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THE ELECTROSTATIC GENERATOR

/NOTE: The following is a translation of a Russian article written by A. F. Ioffe, who is affiliated with the Leningrad Physicotechnical Institute of the Academy of Sciences USSR. The article was submitted 4 October 1939 to the Zhurnal Tekhnicheskoy Fiziki, Vol IX, No 23 (1939), pp 2071-2080./

1. Introduction

Successful high-voltage techniques led in 1931 to the experiments of Cockroft and Wolton and to the rapid growth of nuclear physics. In its turn, nuclear physics stimulated a number of attempts to obtain particles with energies equal to several million electron-volts. Among these attempts, the Lawrence cyclotron and Van de Graaf generator were the most significant.

Dozens of installations of these two types have been realized or are being constructed in all countries, chiefly in the US. Present-day cyclotrons require even now hundreds of tons of metal and hundreds of kilowatts of power. The Van de Graaf generators astound one by their great storey buildings. The cost of a cyclotron or generator is measured in the millions. The employment of high-voltage generators is not limited, however, to nuclear physics. Many clinics are equipped with X-ray apparatuses with voltages in the millions.

High-voltage experiments require such generators. Million-volt electron guns could be utilized in many ways.

Finally, one should not forget the basic problem of transmission of direct current -- a problem which is becoming more and more urgent as demands for long-distance transmission of power become greater; that is, the further increase of voltages.

Obviously, present electrostatic generators giving several milliamperes of current are not suitable for power purposes. Quite obviously, however, future purposeful development can give technically important results. In my opinion electrostatic generators of 1000's of kilowatts are entirely possible.

In the course of four years we have been endeavoring to perfect the electrostatic generator, mainly with the aim of obtaining high-voltage streams of charged particles or X-rays. Constantly in our view were the problems of power concentration in small spaces and efficiency.

Although this work is still far from complete, we consider it useful to publish our results, since they allow one to judge how far we have progressed in the various individual problems and to illuminate the technical side of the problem.

In the course of our work we tried a great number of models and developed many variations of the basic idea, and in our experiences we have resolved very important difficulties of a practical nature. Publication of our experiences will undoubtedly clarify the work for other investigators.

2. Setting up the Problem

The principle governing the operation of each electrostatic generator consists of the movement of a definite charge in an electrical field, in which case the work expended in its transposition is converted into electrical work.

The potential of charge Q is raised from V_1 to V_2. If the charge Q does not change, then the capacitance of the system bearing the charge decreases from an initial value C_1 to C_2, thus:

$$C_1 V_1 = C_2 V_2 \text{ , or } V_2 = \frac{C_1}{C_2} V_1 . \qquad (1)$$

The current strength I is defined as the charge that is transferred to the collector per 1 second.

Let us designate by E the field intensity due to the charge Q; by epsilon ε , the dielectric constant of the medium in which the charge Q moves; by v, the velocity of the charge along the lines of force; and by S, the size of the surface, perpendicular to the field, which (i.e., surface) holds the charge. Then we have:

$$I = \frac{\varepsilon E}{4\pi} S v . \qquad (2)$$

In the Van de Graaf generator the capacitance C_2 practically equals zero, therefore the highest practically attainable potential is determined by the leakage current and the current taken off.

When $E = 100$ abs units, $\varepsilon = 1$, $S = 2$ m, and $v = 20$ m/sec, then we have: $I = 1$ milliamp.

The tremendous space required for insulation of the collector is utilized very inefficiently. The operating space is merely the surface of the moving belt. Therefore, even in generators with compressed gas the power remains negligible -- several kilowatts for a volume of 100 to 200 m^3.

Proceeding from the Van de Graaf or other older type of generator one can try to eliminate these weak points.

The highest possible field intensity E, which the charge density determines, must be regarded as the most important condition. This can be attained thus:

1. By building in the generator a medium with the highest possible electrical strength

2. By making the electrical field, normal to the charge-bearing surface, as homogeneous as possible; in which case the movement of the capacitance must at all times vary uniformly, maintaining a maximum field.

