The Design, Operation, and Performance of the Round Hill Electrostatic Generator

L. C. VAN ATTA, D. L. NORTHRUP, C. M. VAN ATTA* AND R. J. VAN DE GRAAFF, *Massachusetts Institute of Technology*

(Received March 25, 1936)

The design, technique of operation, and performance of the Round Hill electrostatic generator are presented in some detail. The problems of operating wide paper belts, of eliminating vibration, and of controlling humidity are discussed. The original belt charging system, with the belts operated at saturation charge density, is described and its range of usefulness is indicated. A consideration of the problems of voltage control and voltage steadiness at reduced charging currents leads to two modified designs of the belt charging system. The measurement of voltage by means of the generating voltmeter is discussed with special emphasis on the precautions necessary to eliminate or to correct for sources of systematic error. Under the conditions realizable with the Round Hill generator the probable error in voltage measurements is less than one percent on a relative scale and about two percent on an absolute scale. The magnitude of voltage fluctuations is less than 0.1 percent. The generator performance data for the positive and negative terminals are given in graphical form. The maximum charging current is 2.1 ma and is practically independent of voltage. The highest voltage obtained consistently without sparking is 2.4 megavolts positive and 2.7 megavolts negative, giving 5.1 megavolts between the terminals. At this voltage there is 1.1 ma of current available for application to an accelerating tube.

IN 1933, there appeared a general discussion[1] of the principles involved in the electrostatic production of high voltage by means of belt generators operating at atmospheric pressure. There was included a brief description of the external structure of the Round Hill electrostatic generator. During the intervening period a belt-charging system has been designed, constructed, and improved, so that a very steady, controllable voltage is now available for nuclear research. Complete generator performance data have been obtained through the utilization of the generating voltmeter which, with proper precautions, has proved to be a convenient and reliable instrument for voltage measurement.

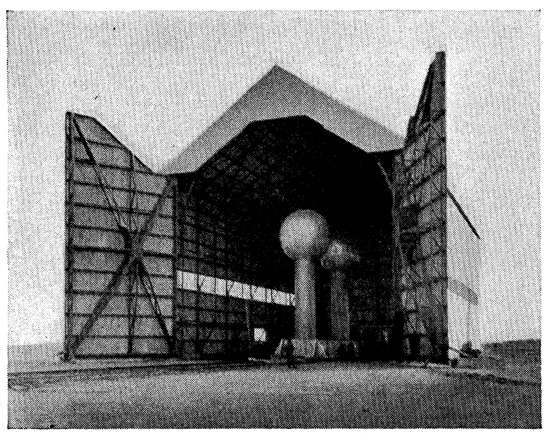

FIG. 1. Electrostatic generator and housing.

EXTERNAL STRUCTURE

The generator structure consists essentially of two spherical terminals supported by cylindrical insulating columns on steel trucks. The spheres are made of aluminum alloy 15 feet in diameter with walls $\frac{1}{4}$ inch thick. The insulating columns are cylinders of Textolite 22 feet in length of free insulation, 6 feet in diameter, and of $\frac{5}{8}$ inch wall thickness. The steel trucks act as heavy bases for the generator units and house the driving and accessory equipment. An electrically-driven winch, with an endless cable passing under the trucks, is used to transport the generator units along a 14-foot gauge railroad track. As shown in Fig. 1, a steel building 140 feet long, 75 feet wide, and 75 feet high houses the generator and the laboratory and shop rooms. Structural girders supporting the roof limit the unobstructed ceiling height to 60 feet. Further details relating to the external structure have been given previously.[1]

BELTS AND PULLEYS

In each generator unit electrical charge is conveyed to the spherical terminal by means of two simple belts running inside the supporting

* National Research Fellow, July, 1933 to March, 1935.
[1] R. J. Van de Graaff, K. T. Compton and L. C. Van Atta, Phys. Rev. 43, 149 (1933).

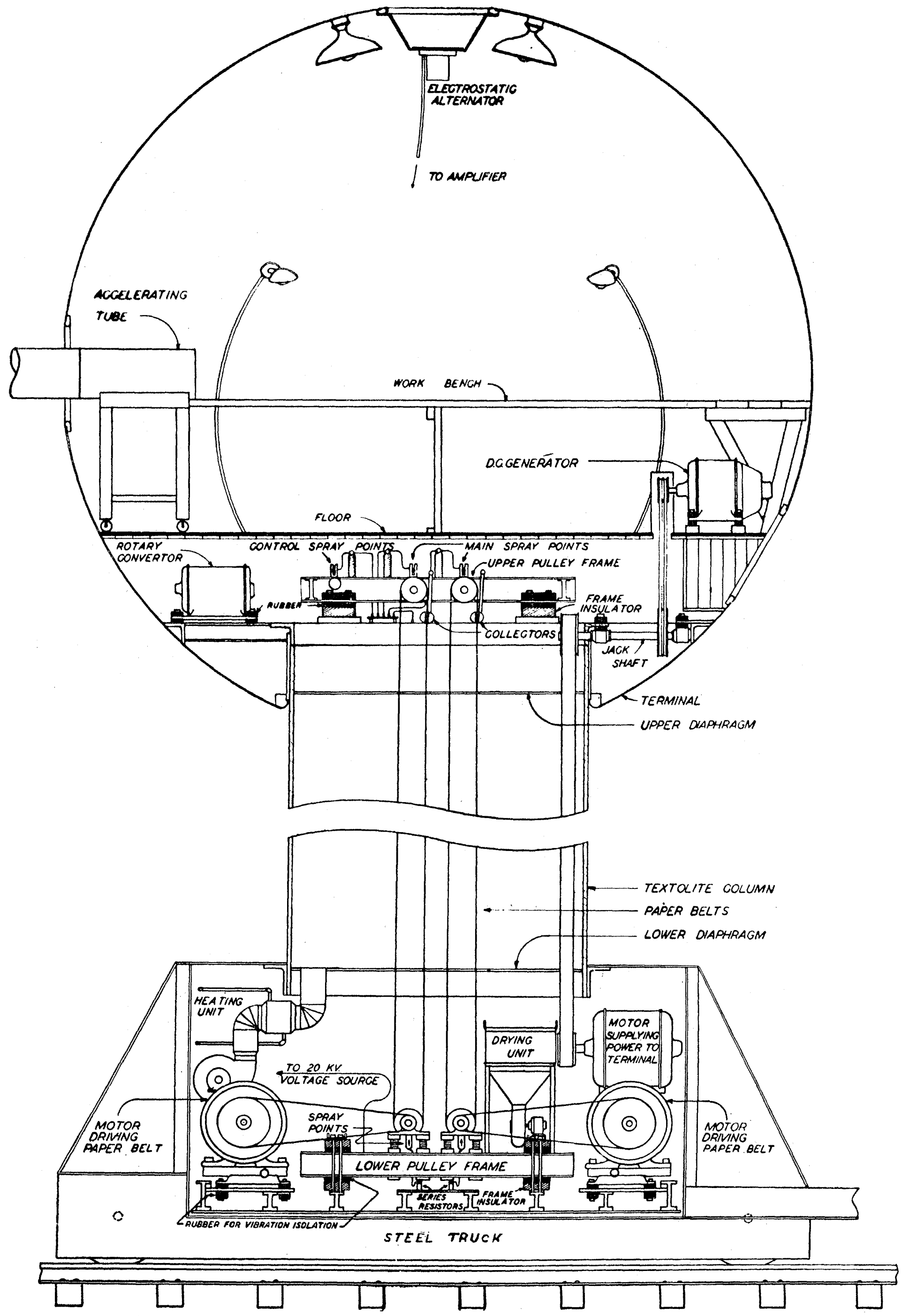

FIG. 2. Sectionalized view of the interior of one generator unit showing the belt-charging system and auxiliary equipment in terminal and truck.

column as shown in Fig. 2. The belt material is electrical insulation paper[2] 0.017 inch thick and 47 inches wide. This material satisfies very well the electrical and mechanical requirements and has the advantage of being inexpensive as compared with silk or rubberized fabric. The seams are made on a 45-degree bias for greater strength and smoother operation. The edges to be joined are tapered to bring all laminations of the paper into the joint and to preserve a uniform belt thickness. A celluloid-base belt cement[3] is used for the joints instead of glue because of its superior electrical properties and its flexibility at low humidity.

