THE DEVELOPMENT OF A HORIZONTAL VAN DE GRAAFF GENERATOR

by

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ABSTRACT

The construction of a pressure-insulated Van de Graaff generator for electron acceleration to give 500 kilovolts was undertaken at the National Research Council of Canada. The generator is of original design, although complying in the main with established principles. One of its features is the successful development of an insulator which seems a good solution thus far to the problem of a horizontal support. A brief historical review is given, after which the components of the generator, as well as the development work involved, are described in detail. Results show the generator is functioning well as a high-voltage source, and can produce a voltage exceeding the design objective.

I. INTRODUCTION

The project for the construction of the generator described in this thesis was begun in 1946. The Electrical Engineering Laboratory of the National Research Council undertook to design and construct a small Van de Graaff generator for the Council's Division of Chemistry for experimental work in radiation chemistry. A maximum voltage of 500,000 volts and a delivered electron beam current of 200 microamperes were the objectives in the design. A horizontal alignment of the generator was chosen, since the emergent beam of electrons can be utilized easily without requiring a 90° deflecting magnet as would a vertical machine.

The Electrical Engineering Laboratory was also engaged at the time in building a larger generator rated at 5 million volts. The two projects were hence carried out concurrently until the completion of the larger unit in November, 1948. The period since then has been taken up with development work, operational testing, and elimination of difficulties of the 500 KV generator. The generator is at this date considered to be functioning quite satisfactorily in producing the desired voltage.

Although many Van de Graaff generators have been built since its invention twenty years ago, most of them differ in some respects to fit the experimental requirements of the designer, so that the design of such machines is by no means standardized. Also, because of the present imperfect knowledge in the high-voltage insulation field, each new design brings forth its own special problems. The generator described herein does not claim any radical departure in design, although some of its component parts are original. A feature of the N.R.C. generator is its very compact size, especially so for a horizontal type of construction. This is due in a large measure, to the successful development of a suitable column insulator.

In recounting the difficulties met with, it is hoped that other workers in this field may gain from the lessons learned during the development of this generator.

II. CHARACTERISTICS OF THE ELECTROSTATIC GENERATOR

Also known under the name of its inventor, Dr. R.J. Van de Graaff, the electrostatic generator has qualities which make it admirably suited for many types of experimental work. It is a source of high energy particles, like the cyclotron, betatron, and linear accelerator, but differs from these machines in that it directly generates the total potential instead of accelerating the particles many times by the same voltage increment. It, moreover, possesses advantages not inherent in other accelerators. It is suitable for acceleration of either electrons or positively charged particles. The potential through which the particles are accelerated is a constant d-c voltage, with a spread in beam energy dependent mainly on the stability of the generator voltage. The voltage can be easily varied over a very wide range. The emergent particles are well collimated with little accompanying stray radiation. Although other types of accelerators can produce voltages many times higher than an electrostatic generator, the latter is the most satisfactory accelerator when precise control of particle energy is needed.

The present highest operating voltages of electrostatic generators are reached in the installations at the Massachusetts Institute of Technology, Chalk River, Harwell and Cambridge, which have maximum voltages of about 5 Mev (million electron volts). Generators to operate up to 10 to 12 Mev are being designed at the Massachusetts Institute of Technology and at Los Alamos.

The electrostatic generator finds application in non-nuclear fields also. It is a high voltage source with no ripple for dielectric testing. Used for electron acceleration, an electrostatic generator provides an intense source of X-rays with a shortest wavelength defined by

$$\lambda = \frac{0.01234}{V} \text{ Angstrom units}$$

where V, the accelerating potential, is in million electron volts.

The deep penetrating power of such X-rays and the sharpness to which they may be focussed make such generators highly useful for industrial radiography and medical therapy. High energy electrons are effective germicidal agents and are used in food and drug sterilization. Their effect in biological fields is being investigated. The generator presented in this thesis was planned for investigations in radiation chemistry. Here, the beam of electrons is utilized directly to initiate reactions between gas molecules, ions, and radicals.

III. HISTORICAL DEVELOPMENT

Classification

Electrostatic machines may be classified according to their means of charge transport, namely: (a) disc charge-transfer, (b) belt charge-transfer, (c) charge transfer by means of dust or liquid particles. Disc-type generators, such as the Wimshurst machine, are now of historical interest only. The increasing demands for higher voltages created by growing interest in X-ray and nuclear physics gave impetus to the development of electrostatic belt generators. Particle-type generators have not developed owing to a lack of interest after the advent of the belt generator, and does not appear to have the potentiality of the latter. The success of belt generators is such that an electrostatic generator has come to mean, practically, only that of the belt-transport machine.

Principle of Operation

A knowledge of the fundamental principles of the operation of a Van de Graaff generator in producing a high voltage is necessary in order to understand the problems involved in the design and development of such a machine.

The Van de Graaff generator operates on the simple principle that if electrical charges are placed on an insulated conducting body, a voltage will develop that is proportional to the charge placed upon it, according to the familiar equation:

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

A belt of insulating material is used to convey the charges from ground to a rounded hollow high voltage electrode suitably supported and insulated from ground (Fig. 1). A corona comb consisting of a row of sharp metal points faces the lower pulley a slight distance away from the surface of the belt. These points are energized by a transformer-rectifier set to a voltage sufficient to give corona. As the electrical charges travel towards the pulley, they are intercepted by the moving belt and transported to the terminal where another comb connected to it removes the charges. As the region inside the terminal is field-free, the charges are sprayed on, transported, and removed in a continuous process independent of the voltage of the terminal.

The voltage will rise until the charging current is balanced by the load current draining the terminal. The load consists of current through potential dividing resistors, plus current down the accelerating tube, plus any corona and leakage losses. The maximum voltage which can be generated depends on the geometry of the high-voltage terminal, the insulation of the supporting column, and the surrounding insulating media. By adjusting the current "sprayed" on to the belt and/or the load current, the terminal voltage may readily be established at any desired value to the maximum.

Dr. R.J. Van de Graaff first designed a generator operating on these principles. An abstract of his paper was published in 1931.[16*]

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* For numbered references, see Bibliography.

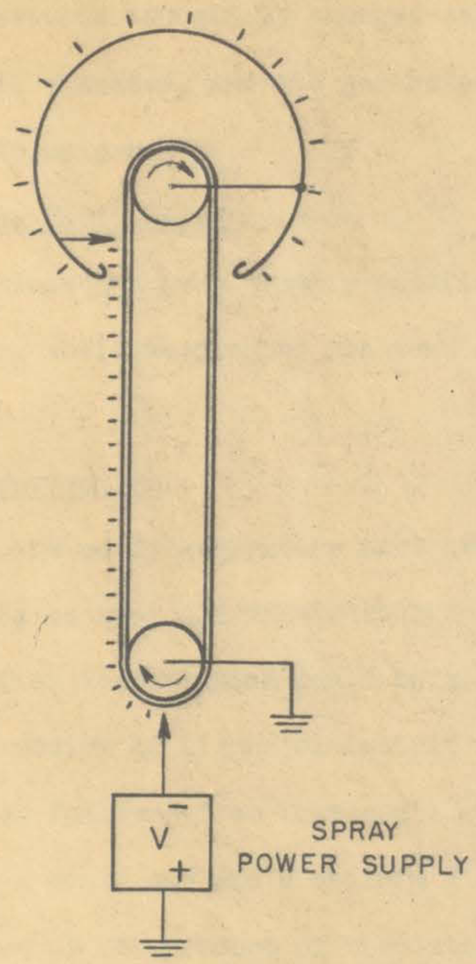


FIG. 1 DIAGRAM OF SIMPLE VAN DE GRAAFF GENERATOR

After his success with this generator, a much larger one was built at Round Hill at M.I.T.[17] It was actually a twin generator developing 5.1 Mev between oppositely charged spheres. The spheres were 15 ft in diameter, and the generator was originally housed in an airstrip hanger.

Major Developments in Basic Design

Later developments have greatly modified Van de Graaff's Round Hill generator, while keeping to the same essential principles.

(a) Pressurization:

The early generators were generally of large dimensions, depending as they did on atmospheric air for insulation. The size and cost of an installation could be greatly reduced by using an insulating medium of higher dielectric strength. Paschen stated the law, which followed from Townsend's analysis of gaseous breakdown, that for a given gas and a uniform field, the sparking voltage is a function of the product of the inter-electrode gap and the gas pressure. Hence for a given electrode configuration, the sparkover voltage would increase in proportion to the gas pressure. The linear increase of sparking voltage with pressure predicted by Paschen's law holds true up to about 10 atmospheres, departing slowly thereafter. Thus, Barton, Mueller and Van Atta[1] made use of compressed air for their electrostatic generator. Practically all generators have since made use of pressurization to obtain compactness.

(b) Column Gradient Control:

Solid dielectrics are required to support the high voltage terminal. The resulting space economies from pressurizing produced greater field strengths which brought out serious insulation troubles. The problem is to avoid non-uniform gradients which lower the insulating ability of the supporting column. Uneven gradients may be due to varying resistivities or to the accumulation of static charge. The breakdown strength can be increased by controlling the voltage gradients. Herb achieved gradient control in the Wisconsin generator[5] by having a series of metallic hoops surround the entire area of the belt, accelerating tube, and the long textolite supports. The hoops were attached at regular intervals to the textolite tubes. The generator voltage was uniformly divided down this type of column by maintaining a small current flow from hoop to hoop through a system of corona points or resistors.

A better way more recently adopted is to construct the column as a series of spaced conducting planes ("equipotential planes") separated by insulated supports. The total terminal potential is then divided into a series of equal increments. A gain in total voltage is further achieved by the fact that a shorter gap can insulate a higher gradient than a longer one.

(c) Belt Field Gradient Control:

The second step in gradient control was made by Trump[15] with the introduction of gradient control in the region of the belt. Besides the longitudinal field from the high voltage terminal, the field near the belt has a transverse component due to the charge on its surface. The gradient normal to the belt surface is given by

$$E = 2\pi q \quad \text{e.s.u.}$$

Since the use of the compressed gases allows higher voltage gradients, more charge can be carried by the belt. However, unless suitable control is established of the belt field, the transverse gradient may be the cause of serious sparking difficulties and the expected increase in current-carrying capacity with pressure may not be attained.

In ~~the~~ Herb's generator[5], for example, the belt's field extends the entire distance to the surrounding equipotential hoop, and causes a high difference of potential between the surface of the belt and the hoop at the same level. Moreover, the belt is at a varying distance from the hoops with a resultant variation in potential across the width of the belt.

Conducting rods placed close to and parallel to each face of the belt eliminate these difficulties by confining the electric field. Those field-control rods are connected to the equipotential ring at the same level, and in effect divide the belt lengthwise into a series of short sections, thereby increasing the breakdown strength along the belt. This method of belt gradient control is important for the full realization of the current-carrying capacity of pressure-insulated generators.

The three important contributions to belt generator design, namely: pressurization to obtain compactness, control of the column voltage gradient, and control of the belt field have become general design practice. They have been incorporated into the design of the N.R.C. machine. Other design considerations and the problems encountered during developmental work will be considered when the various components of the generator are described in the following section.

IV. DESCRIPTION OF THE N.R.C. GENERATOR

Fig. 2 is a photograph of the assembled generator. The high voltage terminal is removed in Fig. 3 to show the equipment mounted within it. The assembly drawing (Fig. 4) shows the arrangement of the major components. These components will be described in detail.

Some explanation is perhaps necessary in the use of the relative terms "upper" and "lower", "top" and "bottom". Since these terms are conventional in the description of vertical generators, they will be carried over to the horizontal generator, only here the terms will refer to the relative potential ends of the column rather than to their disposition in space.

Pressure Vessel

The pressure vessel shown in Fig. 5 has inside dimensions 52 inches long by 28 inches diameter. The cylindrical walls are 7/8 inch thick steel. It is capped by a semi-ellipsoidal dished head at one end. Twenty-four 1-1/4 inch socket head screws fasten the shell of the tank to its 3-1/2 inch thick base on which the generator assembly is mounted. The tank is designed for a working pressure of 500 psig and has been hydrostatically tested to 1000 psig by the manufacturer.