In order to decrease the size of the machine, it is desirable to make as uniform as possible also the field along the lines of force in which the charge Q moves and to ensure a compulsory distribution of potential which (i.e., distribution) does not permit accumulations of space charges.

The second important condition is the greatest possible operating surface of the generator in a given space. This is attained only for a rigid rotating system.

Very important also is to increase the speed of the moving charge up to maximum limits permitted by the strength of materials. This condition requires a rotor with uniform rotation and a medium with the smallest possible viscosity.

Increasing of the dielectric constant presupposes a fluid medium. However, the requirements demanded of insulating properties and viscosity of this medium, it seems, makes a fluid unsuitable for large machines. In small models, a fluid medium (we have found the most satisfactory one to be highly purified kerosene; its method of purification has been described earlier (1)) turns out to be very convenient. From the standpoint of electrical strength, the compressed gases employed by us significantly surpassed fluid dielectrics.

In describing the operating cycle of a generator in the coordinates C, V, or Q, V, we note a very close analogy with Carnot's cycle for thermal engines (see Figures 1 and 1a).

1. At capacitance C_1 or charge q_1, the system is removed from a source at potential V_1 and without the charge varying it diminishes its capacitance to the value of C_2, but the potential increases to V_2; all during this process the product VC remains constant -- the curve in figure 1 represents the equilateral hyperbola.

2. At constant potential V_2, the system is joined to the collector, to which a charge $q_1 - q_2$ is transferred, thus decreasing its capacitance to the value C_3.

3. Then the system is separated from the source at potential V_2, and at constant charge q_2 it increases its capacitance to the value C_4, thus decreasing its potential to V_1.

4. Finally, the system is joined to the source at potential V_1, and increasing its capacitance from C_2 to C_1 it receives from the source a charge $q_1 - q_2$.

The cycle is a closed one. As a result of each cycle a quantity of electricity ($q_1 - q_2$) is transferred from the source at potential V_1 to the collector at a higher potential V_2. The mechanical work expended in this transfer is represented by the area of the rectangle ABCD in figure 1a. The area ADEF is the electrical energy delivered by the source at potential V_1, and the area BCEF is the energy obtained by the collector.

Thus the energy U_2 obtained by a high-voltage system consists partly of the electrical energy U_1 supplied by the low-voltage system, and partly of the mechanical work $U_2 - U_1$.

The ratio U_2/U_1 is determined by the coefficient of transformation $n = V_2/V_1$, which is always considerably greater than unity.

The electrostatic generator is reversible: if one conducts the same cycle clockwise, the high-voltage source supplies energy U_2 and the low-energy source obtains energy U_1, and the difference $U_2 - U_1$ is converted into mechanical work.

The generator can serve also as an electrostatic motor. The coefficient of useful work in this case as in the other is determined only by friction, Joulian heat, and dielectric loss due to the periodic variation of the field in a moving dielectric motor.

If the minimum capacitance equals C_3 when removed from the collector and the maximum capacitance equals C_1 at the moment when removed from the low-voltage source at voltage V_1, then the greatest attainable voltage is:

$$V_m = V_1 \frac{C_1}{C_3} . \qquad (3)$$

The current strength at this potential equals zero, since here $C_2 = C_3$ and $q = V_2(C_2 - C_3) = 0$.

The charge after one cycle equals: $Q_m = V_1(C_2 - C_3)$.