Proper initial conditioning is essential to the successful operation of such a wide paper belt. After being mounted between pulleys in the generator column the belt first undergoes a two-day period of stretching under a tension of about 1000 pounds between pulleys at a relative humidity greater than 75 percent. The belt is then dried over a period of about three days while the humidity is gradually reduced to approximately 25 percent. The belt lengthens by about 0.3 percent of its length during the stretching period and contracts by about 0.2 percent upon drying. The pulley is not allowed to turn until the belt is dry since a damp belt tends to crease as it runs over the pulley.

The belts are carried on steel pulleys 6 inches in diameter and 50 inches long, the lower pair acting as drivers and the upper pair as idlers. The pulleys are of seamless steel tubing having chrome-vanadium forged end plugs which extend with reduced diameter to provide substantial shafts. Self-aligning ball bearings are shrunk onto the shafts and are housed in solid pillow-blocks. One shaft of each of the lower pulleys extends through the bearing for a belt drive to a 10 hp induction motor. An endless rubberized fabric flat belt and a constant-tension motor base[4] are employed to obtain a quiet and efficient drive. Each pair of pulleys is mounted on a heavy square frame of channel iron so that the pulleys and frame can be isolated as a unit, mechanically and electrically.

[2] John A. Manning Paper Co., Troy, N. Y.
[3] Sea Lion Waterproof Belt Cement, Chicago Belting Co., 113 North Green Street, Chicago, Ill.
[4] The Rockwood Mfg. Co., Indianapolis, Ind.

Because of the small stretch in dry paper belts, the pulleys require little crowning. The crowning actually employed is $\frac{1}{32}$ inch in the 6 inches diameter, applied as a uniform taper on the last 4 inches of pulley at each end. Since the pulley is 3 inches wider than the belt only part of this crowning is effective when the belt is centered. The pillow-blocks of each lower pulley are mounted on heavy threaded studs in the supporting frame to provide a sensitive means for adjusting the level of the pulley, since the centering of the belt, as well as its tension, depends critically upon this adjustment.

Two pulley speeds are provided, 3600 r.p.m. and 2880 r.p.m., corresponding to belt speeds of 5650 f.p.m. and 4520 f.p.m. At the higher speed the two belts enter the sphere at the rate of 44,200 sq. ft. per minute. The windage loss per belt is approximately 4 kw at the higher speed and 2 kw at the lower speed. The no-load power consumed by both units of the generator in operation at the higher belt speed is then 16 kw, while the full-load power consumed is 26 kw.

Vibration Isolation

Because of the necessity of using sensitive measuring instruments in the terminal, mechanical vibration and noise must be reduced to a minimum. This has been accomplished by mechanically isolating all moving parts, as indicated in Fig. 2, and by absorbing inside the terminal such noise as is transmitted to it. In addition the heavy pulleys for the paper belts were dynamically balanced until the amplitude of their vibration when rotating at 3600 r.p.m. in free support was less than 0.002 inch.

For isolating the upper and lower pulley frames and all the heavy machinery a soft rubber[5] was used. In the case of lighter equipment and machinery a sponge rubber[5] proved more satisfactory. In addition, all the equipment within the truck is mounted on a heavy false floor, which is supported at the corners on soft rubber. In all cases a one-inch thickness of rubber was used with the proper area to obtain a ten percent deformation in the rubber under the isolated load. The maximum load per square inch is about 100 lbs. for the soft rubber and 10 lbs. for the

[5] United States Rubber Co., Passaic, N. J.

sponge rubber. Because of the marked improvement in quietness of operation gained by such efforts, vibration isolation has been extended to include every piece of machinery associated with the generator.

The interiors of the metal terminals would have extremely poor acoustical properties if a large area of sound absorbing material were not provided. This is partly accomplished by a $\frac{5}{16}$-inch sponge rubber flooring. Additional absorbing area may be obtained by "quilting" $\frac{1}{4}$-inch flameproof felt[6] to the metal wall.

Humidity Control

In the case of any high-voltage, low-current generator, insulation requirements are severe. The unusually high average relative humidity and the fact that the hangar is not completely weather-tight, make this problem exceptionally serious at Round Hill. The average relative humidity is approximately 84 percent during the summer months and 74 percent during the winter months. Normally the hangar is about 300 yards from the sea, but during extreme high tides has been entirely surrounded by water.

The space inside the column and truck is carefully enclosed to make humidity control practicable. Both heating and drying are employed to reduce the humidity. The heating system consists of an automatically operated kerosene water heater mounted on the outside of the truck, a water circulation system which includes a gear pump, an automobile radiator inside the truck, and a blower for circulating the air of the truck through the radiator and into the column. A heater output equivalent to 4 kw is sufficient to maintain the truck and column 10°C above the surroundings, but ten kilowatts are available for emergency use.

The drying system consists of three trays each containing 30 pounds of Silica Gel.[7] Two trays are mounted over small blowers in the truck. The third tray is reactivated outside the truck over a combination blower and heater which circulates air at 160°C through the tray. The trays in the truck are replaced alternately at 12-hour intervals. Water is removed from the air at the average rate of one-quarter pound per hour.

The combined heating and drying systems described above and indicated in Fig. 2, maintain the inside humidity below 35 percent with an outside humidity of 100 percent. Experience has shown that this renders the maximum working voltage of the generator independent of weather conditions.

The resistance of the Textolite column supporting each of the terminals has been maintained above 10^{10} ohms by coating the outer surface with ceresin wax and by keeping the interior of the column warm and dry. The insulation requirements for the charging belts are especially stringent because of the high gradients imposed upon them in the region of the charging mechanism and at the entrance to the high voltage terminal. For this reason the belts are of electrical insulation paper and are maintained thoroughly dry.

Power Supply in the Terminals

Both a.c. and d.c. power are supplied to the laboratories in the high voltage terminals. For reasons of economy, 6 kw of d.c. power are initially developed to care for the major heating and lighting demands, while a 1 kw inverted rotary converter supplies a.c. where this is essential. The long vertical drive from a motor in the truck to the d.c. generator in the terminal was accomplished, as shown in Fig. 2, by the use of a large-diameter, flanged paper pulley at the top, a rubberized fabric endless belt, and a motor base[4]

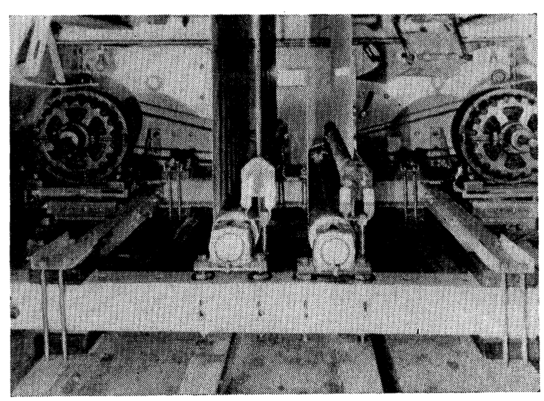

Fig. 3. View of the interior of one of the generator trucks showing the lower pulley frame.

[6] Merchandise No. 3565, American Felt Co., 211 Congress St., Boston, Mass.
[7] Silica Gel Corporation, Baltimore, Md.