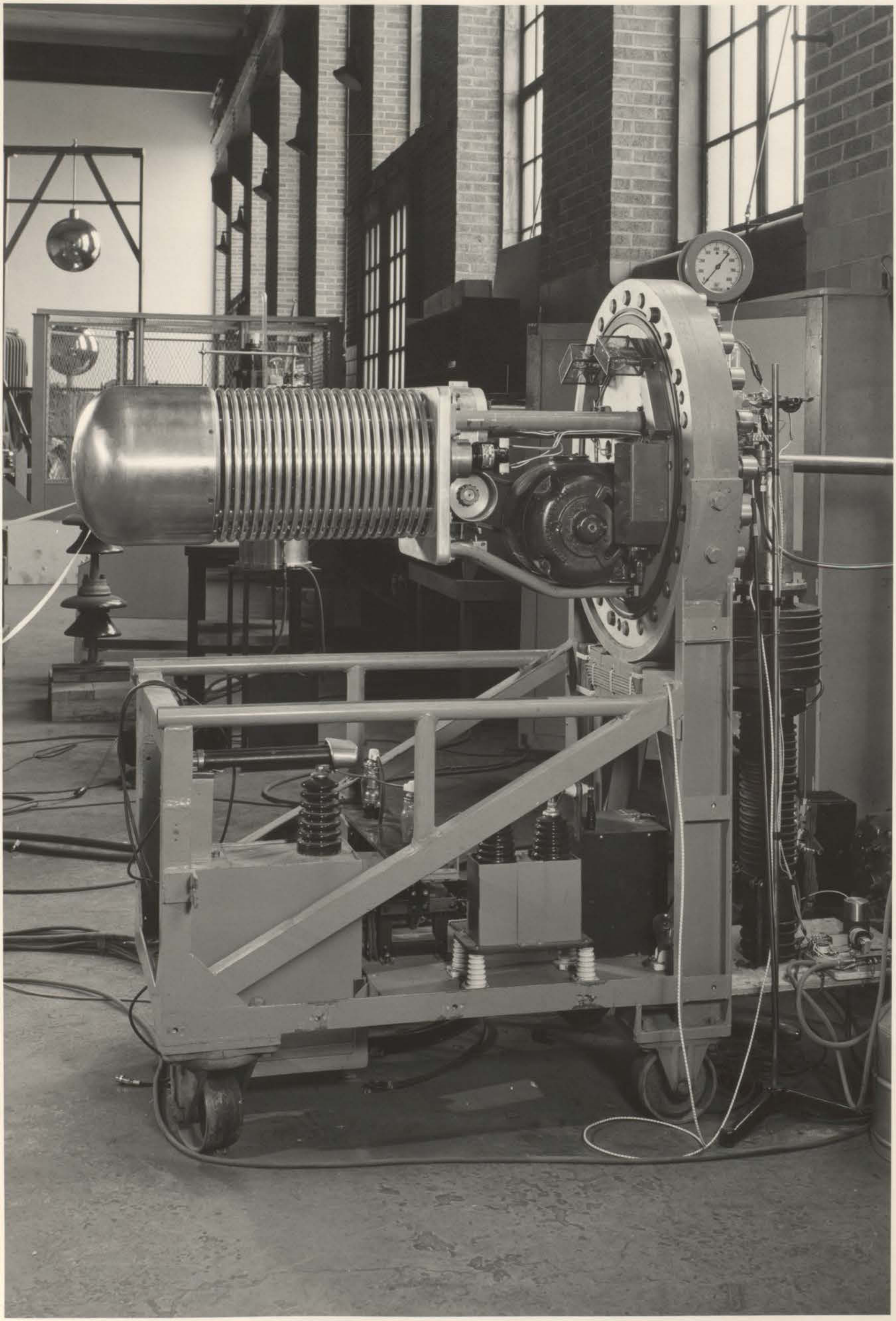
The base is fixed to a movable truck made of angle iron and tubing. The shell has welded mountings with grooved wheels with which it can be rolled into position on rails of tubing onto the base. When desired to get at the generator interior, the shell can be rolled on to a portable carriage out of the way.

Gas and electrical connections are made in the base. The power supply for the spray comb is underneath the tank on the truck. All wiring is brought to a terminal strip where cables connect it to the control panel.

Nozzles with an opening of 4-1/2 inch diameter are provided in the tank for various purposes. Two are used for windows through which the belt and sparking when it occurs may be observed. The glass in the windows is 1 inch thick; it has the trade name Tuf-flex. Four 6 volt, 9 watt lamps (Mazda No. 1718) provide illumination. These lamps are chosen because with their spherical bulbs they are one of the few types able to stand 500 psi pressure. The inside walls of the vessel are aluminum painted, partly for good light reflectance.

<u>The Column Structure</u>

The high-voltage terminal is 12 inches in diameter, ellipsoidal at the end. The diameter gives a ratio with the tank diameter which is close to the theoretical value of $e = 2.718$ for maximum voltage between concentric cylinders. Experience with this generator indicates that a slightly larger diameter for the terminal and for the column structure with the same tank diameter



