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HUMIDITY AND STATIC ELECTRICITY IN PNEUMATIC LOADING OF BLASTING EXPLOSIVES

by

J.A. Darling* and D.A.B. Stevenson**

SYNOPSIS

The occasional generation of static electricity in ammonium nitrate jet loaders is a serious matter because of the potential hazard presented to the operating personnel through the premature ignition of the blasting caps and initiating devices resulting from the development and discharge of static electrical charges.

Previous methods of control of these hazards have included the introduction of conductive hoses and the grounding of the metal injector of loaders. Electric blasting caps have been forbidden in bottom primed drill holes. In addition static proof safety fuses and detonating fuses have been developed.

This work explores the possibility of controlling the generation of static electricity by additions of water or of water vapour to jet loaders. It has been discovered that this water vapour may be automatically provided by exposures of ammonium nitrate or ammonium nitrate-oil mixtures to an air stream of high relative humidity immediately prior to loading. This exposure limits, to safe values, the voltages produced in the ammonium nitrate-hose wall static electricity generating system that may be operating in a pneumatic loader.

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L'HUMIDITÉ ET L'ÉLECTRICITÉ STATIQUE DANS LE CHARGEMENT PNEUMATIQUE DES EXPLOSIFS DE DÉFLAGRATION

par

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RÉSUMÉ

La génération occasionnelle d'électricité statique dans les chargeurs à injecteurs de nitrate d'ammonium pose un problème sérieux: il peut y avoir danger pour le personnel que la création et la décharge d'électricité statique allume prématurément les détonateurs et dispositifs d'amorçage.

Les méthodes précédentes de contrôle de ce phénomène comprenaient l'utilisation de tuyaux flexibles conducteurs et la mise à terre des injecteurs métalliques des chargeurs. On a interdit l'emploi des amorces électriques dans les trous de forage amorcés au fond. De plus, on a mis au point des mèches de sûreté et des cordeaux détonants à l'épreuve de l'électricité statique.

La présente étude explore la possibilité de réduire la génération d'électricité statique par l'addition d'eau ou de vapeur d'eau aux chargeurs à injecteurs. On a constaté qu'il est possible d'obtenir automatiquement cette vapeur d'eau en exposant le nitrate d'ammonium ou les mélanges pétroliers de nitrate d'ammonium à un courant d'air ayant une humidité relative élevée juste avant le chargement. Cela abaisse à des valeurs acceptables les tensions qui peuvent se produire par frottement du nitrate d'ammonium contre la paroi du tuyau dans un chargeur pneumatique.

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INTRODUCTION

Pneumatic loaders for ammonium nitrate (AN) mixtures, presently in use in Canada, all operate on the principle of the aspirating jet. AN prills containing an organic additive such as fuel oil, designated as AN/FO, pass from a hopper through an inlet hose into an injector. They are then transported by compressed air down an outlet hose into a receptacle, such as a drill hole, at a speed sufficient to cause a considerable amount of compaction by breakage of many of the prills.

Pneumatic loaders were introduced into Canada in 1960, for trials at Sudbury, Ontario. It was realized almost at once that the loaders were generators of static electricity. As the background of experience with the jet loaders broadened, it became evident that large electric shocks could be sustained by the operators of the loaders. However, since the shocks were not injurious and since the explosives initiating systems consisted of black powder fuses and non-electric blasting caps, it was felt that no serious hazards were presented.

Nevertheless, on April 3, 1962, a jet loader operator in an Elliot Lake mine was involved in the explosion of a #8 blasting cap. It appeared that he fired the cap by allowing a charged loading hose to touch the attached black powder fuse. Scientists at Canadian Industries Limited investigated the possibility that this premature detonation was caused by static electricity. Their conclusions, as reported by A.E. Dyment (1), were as follows:

> "The mechanism of ignition appears to be that the high voltage of the charged object, when applied to the carcass of the fuse, breaks down the insulation and passes into the black powder core which, while a poor conductor of electricity in the normal sense, will, however, conduct a high voltage discharge. The electrostatic charge travels down the powder core to the end of the fuse. At this point the charge jumps to the conductive cap shell and thence to ground, thus producing a spark which may initiate the sensitive priming composition in the cap."

Tests with high-voltage electricity were also made in 1962 by the International Nickel Company (INCO) in Copper Cliff, Ontario (2). The results of these tests substantiated the mechanism proposed by Dyment, provided that sufficiently high voltages were developed in the jet loaders.

The generation of high voltages in jet loaders was investigated by R.W. Prugh and K.G. Rucker at the duPont Development Laboratories, and they reported their results at the Fifth Rock Mechanics Symposium in 1962(3). They postulated that the electrical circuit for a loader operating as a current generator was from the electrical ground through the rock to the loader by way of one or more paths. From the loader the circuit passed down the loading hose to the ammonium nitrate loaded in the drill hole and thence to ground again through the rock. The resistance of this path was measured by inserting an insulated high-range ohmmeter between the tip of the loading hose and a wire inserted into an AN-filled drill hole. They considered this resistance to be dangerous when its value exceeded ten megohms.

In 1962 the Mines Branch recognized the rapid transition that was taking place in the Canadian mining industry in connection with the pneumatic loading of ammonium nitrate/fuel oil in bore holes. To assist this industry it was important to study the electrical hazards associated with this operation and, if possible, to find methods of combatting the generation of static electricity. Consequently, the Explosives Research Laboratory of the Mines Branch in Ottawa carried out a separate investigation of hazards arising from the generation of static electricity in short hole jet loaders. The purpose of this investigation was to determine under what operating conditions static electrical charges on the loaders became less hazardous.

Difficulties encountered during the preliminary observation of the mechanism of static electricity generation indicated that the process was very complex. For instance, in spite of other views to the contrary, it was concluded that the magnitude of current carried by the AN prills in a loader cannot be measured, as any connection installed to read this value merely becomes another generator of static electricity in an already complex system. Moreover, the magnitude of the voltage produced depends on relative humidity, not absolute humidity.

PRELIMINARY CONSIDERATIONS

It has been pointed out in the introduction that static-electricity generation in AN jet loaders is considered to be a very complex process. On the other hand, operation of experimental loaders in the Explosives Research Laboratory has contributed to the development of the following hypothesis concerning the mechanism of the generation of the static electricity:

From the point of view of classification this system for the generation of static electricity may be classified as a solid-solid one, in which one of the solids is AN carried by a stream of air and the other is the loading hose. It is believed that electric charges on the solid particles of ammonium nitrate are developed by friction or impact with the surface of the loading hose. Loading hoses are generally made of polyethylene, a substance chemically similar to the fuel oil which is a normal ingredient of the AN/FO. Consequently, it makes very little difference, for purposes of static generation, whether or not this surface becomes wet with fuel oil. In any case, the loading hose is a hollow insulator carrying a charge on its inner wall. The opposite charge, after separation from the wall, will be carried by the particles of ammonium nitrate. The larger prills of nitrate with their electrical charges will be transported by the compressed air through the loading hose. This movement of electric charges will constitute an electric current, the magnitude of which will depend on many factors.

Although the charge on the hose causes no electric field inside it, the small particles of ammonium nitrate are driven apart by mutual repulsion and finally settle as closely as possible to the inner surface of the hose with its opposite charge. In fact, a dust layer on the inside of the hose is always found. This layer of dust is partially conducting and any point in the charged layer is able to discharge an electrical pulse of considerable size. The magnitude of this discharge is approximately equivalent to that from a capacitor of 10 picofarads charged to the same voltage. It is from this layer that operators receive their shocks of electricity, and in the case of the accident at Elliot Lake it was the source of the spark which was sufficient to set off the blasting cap.

In theory, one should be able to measure the voltage between the ground and the interior wall of the hose. However, since polyethylene is a non-conductor, charges cannot travel along its surface and a point of contact there cannot maintain even the minute current required when an electrostatic voltmeter is used; in practice one must make an electrical connection in the dust layer. Any point in the dust layer is in contact with a relatively large area and since it is continually replenished with charges from the passing prills of ammonium nitrate, this layer becomes a reliable voltage tap. Since the dust layer consists of ammonium nitrate, the resulting voltage corresponds to that of the transported prills.