If we take the charge at potential V intermediate between V_1 and V_m, then we obtain the relations:

$$V = V_{max} \cdot \frac{C_3}{C_2} ,$$

$$Q = V(C_2 - C_3) = VC_2 - V\frac{VC_2}{V_m} .$$

We designate the quantity by:

$$VC_2 = V_1 C_1 = Q_0 .$$

This is the charge found in the rotor in the section 1-2. Hence:

$$Q = Q_0 \left(1 - V/V_{max}\right) . \qquad (4)$$

Figure 2 depeicts the voltampere characteristic expressed by equation (4). This is a straight line whose slope with the x-axis equals:

$$\tan \alpha = V_m/Q_0 = 1/C_3 . \qquad (5)$$

Thus the capacitance C_3 determines not only the maximum voltage V_m but also the slope of the characteristic which (i.e., slope) gives the magnitude of the charge able to be taken at a given voltage V.

3. The Main Types of Generators

The simplest type of generator in existence is the cylindrical rotor rotating eccentrically in another cylinder grounded to the earth (figure 3).

The charge from the low-voltage source is delivered at the place where the rotor passes closest of all to the container. If the rotor's surface is a dielectric, the charge must be supplied along the entire generatrix (i.e., the line generating the cylindrical surface); for example, through the corona points. The charge can be supplied with a brush at a definite part (for example, at the end parts of the cylinder). To do this, however, one must provide the rotor with sufficient conductivity on the generatrices while maintaining good insulating quality along the circumference. This is easily attained by one's applying on the rotor's cylinder conducting strips separated by insulators.

At the place where the charge is supplied, the capacitance per unit surface of the rotor is a maximum (C_1). Actually, if the scheme represented in figure 1 is to be realized, the charge starts to be supplied somewhat earlier for a capacitance C_4, and at maximum capacitance C_1 the supplying of the charge is completed and contact with the low-voltage source ceases.

The charge located on the rotor's surface moves farther away with further rotation from the container's wall; the capacitance decreases and the potential increases. If the rotor's radius of curvature is very large in comparison with its distance from the container, then the capacitance decreases inversely proportionally and the potential increases directly proportionally with this distance.

Thus the field during the entire time of the motion is almost uniform (the field is bounded by two cylinders with large, although somewhat different, radii) and the field intensity remains identical and equals $E = 4\pi q/\varepsilon$, where q is the charge per 1 cm^2. Considerably weaker is the field along the circumference of the cylinder, although the field is not uniform; the field, however, possesses a given smooth distribution which ensures the electrical strength on the rotor's surface and in the intermediate medium.

When the capacitance of the rotor's surface falls to the value C_2, the charging is effected upon contact with the high-voltage source (with the aid of brushes or points). From this moment up to such a position that the capacitance attains the least possible value C_3, when at the greatest distance from the container, the charge passes over to the collector.

Further movement of the rotor without a charge is unprofitable not only because of the loss of operating area but also because of the asymmetry introduced by this. The left half of the rotor moving in a maximum electrical field experiences a force normal to the rotor's axis, which (i.e., force) which is never in equilibrium with the right side.

If in the compressed gas the field intensity reaches 300 kV/cm or 1000 abs units, than for $\varepsilon = 1$ the left side will experience a lateral pressure p equal to $p = E^2/8\pi = 3/100$ atm.

Therefore it is expedient after the charge is taken off to supply a charge q of potential $V_2 - V_1$. This charge at potential V_1 begins to withdraw to the corresponding low-voltage source or thethe ground at the ppposite end of the rotor's diameter near the container.

One can improve the operation of the described generator in two ways (figure 3a):

1. Distribution of the field along the circumference of the cylinder between the high-voltage collector and ground can be made homogeneous, if instead of the surface of the cylindrical container one introduces a grounded screen 1 of such a form that the field tangent to the rotor's surface would remain constant, then the resultant of the forces normal and tangent to the surface will preserve over the entire expanse an identical magnitude and inclination to the rotor's surface.

Under these conditions we obtain the optimum utilization of the generator's dielectric medium.

2. With the aim of decreasing the capacitance C_3 without increasing the container's size and at the same time with the aim of further improving the field's configuration one should introduce in the generator a screen 2 joined to the collector. The distance between this screen and container can be filled with any insulating dielectric, solid or fluid, with maximum electrical strength. Here we have an almost homogeneous constant field.

