The Direct Transformation of Nuclear Energy into Mechanical Power and its Application to Very Low Power Devices

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From the days of Moseley, back in 1913, through Rappaport, Linder and Christian, in 1951–1954, many authors have worked on the direct utilization of radioactive sources in high-voltage, low-current, generators. The early papers aroused but little interest, in spite of the originality of the process, and long remained but isolated laboratory achievements, mainly due to the fact that the *natural* radioactive sources were scarce and costly. Now, for the last few years, with the development of the industrial techniques of nuclear physics, a great many fission products or artificial sources of radioactivity have become available, if not cheaply, at least readily and in substantial amounts, their main sources of supply being, as is well known, in the countries which operate atomic reactors.

Thus it is that the ideas of the early workers recently were picked up again, giving rise to interesting generator designs (often called "piles" in the popular periodicals) developing high voltages but low powers with isotopes, for instance, such as strontium-90 and tritium. The latest papers even mention the possibility of achieving larger currents, under lower voltage, by bombarding *p-n* junctions with β-particles coming from an artificial source of radioactivity.†

Thus, it now seems possible to make use of the radioactive energy developed by the nuclear process in order to make low power generators, the "life" of which would be 20 to 30 years on an average, and which would be simple, sturdy, and relatively cheap.

Even now, the following question is in order: how can these generators be adapted to very low power mechanical or electromechanical devices, the prime function of which would be, in the last analysis, to transform this radioactive (or electrical) energy into mechanical energy?

As the matter now stands, it would seem to us that the question admits of two answers, on which we will endeavor, in this paper, to expatiate at some length:

1. By using the generators "as are," through "motors" which transform the electrical energy into mechanical power.

2. By transforming the radioactive energy as directly as possible (without going through the stage of a fixed generator), into mechanical energy.

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† Beta particle = high-energy electron.

We shall concentrate our attention on the second solution, and show that it is possible, along those lines, to make a device which will be of some interest for very low power applications, particularly in the watchmaking industry.

Before going into the matter, let us review the practical solutions already found, particularly in the form of high-voltage generators.

NUCLEAR GENERATORS

The principle on which they operate is very simple: a certain amount of radioactive material (a beta emitter for instance) is deposited on an insulated electrode, located in a vessel full of gas under low pressure. Another electrode (the "target") gathers the particles emitted, and thus becomes negatively charged with respect to the former. In fact, it can be stated that this amounts to the charging of a capacitor by means of electrons which are caused to pass from one electrode to the other. In this fashion, it becomes possible to store energy under high voltages, which may reach, under certain conditions, several hundreds of kilovolts, in other words, to carry out the direct transformation of nuclear energy into electrical power. Naturally, the current which such a generator is capable of delivering remains very low, as well as its power.

In fact, it can readily be shown that the maximum power which can be achieved is of some 4 to 5 microwatts per millicurie, for a β-emitter for instance. Figure 1 shows a simple diagram of such a generator.

The source most commonly used, in the current models, is strontium-90, which emits β-particles, the half-life of which is about 30 years, for an energy of about 0.7 Mev.‡ Sr^{90} is transmuted, by that emission, into yttrium-90 which, in turn, by 2.2 Mev emissions, is turned into a stable isotope, zirconium-90, with a half-life of some 60 hours.

The advantages of the use of Sr^{90} are many: it is fairly readily available, its price is not prohibitive, its half-life is relatively long, it does not emit gamma rays§ (if free from impurities) and its chemical preparation is easy. In addition, the energy of the electrons it releases is high, and there are no gaseous byproducts.

‡ 1 Mev = 10^6 electron-volts, namely the energy acquired by an electron accelerated through a potential drop of one million volts.

§ Gamma rays are very energetic (very hard) X-rays.

