RB-3

THE DIRECT CONVERSION OF RADIATION INTO ELECTRICAL ENERGY

RADIO CORPORATION OF AMERICA
RCA LABORATORIES
INDUSTRY SERVICE LABORATORY

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The direct conversion of nuclear radiation into electricity has recently attracted considerable attention, particularly during the past year with the increasing interest in peaceful uses of atomic energy. At the present time, judging from available publications and reports, about a dozen research organizations in the United States have active projects in this field. It appears that the immediate interest lies in the possible application of such a process to produce simple, compact and long-life power sources. However, as will be clear from later discussion, only very small amounts of power are feasible at the present time.

It is intended to present a general survey of the various methods of direct conversion, by which is meant a one-step process of converting the radiation (from radioactive isotopes in the present case) into electrical energy. Some of the more interesting and promising methods will be given specific attention, and the methods which have been studied especially at RCA Laboratories will be described in greater detail. The future prospects of the various methods will be evaluated. In general, the aim will be to give an up-to-date picture of the direct conversion situation.

The grand total of power available from radioisotopes is limited by the supply of fission products produced mainly as by-products of nuclear reactors. It has been estimated that if all the present electrical power consumed in the United States were produced by nuclear reactors the annual output of radioactive waste would be sufficient for the production of power at the rate of 400,000,000 watts, which represents only a few hundredths of 1 per cent of the energy consumed in the country.[1] This figure is further reduced because the radioactive energy could not be converted into electrical energy with more than a few per cent efficiency. In spite of these factors, the power which might be available is still a substantial amount especially when it is compared to the total power supplied in the U. S. from the annual production of batteries which is approximately 2,000,000 watts. It is also estimated that by 1965 the U. S. output of fission products should be 6.1×10^{6} grams. This would correspond to 3×10^{9} curies, which would have a heat power level of 6.1×10^{6} watts at age of one year.[2] However, only a small fraction of this would be convertible to electricity by direct processes. It is evident from these estimates that fission products cannot be considered as a possible principal source of power, in fact their availability in large quantities is contingent upon the use of reactors as the principal source of commercial electric power. They should be considered rather as a possible auxiliary source of considerable magnitude, with a possible maximum roughly equivalent to that produced by batteries at the present time.

[1] Putnam, P. C., ENERGY IN THE FUTURE, Van Nostrand, New York, N. Y. (1953).

[2] Lieberman, J. A., "Handling and Disposal of Radioactive Wastes", presented at a meeting of the Metropolitan Section, American Society of Civil Engineers, New York, April 20, 1955.

Types of Radiation

The types of radiation which are being worked on may be classified into two categories:

(1) Charged radiation.

(2) Uncharged radiation.

Examples of charged radiation are: electrons or beta rays, alpha particles, ions, and fission particles. Examples of uncharged radiation are: X-rays, gamma rays, neutrons, and light also may be included if it is produced by some nuclear process.

The most important source of charged radiation at the present time is radioactive material, which is available in the form of fission products, as mentioned above[3]. The most suitable type is beta radiation. As examples, two of the better known beta-emitting materials, strontium-yttrium-90 and tritium, or hydrogen-3, may be cited. The former comprises about 5 per cent of the bulk radioactive material, the latter is produced in undisclosed quantity. The properties of these which are of interest here, in relation to their use as sources of electrical energy, are shown in Table I.

TABLE I

Electrical Properties of One Curie of Beta Emitter

Property		Sr90-Y90	H3
Disintegration rate	d/sec.	3.7×10^{10}	3.7×10^{10}
Current	amps.	6×10^{-9}	6×10^{-9}
Avg. Voltage	volts	5×10^{5}	6×10^{3}
Power	watts	3×10^{-3}	3.5×10^{-5}
Half Life	years	20	12.4
Weight	gms.	5×10^{-3} (100% pure)	

Fig. 1 shows the beta-ray spectrum of Sr-Y90, after the radiation has passed through 0.0075 cm of aluminum, as measured by L. N. Russell[4]. There are two peaks; one for strontium 90 at about 0.3 mev and one for its daughter product, yttrium 90 at about 0.8 mev. Significant characteristics of this type of radiation are the high average energy of the particles or the quantum energy, and the spectrum extending from zero to a high upper limit.

No suitable fission product sources of other types of charged radiation are available at present, except perhaps polonium-210, which is an alpha emitter. However, alpha particles possess the disadvantage of causing serious radiation damage due to their comparatively large mass.

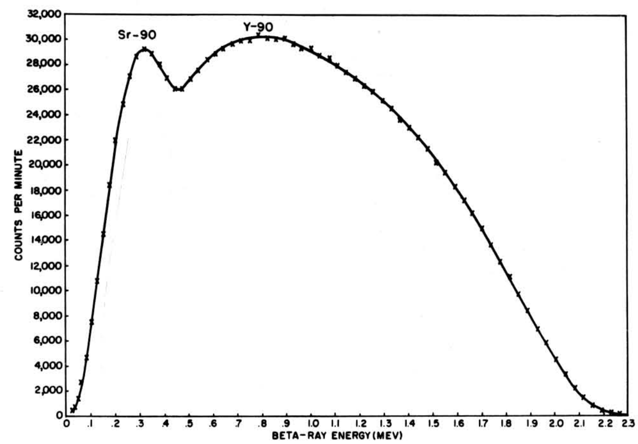

Fig. 1 - Beta ray spectrum of Sr-Y90 after filtering through 0.0075 cm of aluminum.

