STATIC ELECTRICITY

GENERATED DURING THE DISTRIBUTION OF GASOLENE

Thesis by

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SUMMARY

This research project was undertaken to determine the exact hazard represented by static electricity when it is generated during the distribution of gasolene. "Equivalent electrical circuits" have been utilized which, with the knowledge of the magnitudes of charge developed under different conditions, enable one to predict the voltages that will be present and the subsequent chances of sparks occurring and possible fires or explosions resulting.

The amount of charge developed when gasolenes are pumped through pipes has been measured, and several factors influencing the magnitude of this charge have been determined. The problem of "tire static" was investigated, and the general order of magnitude of currents generated by trucks or other rubber-tired vehicles in motion, has been established.

A series of experiments was made in an attempt to determine the amount of energy needed in a spark, caused by a condenser discharge, to ignite a combustible mixture of gasolene and air. It was found that relatively small amounts of resistance in series with a spark gap may, in certain cases completely eliminate the ability of a spark to ignite gasolene vapors. There is apparently a minimum wattage required to ignite combustible mixtures.

All the measurements and analyses indicate that the precautions commonly practiced in the petroleum industry are more than adequate to eliminate all the hazard of fire or explosion due to static electricity.

INTRODUCTION

Static electricity long has been recognized as a hazard in many industries. Petroleum processing and distribution plants, grain elevators, dry-cleaning plants, and mines are some of the industries that often must take elaborate precautions against the possibility of static charges accumulating. Every now and then "mysterious" fires are encountered in operating rooms, explosives plants and in the above-mentioned industries that apparently are explainable only by a static electricity spark.

Of course, it is almost impossible to get direct evidence that will attribute any particular fire or explosion to a static spark. This is due to the fact that the spark and resulting flame or explosion occur virtually simultaneously. In case of a fire due to a match or a welding spark, it is a simple matter to correlate a resulting conflagration with the cause. But no witness can say truthfully, "I saw (or heard) a spark jump, and a couple of seconds (or a half-second) later I saw flames shooting out". All evidence that points to static electricity as a fire source must be purely circumstantial. Despite this fact, many fires have occurred, the only possible cause of which could have been a static spark.

Figure 1, which is a chart of static fires and relative humidity over a year's period, indicates that in general, there has been a great degree of justification for attributing fires to static electricity. During times of low humidity, surface resistances of semi-conductors or insulators are large, and static charges may accumulate much more readily than during the months when relative humidity is high, and leakage paths to ground are more easily established. It is seen from this chart that

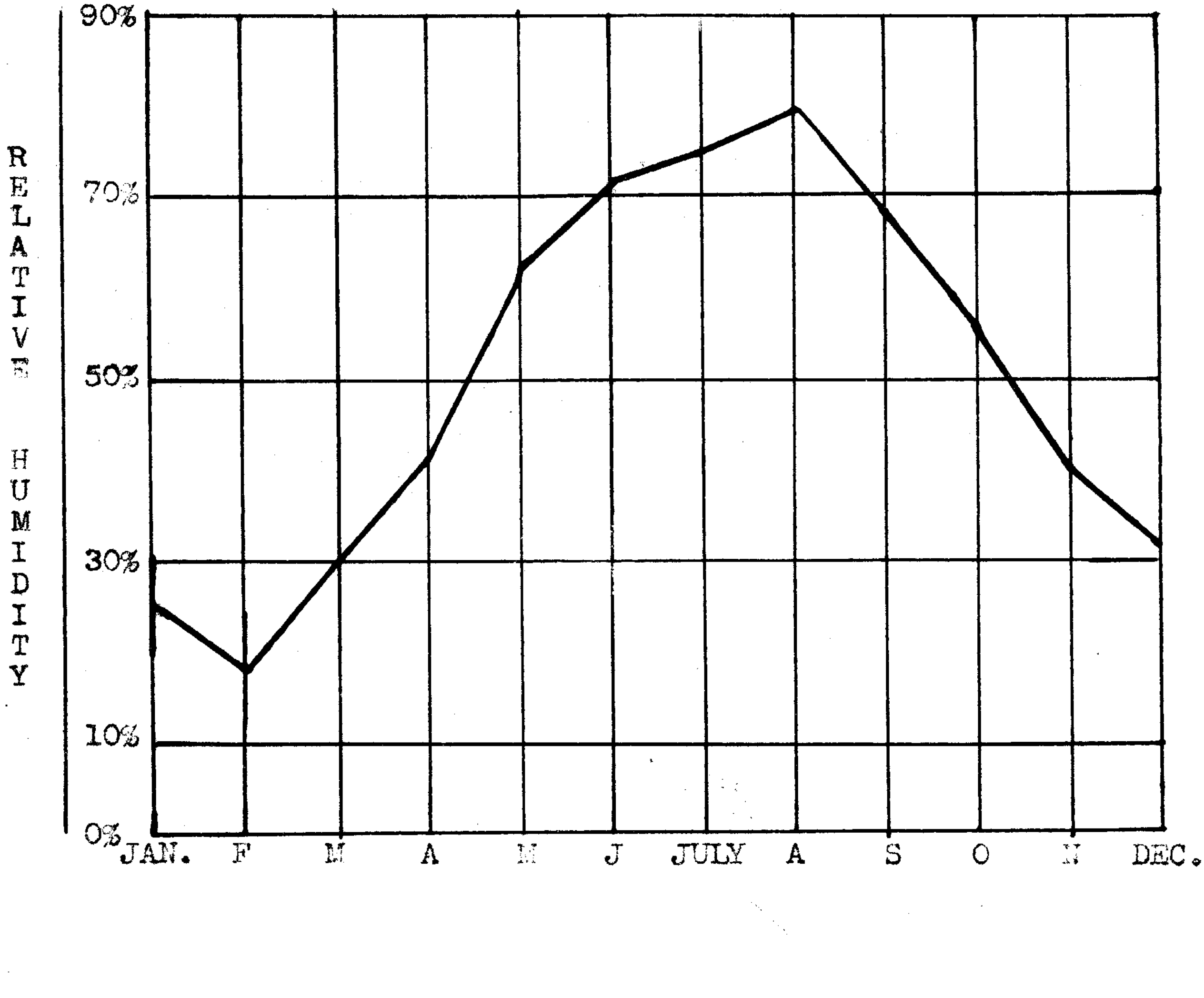

chart prepared by E.E. Turkington for a paper entitled "Static Electricity as a Fire Cause", presented to the National Fire Prevention Assoc., May 9, 1934

Fig. 1

the greatest number of fires was attributed to static electricity when the relative humidity was the lowest, i.e., in February. In August, when relative humidity was the highest, the least number of static fires was reported.

Accordingly, since static electricity is a source of danger, efforts are continually being made to eliminate the hazard. In almost all industries troubled by static, this is done by systems of bonding and grounding. It is obvious that if two conductors are connected together by a conducting wire, no difference of potential can exist between the two due to any steady electric fields or free static charges, Thus, if a tank truck is being filled through its dome by means of a metal pipe extending part-way down into the truck, the simple expedient of connecting the pipe and truck by means of a wire will obviate the possibility of a spark occurring between the two pieces of metal, no matter how much current may flow to the truck due to the gasolene-filling process. Furthermore, grounding either the truck or the filling pipe to a water-pipe, or some other good "ground", will eliminate the possibility of any charge accumulating on the system.

Thus, the two systems of protection, when properly employed, are quite adequate to prevent static-electricity sparks. Bonding prevents voltages from existing between adjacent conductors, and grounding prevents charges from accumulating on any conductor.

The problem now arises: What hazard due to static electricity is prevalent if these simple precautinns are not taken?

The analysis of this problem is reduced to two parts. The first part is the determination of the amount of static electricity generated under different conditions. If we know the quantity of charge generated, subsequent electrical conditions of different parts of the system may be predicted. Secondly, it is necessary to know the characteristics a spark must have to ignite a combustible mixture of gasolene and air. It is a simple matter to determine whether a charged gasolene truck, or a charged body of any kind, can store up enough energy to furnish the spark intensity necessary for ignition, in case a spark should occur.

EXPERIMENTAL PROCEDURE AND APPARATUS

Very little previous work has been done in an attempt to solve static electricity problems quantitatively. Those who have worked in the field, have used a method of approach that never yielded consistent or satisfactory results. All previous investigators have measured voltages generated by the various processes that produce static electricity, be it gasolene flowing through pipes, grain discharged from a conveyor belt, or dust blown through long conduits. Probably the main reason why these experimenters investigated voltages, rather than currents, is that most of us are inclined to think of measuring or detecting static charges by means of electrometers, or other devices that are essentially electrostatic voltmeters. However, if static charges are produced continuously by some process, a sensitive ammeter can readily determine the exact amount of charge being produced.

Because of this, those who attempted to measure voltages got very erratic results, since, if a continuous current is being produced, the voltage will be determined, once a steady state is attained, by the amount of current generated, and the resistance to ground. Thus, on a dry day, very high voltages might be attained with little difficulty, while if it happened to rain the next day, the investigator would discover no voltages, and possibly come to the conclusion that no charges were being developed. The experiments conducted in this investigation clearly indicated that the same amount of current is generated at all times, no matter what the external atmospheric conditions may be.

Accordingly, all of the experiments conducted during the course of this project consisted of the measurement of currents generated under various conditions of pumping and flow of gasolene. In the investigation of "tire static", currents generated were also measured.

Dr. J. M. Pearson*, who is investigating the problem of static electricity in agitator tanks, indicated that currents of the order of magnitude of 10^{-10} amps. should be anticipated. A d.c. meter had to be designed and constructed, which would measure such small currents with a fair degree of accuracy, but which would, nonetheless, be portable, rugged, free from external influences, and maintain its calibration for at least a full day. This latter restriction was desirable because measurements often were made at gasolene pumping stations far from the Institute, where no electrical facilities were available. It was not considered desirable to incorporate a calibration circuit into the meter, because compactness and light weight were essential.

The relatively new 1S4 and 1S5 tubes, used in commercial "pocket" radios, made it feasible to construct a compact meter with high gain. These tubes may be operated with a plate voltage of approximately 45 volts, so a single 90-volt battery could be used for plate supply, and still yield two-stage amplification. The filaments operate on $1\frac{1}{2}$ volts, thus reducing the size of the "A" supply considerably.

A two stage amplifier, with push-pull arrangement in both stages, and with direct coupling between the stages, was built. The circuit employed is illustrated in Figure 2. This circuit is a modification of the one employed by Goldberg†. It is designed to yield high current gains, without voltage gain, while Goldberg's design was for high voltage gains.

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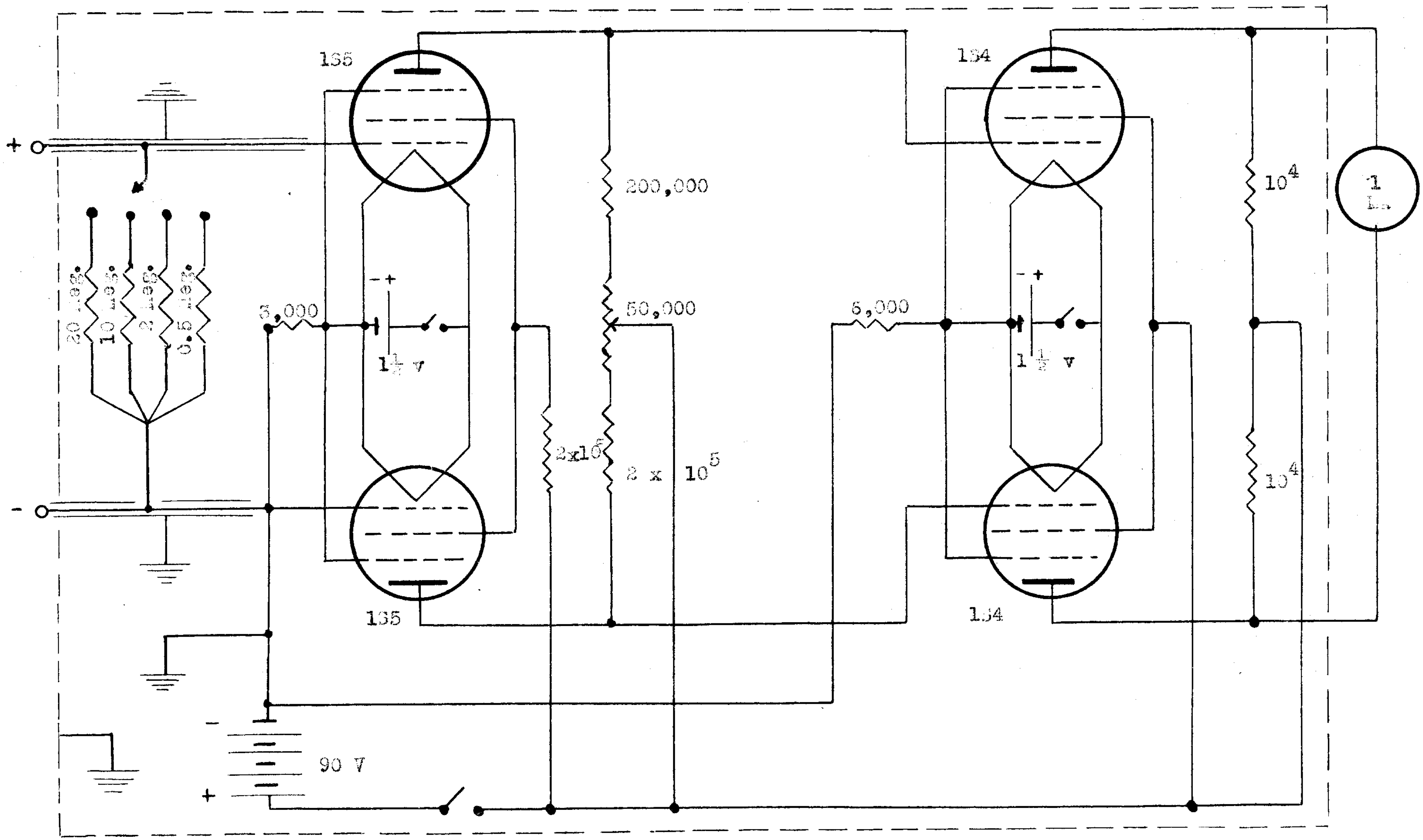
* Ph.D. Calif. Inst. of Tech.. At present Physicist for the Sun Oil Company, Philadelphia.

† Harold Goldberg, "A High Gain D-C Amplifier for Bio-electric Recording", Transactions, A.I.E.E., Jan., 1940, Vol. 59.



Circuit Diagram of Meter Used in Measuring Currents Produced by Flowing Gasolene

Fig. 2

Cathode resistor biasing is employed throughout, thus introducing an inherent large degree of stability. With proper design of the bias resistors, as Goldberg points out, the bias resistor is equivalent to an effective resistance, in the plate circuit, of μR, where μ is the amplification factor of the tube at the operating voltage, and R the value of biasing resistance. Since μ changes only slightly with voltage, the plate current undergoes little change with fluctuations in plate voltage. This same property makes the plate current relatively independent of dynamic plate resistance variations of the tubes, so that aging will not seriously affect the balance or calibration.

Although the control grid in the lower tube is permanently grounded, the biasing resistor makes a balanced push-pull output signal result from an input signal across the upper tube's control grid. Thus, a balanced push-pull signal is applied to the input grids of the second stage. The 1S4 tubes in the second stage are power amplifiers, and are the source of most of the current gain.

In the meter employed throughout the research, a model 421 Triplett 1-milliamp. d.c. meter is used to measure the unbalance output of the final stage. The milliameter has a resistance of about 33 ohms, so an unbalance of about 33 millivolts in the last stage would represent full-scale reading. The device could have been made more sensitive by employing a more sensitive output meter, but this was found unnecessary.

Referring to Figure 2 again, it is seen that the unknown current is sent through a resistance in the grid circuit of the upper tube in the first stage. A selector switch sends this current through one of six

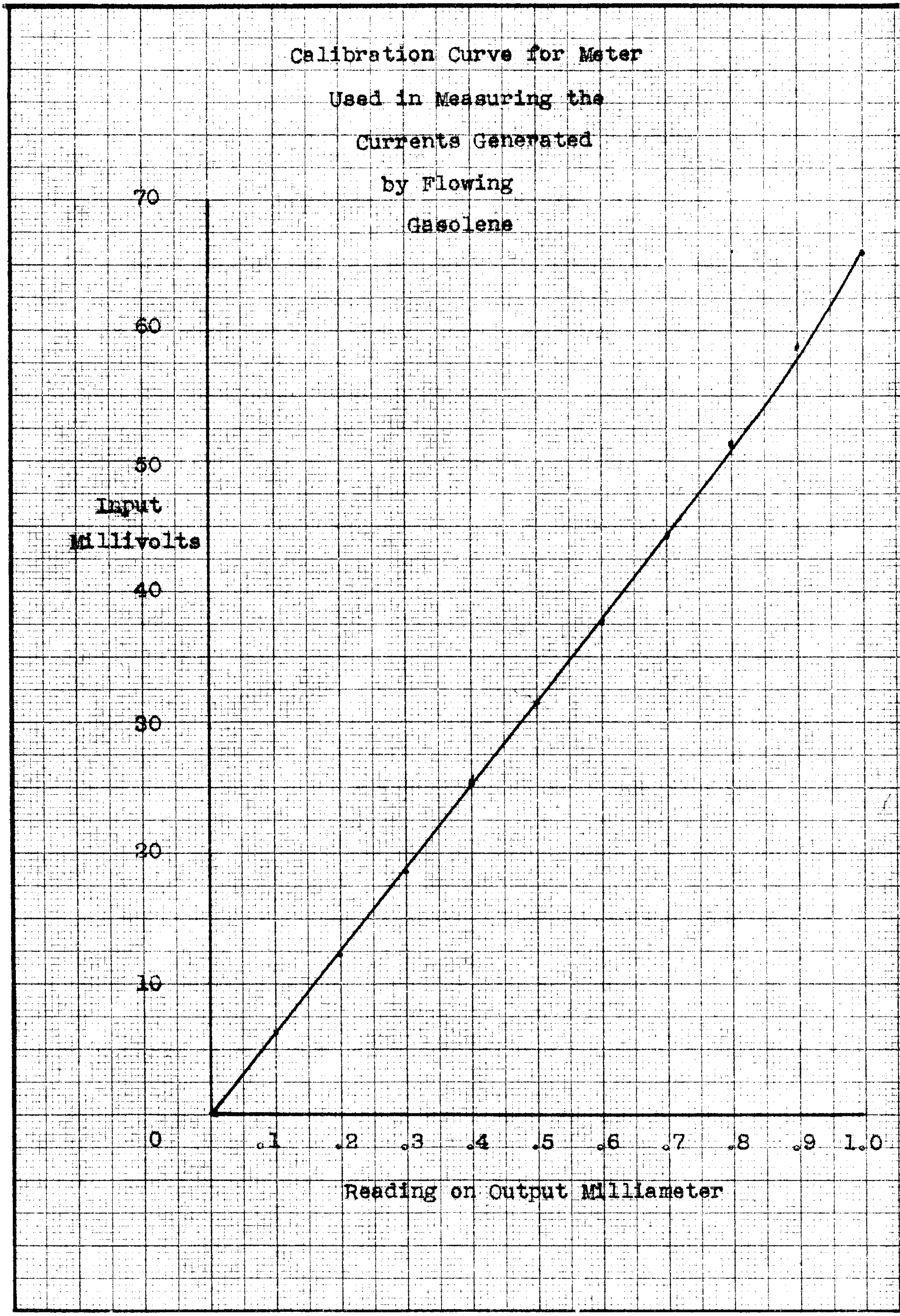

Calibration Curve for Meter
Used in Measuring the
Currents Generated
by Flowing
Gasolene
Input
Millivolts
70
60
50
40
30
20
10
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Reading on Output Milliameter

Fig. 3

resistors (only four of which are illustrated), and thus determines the range of operation.

