 feed dust	do	Nothing							

2.40	7	No. 2 feed dust	do	2 large flashes.	**Flash**	Nothing	**Flash**	Smoke and burned particles.			
2.41	8	No. 2 feed dust (2 quarts).	do	2 flashes	**Flash**	do	**Flash**	do			
2.48	9	No. 3 elevator dust	Off	Small flash	Nothing	Small puff	Nothing	Smoke			
2.50	10	do	do	do	do	do	do	do			
2.51	11	do	do	do	do	do	do	do			
2.52	12	Mixture No. 3 elevator dust and dry flour.	do	5 flashes	do	Large puff	Puff	do			Fire in A. Mill shut down.
4.00									45	48	Mill started again. Induction coil with ½-inch spark used.
4.12		Same as No. 12		Nothing		Large puff					Used induction coil. 5 attempts.
4.20		do		do							Small pieces of flint. 4 attempts.
4.22		No. 3 elevator dust		do		Large puff					Small pieces of flint. 6 attempts.
Summary.		30 attempts		12 explosions (4 with damper on).	4 flashes (damper on).		3 flashes (damper on).	3 smokes (damper on).			

Date: May 16, 1917.
Weather: Mild and clear; temperature, 70° F.
Observers: S. Soars, L. C. Winegardner, J. H. Heishman, G. J. Noth, J. P. Van Gelder, R. L. Sackett, B. W. Dedrick, R. B. Fehr, P. X. Rice, R. E. Campbell.

TABLE 13.—*Series 13. Effect of relief valve.*

Time.	Explosion No.	Feed.	Observations. Mill A.	Damper B.	Relief G.	Conveyor E.	Remarks.
a. m.							
7.30							Started mill; damper on.
8.30							Temperature outside, 64° F. Humidity, 84 per cent. Electric arc.
8.40		Oat hulls	Nothing				3 attempts.
8.47	1	1 pint flour and 1 pint No. 3 elevator dust, unmixed.	3 flashes	Smoke	Flame and 2 puffs	Smoke	
8.50	2	....do	2 flashes	**5-foot flame**	3-foot flame and 1 puff	....do	Relief not effective.
8.58		1 : 2 mixture flour and No. 3 elevator dust.	Nothing				
9.00		No. 3 elevator dust	....do				
9.02		1 : 1 mixture flour and No. 3 elevator dust.	....do				
9.03		....do	....do				
9.05	3	1 pint flour and 1 pint No. 3 elevator dust, unmixed.	2 flashes	Smoke	Smoke		
9.07		No. 2 feed dust	Nothing				
9.08		1 : 1 mixture flour and No. 2 feed dust	....do				
9.10	4	1 : 1 mixture flour and No. 3 elevator dust.	3 flashes	**3-foot flame**			No observations.
9.23	5	....do	2 flashes	**1-foot flame**	2 puffs		Conveyor, 158 r. p. m.
9.25	6	....do	Flash	Smoke	Smoke		Damper, 135 r. p. m.
9.26	7	....do	3 flashes	**Small flame**	3 puffs		
9.28	8	....do	2 large flashes	Nothing	2 flames (4-foot)		Humidity, inside and outside, 72 per cent.
10.34	9	....do	Explosion		Flames and puffs		
10.35	10	....do	....do		....do		
10.36	11	....do	....do		....do		
10.39	12	....do	2 explosions		....do		
10.47	13	1 : 1 mixture flour and No. 2 feed dust	Explosion		....do		
10.48		....do	Nothing				
10.49	14	....do	Explosion		Flames and puffs		
Summary.		24 attempts	14 explosions	4 flames	3 flames (first 8 explosions).	No puffs	

Date: June 9, 1917.
Weather: Clear; mild; temperature, 64 77° F.
Observers: R. L. Sackett, B. W. Dedrick, R. B. Fehr, P. X. Rice, R. E. Campbell, J. Weaver.

TABLE 14.—*Series 14. Various cereal dusts.*

Time.	Explosion No.	Feed.	Observations.					Humidity.		Remarks.
			Mill A.	Damper B.	Relief G.	By-pass C′.	Conveyor E.	In.	Out.	
a. m.								*Per ct.*	*Per ct.*	
9.00										Started mill; damper on.
11.05		Barley malt sprouts							80	No explosions with arc.
11.35		do						68		Do.
12.00										Stopped feeding.
p. m.										
1.20		Malt sprouts	Nothing							Arc on continuously.
2.00			do						66	Closed all holes, to keep in dust while grinding with arc on. No explosion.
2.40	1	Malt sprouts (unground)	Small puff	Nothing	Puff					Large scoopfuls hereafter (2 to 4 quarts).
	2	Malt sprouts (ground)	do	do	do					
	3	do	do	do	do					
	4	do	do	do	do					
	5	do	do	do	do					
	6	do	do	do	do					
2.46		do	Nothing							
2.47	7	Malt sprouts	Small puff	Nothing	Small puff					Collected after explosions in 1–6.
	8	do	do	do	do					Do.
	9	do	do	do	do					Do.
2.50	10	1:1 mixture malt sprouts and No. 3 elevator dust.	Large puff	do	do					
	11	do	Small puff	do	do					
	12	do	do	do	do					
2.55	13	1:1 mixture malt sprouts and barley malt sprouts.	Puff	do	do					
	14	do	do	do	do					
	15	do	do	do	do					
		do	Nothing							
	16	do	Puff	Nothing	Small puff					
		do	Nothing							
.10	17	do	Puff	(Off)	Small puff	Puff				
	18	do	do	do	do	do				
	19	do	do	do	do	do				
	20	do	do	do	do	do				
	21	do	do	do	do	do				
	22	do	do	do	do	do				
		do	Nothing	do						