We turn now to the second category of radiation, namely the uncharged type. The most important source of this is the sun; however, radioactive material is becoming a source of increasing importance although of a somewhat different radiation type within the same category. Radioactive materials may produce X-rays and gamma rays. By use of indirect processes or auxiliary materials for example phosphors, light also may be produced.

The most available radioactive source in this class is the gamma emitter cobalt-60. Its quantum energy is 1.33 mev and its half-life 5.3 years. This is too penetrating to be well-suited for power applications. A softer radiation and a longer life is desirable, but not available now in practical amounts and at suitable prices. Americium-241 may eventually be available, since it is of interest also for medical radiography[5].

[3] For information on presently available isotopes see the ISOTOPES CATALOG published by the U. S. Atomic Energy Commission, Oak Ridge National Laboratory, Post Office Box E, Oak Ridge, Tennessee.

[4] Russell, L. N., (Private Communication) U. S. Atomic Energy Commission, Mound Laboratory.

[5] West, R., "Low-Energy Gamma Ray Sources", *Nucleonics*, Vol. 11, p. 20, Feb. (1953).

Uncharged nuclear radiation has not been investigated as extensively as the charged type in regard to direct conversion processes. This may be due to the fact that the latter, by virtue of its charge, is less far removed from energy in electrical form, and is compatible with a larger variety of conversion processes. Another influential factor is probably the lower specific ionization of the uncharged type. However, the conversion of uncharged radiation, in particular soft gamma rays, is worth further study. This is supported by the promising results obtained in the conversion of solar light by semiconductor junction devices.

A further important consideration related to radiation types is the power available from a radiation source. This can be computed by considering the amount of radiation emitted from a surface (such as an electrode) coated with a layer of radioisotope. The emitted radiation is limited by the self-absorption of the isotope layer. Increasing the thickness does not increase the radiation output indefinitely. Little increase is obtained for a layer exceeding about one beta or gamma range in thickness. Taking the Sr-Y90 mixture as an example, it has been computed that the maximum power available is approximately 0.4 watts/cm^2. This would correspond to a layer about 2.5 mm thick. For Co60 the available power is about 1000 times greater, because of the greater density, the shorter half life and, most important, the smaller absorption coefficient. However, this would require a layer about 12 cm thick. The cost of a limiting layer of either Sr-Y90 or Co60 would be prohibitive at the present time.

Another topic connected with the type of radiation is that of shielding. With any converter it is important that the radiation level it produces in its vicinity does not exceed the tolerance value for health protection of personnel, or for radiation damage to any other organisms or materials. The shielding requirements, therefore, depend upon the nature of the radiation. For alpha or beta radiation the solution is not as difficult as with gamma rays. The former may be absorbed by a few millimeters thickness of almost any common solid. There is, however, some production of bremsstrahlung (about 1 per cent of the energy), and frequently some gamma radiation due to impurities, and additional shielding is necessary because of these. However, for low-energy radiation such as probably eventually will be used, the problem is not serious.

In the case of gamma radiation the difficulties are more serious because of the greater penetration. The absorption is exponential, and thus there is no maximum range as with beta particles. As an example, 2 mev gamma radiation will be reduced in intensity by a factor of 10 for each 5 cms of lead shielding. Thus for intense sources the shielding required is prohibitive except possibly for large, stationary devices, which might eventually be developed. It is only the soft gamma rays that appear to be of possible practical interest now for example, below 0.1 mev, a thickness of only 0.025 cms is required to yield a ten-fold reduction in intensity.

Methods of Conversion

The processes of direct conversion, may be classified into four categories:

(1) Direct charging methods. These are usable only with charged radiation and involve the simple collection of charged carriers by an electrode to create a voltage.

(2) Contact potential methods. These may utilize both types of radiation, and operate by using contact potential fields to separate charges and produce currents.

(3) Thermocouple methods. Either type of radiation is used to generate heat by simple absorption. The heat is used to activate thermojunctions.

(4) Semiconductor junction methods. Carriers are formed within the semiconductor by either type of radiation, and separated by the internal junction field.

This classification is not exclusive and other methods are possible but it does include most of the methods which have been explored up to the present time.