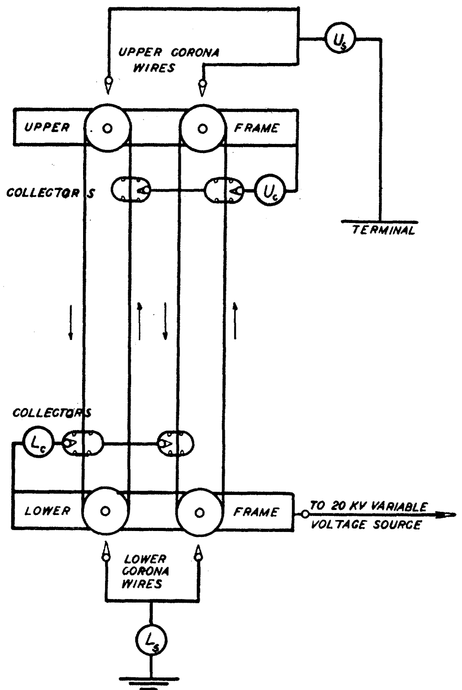

FIG. 4. Schematic diagram of the original belt-charging system.

designed to maintain constant tension on the belt.

From a centralized power panel in each terminal, the a.c. voltage and frequency and the d.c. voltage can be controlled and measured. Convenience outlets make these voltages available at the work benches.

Original Belt-Charging System

The original belt-charging system employed for this generator, shown schematically in Fig. 4, is equivalent in principle to that indicated in Figs. 2 and 3 of a former publication.[1] The structural frames carrying the upper and lower pulley systems are insulated from the terminal and truck, respectively. Voltage is applied to the lower pulley system from a filtered 20-kv rectified a.c. voltage source. Whereas there are two charging belts in each generator unit the following discussion can be simplified by considering the system as comprised of only a single belt. The charging current is supplied at each end of the belt by fine wires[8] stretched across the face of the belt at a distance of about $\frac{5}{8}$ inch from the upper and lower pulleys as shown in Fig. 5 and connected, respectively, to the terminal and to ground.

The charge sprayed on the belt by the lower spray wire under the excitation of the frame voltage is. removed from the ascending belt inside the terminal by a collector connected to the insulated upper frame. The collector consists of a 0.003-inch wire inside a 3-inch diameter cylindrical shield connected electrically to the wire and slotted for the passage of the belt. The shield around the collector wire is almost essential for reliable operation since the collector current is then independent of the upper frame voltage and dependent only on the charge density on the belt.

As the upper frame voltage increases due to the collector current, corona is produced at the upper spray wire and charge is deposited on the descending belt. The equilibrium voltage of the

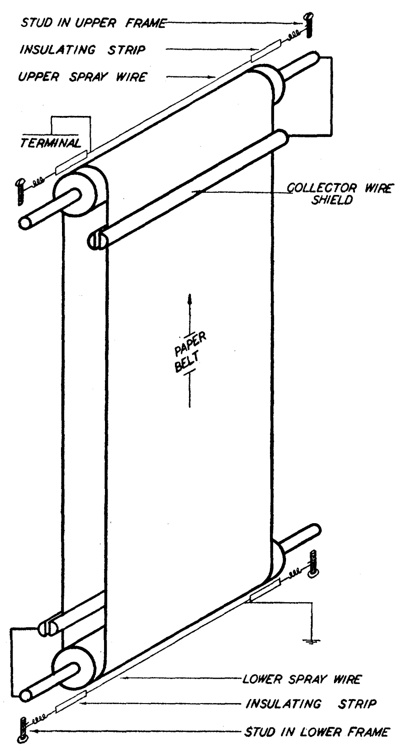

FIG. 5. Isometric drawing of belt showing the location of spray wires and collector shields.

[8] 0.003-inch bright, hard drawn, high carbon steel wire, John A. Roebling's Sons, 107 Liberty St., New York City. Fine wires as corona sources for belt charging were first used on the Carnegie electrostatic generator at the Department of Terrestrial Magnetism, Washington, D. C.

upper frame is reached when the leakage through the belt of charge deposited by the upper spray wire equals the collector current. In effect, both upper and lower spray wires must neutralize the charge brought to them on the belt before producing a net charge of the opposite sign. Unless the lower wire is spraying more than enough charge to saturate the belt, each spray wire current is approximately equal to the generator charging current delivered by the belt.

The collectors on the lower frame enable the generator to operate by self-excitation due to the priming action of frictional charge produced on the paper belts in running over the pulleys. Because of the air conditioning inside the column, the generator consistently delivers its full current under self-excitation. In fact, when the lower collectors are removed the generator still develops half its full current with negative polarity. However, the self-excitation feature is not particularly useful in the present case because of the desirability of definitely fixing the polarity and of controlling the charging current.

Under normal conditions the system just described is operated with saturation charge density on both ascending and descending belts. This condition is realized by the proper choice of the lower frame voltage and spray wire spacing, and the upper spray wire spacing. The adjustment is not critical since excess charge deposited on the belt discharges to the pulley at the point of departure of the belt from the pulley. This charging system has been used considerably and has proved quite satisfactory so long as the belts are operated at saturation charge density.

Control of Generator Voltage

In order to realize the maximum usefulness of the generator, it is necessary to have a convenient method for precise voltage control over a considerable range of voltage. In many cases it would be feasible to operate the belts at saturation charge density and to obtain voltage control by varying the belt speed or by imposing a controllable corona current drain on the terminal. In the present case it would not be practicable to control the speed of the four 10-hp induction motors. A corona device for limiting the voltage has been tested and found to be fairly satisfactory electrically for controlling the voltage of the positive terminal. It is not satisfactory when used with the negative terminal because of persistent sparking to the corona device and is not convenient to use because of the dimensions of the apparatus and the precision required.

The generator voltage may be controlled most conveniently by varying the charge density on the belts. For a given drain on the terminal the equilibrium voltage assumed by the generator will depend on the charging current. If the current drawn from the terminal is altered the charging current must be correspondingly altered to maintain a constant voltage. This adjustment may be made manually, or may be accomplished automatically by employing the output from a generating voltmeter to control the exciting voltage applied to the lower frame.

To test this method of voltage control the exciting voltage applied to the lower frame was made continuously variable. As the charge density on the belts was reduced below saturation, the charging current and the equilibrium terminal voltage decreased in the expected manner. At reduced charge densities, however, there were present violent fluctuations in the charging current having the period of the belt, 1.6 c.p.s., and an amplitude too large to be tolerated. The typical curve in Fig. 6 shows the variation of charging current with lower frame voltage and the limits of the fluctuations encountered.

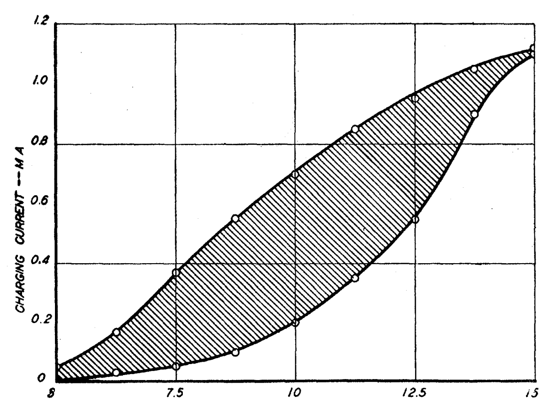

FIG. 6. Limits of the 1.6-c.p.s. current fluctuation encountered with the original belt-charging system at reduced charge densities.

Elimination of Current Fluctuations

Apparently these fluctuations were initiated by the electrical irregularity in the belt at the glue joint and were amplified in effect by the inherent instability of the upper frame voltage. As a first step in the elimination of the current fluctuations, the electrical irregularity in the belt was greatly reduced by making the joint with a celluloid-base cement instead of glue. Then the instability of the upper frame voltage was corrected by a series of alterations in the design of the charging assembly.