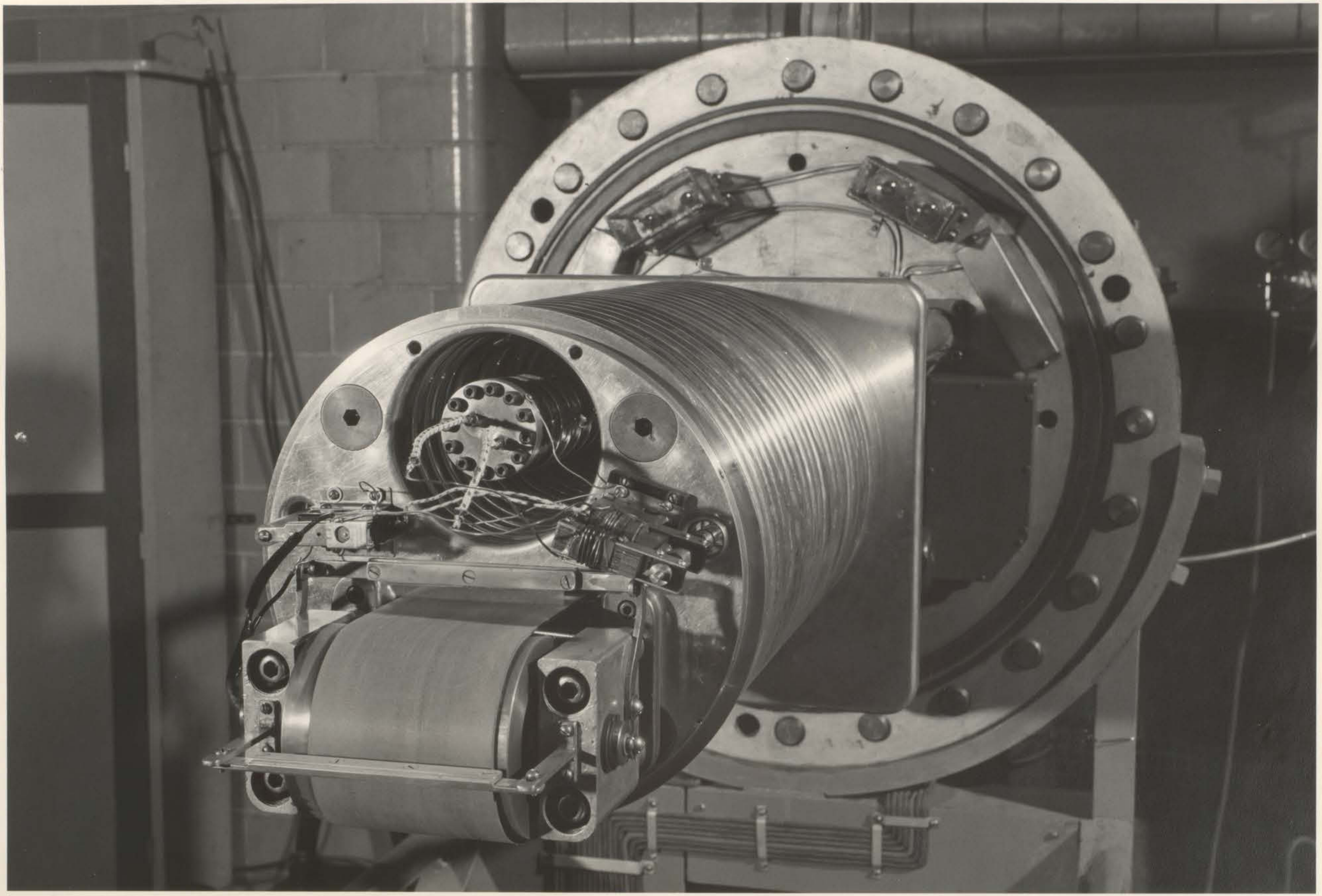


FIG. 3 VIEW WITH TERMINAL DOME REMOVED

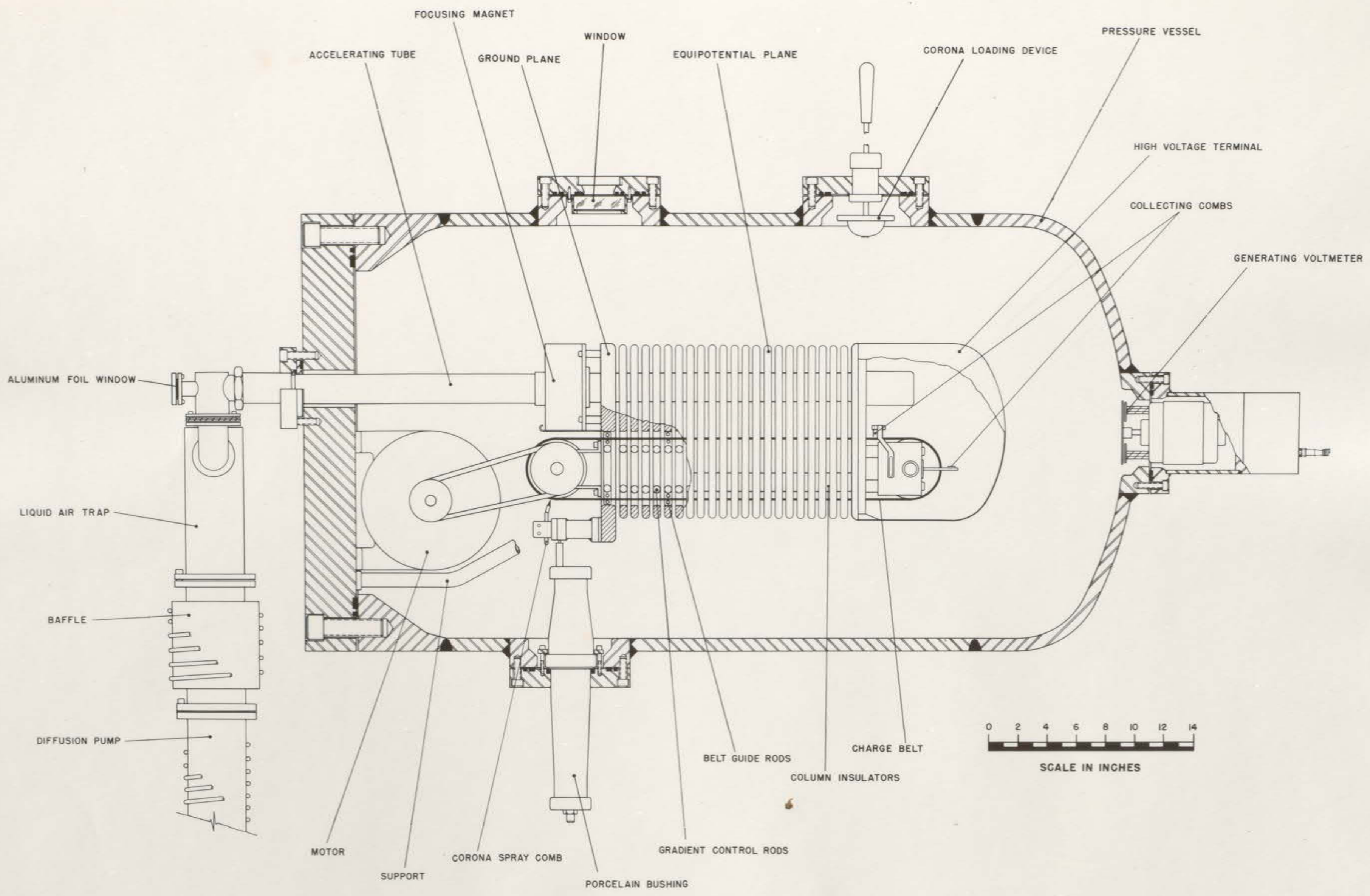


FIG. 4 N.R.C. VAN DE GRAAFF GENERATOR

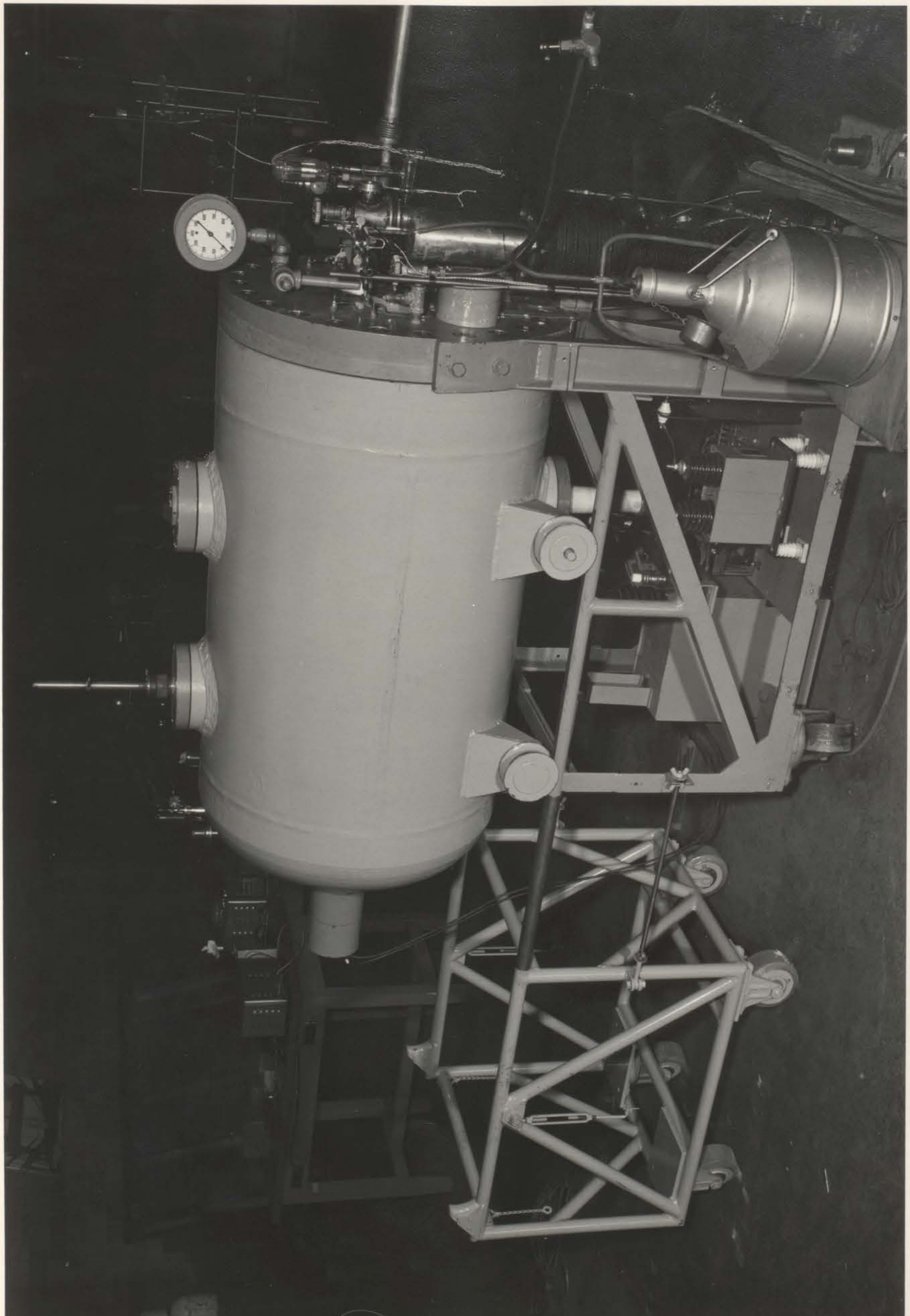


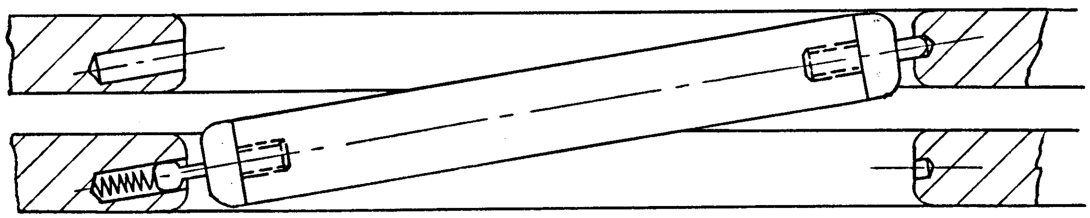
FIG. 5 EXTERNAL VIEW OF GENERATOR

would be beneficial since the voltage limitation has not been the electrode to tank spacing, and since the maximum voltage is a slowly varying function of $\frac{R}{r}$ in the vicinity of e. A larger diameter column would remove some of the space limitations in the region of the belt.

The terminal is supported by four equally spaced rows of Lucite insulators with caps which screw into each other and space the potential-dividing planes of the column. A great deal of development has gone into these insulators, which will be reported in detail later.

The potential-dividing plates, or "equipotential planes" which form the column structure are made of 1/2 inch rolled dural plate. Although a fair amount of machining is required, it is much less expensive than casting, and is believed simpler than fabricating from sheet metal and tubing. The extra weight of solid plates is not significant in this small size of column. There are 21 equipotential planes, not including those at the bottom and the top, which because they are required to support other apparatus are of thicker 1 inch dural plate. The planes are spaced 1/4 inch apart making a column length of 16 inches. Steel tubing supports the equipotential column in cantilever. A space of 16-1/2 inches from the base to the bottom equipotential is available at ground potential for mounting the drive motor, pulley, focussing magnet, and other accessory apparatus.

Division of voltage in the equipotential column is accomplished by a resistance chain inserted within the two runs of belt. A spiral-line carbon resistor with nominal resistance of 1000 megohms made by the Resistance Products Company is connected between plates. They are spring loaded at one end to assure positive contact and ease of assembly (Fig. 6). These resistors are 4 inches long, are rated 6 watts and 25,000 volts. However, they can withstand more voltage when under pressure; and in this generator, they have withstood over 45,000 volts without harm.



Mounting of Resistor in Column

Fig. 6

Potential dividing by means of corona from a series of needle points was tried very early in the development but did not prove very satisfactory for several reasons. The non-linear characteristics of a corona gap requires an additional adjustment since the corona gap must be varied when the generator is operating under different voltages and pressures. Also, the voltage range is restricted to that above the corona onset voltage. Extra mechanical complexity and maintenance of points were also required. Therefore, this scheme was discarded.

A spark gap is in each equipotential plate (Fig. 7). It is usually set at 3/32 inch. The spark gap serves to divert voltage surges from being applied to the accelerating tube and the resistors.

Column Insulator

The design of a suitable insulator for the equipotential column was complicated by mechanical problems arising from the horizontal position of the stack. Besides possessing a high dielectric strength and high resistivity, it must be rigid and have good mechanical strength. Most thermoplastics that are satisfactory electrically are ruled out because of lack of dimensional stability at the temperature to which the tank interior may rise. The heat developed from the driving motor is dissipated solely by radiation from the walls of the pressure vessel, there being no provision for cooling. On a hot day, the interior may rise to 60°C.

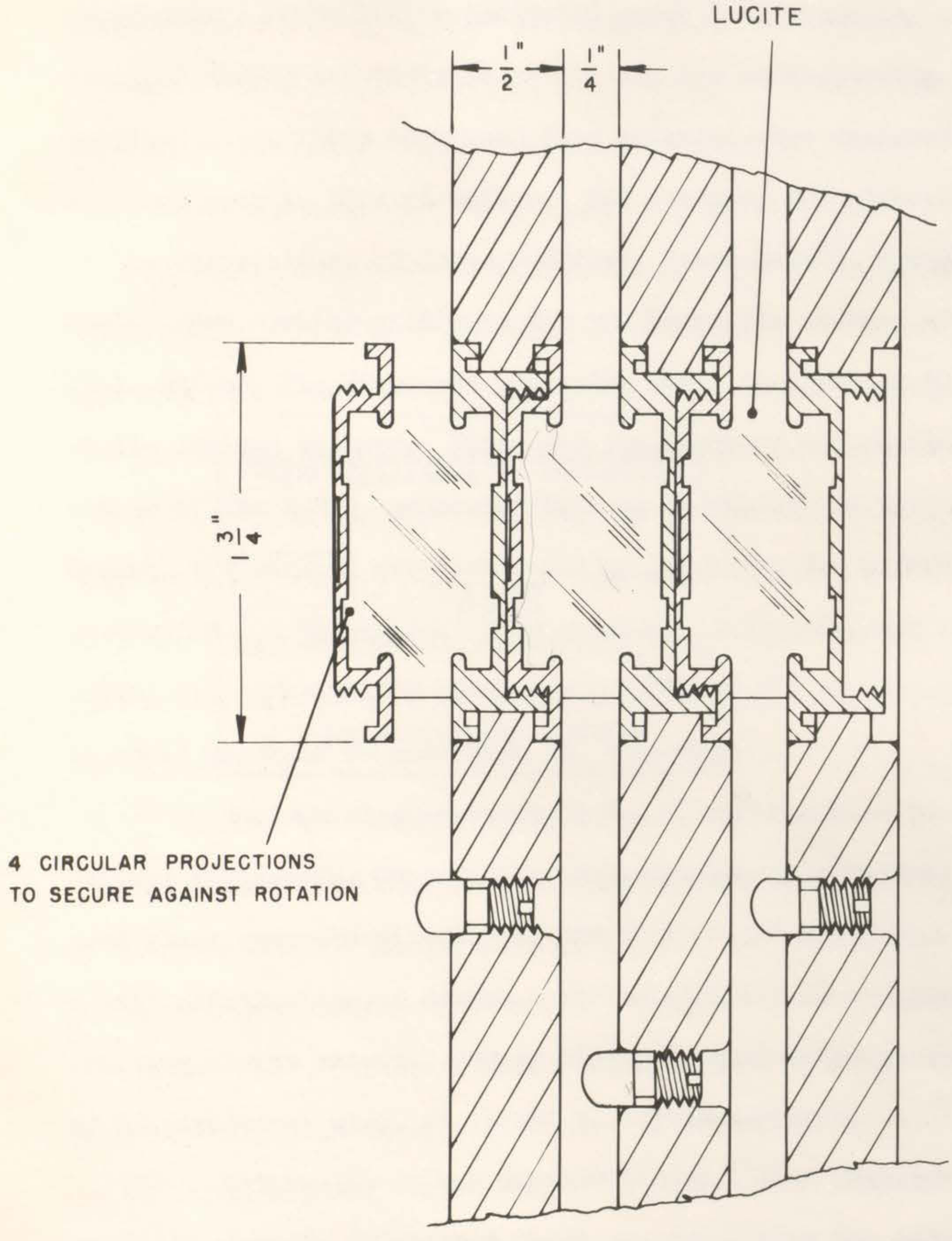


FIG. 7 SECTION THROUGH COLUMN INSULATOR AND SPARK GAP

Textolite has been used in most previous horizontal generators. Textolite, a laminated paper base phenolic, although strong and rigid is relatively low in insulating ability. Generators that used this material were designed for low gradients in this direction. For example, the generators at the Universities of Johns Hopkins[7], Notre Dame[18], and Ohio State[2] have working gradients for the Textolite members of 13-14 kv/in. The Wisconsin generator has a gradient of 30 kv/in at its maximum voltage. Since the thickness of the equipotential planes of the N.R.C. generator take up two-thirds of the column length, the working gradient would be 100 kv/in for a terminal voltage of 500 kilovolts. This gradient is too high for Textolite. Actual use of Textolite rods (grade 2029) in the generator proved it could insulate no more than 150 kilovolts.

Horizontal generators at M.I.T. and those of the High Voltage Engineering Corporation in Cambridge, Massachusetts, have used glass cemented directly to the equipotential planes, making a unit construction of column. The possibility of the glass cracking always exists. Accessibility is restricted in this type of construction; also, it is not easily demountable.

Originally it was planned to use 1 inch diameter pyrex glass cemented to dural caps which can screw into the adjacent unit. A plasticized polyvinyl acetate adhesive, commercially available as Vinylseal T-24-9 was the first adhesive tried. It is hard setting and had excellent adhesion. However, differential thermal expansion of the dural and the glass caused many breakages, on cooling after baking and some during service. Examination of the insulator under polarized light revealed patterns that indicated considerable internal stresses, confirming the cause of failure.

Other softer setting adhesives were tried. These were Pliobond, Bakelite BJ-16320, Bostick 7008, Minnesota Mining and Mfg. Co. EC-847, Plastilock 602, Firestone 6000, Firestone 3004, and Redux. Sample insulators were tested for tensile strength at both room temperature and at the highest tank temperature. Of these, Plastilock 602 possessed the greatest adhesive strength. However, it exhibited a fair amount of cold flow, which rendered it unsuitable for permanent use. A satisfactory adhesive has therefore not been found.

