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ELECTRO-BALLISTIC GENERATOR SYSTEM

SIEGFRIED HASINGER

ENERGY CONVERSION RESEARCH LABORATORY

PROJECT NO. 7116

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AIR FORCE SYSTEMS COMMAND
United States Air Force

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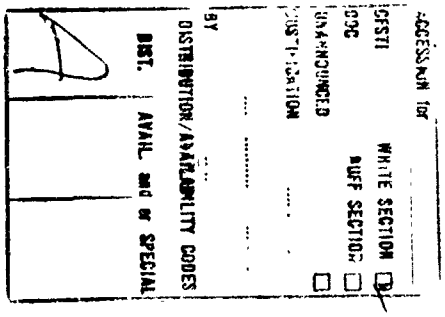

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report describes the outcome of a theoretical analysis about the technical possibilities of the electro-ballistic generator principle, conducted intermittently from 1967 to 1969 at the then Energetics Research Laboratory, ARL. Essential results of the analysis were first documented in an invention disclosure on a "thermo-ballistic" generator in August 1968.

ABSTRACT

An EFD-generator system is described which utilizes the electro-ballistic conversion principle in a high-pressure environment. A special process is employed to produce massive charged particles for an effective ballistic process. A stream of droplets produced by a spray nozzle and containing colloidal material is first charged by induction. The droplets are then subject to evaporation with the electric charges transferring to the non-evaporating colloids. In a subsequent supersonic expansion process these charged colloids are used as condensation nuclei to produce charged droplets which are substantially larger than condensation droplets originating from spontaneous condensation, i.e. from an unseeded vapor. Water vapor near critical vapor conditions is used in the present system with particular advantages as operating medium. With conservative assumptions a generator system consisting of a multiplicity of conversion units and producing 1KW power weighs an estimated 5 lbs., requires about 1/10 ft.^{3} space and has at 300,000 Volt an estimated heat-to-electricity conversion efficiency of about 10%.

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I. INTRODUCTION

The generation of electric power consists basically in separating electric charges of opposite signs from each other. This can be accomplished purely mechanically as demonstrated by the old type "electrostatic machines" which use for charge separation rotating glass discs. The modern electromagnetic generator utilizing the Faraday principle separates charges by moving a metallic conductor in a magnetic field. This latter method of separation proved so far to be the most effective one. For atomic particle acceleration, Van de Graaff revived the electrostatic generator with great success by using a belt for the charge transport instead of discs.

In recent years, attempts have been made by various investigators to use flowing media to separate charges. The basic idea behind these efforts is that flowing media allow very high transport speeds and thus high currents in comparison to a belt system. These new systems open up interesting aspects. Electric power can be produced in amounts comparable with the performance of the electromagnetic generator. Also, the flowing medium in the form of a gaseous jet can come directly from a thermo-dynamic process without the involvement of rotating machinery. Furthermore, the electrostatic conversion principal does not need the heavy magnets necessary in the conventional generator. Thus the result may be a technically useful generator simple to operate and low in related weight. References 1 to 7 deal with recent efforts in this area.

The basic process employed in these new efforts consist essentially in seeding electric charges of one sign, mostly attached to small particles into a nigh speed gas flow which carries the

charged particles to a collector electrode maintained at a high electrical potential of the same sign as the particle. Work is performed by the flow in bringing the electric charges to the high potential, i.e., in separating charges of opposite sign farther apart. By operating in a high pressure environment, very high electric field strengths, i.e., high charge densities can be applied, which are essential for a good conversion efficiency from fluid dynamic to electric energy. Orders of magnitude improvements against the old electrostatic machines have been already demonstrated experimentally. Due to the use of flowing media for the charge separation process, these new generators are generally referred to as electro-fluid dynamic or EFD-generators.

The output voltage of high performance EFD-generators is in its essence determined by geometric conditions in the generator. Quite generally the output voltage is the lower the smaller the generating unit. Fabrication and operating conditions dictate sizes which make, say 100,000 volts a minimum for reasonable performances. Due to the presence of very high voltages in EFD-generators the dielectric strength of the operating medium and of insulating material play a decisive role in the lay-out of these generators. Since basic generating units are extremely simple, no difficulties exist to obtain large absolute power outputs by arranging a multiplicity of small conversion units in a common housing.

A principle difficulty in the realization of high performance EFD-generators is to match the electric field forces with the fluid-dynamic forces in the electric conversion process. These forces must be nearly

in equilibrium for a good generator efficiency. The fluiddynamic forces normally abound, and various schemes have been proposed, as described in the cited literature, to cope with this difficulty. The scheme which is employed here, involves the so-called "ballistic generator", the basic performance potential of which is described in Ref. 8. The idea is in this case to use as "flowing medium" a beam of high speed particles which carry the electric charges against the generator field ballistically, i.e., by their kinetic energy. Very high particle speeds can be employed, while the force balance is readily adjustable by choosing the right number density for the particles in the beam. This ballistic conversion scheme allows a near complete conversion of particle kinetic energy into electric energy. However, great difficulties arise again in producing the high speed particles, if heat is the prime energy source of the generator system. Expanding gases must be employed to accelerate the particles. The expansion process must be extended to a very high vacuum, in the order of 10^{-3} mm Hg, to allow the application of strong electric fields for the conversion process without the danger of electric breakdown. Such vacuum conditions are nearly impossible to provide in a closed cycle conversion system. Only an open end system with pulse type operation in outer space may be able to use such arrangement with good advantage.

In view of the intriguing qualities of the ballistic conversion principle an effort has been made to find a compromise system which allows to utilize a ballistic action in a high pressure environment. To provide sufficient electric field strength in this case the environmental pressure must be, say, at least 10 at. The system which resulted from this effort and which is described in the following, takes advantage of some unusual thermodynamic and electric properties of water vapor near the critical

point to facilitate the production of charged particles with the properties needed for such a compromise ballistic system.* Of special concern in this system is the production of sufficient massive particles to allow an effective ballistic action. A vapor condensation process using colloidal particles as condensation nuclei is employed for this purpose.

In an EFD generator system converting heat into electricity the electric conversion process is intimately connected with the fluiddynamic conditions in the conversion section and also with the thermodynamic process of the overall system. To facilitate an analytical description of the system in the following the electric conversion process is first singled out by assuming certain idealizing conditions. Only later the thermodynamic and fluiddynamic part of the conversion process are considered.

II. The Ideal Ballistic Generator Performance

We assume an ideal ballistic generator, i.e., we disregard the viscous influence of the gaseous environment on the ballistic conversion process. For simplicity we assume the electric field in the conversion region to be two-dimensional as it applies to an electrode arrangement consisting of two infinite plane parallel plates. (In the actual generator this condition is reasonably well approached if the single conversion units are closely enough spaced to space-charge shield the collector electrode, i.e., to bring the electric field strength in the average to zero on the collector. This condition constitutes also the limit for the spacing of the units.) Otherwise, the generator conditions should be compatible with the thermodynamic process from which the charged particles originate and which is

*"Thermo-Ballistic Generator", US - Patent No. 3,577,022

described later. To calculate the generator performance we use the diagram in Fig. 1 taken from Ref. 3. This diagram considers a 25% exit loss to account for the velocity of the particles leaving the conversion section. The proper assessment of this exit loss will be discussed later in Section IV e. From practical considerations we chose for the generator voltage:

$$V = 300{,}000 \text{ volt}$$

A higher voltage would allow a better generator performance, but would require more complex provisions to avoid electric breakdown.

For the speed of the particles entering the conversion region of the generator we assume

$$V_1 = 500 \frac{m}{sec}$$

A higher value would increase the generator power concentration as well as the efficiency of the thermal process, but as we will see below, difficulties may arise in providing the necessary charge to mass ratio q/m for the particles in the charging process. With the chosen values for V and v_1 we find from Fig. 1 for

$$\frac{q}{m} = .3 \text{ Coul/kg}$$

From Fig. 2 we find the range of particle sizes, from which we can choose for a given q/m and a given particle material. This figure shows the limitations for the particle size as dictated by the electron unit charge, by droplet disintegration due to the elimination of surface tension and by ion emission. We find from the plot that for water droplets with q/m = .3 Coul/kg the allowable sizes range from about .1 to 10μ.

In the present case the larger particle sizes are desirable to help overcome viscous influences in the ballistic conversion process. The largest particle we can hope to produce in a condensation process with seeded nuclei, as contemplated here, is about .5μ. A particle of this size would carry about 50 electron charges. It would be safe from droplet disintegration and electron emission.

The electric field strength in the generator conversion region should be as high as possible for good performance. Allowable values increase nearly in proportion with the gas pressure. On the other hand for a good thermodynamic efficiency and a high enough rate of condensation for the particle production the operating medium should be expanded to a pressure as low as possible. Obviously a compromise is necessary. A reasonable value appears to be 20 at. Considering also a operating temperature of around 200°C the allowable electric field strength in the conversion region with water vapor as operating medium may be assumed as

$$E_1 = 2 \cdot 10^7 \text{ volt/m}$$

This value is based on the consideration that the maximum electric field strength which can be maintained in air at ambient conditions in a uniform electric field for an electrode distance of 1 cm is $3 \cdot 10^6$ volts/m and that water vapor can sustain a slightly higher field strength than air according to Ref. 8.

From Fig. 1 we obtain for

$$E_1/\sqrt{p_m} = 1.5 \cdot 10^8$$

With above value for E_a the average particle beam density becomes

$$\rho_m = 1.8 \cdot 10^{-2} \text{ kg/m}^3$$

This value applies for space charge limited current, i.e., for the condition that the electric field strength at the collector electrode is zero due to space charge shielding (under two-dimensional conditions between infinite plane parallel electrodes).

The conversion length is obtained from Fig. 1 with

$$h \cdot \sqrt{\rho_m} = 4.9 \cdot 10^{-1}$$

or $h = 3.7$ cm

In the parallel multi-conversion unit arrangement ρ_m can be readily reduced by increasing the spacing between units at the cost of the power concentration. Thus h can be reduced under these circumstances by about a factor of two as a limit, while maintaining the same generator voltage.

For the current concentration we obtain from Fig 1

$$i/\rho_m = 11$$

or $i = .2 \cdot 10^{-3}$ ma/cm^2

and with $i \cdot V = .2\ 10^{-3} \cdot 3 \cdot 10^5$

$$L = 60 \text{ watt/cm}^2$$

or taking the conversion length of 3.7 cm into account, the electric power per unit volume of the conversion region is

$$L_v = \frac{60}{3.7} = 16 \frac{Watt}{cm^3}$$

Thus in a conversion section (made up of parallel units) of about 5 cm diameter and 3.7 cm length one KW would be produced under above assumed conditions in particular under the assumption of a free ballistic action at 25% exit loss as the only loss occurring in the process.