In the ammonium nitrate loader the metal part of the compressed air jet constitutes one contact with this layer. This metal part is the source of electrical shocks to operators if it has first become detached from electrical ground and if the system is at that time delivering a high voltage. Since the hopper must be refilled from time to time, it is difficult to maintain electrical isolation of the jet. Consequently, for experimental purposes, a more reliable electrical connection to the dust layer was established by inserting a metal nail through the wall of the loading hose at a point at least 10 cm distant from the jet. The shaft of the nail did not protrude past the inner surface of the wall. The nail thus made contact with the dust layer in the interior of the tube, but did not become a generator in its own right.

The minimum distance between any two connections, if interference was to be avoided, was 10 cm. A ground connection made any closer than this decreased the voltage being measured. A 20-cm length of interior hose surface would thus appear to include the area from which it is possible to draw a current from the dust layer. The induction of an operator's hand on the outside of the hose reduces the voltage at a contact within the same distance of 10 cm, noted above. The distance depended on the relative humidity prevailing at the time.

We were not able to prove that the origin of the static electricity is in the loading hose rather than in the air jet or in the inlet hose. However, there is some evidence that such is the case. For instance, when two static voltmeters are connected to two of the connections noted in the preceding paragraph they indicate the same average voltage. They are both subject to fluctuations but the fluctuations are not in phase. If they had been in phase, it would have been an indication that the generating mechanism was located in such a place that the loading hose served only as a collector of charges from the prills.

Recent efforts to solve the problem of build-up of static voltages have led to the use of loading hoses which have a conductivity of the order of one micromho per foot. This enables charges to migrate so that the same potential is maintained throughout the hose. If the hose is connected to ground, the potential difference from ground is effectively zero and there is no electrical shock hazard to loader operators. But when such a hose is insulated from ground, it becomes charged by the passage of prills, indicating that electricity is still being generated in the system. Consequently, it is imperative that loaders using such hoses should be grounded at all times; otherwise, the conductive properties of the hose will serve no useful purpose.

EXPERIMENTAL OPERATION OF THE LABORATORY LOADERS

The arrangement of the jet loader and associated equipment is shown by a sketch (Figure 1) and two photographs (Figures 2 and 3). A gasoline-motor-driven air compressor, capable of delivering 100 cfm of free air at 6 atmospheres pressure, was connected to a heat exchanger which consisted of 120 ft of 1-1/2-in. drain pipe mounted outdoors. This exchanger was very efficient when the outside air temperature was in the neighbourhood of 60°F, but much less so when the air temperature was decreased to 0°F or increased to 85°F. From this exchanger the air was led inside to a small liquid-filled heat exchanger (Figure 2), where the temperature of the incoming air could be adjusted and the final portion of the condensed moisture removed. When outside temperatures were within reasonable limits it was possible to deliver the compressed air at a pressure of 6 atmospheres and a relative humidity of 100% at the temperature of the room in which the jet was operated. This should have resulted in a relative humidity of $100\%/6 \approx 17\%$ when the air was released to atmospheric pressure.

The jet loaders operated with this compressed air were of three types:

(1) The CIL Anoloader is designed around an aluminum hopper, containing 3 gallons of AN prills, which is suspended by straps from the shoulder of an operator. The prills are aspirated by an annular jet and transported down a loading tube.

(2) The duPont short hole loader has a 5-gallon hopper which rests upon the ground. An inlet hose connects this hopper to the low-pressure point in a separate jet, from where the prills are transported down its loading tube.

(3) The last type of loader was furnished by the Stanrock Mining Co., operating in the Elliot Lake area. The hopper of this loader had been fabricated from a 2-gallon polyethylene container. In this case the AN prills were aspirated upwards into a Pemberthy Type 63A injector.

To eliminate dust it was necessary to discharge the loading hoses through the window of the operating room to the outside. An attempt was made to simulate an insulated borehole by discharging the prills into a covered metal garbage pail (Figure 3). Measurement of voltages on the pail was discontinued when it was realized that the escape of dust-laden air from the pail rendered the pail ineffective as a Faraday cage and simply measured voltages in another generating system consisting of the AN prills or AN/FO and the zinc of the garbage pail.

Several methods of reducing the voltages on jet loaders to permissible levels were examined. The first method was based on the erratic behaviour of the voltmeter when the compressed air entered the jet at a temperature below the dew-point of the aspirated air. When this happened, instead of the usual minor variations of ± 1000 volts, the meter readings varied over a much wider range, from minus 20,000 volts to plus 9,000 volts. It was deduced that these wide variations were caused by the cooling of room air by the cold air from the jet, with the subsequent production of fog in the loading tube.

On the assumption that water droplets and fog could drastically reduce the voltage produced in the loader, line oilers were inserted in the compressed air line as close as possible to the loader, to meter water into the air stream. Three types of oilers were tried with the Stanrock Loader and the CIL Anoloader: (1) an Ingersoll-Rand standard line oiler; (2) a Gardner-Denver Type L-12, with interchangeable metering jets; and (3) a Gardner-Denver Type 65 air line lubricator, with a sintered brass wick of adjustable height.

The oilers had to be installed on the compressed air line ahead of the jet, and the air passing through them was already saturated with water vapour. Additions of water from the oilers accumulated in the line and then entered the loader in large slugs. These slugs made the interior surfaces of loader parts wet, so that the loaders tended to clog with wet ammonium nitrate. If clogging could be avoided, two or three of the slugs would eliminate static charges from the loader for periods as long as fifteen minutes. The Type 65 air line lubricator did not produce slugs as large as those produced by the other oilers, but on the other hand it could not feed water fast enough to completely control the static. Consequently, the control of static voltages in the loaders with water feed from line oilers was abandoned as impractical.

A second method of reducing the voltages on the loaders likewise involved additions of water, but in this case the addition was to the released air after the jet where the relative humidity was low. Figure 4 is a sketch of the installation of a 1/16-in. stainless steel water tube (approx. 1/32-in. ID) on the Pemberthy 63A injector of the Stanrock loader which discharged metered quantities of water at the point of minimum air pressure normal to the axis of flow. A similar pipe was installed on the CIL Ano-loader, but it was not as satisfactory because the tube discharged into an annular orifice and the point of minimum pressure was more difficult to locate.

The loading rate of the Stanrock loader, using the jet shown in Figure 4, was 30 lb/min. of ammonium nitrate at an air delivery rate of 55 cfm and a water injection rate of 40 ml/min. Ambient air conditions at the hopper were 70°F and 25% relative humidity. If the water had passed into the ammonium nitrate, its moisture content would have been raised to $\frac{40 \times 100}{30 \times 453} = 0.3\%$. Actually, the moisture content increased only from 0.03% to 0.08%, indicating that most of the water remained in the air blast. This amounted to $\frac{40 \times 15.43}{55} = 11$ grains of water per cubic foot of total air stream.

The use of this modified injector proved to be very effective for the control of static. After ten seconds of water feed, voltages in the loading hose dropped from 25,000 to less than 500. The polarity of the charge then oscillated slowly from negative to positive. Two minutes after the water feed was shut off, the original voltage returned after many surges.

This addition of metered quantities of water would be an attractive solution to the problem of static control in the loaders. It could be effective regardless of extreme ambient conditions which affect the loading process. Practically, however, the method would be a nuisance to loader operators, since only a limited amount of water could be carried and it would have to be replenished frequently.

The above method of eliminating static had been tested in severe winter weather when relative humidities in rooms were below 25%. The method was retested in April, when the room relative humidities had risen to 40 or 50%. At that time, static electricity generation in the loaders became very erratic and it became difficult to produce any static voltages at all. The possibility existed that, if a more complete study of humidities of the air surrounding the loader and the air passing through it were made, yet a third method for static control might be found. Special hope lay in the study of the relationship of these humidities to the phenomenon of deliquescence and the resulting films of saturated solutions on the surfaces of ammonium nitrate crystals.