Figure 3 is a typical calibration curve of the meter. An input voltage on the grid, of approximately 70 millivolts, yields full-scale deflection on the output milliameter. With an input resistance range of 20 megohms to 100,000 ohms, this corresponds to a full-scale reading range of about 30 x 10^{-10} amps. to 0.6 microamps.. Thus, although the voltage amplification is of the order of magnitude of 1/3, the current amplification is of the order of magnitude of 1 million.

Figure 4 is a typical calibration chart, having input volts converted to input amps., for different input resistances.

The meter far exceeded expectations in performance. Even when in use three or four hours daily, it maintains its calibration to within 2 per cent until one of the batteries goes dead. When not in use, its calibration is unchanged over periods greater than one month. A complete replacement of tubes and batteries alters its calibration only 3 per cent.

The warming up period, during which "drift" is perceptible, is only about 6 minutes. After that period, there is virtually no "drift". Any unbalance that may occur is readily balanced out by means of the adjustable resistor in the output of the first stage. This adjuster is always turned until the output meter reads zero before calibrating the meter or before taking readings with it.

This meter is highly recommended for general use as a portable galvanometer. It weighs only 12 pounds, and its over-all dimensions are 10" x 8" x 7". Figure 5 is a photograph of the meter. It could have been made even more compact. Over-all dimensions of 6" x 5" x 5" can

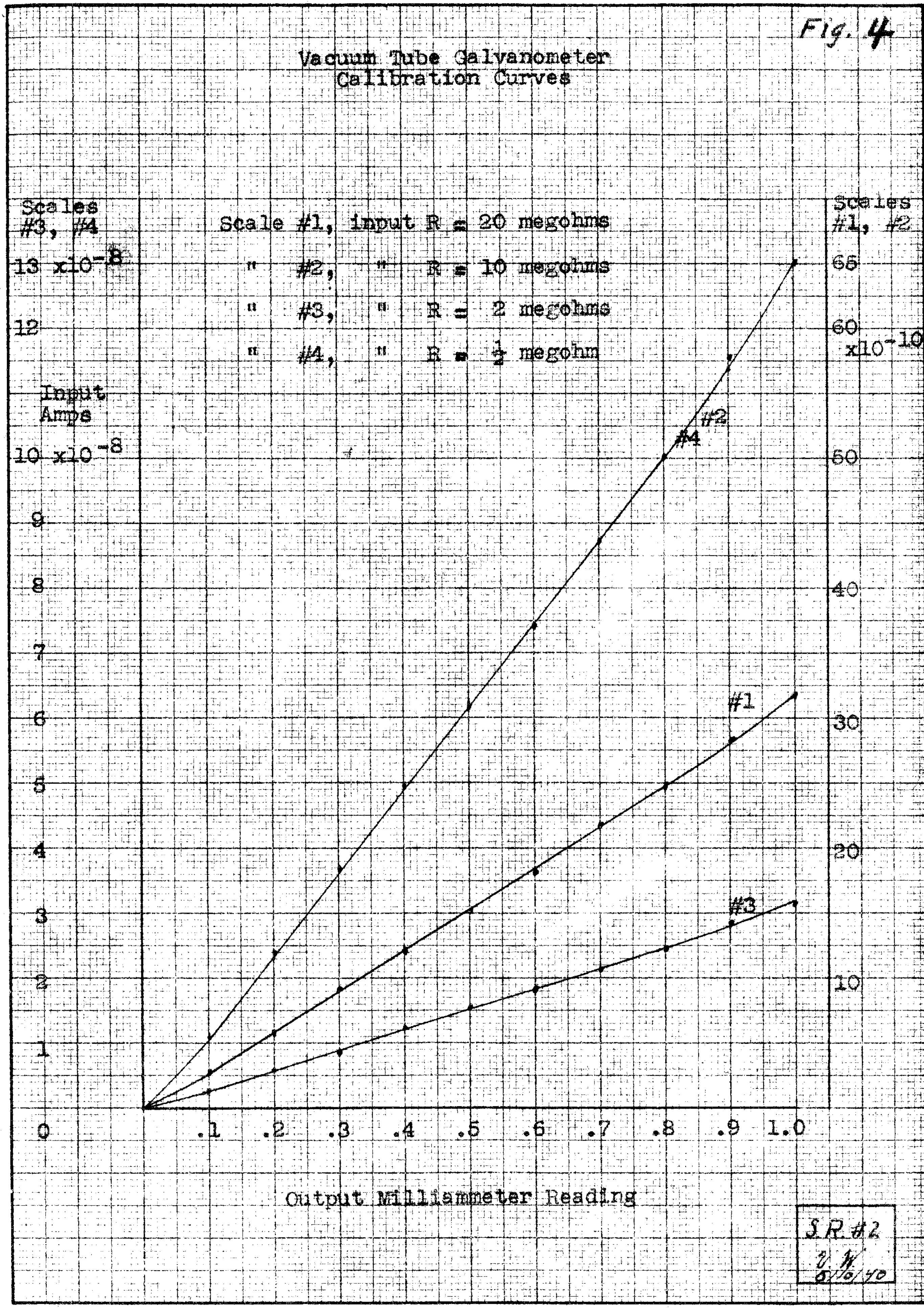


Fig. 4
Vacuum Tube Galvanometer
Calibration Curves
Scales
#3, #4
Scales
#1, #2
Scale #1, input R = 20 megohms
" #2, " R = 10 megohms
" #3, " R = 2 megohms
" #4, " R = ½ megohm
Input
Amps
13 x10^-8
12
10 x10^-8
9
8
7
6
5
4
3
2
1
0
65
60
x10^-10
50
40
30
20
10
#2
#4
#1
#3
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Output Milliammeter Reading
S.R. #2
V. W.
5/10/40

Fig. 4

be obtained with no trouble. With a 12-resistance selector switch, a very wide range of currents may be read with great accuracy, and full-scale reading is obtainable with almost any value of current.

If input resistances much greater than 20 megohms are used, the operation tends to be unstable, and it is difficult to maintain a steady balance. Very careful shielding of input leads is necessary to eliminate external interferences.

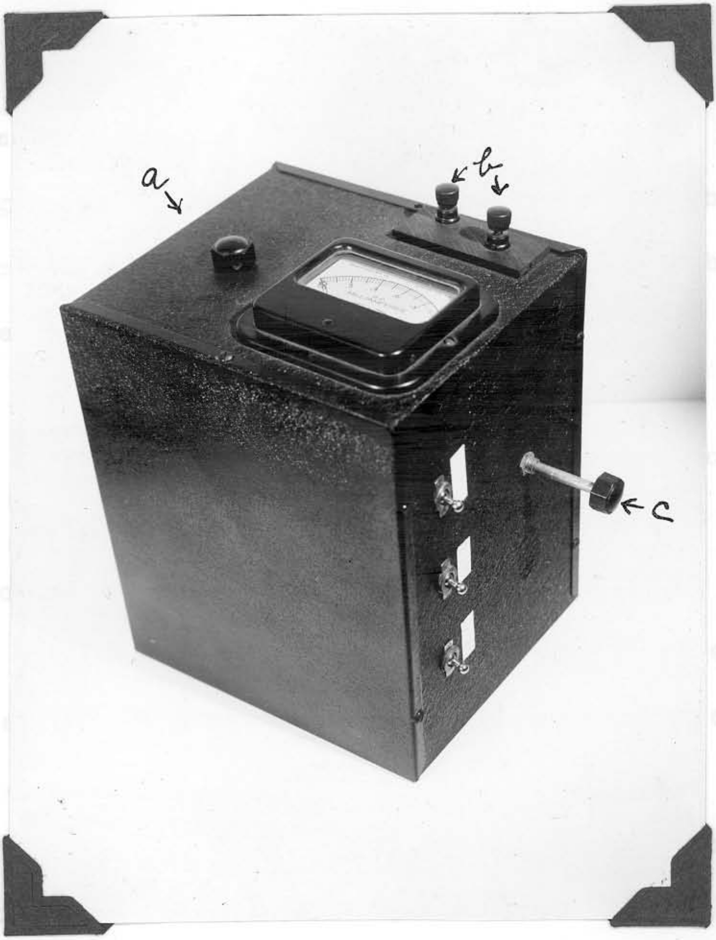


Fig. 5. Photograph of Meter

Used in Making Static Electricity Measurements

a. zero adjustment knob
b. input terminals
c. range selecting switch

MEASUREMENTS

In determining the amount of charge generated due to gasolene flowing through pipes, measurements were made under the three different conditions encountered when gasolene is pumped for distribution purposes. These conditions are:

(1) The loading of a tank truck at a filling rack.

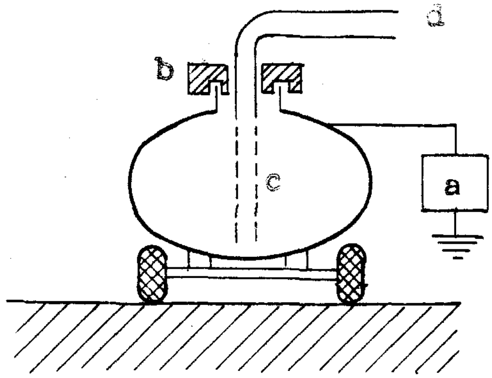
(2) The unloading of the truck at the service station.

(3) The filling of a passenger car from the service station's pump.

Because of the different rates of pumping, different materials in the hose, and different size of hose employed in each case, the amount of charge generated varied considerably with the same gasolene in the various cases.

Extensive tests were made on each of the three different grades of gasolene marketed on the West Coast by the Richfield, Shell, Standard, and Union Oil companies. Currents as low as 10^{-9} and as high as 10^{-6} were encountered. For a given size fill pipe, a proportionality between charge generated and rate of flow of gasolene was quite apparent.

In making the measurements, the positive end of the meter was attached to the tank truck, and the negative terminal was grounded, as illustrated in Figure 6. Measurements were first made in which the truck was insulated from the pavement by means of paraffin-impregnated wooden planks placed under the tires. It was soon discovered, however, that the insulation offered by the tires was so high that it was unnecessary to provide further insulation. At no time was it necessary to use an input resistance in the ammeter greater than 10 megohms. The tire resistance



Experimental Set-up for Measuring Charges

Generated by Gasolene Flowing

Into Tank Truck

a - ammeter
b - insulating wooden collar
c - extension for "submerged filling"
d - grounded filling pipe

Fig. 6

was usually at least 100 times greater than the above value, so that no appreciable error was introduced in assuming that all the charge brought into the truck by the flowing gasolene was dissipated to ground through the ammeter.

A collar of paraffin-impregnated wood was built for the purpose of insulating the metal pipe, through which the tank truck is filled, from the metal body of the truck. This collar could be fitted quickly into place, and its location when in use is illustrated in Figure 6. This collar had a resistance well over 5,000 megohms, as read on a megger, and thus introduced no error into the readings.

As soon as gasolene was pumped into the truck, the output meter on the microammeter deflected, indicating a current through the input resistance of the meter. When the gasolene flow was stopped, the meter reading returned to zero. Readings of the meter were taken every 15 seconds, while the truck was being loaded. The total amount of gasolene which was discharged into the truck was measured, and, since the time of pumping was recorded, the rate of flow could be calculated. It was not deemed necessary to have a rate-of-flow meter in the gasolene line to correlate instantaneous currents with instantaneous rates of flow. There was no need for such accuracy in this project, since external disturbances, as will be pointed out later, made great precision impossible.

In Figure 7, are shown several typical runs. It is seen in all cases that initially, the current is greater than the average value. After a short time this current reaches a fairly steady level, and then

TYPICAL TIME - CURRENT CURVES

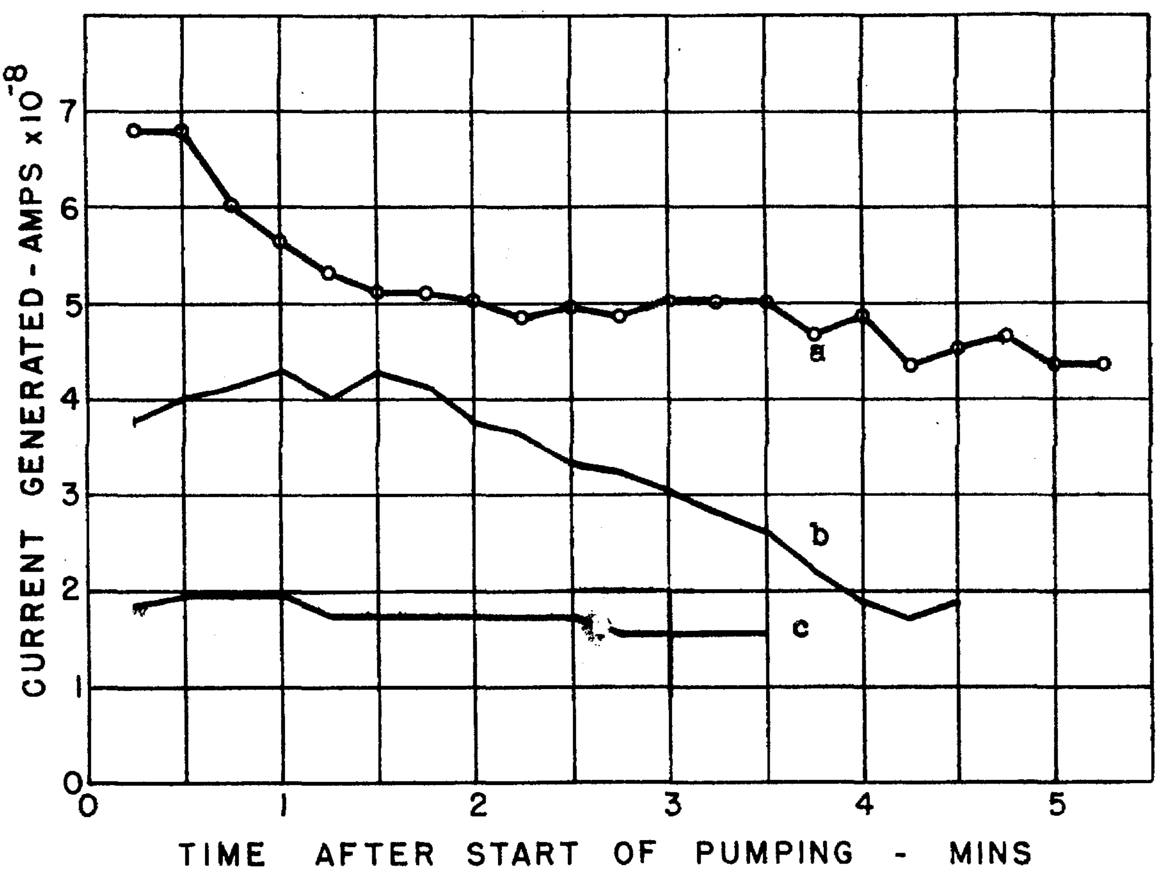


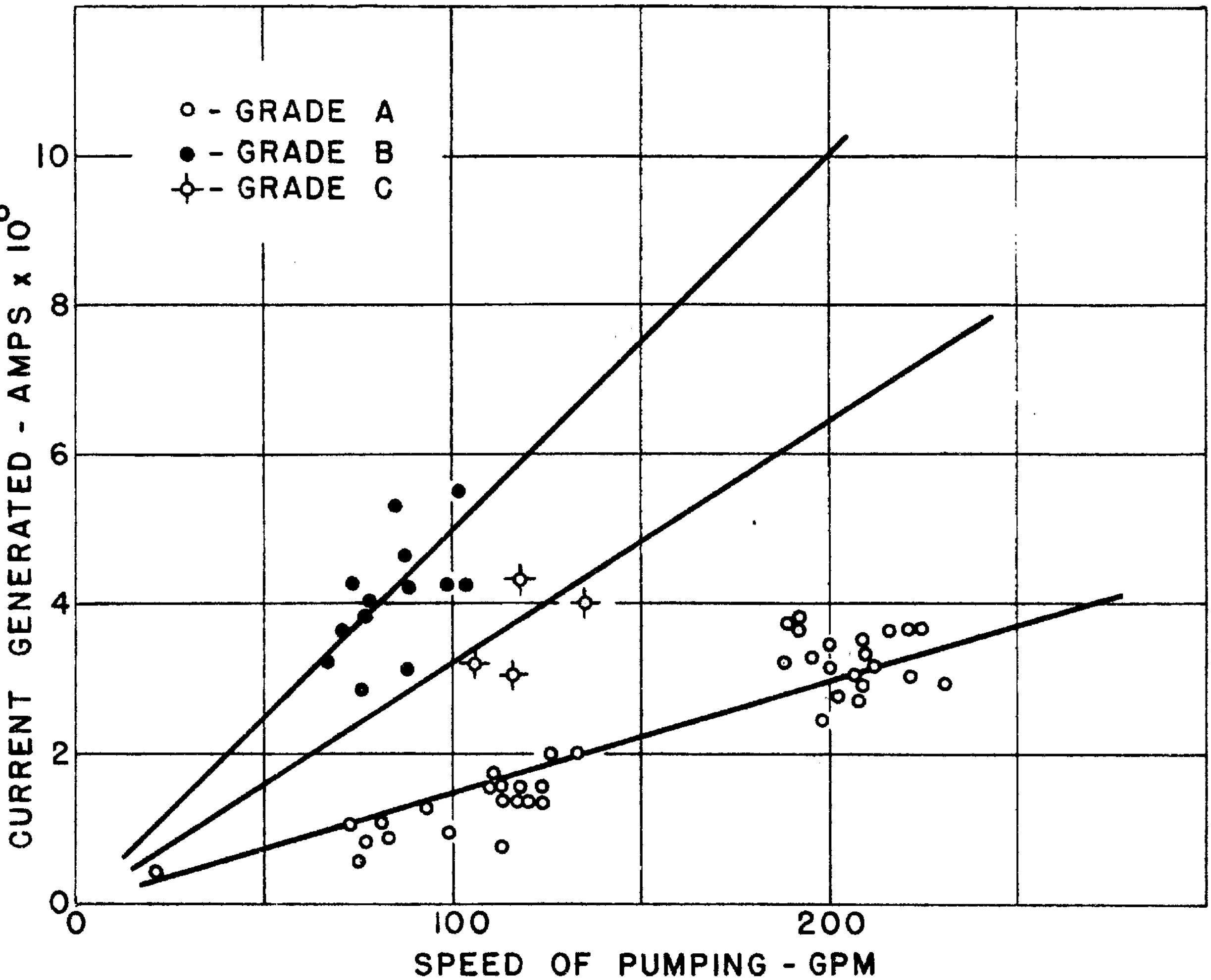
Figure 7.

a. Union "76", rate of pumping 100 GPM
b. Union "Ethyl", rate of pumping 66 GPM
c. Union "76", rate of pumping 58 GPM

starts dropping off again. The final dropping off always coincided with the time the level of the gasolene reached the fill pipe. Once the grounded fill pipe became submerged in the gasolene, it conducted away part of the charge brought in by the gasolene.