In the following sections the thermodynamic process and the charge mechanism are described, which should provide the charged particles assumed in above generator calculations. Furthermore, considerations are given to the effect of the viscous interaction in the ballistic conversion process. Finally, generator design configurations are given.

To demonstrate the limitations imposed on the generator voltage the following example is calculated. We assume that a q/m of 1.0 coul/kg for the particles is possible. Then from Fig. 1 we see that at V_1 = 500m/sec the generator voltage would be somewhat less than 100,000 volts. All other data would remain the same as calculated above, except the conversion length would be shorter by a factor of 3. Later in the report when considering the particle charging mechanism, we will see that with the higher q/m value the liquid jet, from which the particle beam originates in the present system, must be also reduced to keep the field strength of this jet within tolerable limits. Technical difficulties arise with this requirement, since the diameter of the nozzle producing this jet becomes so small (less than 50μ) that it becomes difficult to manufacture such nozzle and to keep it clean during operation.

III. DESCRIPTION OF THE ELECTRO-BALLISTIC-GENERATOR SYSTEM

1. Principle of the charged particle production

The method of producing the high speed charged particles is the following: a conductive liquid containing a certain small amount of colloids or colloid forming material is injected as a high speed jet into a medium which provides heat for evaporating the injected liquid. The jet is subjected during evaporation to disintegration while it is exposed at the same time to an electric field which causes the jet and subsequently the fragments of the disintegrated jet and finally the remaining colloids to become electrically charged. The evaporated jet medium and other added media together with the colloids are then expanded in a supersonic expansion nozzle, in which condensation takes place with the condensation droplets forming around the charged colloids resulting in high speed charged particles of a fairly uniform size, much larger than that occurring commonly in nuclei free spontaneous condensation. This charged particle production principle is incorporated in the following into a complete electro-ballistic generator system for converting heat into electricity.

2. General description of the conversion process

a. Charging process

Fig. 3 shows a schematic arrangement of the generator system. The process begins with the liquid injection: Through capillary nozzles (1) water at supercritical conditions (the critical conditions of water are $t_{crit} = 374.2^{o}c$, $p_{crit} = 225.5\ kg/cm^2$) containing a small amount of colloids, for instance .05% silver colloids of .05μ size is discharged into chamber (2) in the form of a fine jet immediately ahead of the

guide channels (3). Also entering chamber (2) through pipe (4) is a gaseous medium referred to in the following as a "fill-gas" (consisting of superheated vapor of the jet medium or a mixture of this vapor and some amount of a light weight gas like hydrogen, the purpose of which will be explained later). Part of this fill-gas expands into the guide channels (3) surrounding the injected liquid. Another part of the fill-gas will join the expanding flow downstream of the guide channel. The fill-gas has a two-fold purpose. It supplies heat for the evaporation of the injected liquid and protects also the non-evaporating colloids, which are charged as explained in the following, from contact with guiding walls. In particular the fill-gas entering at the downstream end of the guide channel (3) serves the purpose of protecting the charged particles against contact with the wall.

Near the nozzle (1) is an annular attractor electrode (5), which is electrically biased against the injection nozzle to set up an electric field between the nozzle exit and the attractor electrode. In being exposed to an electric field the jet becomes charged by induction (charges of one sign move toward the attractor and the charges of the other sign move back to the nozzle.) Due to the evaporation of the jet medium occurring during its injection and also due to mechanical and electrical effects, the jet is broken up into droplets before passing the attractor electrode. In this way the charges tending toward the attractor must remain with the droplets giving the droplet stream a unipolar charge. The jet fragments coming into contact with the hot fill-gas will evaporate. In this evaporation process the electric charges will finally transfer to the colloids contained in the jet fragments. (Experiments described in Ref. 9 supports this assumption.)

b. Expansion Process

The charged colloid beam surrounded by fill-gas enters then the supersonic expansion nozzle (6). In this nozzle the fill-gas augmented by the vapor of the jet medium becomes accelerated to supersonic speed. Due to viscous interaction the colloids become also accelerated. Due to the small size of the colloids the viscous interaction between the colloids and the expanding gases is very intense assuring a very small slip of the colloids in the gas flow, i.e., the colloids become accelerated to very nearly the velocity of the expanding gases. The supersonic expansion nozzle is designed to give the flow about a Mach-number of 1.5. The expansion ratio associated with this Mach-number fulfills two requirements essential for the effective generator operation: It is high enough to assure a good thermodynamic efficiency for the conversion of heat into gas kinetic energy and is on the other hand not too excessive for keeping the pressure in the conversion section of the generator high enough to maintain a high dielectric strength of the gaseous atmosphere in the conversion section and also high enough to allow a compact design of the system. Variations of the expansion process will be discussed in Section IV b and c.

During the expansion near the critical point quite an essential part of the vapor will condense already at moderate expansion ratios due to the low heat of condensation released under these conditions. Condensation will preferably occur on the charged colloids which act as condensation nuclei. In a so devised condensation process the colloids are first accelerated to very nearly the velocity of the expanding vapor thanks to their very small size. Only after they have gained a very high velocity

they become enlarged in the condensation process. In this way massive high speed particles are produced as they are necessary for an effective ballistic generator operation.

c. Conversion Process

At the end of the expansion nozzle the flow cross section is more or less abruptly increased to form the generator conversion section. The increase in cross section is provided to spread the charge carriers over a large enough cross section to match the kinetic energy density with the electric energy density, a requirement for an effective conversion process, as already pointed out in the beginning. The cross section increase is purposely made abrupt to produce a throttling process instead of an expansion. In this way the pressure level in the conversion section remains more or less constant providing also undiminished protection against electrical breakdown. At the entrance to the conversion section is the entrance electrode (7), downstream forming the end of the conversion section is the collector electrode (8) consisting of two sets of electrode surfaces the particular function of which is explained later. The sudden spread in the flow cross section from the expansion nozzle to the conversion section requires certain provisions to keep the flow in the conversion section under control. This control is obtained by returning some of the fill-gas to the conversion section by return channel (9). It is advantageous for the cooling process to add also a non-condensing, light weight gas like hydrogen to the conversion section. Since it does not condense, it continues to recirculate in the conversion section without need for replenishment.

In entering the conversion section the charged condensation droplets are immediately exposed to the retarding force of the generator field and

therefore slowed down converting in this process kinetic energy into electric energy. At the same time gas kinetic energy is supplied to the slowed down particles. Part of the gas kinetic energy of the expansion flow is dissipated to heat on the periphery of the expansion flow where mixing occurs with the return flow coming through the perforated entrance electrode into the conversion section. This return flow coming from the entrance electrode prevents the backflow of charged droplets in the mixing zone to the entrance electrode under the influence of the generator field.

To prevent the evaporation of the condensation droplets in the mixing zone due to the heat dissipation taking place in the mixing zone the return flow is cooled in the condensor (10) which is otherwise used to condense the vapor phase of the operating medium for reprocessing in the thermodynamic cycle. The condenser may simply consist of the generator housing walls, fitted on the inside as well as on the outside with cooling fins. Guide vanes in the return passage may be used to reduce flow losses. (For condenser see also sect. VI)

Due to the fact that the expansion process is kept fairly near to critical vapor conditions, an appreciable amount of Joule-Thompson cooling occurs in the expanding flow, i.e., the stagnation temperature in the gas flow is appreciably reduced against the pre-expansion temperature, reducing in this way the external cooling requirements.

d. Collector System

The collector electrode collects the charges as well as the droplets themselves by the electric precipitator method. The collector (see Fig. 3b) has two sets of electrodes (11) and (12), one set being directly connected to the load terminal (13), the other one over a resistor (14) to produce a voltage difference between the two sets of electrodes of say 1% of the generator voltage. This voltage difference will deflect the charged drop-

lets inside the collector to the electrodes with the lower potential causing the deposition of the droplets and their charges.

The collector electrode is normally not at ground potential and the liquid collected on this electrode must be removed by applying the Faraday cage principle: Particles in contact with the inside surface of a conducting enclosure which is at a high potential have no charge. Material can be removed from the enclosure if the device used for removal does not bring in charges, i.e. it must be non-conductive. A steam-jet pump made of a non-conductive material may be used for instance. The discharge from this pump is a mixture of steam and droplets, which is practically non-conductive. A more simple arrangement is shown in Fig. 3, where the water leaves the enclosure as a coarse droplet stream together with the return flow through non-conductive outlets. The electric lead from the collector electrode to the outside can be used combined as a conductor and a duct for the collected liquid. With this arrangement the system for removal of the collected liquid can be located outside the generator.

e. Recirculation of the Operating Medium

To stay consistent with a particular aim of the present generator system, namely to avoid rotating mechanical parts, pressurization of the operating medium is accomplished by means of ejector pumps (16) and (19) (Fig.4). This pump type, which is well known as boiler feed pump, can be operated with steam of the same pressure level to which the liquid must be brought,

i.e., with steam from the same boiler to which the liquid is fed. The possibility of using other pump types will be discussed in Section IV.

Two pressure levels are employed in the thermodynamic cycle of the Thermo-Ballistic-Generator: a lower level for the fill-gas and somewhat higher level for the fluid injection. The reason for these two pressure levels will become clear from the detail description of the thermodynamic process. All liquid, coming from the collector as well as from the condensor can be pressurized combined in the ejector pump (16). From this pump the liquid is fed to the fill-gas boiler (17). In the fill-gas boiler (17), the liquid is evaporated and the steam superheated in the superheater (18). In this evaporation process the colloids carried by the liquid will stay with the liquid phase in the boiler. Colloid enriched liquid is fed to the ejector pump (19) to be further pressurized for the injection-liquid heater (20). The liquid heated in heater (20) is then fed to the liquid injection nozzles (1) to complete its cycle in the thermodynamic process. The steam from super heater (18) is fed through pipe (4) to chamber (2) to complete its cycle as the fill-gas.

IV. DETAILS OF THE THERMODYNAMIC PROCESS

a. Supercritical Vapor Conditions

To obtain optimum performance with the present generator system certain thermodynamic conditions must be provided in the system, the most essential one concerning the state of the injection liquid. As a unique feature of the present system this state of the liquid is chosen such that the liquid is at supercritical conditions as indicated in Fig. 5 by Point (a) in the diagram, which represents an Enthalpy-Temperature diagram of water (I-T diagram). Fig. 5 depicts the conditions in the

neighborhood of the critical point of water. The diagram contains besides the lines of constant pressure also lines of constant entropy, constant mass density and also electric conductivities.[10] A unique and most important feature of the supercritical water is that it has the properties of a liquid as well as the properties of a gas. This extraordinary feature is uniquely suitable for an efficient generator operation.