Prugh and Rucker (3) had reported that the charge on the loader depended on the absolute humidity of the air in the loading tube, which was assumed to be a 50/50 mixture of room air from the hopper and compressed air from the jet. They postulated moisture films as the cause of the reduction of static voltages when humidities were high. These films would provide a short circuit within the electrical generating system; preventing the development of high voltages. This dependence of the short circuit on the absolute humidity does not appear logical, since moisture films depend for their formation on the phenomenon of deliquescence. Deliquescence in turn depends not on the absolute humidity but on the relative humidity of air in contact with the salt in question.

The condition for deliquescence to take place is that the partial pressure of water vapour in the air be greater than the equilibrium partial pressure of water vapour over a saturated solution of salt at that temperature. This condition may be expressed as

$$P_a \geq P_x$$

or

$$\frac{P_a}{P_s} \geq \frac{P_x}{P_s}$$

where P_a = partial pressure of water vapour in the air,

P_x = equilibrium partial pressure of water vapour over a saturated solution of ammonium nitrate, and

P_s = equilibrium partial pressure of water vapour over pure water;

and where all partial pressures are measured at the same temperature and therefore $\frac{P_x}{P_s}$ is the critical relative humidity for the commencement of deliquescence.

In the case of ammonium nitrate, deliquescence will take place at values of relative humidity above 65% at 65°F. This critical percentage of relative humidity depends upon the temperature as is shown in Figure 5, which is based on the data reported by Othmer, Frohlich (5) and Prideaux (6). From this work it can be seen that the critical relative humidity increases continuously up to 100% at 0°F.

To investigate the formation of moisture films on AN prills, it was decided to study (a) the relative humidities of the various air bodies associated with the loader, and (b) the relative thickness of the films on the prills at varying relative humidities.

The air bodies associated with the loaders fall into the following categories: (1) air of 6 atmospheres pressure arriving in the compressed air lines and passing through the control valve of the loader, designated as "compressed air"; (2) the compressed air after passage through the injector, designated as "released air"; (3) the air entering the loader from above the open hopper along with the AN/FO, designated as "room air"; and finally (4) the mixture of released air and room air which passes down the loader tube, designated as "mixed air".

The measurement of the relative humidity of the room air presented no difficulty. The relative humidity of the compressed air can, in normal cases, be assumed to be 100%. The relative humidity of the released air should then be 17%, but a substantiating direct measurement was desired. Also, a means of measuring the relative humidity of the mixed air was required but no suitable method had been devised. Lithium chloride humidity elements proved unreliable because of the presence of ammonium nitrate dust. Recourse was therefore had to the use of wet and dry-bulb thermometers. The humidity of the released air was then measured by using a second small air jet, fed in parallel with the injector jet into a flask where the air impinged upon the thermometer bulbs. These indicated that the relative humidity of the released air in our system was between 20 and 25%, rather than the calculated 17%, probably because of entrained water droplets.

As no means of measuring the relative humidity of the "mixed air" was known, it was decided to calculate it from the relative volumes of released air and room air passing into the loader tube. Since the volumes involved were large by laboratory standards, displacement meters could not be used and orifice meters were substituted. An orifice plate of 0.664-in. restriction inserted in the compressed air feed provided ten inches of water pressure drop when the air flow was equivalent to 50 cu. ft. of free air per minute. A 0.750-in. orifice plate installed on the hopper cover of two of the short hole loaders provided a 1.7-in. water pressure drop when 10 cu. ft/min. of room air was drawn into the system.

The proportion of room air entering from the hopper proved to be small. When the hopper was empty it was between 1/4 and 1/3 of the mixed air. When the hopper was full, this proportion dropped to approximately 1/8. When relative humidities of the mixed air were calculated from this latter proportion of 1/8, they were found to vary from 20% to 30%, as room humidities varied from 20% to 90%, assuming that the humidity of the released air was always 20%. The humidity of the mixed air thus varies very little with ambient conditions.

The thickness of moisture films on AN prills was also investigated. Since they were expected to be conductors of electricity, use was made of resistance-measuring equipment. A glass U-tube, 15 cm x 15 cm x 2 cm, was filled with AN prills. Embedded in the prills at each end of the U-tube were platinum foil electrodes with an area of 3 cm^2 each. Air of various relative humidities was drawn through the prills by a vacuum pump. The resistance of this column of prills was measured by passing a current through the series combination of the prills and a Keithley voltmeter equipped with low-current shunts. Measurement of currents as low as 1×10^{-9} amperes from a supply voltage of 400 rendered possible the measurement of resistance as high as 4×10^{11}ohms.

In order to control the relative humidity of the air passing over the prills during resistance measurements, it was necessary to first reduce the loading room's relative humidity, from the prevailing value of 65-70%, to 30-35%. This was done by releasing compressed air into the loading room. The following calculations and table illustrate the quantitative relationship between compressed air volumes and the time necessary to produce a given humidity:

> If it is assumed that the released air and the room are both at a given temperature, and H grains/ft^3 is the absolute humidity of saturated air at this temperature, then X, the humidity fraction* of air in the given room at the end of any time interval of t minutes, may be calculated under the boundary condition that $X = 1.0$ when time $t = 0$. If 0.2 is the humidity fraction of the released air, V $ft^3$is the volume of the room, and K is the volume of air released per minute, expressed as air changes per minute, then the volume of air entering and leaving the room is KV ft^3/min.

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* The humidity fraction is here defined as

$$\frac{W}{W_s} = \frac{P}{760 - P} \Big| \frac{P_s}{760 - P_s} \approx \frac{P}{P_s} = \frac{\%\ \text{Relative Humidity,}}{100}$$

where W and P are the weight and partial pressure of water vapour in a sample of air, and W_s and P_s are the weight and partial pressure of water vapour in saturated air at the same temperature.

The moisture entering the room = 0.2 HKV grains/min, the moisture present at any given time t = XHV grains, and the moisture leaving the room = XHKV grains/min, then the rate of change of humidity = dX and the rate of change in room water content = $HV\frac{dX}{dt} = 0.2\ HKV - XHKV$.

Integrating this expression and removing the common factor HV on both sides of this equation, we have:

$$\int dt = \int \frac{1}{K} \frac{dX}{0.2-X}$$

$$\text{and } t = \frac{1}{K}\left(\ln c - \ln (X-0.2)\right)$$

where c is an integrating constant

but at t = 0 X = 1 and c = 0.8

$$t = \frac{1}{K} \ln \frac{0.8}{X-0.2}$$

$$\text{and } tK = \ln \frac{0.8}{X-0.2}$$

Values of tK and of t, when K = 0.1 air changes per minute, are detailed in Table 1, below, for various desired room relative humidities:

TABLE 1

Time Required to Obtain Desired Relative Humidity in a Room that is Flushed with Compressed Air

Desired Percentage Relative Humidity 100 X	$\frac{0.8}{X-0.2}$	tK	Time Required*, minutes (t)
100%	1.00	0.00	0
90	1.14	0.13	1.3
80	1.33	0.29	2.9
70	1.60	0.47	4.7
60	2.00	0.69	6.9
50	2.67	1.0	10
40	4.00	1.4	14
30	8.00	2.1	21
25	16.00	2.8	28

* Assuming K = 0.1 air change per minute.

These values have been plotted as a graph in Figure 6, to show how quickly the relative humidity of a room can be reduced. In our case, 100 cfm of compressed air was released for 20 minutes in a room volume of 1000 cu. ft. Even though the released air at that time had a relative humidity of 25 to 30%, instead of 20%, it reduced room relative humidities from 60-70% to 35%. The automobile muffler (Item 6 in Figure 1) proved invaluable in keeping noise levels tolerable during this operation.

The room humidity was first reduced for a period of 20 minutes. It was then increased in steps of 5% relative humidity by feeding a water spray into a 12-in. high-capacity electric fan. The fan kept the room air in motion and thus reasonably uniform. The temperature of the room was manually controlled with electric heaters. The temperature of the compressed air was controlled by circulating hot or cold water in the final heat exchanger.