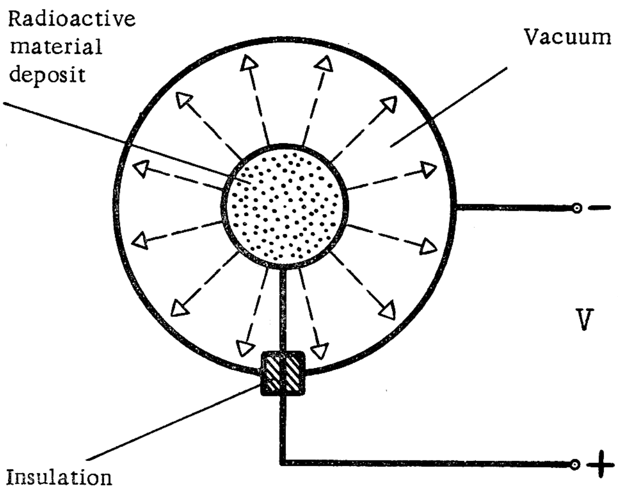

Figure 1

The main difficulties which arise, in making such a generator, are insulation problems, since the current used for charging is very weak and the behavior of a dielectric under very low pressure and radioactive bombardment poorly known.

Linder and Christian made a generator having a maximum voltage of 365 kv, using 250 millicuries¶ of Sr^{90}, under a pressure of 10^{-3} mm of mercury. Zero voltage current was 1.05×10^{-9} amperes.

Naturally, it is possible to make lower voltage generators, which simplifies the insulation problems, but one can expect less power from these generators for the relatively low voltages.

Other prototypes were made, in the USA as well, by Rappaport and Linder, in which the "vacuum" was replaced by a dielectric, such as polystyrene or mica (Fig. 2).

This device offered some advantages: the vacuum installations were eliminated, the voltage obtained high, the $S \rightarrow C$ distance could be covered by high energy particles and, when traveling in the opposite direction, low energy particles were stopped by the dielectric. On the other hand, several interesting studies could be made, particularly on the behavior of the irradiated dielectric, the secondary emission and the absorption of β-particles by matter.

With sources of some 50 mc of Sr^{90}, the authors reached voltages of some 7 kv by using polystyrene as the dielectric. In addition, they were enabled to study the effects of the bombardment on the material used, as well as that of the thickness of the dielectric on the speed at which the device was being charged. They came to the conclusion that the dielectric could be substituted for the vacuum to good purpose.

Finally, a third type of generator was recently mentioned by Rappaport: namely a very low voltage generator. This was a *p-n* junction (germanium or silicon) bombarded by a 50 mc source of Sr^{90}. The current was much stronger than in the generators described above, reaching 10^{-5} amp (short circuit) while the open circuit voltage did not exceed 250 mv. The multiplication factor of the current was of some 1.5×10^{-5} for silicon.

The electrical power of such a generator was some 0.8 microwatt (transformation efficiency, about 0.4%). The author believes he will reach 2 μw by making a closer study of the device.

Such a generator was used for feeding a transistor oscillator operating in the audio range. Nevertheless, some parasitic effects of the bombardment on the junction crystals appear to limit its useful life.

To these three generator types, some of which now already are in production, let us add those which work on the same principle, but in which tritium is the radioactive material, and which are also mass produced. They operate under a voltage of approximately 400 v and can deliver a power of 0.01 to 1 μw.

We thus have rapidly reviewed the principal achievements of the day and can now deal with the principal subject of this article, namely the use of this radioactive energy in very low power devices, more specifically its transformation into mechanical energy.

UTILIZATION OF HIGH-VOLTAGE NUCLEAR GENERATORS

The first idea which comes to mind, when dealing with high-voltage nuclear generators delivering a low current, is the use of electrostatic devices for the transformation of electrical energy into mechanical power. It should be made clear that the other type of generator, that which delivers a low voltage, could be used with conventional electromagnetic devices, but this possibility will not be explored here, since our work has not progressed enough in the direction of an industrial embodiment.