As a gaseous medium, supercritical water can be expanded and thus a part of its thermal energy can be converted into gas kinetic energy. This allows to reach comparatively high injection velocities. A high injection velocity is important for two reasons: (1) it gives a high charge carrying capacity of the liquid jet for a given surface field strength on the jet. (2) it reduces the spread of the broken up jet at given electric field conditions, in particular it prevents the disintegrated jet from hitting the attractor electrode.

As a liquid, supercritical water is dense enough to carry the colloids in suspension and what is particularly important, it can be made conductive by doping it with certain chemicals. The result is that a high speed, conductive jet can be realized. The conductivity of the supercritical water vapor is essentially a function of its density. It decreases very rapidly with a decrease in density. In the wet region of the I-T diagram, where the jet expansion line ends at point (c), the conductivity of the vapor phase at saturation line near point (f) is reduced by about two orders of magnitude against the conductivity at point (a). The conductivity of the liquid phase at (c) is, on the other hand, increased against that of point (a) due to the density increase of the liquid phase, The point representing this state is located at the saturation line below the critical point and not contained i Fig. 5.

In expanding the jet liquid into the wet region according line (a) - (b) - (c) in Fig. 5 a phase split into about 50% water and 50% vapor occurs. This split causes the jet to break up into droplets. Since the jet is during this break-up subject to the electric field of the attractor electrode (5) the jet fragments will carry with them a charge in separating from the conductive jet, which has a polarity opposite that of the attractor electrode. The vapor phase with its greatly lowered conductivity will act as insulator between the droplets and also against guiding walls. Another unique feature of the present thermodynamic process concerns the thermodynamic state of the fill-gas. Due to the imperfect gas conditions in the neighborhood of the critical point, the fill-gas in the form of superheated vapor near critical conditions has a very high specific heat and provides an ideal heat source for the evaporation of the jet fragments. This is demonstrated in Fig.5. At the supply state of the fill-gas, point (d), the temperature is practically the same as that of the jet liquid at its supply state. From (d) to (e) the fill gas is expanded to obtain a velocity close to that of the injection jet. From (e) to (f) the fill gas gives off a comparatively large amount of heat with little change in temperature. For the example entered in the diagram of Fig. 5 the heat given off by the fill-gas is sufficient to very nearly evaporate an equal amount of injected liquid. A practical advantage of this condition is that the heater for the injection liquid and the fill-gas boiler can be combined. Also no thermal insulation is necessary between the supply lines for the injection liquid and the fill-gas.

Evaporation near critical conditions takes place very fast: the evaporation time for a 1 micron size droplet of water at a temperature of 10^{0}C below critical temperature is in the order of 10^{-4} sec [11]. At a

droplet velocity of 100 m/sec the length of travel during evaporation is 1 cm. By a proper choice of the expansion conditions for the jet liquid and the fill-gas the velocity of these two media relative to each other and thus the mixing process between the two media can be sufficiently controlled to allow the transfer of heat from the fill-gas to the jet medium without an undue spread of the jet. The jet emerging from the injection nozzle is already disintegrating due to the phase change during its expansion (see line a - b - c in Fig. 5) before it meets the fill-gas. Evaporation of the jet fragments can take place from the injection nozzle to the beginning of the supersonic expansion nozzle (6).

b. Supersonic Expansion Process

In the supersonic expansion nozzle (6) the flow containing the charged colloids is expanded to a Mach-number of about 1.5. This expansion process is shown in Fig. 6 by line (f) to (g) with the pressure changing from 200 at to about 20 at. In this expansion into the wet region about 35% of the water vapor condenses. If again a light weight gas would expand with the water vapor the rate of condensation could be increased. Some aspects of this possibility will be given farther below.

c. Condensation during the Supersonic Expansion Process

The charged colloids in the expanding flow act as very effective condensation nuclei and allow to control the condensation process in the expansion nozzle. They prevent the condensation delay normally present in nuclei free condensation (spontaneous condensation). This will cause most of the condensation to occur on the charged colloids. Thus, their number will to a great extent determine their size. While it is probably

not possible to provide colloids in a number larger than the naturally occurring nuclei in free spontaneous condensation, it is easy to provide them in a smaller number. The latter process is the one desired here. With a fewer number of nuclei the condensation droplets become larger than the ones which occur in regular free vapor condensation. In the present process about two orders of magnitude less colloids will be provided than nuclei are available in spontaneous condensation. Thus under this condition droplets which are about five times as large as in spontaneous condensation can be expected. This amounts to droplet sizes of about .5 micron which is a size very desirable for the electro-ballistic conversion process.

For the high pressure and the high temperature conditions under which the condensation takes place, condensation time is extremely short. Droplet growth from colloid size to 0.5 micron occurs in the supersonic portion of the expansion nozzle within a travel length of about 1 cm, eliminating the necessity for long nozzles. This is an important consideration since electro fluid dynamic conversion units are inherently small, a condition dictated by the requirement that the charge carrying medium must have a small diameter in order to allow high charge-to-mass ratios at a tolerable electric field strength.

d. Hydrogen Addition to the Working Medium

The addition of a light-weight gas, in particular hydrogen, during the conversion process has a number of beneficial effects for the process. There is, however, also a principal difficulty connected with allowing the hydrogen expand with the water vapor. As a gas hydrogen requires a comparatively high amount of energy for recompression in the

thermodynamic cycle even at a weight portion of only 10% of the total working medium. In view of this high energy requirement, recompression must be accomplished with a high efficiency, which in general only rotary machinery can provide. Inclusion of rotary machinery would, however, defeat the purpose of a direct energy conversion system. (The water vapor used in the system can be condensed and simply pressurized with little energy required by steam injection pumps in a well established manner.)

Very small amounts of hydrogen, say 1 to 2% by weight may possibly be repressurized together with the water in injection pumps. There is also the compromise solution of using free-piston pumps, which have mechanically moving parts but need no shaft power and have a good efficiency, for the recompression of larger amounts of hydrogen, say 10%, with inlet pressures near 50 at. In view of such possibilities it appears worthwhile to consider the influence of hydrogen addition for the conversion process.

The presence of hydrogen is of advantage throughout the complete conversion process, starting from the particle charging process to the gas recirculation in the conversion region. The favorable behavior of hydrogen derives from the fact that the energy content of the single molecules of all ordinary gases is very nearly the same and independent of the weight of the single molecules. Thus, with a small weight addition of hydrogen large energy effects in terms of heat and gas kinetic energy can be provided. For the electric properties it is also important that the size of the molecules is nearly the same for ordinary gases. This means that the electron collision frequency and thus the dielectric strength of a gas is governed by the number density of the molecules and not necessarily by its density.

The energy content of the molecules is also a decisive factor for the transport properties of a gas such as heat conduction and inner friction. Since these properties are basically governed by a molecular diffusion process, they are like gaseous diffusion itself independent of the gas pressure within wide limits. Thus hydrogen addition has no degrading effect on the heat transfer processes occurring in the present conversion system. On the other hand hydrogen in spite of its low specific density does not decrease the viscous drag and thus improve the ballistic action of the charged particles in the conversion process. However, an effective viscous coupling, i.e., gas friction is also a desirable feature for accelerating the charged colloids in the expansion process and for transferring kinetic energy from the fill-gas to the slowed down particles in the conversion region ahead of the collector electrodes.

The molecular weight of hydrogen is only 1/9 of that of water vapor. Thus, with comparatively little weight a sizable gaseous sheath can be provided by hydrogen for protecting the charged particle beam against contact with confining walls. Due to the high energy content of its molecules (at a given temperature) the hydrogen is an ideal source of heat for the evaporation process applied for producing the charged colloids.

During the jet-injection process the hydrogen acts as a true fill-in medium. While due to the presence of the hydrogen the total pressure during the injection and charging process can be kept high, the partial pressure of the water vapor becomes lowered by hydrogen diffusing into water vapor. This lowered water vapor pressure assures low conductivity of the vapor surrounding the jet fragments.

The high energy content of the hydrogen molecules is of benefit also during the expansion process. Firstly, a comparatively low expansion pressure ratio is required to convert enough heat into gas kinetic energy to obtain the desired expansion velocity for the hydrogen - vapor - colloid mixture (500 m/sec in the present case). Secondly, in spite of a high total pressure at the end of the expansion necessary for good electric insulation, the partial pressure of the water vapor is low and a correspondingly high rate of condensation takes place to form the desired high speed ballistic particles for the conversion process. Due to its high release of directed kinetic energy during the adiabatic expansion process the hydrogen can absorb heat of condensation produced in the vapor expansion process, i. e. the rate of vapor condensation is increased due to the cooling effect of the expanding hydrogen, resulting not only in an increased mass of water available for the electric conversion process but also in an increase in particle size at a given number of seeded colloids.

The presence of hydrogen in the conversion region has the benefit that it acts as an effective heat and kinetic energy transfer medium in the ballistic conversion process as it will be described in the following. Hydrogen can be added to the conversion section independently from the conditions in the vapor expansion nozzle, i.e., if hydrogen is solely added to the conversion region no recompression is necessary. Since the effect of hydrogen is wholly beneficial in the conversion region, the hydrogen addition for the electric conversion process is to be considered a standard ingredient of the present system.

e. Electric Conversion Process

The condensation droplets which carry the charge of the colloids on which they have formed, will be slowed down on entering the

conversion section, where an opposing electric field is set up between the entrance electrode (7) and the collector electrode (8). In this process kinetic energy of the droplets is converted into electric energy, i.e., the droplets are brought to a higher electric potential. Since the vapor is unaffected by the electric field, the droplets will eventually lag behind the vapor flow and viscous forces will transfer kinetic energy from the vapor to the slowed down particles. In this way also a part of the vapor expansion energy is utilized in the conversion process. Another part of the vapor energy will be regained from the return flow of the fill-gas through channel (9). The return flow prevents charges at the periphery of the expanding vapor-droplet mixture to return to the entrance electrode. The return flow being alone in contact with the walls provides also the energy consumed by unavoidable wall friction in the conversion process. Some energy of the vapor expansion will also be regained by impact diffusion in the sudden cross section enlargement. Though an appreciable part of the expansion energy of the uncondensed vapor will be lost due to mixing processes, the overall conversion efficiency can still be expected to be near 50% due to the highly efficient process of converting the ballistic energy of the droplets into electric energy. (See sect. VI)

The presence of a gaseous environment has also its benefit for the ballistic process insofar as the 25% exit loss assumed for the ideal ballistic generator performance in Section II can be charged in this case to the environmental medium. In the ideal case, i.e., in the absence of a gaseous medium the ballistically flying particles must retain sufficient kinetic energy after the conversion process to be able to leave the conversion section, otherwise they would accumulate ahead of the collector electrode and interrupt the generator process. In case of a gaseous

environment, which moves more or less with the particles but is unaffected by the electric field, the particles can fully expend their original kinetic energy and rely on energy transferred from the gaseous medium by viscous interaction to clear the conversion section.