It is to be remembered that the current measured can only be that charge brought into the truck from the outside, through the fill pipe. Splashing can only produce a separation of charges within the truck; and, since the truck is virtually a perfect Faraday cage, any charges separated on the inside of it, will produce equal and opposite effects on any measuring device attached to the outside of the cage, and thus will cancel each other. However, as soon as any charge is brought inside the cage from the outside, if the cage is grounded, the ground will supply, or get rid of, the number of electrons necessary to maintain the cage at ground potential.

Different types of pipe were used in filling, and different pumps were employed. The material in the pipe or the pump, and the length of the extension of the fill pipe into the truck, had very little effect. The only important factors were the type of gasolene, the rate of pumping, and the fill pipe diameter. Figure 8 shows the results obtained with the three gasolenes marketed by the Union Oil Company. Each dot represents the average of a curve such as that in Figure 7. It is apparent that the different types of gasolene consistently generate different amounts of charge. This current is of the order of magnitude of 10^{-8} amps.. All these measurements were made with 3-inch diameter fill pipes. Measurements made with different sizes of nozzle yielded currents that



Currents Generated by the Different
Union Oil Co. Gasolenes

Grade A - "Regular", "76 Gasolene"
Grade B - "Ethyl"
Grade C - "White Magic"

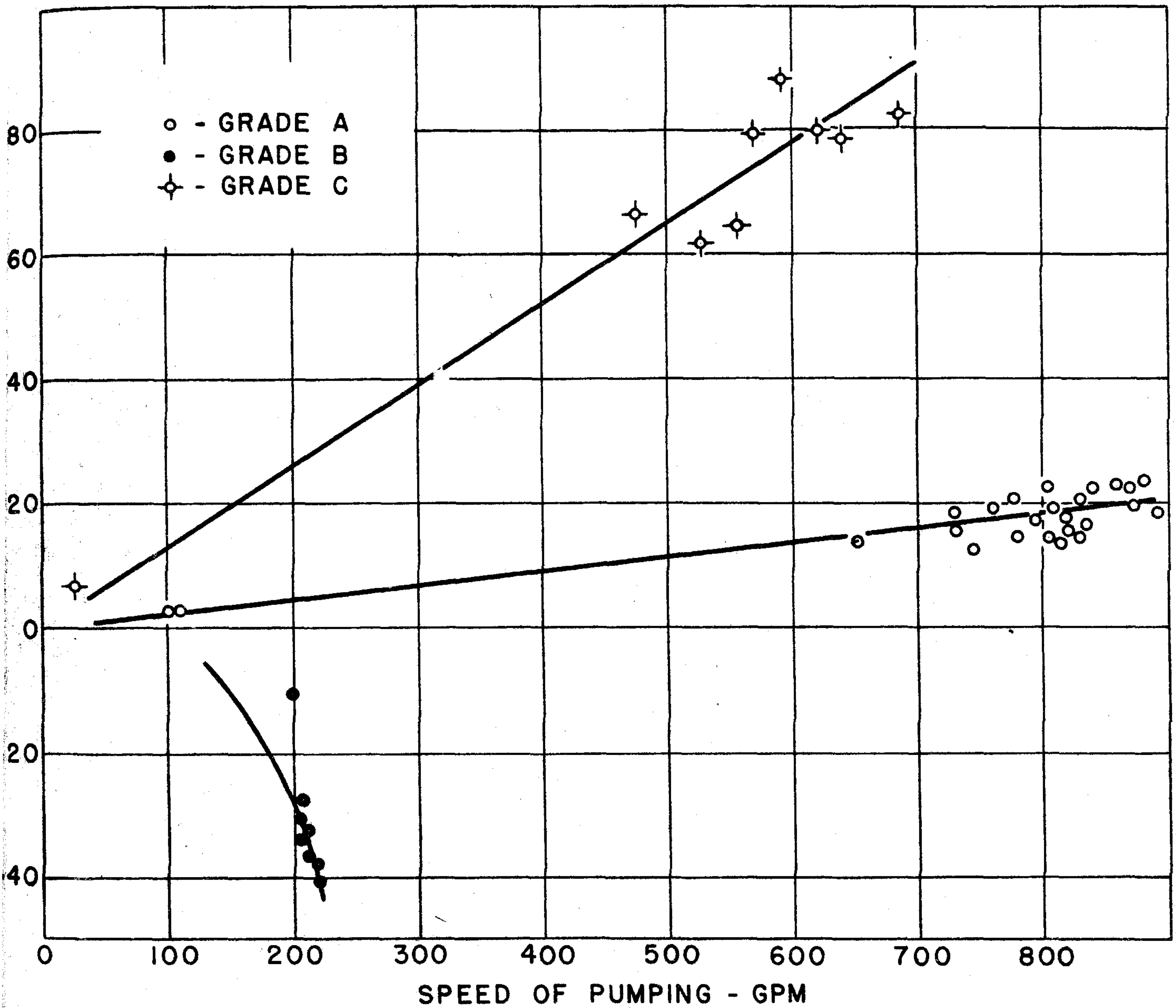
Fig. 8

were approximately inversely proportional to the nozzle area. This general type of variation is to be expected, since, for a given pumping rate, the linear flow speed will vary inversely with the area of the fill pipe.

It is impossible to correlate these current variations with the chemical and physical properties of the gasolenes. It would have involved very precise quantitative analysis of samples taken after each run, and the labor involved would have been prohibitive. It is hoped, though, that some future investigators may undertake this task. It may develop that certain physical or chemical properties of gasolenes, ordinarily very difficult to measure or detect, may be determined readily by measuring the charge generated under some standard flow conditions.

The curves in Figure 8 indicate a scattering of the points about what may be straight lines. This scattering is due to several causes, the most important of which is external disturbances. While measurements were being made, the motion of a person or another vehicle near the vehicle being tested would induce currents often of the order of magnitude of those being measured. It was impossible to stop all traffic in the loading yard during runs, so these disturbances were unavoidable. Another reason for the scattering of the data is that each point is an average of an irregular curve, as indicated in Figure 7, so that discrepancies are to be expected.

The results obtained with the gasolenes marketed by the Standard Oil Company are shown in Figure 9. It will be seen that the curve for the "Ethyl" gasolene differs from the other curves in two respects.



Currents Generated by the Different
Standard Oil Co. of Calif. Gasolenes

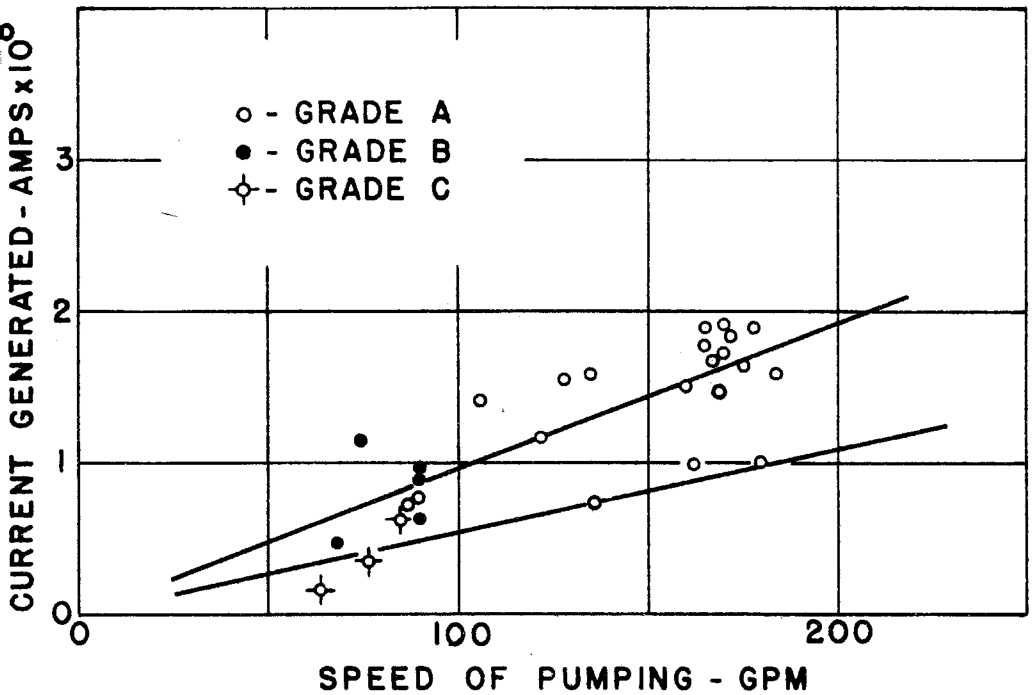
Grade A - "Standard"
Grade B - "Supreme" (Ethyl)
Grade C - "Flight"

Fig. 9

First, it shows a reversed charge. In all eleven other gasolenes tested, the truck, when being loaded, acquired a positive charge, indicating that the gasolene being brought into the truck was charged positively. In this one exceptional case, the truck acquired a negative charge. Furthermore, the curve of charge generated versus rate of pumping does not go through the origin for this gasolene. When measurements were attempted at low rates of fill, inconsistent results ensued. Sometimes the truck would initially acquire a negative charge and suddenly change to positive, and often the reverse was the case. As was previously stated, no attempt has been made to investigate the cause of this anomalous behavior.

Figure 10 indicates the results obtained with the gasolenes of the Richfield Oil Company. There is no marked difference between the charges generated by the "Ethyl" and the "regular" brands. The currents generated by the various gasolenes marketed by the Shell Oil Company are indicated in Figure 11.

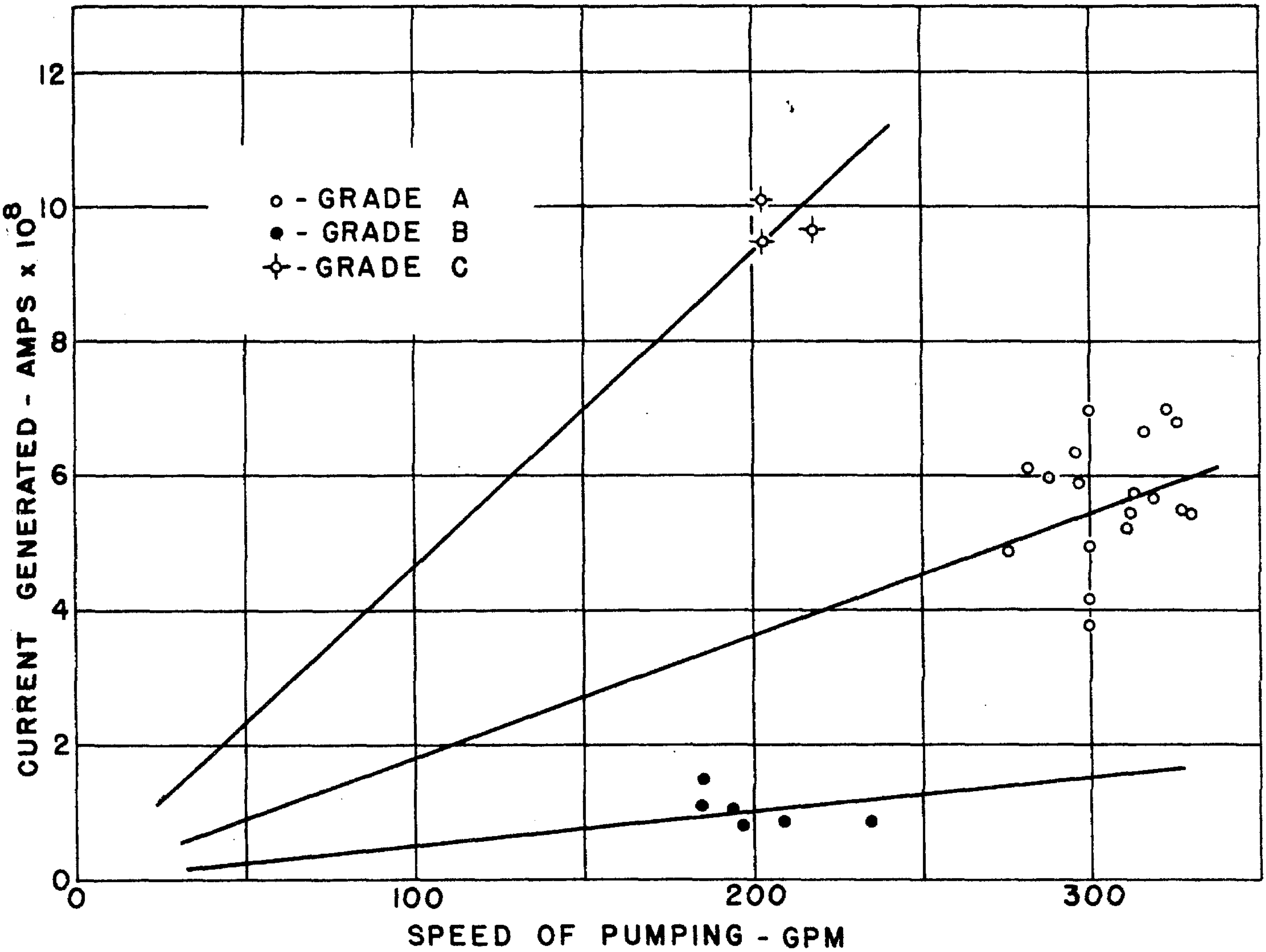
The data represented in Figures 8, 9, 10, and 11 were taken over a period of several months, and gave continuously consistent results over that period. The data were checked a year later, and the orders of magnitude were unchanged. In all cases, currents of the order of 10^{-8} to 10^{-7} ampres were encountered.



Currents Generated by the Different
Richfield Oil. Co. Gasolenes

Grade A - "High Octane" ("Regular")
Grade B - "Ethyl"
Grade C - "Flash"

Fig. 10



Currents Generated by the Different
Shell Oil Co. Gasolenes

Grade A - "Super Shell" ("Regular")
Grade B - "Ethyl"
Grade C - "Green Streak"

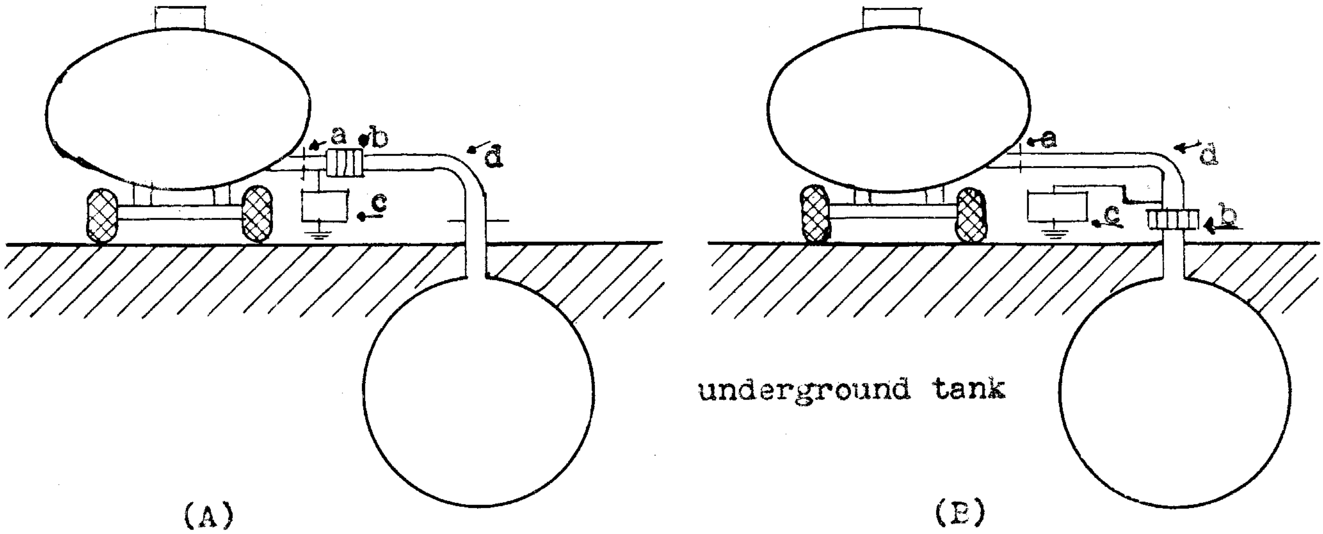
Fig. 11

UNLOADING OF GASOLENE AT SERVICE STATIONS

Over a hundred attempts were made to measure the charge produced when a truck unloads its gasolene into an underground tank at a service station. The charges developed were much smaller than those encountered in the loading of the truck, because of the lower rates of gasolene flow. This required using a more sensitive scale on the meter, and thus the readings were made more susceptible to outside disturbances. Furthermore, since most of these measurements were made on or near the highway, the sources of disturbances were greater. Passing automobiles and trolley cars usually would throw the needle violently off scale, and even the footsteps of the driver when he was walking around the truck, would register plainly. Working at night was not satisfactory either, as Neon lights gave interferences that affected the readings.

However, many good readings were obtained, and these again indicated a proportionality between the amount of charge generated and the rate of flow, for a specific hose and nozzle.

When a tank truck unloads at a service station, a hose is employed that has wire imbedded inthe body of the canvas or synthetic rubber, this wire serving as a bond between the truck and the underground tank. Therefore, in order to be able to read currents generated, it is necessary to install an insulating coupling somewhere in the hose line. Figure 12 shows two positions in which the coupling can be placed. The first is at the faucet on the truck; and the second is at the end of the hose, between the nozzle of the hose and the underground tank. These two locations, of course, give different results.



Two Possible Locations of Meter when

Making Measurements of Static

Generated When a Gasolene

Truck Unloads at a

Service Station

(A) Meter At Faucet

(B) Meter at end of Hose

a) faucet
b) insulating coupling (bakelite)
c) ammeter
d) bonded hose

Fig. 12

Charges are generated due to the motion of the gasolene in the tank truck. They are also generated when the gasolene flows through the faucet, and more charge is generated as the gasolene flows through the length of the hose into the underground tank. Accordingly, when the meter is connected at the faucet, and the hose is connected through its bond wire to the underground tank, the charge which is measured consists of the charge produced by the flowing of gasolene through the faucet, and an unknown portion of the charge produced by the flowing of the gasolene through the hose.

The hoses used contained a bond wire embedded in the hose material, but separated from the gasolene by a layer of synthetic rubber approximately 1/4 inch in thickness. Charges that are produced on the inside surface of this inner layer can leak to ground either over the surface of the artificial rubber, or can be conducted through the rubber to the bond wire. Consequently, the measurements made when the meter was connected to the faucet of the truck, would include those charges that were produced on the inside of the hose and which were conducted back to the faucet along the interior of the hose, and across the insulating coupling. It did not include that portion of the charge generated in the hose that was grounded, by conduction through the rubber, to the bond wire, nor did it include that portion of current conducted to ground through the nozzle and the underground tank, along the inner surface of the hose.