TABLE 14.—*Series 14. Various cereal dusts*—Continued.

Time.	Explosion No.	Feed.	Observations.					Humidity.		Remarks.
			Mill A.	Damper B.	Relief G.	By-pass C′.	Conveyor E.	In.	Out.	
p. m. 3.20	23-27	Brewers' dried grains	5 explosions	(On) Nothing.	5 puffs					No explosion when being recirculated. Not much smoke, except when fed by the scoopful. 8 attempts.
3.45		1:3 mixture conveyor product and brewers' dried grains.						66		
	28-31	do.	4 puffs	Nothing	4 small puffs					4 attempts.
4.35	32-36	Oat hulls containing much dust.	5 puffs	do.	5 puffs					8 attempts. No flames. No explosion when being recirculated, only when fed several quarts at a time.
5.00	37-38	Barley malt sprouts	2 puffs	do.	2 small puffs				68	10 attempts. Much smoke.
5.20										Shut down.
Summary.		59 attempts	38 explosions (32 with damper on).	(On) Nothing.	38 puffs		(Damper on) Nothing.			

Date: September 11, 1917.
Weather: Clear; no wind; temperature, 50-60° F.
Observers: B. W. Dedrick, R. E. Campbell, A. Kerstetter.

TABLE 15.—*Series 15. Various cereal dusts.*

Time.	Explosion No.	Feed.	Observations.					Humidity.		Remarks.
			Mill A.	Damper B.	Relief G.	Conveyor— D.	Conveyor— E.	In.	Out.	
p. m.								*Per ct.*	*Per ct.*	
12.00										Started mill. Damper in service.
1.55		Malt sprouts						52		Started feeding.
2.02		1 quart malt sprouts and about 2 dozen matches.	Nothing							2 attempts.
2.10										Electric arc turned on.
2.15		1 quart malt sprouts	Nothing							
		do	do							
	1	2 quarts malt sprouts	Flash	Puff	4-foot puff	Nothing	Nothing			
2.19		1½ quarts malt sprouts	Nothing							
2.20		do	do							
2.21	2	2 quarts malt sprouts	Flash	Puff	3-foot puff	Nothing	Nothing			
2.24	3	do	do	do	do	do	do			
2.26		do	Nothing							
2.27	4	do	Flame	Puff	3-foot puff	Nothing	Nothing			
2.29	5	3 quarts malt sprouts	do	do	do	do	do			
2.30	6	4 quarts malt sprouts	do	do	do	do	do	56		
2.34		1 quart malt sprouts (finely ground).	Nothing							
2.35		do	do							
2.36	7	2 quarts malt sprouts (finely ground).	Flash	Puff	3-foot puff	Nothing	Nothing			
2.37	8	1 quart floor sweepings	do	do	Flash and puff	do	do			
2.38										Arc off.
2.39		2 quarts finely ground malt sprouts with nails, matches, and flint.	Nothing							No explosion.
2.42		do	do							Do.
3.00		½ bushel "dried grain"						55	62	Recirculated.
3.14		1 quart "dried grain"	Nothing							Arc on.
3.18		do	do							
3.19		2 quarts "dried grain"	do							
3.20		do	do							
3.21		3 quarts "dried grain"	do							
3.22		do	do							
3.26		1 quart 1 : 1 mixture flour and "dried grain."	do							
3.28	9	1 quart dry flour	2 flashes	**7-foot flame.**	Flame and puff.	Flash	Flame and sparks.			
3.30	10	do	do	**3-foot flame.**	2 flames (2-foot).	Flame	Nothing			
3.34		1 quart 1 : 1 mixture "dried grain" and flour.	Nothing							

TABLE 15.—*Series 15. Various cereal dusts*—Continued.