The insulators presently in service are shown in Fig. 7. The insulation is Lucite (methyl methacrylate) which is heat-resistant to 185°F (85°C) approx. The plastic is molded dovetail manner to the metal parts, thus eliminating the need for an adhesive. Small projections of lucite into the metal secure against rotation.

Lucite has properties of high dielectric strength and resistivity, homogeneity, and moderate mechanical strength. It does not form a carbonized track after sparking; therefore, the full strength of the insulator is recovered after the occurrence of any flashover. Trump and Andrias[13] have found, also, that of the three insulating materials — Lucite, Textolite, and Isolantite (a porcelain ceramic) — Lucite has a flashover strength, when immersed in dry nitrogen, most closely approaching the value for the gas-filled gap.

A representative sample molded unit insulated 20,000 volts in atmospheric air and 50,000 volts at 50 psig of nitrogen. Tensile strengths of two samples were 400 and 600 lbs. A droop in the column amounting to 1/4 inch over the 16 inch length exists owing to the elasticity of the Lucite. It is not enough to interfere with the operation of the generator.

The insulator unit of molded-in Lucite construction has proved very satisfactory. It is strong, rugged, and compatible with the over-all compact design. To the author's knowledge, the use of Lucite and the insulator construction are original in horizontal generators. The Lucite insulator is generally superior to the previously used supports of Textolite or glass. The design of horizontal generators had in the past been handicapped by the lack of a reliable insulator under tension — the insulator developed for the N.R.C. generator may be the solution.

Drive

The charge belt runs on 4 inch diameter steel pulleys with a linear speed of 3830 feet per minute. It is driven through V-belts by a 2 hp 550 volt squirrel cage induction motor which is Class B insulated. The motor supplies power to transport the electric charge against the repelling potential of the terminal, to overcome friction of belt and guide rods, to overcome windage, and to drive the generator in the terminal supplying filament power to the accelerating tube.

The power required to overcome windage can be expressed in the form:

$$HP_w = K \cdot PAV^3$$

where HP_w = horsepower

P = pressure, psia

A = belt surface area, sq in. (one side)

V = belt velocity, ft/min

The windage power can be easily segregated by a motor input power versus pressure test, since windage after subtracting the copper losses is the only component that increases with pressure. The value for K was found to be equal to 1.40×10^{-16}.

It is generally desirable to have a fairly high speed for the belt, since the current carrying capacity of a belt is directly proportional to the speed.

Assuming the following operating conditions for the generator:- output voltage = 500 kv; load current = 200 μamp; pressure = 215 psia; the electrical work requires 0.134 hp, windage requires 0.435 hp, with total frictional power of the motor and charge belt system, plus stray load and core losses of the motor taking 0.56 hp. Filament power is negligible. It is seen in this case that the motor is only about half-loaded. Appreciable horsepower capacity remains for additional windage power if the speed of the belt is increased, even though windage power varies as the cube of the speed. The belt speed could comfortably be increased, say 20%, bringing the windage power requirement to 0.75 hp. It is planned to do this in the near future. (Note also that the heat conductivity of a gas is increased when compressed, and hence electrical power consuming equipment may, if necessary, be overloaded somewhat with safety above their ordinary ratings).

The pulleys are 4-3/4 inches long and are tapered $1/2^{\circ}$ for 1 inch at each end. The belt has no trouble staying on centre with this slight camber.

The upper pulley is mounted on ball bearings on a stationary shaft. It is insulated from the bearing block to provide for induced charging of the belt on the down run if this is required. By means of tensioning nuts within the bearing block of the pulley (Fig. 8), the pulley can be raised or lowered along the four guide posts to adjust the centering and the tension of the belt.

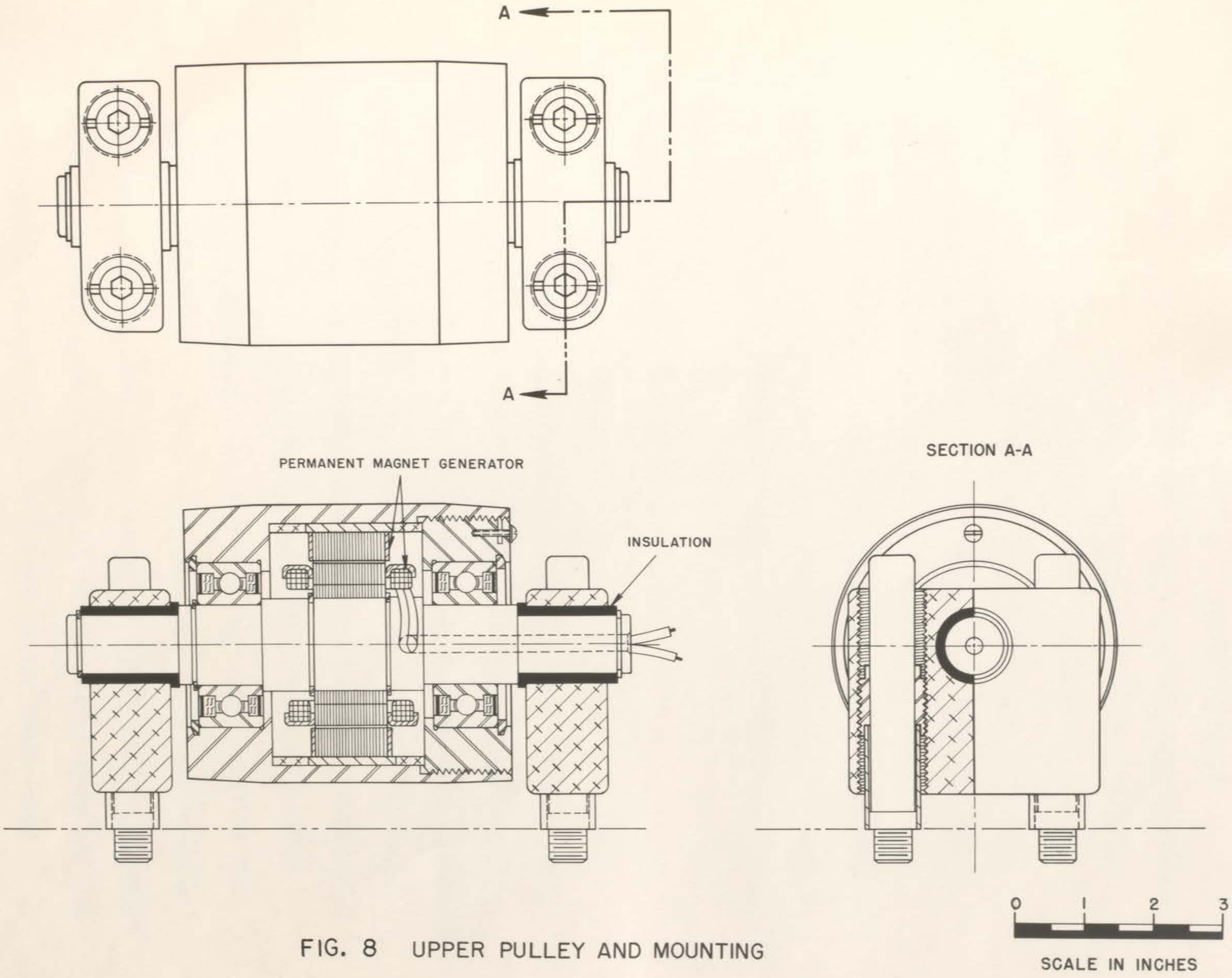


FIG. 8 UPPER PULLEY AND MOUNTING

The behaviour of the belt on adjustment is noteworthy, since the belt runs contrary to the usual notion of riding to the high side of the pulley. If one end of a pulley is raised, the belt moves away from that end. The reason appears to be that the pulley, unlike the ordinary power-drive pulley, is wide compared to its diameter, and consists of a long flat portion in the middle. Hence, when one end is raised, thereby tightening the belt at that end, the effect at the other end is negligible, and the belt while it runs up the camber at the tight end, moves down the pulley as a whole.

Charging System

The power supply for the excitation of the spray combs is a voltage doubler circuit using 8013-A tubes. The circuit is shown in the diagram of the tank and power supply (Fig. 20). Maximum d-c voltage is 40 kv. A smoothing capacitor of 0.25 μfd reduces the ripple to 0.1% at an output of 1 ma. The output voltage is controlled by a variac on the primary of the high voltage transformer. The power supply is located underneath the pressure tank on the truck which supports the tank. A porcelain bushing introduces the high-voltage supply to the charging combs. A resistance of 50 megohms in the output line stabilizes considerably the fluctuations in spray current arising from changes in the impedance of the corona gap.

The corona spray comb consists of hand sewing needles ("Sharps" type) pressed into a brass bar and spaced 0.10 inch apart. It is narrower than the belt by 1/2 inch on each side so that arcing does not take place between comb and pulley. It is placed from 1/8 inch to 1/4 inch away from the belt — the exact distance away is not critical. The charge take-off combs are made of stainless steel mesh, 50 wires to the inch, wire diameter .006 inch. The points are made by shearing the wires and removing one strand from the sheared edge. These combs are set at about 1/64 inch from the belt surface. Take-off combs of needle points have also been tried, but screen combs for this function are presently favoured.

Various kinds of needles were tried before sewing needles were finally chosen. The sharpness of the points are important since it has a bearing on the corona properties, especially when the polarity of the point is positive. Needles used in the order tried are:-

(a) R.C.A. chromium phonograph needles, further honed to a sharp tapering point.

(b) The same needles as they come from the package. A shadow projection giving a magnification of 26 times showed a radius of 3-1/2 thousandths of an inch at the tip.

(c) Sewing needles. Under a projected magnification of 35 times, no discernible radius could be seen at the tip. As these do not require further sharpening, and the points are less susceptible to damage than those in (a), they are the ones being used.

All needles mentioned resist the effects of corona and sparking well.

Emphasis is placed on sharp points for the needles, since not only do they require less voltage to initiate corona but also because they are an aid to the formation of corona from a positive polarity point electrode. In contrast to negative point-to-plane electrodes where the sparkover voltage increases with pressure and is always higher than the corona onset voltage, with positive point-to-plane electrode configurations, a critical pressure exists at which the sparking voltage begins to drop to coincide with the corona onset voltage; in other words, soon after the critical pressure is exceeded, the first breakdown of the gas is not corona but sparkover. It is significant that this phenomena occurs at an appreciably higher pressure for a sharp point than for a dull point.

The critical pressure phenomena for positive polarity points have practical importance in the generator at the corona combs where charge is removed. The relative polarity is such that sparking troubles may arise when operating at high pressures.

There would also be trouble if an attempt is made to spray positive charges on the down run of the belt. Another place where positive corona exists is at the corona loading device protruding through the tank wall opposite the high-voltage terminal.

Without going into too great length into the theory of breakdown of gases, let us examine why there is a difference in the behaviour of negative and positive points at high pressures.

The pre-discharge current consists of an electron avalanche that result from ionization by collision by an initial electron. When the point is negative, the electrons recede from the point, leaving the slower moving positive ions as a space charge about the point. The field intensity at the advancing tip of the avalanche decreases rapidly away from the point, and so ionization by collision may stop, and the avalanche may die out. The space charge further acts to weaken the field. The liberation of secondary electrons by positive ions striking the negative point is another ionizing agent. Corona onset occurs when the ionizing mechanisms can maintain the avalanches over the de-ionizing influences, chiefly the electric field and diffusion. The de-ionizing agents exert a stabilizing effect on the breakdown when the voltage is not too great.

With a positive point, an avalanche starting near the high field region may be propagated outside the avalanche region by photo-ionization. The formation of avalanches beyond the point is facilitated by the positive space charges remaining from previous avalanches, for these will strengthen the field farther away from the point.

The existence of a critical pressure may be explained by this difference in effect of the space charge upon the field. When the pressure is increased, the rate of diffusion of the positive ions is decreased, and the build-up of space charge in the case of the positive point is such that the field about the point is made more uniform. Finally the tendency of the space charge to make the field uniform overcomes the stabilizing nature of the geometrical arrangement of a point-to-plane to a degree that a stable discharge cannot be maintained.