The instability of the upper frame voltage was due partly to the shape of the current-voltage characteristic curves of the spray wires. Current-voltage characteristic curves for spray wires at two different spacings from a grounded metal cylinder are shown in Fig. 7a. Two corresponding curves obtained with a spray comb of fine needles are given for comparison. The spray comb consists of a steel ribbon 0.010 inch $\times\frac{1}{2}$ inch with No. 16 beading needles soldered $\frac{3}{8}$ inch apart and extending $\frac{1}{2}$ inch from the edge of the ribbon. Whereas the ideal characteristic curve of a corona device for belt-charging would begin at the origin and rise linearly with voltage, the actual curves are nonlinear and may be expressed quite accurately by empirical relations of the form

$$I=k(V-V_0)^2.$$

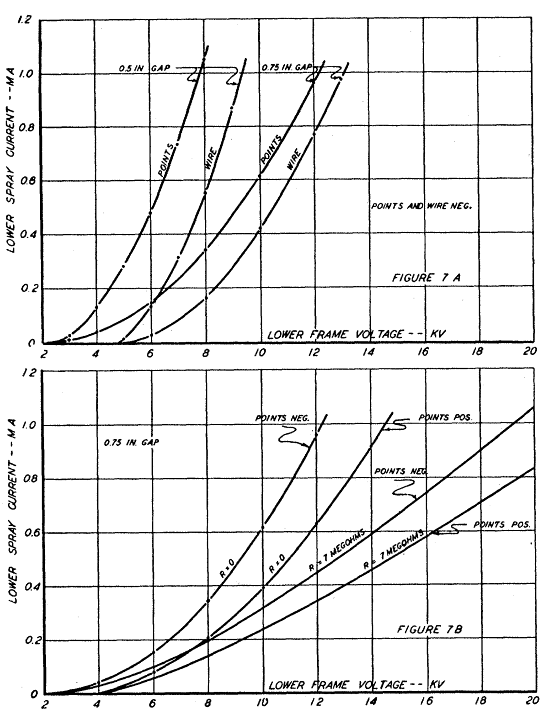

Fig. 7. Current-voltage characteristic curves; a, for negative spray wires and combs with different corona gaps; b, for positive and negative combs with and without series resistance.

From Fig. 7a it appears that combs and larger spacings are to be preferred because of the lower corona threshold voltage of the combs and because of the flatter over-all characteristics obtained with larger spacings. The curves of Fig. 7b show the marked improvement obtained by adding resistance in series with the positive or negative comb. If it were not for other considerations a still flatter characteristic could be obtained by further decreasing the spray gap and increasing the series resistance, i.e., by increasing the ratio of ohmic to non-ohmic resistance in the circuit.

Another factor contributing to the instability of the upper frame voltage was the method of limiting that voltage. In this connection the charge density on the ascending and descending sides of the belts should be equal in order to realize maximum current from the belts and to prevent corona loss of unbound charge from the more heavily charged side. That is, the upper frame should be maintained at such a voltage that the current carried away by the descending belts is approximately equal to that delivered by the ascending belts for a wide range of current values. This condition is realized by placing in parallel with the belt spray combs a voltage control comb of the same design to deposit charge directly on the metal frame. It is desirable to make the proper choice of control comb length, corona gap, and series resistance, though these factors are not critical.

The lengths of the control comb and of the combined belt spray combs should be in proportion to their relative currents. These currents would be equal but for the fact that the collector removes only about two-thirds of the charge from the ascending belt, the remainder being neutralized by the belt spray combs. Since the control comb should have approximately the same current-voltage characteristic as the combined belt spray combs, its corona gap should be the same as theirs and its series resistance should equal their series resistances combined in parallel.

These conditions are expressed more precisely by the following relations

$$(R_v+r_v)/(R_s+r_s)=I_s/I_v \simeq 2.0$$

and

$$R_v/r_v=R_s/r_s,$$

where R_v, r_v, and I_v are the external series resistance, the internal nonlinear resistance, and the corona current, respectively, of the voltage control corona gap, and R_s, r_s, and I_s refer similarly to the combined spray corona gaps. The second relation is necessary in order that the first relation may hold for a wide range of values of frame voltage. The application of these conditions can be made more readily understandable by reference to Fig. 8, in which the current network existing in the upper charging system is shown schematically.

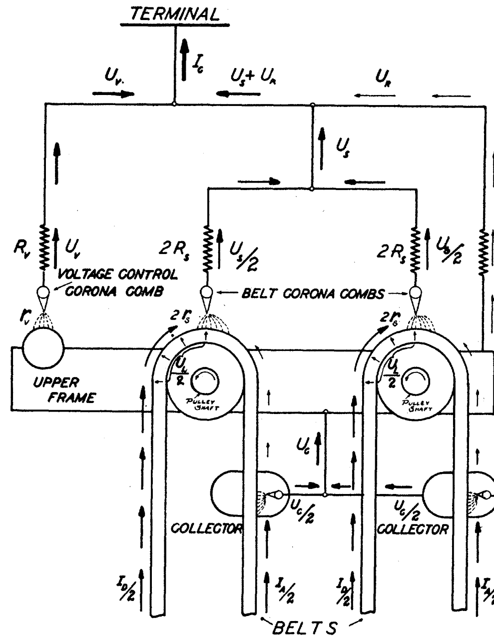

FIG. 8. Schematic diagram of the upper belt-charging system for single excitation.

MODIFIED BELT-CHARGING SYSTEM: SINGLE EXCITATION

The alterations indicated in the preceding section have been incorporated in the belt-charging system described in this section and shown schematically in Fig. 9a. Point spray combs have replaced the spray wires and collector wires. The belt spray combs are used with $\frac{1}{2}$-inch corona gaps and 7-megohm series resistors. The collector combs are placed within $\frac{1}{4}$ inch of the belt, this being the closest safe distance for mechanical reasons. The voltage control comb has half the length of the combined upper spray combs, about the same corona gap, and half the series resistance. In practice minor adjustments in the characteristic of the control comb are made by altering its corona gap. Let us suppose, for example, that saturation charge density on the ascending belts, as indicated by discharge at the point where the belts leave the lower pulleys, is not accompanied by saturation on the descending belts. The corona gap of the control comb should be increased, with a resultant increase in upper frame voltage and current on the descending belts, until discharge appears where the belts leave the upper pulleys. Because of the similarity of the characteristics of the control comb and the belt spray combs, the charge densities on the ascending and descending belts will then be approximately equal for all values of charge density.

The upper and lower frames are connected to the terminal and to ground, respectively, through 200-megohm resistors to prevent the generator from operating self-exciting because of the slight frictional charge generated on the paper belts. These resistors together with those in series with the spray combs are carbon-line resistors of approximately linear response developed in this laboratory for use at high voltage, and will be described in a later publication. The voltage applied to the lower frame is continuously variable from 0 to 20 kv by means of a small adjustable auto-transformer[9] in the primary of the power transformer of the a.c. power supply.

In order to write down in compact form the current relations involved in the operation of this belt-charging system, the following symbols are defined.

I_C = total charging current to the terminal
I_A = current carried by ascending belts
I_D = current carried by descending belts
U_C = corona current at upper collectors

[9] Variac, General Radio Co., Cambridge, Mass.