In this dielectric it is easy to divide the potential with the aid of semiconducting layers.

One can further increase the power and attainable voltage by introducing in the rotor two more internal screens 3 and 4.

3. The internal surface of the rotor can be made an operating surface if one introduces a grounded screen 3 in a form corresponding to screen 1 and supply the charge to both the external and the internal surfaces of the hollow cylindrical rotor. It is simplest of all to connect metal conducting strips in both surfaces. Obviously, the form of the screen 1 must be designed with considerations for the redistribution of the charge in the external and internal sides.

4. By introducing a screen 4 connected by metal to screen 2, we create in the space between them a sort of Faraday pail and sharply lower the capacitance C_3 (figure 1), which determines according to equation (1) the attainable high-voltage potential V_2.

The distance between screens 3 and 4 obviously is smaller than the distance between 1 and 2. However, if within the hollow cylinder there is no rotating axis, the space 3-4 can be filled with a dielectric possessing great dielectrical strength and distributed potential.

For the distribution of potential between screens 3 and 4, and also between screen 2 and the container, one can utilize not only the leakage through a great resistance but also the direct metal bond with the rotor in those parts of it which possess corresponding suitable potentials. To do this one needs, obviously, a supplementary system of intermediate brushes or points.

Tests on small models and small volumes led us to the conviction that kerosene and $C\,Cl_4$ are the most suitable media for a generator.

Their rupture strength exceeds 200 kV/cm; specific resistance for a field of 100 kV/cm can be brought to 10^{13} - 10^{14} ohms, and viscosity is sufficiently small. Actually, as shown in the next article, a small model 9 cm in diameter gave 100 kV in kerosene and sufficient current. However, a large generator with a two-meter rotor shows that the rupture strength of kerosene for such sizes does not succeed for long in rising higher than 30-40 kV/cm; at the same time the expenditure of energy in friction exceeds by many times the useful power.

As a result of this, the generator, which at an operating field of 90 kV/cm should have created about 3 million volts and given a short-circuit current up to 1 milliampere, did not exceed 1.2-1.5 million volts and gave a short-circuit current up to 0.3 milliampere. Its prolonged use turned out to be possible only for voltages of 800-900 kV and currents of 20-50 microamperes.

Therefore we turned to a study of gaseous dielectrics. Besides the well-known $C\,Cl_4$ and freon, we sought a new perfectly inert gas with electrical strength about 70 kV/cm at atmospheric pressure.

Filling of the above-mentioned fluid generator (not designed for high pressures) with one of these gases should raise the maximum potential and almost increase by three times the velocity of rotation. Under these conditions one can expect that the short-circuit current would increase to 600 microampères and the operating current, to 300 microamperes.

The main advantage of our gas is that its pressure can be increased to 10 atm without danger of liquefaction. In this case the gas' rupture strength in a homogeneous field increases according to Paschen's Law proportionally with pressure, reaching 700 kV/cm; that is, to such values beyond which one can already expect the cold extraction of electrons. In a nonhomogeneous field the gas' strength is 2.2 times greater than the strength of air.

The employment of such a medium promises great advantages for electrostatic generators of the closed type, besides for many other problems of high-voltage technology.

4. Multirotor Generator

A glance at figure 3 and 3a shows the insufficient utilization of the space, in particular the space between screen 2 and the container. Here one has to insulate the voltages themselves directly from the earth.

This defect is eliminated by a transition to multirotor models possessing one general container. The number of rotors can be from 2 to 6. Figure 4 shows a four-rotor model.

In the center is located a high-voltage collector. From it to the container the intensity decreases uniformly in all directions. The surfaces of equal potentials in the space between the rotors can be realized with conducting layers possessing potentials decreasing gradually from V_2 to 0; the last layer is grounded to the screens.