The sudden increase in flow cross section at the transition from the expansion nozzle to the conversion section, the purpose of which is to spread the flow without further lowering the pressure in the conversion section, subjects the expanding vapor thermodynamically to a throttling process, which involves kinetic energy dissipation by mixing as already indicated above. Heat produced in this process must be removed to avoid reevaporation of the condensation droplets contained in the throttled flow. The energy dissipation will mainly take place at the periphery of the spreading flow, i.e., where it meets the cooled return flow. Thus the return flow serves two purposes: it prevents charged droplets from returning to the entrance electrode and also cools the flow in the mixing region, where most of the vapor kinetic energy is dissipated.

The return flow is made to consist to a large part of a light weight gas by adding hydrogen. The water vapor in the return flow is simply condensed out and the hydrogen keeps recirculating in the conversion section. The vapor portion in the recirculating flow depends only on the condenser temperature which determines the vapor pressure. If for instance the condenser temperature is 180°C the vapor saturation pressure is 10 at. To maintain in the conversion region a total pressure of 20 at, the partial pressure of the hydrogen would have to be also about 10 at. The volume portion of the hydrogen would be about 50% and its weight portion about 7%. The light weight gas is not only very useful as a cooling medium due to its high heat capacity but also due to the fact that it will mix with

the expanding gas by the process of diffusion providing cooling in this way with a minimum of flow disturbance.

f. Repressurization of the working medium

The removal of the water from the return flow is a necessary process for the thermodynamic cycle, namely to return it to its preexpansion state. Since the water at condenser temperature is essentially incompressible the work required for pressurization is very small in comparison to the power produced in the expansion process. Due to the self-imposed condition that no rotating mechanical parts should be used in the system, rotary pumps known for their good efficiencies, are not considered here. The elimination of rotating mechanical parts in pumping devices is in general only possible with a sacrifice in efficiency. Pumps to be considered here are: ejector pumps, pulsometer pumps and free piston pumps. They are all non-rotating pumps, which contain, however, moving mechanical parts with the exception of the ejector pump. Their efficiency increases with the involvement of moving mechanical parts, thus the free-piston pump being the most efficient one. These pumping devices are all within the state of the art. The ejector pump and the free-piston pump can be operated with steam from the same boiler to which they have to feed the water. The pulsometer type pump would need an ejector pump as end stage. In case no light weight gas is recompressed in the thermodynamic cycle, ejector pumps which are distinguished by their simplicity will be very satisfactory in view of the small amount of work involved in pressurizing the water.

In Fig. 4 the generator reprocessing system with the ejector pumps is shown. The water collected from the collector electrode as well as

from the condenser is fed to the first ejector pump (16), which increases the pressure from 20 at to 210 at, possibly in a multi-stage arrangement. It is operated with steam from the fill-gas boiler (17). The pressurized water is fed into the fill-gas boiler (17), where the water is heated and a part of it evaporated and then superheated from 368°C to 385°C. In this evaporation process the colloids contained in the water are retained in the boiler, from which they are, together with the unevaporated water, fed by pump (19) to the supercritical boiler (20), which supplies the supercritical water to the injection nozzles (1), and consists essentially only of parallel tubes. It is only a heating device and no evaporation in the ordinary sense takes place. It also provides the driving medium for the ejector pump (19). The supercritical heater supplies the operating medium for the injection nozzles (1), while the fill-gas boiler feeds its superheated steam through pipe (4) to chamber (2). With these two feeding processes, the thermodynamic cycle of the operating media is completed.

Free piston pumps could be operated with "low pressure" steam, say 100 at. An extra steam boiler would have to be provided. Such low pressure boiler could be used to assure a more perfect separation of the colloids from the fill-gas. At lower boiler pressures the carry-over of water droplets and thus colloids with the steam is less likely than in the high pressure fill-gas boiler. An extra low pressure boiler for the assured removal of the colloids could, of course, also be incorporated in the ejector pump system if necessary. To further assure colloidal separation the water collected from the collector electrode could be repressurized separately from the water coming from the condensor, which would contain only colloids lost from the collector electrode.

V. DETAILS OF THE CHARGING AND CONVERSION PROCESS

a. Charge to mass ratio

A primary requirement for an effective generator operation is a high electric charge on the liquid jets emanating from the injection nozzles (1). More specifically, each jet must carry a high electric charge in relation to its mass. This requirement determines the jet diameter and with it the dimensions of a conversion unit. A natural limit for the charge carrying capacity is the surface field strength on the jet as given by the number of charges per unit surface area. With the surface field strength given the charges carried by the jet in relation to its mass is the higher, the smaller its diameter. The technical capability to produce and maintain fine jets determines finally the jet diameter to be chosen. Injection nozzles of 50μ diameter can still be considered technically feasible.

The electric charges are deposited on the jet as follows: Influenced by the charges on the attractor electrode (5) which is electrically biased against the injection nozzle, charges of the opposite sign will accumulate on the injection nozzles (1). If a conductive jet emanates from a nozzle the charges will move along the jet toward the attractor (5). When the jet breaks up due to a phase change of the jet medium and also due to fluiddynamic and electric forces, the charges will stay with the fragments. The break-up of the jet must take place before the jet passes the attractor electrode (5), otherwise the charges would move against the jet back to the attractor electrode. Inertia and viscous drag prevent the charged particles themselves from moving back to the attractor electrode.

The charge to mass ratio of the jet is given by the well known relation (Ref. 3):

$$\frac{q}{m} = E_r \frac{2 \cdot \varepsilon \cdot 8.85 \cdot 10^{-12}}{\rho_m \cdot r}$$

E_r field strength on the jet surface
ε dielectric constant
ρ_m mass density
$d=2r$ = jet diameter

The high pressures applied in the generator provide a high dielectric strength gaseous environment and high electric field strengths can be used. The critical vapor conditions favor, on the other hand, a low mass density for the jet medium. Water at critical conditions has only about a third of its normal density. Furthermore, the dielectric constant of high pressure steam is higher than that of high pressure air. Steam of .1 g/cm^3 density has a dielectric constant of about 1.8. With the following values,

$E_r = 6 \cdot 10^7$ Volt/m

$\varepsilon = 1.8$

$\rho_m = 330$ Kg/m^3

$2r = 50 \cdot 10^{-6}$ m

the charge to mass ratio of the jet is

$$\frac{q}{m} = 6 \cdot 10^7 \ \frac{2 \cdot 8.85 \cdot 10^{-12}}{330 \cdot 25 \cdot 10^{-6}} = .231 \ \frac{\text{amp. sec}}{\text{kg}}$$

b. Electric performance

The flow of charges taken along by the jet presents an electric current, the magnitude of which is given by

$$I = E_r \cdot v \cdot r \cdot \pi \cdot 2 \cdot \varepsilon$$

with v being the velocity of the jet. Assuming 160 m/sec for the jet, a velocity which follows from the thermodynamic conditions shown in the example of Fig. 5, the current is

$$I = 6 \cdot 10^{7} \cdot 160 \cdot 25 \cdot 10^{-6} \cdot \pi \cdot 2 \cdot 8.85 \cdot 10^{-12} \cdot 1.8$$

$$= 2.4 \cdot 10^{-5} \text{ amp} = 24 \text{ micro amp}$$

With the previously chosen voltage of $3 \cdot 10^{5}$ volt, the power output of a conversion unit would be

$$L = 2.4 \cdot 10^{-5} \cdot 3 \cdot 10^{5}$$

$$= 7.2 \text{ watt}$$

The requirement to have very small jets makes it obvious that a complete generator would consist of a multiplicity of small units in parallel.

c. Charged Colloid Beam

It is now also obvious that the break-up of the jet into small droplets, say of a few micron diameter decreases greatly the surface field strength on the droplet due to an appreciable increase in the surface area of the disintegrated jet. Already the break-up of the jet into particles of the same diameter as the jet reduces the field strength by a factor 2/3. Actually the jet, as explained before, will break up into much smaller droplets under the influence of the phase change as well as due

to the influence of aerodynamic and electric forces, causing the surface field strength to decrease by orders of magnitude. In passing through the attractor electrode the jet fragments are subject to deflection towards the attractor electrode (5). However, inertial effects and also viscous drag prevent the droplets from excessive deflections.

While in contact with the hot fill-gas during their travel from the injection nozzles to the supersonic expansion nozzle the jet fragments evaporate. In this evaporation process the charges will not leave the droplets as already pointed out in Section III,2a except together with material separated from the droplets by electric forces. Thus, the electric charges will always stay with the jet medium and will finally stay with the colloids, which are of a material not evaporating at the prevailing temperatures. With the jet medium evaporated and the charges staying constant, the charge density on the colloids is increased again, and so is the surface field strength in the colloids. It depends on the allowable surface field strength on the colloids, how many colloids must be provided in relation to the jet fluid. If one stays about an order of magnitude below the surface field strength which causes ion emission from the colloids, the percentage of colloids in the jet fluid needs only to be about 2/10%, if the colloid diameter is .05 micron, the jet diameter is 50 micron, and the jet current is 24 micro amp as calculated in the preceeding example.

An important consideration for the charged colloid beam is its spread under the influence of its own charge. The velocity with which two colloids under above conditions drift apart is about in the order of 1m/sec. Since the jet velocity is in the order of 100 m/sec no appreciable spread should occur. Even if it should be desirable to slow down the jet after break-up

to facilitate evaporation, a considerable margin for a slow down is available. On the other hand in entering the subsonic portion of the expansion nozzle (6) the flow is accelerated with comparatively little change in pressure, i.e. with little change in dielectric conditions in the vapor. The increased flow velocity reduces the charge density in the charged particle beam and thus its tendency to spread.

d. Energy Conversion Mechanism

At the end of the expansion nozzle the flow cross section is abruptly increased to form the conversion section. At the entrance of the conversion section is the entrance electrode (7). At the exit of the conversion section is the collector electrode (8). The electrofluid dynamic conversion process requires the surface area of the entrance electrode to be in proper proportion to the amount of charges present at any time in the conversion section. This can also be conveniently expressed in terms of kinetic energy density or dynamic pressure which the charge carrying flow or particle beam may have in reference to the entrance electrode surface area. The fluid dynamic pressure should be in the order of .1 kg/cm^2. If one would consider the liquid jet coming from tube (1) accelerated (without break-up) to say 500 m/sec, its dynamic pressure would be around 1000 kg/cm^2. (With the original cross section reduced by about 1/3 due to increase in water density) Since the jet provides essentially the mass which carries the charges in the conversion section, it has to be spread out in the conversion section in the order of at least thousand times against its original cross section to satisfy electrofluid dynamic requirements.