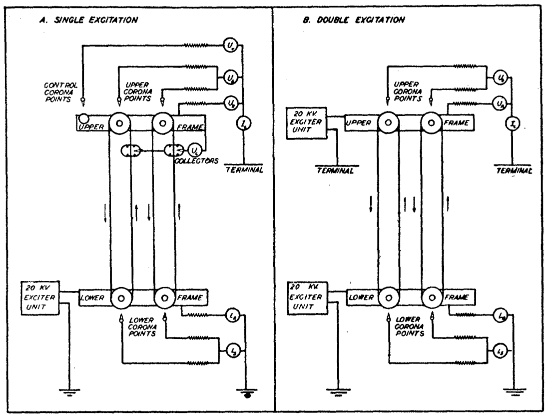

FIG. 9. Schematic diagram of the modified belt-charging systems; a, single excitation; b, double excitation.

U_S = corona current at upper spray combs
U_V = corona current at upper voltage control comb
U_L = leakage current through belts at upper pulleys
U_R = current through grounding resistor on upper frame
L_S = corona current at lower spray combs
L_L = leakage current through belts at lower pulleys

The following exact current relations are then obvious from an examination of Figs. 8 and 9a.

$$I_C = I_A + I_D = U_S + U_V + U_R$$
$$= U_S + U_C - U_L = L_S - L_L.$$

Since in practice U_R is always relatively small and U_L and L_L are small except at saturation charge density, the above relations may be written, approximately,

$$I_C = I_A + I_D = U_S + U_V = U_S + U_C = L_S.$$

These relations give a concise description of the operation of the charging system and are useful in connection with initial design and adjustments.

The belt-charging system described in this section was used for the major part of the current and voltage measurements to be described. It has proved capable of giving very steady currents over a wide range of current values. This system will probably be used here considerably in the future, in spite of certain advantages offered by the belt-charging system which employs double excitation.

MODIFIED BELT-CHARGING SYSTEM: DOUBLE EXCITATION

The necessity for obtaining excitation at the upper charging system from charge on the ascending belt introduces certain complications and adjustments which can be avoided if an independent voltage source for excitation is employed in the terminal. The resulting charging system is shown diagrammatically in Fig. 9b.

It is unnecessary that the upper and lower exciting voltages have the same value except at small charge densities, when they must be kept the same within about ten percent in order to realize steady currents. Thus the current can be adjusted over rather wide limits by varying either exciting voltage independently. For most convenient operation, however, the controls on the two exciting voltages should be operated in tandem by means of a cord or insulating rod connection.

In Fig. 10 several comparative charging current curves are given. These curves show that

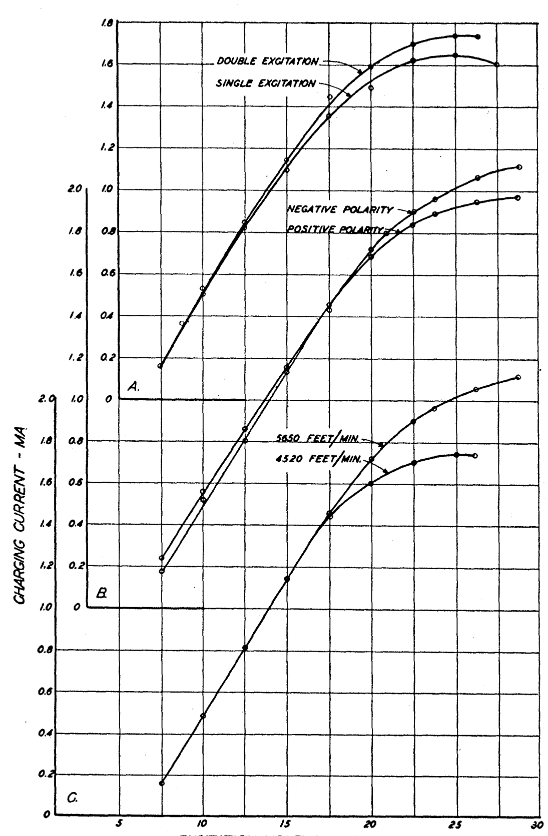

FIG. 10. Comparative charging current curves; a, single and double excitation with negative polarity and 4520 f.p.m. belt speed; b, positive and negative polarity with 5650 f.p.m. belt speed and double excitation; c, 4520 f.p.m. and 5650 f.p.m. belt speeds with negative polarity and double excitation.

greater currents may be obtained with double excitation than with single excitation, that greater currents may be delivered to a negative terminal than to a positive terminal, and that the current increases with belt speed, though not quite proportionally under the conditions obtaining. In addition, the amplitude of fluctuations in the charging current with double excitation is about half that obtained with single excitation.

The maximum charge density on the belts realized experimentally is 30 percent of the theoretical limit which corresponds to a charge density of 2.65×10^{-9} coulomb per sq. cm on each surface of the belt. Actually, since the charge is practically limited to one side of the belt at the time that the belt leaves the pulley, this charging current represents 60 percent of the theoretical limit available with the present charging arrangement.

The results described above indicate that a charging system employing double excitation is to be preferred when the second voltage supply can be obtained without inconvenience.

Voltage Measurement

The problem of obtaining a convenient and reliable measurement of the high voltage has received considerable attention. Several possible methods of voltage measurement have suggested themselves: high resistance, attracted disk, generating voltmeter, magnetic deflection of ions, and proton range. The high resistance method requires a resistance difficult to construct, difficult to shield from corona, and almost necessarily nonlinear because of the dimensions of the apparatus and the magnitude of the voltage involved. An attracted disk voltmeter is subject to large calibrating errors because of the squared scale and the relatively low available calibrating voltage. The magnetic deflection and proton range methods are more complicated than is desirable for many purposes, but may serve to confirm and standardize the results of some more direct method.

The generating voltmeter method has been used with good results for a variety of purposes.[10] Conflicting results have been obtained, however, concerning the reliability of generating voltmeter measurements made on belt electrostatic generators.[11] Because of the advantages offered by its relative simplicity and its independence of the ion beam, the method has been experimentally tested in this laboratory with special attention to systematic errors.

The generating voltmeter consists essentially of an electrostatic alternator excited by the field associated with the voltage to be measured, together with an amplifier and an output meter. In the alternator shown in Fig. 11, a two-bladed grounded rotor plate is mounted in front of a grounded stator plate on a shaft extending through a small hole in the stator plate to a synchronous motor. Two diametrically opposite

[10] P. Kirkpatrick and I. Mayake, Rev. Sci. Inst. **3**, 1 (1932); Ross Gunn, Phys. Rev. **40**, 307 (1932); P. Kirkpatrick, Rev. Sci. Inst. **3**, 430 (1932); G. P. Harnwell and S. N. Van Voorhis, Rev. Sci. Inst. **4**, 540 (1933); J. E. Henderson, W. H. Goss and J. E. Rose, Rev. Sci. Inst. **6**, 63 (1935).

[11] M. A. Tuve and L. R. Hafstad, Phys. Rev. **45**, 651 (1934); M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **48**, 315 (1935); R. G. Herb, D. B. Parkinson and D. W. Kerst, Rev. Sci. Inst. **6**, 261 (1935).

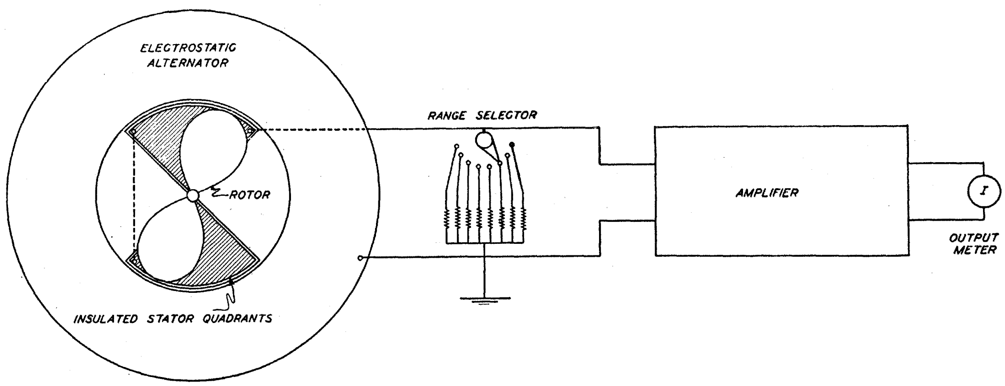

FIG. 11. Component parts of the generating voltmeter.

quadrants are insulated from the remainder of the stator plate and connected to ground through resistors ranging from 300 to 1×10^6 ohms by means of an eight-point selector switch. As the rotor alternately shields and exposes the stator quadrants in the presence of an electrostatic field, an alternating current is produced in the grounding resistor.