Charge Belt

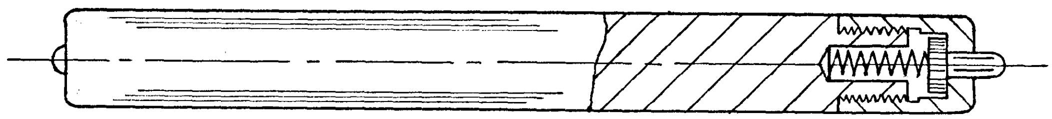
The belts that have been most frequently used are the rubber-impregnated cotton type made by the Fabreeka Company. They are 4 inches wide by 62 inches circumferential length. They are 5-ply, spliced construction, and approximately 3/32 inch thick. They run quite smoothly on the pulleys. The belt tension is around 70 to 100 lbs. The seam of the splice tends to open under the tension in running, — probably accentuated by the corona. The insulating quality of Fabreeka belts has been variable, but on the whole satisfactory if precautions are made to keep them from humid atmospheres.

An endless woven cotton belt made by the Arthur S. Brown Mfg. Company at Tilton, N.H., and coated with rubber (EXE 272 supplied by B.B. Chemical Company, Cambridge, Mass.) has also performed quite satisfactorily.

Dr. Trump has recommended a HICO Red 4-ply medium belt from the Globe Woven Belt Company. This belt presumably works best if the surface is given a coating of Formvar. These belts have been procured but have not been given a fair trial.

What seemed to be an attractive possibility at one time was an endless woven fiberglas belt impregnated with Silastic rubber. Besides its high resistivity, such a belt is immune to humidity effects and is non-tracking. One such belt was made, but the belt had very low abrasion resistance and quickly wore away. Very heavy frictional charges were also produced.

Belt gradient control is established by 1/2 inch diameter dural rods 7/16 inch away from the inside runs of the belt. The 1/2 inch thick edge of the equipotential plane's belt opening, suitably radiused, controls the outside belt surface gradients. The gradient control rods have a spring-loaded prong (Fig. 9) for easy snap-on attachment. The belt is constrained to run midway between the gradient control bars



Belt Gradient Control Rod

Fig. 9

by sets of 1/4 inch diameter glass rods which are clamped at the ends by a holder. They are located in the top and bottom equipotential planes with three sets spaced in the remainder of the column. Without these rods, the electrostatic forces could cause the belt to be pulled over to the equipotential plate and thus lose its charge. The belt gradient control and guide rods may be seen in Fig. 10.

A corona loading device is used for loading the belt for testing purposes when it is not desirable to have the

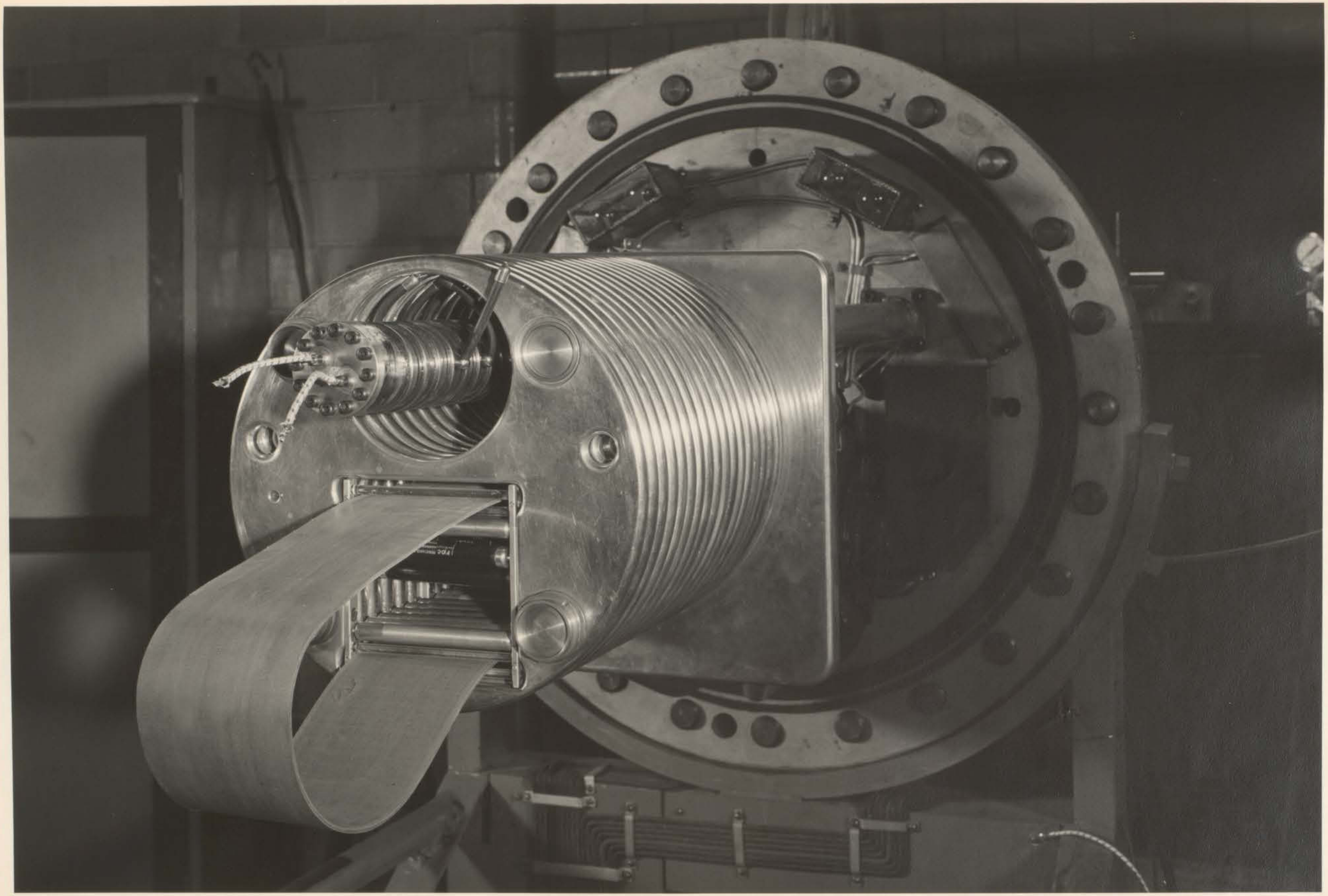


FIG. 10 PARTIALLY ASSEMBLED VIEW OF GENERATOR

accelerating tube in an unconditioned machine. Some corona load is also useful for its stabilizing influence on the terminal voltage, when the generator is operating with a light accelerating tube load, since it swamps variation in tube load caused by irregular emission. The corona loading device consists of a cluster of needle points which could be set at any distance to draw the desired amount of corona current from the high voltage terminal. Sparking tendencies might be expected to ensue with a single point, since it will be at a positive polarity with respect to the terminal. These anticipated troubles are minimized by massing a large number of sharp points and protecting against sparking by a surrounding hemispherical cup.

Self-Excitation Phenomena

The correct placing of the corona combs to remove all possible charge is very important for the proper functioning of the generator. Only with the realization that there are other factors involved in producing charge on the belt than external spraying, and with the correct appraisal of the internal charging process, was the generation of controllable steady voltages made possible.

The present corona collecting system developed from two previous arrangements which proved faulty. The simplest conventional arrangement is shown in Fig. 11 and was originally used. The take-off comb is located below the line of contact of belt and pulley.

A large self-charging effect was noticed. When the filaments of the spray supply rectifier tubes were switched on but without voltage being applied to the plates of the tubes, the spray current meter showed an increasingly large current and breakdown of the equipotential column followed. Even with the rectifier filaments switched off, a sizeable current was still registered by the spray current meter, and the spray voltage meter read in the negative direction. The self-charging was attributed to positive charges being produced and carried on the down run of the belt, this being equivalent to negative charges on the up-run. Passing the spray comb, the positive charge on the belt ionizes the gap and flows through the spray supply circuit. This part of the self-excitation process proved correct, but the source of the self-excitation charges was incorrectly thought to be frictional rubbing of the belt as it flaps against the screen-type collector comb.

Hence the collector comb was moved to a position near the contact line of belt and pulley (Fig. 12), where flapping of the belt is at a minimum. Self-excitation did not arise now, but it was later discovered that it was not owing to removal of the source of frictional charge, but rather, it was owing to the inefficiency of charge removal at the top comb.

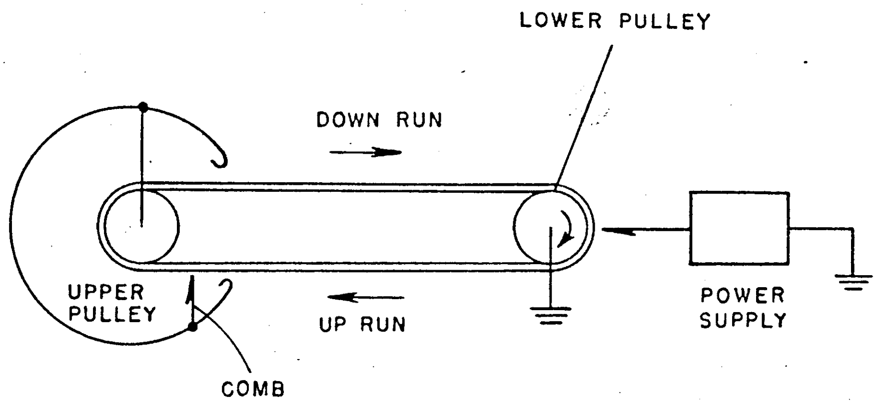


FIG. 11 FIRST ARRANGEMENT OF TAKE-OFF COMB

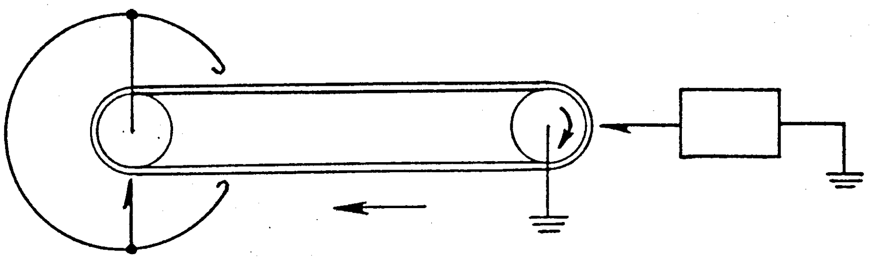


FIG. 12 SECOND ARRANGEMENT OF TAKE-OFF COMB

Belt pull-over was very pronounced, especially at high pressures, and had some dependency upon belt tension. Erratic sparking along the belt occurred independent of the voltage, and prevented any increase of maximum voltage with increasing pressure when above about 60 psig. Belt pull-over was then believed to be a flapping which was due to aerodynamic or mechanical reasons rather than to electrostatic forces, since the charge current being sprayed on was small and, in equivalent charge density, was well within what the belt is known to be able to carry.

These seemingly puzzling phenomena resolved themselves with the understanding of the true cause of frictional charging. The following theory of self-charging* was brought to the author's attention and seems to fit all the phenomena observed.

The movement of a belt over pulleys causes frictional charge to be deposited on the <u>inside</u> belt surface. Sliding contact is not necessary, since the process is one of contact electrification between two dissimilar materials. The contact potential of rubber to steel is such that the rubber belting comes away from the pulleys negatively charged (Fig. 13).

With the arrangement of combs as in Fig. 11, the charge on the inside of the belt cannot be removed by either comb, but the gradient induced by the negative charge at the upper set will cause positive charge to be sprayed on the outside of the belt (Fig. 14), which is carried around and removed by

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* "Notes on Self-Charging of Van de Graaff Generators", J.G. Trump and R.W. Cloud.

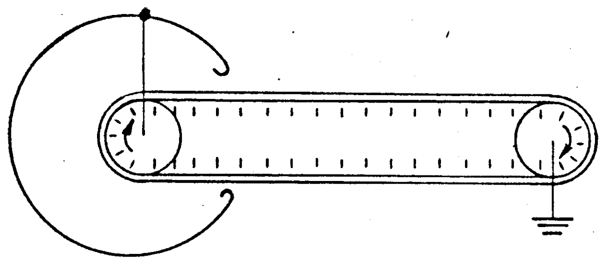

FIG. 13 CONTACT FRICTIONAL CHARGE ON BELT

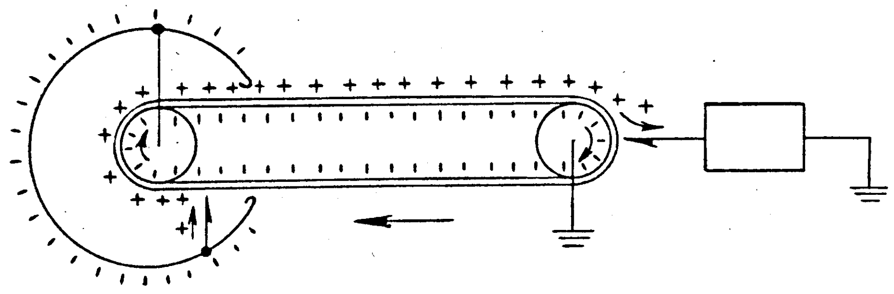

FIG. 14 SELF-EXCITATION DUE TO FRICTIONAL CHARGE

the spray comb. Fig. 15 shows the belt with negative charge going up in addition to the self-excitation charges. The net current reaching the terminal is equal to the total negative charge on the up run.