In a more exact way we compare the original jet density which was 330 kg/m^3 with the average particle beam density required in the conversion section which was $1.8 \cdot 10^{-2}$ kg/m^3 as found in section II. From flow continuity the necessary enlargement from jet cross section A_{jet} to conversion region cross section A_{con} is

$$\frac{A_{con}}{A_{jet}} = \frac{V_{jet}}{V_{con}} \cdot \frac{\rho_{jet}}{\rho_m} = \frac{150 \cdot 330}{500 \cdot 1.8 \cdot 10^{-2}} = 5.5 \cdot 10^3$$

Assuming that only 80% of the injected water appears as charged droplets, the conversion region diameter would have to be for a 50μ jet:

$$d_{con} = 50 \cdot 10^{-4} \cdot 5.5 \cdot 10^3 .8 = .33 \text{ cm}$$

The larger part of the required spread has been already accomplished by the expansion process. A cross section area increase by a factor of about 20 to 30 is still necessary, i.e., the diameter of the conversion section is to be enlarged against the nozzle exit diameter by a factor of roughly 5.

The flow leaving the expansion nozzle will in its bulk penetrate deeply into the conversion region. Due to momentum exchange with the surrounding gas it will lose energy at its periphery and spread out. Possessing appreciable kinetic energy, the charged particles will tend to follow a ballistic course in the conversion section. An uncharged water droplet of 1 micron diameter with a velocity of 500 m/sec has a relative penetration depth in the order of a few millimeter in the here considered environment. The movement of the particles in the conversion section, which has a length in the order of 15 mm, will not be completely ballistic. However, the particles and the gas flow move in the first part

of their travel through the conversion section very closely together. In entering the conversion section, the particles are immediately exposed to the retarding force of the generator field and, therefore, slowed down while converting already kinetic energy into electric energy. In this phase, kinetic energy will also be transferred from the gas flow to the slowed down particles. Closer to the collector electrode the particles have been further slowed down by continuing conversion of their kinetic energy into electricity, but also the gas flow has lost energy by mixing with its more or less stagnant surrounding and by internal shocks. The gas flow will still assist the particles particularly in clearing the conversion section but the common slow down minimizes viscous interference between the particles and the gas.

The conditions are very different at the periphery of the spreading gas flow. In this region the particles will be considerably slowed down by viscous interference and the danger exists that they will return to the entrance electrode under the influence of the generator field. Provisions are necessary to prevent the return of the charged particles. This is, as described before, accomplished by returning some of the fill-gas together with some lightweight gas like hydrogen to the conversion section through channel (9). The return flow enters the conversion section through the entrance electrode (7), which has the form of a grid allowing the passage of the flow. The return flow coming from the entrance electrode carries stray charges to the collector electrode (8) by viscous interaction. The vapor flow in the conversion section contributes thus in a twofold way to the energy conversion process: first it transmits kinetic energy directly to the slowed down particles emerging from the expansion nozzle and secondly it carries as return flow additional charges

to the collector electrode. It contributes further indirectly to the conversion process by taking on practically all wall friction losses occurring in the conversion section.

A process which would preserve some of the expansion energy of the vapor flow is the recovery of its kinetic energy in a diffusor. This can be accomplished by properly increasing the conversion cross section and also the channels of the collector electrode. A generator system which is very inducive to this process is the radial arrangement shown in Fig. 7. The radial arrangement of the conversion units provides a natural enlargement of the flow channels. The radial type generator allows in addition a convenient placement of the parts which carry the high pressure media in the center of the drum-like generator, while the outer generator shell is only exposed to the lowest pressures occurring in the generator. Undesirable heat losses are minimized, while almost the entire housing is available as cooling surface, where needed.

VI. EFFICIENCY CONSIDERATIONS

Due to the complex interactions which take place between the electric conversion process and the vapor throttling process in the conversion region, neither the thermal nor the electric conversion efficiency can be clearly defined and calculated. In the description of the conversion mechanism we have seen that next to the entrance electrode some of the particle kinetic energy as well as some of the vapor kinetic energy (by way of viscous interaction) is transferred into electric energy before flow mixing (induced by the throttling

process) occurs. Midway in the conversion region both the vapor and the particles are slowed down, the vapor by mixing and the particles by electric action. Thus, interference between vapor and particles may be nearly absent. Closer to the collector electrode the particles are still slowed down by the electric field, though, weakened by space charge influences; but not the vapor since mixing is more or less completed at this location; then again vapor kinetic energy is transferred to the particles. Thus, for calculating the conversion efficiency, the conversion of heat into electric energy can be divided into two parallel processes: One concerns the condensing portion of the operating medium plus a small part of the uncondensed vapor. It undergoes a more or less ideal thermal and electric conversion process, subject only to the inherent thermodynamic cycle losses. The other process refers to the remaining non-condensing portion, which is unaffected by the electric field and loses its kinetic energy nearly completely by mixing and wall friction, i.e., its kinetic energy is converted back to heat. In a first approach the overall conversion efficiency under these considerations can be expressed in the following way:

η_{tot} = (cycle efficiency) x (specific content of condensate in the expanded vapor) x (upgrading factor to account for the mainly beneficial viscous interaction between vapor and particles),

or written as formula:

$$\eta_{tot} = \eta_{therm} \cdot (1 - X) \cdot f_{up}$$

f_{up} accounts for vapor kinetic energy preserved in the return flow, which reduces mixing losses. X is the so-called "quality" of the vapor-condensate mixture.

Fig. 8 shows Rankine-cycle efficiencies for expansion of water vapor from saturated conditions. For the present system, in which water vapor is expanded from 200at to 20at, the thermal efficiency is about 20%. This efficiency value may be increased by 1% to 2% to account for the fact that the expansion starts actually, though with some losses involved, from superheated condition in the charging process. Without the addition of hydrogen the steam quality X is about .64. Without an upgrading factor the overall conversion efficiency would be about 8%. With some upgrading 10% total conversion efficiency may be justifiable. This figure is very low compared to the performance of big generating plants, which approach 40% overall conversion efficiency, but in the few KW it is encouraging since it is competitive with generating equipment available in this range.

Obviously the requirement for a high pressure environment in the conversion section puts severe restrictions on the thermodynamic cycle efficiency. On the other hand, the high condensation temperature of around 200°C associated with the high expansion end pressure makes a simple air or radiation cooled condensor feasible. Also the high operating pressure allows a compact condensor design.

In the present design (Fig. 3) the condenser is incorporated into the generator by providing cooling fins on the inside and outside of the generator housing. This simple arrangement is possible due to the very high heat transfer rates associated with condensing steam (in the order of 5000 kcal/hr m^2 °C). The wall and fin area available on the inside is adequate to transfer the waste heat of 9 KW (!) to the wall (at 1 KW electric power output). On the outside, however, the specific heat transfer by free convection is nearly 1000 smaller. Counting also radiated heat all the heat transfer area which can be provided on the outside is only adequate for, say, 200 watt electric output. Thus forced air or intermediate liquid cooling becomes a necessity.

Forced air cooling is not applicable in the present case, since it would require rotating machinery for an effective air movement. However, the liquid transfer of heat from the generator to a separate cooler can be readily accomplished without rotating machinery by using waste heat to produce steam for operating a steam jet-pump to circulate the cooling liquid.

Waste heat may be also used to operate a low pressure EFD-generator. Ultimately, a multi-stage generator system can be applied where each stage is optimized for electric performance without thermodynamic constraints. A variety of possibilities exists for using a steam cycle in a multi-stage arrangement. Final expansion end-pressure may then also be lowered to, say 5 at, and a gain of 5 percentage points or more in overall conversion efficiency is a possibility.

VII. Conclusion

The preceeding description of an electro-ballistic generator system presents an attempt to explore the practicality of converting heat into electricity directly by the application of a ballistic type charge transport as one way to utilize the electro-fluid dynamic or EFD generator principle. Actual proof for the workability of the present system requires still detail experimental investigations, in particular, where new combinations of otherwise well established phenomena have been employed, such as the induction charging of a droplet spray near critical vapor conditions. Practical difficulties may also appear with wall deposition of the colloids used as part of the operating medium in the present system. Since a wide variety of colloidal materials including such materials which dissolve in the liquid phase and form colloidal crystals during the evaporation of the water, are available, prospects to overcome such difficulties are reasonably good.

There are uncertainties in the present design, which more or less afflict any kind of EFD-generator design. Due to the inherent presence of high electric field gradients, the electric breakdown strength of the operating medium and the structural material is always a crucial factor for the proper functioning of the system. Though the electric breakdown behavior of gases is very well known and side effects reasonably well understood, the electric breakdown along insulator surfaces is of an evasive nature and more difficult to keep under control.

Though water vapor is a slightly better insulator than air, it adversely affects the breakdown field strength on solid surfaces if sufficiently close to saturation. Due to condensation on the walls when the vapor reaches

the state of saturation or due to droplet deposition, insulator surfaces may even become plainly conductive. In the present system the water vapor is always at superheated conditions where it is in contact with the walls. During the charging process the liquid jet is surrounded by the hot fill-gas evaporating the droplets coming from the injected water. In the expansion nozzle, where condensation in the mainstream takes place, the stagnation temperature in the boundary layer prevents condensation on the walls. Only in the conversion section provisions are necessary to prevent wall condensation. By proper protection against heat loss to the outside the confining walls can be kept at a temperature above that of the cooled return flow. The return flow, can then be used to form a non-condensing sheath along the insulator surfaces exposed to the conversion section.

In an EFD-generator, where electric charges must be transported against strong electric fields, there is always danger that stray charges appear, which accummulate on insulating walls. If the walls are perfect insulators continuing charge accummulation leads to increasing field gradients on the walls causing eventual breakdown along the walls. A controlled conductivity or the well known voltage grading along insulators must be applied.

A common method of producing charge carriers in an EFD-generator consists in seeding ions into the gas flow by a corona discharge. These ions can either be used directly as charge carriers or attached to particles carried by the flow. Though this method is very convenient and very effective, corona discharge is liable to produce undesirable chemical changes in the operating medium. The here considered generator design avoids the corona charging method and attempts instead to utilize

induction charging for producing the charged particles. As the results indicate reasonable performances appear to be possible with this alternative method. No completely satisfactory EFD-generator design has been found so far. By exploring various schemes like the present one, design elements may be developed which combined in the proper way may eventually lead to a technically useful generator.