Limiting ourselves, for the time being, to the field of watchmaking in which the powers which come into play happen to be very small, it will at once be apparent that there are two possible applications for

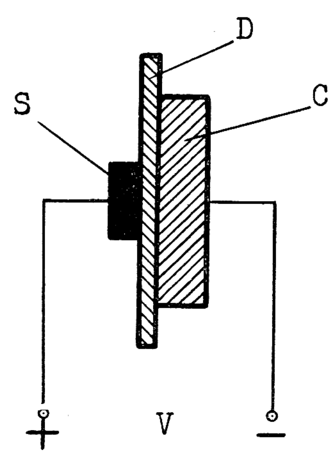

Figure 2. Principle of operation of the dielectric type of nuclear generator: (S) radioactive source; (D) dielectric; (C) collector or "target"; and (V) voltage obtained at terminals

¶ 1 millicurie = 1 mc, the quantity of a radioactive material which emits the same number of particles as one milligram of radium.

such an electrostatic device: (*a*) as an oscillator (regulating device); (*b*) as a winding-up engine (driving a spring or microspring) coupled with a conventional regulating device, through a reduction gear train giving a more or less important ratio.

It should be remembered that, as an oscillator, the period of this device will be relatively large, by reason of the charging time of the generator. In addition, adequate precision is hard to achieve, since the duration of the impulse, from the very nature of things, is rather long.

Let us remember that a particularly simple prototype of an oscillator (torsion wire for instance) was made by one of the authors at the Geneva Institute of Physics, and that it operated perfectly. Naturally, the only source of energy it used was a radioactive isotope, in this case some Sr^{90}.

In addition, long before the first nuclear generators appeared, the Patek Philippe laboratory studied, for other purposes, an entirely electrostatic regulating device (oscillator) which operated on the basis of a very simple principle, and now can be adapted to high-voltage supply from a nuclear source.

The oscillations were perfectly kept up and, but for a few points of detail, the operation was perfect when the device was tested with a common or conventional type generator. Its adaptation to a radioactive type generator raises several problems which are new, but not essentially different from those encountered before.

As regards the winding engine, it can readily be visualized, either as an electro-motor in the true sense, which places a spring under load, or again as a mechanism which transmits its torque to a moving part located relatively close to the conventional adjusting device through the storage of a small amount of power (microbarrel). In this last case, as it were, one would have a "loose" coupling. Rotary motion of the engine can take place, either continuously or by relaxation (this point will be taken up again with regard to the direct transformation of radioactive energy into mechanical energy).

Thus, the devices which have just been very briefly described above play the part of actual electrical engines, which transform electrical energy into mechanical power. Accordingly, consideration has been given to the entirely conventional system shown in Fig. 3.

We shall now see how it is possible to do without such a system and study, in greater detail, the main purpose of this article.

DIRECT TRANSFORMATION OF NUCLEAR ENERGY INTO MECHANICAL ENERGY

The principle is extremely simple: a radioactive deposit is to be made *directly* on the moving assembly of the engine, which is always of the electrostatic type. This rules out the need for a cumbersome outside fixed generator having a complicated set of connections, at times involving friction contact

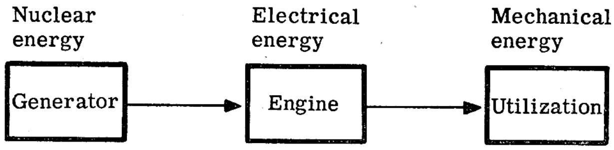

Figure 3

(Patek Philippe patent). Figure 4 shows a schematic diagram of such a device.

The rotor is electrically insulated from the stator, and we are again dealing with the process of charging a capacitor, hence with the creation of electrostatic attraction forces, and finally with the displacement of a rotor plate which can move with respect to the stator.

It will readily be seen that we have a torque, thus mechanical energy, usable on the rotor shaft.