To prevent self-charging, the frictional charge on the inside surface of the belt must be prevented from building up to high values. A collecting comb on the inside surface will not remove charge on the inside of the belt if there is charge on the outside surface. It is, however, possible to remove the outside charge at the upper pulley with another close comb and then remove the inside charge with a comb as shown in Fig. 16.

The final arrangement of collector combs shown in Fig. 16 was adopted for regular operation. The inside collector comb picks up from 1/2 to 3 microamperes, which while small is an amount that prevents the cumulative effects of inside belt charge. Steady voltage conditions and continual gain in maximum voltage with increasing pressure have been the consequent result.

All combs at one time were the needle type. However, tracking was evident on some belts indicating incomplete charge removal. The switch to fine wire screen collecting combs was made in view of their greater efficiency of charge removal — the reason probably being that the area of ionization about each

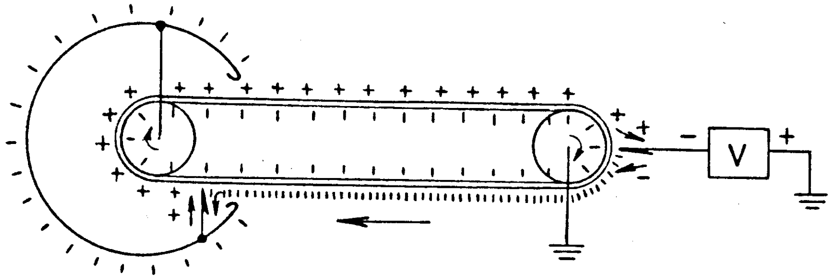

FIG. 15 NEGATIVE CHARGING AND SELF-EXCITATION

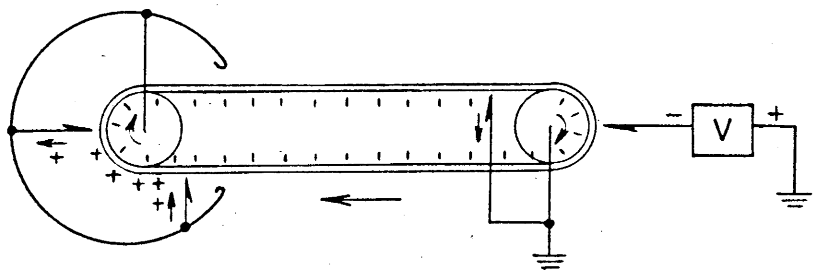

FIG. 16 REMOVAL OF INTERNAL CHARGE

point at high pressures is small, and the use of many close points as in a screen comb would remove more of the charge than the more widely spaced points of the needle combs.

It can be easily seen how the first take-off arrangement of Fig. 11 caused trouble. The subsequent arrangement of Fig. 12 caused trouble because with the collector comb close to the pulley, the capacitance between pulley and comb is too high, and therefore the voltage of the point gap is too low to remove appreciable charge. As a result, there is a large residual circulating current on the belt, and the actual charge density on the belt may be many times more than is indicated by the spray current. The belt easily becomes saturated with charge and sparking ensues. In addition, the contact charge on the inside belt surface is allowed to accumulate until sparkover occurs. The situation is aggravated on increasing the pressure because more voltage is required to break down the gap at the points, so that a greater circulating charge density to give the greater voltage remains on the belt. It is clear how belt flap occurred as a result of the electrostatic forces, and why it depended somewhat on belt tension, since the amount of tension affects the intimacy of contact of belt and pulley.

Gas System

The compressed gas insulation is nitrogen. It is slightly lower in insulating ability than air but has the advantage of being non-supporting to combustion — the combustion hazard being greatly increased with compressed air. It is, furthermore, readily available in cylinders.

Other gases and gas mixtures, such as carbon dioxide, sulfur hexafluoride, and the halogenated methanes (commonly known as Freons) are known to have greater insulating strength. A reason for their greater strength is due to their ability to form negative ions and so inhibiting breakdown by capturing electrons. Very little experimenting with these gases was done in the present project since the insulating strength of nitrogen was adequate, and the limitation to voltage would seem to lie in the accelerating tube, rather than the column structure.

It was not worthwhile to provide storage or recirculating means for the gas for the purpose of conserving it as the pressure vessel has the small volume of only 18 cu ft. The gas is simply fed from the commercial cylinders and released to the atmosphere on reduction of pressure.

The relative humidity of the gas is generally kept below 1% corresponding to a dew-point of minus 30°C. The tank is evacuated, preparatory to filling, by a Kinney pump to remove the moisture of the atmospheric air. "Dry" nitrogen is then admitted through a regulator valve. The use of "dry" nitrogen (with moisture content of 4 grains per 1000 cu ft) eliminates the need for cold traps in the supply line previously required when using "water-pumped" nitrogen.

Accelerating Tube

The accelerating tube for the electrons is made up of Vycor glass (96% silica content) sections with nickel electrodes along the accelerating length. The electrodes have a cylindrical length in the center to give some electrostatic focusing of the beam and afford some shielding of the beam from static charges on the glass walls. The internal diameter of the electrodes is 7/8 inch; the O.D. of the tube is 2-1/4 inch. The sections are cemented with Vinylseal adhesive.

The cathode has for its electron emission source a directly heated tungsten wire .010 inch diameter in the shape of a V with the apex partially ground off. The filament leads are introduced through kovar-glass seals. The removable cathode head is sealed by a copper gasket.

The electrodes of the tube have connected to them conductive rubber links of 2-3 megohms each. They connect each of the electrodes to the equipotential plane at its level by hooking onto a groove in the circular tube opening in the equipotential plane (see Fig. 10). They serve the additional purpose of damping out surges originating from the equipotential column.

A short magnetic focusing lens is mounted at the end of the accelerating length. This section of the tube is made of non-magnetic stainless steel. The magnet coil is made up of 3100 turns of #22 ga wire. It is surrounded except for a 1 inch focusing air gap by 1/4 inch thick mild steel (SAE 1010). Advantage is taken of the increased heat conductivity of the compressed medium to achieve a small size coil.

The accelerating tube ends as an integral unit with the open threaded end of the stainless steel tubing, which connects to the coupling unit containing the window through which the electron beam emerges and the outlet to the pumping system. The window is a 1 mil thick aluminum foil, 3/4 inch in diameter, which adequately withstands the atmospheric pressure upon it, is vacuum tight, and in view of its low density, has a low energy loss for electrons passing through it. Very little of the flat rubber gasket holding the foil is exposed to the action of the electron beam.

A fluorescent screen is used in place of the aluminum foil to check the focusing behaviour of the electron beam. The screen is made of celluloid with a semi-transparent aluminum coating over which willemite powder is spread. A visual indication of the sharpness of focus is thus obtained. Observation is by means of a mirror to avoid being in the cone of harmful beta and X-radiations.

Filament power is supplied by an 8-pole permanent magnet generator which is built inside the upper pulley (Fig. 8). The stator winding is brought out through a drilled hole in the shaft. The filament emission is controlled by a variable ratio step-down transformer whose primary is fed from the permanent magnet generator. Since the emission changes very rapidly with filament current, a very slowly variable secondary voltage is desired.

The transformer, ~~as~~ shown in Fig. 17, is made from the core of a Hammond 167C filament transformer. The laminations are separated, re-stacked and glued with Vinylseal adhesive in a jig. The E-shaped stacking forms the stationary part, with the primary coil on the center leg and with the secondary wound partly on the center leg and partly on an outside leg. The other straight stacking forms a movable armature, which, depending on its position, shunts a varying

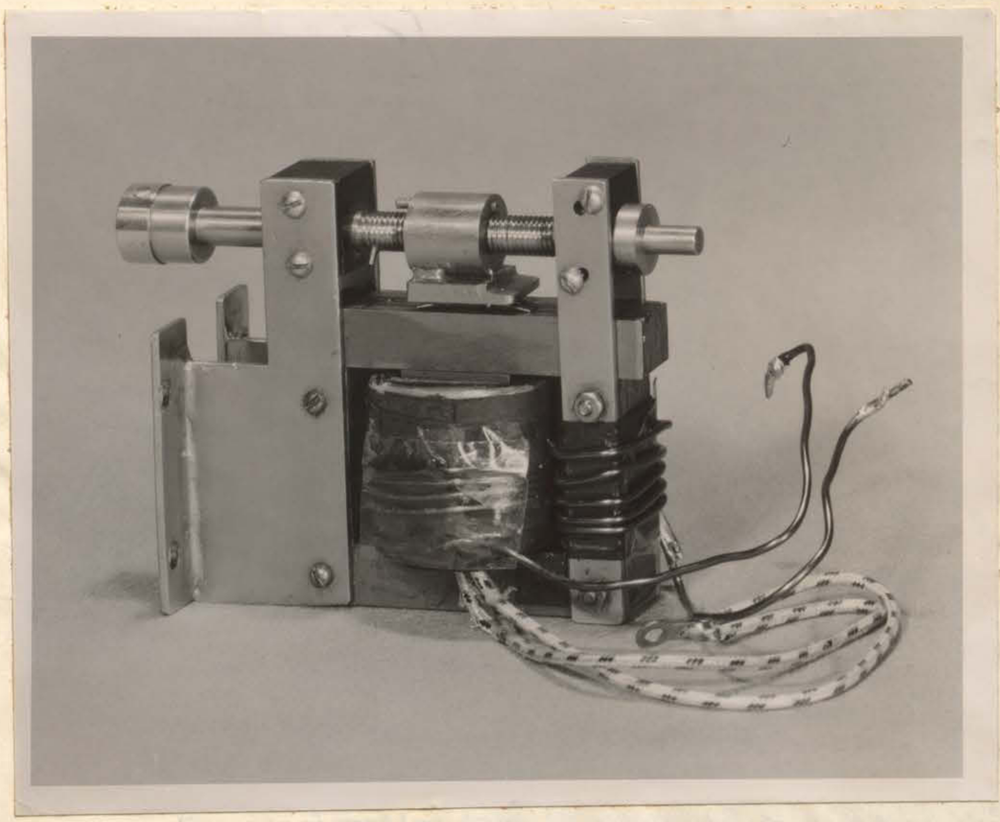

FIG. 17 VARIABLE SECONDARY FILAMENT TRANSFORMER

amount of flux from that portion of the secondary winding on the outside leg. A slowly variable output voltage is thus available for fine control of the emission current. Fig. 18 indicates the characteristics of this transformer.

The armature is actuated by a screw drive linked by a Lucite rod to a geared selsyn motor mounted on the ground plane. The mating surfaces of the iron is ground so as to minimize the air gap and thus the exciting current. The phosphor bronze leaf spring aids in maintaining good contact. Very little backlash is noticeable on reversal of motion of the armature. A point worth mentioning is that the mounting angle pieces will constitute a short-circuited secondary turn unless they are insulated from the top plate. A solenoid beneath the ground plane operates a microswitch to open the primary side of the transformer when filament power is not desired.

Vacuum System

The accelerating tube is evacuated by a 4-inch water-cooled oil diffusion pump, Type MC-275 with baffle, made by the Distillation Products Company. Its speed is 275 litres per second at 10^{-4} mm Hg. A Cenco-Megavac pump is in the foreline. A liquid air trap in the line helps to bring the vacuum down to around 5×10^{-6} mm Hg, and helps to prevent diffusion of oil into the accelerating tube, where if allowed to accumulate would adversely affect its breakdown strength.