When the meter is connected between the nozzle of the hose and the fill pipe of the underground tank, then all of the charges produced, both at the faucet of the truck and during the motion through the hose, will be measured by the meter. In all cases a greater current was read when the meter was connected at the end of the hose. This indicates that the charge generated by the flow of the gasolene is of the same sign in the metal pipe and in the insulating hose. Were the charges of different signs in the two cases, it is entirely feasible that a proper design would completely eliminate any net charge production.

Table I. shows the average current produced, in amperes per gallon per minute, by some of the gasolenes of the Union and Standard Oil Companies: The last column includes the values obtained at the loading racks, for comparison purposes. It is seen that the general order of magnitude of current generated in all cases is 10^{-10} amps. per gallon per minute. Since pumping rates at loading racks are usually of the order of hundreds of gallons per minute, currents of the order of 10^{-8} amps. are to be anticipated. In unloading trucks, currents about one-tenth as large are to be expected.

This table also indicates that the currents measured at the nozzle are about three times greater than those measured at the faucet, indicating that most of the charge is generated during the flowing through the hose. Furthermore, the total charge produced, for the same number of gallons pumped, is smaller when the truck is being emptied, than when it is being filled. This is readily explained by the fact that in the filling process, the gasolene usually flows through a hundred or more feet of pipe-line before being discharged into the tank truck, while during the unloading process, the distance of flow is rarely more than twelve feet.

In all of the measurements made, except those of the Standard "Ethyl" gasolene, the truck acquired a negative charge. In the case of the Standard "Ethyl", the truck was positive during unloading. These results are in complete agreement with those obtained when the truck was being filled. In the filling process, the truck acquires the same sign of charge as that on the gasolene being introduced. When the gasolene flows out of the truck, it acquires the same charge that it had when first flowing into the truck, and so must leave the body of the tank truck itself with an opposite sign charge.

TABLE I.

Currents Generated When Unloading Trucks at Service Stations

Gasolene	Size of Nozzle	Amps. per GPM	Meter Connected at	Amps. per GPM When Loading Figs. 5 & 6
Company A				
2nd Grade	$2\frac{1}{2}$" diam.	0.5×10^{-10}	faucet	1.5×10^{-10}
2nd Grade	$2\frac{1}{2}$" "	1.7×10^{-10}	nozzle	
1st Grade	2" "	0.9×10^{-10}	faucet	5.0×10^{-10}
1st Grade	2" "	2.1×10^{-10}	nozzle	
Company B				
1st Grade	1-3/4" "	-7.25×10^{-10}	faucet	-41.7×10^{-10}
2nd Grade	$2\frac{1}{2}$" "	$.5 \times 10^{-10}$	faucet	2.5×10^{-10}
3rd Grade	$1\frac{1}{2}$" "	3.2×10^{-10}	faucet	13.0×10^{-10}

FILLING OF AUTOMOBILES AT SERVICE STATIONS

Measurements were made of the currents generated when an automobile is being filled at a service station. Because of the low rates of pumping, disturbances were again severe, and readings were obtained only with difficulty. As was to be expected, the currents generated were much smaller than those encountered during the filling and unloading of the tank trucks. However, although the rates of pumping were from 1/10 to 1/5 as great as those previously encountered, the currents generated were about 1/4 to 1/2 as large. This is probably due to the inverse relationship between charge generated and nozzle diameter, for constant rates of pumping, previously mentioned. The nozzle of the service station hose is usually about 5/8" in diameter, as compared with the 2 and 3 inch diameter nozzles used when loading and unloading the tank trucks.

The Union Oil Company's "76" brand was the only gasolene thus tested. At a pumping speed of 12 gallons per minute, which is a normal value for service stations, the current generated was 2.8×10^{-9} amps.. This corresponds to a rate of production of charge of 2.33×10^{-10} amps./GPM. A few measurements at higher rates of pumping indicated a direct proportionality between the charge generated and the speed of pumping.

RESISTANCE OF TIRES

In order to be able to make quantitative statements about the hazards represented by the currents encountered in the three methods of production of charge, it is necessary to know the resistances to ground that tires afford. Accordingly, in order to determine the general order of magnitude involved, measurements were made of the resistances of tires on automobiles chosen at random.

A high voltage was applied between the body of the car and a metal plate under the tire whose resistance was being determined. The applied voltage was measured with a 10,000 volt scale electrostatic voltmeter, and the current through the tire was measured with a microammeter. Ohm's Law was used to determine the resistance. Although the resistance of rubber is a function of the current, such small currents were involved in these measurements that no appreciable difference in resistance was encountered when 1 micro-amp. or 5 micro-amps. flowed.

A Wimshurst Influence Machine was used as a source of high voltage. When making the measurements, the car was rolled onto the metal plate that formed one electrode, and the metal plate was insulated from the pavement by means of a paraffin-impregnated wooden board, so that the leakage over the surface of the pavement from other tires was negligible.

The results obtained yielded values of resistances, for individual tires, ranging from 12,000 megohms (12×10^9) to 2×10^9 ohms. These measurements were made during the summer under conditions of fairly low humidity. In general, it was found that resistances measured were less for older tires. When the tire is damp, however, the surface leakage is great enough to make the resistance readable on an ordinary ohmmeter. Tire resistances as low as 10 megohms have been encountered under such conditions.

STATIC CHARGES AS A HAZARD

Now that the order of magnitude of charges and currents that may be encountered during the distribution of gasolene are known, the problem of the hazard represented by these charges may be investigated intelligently.

There is no way of eliminating the production of these charges, as long as gasolene has such low electrical conductance. Helmholtz' "Double Layer" Theory*, combined with Quincke's experiments on "Streaming Potentials"*, indicate that there is always a difference of potential between the liquid boundary and solid pipe boundary. A motion of the fluid will result in a separation of charge. The separated charges will accumulate throughout the body of the gasolene; and, when the gasolene comes to rest in some metal container, these charges will move to the container. Thus, the potential of the container may be raised considerably above that of ground, if the charges are allowed to accumulate. If the charges are dissipated by grounding, as mentioned at the beginning of this paper, no hazard exists. But what if no precautions are taken (whether purposely or through negligence)?

Figure 13 shows the electrical equivalent of a tank truck which is either being filled or emptied of gasolene. The truck has a capacitance to ground, which is represented in the diagram by the condenser C. This capacitance is shunted by the resistance of the

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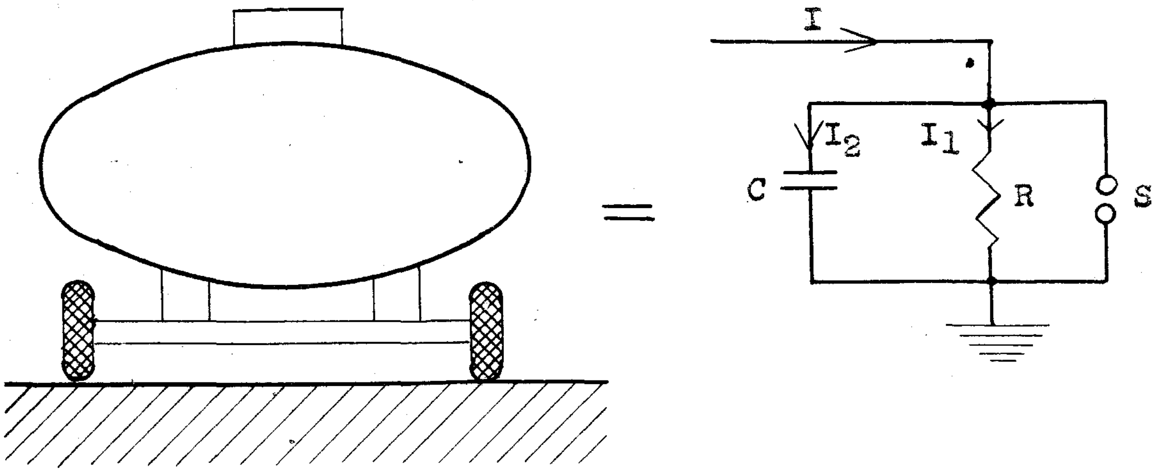
*An excellent account of these is given in "Electrokinetic Phenomena", by H. A. Abramson, an A.C.S. Monograph, Chaps. I. & II.



Equivalent Circuit of A Tank Truck

Being Emptied or Filled with

Gasolene or Other Petroleum Product.

C - Capacitance to Ground of Truck

R - Resistance to Ground of Tires

S - Spark Gap that may extend between
truck and a grounded metal object.

Fig. 13

tires, the drag chain, etc., and all these shunting resistances are combined into the equivalent resistance R. In the case that we are considering, there is also a spark gap S shunting the resistance and capacitance, and we are trying to determine if a high enough voltage can be built up to break over the spark gap.

As soon as gasolene starts flowing, we may consider that a constant current "I" is injected into the circuit. Then, in the usual notation:

$$E_r = I_1 R$$

$$E_c = \frac{1}{C}\int_0^t I_2\,dt$$, with the further restriction that

$$I = I_1 + I_2$$

Using operator notation:

$$I_1 R = \frac{I_2}{CD}$$, and, since $I_1 = I - I_2$

$$IR - I_2 R = \frac{I_2}{CD}$$

Yielding the final equation:

$$(CRD + 1)I_2 = 0$$

The expression for I_2 is obviously of the form:

$$I_2 = A\,e^{-\frac{t}{RC}}$$

For the boundary condition, we realize that at time $t = 0$, the voltage across the resistance and the condenser must both be zero. Hence, all the current I must flow into the condenser, at the instant the process begins.

So, finally:

$$I_2 = I\, e^{-\frac{t}{RC}}$$

and

$$I_1 = I\,(1 - e^{-\frac{t}{RC}})$$

Thus, the maximum possible voltage that can be encountered exists when the steady-state is reached, and the condenser is all charged up. From that time on, all the current flows through the resistance. It is possible to estimate the "time constant" of this circuit.

Measurements of the capacitance to ground of a normal tank truck, were made with a standard, portable impedance bridge. Values of approximately 1,000 micro-micro-farads, or 10^{-9} farads, were encountered. This corresponds closely to that determined by Beach*. Therefore, for a "time constant" of one second, R would have to equal 10^9 ohms. For a time constant of ten seconds, this value goes up to 10^{10} ohms, or 10,000 megohms. From the measurements made on tire resistances, it is seen that a time constant well over 10 seconds is not easily obtained. Therefore, we can conclude that within a relatively short time after the start of pumping, the tank truck reaches its maximum voltage V_m, determined by $V_m = IR$.

It is to be emphasized at this point, that the maximum voltage obtainable is a function only of the current generated and the resistance to ground. The condenser has nothering to do with the voltages that may be encountered. What the condenser does do, though, is to determine the amount of energy that will be dissipated in a spark, if the spark gap S should break down.

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*Beach, Robin "Static Electricity on Rubber-Tired Vehicles", Elec. Eng., Vol. 60, May, 1941.

With the knowledge of the magnitude of "I", it is now possible to calculate what value of R is needed to obviate completely the possibility of a spark. This we can do, because of the well-known phenomenon of "Minimum Sparking Potential". That is, no matter how closely two conductors are brought together, or no matter how great a gradient may exist between the two, no spark can result unless the actual difference of potential between the two exceeds a certain minimum value. This minimum value has been determined for many gases*, and for air it is about 300 volts. Thus, if the voltage of the truck can be kept below 300 volts, there is absolutely no danger of a spark occurring.

One must be careful to differentiate an arc from a spark. An arc occurs when a circuit carrying current is broken, or, if a spark occurs and the spark is backed up by a relatively large source of charge. However, the voltage across an arc is very small, and a relatively large amount of current must flow to sustain the arc. An arc could never be formed by interrupting any part of the system that is grounding the static electricity currents involved in pumping phenomena. Of course, the grounding system may be carrying "stray currents" from nearby power lines. Interruption of the grounding circuits under such circumstances may well produce arcs. But this is an entirely different problem. If the grounding system is carrying only the static currents, then no danger of arcing exists.

By using Ohm's Law, it is a simple matter to calculate the necessary protective resistance. As an example, we might assume that

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*Cobine, J. D., "Gaseous Conductors", page 165.

a current of 5×10^{-8} amperes is being produced by a specific filling operation, and that the minimum sparking potential is 300 volts. Then, using Ohm's Law, $V = IR$,

$$R = \frac{V}{I} = \frac{300}{5 \times 10^{-8}} = 6 \times 10^{9} = 6{,}000 \text{ megohms.}$$

Thus, with our assumed value of current generated, a resistance to ground of less than 6,000 megohms will completely eliminate any possibility of a spark occurring. This is an enormously high value of resistance, and can probably exist only under conditions of very low humidity and in the absence of any bonding wire. Under these conditions, there is no electrical connection betweenground and the truck except through the rubber tires, and the pavement.

Even if we assume the highest value of tire resistance measured, 12,000 megohms, the fact that there usually are at least four of these in parallel will reduce the effective resistance of all tires to a value well below the 6,000 megohms needed for protection.

This simple analysis shows that under normal operating conditions, the resistances to ground of the tires is sufficiently low to prevent a tank truck being filled with gasolene from acquiring a high enough potential to produce a spark. Measurements have been made on the surface resistances of pavements*, and the results indicate that with relative humidities greater than 50% at 56°F., the surface resistances are also below 6,000 megohms.

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*"Static Electricity and Its Effect on Car Radio Performance", Cadwell, Handel and Benson, Amer. Chem. Soc. "News Edition", Vol. 19, No. 20, Oct. 15, 1941.

It seems likely, therefore, that if the relative humidity is above about 40%, there is no danger of sparking potentials building up on ungrounded trucks being filled with gasolene.

However, in case of very low humidities, when the leakage resistances are exceptionally high, the problem may be analyzed by assuming that all of the charge generated is being stored in the truck. In that case, then, the voltage of the truck at any instant is given by:

$$V = \frac{Q}{C}$$

As stated before, the normal value for C is about 10^{-9} farads. Then, if we again assume a generation of charge at the rate of 5×10^{-8} amps., it is obvious that the voltage is building up on the truck at the rate of:

$$\frac{5 \times 10^{-8}}{10^{-9}} = 50 \text{ volts/sec.}$$

Thus, at the end of one minute the tank truck would be at a potential of:

$$50 \times 60 = 3{,}000 \text{ volts.}$$

Currents ten times as great as the one assumed may be encountered, as Figure 9 shows. In that case, the truck's voltage would rise at a rate ten times that calculated.

Accordingly, it is seen that in case of the complete absence of any grounding system or contact by the tank truck with any semiconducting material, on very dry days the possibility of sparking potentials developing does exist. However, even if bonding has been neglected, the loading operation is conducted by a loader who usually stands on the truck and who has to hold down a valve lever in the loading pipe to permit the gasolene to flow. Unless the soles of his shoes are excellent insulators, or if he is not wearing good insulating gloves, he will usually offer a good enough grounding path for the static electricity generated. In the several hundred measurements we made, it was always necessary for the loader to install a "prop" to keep the valve open. His presence on the truck, and contact with the valve, always reduced our readings, and often made readings impossible.

Granted the possibility of sparking potentials being produced, the question still exists as to whether or not the energy stored in the truck is enough to ignite a combustible mixture of gasolene and air.

Similar analysis can be applied to the case of a truck being unloaded at a service station and to the case of a passenger car being filled. Because of the smaller currents involved, much greater resistances can still be considered safe enough to keep the potentials below the minimum sparking level. Thus, if we assume a rate of discharge of 80 GPM, and assume that there is no bonding wire in the hose, then a reasonable rate of charge to be expected, from Table I., is about 2×10^{-10} amps./GPM. Thus, a current of about 1.6×10^{-8} amps. would result; and, to keep the voltage below 300 volts, it is apparent that any resistance below 19,000 megohms will prevent sparking.

During normal truck unloading operations, the hose rests on the ground, and thus presents a broad area of contact in case no grounding wire is included in the body of the hose itself. It is quite improbable that resistances as high as the one just calculated can prevail.

The results obtained in the previous two cases apply also to the case of a passenger car being filled, for during that process the current generated is never much more than 3×10^{-9} amps.. Thus, for the minimum sparking potential to be precluded, the enormous resistance of 100,000 megohms would have to exist. It is conceivable that this resistance might exist. However, in that case, it is readily shown that during the normal filling of a passenger car, not enough total charge is generated to raise the potential above the minimum sparking value.

Thus, if the pumping rate is 12 gallons per minute, and the rate of generation of charge is 3×10^{-9} amps., then, if all the charge goes into energizing the car's capacitance; i.e., no current leaks off, then, the TOTAL charge produced will be:

$$Q = i \times t = 3 \times 10^{-9} \times t$$

If 10 gallons are pumped, the total time will be:

$$t = 60 \times \frac{10}{12} = 50 \text{ seconds}$$

So:

$$Q = 50 \times 3 \times 10^{-9} = 150 \times 10^{-9} \text{ coulombs.}$$

The voltage of the truck will then be:

$$V = \frac{Q}{C}$$

For an ordinary passenger car, C is about 750 micro-micro-farads, according to Beach*. Thus, the voltage to be anticipated is:

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*Beach, Robin, loc. cit.

$$V = \frac{150 \times 10^{-9}}{.75 \times 10^{-9}} = 200 \text{ volts.}$$

A fill of about 15 gallons would have to be made to generate the charge required to raise the potential of the car to the 300 volt level.

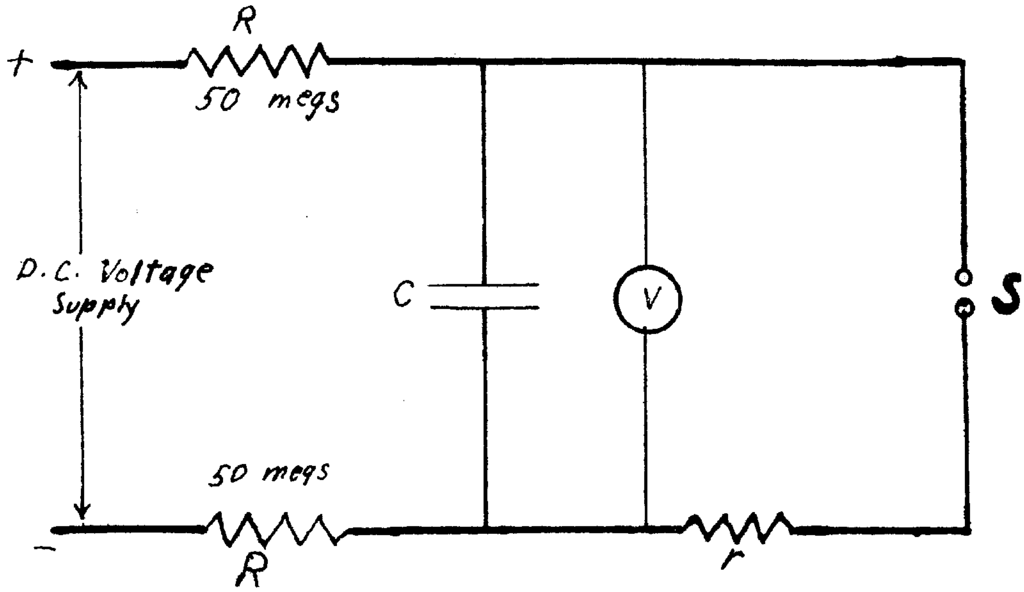
It is safe to conclude that the hazard due to static electricity in the filling of gasolene tanks on passenger vehicles is virtually non-existent.