Time.	Explosion No.	Feed.	Observations.					Humidity.		Remarks.
			Mill A.	Damper B.	Relief G.	Conveyor— D.	Conveyor— E.	In.	Out.	
p. m.								*Per ct.*	*Per ct.*	
3.36		1 quart 1 : 2 mixture "dried grain" and flour.	Nothing							No explosion.
3.37	11	do	2 small puffs	**Large flash**	2 puffs (3-foot)	Flash	Burned particles.			
3.38										Arc off.
3.40		1 quart flour with matches, nails, and flint.	Nothing							No explosion.
3.45								56	60	Arc on. No recirculation.
3.58		1 quart oat hulls	Nothing							
4.00		2 quarts oat hulls	do							
4.01		3 quarts oat hulls	do							
4.03		1 quart barley malt sprouts	do							
4.04		2 quarts barley malt sprouts	do							
4.06		3 quarts barley malt sprouts	do							
4.07		1 quart brewers' dried grain	do							
4.08		2 quarts brewers' dried grain	do							
4.09		3 quarts brewers' dried grain	do							
4.13		2 quarts 1 : 1 mixture oat hulls and flour.	do							
4.14		2 quarts 1 : 1 mixture barley malt sprouts and flour.	do							
4.16	12	2 quarts 1 : 1 mixture brewers' dried grain and flour.	Puff	Small puff	3-foot puff	Nothing	Nothing			
4.18		1 quart conveyor mixture	Nothing							
4.19		2 quarts conveyor mixture	do							
4.20		3 quarts conveyor mixture	do							
4.21		1 quart 1 : 1 mixture conveyor mixture and flour.	do							
4.23	13	2½ quarts 1 : 1 mixture conveyor mixture and flour.	5 puffs	**3-foot flame**	5 puffs	Nothing	Nothing			
4.27								55	70	Mill shut down.
Summary.		43 attempts	13 explosions (damper on).	4 flames (damper on) 9 puffs (damper on).	3 flames, 10 puffs	3 flashes (damper on) no puffs.	1 flame (damper on).			

Date: October 3, 1917.
Weather: Clear; no breeze; temperature, 67–64° F.
Observers: R. L. Sackett, B. W. Dedrick, R. B. Fehr, R. E. Campbell, H. R. Brown, J. Weaver, A. Kerstetter.

DISCUSSION OF RESULTS AND CONCLUSIONS.

SPARKS EMITTED BY FOREIGN SUBSTANCES.

Many attempts were made, in both the preliminary and the regular tests, to produce dust explosions in an attrition mill by introducing with the feed various kinds of foreign substances, such as nails, small pieces of stone and flint, and matches, but not once did an explosion occur. Various kinds of grain products, with different degrees of fineness, and both normal and minimum moisture contents, were fed during these attempts. Evidently, however, the intensity and amount of the heat generated by the sparks from these foreign substances were not sufficient to ignite the dust, although an explosive mixture of air and dust may have been present, as manifested by the regularity of the explosions obtained by the electric arc under identical conditions. In rare cases, and especially with very low humidity and moisture contents, it might be possible for a nail or other hard substance to be caught in such a way that a very long succession of sparks would be emitted with sufficient intensity to cause ignition. The results of these tests, however, point strongly to the following conclusions:

1. Sparks emitted by foreign substances passing through an attrition mill do not in general appear to be hot enough to ignite an inflammable dust.

2. Nevertheless, to take care of the exceptional case, every precaution should be taken to keep all foreign substances from entering the grinding machines.

NAKED FLAME.

Only two attempts were made to obtain explosions by means of a naked or open flame, but both were entirely successful (p. 11). Safe conclusions are as follows:

1. Naked flames can readily ignite inflammable dust mixtures.

2. A naked flame should never be allowed in the vicinity of dust.

CARBON ARC IN ATTRITION MILL.

The summary of all results obtained with the use of the electric arc is shown in Table 16. It is to be noted that in practically two-thirds of the attempts with materials which gave explosions at one time or another, explosions were obtained by means of an electric arc located near the grinding discs. In every one of the 201 explosions, except Explosion 3 of Series 12, it was necessary to feed the material in the amount of at least a handful to produce an explosion. Apparently, a fairly dense cloud of dust was required to produce an explosion with even the most intense source of ignition available, the electric arc. The following conclusions can be drawn:

1. An attrition mill is capable of producing mixtures of dust and air which can be easily ignited by a sufficiently intense source of heat.

2. There is much less danger of an explosion, when the rate of feeding is less than the amount which the mill can take care of.

TABLE 16.—*Summary of explosions in attrition mill (electric arc and foreign substances).*[1]