The remainder of the model (in figure 3 here, namely, the entire space), excluding the gaps around the four rotors, can be filled with a solid dielectric with conducting laminae (in the model of figure 3 this would lead to the appearance, on the surface of the dielectric, of charges which eliminate the field near the rotor).

On the surface of the gap opposite the rotor these laminae create a potential V differing from the potential of the rotor's surface by the amount ΔV such that $\Delta V = Ed$, where E is the field attainable for a medium filling the gap and d is the gap width.

Obviously, the conditions governing the insulation both for the dielectric filling the container and for the medium in the gaps are much more favorable than in the model of figure 3. Since the transverse field in the gap is considerably greater than the longitudinal field, the insulation needs actually to be designed only for the potential difference ΔV and not for the entire applied voltage V_2.

This fact introduces a new tempting possibility of transition to a vacuum as the medium in which the rotor rotates.

Van de Graaf in his first article introduced the notion of a vacuum, but the idea turned out to be impracticable and was not able to be realized by him, since the technology of the vacuum at one million volts is still non-existent. A totally different matter is a vacuum for voltages equal to 50-60 kV. Here one can rely on well developed techniques that ensure safe operation. The field in this case can be brought up to 500-600 kV/cm, which means a gap of the order 1 mm. When the rotor operates with an accuracy of 0.1 mm, we should have a field steady to 10% of its value, which permits the indicated fields to be actually used.

At the same time the vacuum perfectly eliminates the main source of losses -- namely the friction and turbulent motion in the medium surrounding the rotor.

The remaining losses -- namely, friction in the bearings (the gaps in them can play the role of a vacuum pump), Joule heat, and dielectric losses -- can be reduced to very small values. Under these conditions the vacuum electrostatic generator can approximate in efficiency the electromagnetic machines. However the actual characteristics of vacuum generators can be judged only after suitable models are made and studied.

The operating principle itself of the multirotor generator differs some- In fact, in-
what from the unirotor rotor illustrated in figures 3 and 3a. In fact, in-
stead of a continuously decreasing capacitance (from C_1 to C_2), we have dur-
ing the motion of a rotor shown in figure 4 a constant capacitance in the con-
denser with gap d, but the potential of the electrode opposite the rotor grad-
ually increases from 0 to $V_2 - \Delta V$; when already, for a potential of the rotor
equal to V_2, its connection with the high-voltage collector is happening.
The potential distribution between the laminae is most easily effected with
the aid of large resistances.

We have considered the problem of insulation in the transverse cross-section. At the ends of the rotor and at the load outlet of the collector it is necessary to provide a similar system of distributed potentials which is realized by means of conducting laminae.

The author considers the multirotor model in a compressed electrically-strong gas (or in a vacuum) as the most suitable of all the types of electrostatic generators discussed here, for voltages in the millions.

In order to install the cathode-ray tube (NOTE: called literally a "vacuum tube" in Russian) one can utilize the space between two rotors where there is already dielectric divided by laminae. One can also, when selecting one rotor, use this space for one or a whole series of tubes.

The fact is, the power attainable with a generator exceeds that which we can handle at present in a discharge tube. In fact, we think that three rotors rotating with a linear velocity of 100 m/sec for a length of 1 meter create a field in the gap equal to 100 kV/cm. This gives a current equal to 40 milliamperes. It is impossible to create such a current in a present-day cathode-ray tube for voltages in the millions. When the voltage is 2 million volts the power of such a generator is 80 kilowatts. Obviously, this power can be supplied to a number of tubes.

5. Multidiscous Generator

From the point of view of space utilization, the multirotor generator cannot be admitted as satisfactory: the operating surface is only the surfaces of the cylinders; all the remaining space is unused. In comparison with electromagnetic machines the multirotor generator's main defect is its negligible specific power -- namely, of the order of 6 kW/m^3.