Some of the principles involved in the direct charging method go back to the early days of radioactivity. The Curies[6] appear to have

[6]Curie, P. and Curie, M. P., "Sur la Charge Electrique des Rayous Deviable du Radium," *Comptes Rendus*, Vol. 130, p. 647 (1900).

been the first to have detected a voltage by a direct charging method. This work was done in 1900. However, the Curie device was not a power generator which supplied useful energy to a load circuit. Their interest was in studying properties of radioactive materials and radiation, and in particular in demonstrating that one of the components of radium radiation carried a negative charge. In 1903, R. J. Strutt[7] in England performed a direct charging experiment, in which he enclosed radium in a thin-walled glass container and was thus able to charge a gold leaf electroscope. In 1913, a more ambitious attempt was made in England by H. G. J. Mosley[8]. His apparatus was basically similar to Strutt's. Using 20 millicuries of radon he reported potentials near 150,000 volts. The voltage was limited by insulation breakdown. None of these workers, however, was interested in power generation nor were their devices suitable for that purpose.

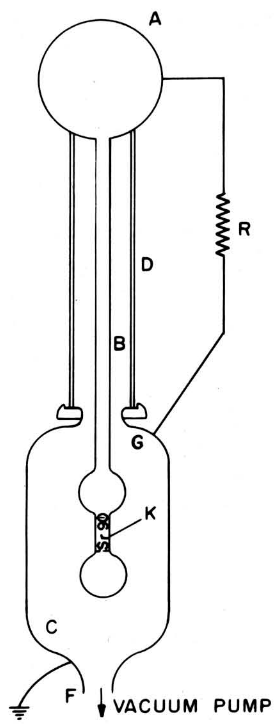

Fig. 2 - Schematic diagram of high-voltage direct charging.

[7] Strutt, R. J., "An Experiment to Exhibit the Loss of Negative Electricity by Radium", *Phil. Mag.*, Vol. 6, p. 588 (1903).

[8] Moseley, H. G. J., "The Attainment of High Potentials by the Use of Radium", *Proc. Roy, Soc.*, Vol. A88, p. 471 (1913).

The first RCA work in this field with which the authors were associated was started immediately after World War II, and was aimed specifically at power generation. This early research was done by Linder and Christian[9] and was published in several papers in 1947 and 1948. A sketch of the apparatus is shown in Fig. 2. The radioactive material which was Sr-Y90 was contained in electrode K. This was connected by a supporting shaft B to the high-voltage terminal A. K was surrounded by a collector C. The high-voltage insulator D, separated and insulated the two terminals A and C. The collector C was evacuated so that negatively charged beta rays or electrons passed from K to C leaving a positive charge on K and charging C negatively. This type of device is essentially a self-charging condenser. Using one-fourth of a curie of radioactive material, a voltage of about 365,000 volts was generated. The power produced was 0.2 milliwatts at an efficiency of 20 per cent.

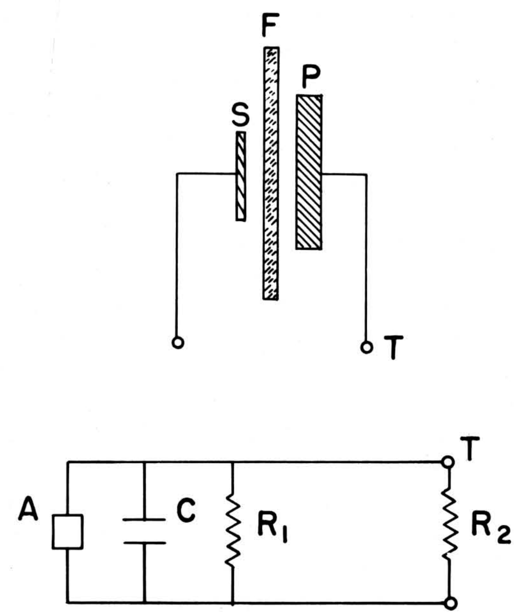

Fig. 3 - Dielectric-type direct-charging device and equivalent circuit.

This is a comparatively high efficiency, but unfortunately the characteristics of this particular device did not lie in a range prac-

[9] Linder, E. G., "Nuclear Electrostatic Generator", *Phys. Rev.*, Vol. 71, p. 129, (1947). Linder, E. G., and Christian, S.M., "The Use of Radioactive Material for the Generation of High Voltage", *J. Appl. Phys.*, Vol. 23, p. 1213 (1952).

tical for wide application. The available current was only about 10^{-9} amperes, and the impedance was about 10^{14} ohms. However, it is possible for the current to be increased and the impedance decreased by using larger amounts of radioactive material. The limitations on this are largely economic at the present time.

Fig. 3 shows a second type of direct charging device. RCA work on this began about in 1950 and was first published in 1953. These papers were by P. Rappaport and E. G. Linder[10]. Recently further work on this method has been published by J. H. Coleman[11]. The device consists of three principle parts; a radioactive source S, a dielectric film F, and a metal collector P. A unidirectional flow of current takes place through F which is thin enough to pass beta particles but acts as an insulator for other forms of current. This is perhaps the simplest type of direct charging device but it is subject to the same limitations as the first type. It can produce several thousand volts but the current and the impedance depend upon the amount of radioactive material used, in fact all direct charging methods suffer this same limitation. They should become more feasible commercially as fission products become cheaper and more plentiful.