Mixture No.	Variety designation.	Material.	Series. 1	2	3	8	9	11	12	13	14	15	Attempts with foreign substances.	Total.
1	A	Fine oat hulls	0/2					0/2	1/12		5/8	0/3	1	6/27
2	B	Elevator dust	2/2	4/5	3/4								1	9/11
3		Mixture of fine oat hulls and elevator dust	1/1											1/1
4		1:3 mixture of oat hulls and sweepings, and elevator dust.	1/1											1/1
5		1:1 mixture of elevator dust and oat hulls		1/1		2/2								3/3
6		1:2 mixture of elevator dust and oat hulls		2/2	1/1									3/3
7		1:3 mixture of elevator dust and oat hulls		2/2		1/2		0/1						3/5
8		1:4 mixture of elevator dust and oat hulls		3/3										3/3
9		1:5 mixture of elevator dust and oat hulls		1/1		0/1								1/2
10		1:7 mixture of elevator dust and oat hulls		2/2	1/1									3/3
11		1:9 mixture of elevator dust and oat hulls		0/3										0/3
12		Conveyor mixture and oat hulls		1/1										1/1
13	C	Oat hulls		0/1						0/3				0/4
14	D	Flour (8 to 14 per cent moisture)			5/6	17/17	2/8	11/19	0/6			2/2	1	37/58
15	E	Graham flour			1/1									1/1
16		1:1 mixture of flour and elevator dust			1/1									1/1
17	F	Wheat scourings			2/2	4/5	2/6	0/3						8/16
18	G	Corn			4/4								2	4/4
19		1:1 mixture of corn and elevator dust			4/4								2	4/4
20		1:2 mixture of corn and elevator dust			1/1									1/1
21		Flour, corn, and elevator dust			1/1									1/1
22	H	Wheat shorts			0/1									0/1
23		1:2 corn and flour			1/1									1/1
24	I	Coarse floor sweepings			3/3							1/1		4/4
25	J	Fine floor sweepings			4/4									4/4
26	K	Conveyor mixture			4/4		7/8	0/3				0/3		11/18
27		1:1 mixture of wheat scourings and flour					22/24							22/24
28	L	No. 2 feed dust						0/5	2/2	0/1				2/8
29	M	No. 1 feed dust						0/4	0/1					0/5
30	N	Fine oat hull dust							3/3					3/3
31		Mixture of dry flour and No. 2 feed dust							1/1					1/1
32	O	No. 3 elevator dust							4/4	0/1			6	4/5
33		Mixture of dry flour and No. 3 elevator dust							1/1				4	1/1
34		1:1 mixture of flour and No. 3 elevator dust								12/14				12/14
35		1:2 mixture of flour and No. 3 elevator dust								0/1				0/1
36		1:1 mixture of flour and No. 2 feed dust								2/4				2/4
37	P	Barley malt sprouts									2/12	0/3		2/15
38	Q	Malt sprouts									9/11	7/13	4	16/24
39		1:1 mixture of malt sprouts and No. 3 elevator dust									3/3			3/3
40		1:1 mixture of malt sprouts and barley malt sprouts									10/13			10/13

41	R	Brewers' dried grain									5/8	0/3		5/11
42		1:3 mixture of conveyor product and brewers' dried grain									4/4			4/4
43	S	Dried grain										0/6		0/6
44		1:1 mixture of dried grain and flour										0/2		0/2
45		1:2 mixture of dried grain and flour										1/2		1/2
46		1:1 mixture of oat hulls and flour										0/1		0/1
47		1:1 mixture of barley malt sprouts and flour										0/1		0/1
48		1:1 mixture of brewers' dried grain and flour										1/1		1/1
49		1:1 mixture of conveyor mixture and flour										1/2		1/2
		Total	4/6	16/21	36/39	24/27	33/46	11/37	12/30	14/24	38/59	13/43	21	201/332

Number of attempts with materials that gave explosions at one time or another, 305.
Maximum temperature, 87° F.; minimum temperature, 41° F.; maximum humidity, 97 per cent; minimum humidity, 44 per cent.

[1] Each variety of material tested is given a letter (p. 10), while each different mixture and variety of material is given a number (1 to 49) for ready reference. The denominator of a fraction indicates the number of attempts to obtain explosions, and the numerator indicates the number of successful attempts—i. e., explosions obtained with a particular material in a given test. An expression like "1:3 mixture of elevator dust and oat hulls" means that there is 1 part (by volume) of elevator dust to 3 parts of oat hulls.

CARBON ARC IN DUST ROOM.

The location of the arc in the dust room, at the end of the screw conveyor, did not cause an explosion (Series 4). This fact, however, merely indicates that the many conditions involved in an explosive mixture did not happen to be met in this particular case. Probably the dust cloud was not dense enough. In any event, it would be well to draw the following conclusion, especially in view of past explosions in mills, and those obtained by the arc located near the grinding discs of the attrition mill:

It is always very dangerous to allow an open flame (or any source of ignition) in the vicinity of a dust-laden atmosphere.

EXPLOSIBILITY OF VARIOUS GRAINS.

The summary of all the explosions of various materials obtained with the electric arc (except those in the demonstrations, Series 5) is found in Table 16. From the explanation of the meanings of the terms of the fractions appearing in this table it would seem that each fraction ought to indicate the inflammability of the material. As a matter of fact, these fractions, especially those of the same series, serve as rough indications of the relative inflammabilities of the various materials; but too much stress should not be laid upon this point, as most of the conditions of testing were beyond control. Relative inflammability can properly be determined only by careful laboratory methods which control the many factors entering into the question.