Apart from inherent uncertainties afflicting the present system, it is based on design data, which are derived from well established physical principles and to be considered conservative. Its electric performance, which does not necessarily present the ultimate possibility for an EFD-generator, is the following: an array of 140 conversion units each generating 7 watts and arranged in a circle of about 2 inches generates a total of 1 KW power. The pressure vessel containing the system measures about 6 inches in diameter and is about 6 inches long. A rough estimate for the weight of the generator is 5 lb for a 300 psi expansion end pressure. A larger number of such generator containers could be connected to one steam supply system and also to one outside electric terminal. The estimated overall conversion efficiency from heat to electricity is around 10%. Better performances may eventually result from further exploration of the EFD-generator principle. The present system appears, however, already in some way attractive as an indepedent high voltage power source in the 10 to 100 KW range, with no need for a bulky voltage conversion gear and with a promise for simple operation.

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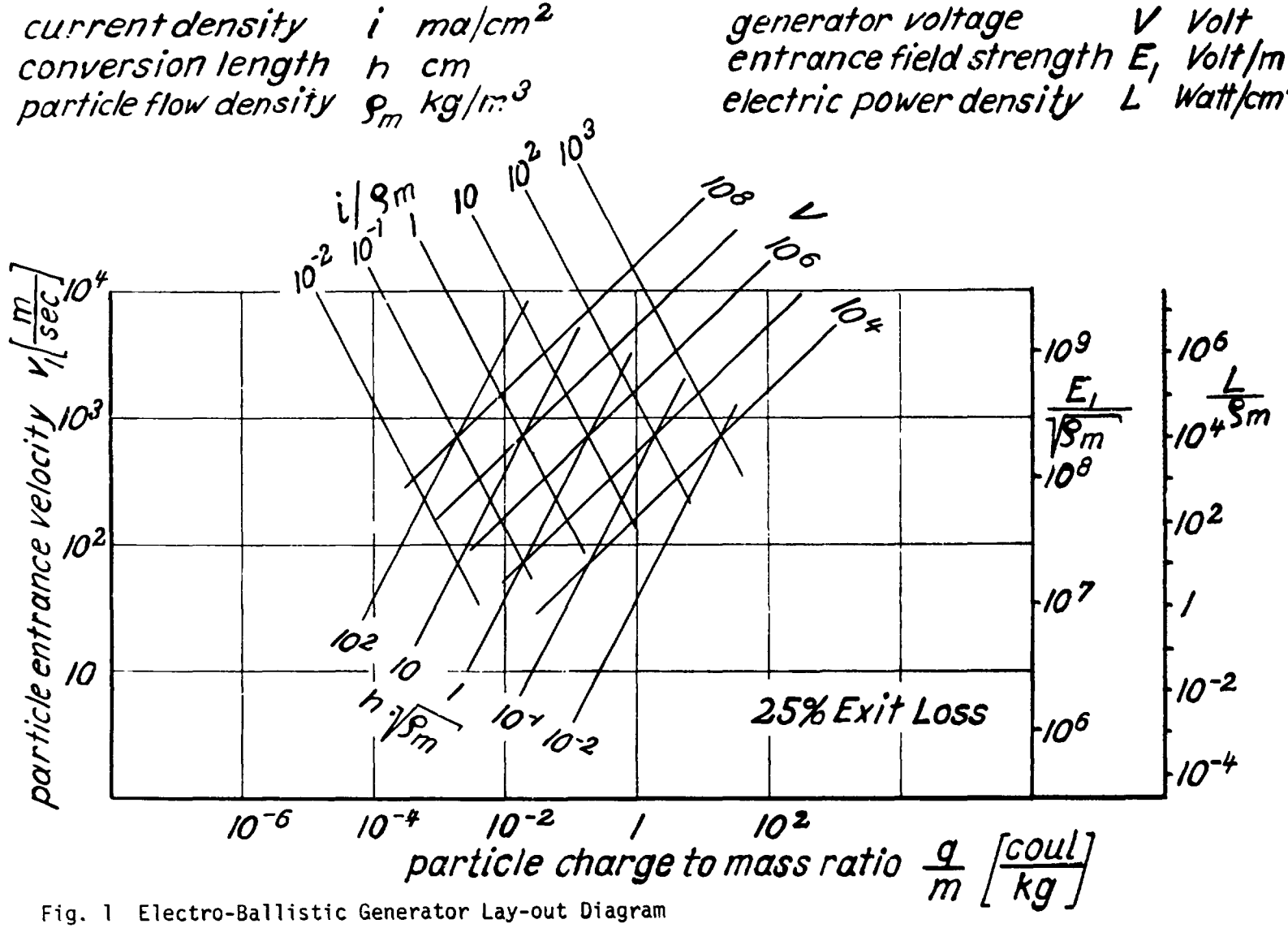

