Atomic Energy of Canada Limited

A PERSPECTIVE ON DIRECT CONVERSION

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Chalk River, Ontario

October, 1963

AECL-1852

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Paper presented at the Canadian Electronics
Conference in Toronto, Ontario,
September 30 - October 2, 1963

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Abstract

As flowing energy, electricity is sought for its versatility. Its generation from some other flow or release of energy without mechanical power, or even sometimes heat, as intermediary is called direct conversion. The objective is high electrical output for minimum total cost and not always high conversion efficiency. The wide range of techniques embracing cryogenics and hot plasma derives from the special requirements of source, environment and application. Sources include solar and other radiation, nuclear fission and fusion, chemical energy and heat. Environments and applications range from space vehicles to submarines and from giant power networks to isolated buoys and pocket devices.

A PERSPECTIVE ON DIRECT CONVERSION

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1. Energy Stores and Flows

The generation of electricity without the intermediary of a machine or mechanical engine is known as "Direct Conversion". The energy must come from some store or flowing stream. The large energy reserves the world possesses may be classed as chemical and nuclear. In addition, the earth receives a nearly constant stream of energy from the sun, some of which becomes stored as chemical energy for a long time as in forests, agricultural and marine crops and their residues, coal, oil and natural gas. Some solar energy becomes stored for a shorter time as water raised against gravity to lakes and rivers.

Table 1

WORLD ENERGY FLOW

	Millions of kilowatts	
Solar radiation	1.7×10^8	on day hemisphere
	3.5	per sq. mile (projected area)
Heat flow from interior of the earth	25,000	continuously
World consumption of		
coal (1960)	2,000	thermal
petroleum (1960)	1,500	thermal
electricity (1960)	260	electrical
Canadian water power developed capacity (1961)	20	electrical
Nuclear Fission 1 tonne per year	2.6	thermal

Table 1 reminds us of the magnitudes involved in the principal flows of energy in the world. These rates are shown in millions of kilowatts, and to appreciate the scale, it may be noted that the generating capacity of

Canadian harnessed water power passed the 20 MkW mark in 1961. From the figure of 260 MkW for the world total, it might seem that Canadian water power was nearly 8% of the world total, but that is not so because the 260 MkW figure is the average reported consumption and corresponds to only about 50% of the total generating capacity. Much of the world's electricity is produced by burning coal and oil at 30 to 40% conversion efficiency, but that represents only a small though significant fraction of the total consumption of coal and oil that includes heating buildings and industrial processes such as iron and steel, chemicals and transportation. At the top of the table the heat from the sun may seem large, but considering that it would be necessary to trap all the energy from a square mile to obtain 3.5 MkW, by comparison our giant generating stations using water power, coal, oil or nuclear fission energy set a high standard for compactness, simplicity and efficiency. The world is increasing its rate of energy consumption, and resources appear very adequate. It is to be noted that an increasing fraction is taken in the form of electricity because that is a versatile form of energy easily and efficiently applied for mechanical and other forms of work.

2. Objectives for Direct Conversion

In the context of "Direct Conversion" we must, however, note that electricity has limitations. The lowest cost electricity comes from giant generating stations via transmission and distribution networks. For many uses this is excellent, and our remaining desire is to increase the amount and lower the cost. The cost of conversion from the energy store could in principle be reduced by a suitable combination of increased efficiency and reduced capital cost. Some studies of direct conversion are directed to this combined objective of high efficiency and low capital cost. There are also, however, other objectives for direct conversion. For example, electric power may be needed in an aircraft or space vehicle where connection to a transmission line is out of the question and the weight or mass of the converter must be minimized. As another example, a railway locomotive can be envisaged in which fuel cells, directly converting chemical to electrical energy, replace the now customary Diesel engine and electric generator.

In some situations, simplicity and reliability may be the overriding objectives, for example, for an unattended buoy or radio marker beacon. A heat engine, whether based on internal combustion as in the Diesel or in the gas turbine, or externally fired as in the steam engine, coupled to an electric generator is somewhat complex, although now engineered to a very high degree of reliability for unattended operation. In comparison, a thermoelectric generator, which is a static direct converter requiring only a heat source in the form of a burner or a radioactive source and a heat sink or cooler, could be simpler, reliable, and in some circumstances cheaper, and preferred although it is likely to be less efficient for a fundamental reason that will appear later.