In view of the fact that the grinding of oat hulls constitutes an important part of the work done by attrition mills, it is interesting to note that oat hulls alone (Mixtures 1, 13, and 30) were not found to be very inflammable. Only extremely fine oat hulls, or those with considerable dust, were capable of giving inflammable mixtures, in spite of the fact that in series like 11 and 12 oat hulls were fed into the mill and recirculated continuously for several hours without a resulting explosion, except in the case of Explosion 3 of Series 12.

A study of Table 16, together with a knowledge of the conditions of testing, makes possible the following conclusions:

1. Elevator dust, flour, wheat scourings, and malt sprouts seem to produce explosions the most consistently.

2. Oat hulls do not appear to give very inflammable mixtures, unless they contain a considerable amount of fine dust.

3. Every precaution should be taken to remove dust as fast as it is formed, and to prevent it from coming in contact with any possible source of ignition.

STATIC ELECTRICITY IN ATTRITION MILLS.

Repeated tests were made on various days, June 22, 23, 26, and July 1, 1916, to detect any charges of static electricity that might have been built up during the operation of the attrition mill. The devices employed for transferring the charge to the electroscope included the copper wire described in Series 10 (p. 16), and also a proof plane, consisting of a penny attached by sealing wax to a ¼-inch glass tube 10 inches long. The copper lead and proof plane each gave good deflections of the electroscope when these devices were applied to bodies known to have charges of static electricity, and therefore it was certain that the methods employed for indicating the presence of static electricity were reliable. In the tests involving the use of the proof plane, it was held near the moving belt, or brought in contact with the frame of the machine, and then touched to the binding post of the electroscope, which was grounded by holding in the hand.

None of the tests run on the summer days mentioned, in none of which the humidity was lower than 70 per cent, indicated the slightest trace of static electricity during the operation of the attrition mill, with and without the feeding of various grains. This result indicated either that no static charge was being generated or the machine was too well grounded, either directly or by leakage, to retain any charge that might have been generated.

By means of the usual voltmeter method the metal frame of the attrition mill was found to be well insulated as far as low voltages (110) were concerned.

In order to test qualitatively the insulation and leakage for high voltages, one terminal of a Wimshurst machine was connected to the frame of the attrition mill. By means of the proof plane and electroscope it was found that the attrition mill was capable of retaining a slight charge for a few seconds after the charging wire had been removed. The indications of the very sensitive electroscope, however, were so feeble as to lead to the conclusion that, while the attrition mill was fairly well insulated, its leakage (owing to the many corners and edges, covering of dust, and also atmospheric moisture) and its capacity were so great that a considerable quantity of electricity would be required to establish a high potential on the frame.

Further tests (Series 10) on a winter day (temperature 42° and humidity 54 per cent) indicated the development of static electricity in the driving belts, due probably to the comparatively low moisture content of the air, but not in the frame of the machine.

Safe conclusions from these tests are as follows:

1. Any static electricity that may be generated in this particular machine is dissipated so rapidly by leakage, which is largely due to

the relatively high atmospheric humidity of this region, that no potential is built up in the frame of the machine.

2. Should an excessive amount of static electricity be developed in a mill of any kind, proper methods of grounding the machine [1] will go far toward eliminating any danger that may be due to sparks from static charges.

STATIC ELECTRICITY AS CAUSE OF EXPLOSIONS.

In 25 attempts to ignite inflammable dusts with the spark from an induction coil, not a single explosion was obtained (Series 6, 7, and 12). From the fact that an electric arc would produce explosions under identical conditions, it would seem that the production of an explosion is largely dependent upon the extent as well as the intensity of the source of ignition, especially when there is a high velocity of the dust past the igniter, as is the case in the attrition mill. The temperature of the electric arc is estimated at about 6,200° F., but laboratory experiments [2] have shown that certain dusts can be ignited at as low a temperature as 1,100° F. with a source of heat having a comparatively small area. Consequently, great care should be exercised to eliminate every possible source of ignition.

Conclusions:

1. It is comparatively difficult to ignite inflammable dusts in an attrition mill by means of static electricity.

2. Nevertheless, every precaution should be taken to eliminate static electricity in the operation of any kind of mill.

EFFECT OF ATMOSPHERIC HUMIDITY.

The effect of humidity, both relative and absolute, upon the inflammability of dusts is not yet known, and can not be definitely determined except by laboratory investigations under carefully controlled conditions. In the tests in the attrition mill the humidity of the atmosphere was always determined by means of a carefully calibrated sling psychrometer. The relative humidity ranged from 44 per cent to very nearly saturation, or 100 per cent, in the case of a steady rain. No deductions could be made as to the effect of the relative humidity on the inflammability of grain dusts, for too many variable factors were involved. It is, however, of interest to note that in Series 3, during a steady rain, the regularity of explosions happened to be greater than in any other series. This fact seems to indicate, at least, that a high relative humidity does not tend to decrease the inflammability of dusts, except in so far as the moisture content of the materials fed into the mill may be considerably increased after a sufficient length of time.