In order to avoid harmonics of the fundamental frequency and to simplify calculations, the rotor blades are so shaped that the generated current is sinusoidal. This reduces the effective area of the rotor by a factor of $\pi/2$. Since the alternator arrangement produces an electrical frequency twice the mechanical frequency, the rotor speed of 3600 r.p.m. produces a 120 c.p.s. alternating current.

The peak value of current delivered by the alternator may be written

$$I=\tfrac{1}{2}FAS \text{ statamperes}$$

or

$$I=2\pi CVS \text{ statamperes}$$

where F = electrostatic field on the voltmeter (e.s. volts/cm)
A = effective area of the rotor (cm^2)
S = rotor speed (r.p.s.)
C = capacity between area A on the quadrants and the voltage terminal (cm)
V = voltage applied to the terminal (e.s. volts)

The former expression has proved more useful with this type of alternator, while the latter is equivalent to that used by Kirkpatrick. For convenient use the root-mean-square voltage across the resistor is given by the expression

$$E=3.93\times10^{-10}\ FASR \text{ millivolts}$$

where R = grounding resistance for the quadrants (ohms) and F is measured in volts/cm. This expression has been verified experimentally.

The voltage generated across the resistance by the alternator is applied to the input of a three-stage, resistance-capacity coupled amplifier employing type 41 tubes operated at reduced voltages from self-contained B and C batteries. The impedance of the output stage is matched to that of a 10-ma thermocouple meter providing a measured over-all transconductance of 14.0 milliamperes per millivolt at 120 c.p.s. A full-scale reading on the output meter is thus obtained with a field strength on the voltmeter ranging from 0.5 volt/cm to 2000 volts/cm depending upon the input resistance employed.

The alternator and amplifier described above have proved quite useful in the early phase of the voltage measurements because of the sensitivity and wide range afforded. Experience with this voltmeter and earlier models has led to the design of a much simplified voltmeter which will be described in some detail in a future publication.

In order to obtain a measure of the linearity of the voltmeter response, known voltages were applied to an insulated metal plate temporarily mounted at a known distance in front of the voltmeter surface. The output current from the amplifier proved to be accurately proportional to the gradient over the entire range within which measurements are to be taken. This calibration served to determine the constant in the expression

$$F=k_1\cdot I/R$$

for the gradient on the voltmeter in any location, where I is the current in the output meter and R is the input resistance.

For a particular location of the voltmeter and high voltage terminal a known calibrating voltage, separately measured by means of a precision high resistance[12] and milliammeter, is employed to determine the constant in the expression

$$V=k_2\cdot I/R.$$

Serious errors in voltage measurement, especially at calibrating voltages, may result from the large effect on the voltmeter of charged insulating surfaces. The first step in avoiding these errors is to locate the voltmeter as favorably as possible. Even with the voltmeter mounted in the top of the terminal opposite the grounded metal roof, the effect of charge on the surface of the supporting column must be taken into account at calibrating voltages to obtain an accurate calibration constant. If the current output from the generating voltmeter, I_0, due to column charge, is measured with the terminal grounded, it may be taken into consideration by modifying the above expression as follows

$$V=k_2\cdot(I\pm I_0)/R,$$

the sign being determined by the sign of the

[12] Taylor high voltage resistor, Shallcross Mfg. Co., Collingdale, Pa.

charge on the column. With this correction it is possible to obtain results with a probable error of less than one percent for individual readings.

When no correction is made for column charge, the apparent value of k_2 varies with calibrating voltage as is illustrated by the curves of Fig. 12, taken at low calibrating voltages for two different positions of the generating voltmeter at the top port hole of the high voltage terminal. An examination of these curves in the light of the expression just above indicates that in the case of the upper pair of curves the column charge was of the same polarity as the terminal, whereas in the case of the lower pair of curves the column charge was negative for both curves. This difference is correlated with the past history of the generator in the two cases.

The voltmeter has been used also, high on the side wall of the building, directly opposite the terminal. Whereas this position might appear to be quite favorable, the column effect is considerable. For example, with 25 kilovolts applied to the terminal the uncorrected reading of the voltmeter may gradually increase from 25 kilovolts to 50 kilovolts over the period of an hour. Since the change is very slow it is still possible to get accurate results by taking the value of I_0 by grounding the terminal after each voltage reading. The difficulty is that this correction must be made even at voltages as high as one megavolt with the voltmeter in this relatively unfavorable location.

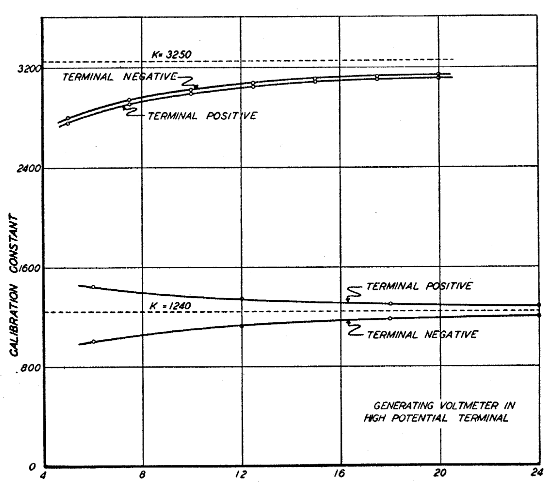

FIG. 12. Uncorrected calibration curves for the generating voltmeter, obtained with low calibrating voltages.

It should be mentioned that these corrections for the effect of charged insulators depend critically upon the humidity and may become quite negligible in damp weather.

The presence about the high voltage terminal of a space charge of ions produced by corona has been suggested[13] as a possible source of systematic error in generating voltmeter measurements. With certain simplifying assumptions, the approximate magnitude of this effect may be readily calculated. If we assume as one of the two extreme cases that all the corona is produced at the surface of the terminal, and therefore that the space charge is all of the same sign, we can calculate the maximum space charge effect.

The geometry is simplified by assuming a spherical terminal in a spherical metal room. Then the current through a spherical surface about the terminal is

$$i = dvA$$

where i = corona current between terminal and ground (amperes),
d = density of charge (coulombs/cc),
v = velocity of ions (cm/sec.),
A = area of spherical surface (sq. cm).

Then, if we make the substitutions

$$v = FM = F_0 r_0^2 M/r^2$$

and $$A = 4\pi r^2,$$

we obtain the expression for the density at any point in the intervening space:

$$d = i/4\pi M F_0 r_0^2,$$

where M = mobility of ions in air $\simeq 1.6$ cm/sec./volt/cm,
F_0 = gradient at the surface of the terminal (volts/cm),
r_0 = radius of the terminal = 230 cm.

At the maximum generator voltage

$$F_0 \simeq 20{,}000 \text{ volts/cm}, \quad i \simeq 5 \times 10^{-4} \text{ ampere},$$

so that $d = 2.3 \times 10^{-14}$ coulomb/cc.

Then the total charge in the intervening space between the terminal and the wall of the room, $r_1 = 800$ cm, is

$$Q_1 = (4/3)\pi(r_1^3 - r_0^3)d = 4.9 \times 10^{-5} \text{ coulomb}.$$

[13] M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **48**, 315 (1935).