Fig. 1 Electro-Ballistic Generator Lay-out Diagram

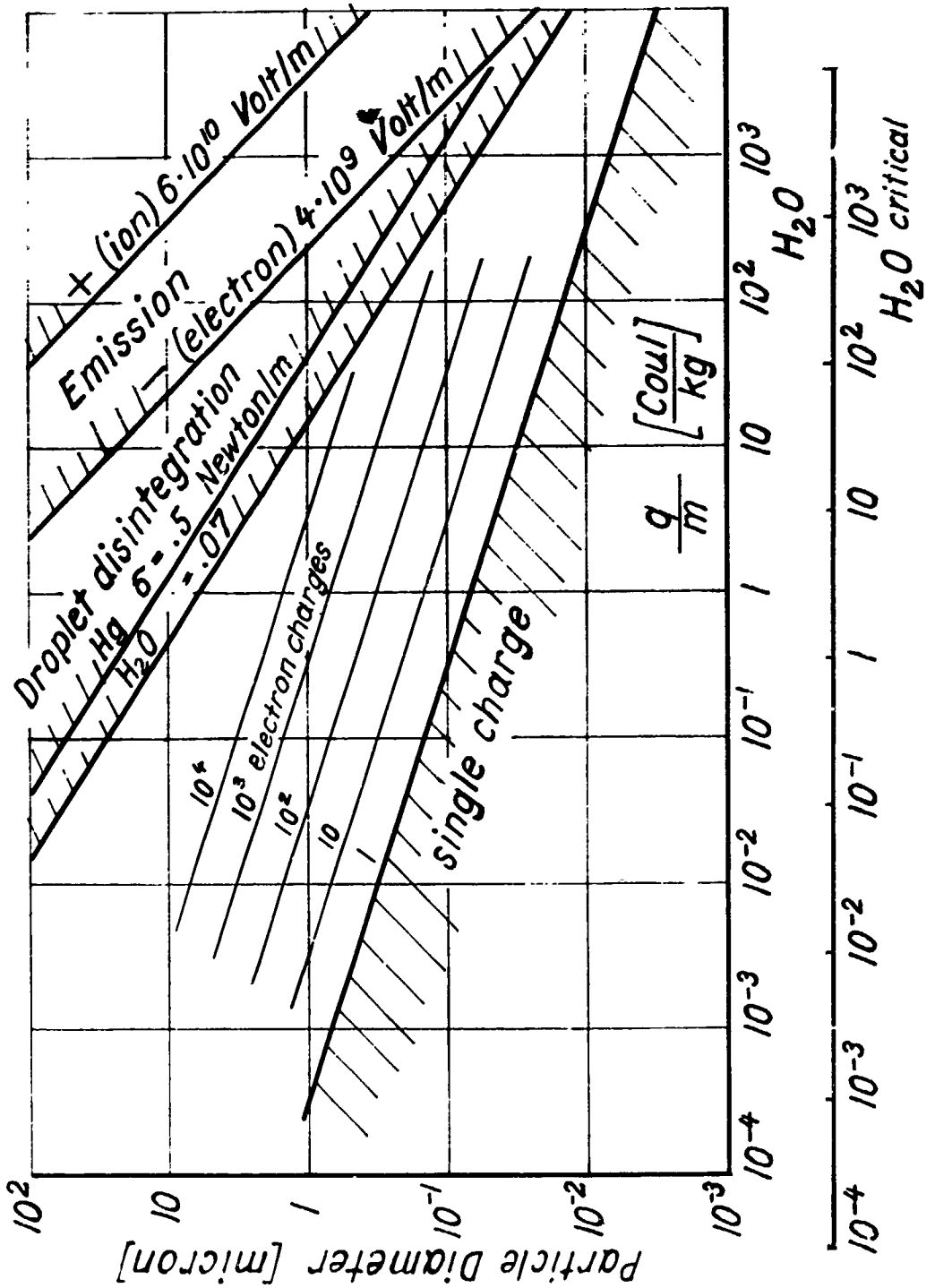

Fig. 2 Limits for the Particle Charge to Mass Ratio

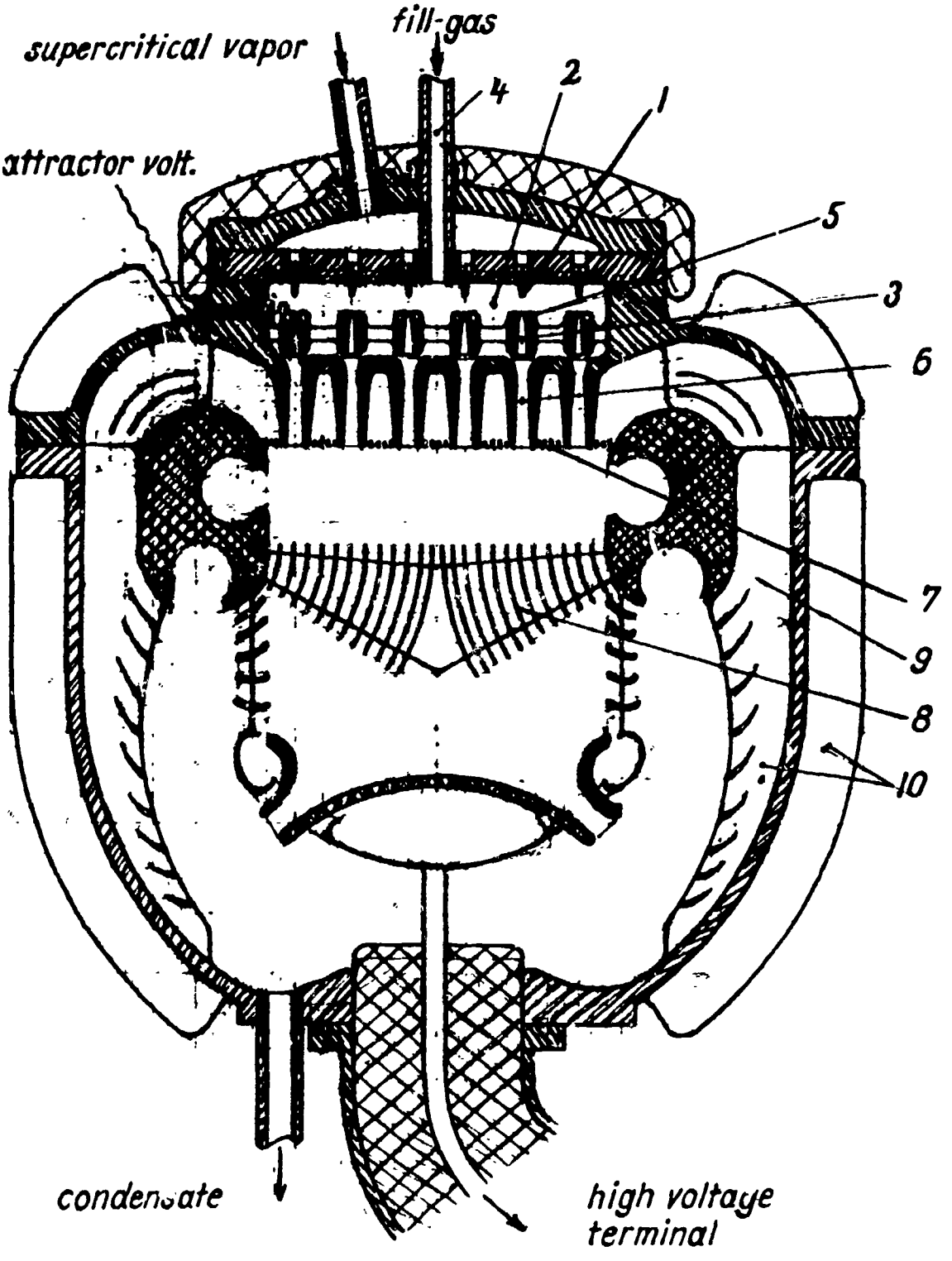

Fig. 3a Scheme of a High-Pressure Electro-Ballistic Generator System (for numbers see sect. III). Diameter: 6 inches; potential performance: 1 KW at 300,000 Volt, (For outside cooling fins see sect. VI).

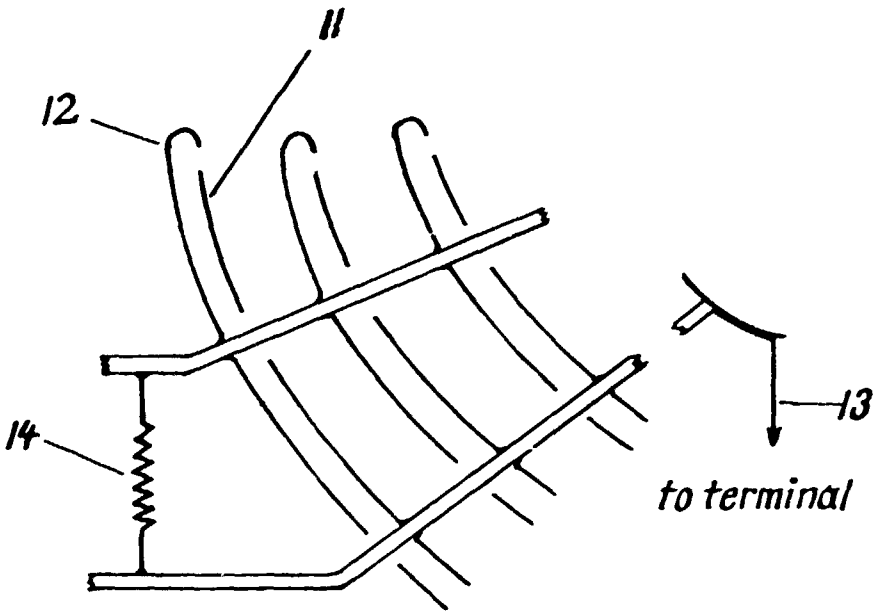

Fig. 3b Precipitator Type Collector Scheme (for numbers see text, Sect. III)

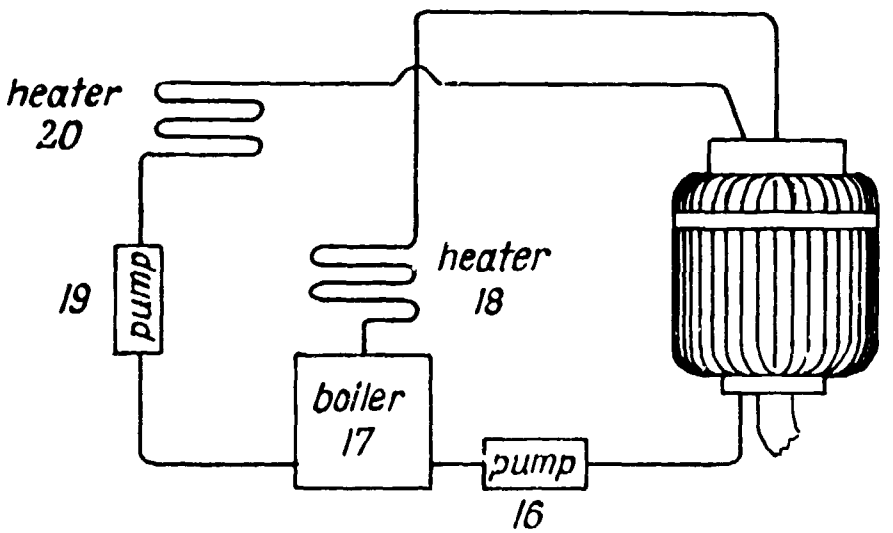

Fig. 4 Recirculation of the Operating Medium (for numbers see text, Sect. III)

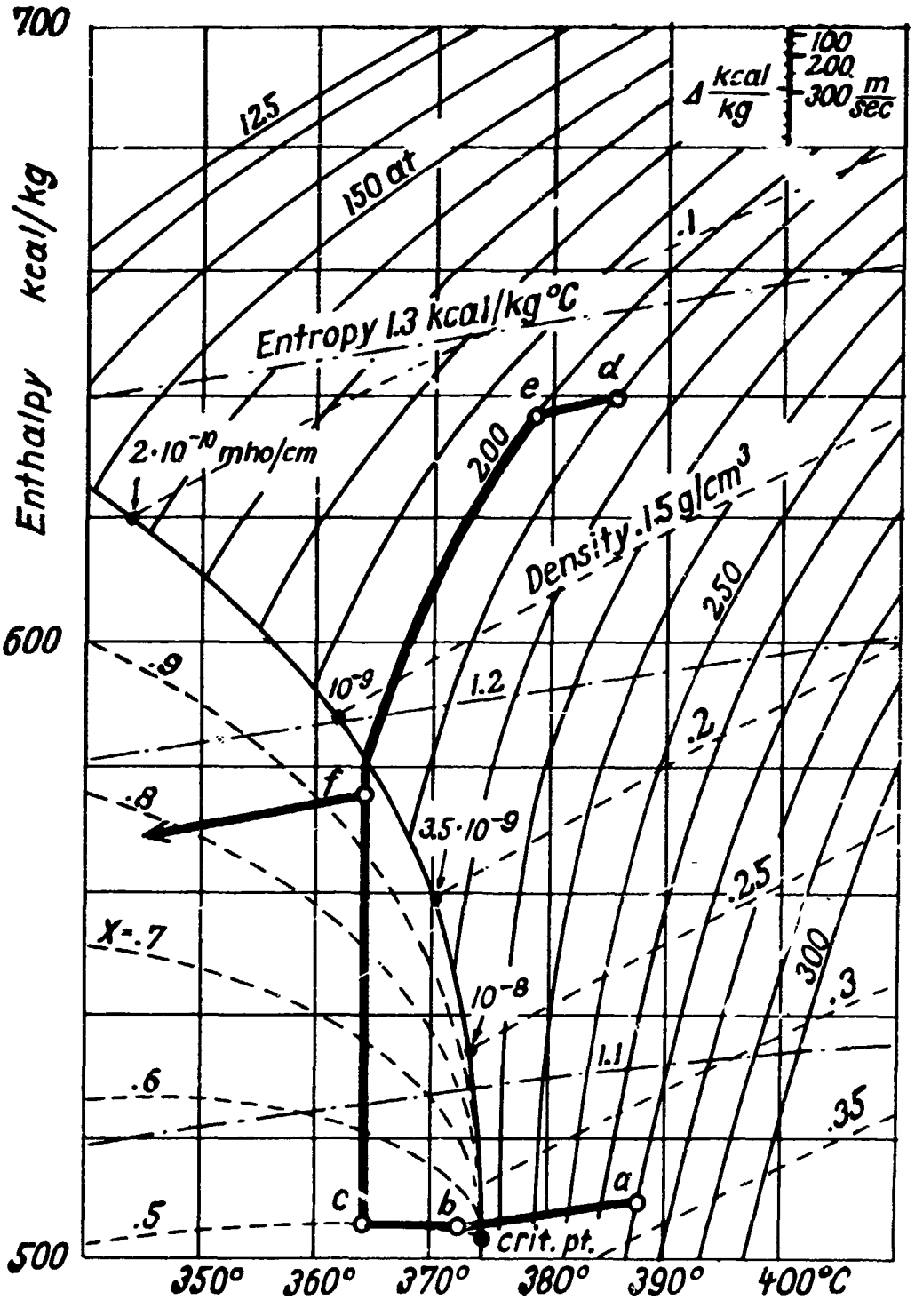

Fig. 5 Enthalpy-Temperature Diagram of Water Near Critical Conditions Showing Injection Process for the Electro-Ballistic Generator (for letters see text, Sect. IV)