[1] References 38 and 39, Bibliography. [2] Reference 26, Bibliography.

Conclusions: There is no positive indication in the present series of tests that the humidity of the atmosphere has any material effect on the inflammability of dusts in this region, where the relative humidity is usually above 50 per cent.

TABLE 17.—*Moisture contents of materials.*

Designation.	Material.	Series.				
		5[1]	11	12	14	15
		Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
A	Fine oat hulls	9.6	9.9	5.7		
B	Elevator dust	9.8				
C	Oat hulls	8.9		3.2	9.2	3.3
D_1	Flour (direct from store)		14.1			
D	Flour (oven dried)		9.3	10.2		8.5
F	Wheat scourings	10.4	9.0	5.7		
G	Corn	9.9				
I	Coarse floor sweepings	8.6				
K	Conveyor mixture	9.0				
N	Fine oat hull dust			5.2		
P	Barley malt sprouts				9.4	4.0
Q	Malt sprouts				12.0	3.5
R	Brewers' dried grain				9.4	4.7

[1]Also typical of the first 9 series.

EFFECT OF MOISTURE CONTENT OF MATERIALS.

Table 17 gives the results of moisture determinations made in several tests. Average samples were obtained during the feeding of the materials into the attrition mill, and were kept in carefully stoppered bottles. The method for making the moisture determinations was similar to that employed for coal analysis, in which the samples are placed in a constant temperature oven at 220° F. The crucibles containing the samples were weighed, by means of analytical balances, at frequent intervals of time until the material was dried out, as indicated by two successive weights of practically the same value. The percentage of moisture was then calculated on the basis of the original wet sample. Duplicate determinations were made in each case.

The number of moisture determinations and the range of moisture contents were not sufficient to enable one to draw any positive conclusions, but, in the case of oven-dried flour at least, a tendency toward more regularity and violence of explosions was noted. Undoubtedly the same tendency would be noted in all grains if the conditions of testing could be properly controlled, and it would perhaps be advisable to determine the minimum amount of moisture to render the material noninflammable. For the present it seems that the following conclusions may safely be drawn:

1. The less moisture a dust contains, the more inflammable it is likely to be.

2. It is probable that for inflammable dusts there is a maximum moisture content above which the dusts can not be ignited.

TESTS OF REVOLVING DAMPERS OR FIRE TRAPS.

The tests with the revolving dampers gave the following important results:

TABLE 18.—*Tests of revolving dampers or fire traps.*

Observations.	Single damper.	Double damper.
Explosions with dampers in service	29	69
Flashes past damper	6	14
Puffs past damper	0	10

Observations.	Single damper.	Double damper.
Flashes at D	....	8
Puffs at D	....	1
Flashes at E	0	1
Puffs at E	0	0

These results indicate that the double damper showed no superiority over the single damper as a preventive of flame propagation. With both single and double dampers there were cases in which flames got past with enough force to shoot out of the peephole (B) for several feet toward the observer. The devices, however, were effective to the extent that no puffs of smoke and only one flame were observed at the end (E) of the conveyor.

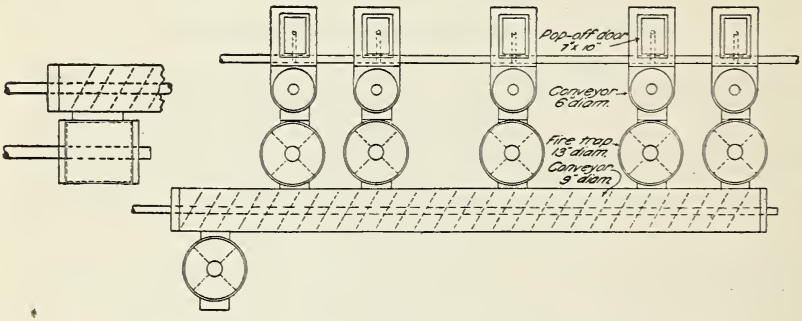

FIG. 5.—Attrition mills, showing fire traps or dampers.

An interesting practical application of the revolving damper as a "fire trap" is noted in the following report of an investigation by R. L. Sackett:

A large milling company in Buffalo, N. Y., has placed its battery of attrition mills in a separate building of corrugated iron (fig. 5).

Before the oats pass to the mill they have been screened and have passed a magnetic separator, which removes splinters of wood, metallic substances, and other foreign matter.

The material passes through the attrition mills and drops down toward the conveyor below.

The vertical leg below the mill has a 6-inch galvanized spout running horizontally through the side of the mill. On the end of this pipe is a flap valve with a circuit so arranged that if an explosion takes place in the mill the pressure will open the flap valve, break the electric circuit, which will in turn stop the motor which drives the mills. The pipe serves as a safety valve for the escape of gases in case of explosion.