Naturally, for continuous operation, the capacity must be discharged, which immediately leads to the following two possibilities of operation: (*a*) continuous rotation, and (*b*) relaxation.

The prototypes made and studied at the Patek Philippe laboratory were of the two types described above. Nevertheless, the relaxation type system was the only one considered, for being much more advantageous from a mechanical standpoint, particularly as regards losses by dry friction.

It can readily be shown that the usable work, in a mechanism of that type is

$$\tau u = i \int_0^T v(t)dt - W_c \quad (1)$$

in which: i = radioactive current; T = period (time elapsed between two discharges); $v(t)$ = voltage variation during the cycle, as a function of time; W_c = energy stored in the capacitor.

On the other hand, since the torque is given by:

$$M = \frac{V}{2} \frac{\partial C}{\partial \theta} \quad (2)$$

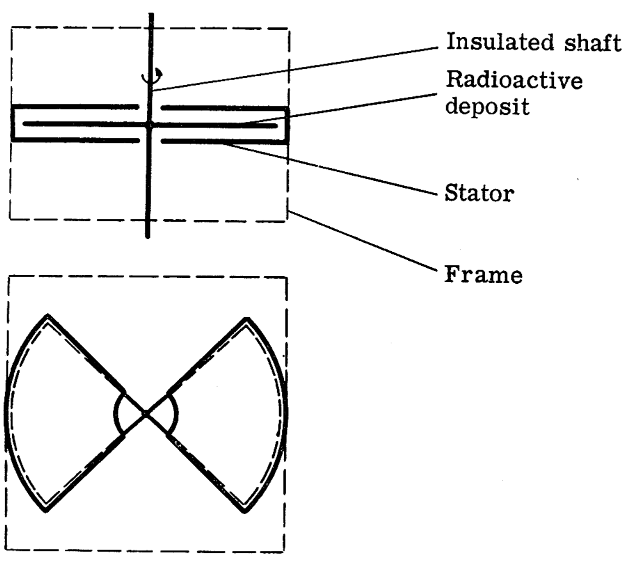

Figure 4

and if provisions are made for $\delta c/\delta\theta$ to remain constant, as well as the angular speed (w) of the rotor, one gets:

$$\frac{\partial C}{\partial \theta} = \frac{1}{\omega}\frac{dC}{dt} \qquad (3)$$

from which dC/dt = constant. Or again:

$$V = \frac{it}{C} = \frac{it}{\frac{dC}{dt}\cdot t} = \text{const.}$$

Thus, from Equation 2, M = constant. It can be shown, by rearranging Equation 1, that with $\tau u = M\omega T$:

$$M\omega T = i\int_0^T v(t)dt - \frac{1}{2}C_tV^2 \qquad (4)$$

$$MT = iVT - \frac{1}{2}C_tV^2$$

in which C_t is the maximum capacity, just prior to discharge. Thus, Equation 3 can be written:

$$\frac{\partial C}{\partial \theta} = \frac{1}{\omega}\frac{C}{T}$$

and with Equation 2, one will get:

$$\underbrace{M\omega}_{\text{useful } P} = \underbrace{iV}_{\text{generator } P} - \underbrace{M\omega}_{\text{power lost in the discharge}}$$

Thus, useful $P = (\frac{1}{2})\ P$ gen.

Thus, when disposing of 50 mc of Sr^{90}, half of the electrons of which are lost by absorption, and working under 10,000 volts: $i = 300 \times 10^{-12}$ amp; P gen. $= iV = 3 \times 10^{-6}$ watts = 3 microwatts, and useful $P = 1.5\ \mu$w which is sufficient to operate the works of a clock.

Figure 5 shows a schematic diagram of one of the devices made by the Patek Philippe laboratory. This was a nuclear engine of the direct transformation type, relaxation operated, and coupled to the middle-sized gear of a clockwork through a very weak spring.

The overlap angle was about 90 degrees, and discharge took place at maximum overlap (maximum capacity).