When the relative humidity of the room was increased, the resistance of the column of prills dropped quickly to the equilibrium value. The reverse process of building up resistance when the humidity dropped occupied about fifteen minutes. The postulated layer of moisture thus forms very quickly to a thickness dependent upon the ambient relative humidity. In contrast, the removal of this layer by dry air takes a relatively long time.

The measurement of resistance in the column of prills was therefore always made when the relative humidity of the room was being increased. The results are shown in detail in Table 2 along with calculations of the logarithm of the resistance, and also this value multiplied by the humidity fraction.

The relative humidities of the air passing through this column of AN prills were all below the critical one of 62% required for the deliquescence of ammonium nitrate at 75°F. Nevertheless, contrary to expectations, the resistance decreased gradually over the range 37-56%. The inverse relationship between the logarithm of the resistance and the relative humidity is apparent and by inspection of the above table one can write:

$$\log R = \frac{4.5}{H_r},$$

where R = resistance of the column of prills;

H_r = relative humidity of air drawn through the prills, expressed as a fraction rather than as a percentage;

and 4.5 = average value of $H_r \log R$.

TABLE 2

Electrical Resistance of AN Prills at 75°F

(Column, 30 cm. x 2 cm. dia.)

Relative Humidity H_r (Fraction)	Resistance R = ohms	log R	H_r log R
0.37	3.6×10^{11}	11.6	4.3
0.38	1.6×10^{11}	11.2	4.3
0.39	8.0×10^{10}	10.9	4.3
0.40	4.0×10^{10}	10.6	4.3
0.43	2.5×10^{10}	10.3	4.4
0.45	1.2×10^{10}	10.1	4.5
0.46	8.5×10^{9}	9.9	4.6
0.47	5.2×10^{9}	9.7	4.6
0.49	2.2×10^{9}	9.3	4.5
0.50	1.4×10^{9}	9.1	4.5
0.52	7.0×10^{8}	8.8	4.6
0.52.5	4.5×10^{8}	8.7	4.6
0.55	1.9×10^{8}	8.3	4.5
0.56	1.0×10^{8}	8.0	4.5

TABLE 3

Variation of Loader Voltages with the Relative Humidity of Air Entering Hoppers

(Grand average value of H_r log V = 1.55 with Sigma = 0.13)

	Relative Humidity H_r (Fraction)	Loader Volts V	log V	H_r log V	Sigma
CIL Anoloder with AN Prills at 72°F	0.40	12,000	4.1	1.6	
	0.46	10,000	4.0	1.8	
	0.48	7,000	3.8	1.8	
	0.49	4,500	3.65	1.8	
	0.64	250	2.4	1.5	
	0.77	75	1.9	1.5	
			Average	1.7	0.17
CIL Anoloder with AN Prills at 80°F	0.38	20,000	4.3	1.6	
	0.41	11,500	4.1	1.7	
	0.45	6,500	3.8	1.7	
	0.48	3,500	3.5	1.7	
	0.57	700	2.8	1.6	
	0.63	150	2.2	1.4	
	0.74	75	1.9	1.4	
			Average	1.6	0.13
CIL Anoloder with Amex at 68°F	0.39	6,000	3.8	1.5	
	0.43	3,000	3.5	1.5	
	0.50	1,500	3.2	1.6	
	0.54	1,000	3.0	1.6	
	0.56	350	2.6	1.5	
	0.58	200	2.3	1.4	
	0.71	75	1.9	1.4	
	0.74	—	—		
			Average	1.5	0.08
CIL Anoloder with Nilite at 65°F	0.34	12,500	4.1	1.4	
	0.39	10,000	4.0	1.6	
	0.44	4,000	3.6	1.6	
	0.48	2,500	3.4	1.6	
	0.52	750	2.9	1.5	
	0.56	200	2.3	1.3	
	0.63	75	1.9	1.2	
			Average	1.5	0.11

(Continued -

TABLE 3 (Continued)

	Relative Humidity H_r (Fraction)	Loader Volts V	log V	H_r log V	Sigma
CIL Anoloder with "Anti Static" AN/FO at 75°F	0.37	13,000	4.1	1.5	
	0.41	7,000	3.8	1.6	
	0.44	3,000	3.5	1.5	
	0.54	800	2.9	1.6	
	0.63	150	2.2	1.4	
			Average	1.5	0.09
duPont Loader with AN Prills at 75°F	0.31	25,000	4.4	1.4	
	0.37	17,500	4.2	1.6	
	0.47	7,000	3.8	1.8	
	0.58	1,300	3.1	1.8	
	0.69	200	2.3	1.6	
			Average	1.6	0.14
duPont Loader with AN Prills at 86°F	0.30	23,000	4.4	1.3	
	0.33	11,000	4.1	1.4	
	0.48	1,500	3.2	1.5	
	0.51	700	2.9	1.5	
	0.60	300	2.5	1.5	
	0.63	200	2.3	1.5	
			Average	1.5	0.08
duPont Loader with Amex at 74°F	0.32	23,000	4.4	1.4	
	0.39	12,500	4.1	1.6	
	0.46	5,000	3.7	1.7	
	0.52	800	2.9	1.5	
	0.59	200	2.3	1.4	
			Average	1.5	0.11

(Concluded -

TABLE 3 (Concluded)

	Relative Humidity H_r (Fraction)	Loader Volts V	log V	H_r log V	Sigma
duPont Loader with Nilite at 77°F	0.33	20,000	4.3	1.4	
	0.39	10,000	4.0	1.6	
	0.45	1,500	3.2	1.4	
	0.50	700	2.8	1.4	
	0.58	400	2.6	1.5	
			Average	1.5	0.10
Stanrock Loader with AN Prills at 79°F	0.39	12,000	4.1	1.6	
	0.42	7,500	3.9	1.6	
	0.45	4,000	3.6	1.6	
	0.48	3,000	3.5	1.7	
	0.54	1,500	3.2	1.7	
	0.63	500	2.7	1.7	
	0.67	200	2.3	1.5	
			Average	1.6	0.08
Stanrock Loader with Amex at 80°F	0.42	6,500	3.8	1.6	
	0.46	3,000	3.5	1.6	
	0.52	1,500	3.2	1.7	
	0.60	400	2.6	1.6	
			Average	1.6	—
Stanrock Loader with Nilite at 75°F	0.39	12,500	4.1	1.6	
	0.43	8,500	3.9	1.7	
	0.49	2,500	3.4	1.6	
	0.62	250	2.4	1.5	
			Average	1.6	—

At relative humidities lower than the critical one for deliquescence, it was to have been expected that moisture films, if present on the surface of ammonium nitrate crystals, would dry out. In that case the resistance of a column of crystals would increase indefinitely to the dry value. Since this is not borne out by the values of the resistances in Table 2, such a tendency must be counteracted by the adsorption of water on the surface of the ammonium nitrate.

At any one relative humidity there is established an equilibrium which maintains films of solution varying from monomolecular thicknesses upward. The equilibrium is established almost immediately when approached from the dry state but takes longer when approached from the opposite direction.

This time lag in the drying out of moisture films on the AN prills is very important in the consideration of static-electricity generation. For instance, if the prills are moved from a high-humidity equilibrium state in a loader hopper to the low-humidity condition of the mixed air in the loader tube, over a period of one to five seconds, the high-humidity equilibrium still applies because the moisture film has not had time to dry out.

On the other hand, the moisture film must have been deposited within a period of some minutes prior to the test. AN prills and AN/FO are sometimes bagged in humid weather, but no sample of AN prills or AN/FO taken from sealed containers has ever failed to produce static electricity when other conditions were favourable. It is assumed that, if the moisture layer is not replenished at a critically slow rate from surrounding air, moisture from films of limited thickness will migrate into the interior of the prill.

The thickness of the equilibrium films is not known from the resistance measurements results that were shown in Table 2, but when the relative humidity had risen to 56% the resistance of the column was only 100 megohms but to the naked eye the prills appeared perfectly dry. The films are thus so thin that it is difficult to picture a model that will predict their physical properties. Also, although the resistance measurements applied only to a specific column of prills, it appeared that a relative humidity over 56% at 75°F would be necessary to produce an equilibrium film of moisture with an electrical resistance low enough to seriously interfere with static-electricity generation.