The second conversion method to be discussed is the contact potential method. The principle involved here goes back to 1897, when Lord Kelvin[12], only a year after the discovery of radioactivity by Becquerel, used the radiation from uranium to ionize the air between two plates of dissimilar metals and reported that he had observed a potential between them of up to 1.9 volts. However, there is no indication that he considered his device to be a power generator. He was interested in the properties of uranium and his paper was entitled "Experiments on the Electrical Properties of Uranium". More recently work in this field has been done by J. V. Kramer[13], who published in 1924, and still more recently by P. F. Ohmart[14], and also by A. Thomas and J. Petrocchi[15], who are carrying on investigations of this method at the present time.

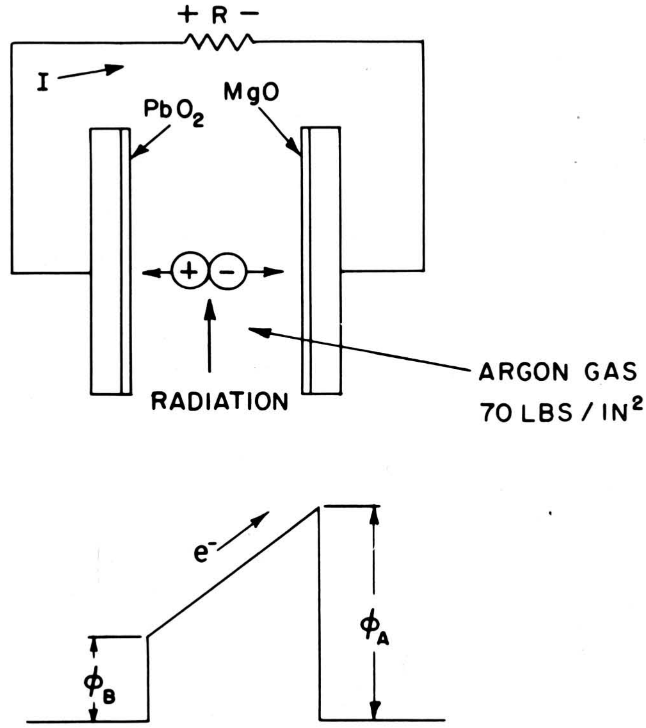

Fig. 4 - Contact-potential device.

The basic principle is illustrated in Fig. 4. Here are shown two electrodes of dissimilar metals between which there is enclosed an atmosphere of gas, for example argon. Radiation of any type having sufficient energy to ionize the gas will produce carrier pairs. These will be acted upon by the field due to the contact potential difference of the metal surfaces, the positive ions flowing in one direction and the negative electrons in the opposite. This produces an electric current which may pass through an external load R, and thereby do useful work. This particular device has an especially low efficiency due mainly to the low absorption co-

[10] Linder, E. G. and Rappaport, P., "Radioactive Charging Through a Dielectric Medium", *Phys. Rev.*, Vol. 91, p. 202 (1953); also Rappaport, P. and Linder, E. G., "Radioactive Charging Effect With a Dielectric Medium," *J. Appl. Phys.*, Vol. 24, p. 1110 (1953).

[11] Coleman, J. H., "Radioisotopic High-Potential Low-Current Sources," *Nucleonics*, Vol. 11, p. 42, (1953).

[12] Kelvin, Lord, "Experiments on the Electrical Properties of Uranium", *Edinb. Roy. Soc. Proc.*, Vol. 21, p. 417 (1897); also Mattr. and Phy. Papers, Vol. 6, p. 84 (1911).

[13] Kramer, J. V., "A New Electronic Battery", *The Electrician*, Vol. 93, p. 497 (1924).

[14] Ohmart, P. F., "A Method of Producing an Electric Current from Radioactivity", *J. Appl. Phys.*, Vol. 22, p. 1504 (1951).

[15] Thomas, A., "Nuclear Batteries", Annual Battery Research and Development Conference, Asbury Park, N. J., May 26, 1954.

efficient of gases for radioactive radiation, and the high ionization energy for gases (about 30 ev) as compared to semiconductors (about 3 ev) to be discussed later. However, the efficiency may be somewhat improved by using low-energy radiation or gas under pressure.

The third or thermocouple method converts radiant energy directly to heat and this in turn to electricity by means of the thermoelectric effect. If the absorption of the radiation is complete, and in practice it could be made nearly so, the efficiency of the method would be that of the thermojunction. Since the efficiency increases with junction temperature difference it will in general be low for low power inputs. A thermocouple device of this type using polonium 210 has been studied by K. C. Jordan and J. H. Birden[16]. With 57 and 146 curies the electrical power delivered to a load was respectively 0.1 and 0.2 per cent of the power developed as heat. The maximum power delivered was 1.8 and 9.4 milliwatts respectively. Using solar radiation, efficiencies of about 1.0 per cent have been attained, and by using concentrating reflectors or lenses it is estimated that an efficiency of about 5 per cent would be possible[17].

The thermocouple method is clearly a simple, rugged and long-life process. Furthermore, the application of modern solid state theory and experience towards the improvement of thermocouples would likely prove to be profitable. It appears that this method is worthy of further study.