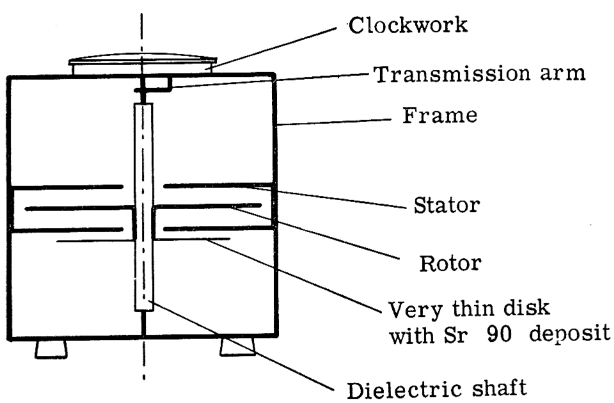

Figure 5

Since half of the generator power was lost during discharge, it was thought that a part could be recovered by modifying the manner in which the plate overlap varies (sudden change in capacity) in such a way as to come to the end of the stroke with very little voltage.

This mechanism operated under the following conditions at the end of the year 1954, as follows: vacuum, about 10^{-4} mm Hg; voltage, 6 to 7000 volts; period, 10 minutes approximately; and amplitude of balance motion, 200 degrees.

The main difficulties encountered in the design and manufacture of such an engine are due to several factors, namely:

Insulation Difficulties

The dielectric must meet very exacting specifications. It must not change under radioactive bombardment and, similarly, it must not release gas under a high vacuum. Polystyrene and Teflon had to be abandoned in favor of glass and porcelain. In addition, the dielectric-vacuum interface often was the seat of microdischarges, as well, in fact, as the space between the electrodes. The true mechanism of these discharges still is poorly known, particularly in the presence of a nuclear bombardment. It is believed that it bears a strong correlation with gases absorbed by the material (metallic or other) such, for instance, as hydrogen.

Degassing

All materials, even the stablest of them, release a small amount of gas under such high vacuum and preliminary degassing, therefore, is necessary. This, however, is not very serious where the vacuum is maintained. In a sealed vacuum, the presence of "getters" is known, even now, to be most useful, and could be applied, for instance, to future devices.

Radioactive Material Deposit

It is rather difficult to achieve this deposit in a stable fashion without any risks of absorption and substantial self-absorption by the carrier, if the yield is to be satisfactory. This is one of the points on which the researchers now concentrate their efforts.

Choice of the Material for the Fixed and Movable Electrodes

This choice must be made with the objective in mind of avoiding a new emission of electrons, where it is bad, and favor it where useful. Since this depends a great deal on the atomic number of the element under consideration, a light material is chosen for the fixed parts (A1, for instance), while a heavy element is used for the rotor. Let it be specified that this re-emission is all the greater as the bombarded element has a larger atomic number.

Finally, it is necessary, in order to operate with the most favorable solid angle, that the part of the engine which "gathers" the electrons, should surround that which contains the isotope as much as possible.

Sharp angles also are to be avoided, in order to rule out any effects due to field edges, which would be particularly bad in this type of equipment.

Needless to say that very special care must be given to the making of the mechanical parts of the device, for very obvious reasons.

It will be seen, from all the above, that we now have a real possibility of making use of nuclear energy in very low power mechanisms and, particularly, in the field of clockmaking. The fact remains that the road which still has to be traveled before an industrial version can be made is fairly long. The change, in particular, from a compensated vacuum to a sealed vacuum, the transmission of motion (by a magnetic device for instance) outside the capsule, and the delicate degassing problems come to the forefront.

It may not be out of order to feel that all these difficulties will be overcome in a short time, and that one of the peaceful applications of nuclear energy, its direct transformation into mechanical energy, soon will be an industrial reality.

We propose, in a paper to be published at a later date, to come back in greater detail, scientifically speaking, on this problem, the multiple aspects of which we have now merely touched upon.

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