It has previously been shown that the only air body associated with jet loaders with a possible humidity above 30% was the loading room air. Consequently, the relative humidity of our loading room was again deliberately altered, by alternately drying the room with compressed air and then increasing the humidity gradually with water sprays. At discrete relative humidity levels, voltage measurements were taken at the loading hose connections during the operation of the three jet loaders. Special care was taken to approach the humidity equilibrium from the low side.

Correlation of the produced voltages with the relative humidity of the loading room revealed an inverse logarithmic relationship similar to the one found applicable to the resistance measured in the U-tube. This relationship was tested with all three loaders, using AN prills, and also commercial AN/FO mixtures such as CIL Amex and duPont Nilite, at various loading room temperatures from 68 to 86°F. It was also tested with a trial AN/FO mixture reputed to be an "anti-static" one.

No exceptions to the logarithmic relationship were found. The standard deviation of the product of the relative humidity fraction and the logarithm of the loader voltage was 0.13. This corresponds to a relative humidity error of ± 2% at 35% and ± 4% at 70%, which are error values to be expected from wet-and dry-bulb thermometers. Detailed results are shown in Table 3, and the average voltages corresponding to various relative humidities are plotted as a graph in Fig. 7.

The relationship shown in Table 3 between static-electricity generation and relative humidity is a normal one for all static-electricity generating systems of the solid-solid type. For instance, the generation of electric shocks by personnel walking on rugs to a ground connection occurs only when ambient relative humidities are low. On the other hand, intermittent occurrences of high loader voltages continued to be found in tunnels underground. Relative humidities there are nearly always over 80%. Seepage of ground waters leaves most rock surfaces wet. Consequently, even if dry air is fed into the ventilation system of a mine, humidities tend to approach 100% as air descends into the mine.

Table 4 shows a series of mine-air temperatures and relative humidities measured by M.A. Twidale* during February 1963, when surface temperatures were -5°F and relative humidities above ground averaged 70%.

These relative humidities are, of course, too high to permit static generation in the loaders when the hoppers are exposed to them. In fact, no appearances of static were reported by Twidale during his visit to the above mines at that time. Sporadic static voltages were still being noted, but they could not be exhibited as required. The only explanation possible appears to be that on occasion the air of a jet loading area becomes dry. The most probable cause would seem to be the use of ventilation by compressed air in blind headings. Our method of reducing humidities in our loading room illustrates the efficiency, for humidity reduction, of the release of compressed air in a confined space.

TABLE 4*

Underground Mine Air Conditions As Measured
by M.A. Twidale, February 1963
(Surface Air: Temp. -5°F, R.H. 70%)

		Temperature, °F	Relative Humidity, %
Hollinger:	950' level	50	93
Falconbridge East:	2950' level	55	87
	3000' level	65	73
	3300' level	62	87
Creighton	1600' level	50	85
Milliken Lake	----	63	85

* Contributed by M.A. Twidale, Senior Metalliferous Mining Engineer, Mining Practice Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, May 1964.

Whether or not this is the mechanism of humidity reduction, it can be asserted that a third method for control of static electricity voltages in the loaders has been found, in that it is only necessary to avoid low humidities in loading rooms of mines to eliminate high voltages in short hole loaders with open hoppers.

GENERAL DISCUSSION AND APPLICATION

Ammonium nitrate jet loaders are an example of solid-solid static electricity generators in which both solids are exposed to the air. As is usually expected with this type of generator, the presence of significant voltages depends upon the absence of leakage paths, such as may be provided through films of water. When one of the solids is ammonium nitrate, the film of moisture provides efficient leakage paths at relative humidities higher than 60%. With lower humidities this film may be lost by evaporation of water from it or by the migration of the water throughout the interior of the prill. Both processes appear to occupy periods longer than five minutes if the change of humidity has been more than five per cent. Consequently, ammonium nitrate prills, when acting as part of a static-electricity generator, behave according to the equilibrium of the highest humidity to which they were exposed during the five minutes preceding the test.

The amount of water vapour necessary for saturation of a given volume of air changes very little with pressure. Consequently, when air with a relative humidity as low as 17% is compressed to 6 atmospheres and cooled to its original temperature, its relative humidity then becomes 6 x 17% ≈ 100%. Excesses above the amount necessary for saturation are deposited and collected in water traps. Unless the air is reheated, it arrives at the loader site saturated with water vapour. However, assuming that the compressed air and the loader are at the temperature of the operating site, the relative humidity of the air will drop to a theoretical 17% upon release to atmospheric pressure. At this point it presents an atmosphere favourable for production of static in the loader, provided the incoming prills are free of moisture films.

Because of underground waters the relative humidity of the free air in mines is normally above 80%. Special conditions of ventilation are required to reduce this percentage to below 40 to 50%. The most probable condition would appear to exist in a blind heading which has been ventilated by the release of compressed air. It has been shown that it is possible to reduce humidities to 20% by such a method.

This postulated reduction in humidity becomes important when short hole loaders are operated, because this air passes into the jet along with the prills from the loader hopper. Normally it is of high humidity and deposits moisture on the prills which is not removed by the dry released air of the jet in time to produce high voltages in the loader. Thus, high short hole loader voltages can be avoided if loading operations are not scheduled for times when mine relative humidities are unusually low.

The hoppers of long hole loaders are not affected by prevailing room humidities. The hopper is filled with prills and closed, and then compressed air is admitted. This air has a relative humidity of 100% and deposits a film of moisture on the contents of the hopper. However, the loading operation in this case is a lengthy procedure and the moisture film has time to migrate into the interior of the prill. Once this has occurred, the generation of static electricity in the loading hoses becomes possible. Very high voltages have been reported. The remedy in such cases would appear to be to place the compressed air inlet to the hopper at the exit point for prills. Then a small air bleed at another point in the hopper would ensure that the moist compressed air continuously deposits a moisture film on the prills leaving the hopper and flowing into the inlet tube. This method would be effective only if hopper pressure was maintained between 60 and 100% of the compressed air supply pressure, thus maintaining the relative humidity of air released in the hopper above 60%.

Freshly drilled boreholes are flushed with water to clear them of drilling chips, thus keeping the interior of the holes damp. Under such conditions, a circuit between two drill holes in quartz has a resistance value of less than 100 megohms (4). This value of resistance will not isolate high voltages arising in loaders, because of the small currents involved. The generation of voltages in boreholes is therefore, as a rule, not to be expected.

This argument does not apply, however, when plastic insulating hole liners are used. If one of these holes should be filled with prills without a moisture film, it could become in effect a second static generator and the contents of the hole liner could become highly charged. If naturally-existing insulated boreholes are encountered a similar reasoning applies, but in this case the two contacting solids of the static generator will be prills and rock instead of prills and plastic.

The prills constitute the common factor in any generating system that may be operating in the compressed-air stream of ammonium nitrate loaders. Thus, all these generating systems fail to produce high voltages when the prills are provided with moisture films. In the case of short hole loaders, this avoidance of high voltages can be arranged by scheduling loading operations to take place during periods of high relative humidity in the loading area of the mine. In the case of long hole loaders, alterations to the pressure hoppers to provide an air bleed will be necessary.

However, other methods have been suggested. The provision of conductive hoses will eliminate high hose voltages, assuming the hose is properly grounded. The hoses will not prevent the accumulation of electrical charges in boreholes but these changes will not build up to a serious level unless the resistance through them to ground becomes higher than 100 megohms.

If, for any reason, further precautions are required, the use of a safety fuse having a conductive covering is to be recommended. This covering shunts electricity away from the core of the fuse and prevents operation of ordinary blasting caps by the mechanism described in the quotation from Dyment in the Introduction. This type of fuse is available from the Canadian Safety Fuse Company Limited, under the trade name of "Static-Safe" safety fuse.

In this connection it should be mentioned that no mining authority of any province in Canada approves the use of electric blasting caps in bottom-primed AN/FO boreholes.