Below the safety valve is a "fire trap" or "damper," consisting of four blades revolving on a shaft, within a casing, so designed that in case of an explosion the propagation of flame to the conveyor will be retarded or prevented. This damper is similar to those used in experiments in the special mill built at The Pennsylvania State College for the purpose of this investigation.

This company reports that no damage has been done, and, so far as they know, explosions have not been transmitted beyond the safety pipe and damper.

The double damper as installed in the present series of tests did not give the desired effect, probably because the two sets of revolving paddles were too close together. If the flame can pass one set of blades, it is likely that it can pass an adjacent set of blades before it has been extinguished. It seems reasonable to suppose, however, that a sufficient volume or extent of passage between the two revolving dampers may cause the flame to expend its energy to such an extent that the second damper would be able to check it absolutely.

The following conclusions can be drawn:

1. A single revolving damper is a fairly effective device for preventing the violent propagation of flames, but is by no means an absolute preventive.

2. A double revolving damper does not appear to serve the purpose of a fire trap any better than a single damper.

RELIEF VALVE AND PIPE.

Although the three tests with the relief valve and pipe leading from the hopper of the attrition mill to the outside of the building showed that this device was not effective in preventing the propagation of flames, even past the double revolving damper, it is quite possible that a larger size of valve and pipe may aid materially in accomplishing the desired result. The principle of permitting the immediate escape of confined gases that have just been ignited seems to be a proper one on which to base a preventive device.

Conclusions:

1. The relief valve and pipe as installed alone are not successful in preventing flame propagation.

2. In view of the correct principle involved, it may be worth while to try changes in the design and location of the relief valve and pipe.

A study of the foregoing discussion of the tests performed at the experimental plant of the college may lead to the objection that not enough attention was paid to the quantitative side of the problem, involving such factors as the exact amount of grain fed into the mill, the rate of feeding, the physical and chemical analyses of the material, the minimum temperature and minimum amount of heat to produce ignition, the velocity and analysis of the dust-laden gases at various points between the attrition mill and the end of the conveyor, the pressure developed by the explosion, the minimum humidity and the minimum amount of inert gases to prevent ignition of inflammable dusts, and the limits of inflammability for various dusts. To such a criticism the authors would reply that the quantitative side of the problem could be taken care of only by careful laboratory investigations such as are being conducted by the Bureau of Mines and the Bureau of Chemistry. The chief purposes of an experimental mill, such as that installed at the college, are to show that explosions can be produced in the grinding mill and propagated a considerable distance, and to test various preventive devices recommended by manufacturing concerns or by the Government. Both of these purposes have been served to some extent.

Although it has not been demonstrated that static electricity, or sparks emitted from foreign substances, are capable of producing explosions in an attrition mill, it has been positively proved that more intense sources of ignition, such as an open flame or electric arc, can easily ignite dust mixtures, and that the resulting explosion can be propagated through fire traps and the screw conveyor. Consequently, the safest plan is to guard against every possible source of ignition.

As to the second use, only three preventive devices have thus far been tested—a single revolving damper, a double revolving damper, and a relief valve. It would seem, however, that the present equipment would warrant further tests of preventive measures in cooperation with the Government.

SUMMARY OF CONCLUSIONS.

The final conclusions reached after studying grain-dust explosions in an experimental attrition mill, together with the other results obtained by Government investigators, may be summarized as follows:

1. Every effort should be made to collect and remove the dust from the grinding mill and surrounding atmosphere.

2. In some cases it may be advantageous to use inert gases to decrease the oxygen content and thus prevent the formation of an explosive mixture of air and dust.

3. Every possible source of heat should be eliminated where there is any danger of having a dust-laden atmosphere.

4. Every precaution should be taken to eliminate sparks due to static electricity.[1]

5. Greater use should be made of sheet iron on account of the very great danger from smoldering lumps of grain (Series 12, p. 17).

6. Revolving dampers, as installed here and elsewhere, appear to be of some value as preventive measures for the propagation of explosions.

7. The principle of the automatic relief valve should receive more attention as a possible remedy to apply for the partial prevention of the propagation of the flame.

[1] References 38 and 39, Bibliography.

APPENDIX.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS.

In closing, the authors desire to offer the following recommendations for future investigations:

I. Laboratory experiments to determine the limits of inflammability as affected by the following factors:

1. Density of the dust cloud.
2. Fineness of the dust particles.
3. Chemical composition of the dust.
4. Moisture content.
5. Inert gases.
6. Atmospheric humidity.
7. Minimum temperature and amount of heat required for ignition.
8. Sparks from metallic substances.
9. Static electricity (not merely the voltage, but current measurements as well.)

II. Field experiments on various types of machines handling dusty materials:

1. Tests to prove that dust mixtures outside the limits of inflammability, as already determined, with reference to moisture content, inert gases, or atmospheric humidity, can not be ignited under the most severe conditions of ignition, such as those produced by an electric arc.
2. Tests of various devices designed to prevent the propagation of explosions.