Continuing the discussion of objectives, we should recall the many uses of that well established direct converter of chemical to electrical energy, the primary battery, and its cousin, the secondary or storage battery. Such portable batteries are in widespread use for pocket flashlights, transistor radios, hearing aids, and "cordless" devices from razors to portable drills and cathode ray oscilloscopes. Batteries that are not necessarily portable are used for emergency local lighting and in very many isolated places for minimal electric services such as radios, bells and telephones. Recall also the very many functions performed by the battery on the modern automobile. The unit cost of a battery is often low compared with the installation it serves, but the cost per kW hour and the weight-to-power ratio are high (e.g., 40 lb/kWh for a dry battery or 100 lb/kWh for a secondary battery (NiFe) cfd 0.7 lb coal/kWh in a large steam plant). There is accordingly an objective for direct conversion devices to achieve lower cost and weight-to-power ratios than those of existing primary and secondary batteries for any of their many uses.

Although these considerations about batteries may seem obvious, it should not be forgotten that they may point to a very considerable change in our ways of life and communications. Not long ago the portable radio was rather massive, and where electric supplies were available, the A.C. models were preferred; now the transistor has changed the pattern. Today relatively few people carry portable telephones on their persons or electric motor scooters in their cars. Other less common needs suggest an ever-widening range of battery-operated devices.

There would be uses for simple and efficient fuel cells or other direct conversion devices for many types of mobile vehicle, such as boats, farm tractors and delivery vehicles even if no device captures the main uses of the internal combustion engine. Objectives for development, besides high power, low cost and low weight-to-power ratio, include freedom from noxious exhausts.

Customarily an efficiency of about 40% is obtained from large thermal generating stations using steam. This low efficiency is attributable to the large fraction of the energy that enters the steam cycle at a temperature set by the pressure at which the water evaporates to steam. For example, at 100 atmospheres (1470 psi) this is (593.5°F) (312.1°C) 585.3°K, and for exhaust at 25 Torr (1" Hg)(79.03°F)

(26.1°C) 299.3°K the Carnot cycle, or maximum efficiency is 48.86%, and a practical efficiency would be 38%. Since the temperature of the burner flame or nuclear fuel is considerably higher, there is an incentive to obtain more energy from above the water evaporation temperature (i.e., > 585°K). Various magneto-hydrodynamic and thermionic systems have been proposed for direct energy conversion in this high temperature range. Except in nuclear reactors where the heat transfer fluid is often kept clean and recycled, there is nothing very new about somewhat higher temperatures being available. What has held back their exploitation in the past and still does, is the limited life of strong solid materials when exposed to steam or any of the other working substances that have been explored, such as mercury. The magneto-hydrodynamic and thermionic systems seek to use materials that will be compatible for a longer life. The problems are not simple, for although many materials are strong, hard and long-lived at our familiar room temperatures, they become plastic and subject to atomic interdiffusion at red heat (500-800°C) and higher temperatures.

The high temperature region must, however, be mastered for significant long-term power generation in space vehicles, because from any heat engine the waste heat must be removed, and for long term operation in space this must be by radiation. A massive radiator would be required if the temperature were not high. The heat engine in the space vehicle must have its low temperature in the radiating range at or above red heat (e.g., 5.7 W/cm^2 for T = 1000°K). Thermionic devices are well suited for such conditions.

3. Fundamentals of Energy Degradation

Having taken these glimpses at applications and objectives, we may shift our perspective to review some fundamental aspects of the energy degradation process. On the energy scale, 1 electron volt corresponds to a temperature of 1.16 x 10^4 °K by the relation eV = kT. Now in nuclear fission the two fragments recoil from each other in opposite directions sharing an energy of about 160 MeV. The lighter fragment may take about 100 MeV or 10^{12} °K. To convert any high fraction of this energy directly would involve putting the fission fragment to work against extremely high electromagnetic fields in a high vacuum. The rapid interaction of a fission fragment with matter degrades the energy rapidly, and the high density of matter required in a nuclear reactor makes any such direct attack impractical. But, typically, a large fraction of the energy of such high energy particles or ionizing radiations appears as electrons or ions having energies in the range, say, of 0.2 to 5 eV, i.e., at temperatures 2000°K to 50,000°K from which energy could still be extracted at high efficiency. Designers attacking the problem usually find themselves resorting to the conversion of as much energy as possible before the energy has been degraded to, say, 1000 - 2000°K, beyond which point a heat engine works with the residual heat at 40 to 50% efficiency. The energy derived from the direct conversion of radiation energy is therefore to be regarded as a bonus taken at 100% conversion efficiency before the residue is converted conventionally at 40 to 50%. A bonus of 5 to 10% of the total would be worth the complication if the extra capital and maintenance costs are not too large.

Some of the processes of converting radiation energy to another form of radiation are quite efficient. Typically, for example, organic scintillating materials comprising benzene ring organic compounds can convert about 25% of radiation to light of quantum energy of 0.2 eV. In the process, however, there is some destruction of the scintillating material by radiolysis, the apparent efficiency drops, and repurification becomes necessary to restore the light output.