In conclusion, it can be stated that, although the electrical generator mechanism operating in a loader hose cannot be fully explained, it is now possible to eliminate high voltages in ammonium nitrate loaders or, alternatively, to minimize the hazards associated with them.

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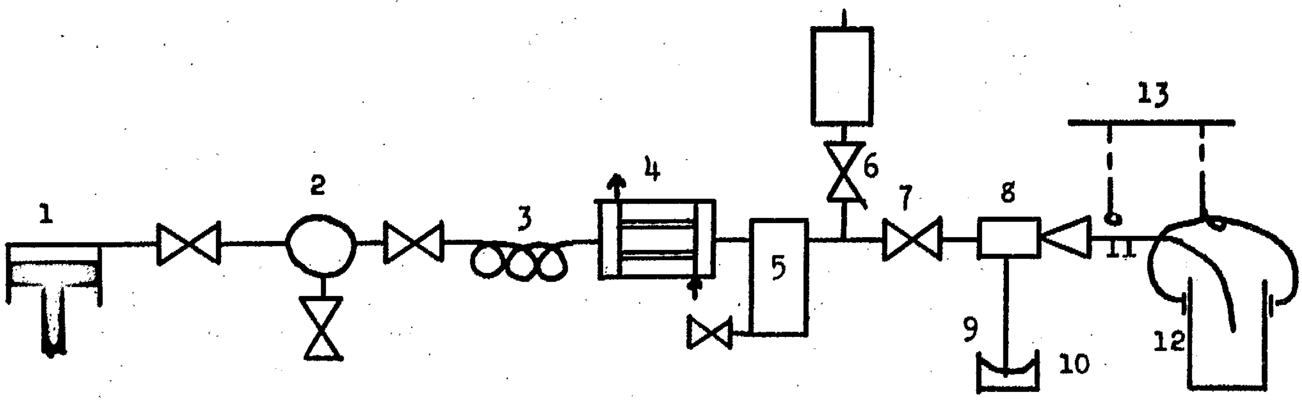
JAD:DABS:(PES):gdb



(1) Air compressor, 150 cfm
(2) Receiver
(3) Heat exchanger, 120 ft of 1 1/2" pipe
outside air cooled
(4) Heat exchanger, liquid gas type, used to
adjust air to room temperature
(5) Water trap
(6) Air bleed valve with muffler
(7) Quick action valve
(8) Loader injector insulated for 30 kv
(9) AN/FO hopper
(10) Secondary air from atmosphere
(11) Plastic loading hose, insulated for 30 kv
(12) Garbage can, serving as insulated borehole
(13) Supports for loader

Figure 1. Sketch of Experimental Jet Loader.

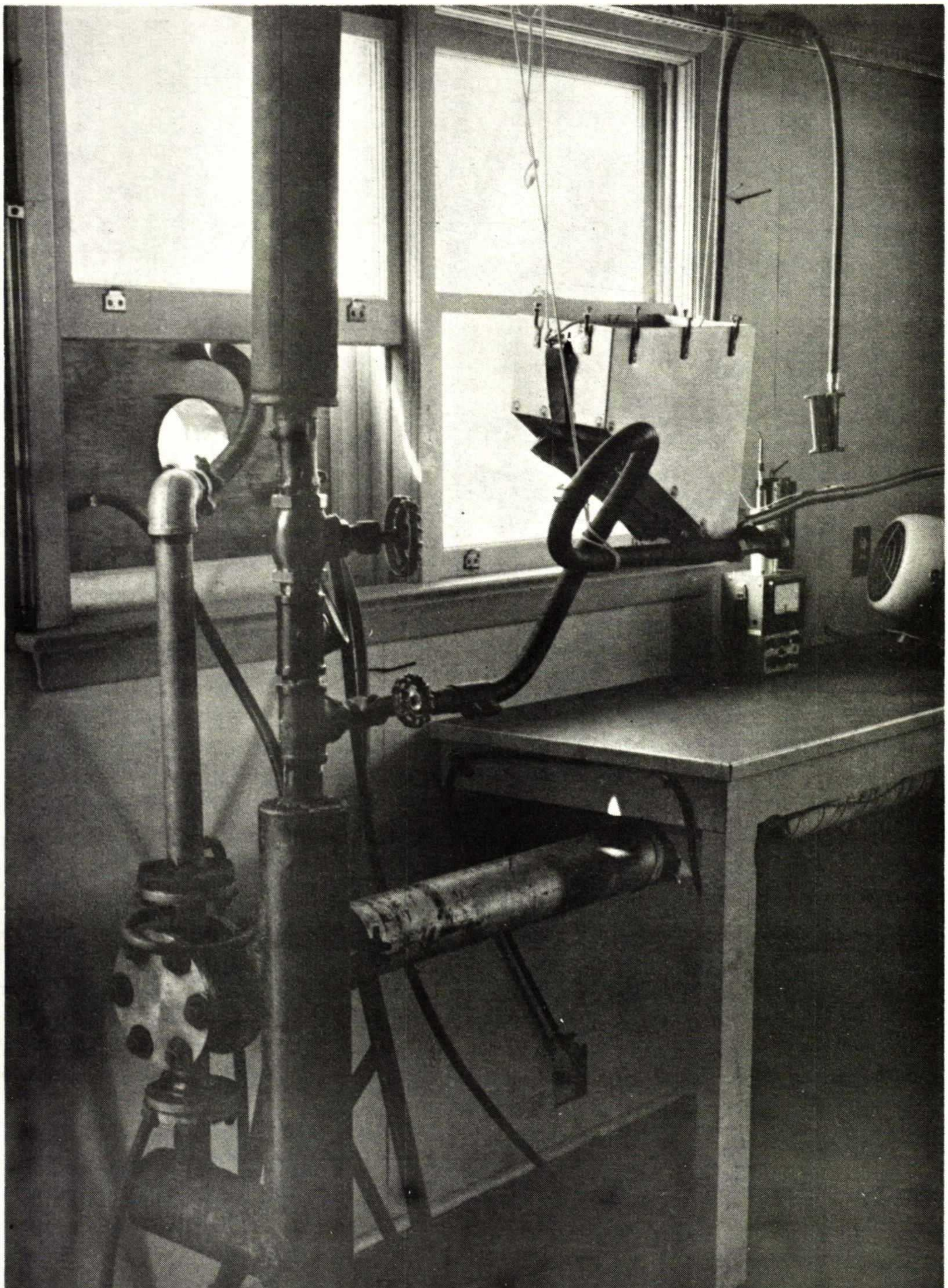


Figure 2. Loading Room.