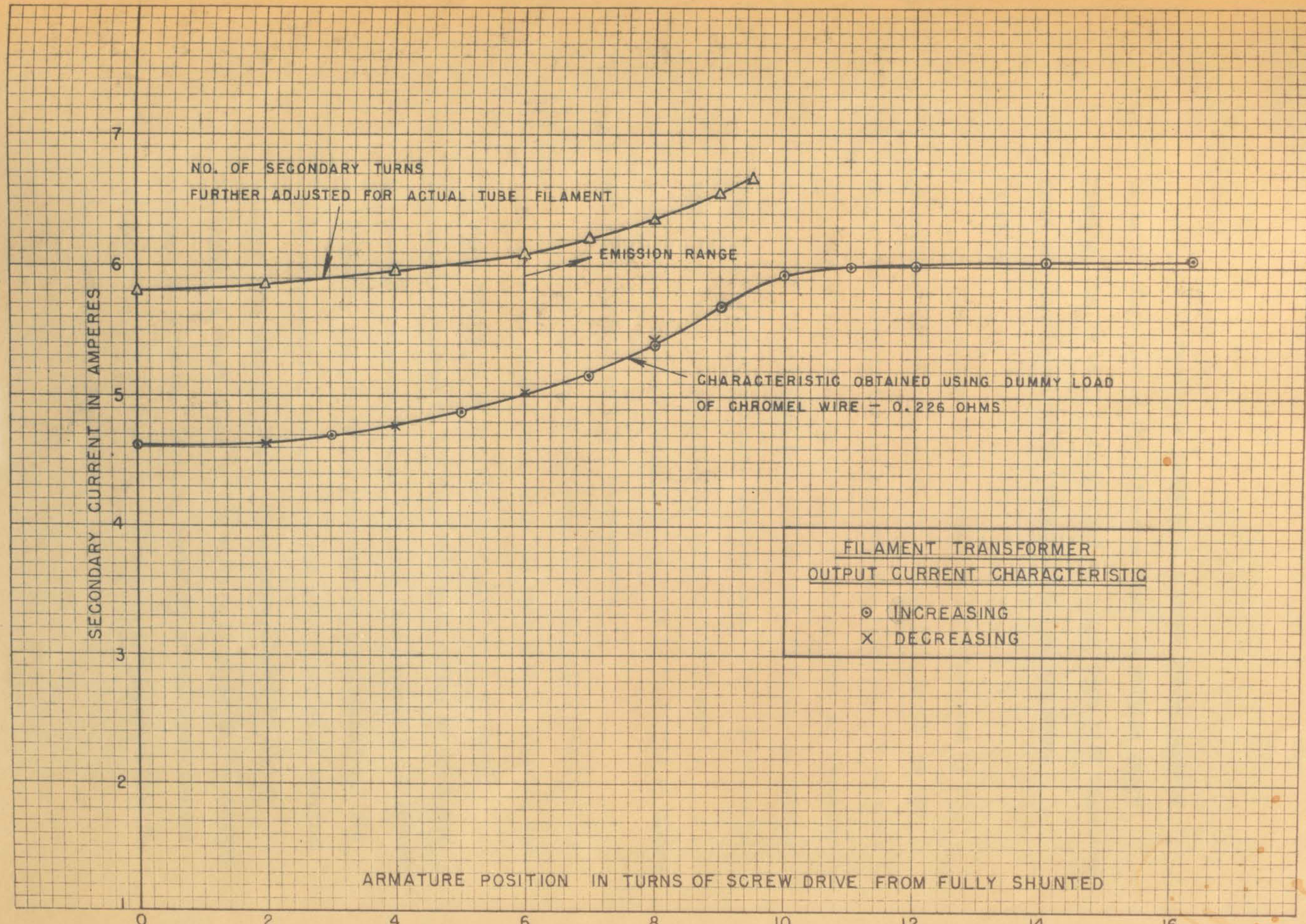
7
6
5
4
3
2
1
SECONDARY CURRENT IN AMPERES
NO. OF SECONDARY TURNS
FURTHER ADJUSTED FOR ACTUAL TUBE FILAMENT
EMISSION RANGE
CHARACTERISTIC OBTAINED USING DUMMY LOAD
OF CHROMEL WIRE – 0.226 OHMS
FILAMENT TRANSFORMER
OUTPUT CURRENT CHARACTERISTIC
⊙ INCREASING
X DECREASING
ARMATURE POSITION IN TURNS OF SCREW DRIVE FROM FULLY SHUNTED
0
2
4
6
8
10
12
14
16

FIG. 18

A thermocouple gauge with a range 5-1000 microns is in the foreline of the diffusion pump. A Philips gauge reading from 25 to .02 microns and an R.C.A. Type 1949 ionization gauge are located close to the window end of the tube.

Metering

The voltage of the generator is determined by a generating voltmeter[14], which is mounted in a nozzle at the end of the tank facing the high voltage terminal. It consists of a set of insulated sector-shaped plates which are periodically exposed to and shielded from the electric field of the terminal dome by a rotating grounded sectored disk. The induced current resulting from the periodically varying capacitance is proportional to the terminal voltage. It is rectified by diodes and read directly on a d-c microammeter.

The generator voltmeter has been calibrated in place with the rotor blades flush with the tank wall by applying d-c voltages from a 50 kv transformer-rectifier power supply accurately measured by the drop through a string of precision wire-wound resistors, and at the same time observing the current developed by the generating voltmeter on a galvanometer. The curve of generating voltmeter output as a function of terminal voltage is a straight line. It is extrapolated to higher voltages. A rough check on the voltage is given by the current through the potential dividing resistors of the equipotential column. The column current, however, is not depended upon for close estimation of voltage.

As there will be intense beta and X-radiations near the window of the accelerating tube, the control panel with the meters (Fig. 19) are located at some distance away. The wiring of the power supply and tank is given in Fig. 20, while the wiring of the control panel is given in Fig. 21.

It is necessary to guard against high induced voltages arising from surges in the generator. This is done by using shielded wire of extruded aluminum for all interior tank wiring. All exposed terminals are shielded. The light bulbs are likewise shielded by enclosing them in copper screen cages. The 550 volt motor leads are protected by Thyrite resistors to prevent surges from entering the power supply lines.

Meters are protected against surges and overload by placing a small neon across a suitable resistor in series with each meter. If the current through a meter exceed the margin allowed for, the voltage drop across the resistor will reach the striking voltage of the neon (90 volts d-c) and the current is safely by-passed. It is generally apparent by the flashing of the neons approximately where sparking inside the tank occurs.

The metering is arranged to give as complete a picture of the load current distribution as possible. Thus the column current is collected from the equipotential plane next to the