RÉSUMÉ OF SOME PAST EXPLOSIONS.

The first large grain-dust explosion occurred in 1878 in the Washburn mill, at Minneapolis, Minn. At that time the "new process" system of milling, in which the grinding of wheat was done by millstones, was in vogue. It was assumed that, owing to a choking up of the feed spouts leading to the millstones above, one or more of the millstones became empty, and the running of the two stones against each other caused sparks, which ignited the dust in the conveyor boxes and dust rooms, causing an explosion in the dust room which destroyed the walls of the building. It is possible, and even probable, that the fire originated from open lights which were used at that time.

Another very serious mill explosion occurred on June 24, 1913, when a feed-grinding plant in Buffalo, N. Y., was completely wrecked by an explosion, presumably of dust. None of the survivors of this explosion was able to give any information as to the cause of the initial fire, but it is stated that without a doubt the explosion was caused by the ignition of feed dust.

A rather curious explosion took place in a flour mill in Nebraska on September 22, 1914, in which the entire wall on one side above the second story was blown out. One end showed a bad bulge, but the roof remained intact, except that it sagged over the side from which the wall was blown out. Apparently the force of the explosion was exerted in one direction, or, rather, the wall on this side offered less resistance than the others. It is believed that the dust in one of the flour bins was ignited by a match struck by one of the workmen.

On December 11, 1916, a large cereal mill in Ontario, Canada, was totally destroyed by an explosion and subsequent fire. The fire was started by an explosion in the feed-grinding building, and was ascribed to the ignition of feed dust in one of the grinding machines.

One of the authors witnessed several dust explosions in flour mills. Although these explosions were of minor importance, because no serious consequences followed, the observations tend to give an idea as to the explosibility of flour dust, the conditions under which explosions may take place, and, in some cases, the cause of the initial explosion.

At a certain mill the settlings of the dust room, into which was blown the dust drawn from the middlings purifiers and from the exhaust off the millstones, were gathered periodically into a bin and ground on a small stone. This mixture was composed of very fine pieces of bran, fiber, larger pieces of endosperm, and a fine, impalpable, starchy, flour dust. Often, when the spout became nearly empty and the pile above started down, the dust descended with sufficient force to spurt out of the opening in the spout over the hopper, creating a dense cloud of dust. On one occasion an open light was close at hand when this dust fell, and an explosion followed. There were three distinct explosions or flashes of the burning dust, one following the other at intervals of a few seconds. These explosions were succeeded by a faint crackling sound. Each successive flash was wider in extent as the dust spread and diffused.

The first enveloped only the vicinity of the spouts and millstone; the second, a still larger area; and the third, almost the entire area of the grinding floor. The first zone, composed of the heaviest and largest dust particles, burned the most slowly, as if partially smothered; the next, more rapidly; and the last and largest zone, composed of the very lightest of the starchy particles in the state of greatest diffusion, burned most rapidly, and, consequently, with the greatest heat. This last explosion had more force than the others, and was more of the nature of an explosion than the other two.

On another occasion some purified middlings were shaken down from the side of an empty bin, and, coming in contact with the flame of an open lamp, burned with two distinct flashes, the second one spreading somewhat beyond the confines of the bin. These middling particles were too heavy to float far, and too large to burn rapidly.

Only a few years ago a certain packer lifted the lid of a flour bin, and held a lighted match within the opening to see how much flour the bin contained. Apparently the flour had been drawn down partially, leaving some piled up on one side. Set in motion by a slight jar, it fell, causing a rush of air and a thick cloud of dust, which was followed immediately by a long flame issuing from the opening in the bin. The current of air caused by the fall of the flour was evidently strong enough to prevent the flame from extending down into the bin; otherwise a disastrous explosion might have resulted. The flame burned the packer's face and arms to some extent, and caused him to fall backward. In doing so, he let the lid of the bin fall, and thus cut off the flour dust inside the bin from the flaming dust outside.

The conditions and circumstances existing just previous to each of these various explosions were similar in all cases. From such observations as were made the conclusion has been reached that only under certain favorable conditions will a serious explosion of flour dust occur. If the dust is very dense and confined within a certain volume, or if the particles forming the dust are very large, the danger of a real explosion is less than in the case of the very fine, starchy dust in less density, which may, however, burn very rapidly. The theory is that these particles of a fine, starchy nature must be separated by a layer or thin wall of air, and at the same time be near enough together to ignite each other. Dense clouds of dust, especially those containing coarse particles, are comparatively slow burning.

A dust may also be very fine, yet so widely diffused as to be incapable of ignition, even from an open light. The old-fashioned dust room, sometimes merely partitioned off with fine muslin or other cloth, constituted a dangerous source of fire or explosion, as the dust blown from machines was held more or less in suspension before settling, and, being for the most part finely divided, it would be all the more dangerous should it come in contact with an open light.

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