IGNITION OF GASOLENE VAPORS BY ELECTRIC SPARKS

The field of ignition of vapors by electric sparks has been explored by many previous investigators, but none was interested in this particular substance; i.e., gasolene. Also, most of these investigations were carried out in an attempt to determine the exact mechanism of ignition, rather than establishing minimum sparking energies.

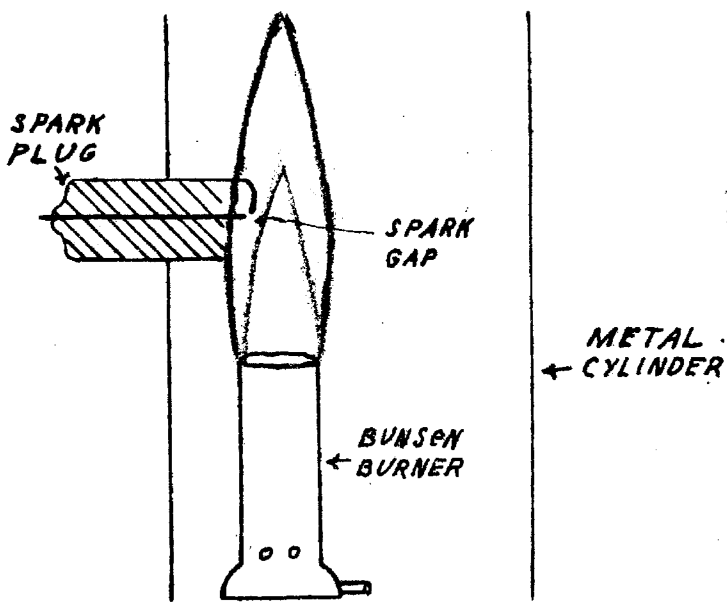
The problem investigated was this: can a gasolene truck charged up by static electricity generated during a filling process cause a spark of sufficient intensity to ignite a combustible mixture of gasolene vapors and air? In the laboratory, this problem could be evaluated accurately by replacing the truck with a condenser of capacitance equivalent to that of a truck, and determining the ignition properties of this charged capacitance.

Work of a preliminary nature was done with ordinary household gas issuing from a bunsen burner. Figure 14 shows the electrical circuit used. A condenser C was charged from a high voltage D.C. supply through 50 megohm resistors. An electrostatic voltmeter V measured the voltage at which the spark gap S broke down. The 50 megohm resistors were utilized to ensure the isolation of the condenser-spark circuit, when discharge occurred, from the high voltage supply. A spark plug was suspended about 2 inches above the top of a bunsen burner, as illustrated in Figure 15. The plug was mounted in a metal cylinder that acted as a shield to prevent drafts from disturbing the flow of gas from the burner.



Electrical Circuit Employed for investigation of ignition of gas by static sparks.

Fig. 14



Arrangement of Sparking Apparatus.

Fig. 15

It was found very quickly that sparks of apparently identical characteristics; i.e., discharging from the same condenser through the spark plug that broke down at the same voltage, would sometimes ignite and sometimes fail to ignite the gas. Consequently, it was necessary to adopt a statistical method of studying this effect. The method used was to cause a succession of sparks, of exactly the same characteristics, to occur at 5 second intervals, and to count the number that produced ignition and the number that failed to produce ignition.

J. D. Morgan* established rather conclusively that there is a minimum amount of energy required to ignite combustible vapor mixtures. With smaller spacing of electrodes, more energy is required than with larger spacing of electrodes. However, a limit is reached at about 4,000 volts. Increasing the spacing of electrodes, and thus increasing the voltage at breakdown, decreases the required capacitance to ensure ignition just sufficiently so that the energy in the condenser, represented by $\frac{1}{2}CV^2$, is a constant. His experiments were conducted to establish the validity of his "Thermal Ignition" theory, as against the "Electrical Ignition" theory of Finch and Thompson**. Accordingly, it seemed unnecessary for experiments to be conducted at very high voltages. We, therefore, used a constant sparking voltage of 3,700 volts, and varied the capacitance of the condenser in order to vary the amount of energy dissipated in the spark.

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*J. D. Morgan, Philosophical Mag. (6) Vol. 45, page 968, 1923.

**Finch, G. I., and Thompson, H. H., Proc. Royal Soc., Vol. 134A, page 343, 1932.

Figure 16 shows the results obtained. Each individual dot represents the average of approximately 200 sparks. The percentage of the sparks that caused ignition is plotted as ordinate, and the amount of capacitance used for the condenser C is plotted as abscissa. It is seen from the curve that it is impossible to state that a certain type spark will always produce ignition of a moving stream of combustible gases issuing from a jet. The best one can do is state the probability that such a spark will produce ignition.

These results indicate that with the arrangement used, a condenser of 500 micro-micro-farads capacitance caused ignition approximately 6% of the time, while increasing the capacitance to 5000 micro-microfarads, thus increasing the total energy dissipated in the spark ten times, increased the igniting ability to 78%. Further increases of energy do not produce proportionate increases in igniting ability, because the curve flattens off. The energy represented in the condenser of 5000 micro-microfarads charged to 3,700 volts is:

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\ 5 \times 10^{-9} \times (3.7 \times 10^3)^2 = 0.034 \text{ joules.}$$

This value of energy, which caused ignition almost 80% of the time, agrees very well with Morgan's value.

However, it is not the total energy dissipated that is primary in determining the ignition ability, but it is the rate of dissipation of that energy. This conclusion was reached when additional resistance "r" was inserted in the condenser-spark gap circuit, Figure 14.

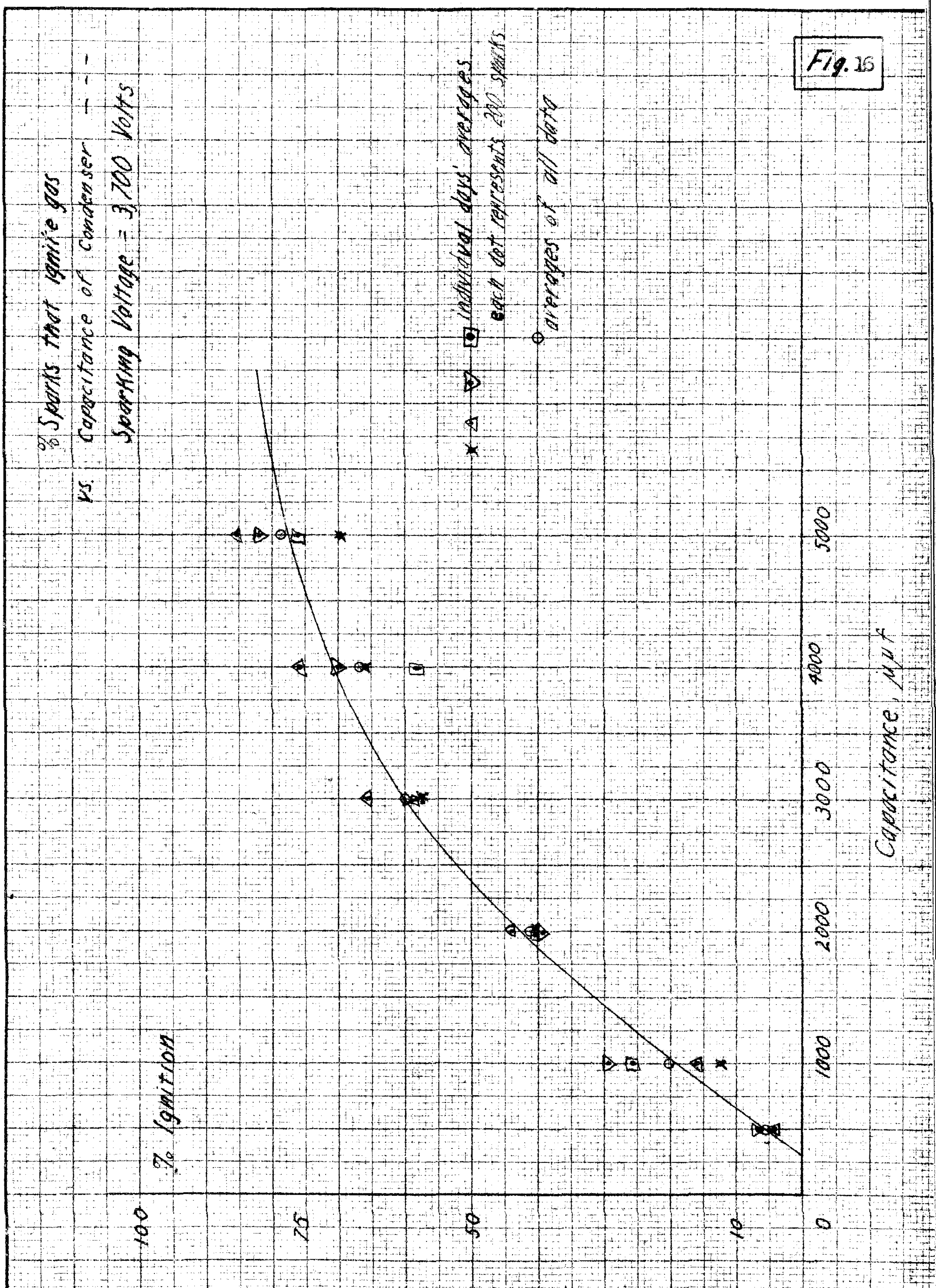


Fig. 16
% Sparks that ignite gas
vs. Capacitance of Condenser
Sparking Voltage = 3,700 Volts
individual days' averages
each dot represents 200 sparks
averages of all data
% Ignition
100
75
50
10
0
1000
2000
3000
4000
5000
Capacitance, μμf

Fig. 16

A relatively small amount of resistance thus inserted was able to eliminate almost completely the igniting power of the original spark.

In Figure 17, is shown the effect of adding resistance to the spark gap circuit. The data were determined with a condenser of 9,000 micro microfarads capacitance, and a spark breakdown voltage of 3,700 volts. It is seen that with no external resistance in the spark circuit, the only resistance being the resistance of the spark itself and the small copper resistance of the leads (the latter was well below one ohm), ignition resulted from 83% of the sparks. The relatively small resistance of 30 ohms was sufficient to reduce the igniting power of the sparks to only a few per-cent. No ignition was obtained with 40 ohms in the circuit.

This experiment shows clearly that it is not the total energy dissipated in the spark that determines its igniting power, but the rate of dissipation of that energy; i.e., the wattage in the spark. No matter how much resistance is in the circuit, if a constant capacitance is charged up to a constant voltage, a constant amount of charge must pass through the spark gap. However, larger series resistances will spread out the wave form of this discharge.

The same experiments were repeated using gasolene. The apparatus consisted of a plastic cylinder with an imbedded, adjustable spark gap, as illustrated in Figure 18. The volume of this cylinder was approximately 342 cc, and a calibrated dropper was used to put in 3/130 cc of gasolene. This was thoroughly agitated so that a uniform mixture of air and gasolene prevailed throughout the volume. The mixture corresponded

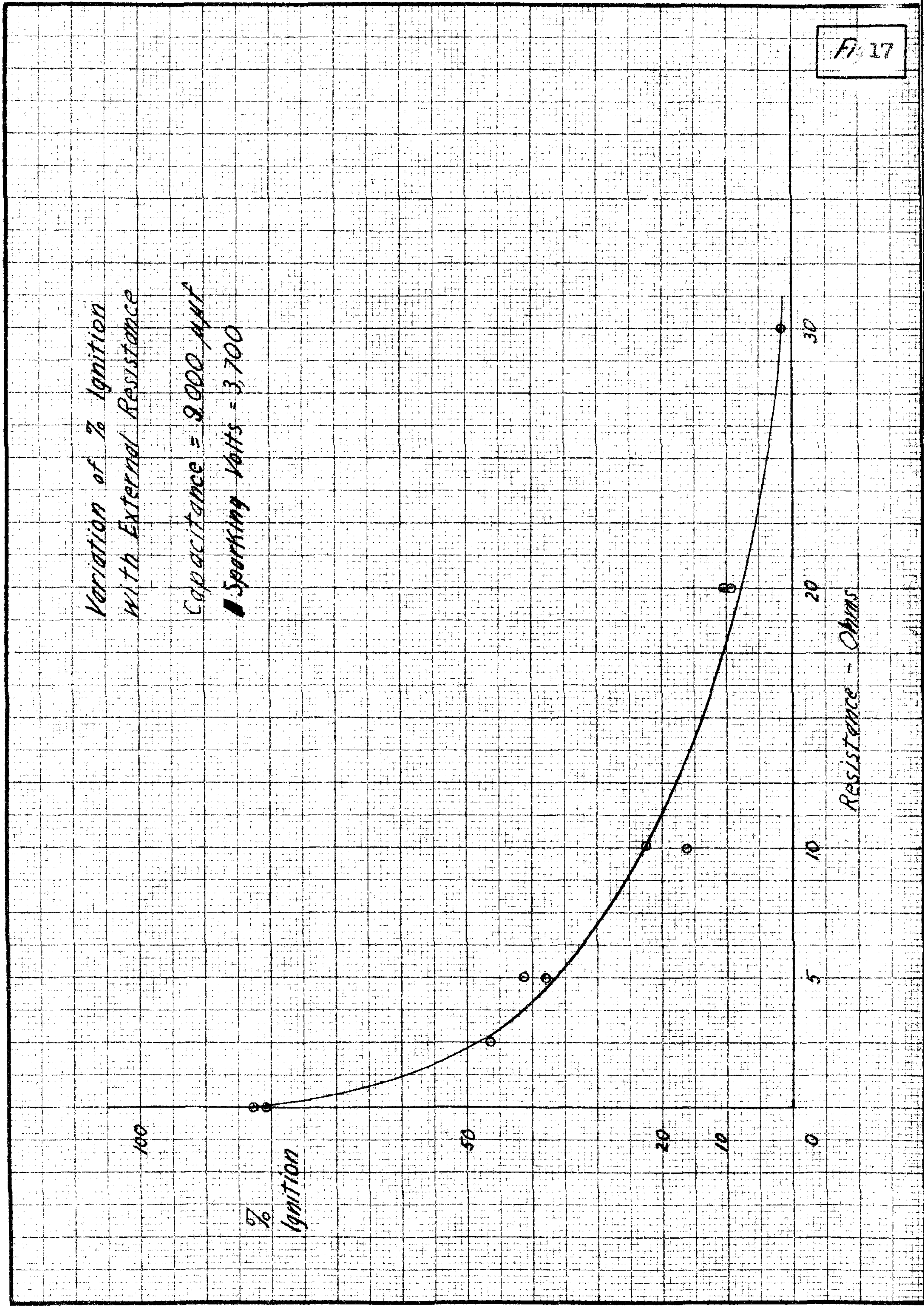
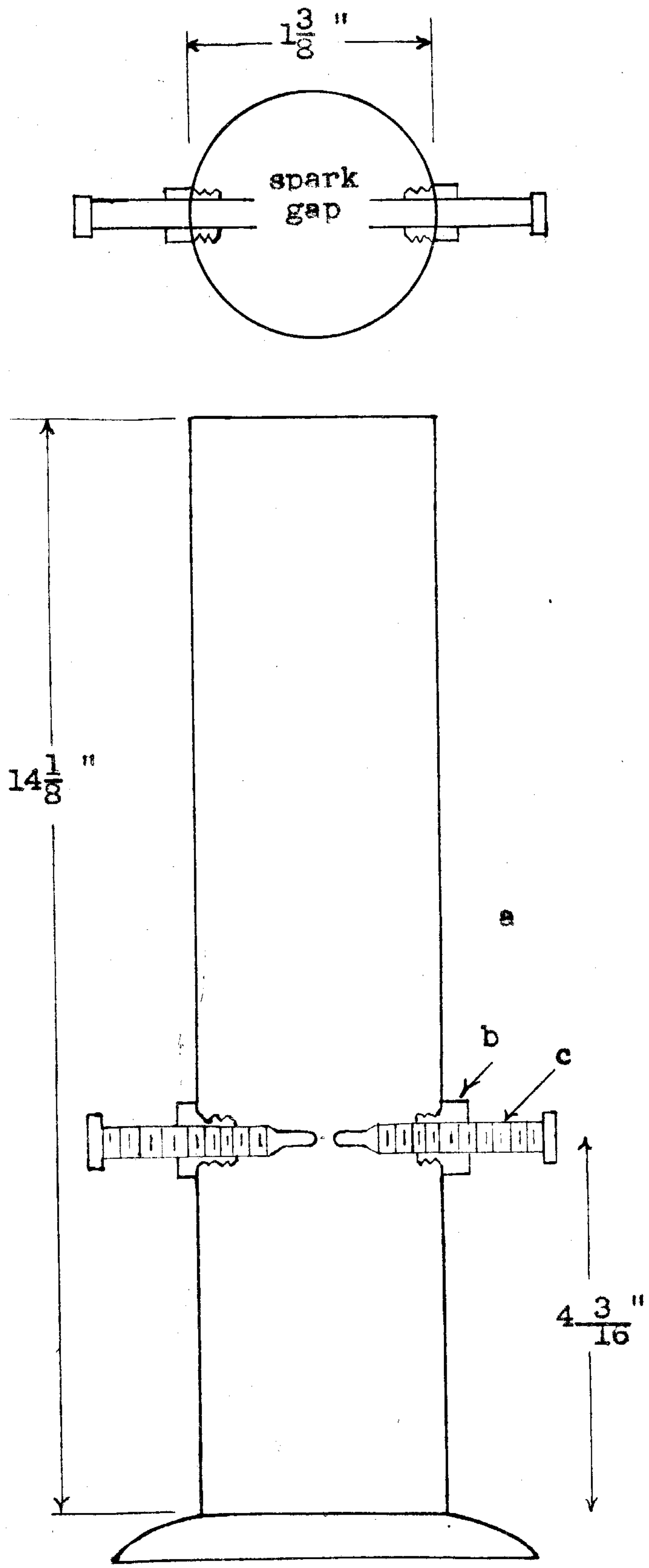

17
Variation of % Ignition
with External Resistance
Capacitance = 2,000 μμf
Sparking Volts = 3,700
% Ignition
100
50
20
10
0
5
10
20
30
Resistance - Ohms

Fig. 17



Apparatus used to determine the gasolene igniting proprties of static sparks.

a - plastic cylinder

b - $\frac{1}{4}$-20 brass screw, tapped for 6-32 screw

c - 6-32 brass screw, used as spark gap. End rounded to 1/16" diam. 45° taper started $\frac{1}{2}$" from end of screw

Electrical circuit given in fig. 14.

Fig. 18

to a 0.00675% gas-air mixture, by volume, or a 5% mixture, by weight.