The next stage of our work was, therefore, to increase the operating surface of the cylinder. At first we proposed to give the cylinder a strongly undulating surface. Later, following the suggestions indicated by academician Mitkevich, we decided on flat disks, sacrificing deficiencies of insulation to the advantage of simpler manufacturing techniques.

The multidiscous model is shown in figure 5. In principle it does not differ at all from the multirotor model, but the multidiscous model's space is utilized considerably better. Instead of one condenser normal to the rotor's axis, as in the multirotor model, we have here numerous condensers disposed perpendicularly to the rotor's axis, whose (i.e., condensers') fields are parallel to the axis. The multidiscous generator consists of a multidiscous stator A whose disks lie between the disks of rotor B. Each of the disks are separated by a large number of conducting sectors kept separate by nonconducting laminae. Sector 1 of the stator is grounded, and sector 2 is the high-voltage collector. All the intermediate sectors receive from the distributor system C intermediate potentials. In place of the external distribution, the stator's disks can serve as distributors, if they are covered with a semi-conducting layer. In this case the separation into sectors is dropped.

The rotor's sectors receive from the low-voltage source a charge when they are located within the sectors 1 of the stator. They give up their charge to the collector upon entering sectors 2 of the stator. Here occur the transference from the sectors and the imparting to the sectors of a charge q of opposite sign.

As for the rest, the operation of the multidiscous generator is similar to that of the multirotor one, being one of its existing variants. In particular, according to the considerations expressed above, it is expedient to install several (2 to 6) multidiscous rotors in one container with the whole collector in the center.

For a transition to zero potential at the end parts, one can use on the same axis of the rotor a system of disks possessing dead action with the step-down potential of the collector.

In the multidiscous generator one can use compressed gas. For a vacuum, the generator offers all the advantages of subdivided potential.

The entire generator satisfies the main requirement for a machine using a vacuum: in no one place can the charge be at a potential exceeding 50-100 kV for a total generator voltage equal to 10^6 volts.

In calculations of the current strength attainable by the generator, it is necessary to take into consideration that each disk is charged on both surfaces and that transference of the charge occurs in the high-voltage sector, so that after one full revolution a sector transfers 2 q units of charge.

The charge is supplied not to the entire area of a disk but only to the metal conducting sectors, whose area consists of a certain fraction a of the total area. Ordinarily in our models a equals 0.6 to 0.75, thus the current strength of a four-rotor multidiscous generator is expressed thus:

$$I = 4aENv(R-r)/4\pi\cdot 9\cdot 10^{11},$$

where N is the number of disks and R, r are the radii between which the rotor's sectors are included.

In calculating the voltage which can be expected from the generator, we proceed from the permissible field along a disk's surface between two successive conducting sectors.

This field E' equals: $E' = V_2/\pi rb$, where b is the ratio of the width of the free gap to the width of a sector at its base; ordinarily b is larger than 0.5.

If such a generator with a vacuum were successfully made, then it would compare both in efficiency and in specific power with electromagnetic machines, giving at the same time a direct current instead of an alternating current and permitting one to use it as an electrostatic motor with almost the same power.

We will present a comparative evaluation of generators from the point of view of specific power.

1. The Van de Graaf generator at 4 million volts and 2 milliamps possesses a volume of about 10,000 m^3 and gives 8 kW power. The specific power thus is $8\cdot 10^{-4}$ kW/m^3.

2. The generator of the type represented in figure 3a gave in kerosene voltages up to 1 million volts for currents up to 0.1 milliamps and power 0.1 kW; its volume was about 20 m^3. Therefore the specific power is $5\cdot 10^{-3}$ kW/m^3. With new gas one can achieve considerably greater power, which gives a specific power greater than 10^{-3} kW/m^3.

3. The Van de Graaf generator in gas compressed up to 7 atm possesses, for 5 million volts and 2 milliamps, a volume of about 200 m^3, which gives a specific power of $5\cdot 10^{-2}$ kW/m^3.