For the sake of comparing this total quantity of space charge with the charge, Q_2, on the surface of the terminal with regard to their effects on the voltmeter in the wall of the room, both charges may be considered to be concentrated at the center of the sphere. For the conditions assumed above,

$$Q_2 = F_0 r_0^2 \times 1.1 \times 10^{-12} = 1.16 \times 10^{-3} \text{ coulomb},$$

so that $Q_1/Q_2 = 4.2$ percent. This effect would be smaller on a smaller generator in proportion to the linear dimensions of the apparatus. With a given apparatus the voltmeter should be as near the terminal as possible, since the effect depends upon r_1^3.

As an indication of the relative importance of space charge to surface charge on insulators, the surface charge density corresponding to a field of 20,000 volts/cm is 1.8×10^{-9} coulomb/sq. cm. Since the total space charge, Q_1, is equivalent to this surface charge on 27 sq. ft. of insulation and since the surface exposed by one supporting column is 400 sq. ft., space charge might be expected to have a considerably smaller effect than insulator charge.

An experimental search for space charge is possible since the effects on the gradients at the terminal and at the wall of the room would be of opposite sign. With a uniform space charge of the same polarity as the terminal, a voltmeter at ground potential would read too high, while a voltmeter in the terminal would read too low. Measurements based on these considerations have been made to ascertain whether space charge produces an appreciable effect under the conditions existing in this laboratory.

The curves of Fig. 13 represent the positive terminal voltage as a function of charging current. For one curve the voltmeter was located at the top of the high voltage terminal as indicated in Fig. 2, while for the other the voltmeter was mounted in the side port hole of the grounded terminal facing the high voltage terminal at a distance of 25 feet. Since one of these curves was taken several weeks before the other, the small difference between them may be explained as due to a slight change in the charging current necessary to realize the corresponding voltage. Differences as great as these have been obtained from day to day between curves taken under apparently identical conditions. In other pairs of curves similar to that shown in Fig. 13 the relative positions of the two curves have been reversed. The most significant part of the curves is the upper end, where an increasing departure would be evident if there were an appreciable error due to space charge.

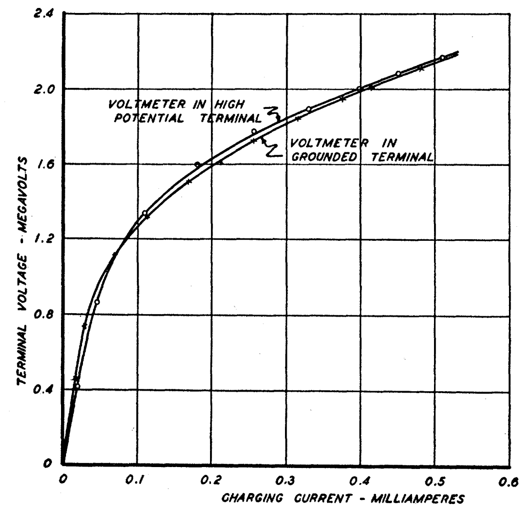

FIG. 13. Voltage-current characteristic curves for the positive terminal measured with the voltmeter in two different locations.

These experimental results indicate that the space charge effect does not approach the extreme value calculated above. This is not surprising in view of the inherent uncertainty in the calculations introduced by the simplifying assumptions. In the first place it has been actually observed that, in addition to the corona produced at the surface of the terminal, corona of the opposite sign originates at the hangar wall resulting in a partial cancellation of space charge effects. In the second place the interior surface of the hangar is very irregular and far from spherical.

Finally, generating voltmeter measurements were compared directly with sphere gap measurements up to 1 megavolt using 62-cm spheres. Typical results are shown in Fig. 14. The points represent the sparking voltages as measured with the generating voltmeter. The upper curve was calculated from Peek's formula,[14] but the lower curve, which is two percent lower than the

[14] F. W. Peek, Jr., Trans. A.I.E.E. **33**, 923 (1914).

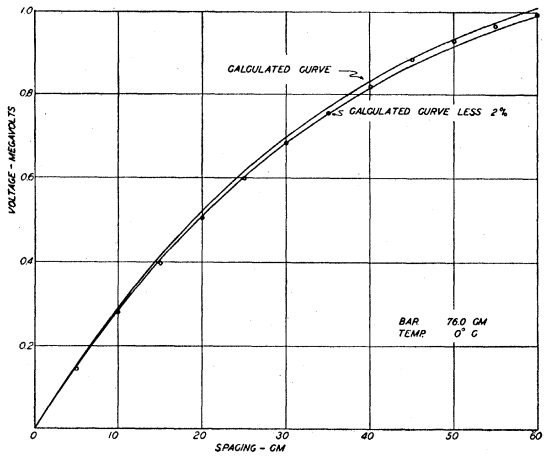

FIG. 14. Sphere gap voltage measurements with 62-cm diameter spheres.

other throughout, gives the best fit for the experimental points to be obtained with a curve of this form. In view of the fact that more recent experimental work[15] has shown that Peek's formula gives results consistently high, it appears that the absolute magnitude of the generating voltmeter results has been confirmed within an estimated probable error of two percent.

The considerations outlined in this section indicate that the generating voltmeter method may be made reliable and reasonably accurate, as well as convenient. A final comparison with proton range and deflection measurements will be made at the earliest opportunity.

Current and Voltage Fluctuations

Preliminary current and voltage fluctuation measurements have been made to determine the usefulness of the generator for the study of resonance disintegration effects. Current fluctuations were measured with the terminal at high voltage by means of a cathode-ray oscillograph[16] across a resistor in the connection between the upper charging assembly and the terminal. Current fluctuations with the terminal grounded were made with the oscillograph across a resistor in the terminal grounding lead.

A visual examination showed that the principal component of the current fluctuations may be represented with sufficient accuracy for the present purpose by a single loop of a 12 c.p.s. sinusoidal wave appearing once for each revolution of the belt. It was found to be caused by a slight dip in the charging current at the time that the belt joint was passing over the upper pulley. Since the resulting regularly-spaced pulses were much larger than the irregular background upon which they were imposed, the percentage current fluctuation is defined in terms of the ratio of this a.c. component peak value to the d.c. component. The results for singly-excited and doubly-excited charging systems are given in Fig. 15.

Since the terminal voltage represents an equilibrium between charging current and load current, fluctuations in this voltage may arise from fluctuations in either current. The load current consists of insulator leakage principally down the supporting column, ion current in the accelerating tube, and corona current. Except at the highest voltages, the ion current should be the principal source of load current fluctuations.

If we neglect for the moment load current fluctuations, the percentage fluctuation in terminal voltage is considerably smaller than the associated fluctuation in charging current because of the smoothing effect of the terminal-to-ground capacity. To the extent that the a.c. component of the current can be represented by a sinusoidal wave form of frequency ω, the smoothing effect can be calculated from the

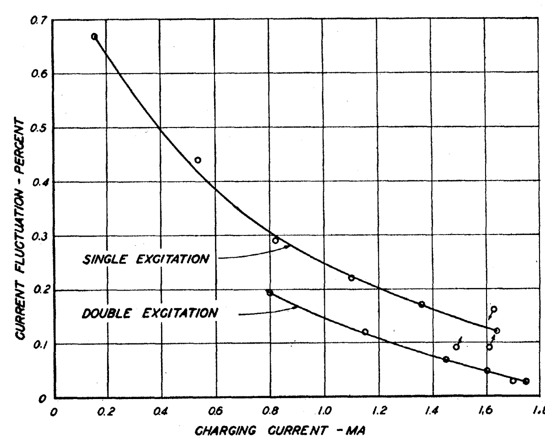

FIG. 15. Fluctuations in charging current with single excitation and double excitation.