For the direct conversion of the energy of free ions and electrons to electricity, two lines of development - generally known as the thermionic and the magneto-hydrodynamic systems - have become prominent.

4. Thermionic Converters

Some of the difficulties of obtaining long life and reasonable efficiency from a thermionic converter will appear if we review the several parts and their functions. There must be the thermionic emitter at a high temperature, say, 2300°K, so that sufficient electrons have enough energy to surmount both the work function and some space charge. If the emitter were a black body, it would radiate 160 W/cm^2 at 2300°K so some surrounding radiation reflector is desirable to act as a heat baffle to reduce this loss. There must be a collector which must be at a considerably lower temperature if there is to be much energy conversion and any significant efficiency. The true work function of the collector (i.e., the potential difference between a free electron at the surface and the Fermi level) may with advantage be low. Since the e.m.f. that will be developed is perhaps less than 2 volts, the current density we are seeking must be at least several amperes/cm^2 to compete with the heat loss by radiation. Such currents can only be obtained across very small gaps unless the electron space charge is neutralized by forming a plasma with a thermally ionized material which at these temperatures means caesium. One advantage follows that caesium will condense on the collector because it is the cold spot in the system. The condensed caesium will lower the work function. The temperature of the emitter must be sufficient to keep the caesium vapour ionized. There must be insulators to enclose the vapour between the electrodes and keep out air. If the insulators are cooled, there will be more loss of heat, and if allowed to get hot, they are liable to contaminate the vapour with unwanted atoms of carbon, oxygen, etc. To prolong the life, a reserve of caesium and relatively cool surface may be maintained in another chamber connecting with the diode. The problems of the thermionic plasma diode are compounded when it is desired to use as emitter a nuclear fuel such as uranium carbide in a reactor and to form the heat baffles and collector from materials that will not capture too many neutrons and yet have an adequate life at a temperature sufficient to maintain the caesium vapour pressure.

By drawing attention to these features, I am not intending to suggest that useful thermionic converters cannot be made: rather, I suggest that great respect should be accorded to working devices even if their lives and efficiencies do not appear great.

5. Magneto-hydrodynamic Converters

The first problem of a magneto-hydrodynamic converter is to obtain sufficient conductivity in the working gas. At lower temperatures ionization of the desired concentration is rapidly lost by recombination, and most work has therefore considered higher temperatures above 2000°K where a gas seeded with caesium or potassium has sufficient conductivity. It does not seem very practical to heat a gas to such a high temperature by contact with a solid at still higher temperature, so consideration falls on achieving the high temperature by some form of combustion or radiation energy release within the working gas. It is also customary to accept that the gas will lose heat to the walls of the MHD chamber so the walls may be cooled by a fluid that takes part in the subsequent lower temperature working cycle. The gas volume to surface ratio is much higher than in thermionic devices, and the walls may be cooler. Accepting these principles, the MHD generator offers a large output at a conveniently high voltage of many hundreds or even thousands of volts from a relatively simple channel. To be economic, however, it must be a high power device contributing not less than about 100 eMW to the output of perhaps a 400 eMW plant. The problems lie in achieving the high temperature or at least the ionization density required while preserving a reasonably long life for the components of the system.

6. Thermo-electric Converters

Thermo-electric converters deserve some special mention. Fig. 1 shows the basic form. The dissimilar metals of the familiar thermocouple are replaced by blocks or wafers of p and n type semiconductor, connected by low resistance contacts between conductors, one at T_1 receiving heat from a source, and the other at T_2 cooled by a heat sink. As in the case of the thermionic converter, the efficiency is severely limited by the direct heat loss from the source to the sink, in this case via the thermal conductivity K of the semiconductor. It has become customary to assess thermo-electric properties of materials in terms of a figure of merit $X = S^2T/K\rho$ where S is the thermo-electric power or Seebeck coefficient at temperature T and ρ is the specific resistance. For most materials $X < 1$. Fig. 2 illustrates the theoretical efficiency as limited by X of a typical system where $T_1 = 2T_2$ so that the efficiency of the Carnot or reversible cycle would be 0.5.

At high temperatures intrinsic conductivity overrides the p and n type conductivity so the efficiency falls. Thermo-electric conversion is therefore not well suited to be a high temperature "topping" device by which a bonus of power is taken above the temperature of the main converter. As we have suggested, thermo-electric converters seem likely to find their main use where simple and reliable small power sources are required. For these uses long life may be important and will limit the top temperature where it becomes difficult to maintain a good low resistance contact and where the properties of the semiconductor change due to atomic diffusion. Because of its low ratio of thermal to electrical conductivity, lead telluride PbTe has been developed, but the top temperature that will be practicable for long life seems likely to be nearer 300°C than 600°C. For higher temperatures other heavy element alloys and oxide semiconductors have been suggested but do not remove the limits set by atomic diffusion on the life of low resistance contacts.