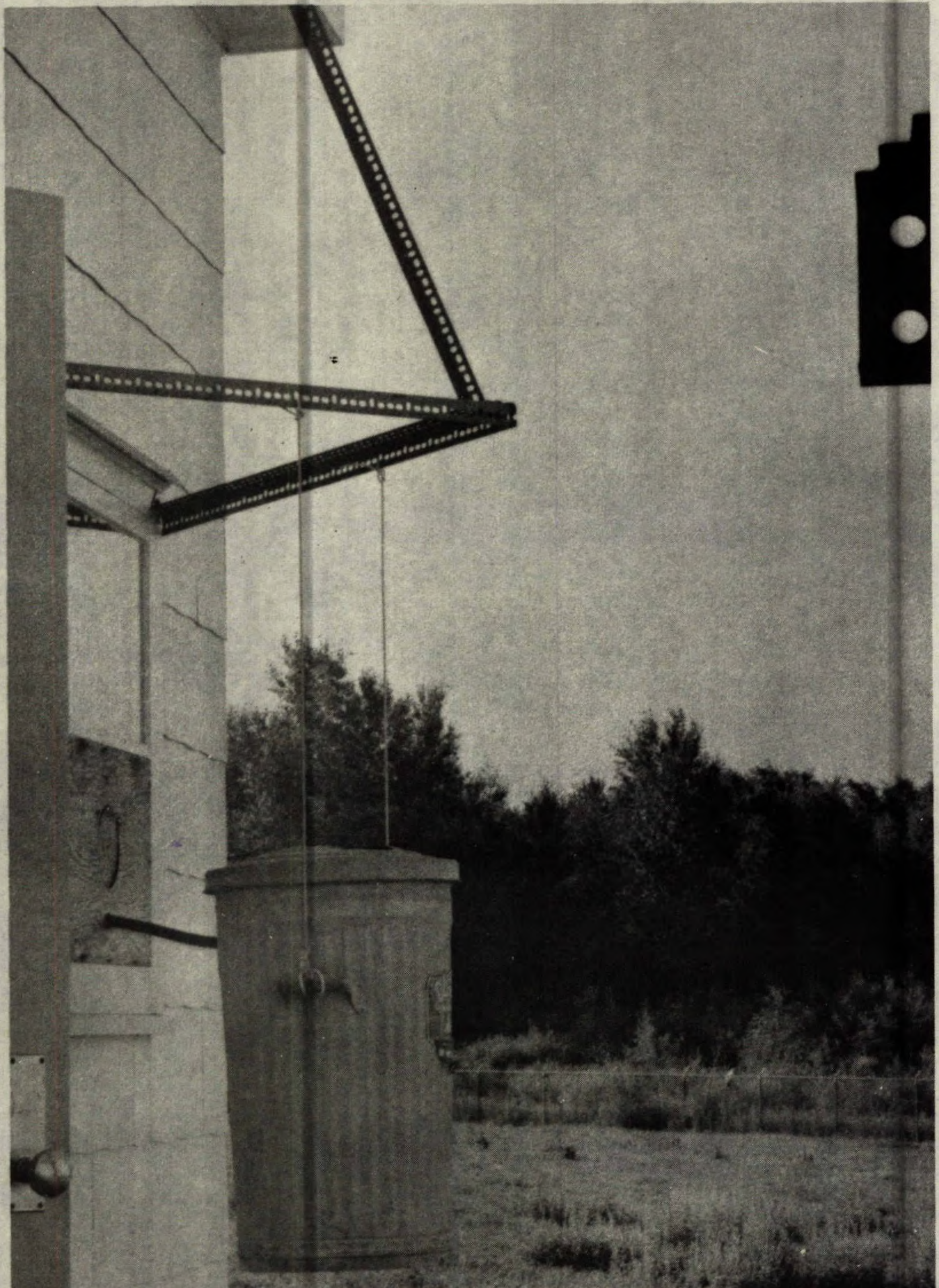


Figure 3. AN/FO Collector.

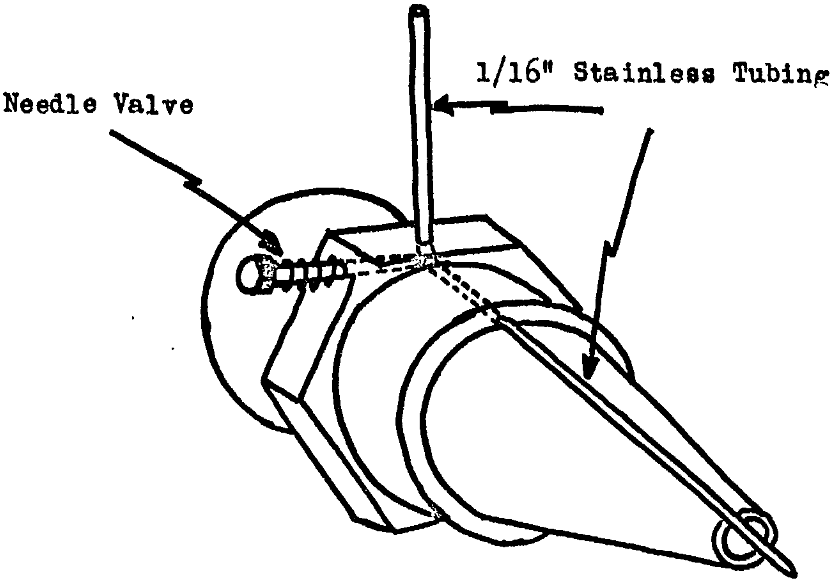


Figure 4. Sketch Showing Alterations to the Compressed Air Outlet of a Pemberthy 63A Injector.

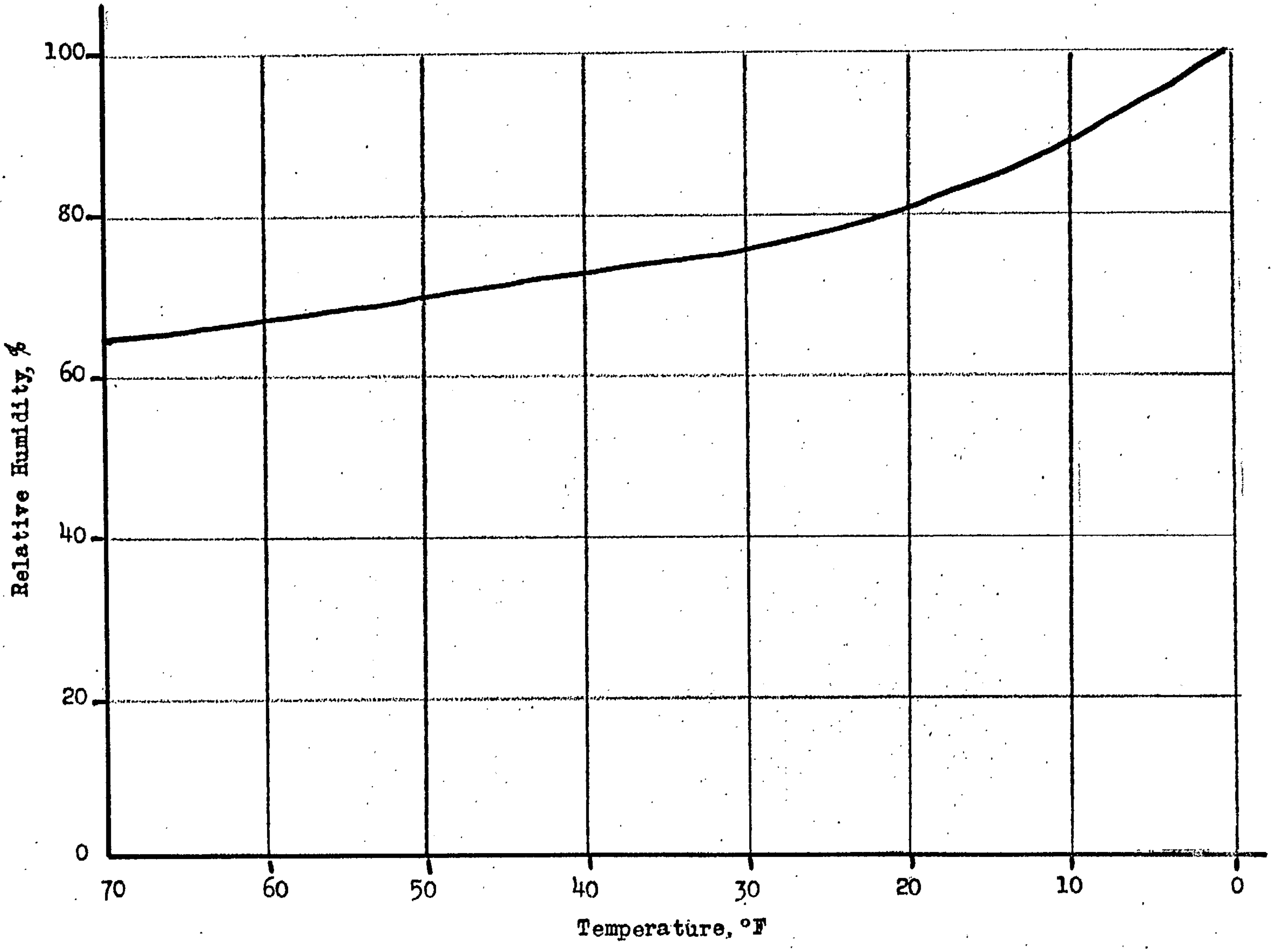


Figure 5. Critical Relative Humidity for the Deliquescence of Ammonium Nitrate.