As might have been anticipated, the results obtained with gasolene are quite similar to those obtained with household gas. The minimum energy that produced a perceptible percentage of ignitions was that corresponding to about 500 micro microfarads, and 3,700 volts, or 0.0034 joules. One marked difference between the results obtained with gasolene and household gas is that with gasolene, a minimum energy was found that gave 100% ignition. From Figure 19, this is seen to correspond to about 3,000 micro microfarads and 3,700 volts, or about 0.020 joules. The results of Figure 16 have been included in Figure 19 for comparison purposes.

The reason why 100% ignition was not obtained with household gas is undoubtedly that the gas stream was moving. This exerted a cooling effect on the electrodes; but, what is more important, gases that may have started to ignite, when carried past the inter-electrode space, would immediately expand and cool off, thus preventing the propagation of the flame. With stationary gasolene vapors, this phenomenon was not encountered, and 100% ignition could be effected.

From Figure 19, it is apparent that a charged gasolene truck does represent a hazard. About 30% of the sparks resulted in ignition when a capacitance of 1,000 micro microfarads was used. As mentioned previously, this is a good average value for the capacitance of a tank truck. Thus, we might expect one out of three sparks, if occurring in a place where a combustible mixture of gasolene and air is existent, to cause ignition, if the spark broke down at about 4,000 volts. Correspondingly higher voltages, to represent 0.020 joules with 1,000 micro microfarads capaci-

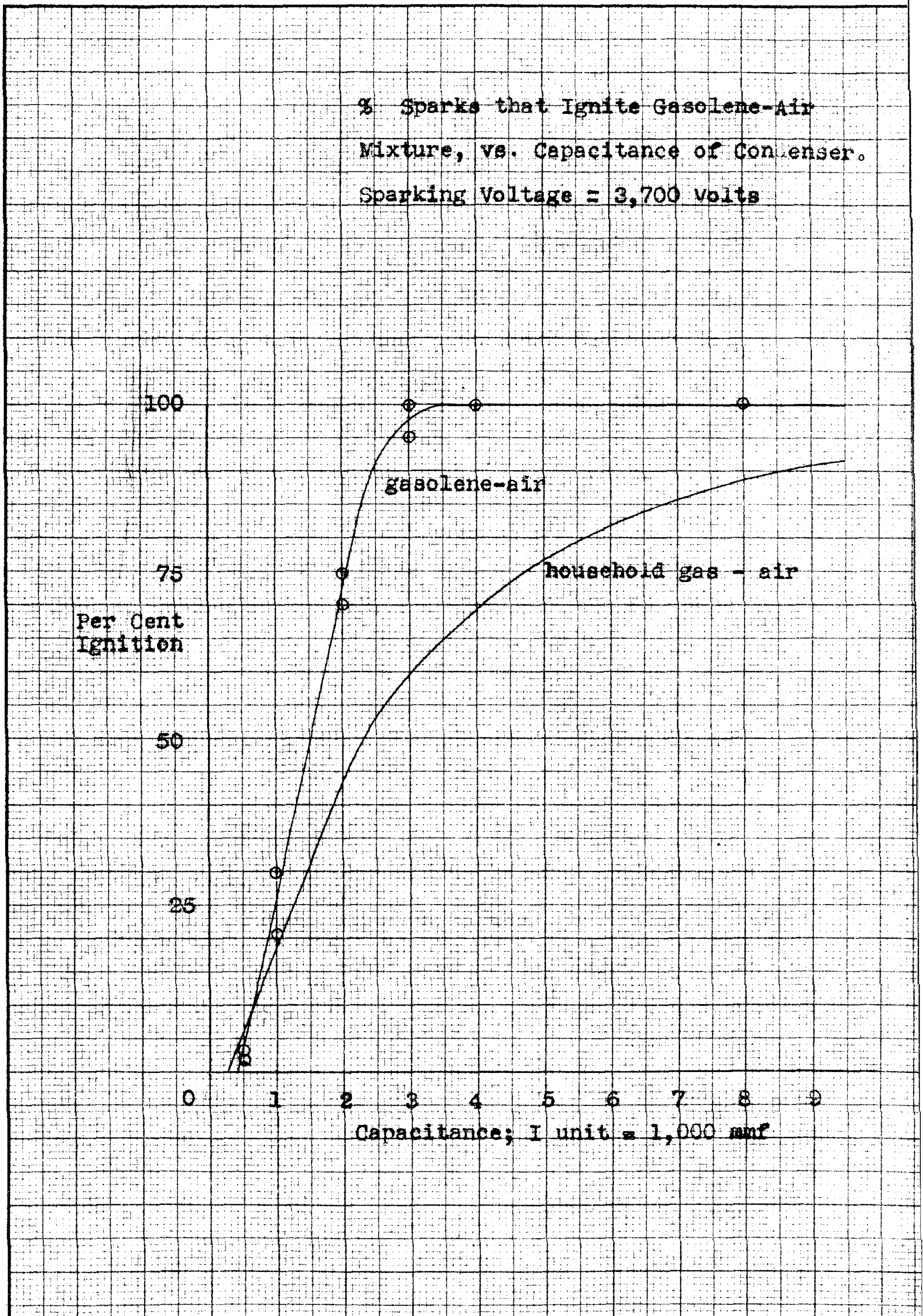

% Sparks that Ignite Gasolene-Air
Mixture, vs. Capacitance of Condenser.
Sparking Voltage = 3,700 Volts
100
75
50
25
Per Cent
Ignition
gasolene-air
household gas - air
0
1
2
3
4
5
6
7
8
9
Capacitance; I unit = 1,000 mmf

fig. 19

tance might produce certain ignition. However, as discussed on page 25, in order to attain voltages as high as 4,000 volts during a truck filling process, resistances to ground of the order of magnitude of tens of thousands of megohms must exist. This would occur only on very dry days. Furthermore, the only likely place that a spark would occur is between the fill pipe and the dome of the truck, since there usually is no other projecting metal near the truck during filling. If the truck has been filling for some time, then the mixture in the dome would be far too rich to be ignited by a spark; and, at the beginning of the filling process, when a mixture of the right proportions might exist,(because of the fact that the tank is full of air at that time), not enough charge has accumulated, due to pumping, to raise the voltage above breakdown potential.

Accordingly, although a hazard does exist, it is a very small one. The precautions ordinarily taken by the Petroleum Industry are entirely adequate to eliminate every trace of hazard. This is proved by the excellent record in the industry. Considering the fact that millions of gallons of gasolene are pumped daily, representing over 100,000 single pumping operations each day, the per cent of accidents truly attributable to static ignition (and not matches), is almost microscopic.

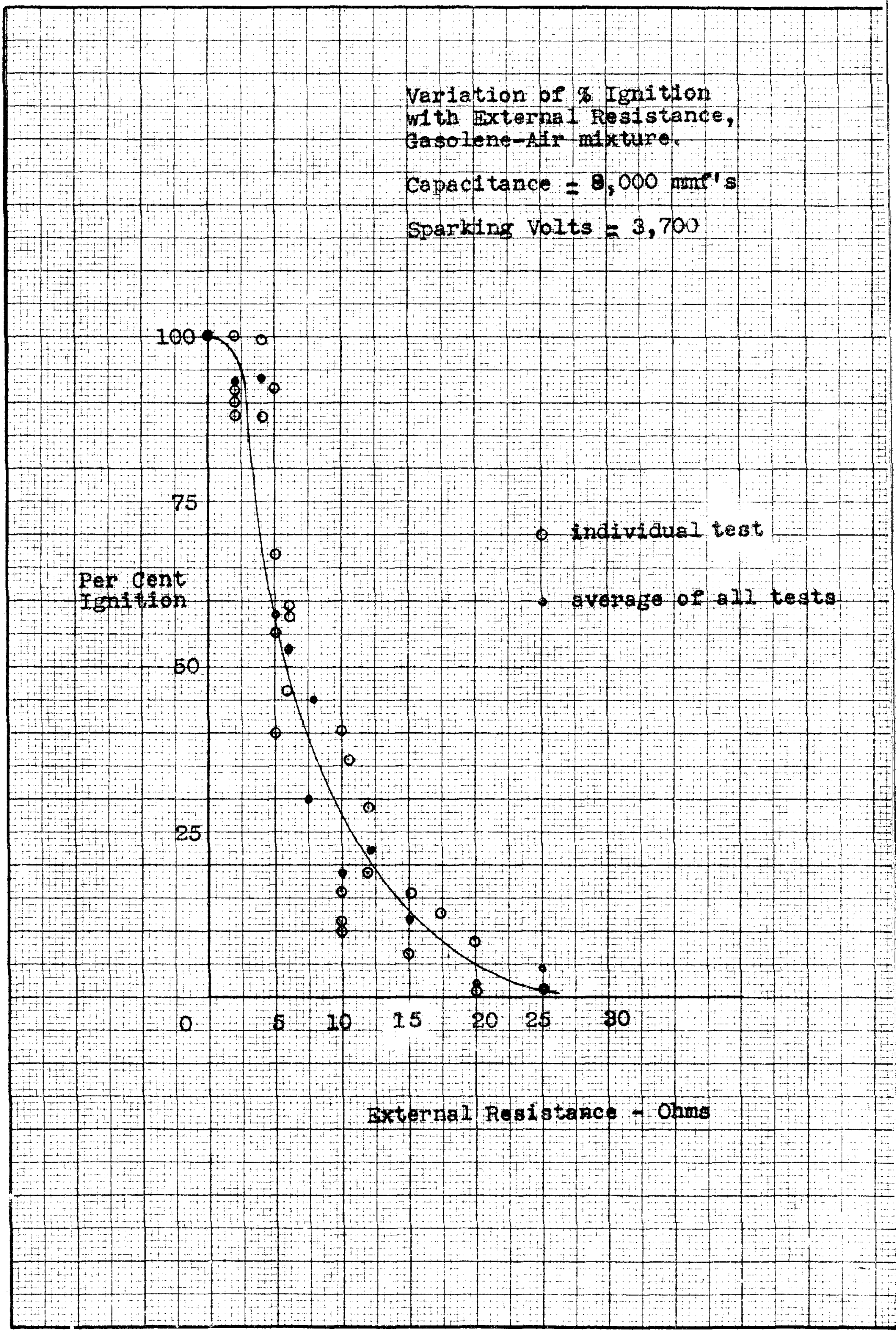
MINIMUM WATTAGE NEEDED TO IGNITE A COMBUSTIBLE MIXTURE

The results obtained with household gas, when resistance was added to the circuit, were duplicated almost exactly with gasolene. Thus, in Figure 20 is seen the effect of added resistance, when a sparking voltage of 3,700 volts was utilized with a condenser of 8,000 micro microfarads capacitance. In these experiments, 25 ohms were enough to reduce the igniting power of the spark to but a few per cent.

As was previously mentioned, this indicates that it is not merely the total energy dissipated in the spark that determines its ignition properties. The rate at which this energy is dissipated is a determining factor.

The wave form of the current through the spark gap must be known, if an exact determination of the rate of dissipation of energy is desired. A series of attempts were made to get oscillograms of the wave forms with different resistances and a constant capacitance, and with various capacitances but no external resistance. These attempts were not successful, though, mainly because of the high speed of the discharge, and the corresponding difficulty of using an ordinary cathode-ray oscilloscope to record the wave.

It is also virtually impossible to calculate the wave form, since the resistance of the spark varies so widely with current. When the spark is not conducting, its resistance is obviously infinite, When current is flowing, after the arc breaks down, the resistance depends on the current. Many different values of resistance are accordingly assumed during the discharge process. An attempt to solve the circuit equations



Variation of % Ignition with External Resistance, Gasolene-Air mixture.
Capacitance = 8,000 mmf's
Sparking Volts = 3,700
100
75
50
25
Per Cent Ignition
individual test
average of all tests
0
5
10
15
20
25
30
External Resistance - Ohms

Fig. 20

using some known variation of spark voltage with resistance has not been attempted. The determination of the exact effect of wave form on igniting properties of condenser discharges might well be a separate research project.

FILLING OF BALLOONS WITH HYDROGEN

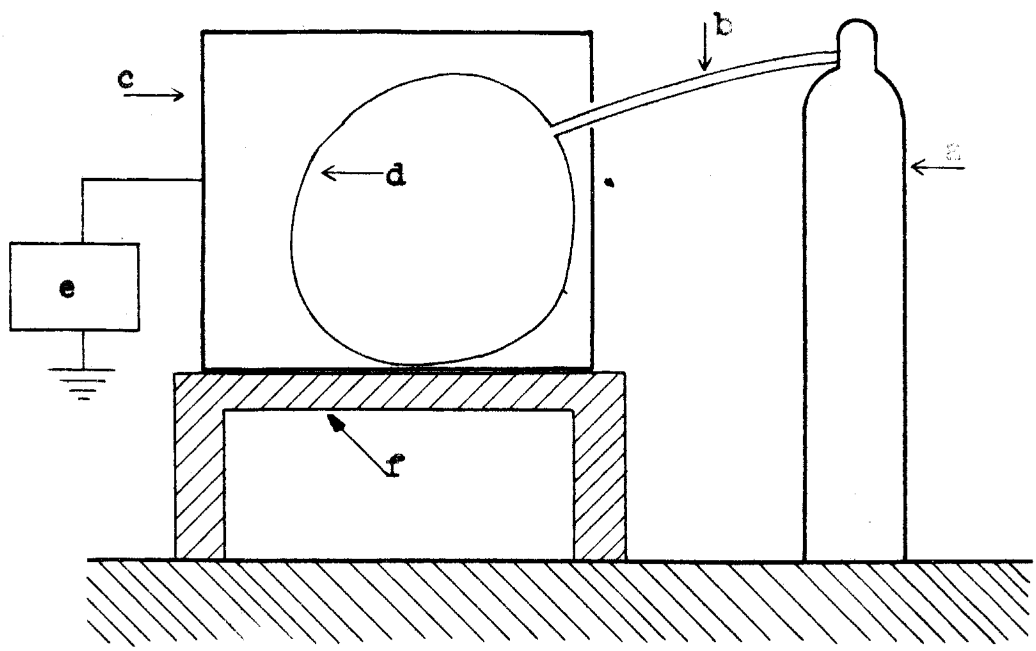
It is common practice in the United States Weather Bureau to fill sounding balloons with helium, rather than hydrogen. This is done because it is feared that static charges generated during the filling process might accumulate on the balloon, thus presenting a fire or explosion hazard.

However, hydrogen is a more desirable gas to use in every other respect. It is much less expensive and has greater lifting power. Accordingly, it was worthwhile to measure the charges generated during balloon filling processes, and, using the same methods of analysis applied to the filling of gasolene trucks, to determine if a hazard was present.

Measurements made indicated that a current of less than 10^{-10} amperes is generated when a balloon is filled with hydrogen from a standard hydrogen tank in the normal manner. Figure 21 illustrates how the measurements were made. The balloon rested inside a large metal container and was filled through a rubber hose. This metal container was supported on an excellent insulator, and was grounded through the micro-ammeter. Since the metal container is a perfect Faraday Cage, all charges brought into its interior, as explained on page 11,are recorded on the ammeter. If charges are brought in continuously, a steady deflection of the ammeter results.

Various rates of filling were used, ranging from a bare trickle of hydrogen to a flow that inflated the balloon to a 3-foot diameter in about 5 seconds. In all cases, currents were well below 10^{-10} amps.. It made no difference at all whether the hydrogen tank was grounded or

Fig. 21



Method of Measuring Static Charges Produced during the Filling of a Balloon with Hydrogen.

a - Hydrogen tank

b - rubber filling-hose

c - metal container surrounding balloon (Faraday Cage)

d - balloon being filled

e - ammeter

f - insulating stand

(not to scale)

ungrounded. This method using a Faraday Cage grounded through an ammeter to determine the charge brought into the system, has also been used to measure static charges generated by blowing dust through pipes. Currents from 10^{-10} to a microamp were recorded, indicating that there is nothing at all wrong with this method of making measurements.

Accordingly, we are safe in concluding that the maximum current that would ever be encountered in a weather-balloon process would be about 10^{-10} amperes.

Since the balloon is usually filled through a rubber hose of good insulating properties, we can assume that all the charge that enters the balloon remains in the interior or drifts to the surface. In that case, it is a simple matter to calculate the voltages that will arise. Assume that a balloon is filled to a 4-foot diameter in 30 seconds. Then, the charge present will be:

$$Q = i x t = 10^{-10} \times 30 = 30 \times 10^{-10} \text{ coulombs.}$$

The capacitance of a 4-foot diameter balloon is readily determined by the relationship:

$$C = \frac{r}{9} \times 10^{-11}$$

where "r" is the radius in centimeters, and "C" is in farads.

For a 2-foot radius balloon:

$$C = \frac{2 \times 12 \times 2.54}{9} \times 10^{-11} = 68 \text{ micromicrofarads.}$$

Then, the voltage to which the balloon is raised will be determined by:

$$V = \frac{Q}{C} = \frac{30 \times 10^{-10}}{68 \times 10^{-12}} = 44 \text{ volts.}$$

Thus, if the balloon charged by the hydrogen filling process, were brought near a grounded system, for instance, the filling tank, the voltage existing between the balloon and the metal would be about one-tenth of the minimum sparking potential. There would be absolutely no danger of any spark occurring.

Furthermore, even if the minimum sparking potential were exceeded, the energy represented by the charged capacitance of the balloon would be well below the 0.0034 joules below which no ignition takes place, as illustrated in Figure 19. This minimum energy held for gasolene and household gas, and it is reasonable to conclude that it will also hold approximately for hydrogen, since household gas consists mostly of hydro-carbon gases.

Finally, in the above discussion it was tacitly assumed that if a spark were to occur between a portion of the balloon and a grounded conductor, then all the energy stored in the balloon would be dissipated in the spark. This is not at all the case. If the balloon's surface were a conductor, then all the charges would be dissipated through the spark to ground. But the rubber balloon is an excellent insulator, and accordingly the charge only on that portion of the balloon in immediate contact with the grounded metal will be dissipated. All the other charges will leak across the surface to ground at a rate determined by the resistance and the voltage. Since the voltages, as shown previously are very small, and the resistances are very high, this discharge will take place very slowly. This is equivalent to putting a resistance of thousands of megohms in the circuit of Figure 14. Figure 17 shows that only about 30 ohms are needed to destroy the ignition abilities of a spark, so a spark with several thousand megohms is inconceivable.

The conclusion that filling weather balloons with hydrogen is perfectly safe, is unavoidable. The reasons can be easily summarized:

(1) Under normal circumstances, not enough charge is generated to raise the voltage of the balloon above the "Minimum Sparking Potential".

(2) If the potential were great enough to cause a spark, there isn't enough energy represented in a charged balloon to ignite a combustible mixture of gas and air, or hydrogen and air.

(3) Even if there were enough energy stored in the balloon to cause ignition, the high resistance of the discharge path, in case a spark should occur, would destroy the igniting ability of the spark.

GENERATION OF STATIC CHARGES BY MOVING RUBBER TIRED VEHICLES

It is common experience that a rubber-tired vehicle in motion often accumulates enough charge to shock a person who touches conducting portions of the vehicle after it has come to rest. The question naturally arises as to whether the charges thus generated represent a fire hazard to the Petroleum Industry.