[15] J. R. Meador, Elec. Eng. **53**, 942 (1934); J. E. Henderson, W. H. Goss and J. E. Rose, Rev. Sci. Inst. **6**, 63 (1935).
[16] RCA Model TMV-122-B.

expression

$$S=\frac{\text{voltage fluctuation (percent)}}{\text{current fluctuation (percent)}}$$

$$=\frac{R_{\mathrm{ac}}}{R_{\mathrm{dc}}}\cdot\frac{1}{(R_{\mathrm{ac}}\omega^2C^2+1)^{\frac{1}{2}}},$$

where R_{ac}, R_{dc}, and C are, respectively, the terminal-to-ground a.c. resistance, d.c. resistance, and capacity. R_{ac} and R_{dc} for any given voltage may be determined from such curves as those shown in Fig. 13. For example, if we assume an effective frequency of 12 c.p.s. and a terminal capacity of 300 micromicrofarads and take R_{ac} and R_{dc} from Fig. 13, the smoothing factor, S, at 2 megavolts is 0.01 for no ion current and 0.03 for one ma of ion current, and at 1 megavolt the factor is 0.003 for no ion current and 0.06 for one ma of ion current. In view of the assumptions involved in these calculations, the results are useful only in showing the trend of the smoothing effect and in indicating that this effect is considerable.

A direct measurement of voltage fluctuation was made by exposing an insulated 15-cm hemispherical electrode to ground at a port hole of the terminal. With the electrode connected to the terminal through the input resistor of an amplifier and cathode-ray oscillograph, a small fraction of the terminal voltage fluctuation appeared on the oscillograph. The amplitude of fluctuation measured in this way was consistently much smaller than 0.1 percent, but exact values are not given because the calculation of the percentage of the a.c. terminal voltage on the insulated electrode involved uncertainties.

These preliminary current and voltage fluctuation measurements have sufficed to show that the limitation in precision of voltage setting imposed by voltage fluctuations is small compared with other limitations. This point will be confirmed by an improved method for measuring voltage fluctuations at the time that the disintegration experiments are performed.

Voltage variations requiring a time greater than a few seconds may be distinguished arbitrarily from the fluctuations discussed above because of the fact that they can be considerably reduced by automatic or manual control of the excitation voltage. These variations are not large. By the use of a double Variac arrangement for manual control, a given terminal voltage can be maintained constant with a probable error of 0.1 percent.

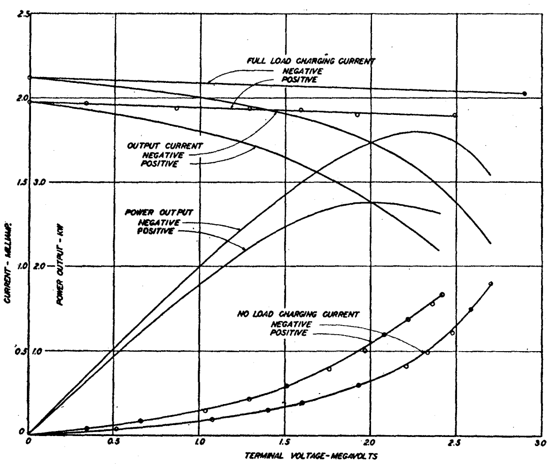

FIG. 16. Generator performance curves for the positive and negative terminals.

GENERATOR PERFORMANCE DATA

The maximum measured voltage of a single generator unit, obtained with a charging current of 1.5 ma, was 2.72 megavolts positive and 3.15 megavolts negative. The highest voltage which has been obtained consistently without sparking is 2.4 megavolts positive and 2.7 megavolts negative, giving a total voltage of 5.1 megavolts between the generator terminals. At this voltage there is still 1.1 ma available for use with an accelerating tube. The humidity control inside the generator column makes it possible to obtain this voltage with an external humidity of 100 percent.

A typical set of generator performance curves for the positive and negative terminals is given in Fig. 16. The full-load charging current, I_c in Fig. 9a, was measured as a function of voltage for the positive terminal with saturation charge density on the belts and the terminal voltage limited by a grounded corona comb mounted in the opposite terminal. Because of the persistent sparking to the corona comb limiting the negative voltage, the full-load charging current for the negative terminal was measured at zero and full voltage only. For both curves the charging current decreases by only 4 percent between zero and full voltage.

The no-load charging current curves of Fig. 16 were obtained by varying the charge density on the belts and measuring the resulting voltage of the unloaded terminal. Below one megavolt the loss current is largely leakage down the column, as measured by a meter at the base of the column, while above one megavolt loss by corona predominates.

The difference between the full-load and the no-load charging current represents the available output current. Reference to the figure indicates that more than half of the full-load charging current is available at the maximum generator voltage. The reliability of the output current curves obtained in this way has been confirmed for the positive terminal by direct measurement of the current to an external corona comb used for voltage limitation.

The power output curves in the figure represent the product of the output current and the corresponding voltage. The power available from the generator increases with voltage to a maximum of 6.3 kw at a total voltage of 4.4 megavolts.

Acknowledgments

We are pleased to acknowledge our indebtedness to Dr. R. H. Gerke of the United States Rubber Company for his advice in connection with our vibration isolation problems, and to Mr. M. F. Witherell of the Behr-Manning Paper Company for his suggestions and assistance in connection with the problem of jointing and operating the large paper belts.

We are grateful to Mr. E. W. Nickerson, the machinist on this project, for the active interest and the ingenuity with which he has carried out his part of the design and construction of equipment.

We greatly appreciate having had the cooperation of Dr. E. W. Samson who was located at Round Hill during the period, August, 1932 to December, 1933, as a National Research Fellow, and who assisted in the construction and initial tests of the original belt charging system.

We are indebted to Research Corporation for the original grant which made possible the launching of this project, to Colonel E. H. R. Green for the continued use of the extensive facilities at Round Hill, and to Professor E. L. Bowles in administrative charge of these facilities on behalf of the Massachusetts Institute of Technology.

Finally, it is our pleasure to express our profound appreciation for the unfailing support and helpful advice of Dr. K. T. Compton during the long period of generator development.

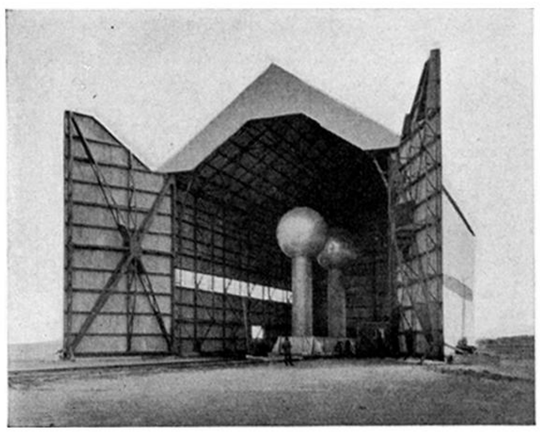

FIG. 1. Electrostatic generator and housing.

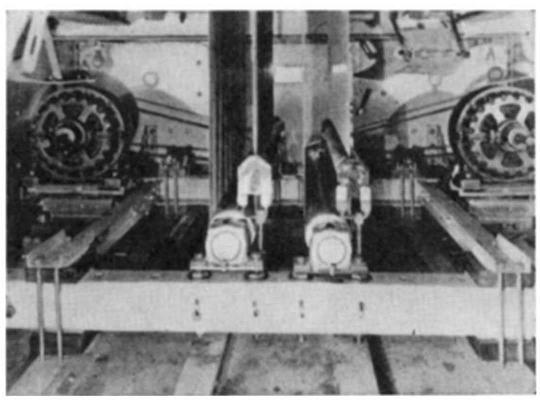

FIG. 3. View of the interior of one of the generator trucks showing the lower pulley frame.