The fourth or semiconductor method is one in which there has been much recent interest. The first work in this field was reported by P. Rappaport in 1954[18]. This method employs a p-n junction of materials such as silicon, or germanium. The device may be energized by radiation of either the charged or uncharged type. By a simple process utilizing the internal electric field of the junction the radiation energy is converted directly into electrical energy. When electromagnetic radiation is used the process is called the photovoltaic effect, and when electrons are used it is termed the electron voltaic effect.

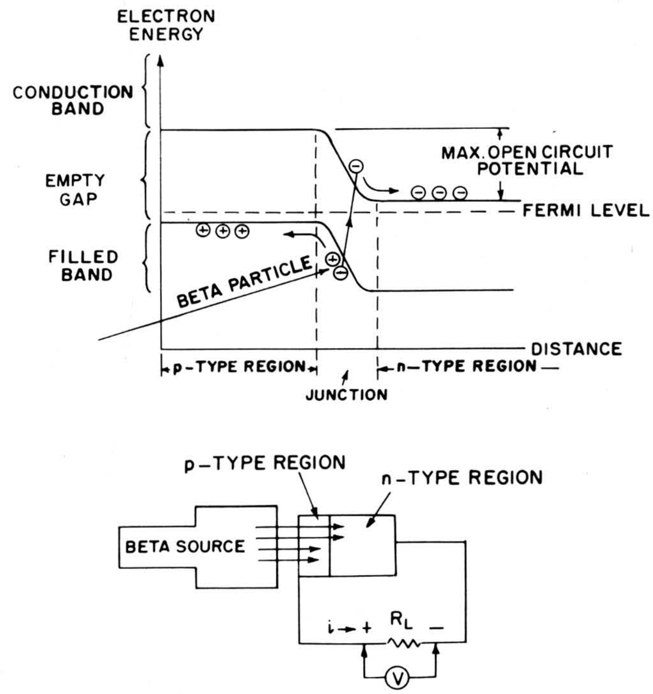

Fig. 5 - Energy level diagram for a p-n junction (above); schematic arrangement (below).

The details of a typical device are shown schematically in Fig. 5. The junction, itself, may consist of silicon, for example, with p-type on the left and n-type on the right. A lead is connected to each of these regions by means of an ohmic contact. These leads in turn are connected to a load resistance R. To the left of the junction is shown a source of any type of ionizing radiation.

At the top of the figure the internal conversion process is illustrated. Here are shown the energy levels in the p-region, and n-region, and in the intermediate region, in which the junction occurs. Each of these regions contains a filled band, a forbidden band or empty gap and a conduction band. As shown, there is an internal electric field in the region of the junction. Incident ionizing radiation creates

[16] Jordan, K. C. and Birden, J. H., "Thermal Batteries Using Polonium-210", Mound Laboratory Report MLM-984, Oct. 1954.

[17] Telkes, Maria, "Future Uses of Solar Energy", presented at the Conference on Atomic Energy in Industry of the National Industrial Conference Board, Inc., New York, N. Y., Oct. 1954.

[18] Rappaport, P., "The Electron-Voltaic Effect in p-n Junctions Induced by Beta-Particle Bombardment", *Phys. Rev.*, Vol. 93, p. 246 (1954). A more detailed paper will appear soon. See also Pfann, W. G., and van Roosbroeck, W., "Radioactive and Photoelectric p-n Junction Power Sources", *J. Appl. Phys.*, Vol. 25, p. 1422, (1954).

free carrier pairs, the electrons being raised into the conduction band, and the holes remaining in the filled band. These carrier pairs diffuse to the junction region where they are acted upon by the electric field in the junction, so that the electrons move to the right and the positively charged holes to the left. Thus an electric current is created due to the motion of these charged particles. This current then may flow into an external circuit and do useful work.

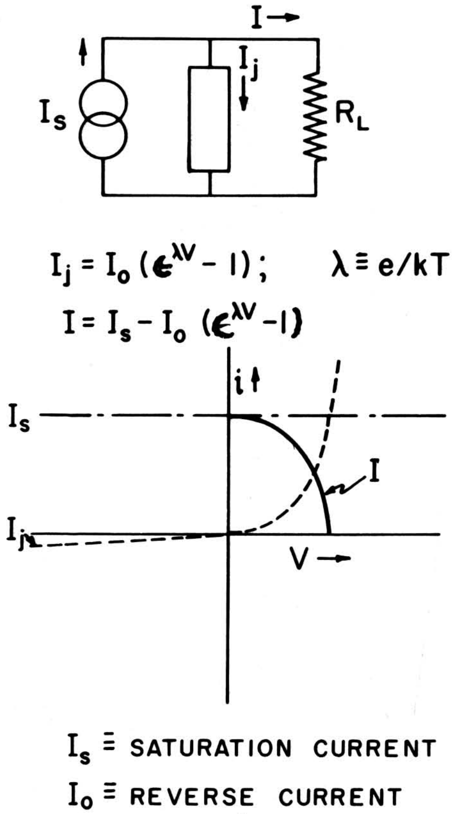

Fig. 6 - Equivalent circuit and current-voltage curve for semiconductor converter.