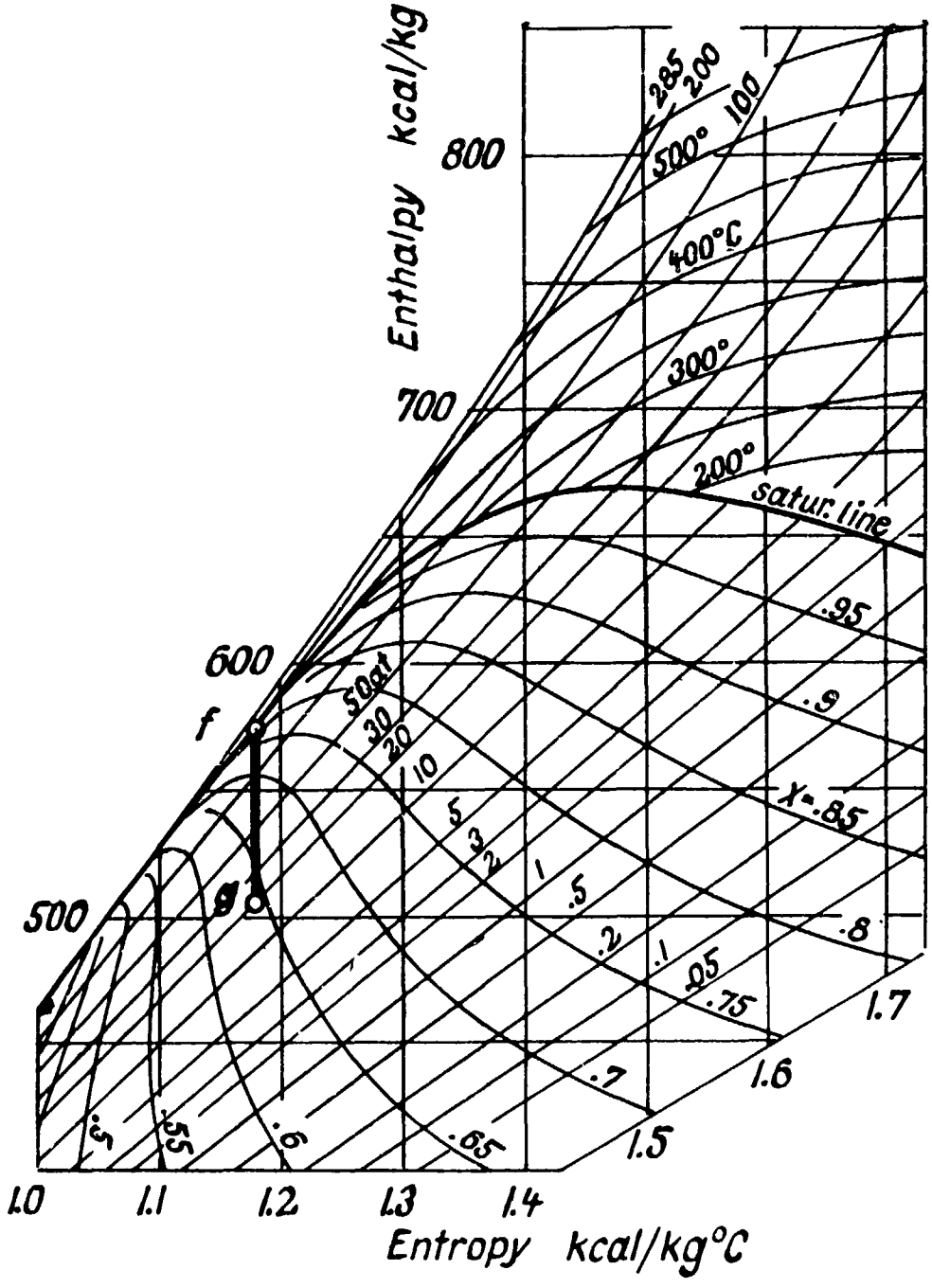

Fig. 6 Enthalpy-Entropy Diagram for Water Showing Expansion Process for the Electro-Ballistic Generator (for letters see text, Sect. IV)

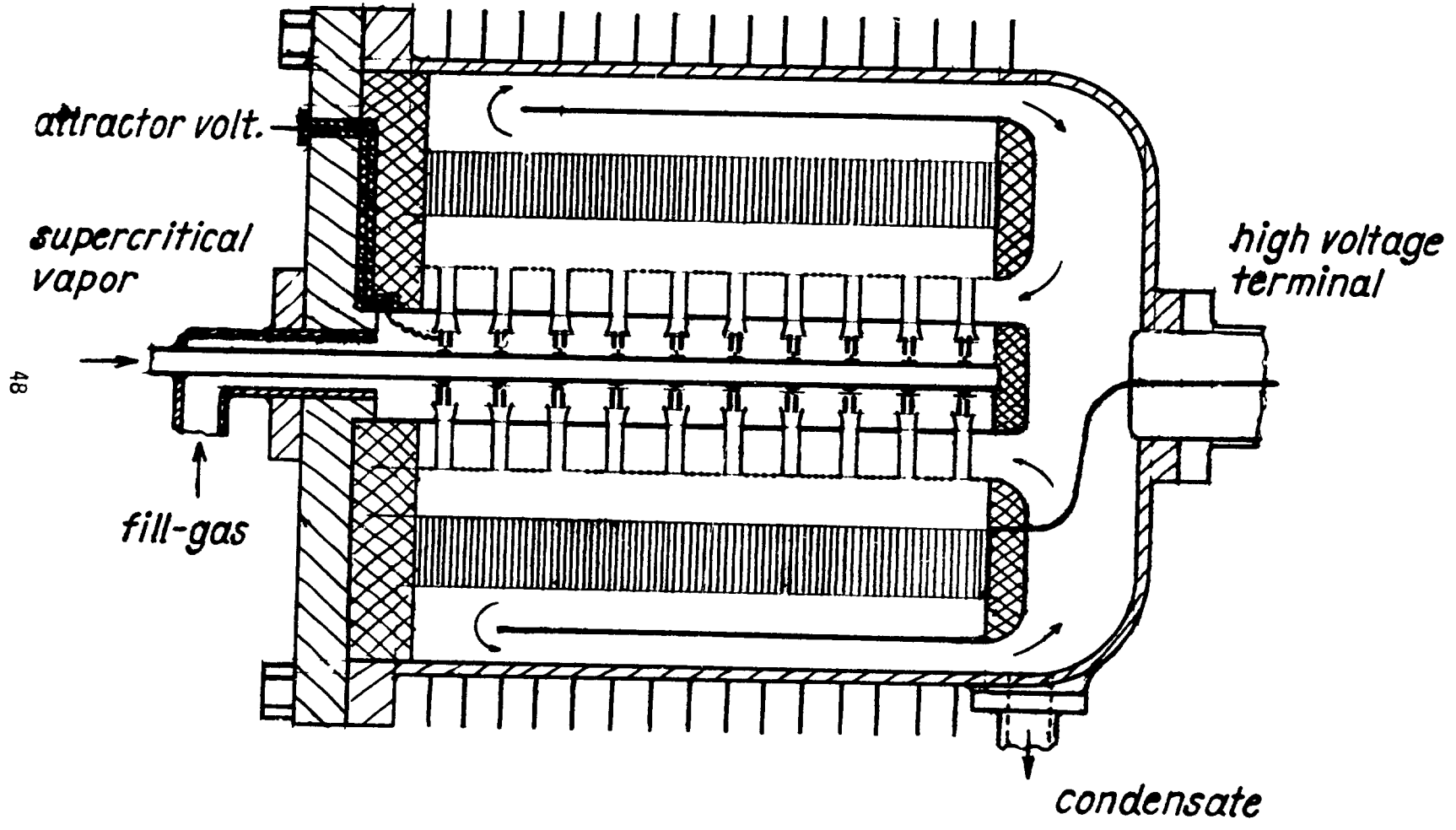

Fig. 7 Scheme for the Radial Arrangement of Conversion Units in an Electro-Ballistic Generator System

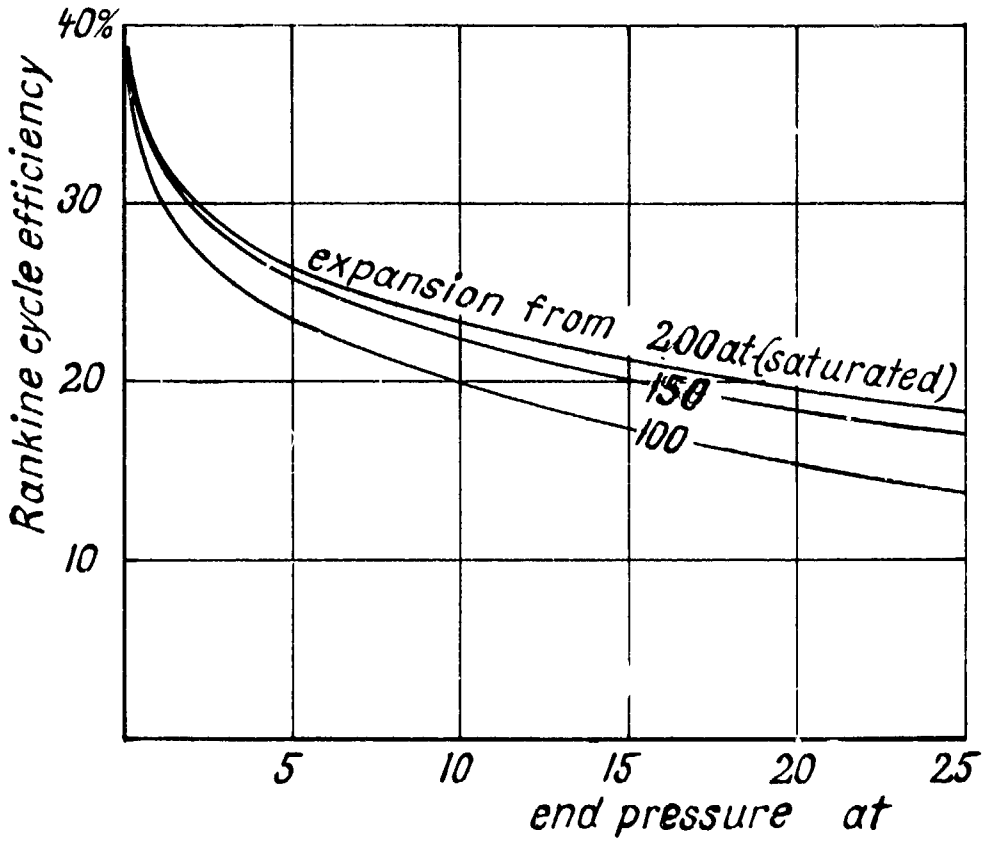

Fig. 8 Rankine-Cycle Efficiencies for the Expansion of Saturated Vapor

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13. ABSTRACT

An EFD-generator system is described which utilizes the electro-ballistic conversion principle in a high-pressure environment. A special process is employed to produce massive charged praticles for an effective ballistic process. A stream of droplets produced by a spray nozzle and containing colloidal material is first charged by induction. The droplets are then subject to evaporation and the electric charges transferring to the non-evaporating colloids. In a subsequent supersonic expansion process these charged colloids are used as condensation nuclei to produce charged droplets which are substantially larger than condensate droplets originating from spontaneous condensation, i.e., from an unseeded vapor. Water vapor near critical vapor conditions is used in the present system with particular advantages as operating medium. With conservative assumptions a generator system consisting of a multiplicity of conversion units and producing 1 KW power weighs an estimated 5 lbs., requires about 1/10 ft^3 space and has at 300,000 volt an estimated heat-to-electricity conversion efficiency of about 10%.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Electro-static generator						
Charged Colloids						
Supercritical vapor jet						
High voltage generator						
Electro-fluid dynamics						
EFD-generator						
Induction charging						

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