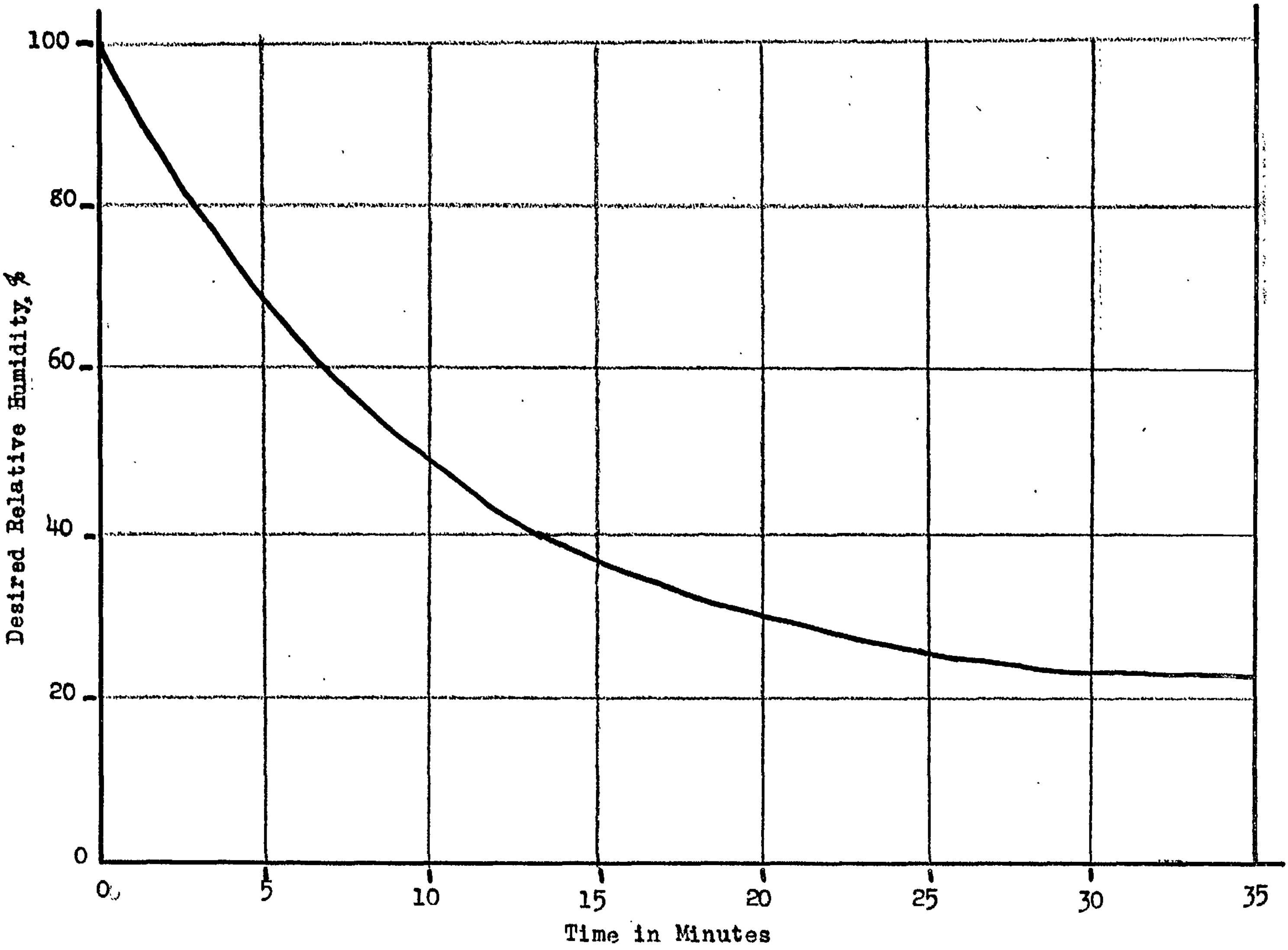


Figure 6. The Time required to reduce the Room Relative Humidity from 100% to a given Value by the Release of 0.1 Air Changes per Minute of Air with a Relative Humidity of 20%.

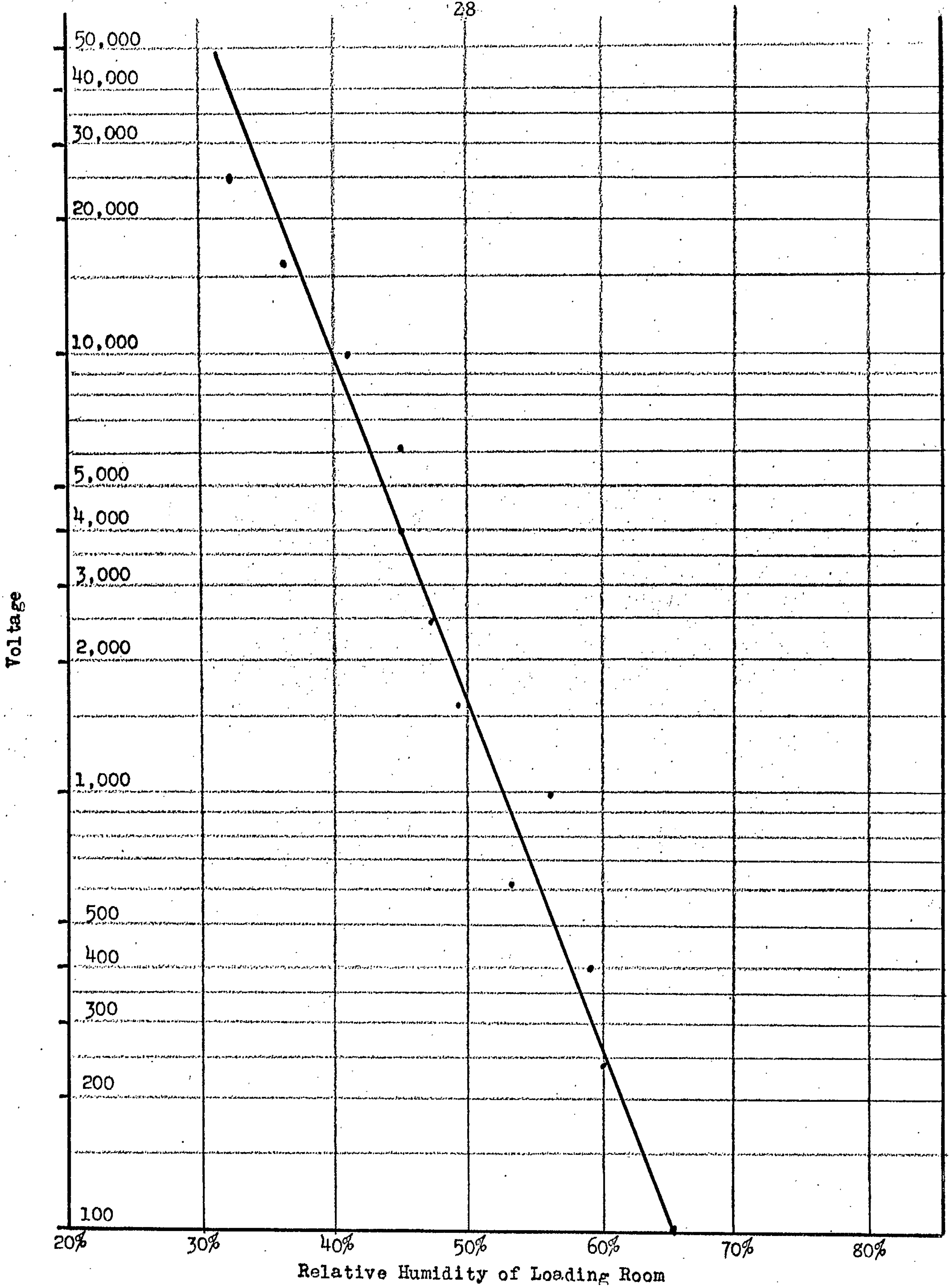


Figure 7. The Magnitude of Voltages Generated in AN Jet Loader Hoses at Various Loading Room Humidities Within a Temperature Range of 68°F to 86°F.