Fig. 6 shows an equivalent circuit for this type of device. The short circuit current I_s produced by the bombarding radiation is shown as generated by the current generator on the left. This current divides into two parts; the first of which I_j flows back through the junction as shown, and the second I flows through the load to do useful work.

The total current I_s produced by the absorbed radiation, that is, the saturation current, is given by

$$I_s = eGL, \qquad (1)$$

where e is the electronic charge, G is the rate of generation in carriers per second, and L is the diffusion length.

The expression for the current I_j which flows back through the junction is one well-known in rectifier theory[19], and may be written

$$I_j = I_o(\varepsilon^{\frac{Ve}{kT}} - 1). \qquad (2)$$

The net current through the external load is therefore

$$I = I_s - I_j = eGL - I_o(\varepsilon^{\frac{Ve}{kT}} - 1). \qquad (3)$$

From these equations a formula for efficiency can be derived, and it can be reduced to the approximate expression:

$$\eta \approx \frac{kT}{e}\frac{m}{V_I} \ln \frac{I_s}{I_o}, \qquad (4)$$

where $m = I_s/I_I$, V_I is the average incoming particle voltage, and I_I is the bombarding current. The approximation is valid only for

$$\ln \frac{I_s}{I_o} > 10.$$

The current-voltage characteristic as represented by these equations is shown at the bottom of Fig. 6. Since this is not a straight line as in an ohmic device it can be seen that the internal resistance of such a generator is a function of the current drawn from it. Experimental current-voltage curves are shown in Fig. 7. The output voltage is plotted vertically and the current generated horizontally. The different curves are for three different silicon units.

The geometry of such devices is important to the efficient use of the emitted radiation. This is true, of course, in the case of any device utilizing such radiation. Radiation from radioactive material is emitted in all directions. It cannot be reflected or refracted, and thus focused, beamed or concentrated, by any known practical method. Hence, for the sake of efficiency, energy converting devices must be designed to intercept as nearly as possible through a solid angle of 4π steradians. Furthermore, in the case of the p-n junction

[19] Wagner, C., "Zur Theorie der Gleichrichterwirkung", *Phys. Zeits.*, Vol. 32, p. 641 (1931).

type of device it is important that the radiation be as intense as possible since the efficiency increases with increasing radiation intensity. This may be seen from Eq. (4), since I_S is proportional to radiation density. A practical type of design incorporating these features is shown in Fig. 8, where a layer of radioactive material is sandwiched between two p-n junctions as shown.

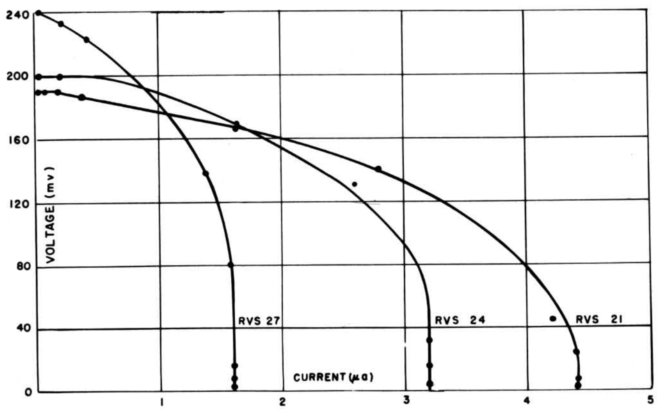

Fig. 7 - Experimental current-voltage curves for silicon p-n junction converters.

A further geometrical requirement for good efficiency is that the diffusion length of the carriers in the semiconductor, the thickness of the semiconductor, and the depth of penetration of the radiation all be of the same magnitude. This insures that the radiation will be completely absorbed and that the maximum number of produced carriers will reach the junction. This requirement becomes impractical for high-energy uncharged radiation, and is one of the reasons why this method is best suited to charged types or soft electromagnetic radiation.

The semiconductor type of device has an important characteristic which enables it to overcome two disadvantages associated with the direct charging types of devices, namely small current and high internal impedance, as was pointed out previously. These disadvantages are overcome by high current multiplication in the semiconductor. In other words, each Sr-Y90 beta particle that penetrates silicon, for example, will produce on the average about 200,000 new electrons. This high electron multiplication increases the output current by a similar factor and reduces the internal impedance by the same factor. Because of these changes in current and impedance this type of device has characteristics which are in a practical range for the operation of electronic equipment, especially transistorized equipment. With practical amounts of radioactive material it is possible to design small power units, with sufficient current and a suitable impedance for operating equipment of this type.