4. A multirotor generator with the size just described can give an estimated 80 kW, requiring a volume equal to 40 m^3. Thus the specific power is 2 kW/m^3.

5. Finally, the multidiscous four-rotor generator with a volume of 10 m^3 can give several 1000 kW; that is, the specific power is greater than 100 kW/m^3.

Thus not only from the point of view of attainable voltages and currents but also according to size, the electrostatic generators can, in the course of further development, be made into technological equipment for the transmission of direct-current energy and for many other uses in electrical engineering.

Those who took active part in the actual work of realizing and developing the ideas proposed here were S. A. Bobkovskiy, B. M. Gokhberg, N. M. Reynov, and L. A. Artsimovich. These investigations will be described in our subsequent articles. It is necessary, however, to note that the success of our work was determined in a large degree by the expert execution of the generator models by master F. Nikolayev and D. V. Filippov and by the expert construction of a million-volt cathode-ray tube by L. A. Artsimovich, G. Ya. Shchepkin and also D. V. Filippov. A. Boronin afforded us great service during all stages of the work and erection of the generators. To all these persons I express my gratitude.

In the course of the work, not less than 10 generators were made, of which number one measured up to 4 meters and several were 1 meter in size.

Every kind of assistance afforded by the government in this work, in spite of the deficiencies in the first stages of the work, permitted us to cope with the many difficulties and to secure certain -- still, it is true, imperfect -- successes.

It is still necessary to study and select suitable insulating materials both for the rotor's disks and for the stator's, from the standpoint of their mechanical strength, stiffness, brittleness, volumetric and superficial conductivity and behavior in a vacuum. Further it is necessary to develop techniques for the insertion of the insulating and semi-conducting layers and of the distributing laminae and corona points.

Still untested by actual experiments is the possibility itself of building machines using a vacuum.

A complex problem is the elimination of field distortions at the edges of the disks, in the distributing resistances, and in the laminae which distribute the potential. High-voltage installations with output in the millions of volts also require careful investigation.

However, as it seems to the author, our work is setting up the problem of the electrostatic generator not only before physics but also before high-voltage engineering.

/Figures appended/

Figure 1

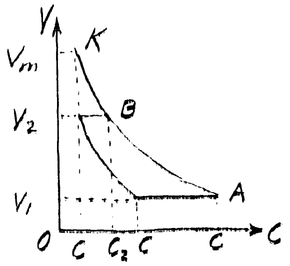
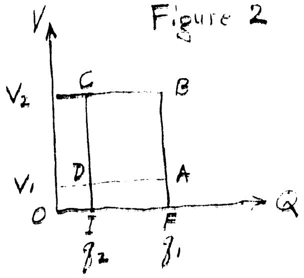


Figure 2



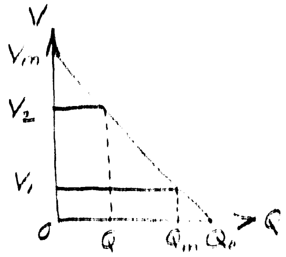


Figure 2

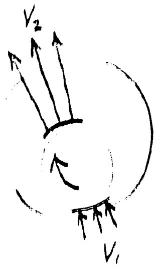


Figure 3

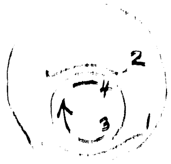


Figure 3a

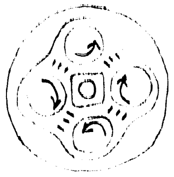


Figure 4

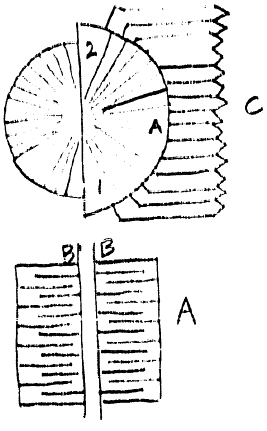


Figure 5

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