The thermo-electric converter appears most promising as a low weight (7 to 15 watts/lb) converter if not pushed to the limit of temperature or maximum efficiency. The cost lies in the range \$3000 to \$1000/kW using PbTe at about 0.5 W/cm^2, and 3 to 4% efficiency.

7. Fuel Cells

Several objectives were seen for fuel cells. One attraction is high efficiency potentially in the range 60 - 70%. The fuel cell is usually characterized as taking a continuous feed of fuel in the form of oxygen and hydrogen, or oxygen and a fuel oil or natural gas. To obtain a sufficiently rapid chemical action, the temperature has to be raised (e.g., 200°C) requiring some special procedure for starting from cold. A cell has been proposed for natural gas that operates at much higher temperature and burns the supply gas to raise the temperature initially. Many different types of fuel cell are under development throughout the world. Most encounter problems from the progressive accumulation of impurities from the fuel that reduces output and efficiency.

8. Photo-voltaic Converters

Generally on the small scale of tens or hundreds of watts photo-voltaic converters deserve mention. Perhaps their special field of utility is to charge storage batteries from sunlight in isolated locations and in space satellites. In principle, they consist of a thin layer of semiconductor formed on the surface of a semiconductor of the opposite type of conductivity, that is to say, p on n, or n on p. They are often termed solar batteries, and for space applications the materials have to be chosen to be resistant to damage by high energy radiations and particles. Efficiencies of 15% or more can be attained.

9. Another Viewpoint

To obtain perspective on direct conversion from a physicist's viewpoint, consider the means available for generating electricity. Electronic or ionic charges may be caused to lose kinetic energy by moving up a static potential gradient. This process can take place within a solid or liquid as in the chemical cell and in certain photo-voltaic cells, or it can take place between electrodes in a plasma or vacuum as in most thermionic generators. In other systems such as the magneto-hydrodynamic generators, streams of charged particles perhaps carried by a gas or liquid can lose their energy as well as energy from the gas or liquid to a combination of electric and magnetic fields. The energy then passes to electrodes or current streams and on to meet the demand.

Electricity may be generated as direct current or alternating even up to the highest radio frequencies. For the latter, devices that are in some respects the inverse of ion accelerators are considered; others are like travelling wave tubes.

10. Conclusion

To conclude, many objectives could be achieved by satisfactory solutions of the engineering of direct conversion devices. It does not, however, seem likely that these will take over from established methods of generation, but will be applied to more limited although numerous situations where the versatility of electricity is attractive. The most difficult problems appear to lie in achieving long life at high temperatures where atoms are mobile.

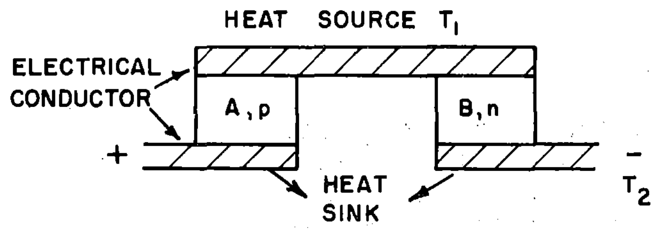
HEAT SOURCE T1
ELECTRICAL CONDUCTOR
A, p
B, n
+
-
HEAT SINK
T2

FIG. 1

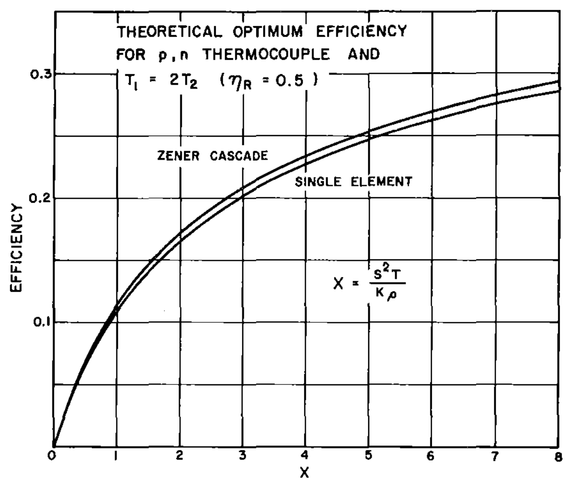
THEORETICAL OPTIMUM EFFICIENCY FOR p, n THERMOCOUPLE AND T1 = 2T2 (ηR = 0.5)
ZENER CASCADE
SINGLE ELEMENT
X = S²T / Kρ
EFFICIENCY
0.1
0.2
0.3
0
1
2
3
4
5
6
7
8
X

FIG. 2