We are all familiar with the "cat's whiskers" employed at toll bridges, for the purpose of draining off the charges on vehicles and eliminating shocks to the toll collectors. At gasolene filling racks, the equivalent of these "cat's whiskers" lies in the grounded bonding hose that is attached to the truck as soon as it pulls up to be loaded.

It is maintained by some that such measures do not permanently eliminate the hazard due to static charges generated by "tire friction". Their contention is that the vehicle is charged by induction. The tires, due to contact potentials, become charged because of the motion across the pavement. If the tires are charged negatively, they will repel electrons to the parts of the car most distant from the tires, and will leave the portions of the vehicle near the tires charged positively. If now, it is contended, the truck is grounded, all the repelled electrons will leave the truck, and the positive "bound" charges will remain near the tires. If the ground is now taken away, and the charge on the tires is dissipated, the "bound" positive charges will be free to redistribute themselves throughout the body of the vehicle, and the car will now be charged.

This is the well-known phenomenon of charging a conducting body by "induction". If the vehicle were charged by induction, then grounding the metal would indeed not be effective in permanently removing the static hazard, and the grounding systems employed by the Petroleum Industry would be useless.

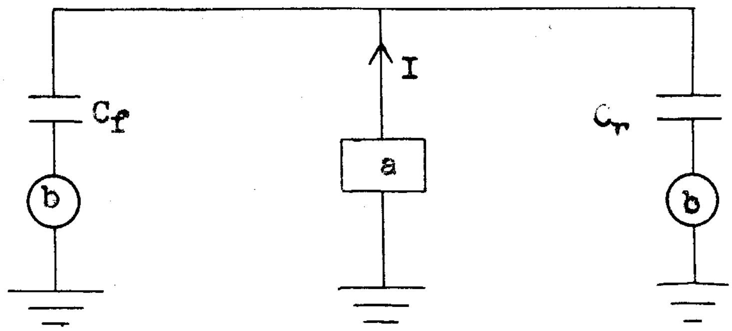
However, is the car really charged by industion? Those who advance this theory have made measurements of voltages to which vehicles have been raised. At any speed, a voltage is measured that is proportional to speed, up to a speed at which a flattening of the voltage vs. speed curve occurs. A "steady state" is supposed to be reached that determines the voltage to which the vehicle should be raised.

A very simple experiment establishes the fact that the vehicle is charged not by induction, but by actual conduction of the charges, through the tires to the metal body of the vehicle.

Consider a vehicle moving along a dry pavement, with an ammeter on the inside. One terminal of the ammeter is connected to the vehicle, and the other terminal of the meter is connected to a wire which is thoroughly insulated from the body of the car. This wire leads to a chain, also insulated from the body of the car, which drags in a grounded trolley track. When the vehicle is in motion a STEADY current is indicated by the meter. It is obvious that an induction process cannot produce a steady current. This current must be a conduction one.

More specifically, Figure 22 illustrates the electrical conditions that would be prevailing if the charging process were inductive. The condensers C_f and C_r represent the capacitance between the front tires and the body of the car, and the rear tires and the body of the car. The ammeter "a" between the body of the car and ground reads a continuous current, "I", by experiment. This last condition is unobtainable if Figure 22 is a true representation of the phenmmenon.

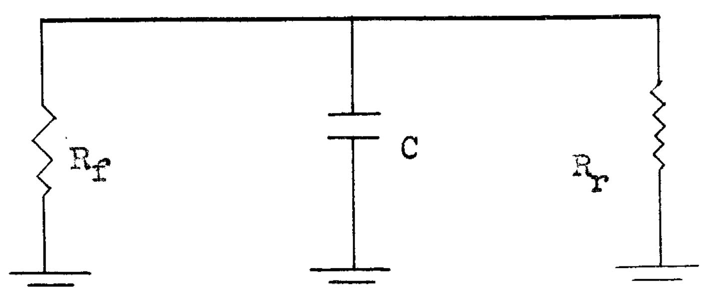
Fig. 22



Equivalent Electrical Circuit of Vehicle being Charged by Static Electricity, According to the "Induction Theory".

a - ammeter
b - static charge generators
C_f - capacitance between front wheels and vehicle body
C_r - capacitance between rear wheels and vehicle body

Fig. 23



Equivalent Electrical Circuit of Vehicle at Rest, According to the "Conduction Theory".

R_f - Resistance of front tires to ground
R_r - Resistance of reat tires to ground
C - Capacitance of body of car to ground

The fact that a steady current has been experimentally demonstrated to exist for an indefinite period of time, shows that the current must be flowing in reality through the tires. This conductive current is so large, that any currents due to inductive effects may be neglected. The inductive effects, due to the existence of charges on the surface of the tires in proximity to the body of the vehicle, can cause a slightly different distribution of charges on the surface of the vehicle. The potential of the car, however, is constant at all points, and is determined by the IR drop.

The conclusion that the car is charged by conduction through the tires, rather than by induction, is mandatory.

The "electrical equivalent" of a car standing still is illustrated in Figure 23. The main body of the car is connected to ground through the resistances of the front tires and the resistances of the rear tires. The capacitance of the car to ground shunts these two resistances.

It was difficult to make accurate measurements of currents generated on the road. Accordingly, in the attempt to determine the currents generated by moving vehicles, experiments were conducted on an engine-testing dynamometer stand. This device is essentially a large prony-brake. The rear wheels of the automobile rest on a drum that is free to revolve. Thus, the rear wheels can be driven at a rate corresponding to any desired road speed, and, if desired, different load conditions can be simulated by applying a friction load to the revolving drum.

In making measurements of currents generated, the body of the car was grounded through a microammeter. The currents generated were large

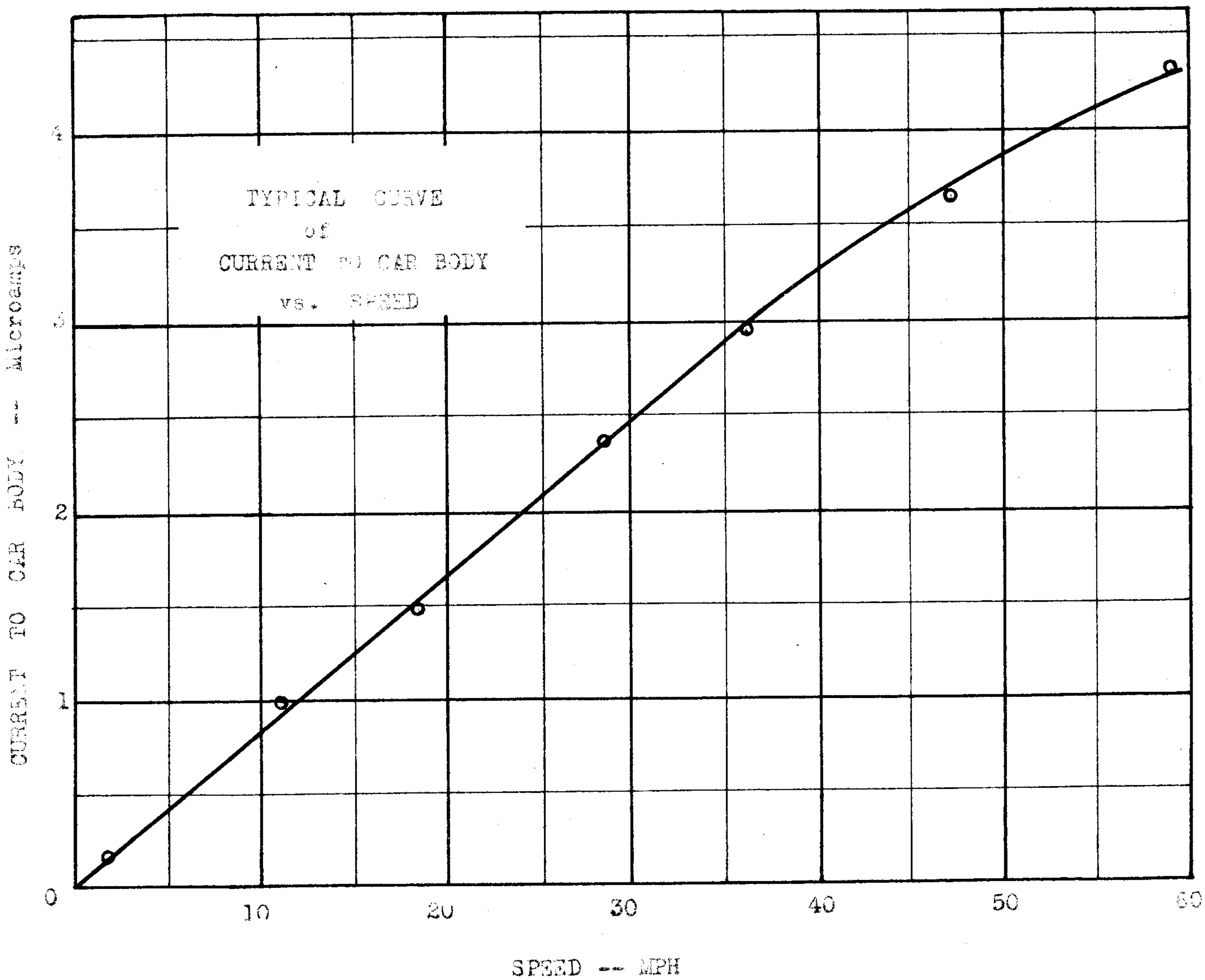

TYPICAL CURVE
of
CURRENT TO CAR BODY
vs. SPEED
CURRENT TO CAR BODY -- Microamps
SPEED -- MPH
0
1
2
3
4
10
20
30
40
50
60

Fig. 24

enough so that an ordinary microammeter could be employed.

Figure 24 is a typical curve of current measured vs. speed. The data were taken with a 1941 Chevrolet having the standard 6:00-15 tires. This curve was duplicated about twenty times over a period of 10 months, within 10 per cent. The external atmospheric conditions had no noticeable effect on the measurements. Various tire pressures were used, and a wide range of loads was applied to the dynamometer. However, these loads had very little effect on the currents generated.

When the rubber tire comes in contact with the pavement, or dynamometer drum, a difference of potential is set up between the faces of the rubber and pavement, and a charge is separated. As the tire moves from this position, due to the rolling along the dynamometer, the potential of the charges must increase. As the potential increases, the charges seek a path to ground. Experiments have led us to the conclusion that two paths are taken; one path is directly across the tires to the car body, and from the car body to ground through the ammeter. The other path is back along the surface of the tire to the grounded dynamometer, or, in the case of a moving vehicle, to the ground plane existing under the pavement. Thus, the equivalent circuit of a car on a dynamometer stand would be represented in Figure 25. There is a current "I" that has two paths to follow: one to the wheel through the resistance of the tires, R_w, to the car body, and through the ammeter to ground; and the other back to ground across the surface of the tires, through a "shunt" resistance R_g.

The experiment that indicates the existence of two paths is a simple one. A series of current vs. speed readings are taken. Then,

EQUIVALENT ELECTRICAL CIRCUIT

OF CAR ON DYNAMOMETER STAND

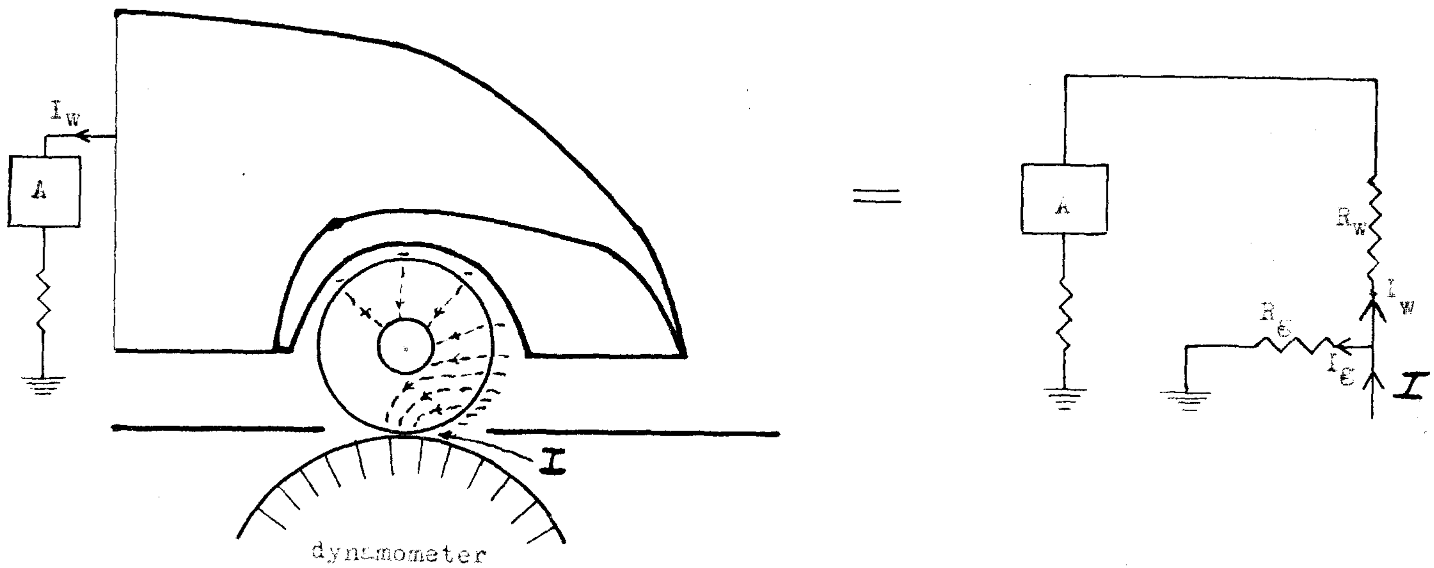


Fig. 25

the tires are coated with a conducting mixture of carbon and an adhesive agent. This coating extends from the hub of the wheel to within an inch of the outer edge of the sidewall of the tire. The tread is not touched, so that, with the same speeds as before, the same total currents are generated, since the entire seat of the generating process is in the tread. However, with this conducting bead on the tire, larger currents are measured for the same speeds. This clearly indicates that the meter connected to the car does not read all the current generated, but only records that percentage of the total current generated that seeks ground through the body of the tire to the wheel.

It is much more reasonable to assume that a constant <u>current</u> is generated for a given speed, or a current proportional to speed is generated, than to assume that a constant voltage is generated. After all, the "contact potential" phenomenon is essentially a charge producing process. The voltages that may exist will be determined by the resistances and capacitances present. Therefore, the reason the curve in Figure 24 flattens out at high speeds is probably that the relative values of R_W and R_g change.

With increased speed, it is to be expected that the tires will warm up. Rubber, as compounded and used in tires, has a negative temperature resistivity coefficient. Therefore, the tread, and the surface of the tire near the tread, will decrease in resistance much more than the main body of the tire, since the tread is heated the most. And, since most of R_g resides in the tread, and in portions of the tire near the tread, R_g decreases much more than R_W as the wheels speed up.

A greater proportion of the total current generated thus goes to ground through the "shunt" path, and the readings of the ammeter flatten out.

It is impossible to determine directly the total current generated at any particular speed. This can be seen if Figure 25 is rearranged into an equivalent π network, as is done in Figure 26. From 4-terminal network theory, it is known that three independent measurements must be made to determine the characteristics of the circuit. This means that two measurements must be made on one side of thenetwork, and one on the other. This is physically impossible, though, for we cannot possibly get to the side where the constant current "I" is being injected into the circuit.

However, if we analyze Figure 26, certain interesting results may be obtained. The total current "I" divides up between the two possible circuits to ground, one through the "leakage resistance" R_g back to the grounded dynamometer, and the other through the tire to the car body and through any external resistance, R_e, that we may care to insert in the ammeter circuit, back to ground. It is seenthat:

(1) $I = I_w + I_g$, where only I_w may be measured.

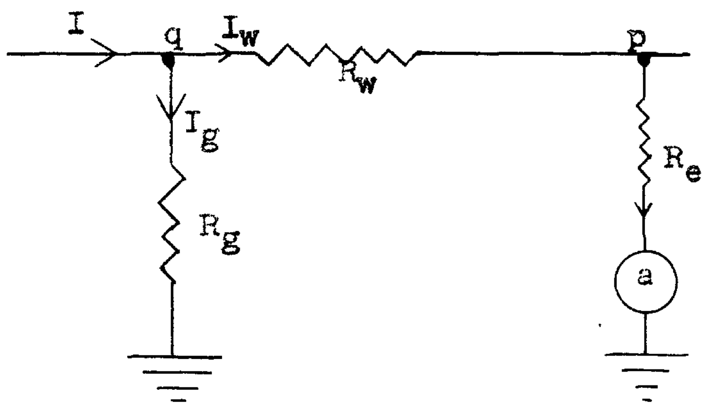
However, we may also write, because of the equal voltage drops between point "Q" and ground, that:

(2) $I_w(R_w + R_e) = I_g R_g$

Solving Equation (2) for I_g, and substituting back into (1), yields:

$$I = I\ (1 + \frac{R_w + R_e}{R_g})$$

fig. 26



Equivalent Circuit of a Vehicle on a Dynamometer Stand rearranged into a π Network.

I - total current generated

I_w - current to body of car across wheel

I_g - current back to dynamometer stand, along tread and surface of tire.

R_w - resistance to body of car through tire.

R_g - "leakage" resistance to dynamometer.