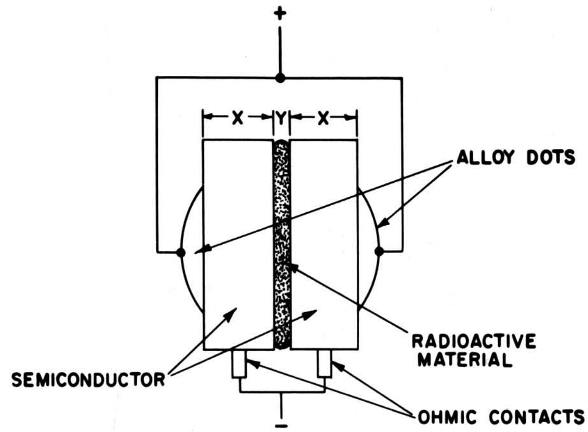

Fig. 8 - Double junction arrangement for the efficient use of radioactive emission.

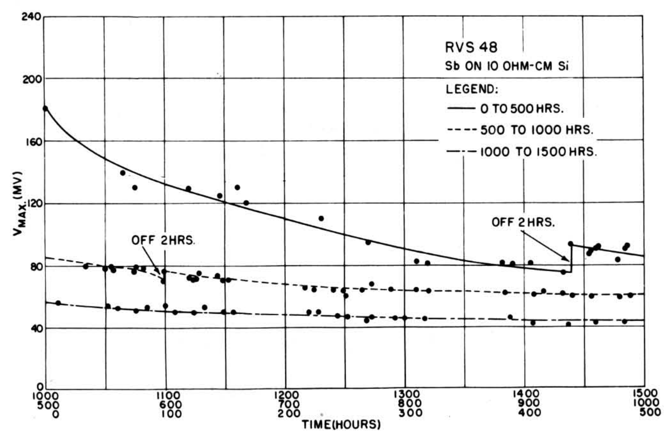

Fig. 9 - Life test of silicon converter showing decay of open-circuit voltage with operating time.

On the other hand, this semiconductor type of converter is subject to a significant amount of semiconductor radiation damage, when it is used with radioactive material of certain types. If the incident radiation is sufficiently energetic it may damage the structure of the crystal by knocking atoms out of their equilibrium lattice positions, that is, by the production of Frenkel defects. This results in a deterioration of the device so that there is a decrease in efficiency and output. An example of this is shown in Fig. 9 which shows the results

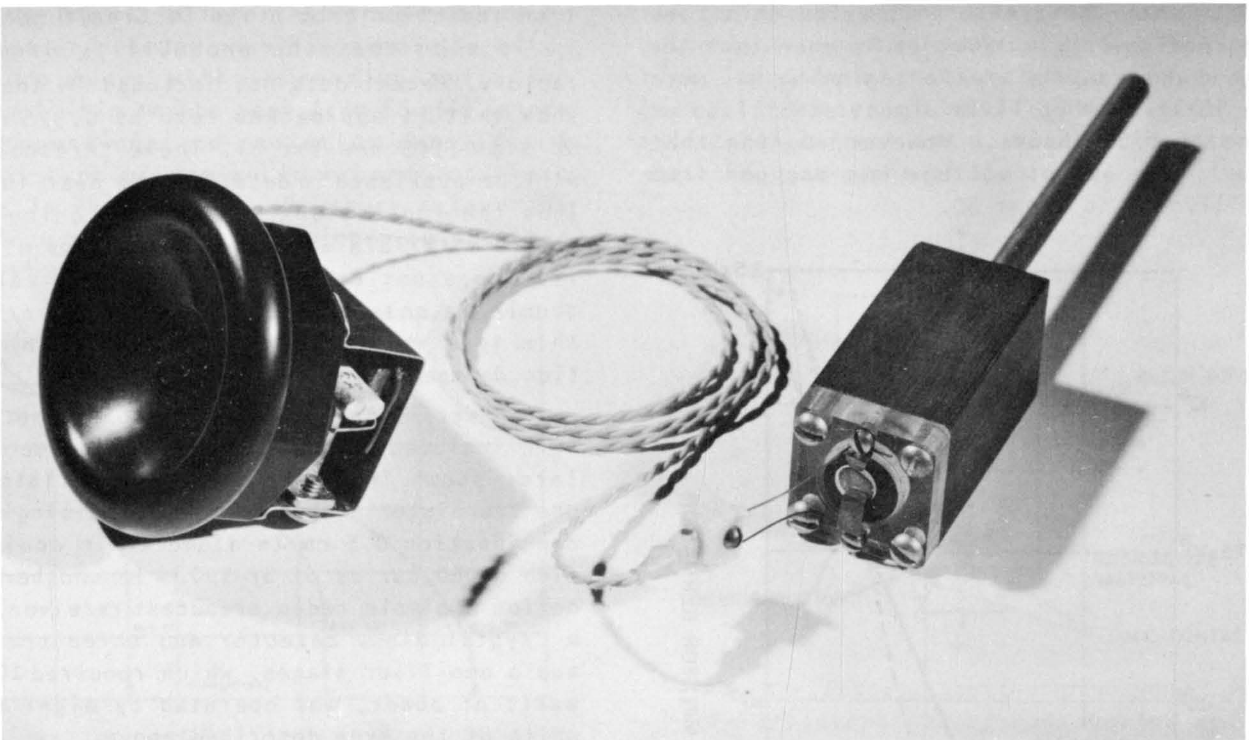

Fig. 11 - Experimental transistorized audio oscillator (left) powered by radioactive battery (right).

the power requirements are in the sub-microwatt region. In these applications direct charging devices especially of the dielectric film type (see Fig. 3) may come into use in the immediate future. Except for such as these it does not seem likely that this type of device will be of great practical interest until radioactive material becomes cheaper by several orders of magnitude than it is at the present time.