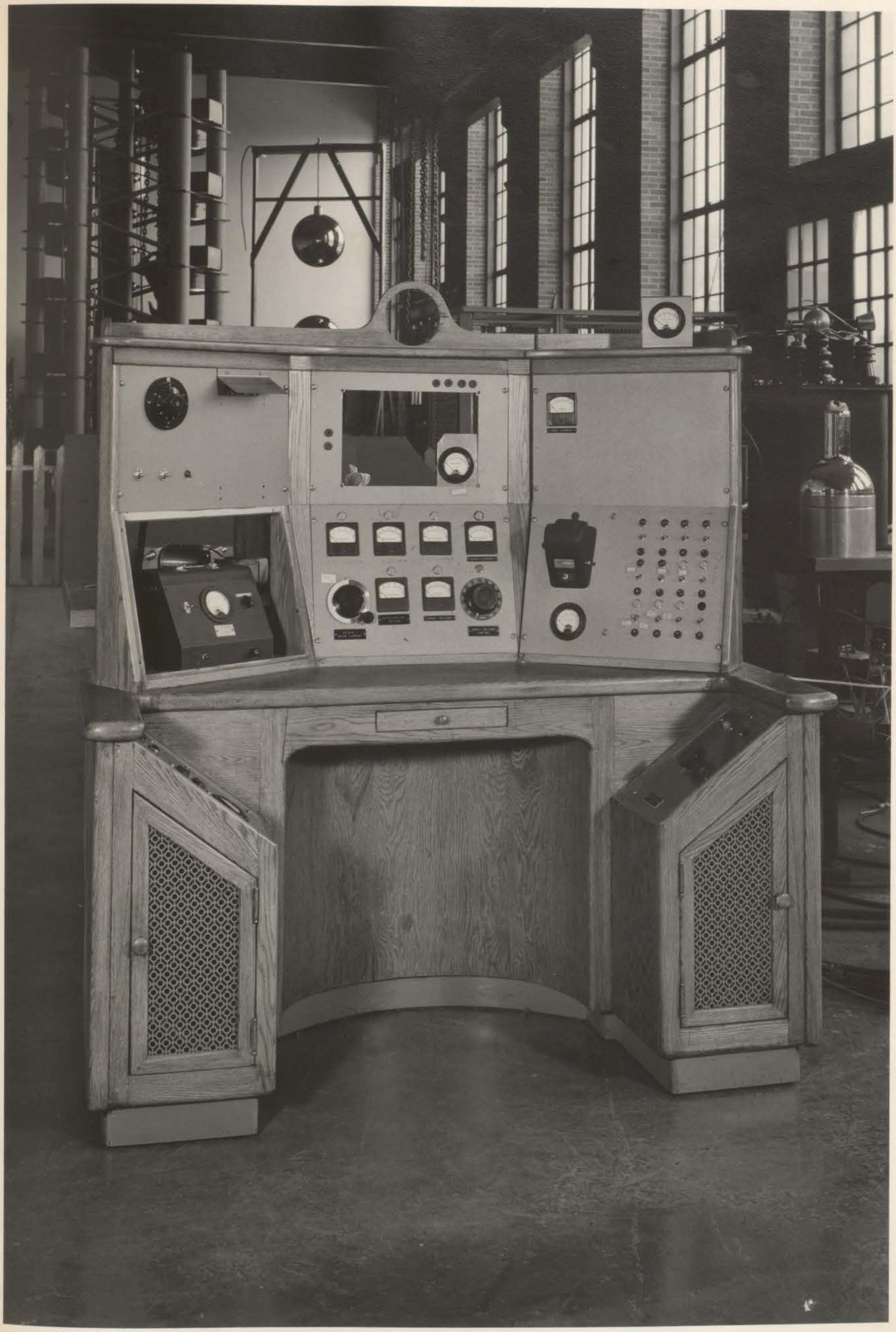

FIG. 19 CONTROL CONSOLE

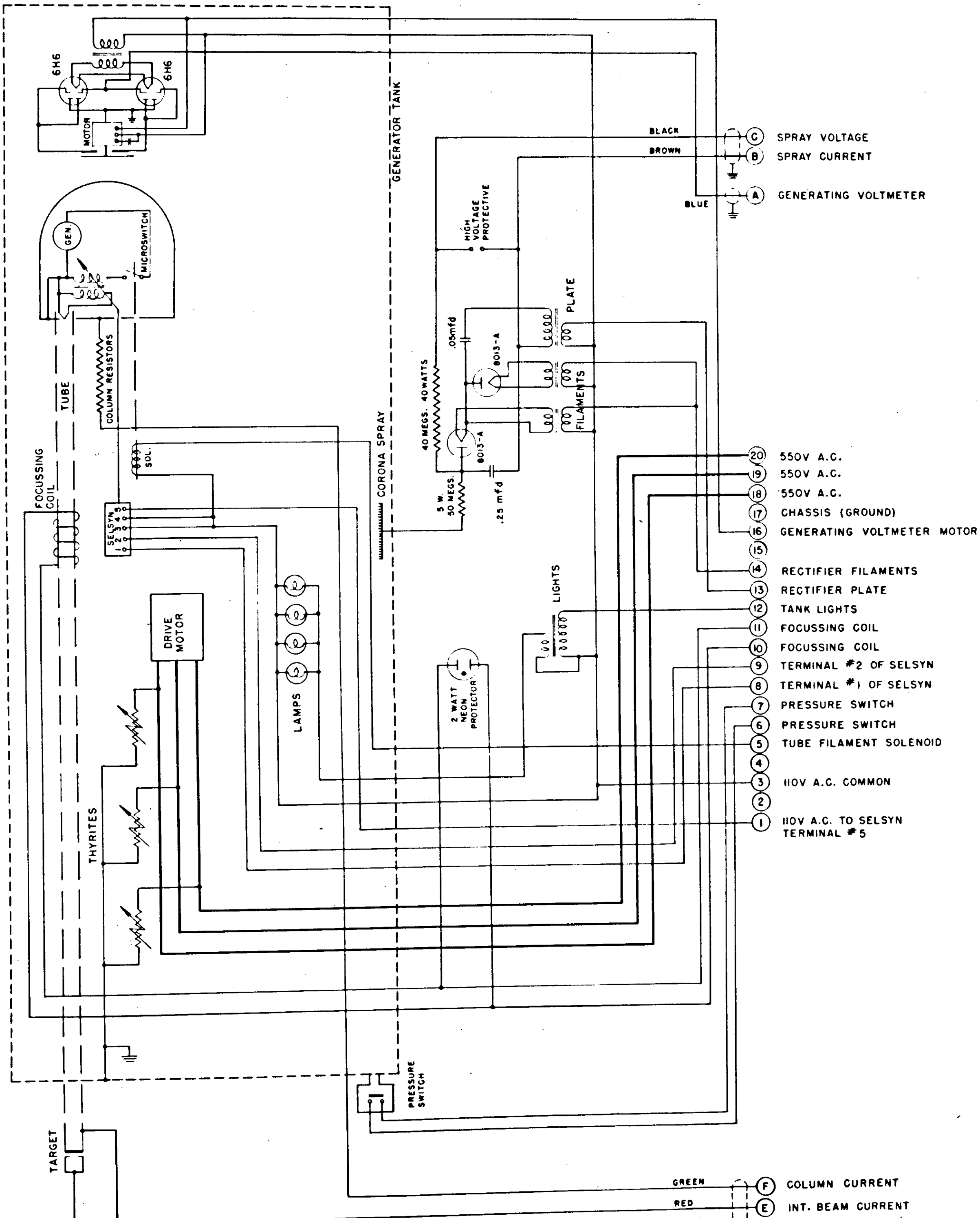

FIG. 20 TANK AND POWER SUPPLY WIRING

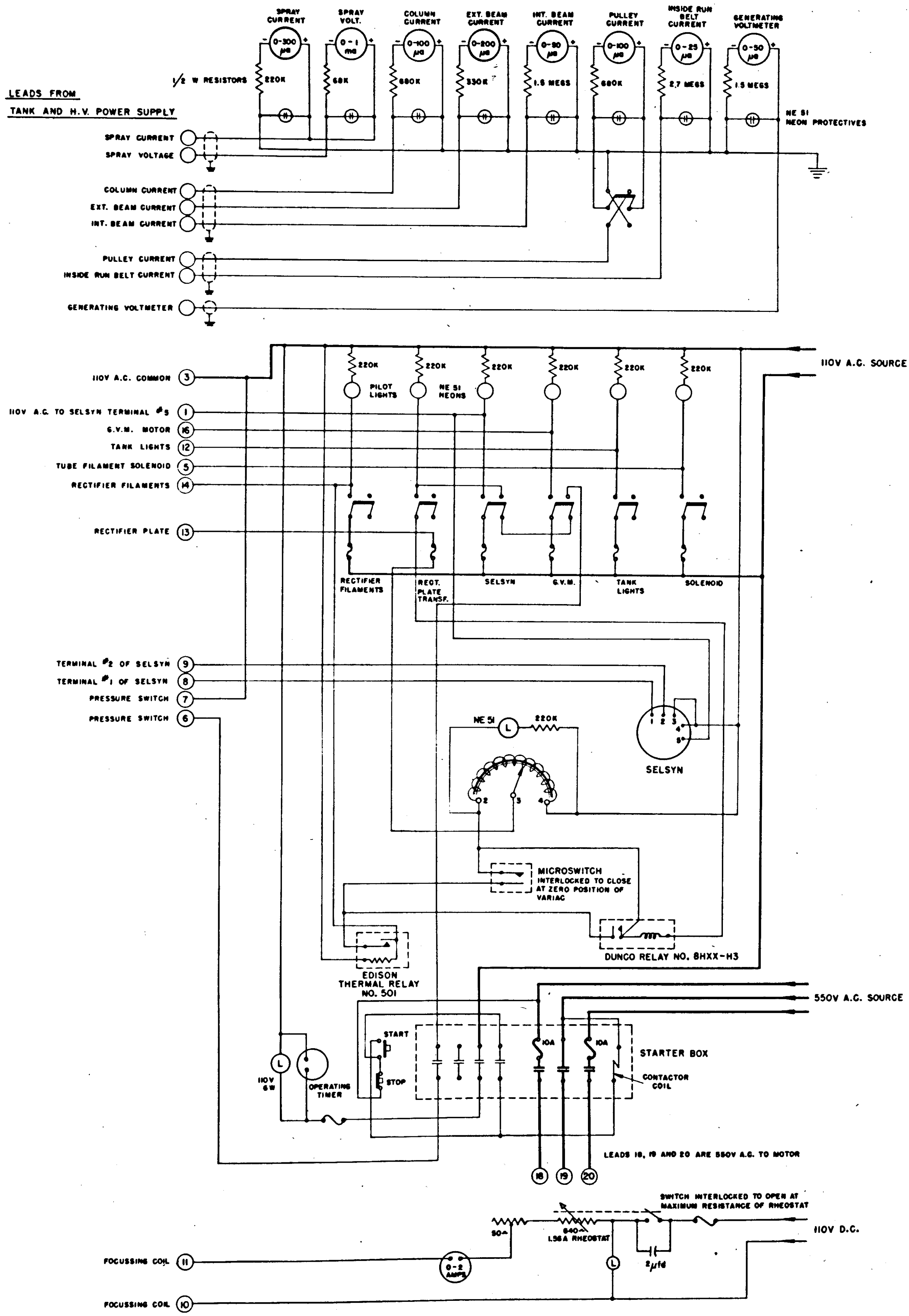

FIG. 21 CONTROL PANEL WIRING

rectangular 1 inch thick ground plate. This plate in turn is insulated from the tubular supports to check for any current flowing to or from the pulley arising from either self-excitation or charge leakage through the belt. The tube current that does not get through the window is metered by mounting the tube with insulated bolts, and is termed "internal beam current". That tube current that emerges through the window and termed "external beam current" is caught by a Faraday cage.

Interlocks and relays in the spray current circuit in the control panel require that the variac must start from an initial zero position, that the drive motor and the generating voltmeter motor be running, and that the rectifier tube filaments are warmed up, before the rectifier plate transformer can be energized from the variac.

V. RESULTS AND CONCLUSION

The performance of the generator without the accelerating tube in has exceeded the design figure of 500 kilovolts by a comfortable margin. The results of a "no load" voltage test is graphically presented in Fig. 22. At a pressure of 175 psig nitrogen, a voltage of 980 kilovolts was reached. The test was not carried to the voltage limit which would be set by belt breakdown, since in actual use, it is unlikely the tube can withstand so high a voltage. If the machine is in clean condition, the points in the graph represent sharply defined voltages, below which the generator can run apparently indefinitely without sparking disturbances.

The curve is linear to approximately 120 psig pressure. It confirms what other investigators have found about the validity of Paschen's Law — that the sparking voltage increases linearly with pressure up to about 10 atmospheres, departing slowly from linearity thereafter. The slope of the curve would depend, of course, on the spark gap setting.

During the voltage tests, it was found essential to have the interior free of all lint particles. Lint would attach to the equipotential column to form filamentary

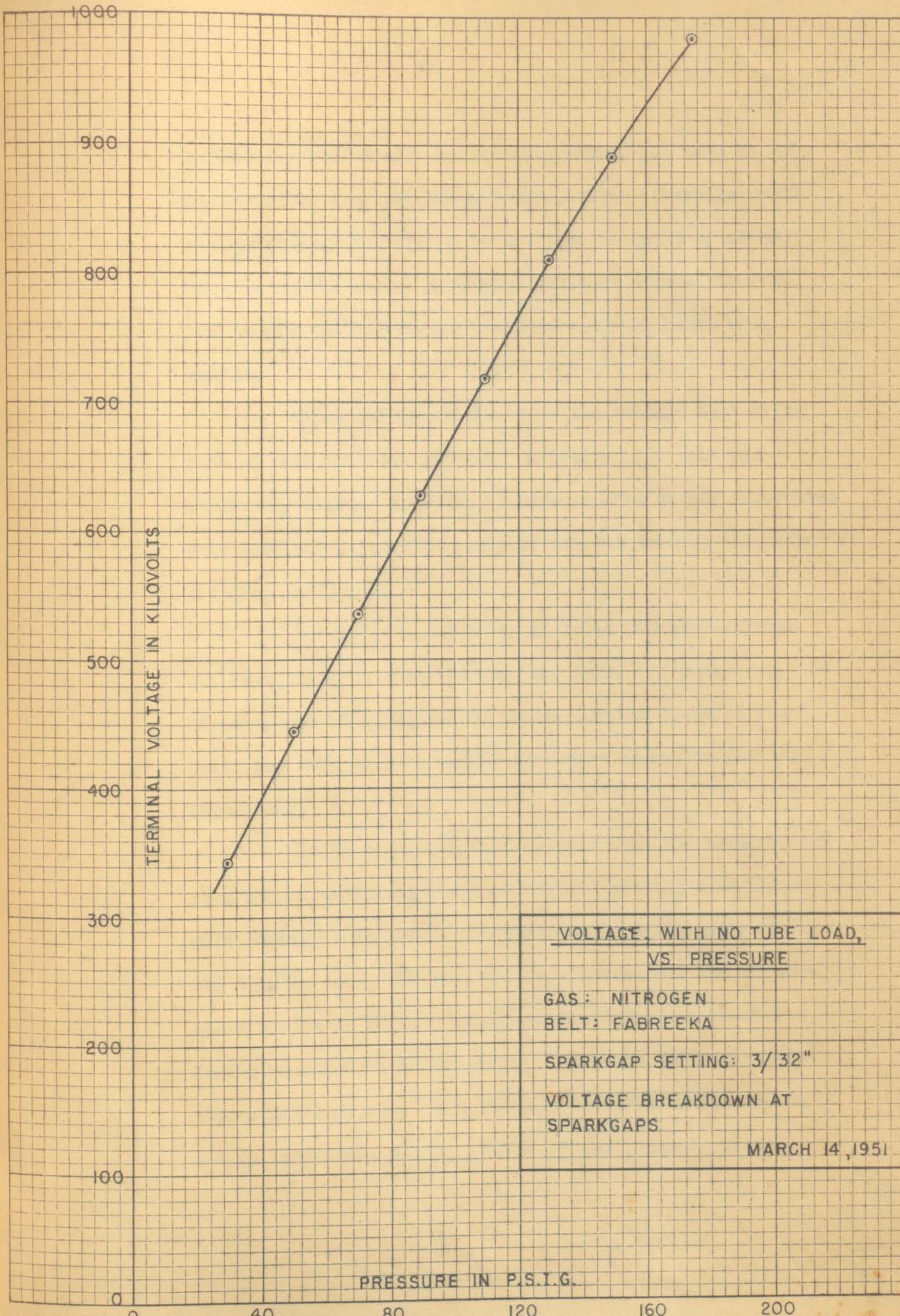
1000
900
800
700
600
500
400
300
200
100
0
TERMINAL VOLTAGE IN KILOVOLTS
0
40
80
120
160
200
PRESSURE IN P.S.I.G.
VOLTAGE, WITH NO TUBE LOAD, VS. PRESSURE
GAS: NITROGEN
BELT: FABREEKA
SPARKGAP SETTING: 3/32"
VOLTAGE BREAKDOWN AT SPARKGAPS
MARCH 14, 1951

FIG. 22

projections that drain considerable charge (as much as 200 microamperes) away as corona losses, which otherwise would be negligible. Voltage could not then be built up without overloading the belt. A routine blow-out of the interior just before putting on the pressure tank has hence been adopted.

"No load" in reference to the voltage test means that no tube load was imposed. Actually, the belt was moderately loaded, carrying 95 microamperes at 980 kilovolts; this load being made up mostly of current through the potential dividing resistors.

A current capacity of at least 200 microamperes can reasonably be expected from the belt. If necessary, the capacity can be increased by increasing the speed of the belt, say 20%, without making much more demand in driving horsepower.

It is regretted that results with the accelerating tube cannot be reported at the time of writing owing to difficulties encountered in obtaining a tight vacuum when the tube is under the external tank pressure. The trouble seems to lie in a Vycor glass section which was cracked during manufacture of the tube. The crack had been sealed over with Vinylseal, but evidently the leak has re-opened and is noticeable during filling of the pressure vessel.

There is at present no means for automatic stabilization of voltage. Changing corona conditions between the belt and the combs cause voltage fluctuations of about ± 10-15 kilovolts. For periods of minutes, sometimes, the voltage can be held steady with a much smaller variation. This degree of stability is believed to be sufficient at the beginning to obtain qualitative results in radiochemical experiments. Probably the best approach to the problem of stabilization would be to use the generating voltmeter output to effect a change in the spray voltage. The belt being short (transit time for charge to arrive at the terminal from the spray comb is 1/30 th second), sufficiently rapid correction could probably be made to achieve fairly good voltage stability.

A source of satisfaction has been the performance of the molded Lucite insulators. Unlike Textolite, it has a high degree of insulating strength; unlike glass, it is shockproof. There are good possibilities for its use in future generators, especially those designed to be portable, or to have their axes inclined.

Taking into account the lack of voltage stabilization means, the generator in its present state is performing with complete satisfaction in the function of producing high voltages. The voltage is steady, and smoothly controllable; the generator performance is entirely predicable. It remains for future work to be directed towards obtaining an electron beam out from the accelerating tube.

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