R_e - external resistance added in ammeter circuit.

a - ammeter

p - body of car

q - fictitious point on tire, where constant current is assumed injected into the system.

or, finally:

$$(3) \qquad \frac{1}{I_w} = \frac{1}{I} + \frac{R_w}{IR_g} + \frac{R_e}{IR_g}$$

Equation (3) implies that if we plot the reciprocal of the measured current against the external resistance inserted, for a constant generated current "I"; i.e., for a constant speed, a straight line should result. The slope and intercept will yield values of R_g and R_w in terms of the total current generated. For, if (3) were to be written in the form:

$$y = b + mx,$$

it is obvious that:

$$b = \text{intercept} = \frac{1}{I}(1 + R_w/R_g)$$

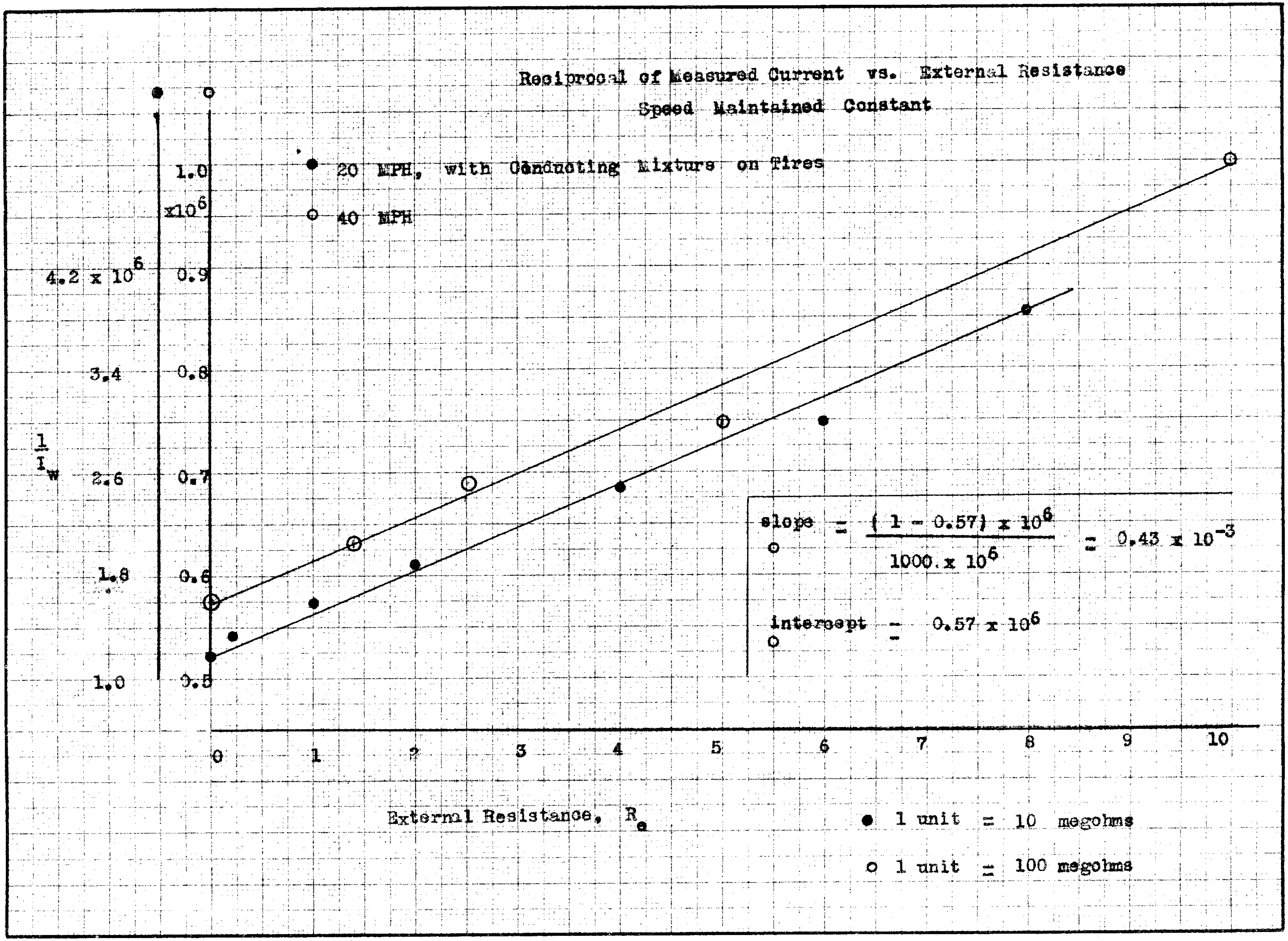
and $$m = \text{slope} = 1/IR_g$$

Therefore,

$$\text{intercept/slope} = R_g + R_w \, .$$

Many runs were made in which the speed was held constant, and external resistance added. Two typical plots of the inverse of the current measured vs. the external resistance, for a constant speed, are shown in Figure 27. It is seen that a straight line results.

It should be pointed out that this does not prove that the equivalent circuit hypothesized is the only one possible. If it is assumed that a constant potential is generated, a corresponding analysis will yield a straight line relationship when $1/I_m$ is plotted against R_e. It is also undoubtedly possible to assume that "I" varies with R_e, and R_w and R_g also vary in some manner to yield the results obtained. However, the assumption of constant current is the more logical one.



Reciprocal of Measured Current vs. External Resistance
Speed Maintained Constant
● 20 MPH, with Conducting Mixture on Tires
○ 40 MPH
1/I_w
4.2 x 10^6
3.4
2.6
1.8
1.0
1.0
x10^6
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
5
6
7
8
9
10
slope ○ = (1 - 0.57) x 10^6 / 1000. x 10^6 = 0.43 x 10^-3
intercept ○ = 0.57 x 10^6
External Resistance, R_e
● 1 unit = 10 megohms
○ 1 unit = 100 megohms

Fig. 27

One of the two groups of data plotted in Figure 27 is for a speed of 40 MPH, and it is seen that external resistances of 1,000 megohms had to be added to get an appreciable change in I_m. The other group was taken withthe rear tires coated with a conducting mixture of carbon. The speed was kept down to 20 MPH to obviate the difficulties arising from the conductor flying off the wheel. It is seen that only 80 megohms in this case was enough to change the readings considerably. This, of course, is to be expected, since R_w and R_g are much less than previously existent.

For the 40 MPH data, it is to be seen that the slope is 0.43×10^{-3}, and the intercept is 0.57×10^6. Therefore,

$$R_w + R_g = \frac{0.57}{0.43} \times 10^9 = 1325 \text{ megohms.}$$

The corresponding data for the "conducting" tires yield a value of $R_w + R_g = 41.3$ megohms.

Without a knowledge of "I", it is impossible to determine the exact values of R_g and R_w. There is also no point to trying to guess a value of "I", to see if it yields consistent results. Any value guessed will yield consistent results, since all the measurements made are not linearly independent. As was stated previously, to determine the circuit completely, three independent measurements must be made. Making a series of current readings in the R_e branch does not yield independent data.

However, it is interesting to note what the slope yields. The slope is I/IR_g. Therefore, the reciprocal of the slope is IR_g. This is the voltage to which the car would be raised if all the current generated were to be dissipated through the "shunt resistance" to ground. This situation is approximated when extremely high external resistances R_e are used. For the data taken with the normal tire, this value is:

$$V = \frac{1}{0.43} \times 10^{-3} = 2,320 \text{ volts.}$$

This order of magnitude of voltage has actually been measured. If an electrostatic voltmeter is applied to the car, instead of an ammeter, then R_e will be the resistance of the front tire and the surface leakage over the pavement to ground. Since very little current will be flowing through R_w, the drop across it will be very small, and a voltmeter attached to the point "p" of Figure 26, corresponding to the body of the car, will be measuring the voltage of "Q".

It would be very desirable to determine a "generating constant", such that we could say the total current generated at any speed is $I = kS$, where "k" is this generating constant and "S" is the speed of the vehicle. However, since it is impossible to measure "I" experimentally, or perform independent experiments that will yield "I" indirectly, the best that can be done is to establish an order of magnitude of this constant.

The highest current measured in these experiments was 10 microamps. at a wheel speed corresponding to 50 MPH. This was obtained when the wheels were coated heavily with a conducting mixture, so that the resistance between the body of the car and the edge of the coating, which extended to within $\frac{1}{2}$ inch of the tread, was less than 300,000 ohms. The tread surface resistance was well over 500 megohms between test probes spaced 3 inches apart.

This value of 10 microamps. at 50 MPH yield a value of "k" equal to 0.5 microamps. per MPH. It is reasonable to assume that this is the order of magnitude of the constant for the total current generated. A factor of possibly two or three may be omitted, but this is most probably the order of magnitude involved. Since this "k" was taken for two tires, the value for one tire would be 0.25 microamps. per MPH.

Various brands of tires were tested, and they all yielded currents of the same order of magnitude. The behavior of the measured current vs. speed curves was the same as that illustrated in Figure 24.

In all the experiments, the car was charged negatively, indicating that the rubber tire receives that sign charge when leaving the pavement. Figure 28 shows a typical time variation of current generated, for a constant speed. This variation occurred only at the beginning of any set of experiments; it is probably best explained by the fact that the tires were relatively cool, and there probably was a film of moisture on the surface of the sidewalls, thus decreasing R_W considerably. After a minute or so, most of the moisture was driven off by evaporation, due to the speed of the wheel, or by the heating up of the tire. Figure 28 was determined at a constant speed of 40 MPH. It is seen that after about 30 seconds there is little change in the current measured. All the readings taken during the course of the experiments were made after this "steady state" had been reached.

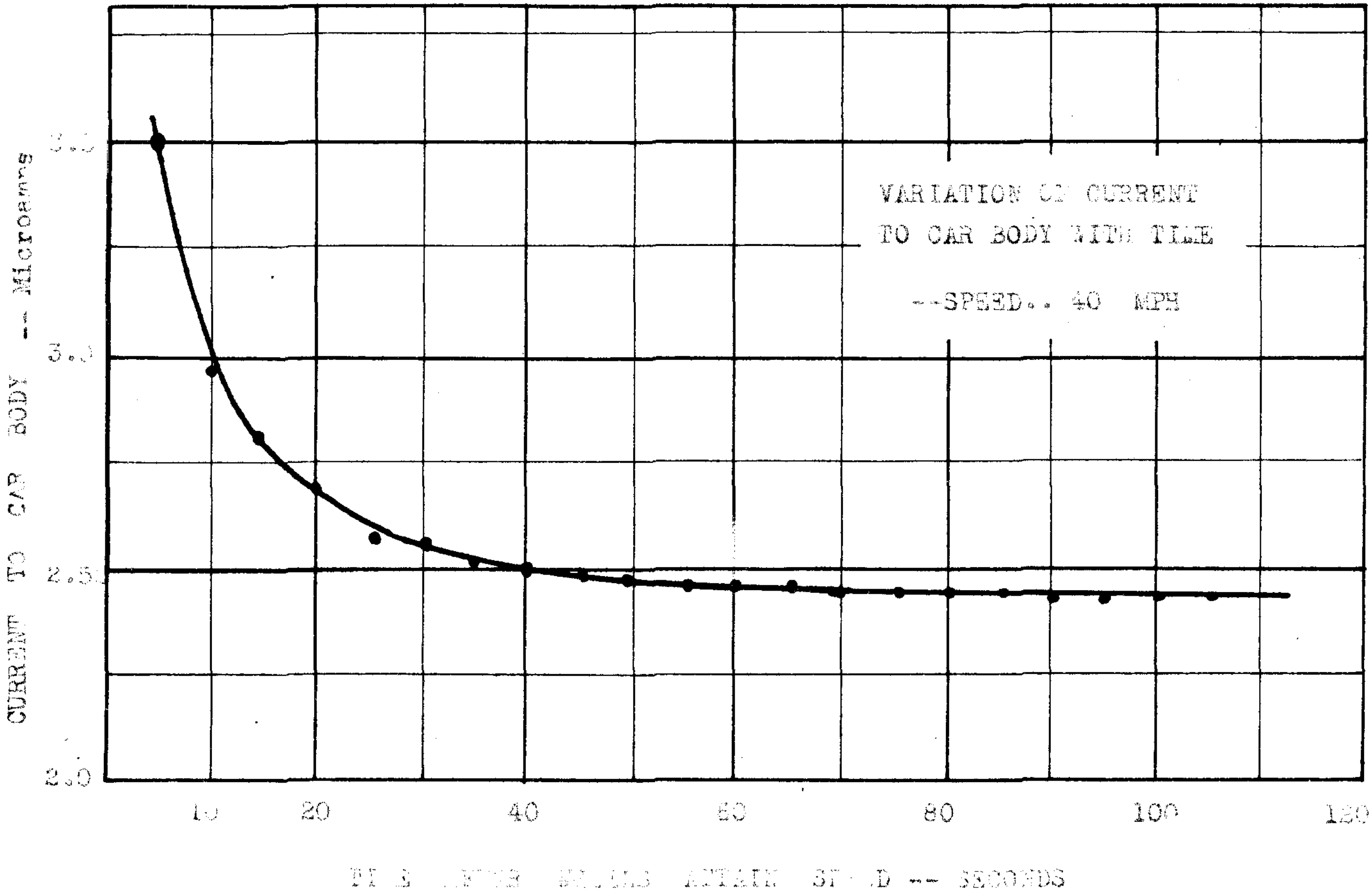

CURRENT TO CAR BODY -- Microamps
--SPEED.. 40 MPH
2.0
20
40
80
120
-- SECONDS

Fig. 28

Further tests were made in which a layer of tinfoil was put under the front tires, the tinfoil being insulated from ground by means of rubber mats. The tinfoil was then grounded through the microammeter. As soon as the rear wheels started to turn, the microammeter indicated a current of about half the size previously encountered, and a voltmeter connected between the car body and ground read several thousand volts. This, of course, is equivalent to inserting a very high R_e in the circuit of Figure 26. Those who previously made measurements of voltage, in attempting to analyze the problem of tire static, were performing this identical experiment, without realizing that the voltages measured could be correlated directly to an IR drop through the front tires.

This identical experiment was repeated when the rear tires had been coated with the conducting mixture. Under these circumstances, virtually no current flowed through the front tires, and no reading could be obtained on the voltmeter. This is to be expected, since adding the conducting coating decreases R_g, besides reducing R_w. Thus, the series combination of R_e and R_w, since the resistance of the front tire was well above 1,000 megohms, was much greater than R_w. Accordingly, most of the current generated was shunted to ground along the "leakage" path, rather than going to the car.

It is seen that the problem of keeping down the car's voltage resolves itself into keeping down the value of R_g. Figure 29 shows an "electrical equivalent" of a vehicle moving with uniform speed. All four wheels were generating current, but only one is indicated. As the

EQUIVALENT ELECTRICAL CIRCUIT
OF CAR MOVING ON ROAD AT A
UNIFORM SPEED

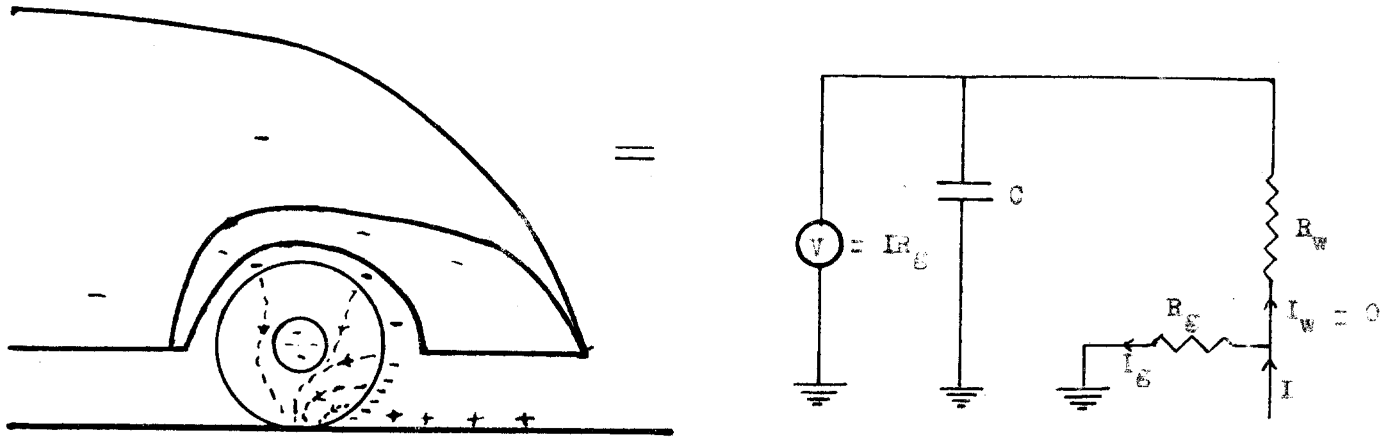


Fig. 29

car starts moving, the total current "I" divides between the two possible paths. The current through R_w goes into charging up the capacitance of the car. Once the capacitance is charged up to a voltage equal to IR_g, no further current can flow to the body of the car. If R_g is low, then the voltage will be low.

The drag chain commonly used on gasolene trucks would be represented by another resistance shunting "C". However, in series with the resistance of the chain itself, is the surface resistance of the pavement. On dry days, when this surface resistance is high, the supposedly low drag-chain resistance is obviously of no aid in serving as a leakage path for the car capacitance. On damp days, R_g is usually low enough to eliminate the necessity of a drag chain. Furthermore, we made over two dozen measurements of the resistances between the body of a truck and a metal plate resting under the drag chain. Almost all these measurements showed a value of resistance greater than 2,000 megohms. This is due to the fact that rust and dirt accumulate between the links of the chain, acting as excellent insulators.

Conducting tires is an answer to the static problem. Since they offer a very low value of R_g, it would have to be an exceptionally dry pavement for any voltage to build up. On a normal day, when pavement resistances are not more than a few hundred megohms, conducting tires will prove particularly useful. A non-conducting tire, after a short driving period, will have its moisture driven off, and a large R_g will ensue due to the tire itself, even though the contribution from the pavement surface may be small. Conducting tires will elminate the ensuing voltages.

Experience has proven this theory to be correct. The Pasadena Police Department used to have trouble with their car transmitters and receivers, because of "tire static"; i.e., because of discharges from the car to metal objects on the pavement, or brush discharges across the surface of the tire. Low resistivity tires eliminated all this difficulty.

Data were also taken with vehicles actually in motion. However, it was rather difficult to get good readings. First of all, other cars passing nearby would induce currents of the order of magnitude of those being measured. Mechanical meters, sensitive enough to read the currents generated, were not rugged enough to stand the inevitable bouncing they would receive in a moving vehicle. Electronic meters were too susceptible to outside influence, such as power lines, etc.. Despite this, the data obtained checked well with what might be anticipated from the dynamometer tests.

In the road tests, a chain about 10 feet long was dragged in a railroad track, serving as a constant ground. The chain was insulated from the car by means of a wax-impregnated rope which also served as the strain absorber. The wire leading to the ammeter inside the car, as described on page 43, was insulated from the metal of the car by vacuum-held rubber cups. Accordingly, measurements could be made corresponding to I_w of the dynamometer experiments.

The most reliable data obtained are listed in Table II., with the operating conditions detailed.

Table II.

Data Obtained on Road

Speed MPH	Current Measured Microamps.	R_e megohms	Remarks
10	3.0	0	All tests were made on an asphalt pavement
20	4.8	0	
10	2.5	100	
10	4.5	0	Conducting carbon layer on all four tires
10	1.5	0	Both right tires on grounded railroad track
10	2.0	0	Conducting carbon layer on right two tires, on railroad track
10	1.5	60	Conditions as above.

It is seen from this table that the order of magnitude of currents generated is the same as that encountered on the dynamometer. Closer correlation is scarcely to be expected. The materials producing the charges are different; i.e., on the dynamometer it is rubber against metal, while in these tests it was rubber against asphalt.

We may see further, from the data taken with the right wheels in the grounded track, that reducing the value of the "leakage resistance" to ground will reduce considerably the amount of current going to the car. On the dynamometer stand, the only contribution to R_g, as mentioned above, was the rubber between the charges and the grounded dynamometer, while on the road, the pavement resistance is added. Therefore, driving on the tracks should reduce the current to the car, since the "leakage" path to ground is now of lower resistance. With the wheels on the track, additional resistance in the grounded part of the circuit has a much greater effect than if the wheels are not in the track, as may be seen from entries #3 and #7 in Table II.. Referring to Figure 26, it is seen why this should be so. With the wheels in the track, R_g is relatively small, so putting in additional resistance, R_e, will force more of the generated current through the "leakage" path to ground, thus decreasing the ammeter reading.

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The method of charging rubber-tired vehicles has definitely been established as a conduction process. Accordingly, grounding the charged vehicle, as is practiced at all petroleum loading racks, is entirely adequate for the purpose of eliminating all the hazards due to the charges generated by the vehicle in motion on the highway. Also, since this same procedure of grounding the vehicle is desirable during the filling process, the present precautionary measures employed throughout the Petroleum Industry are to be recommended.