The second method, namely the contact potential one, uses both types of radiation provided that the quantum energy exceeds that required to produce ion pairs in gases, which is about 30 ev in general. Devices of this type produce a fraction of a volt per cell, and about 10^{-9} to 10^{-10} amperes (in models currently being investigated). Hence the current and impedance are not in a very practical range. The cells appear to be quite sensitive to the surface condition of the electrodes. No data appear to have been published regarding possible radiation damage to these surfaces. The power conversion efficiency of this method is severely limited by the high energy cost per carrier pair produced. Possible present applications are the same as those mentioned for the direct charging method.

The third or thermocouple method, depends upon the development of heat and therefore is able to use all types of radiation. The devices are rugged, compact and of long life. Their only disadvantage appears to be their low power conversion efficiency. If further research could multiply this by a factor of ten or more, the thermocouple method would likely move into the practical realm.

The semiconductor method has attracted more attention than any of the others. It can be used to convert the energy of both types of radiation, including visible light, and is the basis of the so-called "atomic batteries" and "solar batteries". With silicon, which is the best material found thus far, outputs of about one-half a volt are obtainable. The current is about 10 microamperes for a 0.3 cm^2 unit when 50 millicuries of Sr-Y90 are used. The best observed efficiency is 3 per cent. However, the current should increase linearly and the efficiency logarithmically with power input according to Eqs. (1) and (4). For example, if 7.5 curies of 100 per cent radioactive Sr-Y90 were used, the power input would be 0.1 $watts/cm^2$ and equivalent to that obtained from sunlight. The computed values are I_s = 5 milliamperes and

η = 6.6 per cent. No experiments have been made with this high a level of radioactive input power, but the comparable experimental figures for solar energy are I_s = 8 milliamperes and η = 5.95 per cent[21]. It should be remembered however, that operation at this level using silicon and Sr-Y90 would result in a very high rate of radiation damage. It would be feasible only if this difficulty were circumvented.

Finally, in regard to all types of power sources using radioactive material, there are several problems yet to be solved before such devices can be considered practical. These are related to:

(1) The high cost of radioactive material,
(2) Radiation shielding,
(3) Radiation damage,
(4) Low efficiency.

In regard to the cost, the more abundant and cheaper beta materials include Sr-Y90 which is $500.00 per curie, and H3 which is $100.00 per curie. The most abundant and cheapest gamma material is Co60, which costs $50.00 per curie. U.S. Atomic Energy Commission facilities for the production of these materials are being enlarged, but vast reductions in cost will be necessary before practical applications will be possible for any power range greater than a few microwatts.

As pointed out above, the shielding requirements for Sr-Y90 are such that small-sized sources are not possible if the external radiation is to be held below the tolerance level. Low-quantum energy radiation seems to be the logical answer.

The solution of the radiation damage problem seems to lie also in the use of low-quantum-energy radiation, so that the damage threshold is not exceeded. Unfortunately, there is not available at the present time an abundant, cheap, long-life material of this sort. In regard to the damage in the case of the semiconductor process, another solution would be the use of a semiconductor material of high atomic weight so that the threshold would be raised.

Although efficiencies of only a few per cent have been achieved thus far (except for the direct-charging, high-voltage device) higher efficiencies are theoretically obtainable by the use of larger quantities of radioactive material, as has been indicated above. And here again the problem of cost and availability arises.

Thus it appears that all the obstacles to a practical larger power source could be solved by the appearance of a radioactive material which was of low cost, had low quantum energy, and a suitable half-life. Among available isotopes nickel-63 meets all these requirements except that of cost. It emits 0.063 mev beta radiation, and has a half-life of 85 years, however the present A.E.C. price is $45.00 per millicurie. It is to be hoped that attention will be given to this and other materials in the same category.

Until this ideal radioactive material is available it appears that commercial radioactive power sources can be considered only for microwatt applications. These might include radiation meters, dosimeters, condenser chargers and leakage compensators, timing circuits, current and voltage reference sources, biasing units, simple transistorized equipment, etc. It is to be expected that the practical energy level for commercial applications will gradually rise as the atomic energy industry develops and radioactive material becomes more plentiful. What the ultimate possibilities are for commercial applications at higher power levels can be clarified only by future developments.

Joseph J. Loferski

Paul Rappaport

E. G. Linder

[21] Pearson, G. L., "The Bell Solar Battery", presented at the Conference on Atomic Energy in Industry of the National Industrial Conference Board, Inc., New York, N. Y., Oct. 1954. However, in a recent newspaper account an efficiency of 11 per cent was reported.