Energy and physics[1)]

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The culture and civilization of a people depends primarily on the amount of energy at its disposal, and therefore continuous searches are made for new sources of energy. These searches are intimately related to questions of the transformation and conservation of energy. The fundamental laws of physics set definite limits within which these questions can be answered. It is well known that the laws of thermodynamics prevent one making perpetual motion machines of the first and second kind. But there are other restrictions imposed by the laws of physics on the practical use of energy processes. This paper considers a number of processes of energy transformation in which the energy flux density (the Poynting vector) is restricted, which precludes the possibility of using them in practice to obtain high powers. A number of energy sources are discussed as examples—thermal, chemical, biological, and finally, nuclear. The restrictions delineate the most promising directions for searching for new powerful sources of energy.

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It is widely recognized that the main factor determining the development of the material culture of nations is the creation and use of energy sources. The work performed by people now exceeds by many times their muscular work. For example, in the most developed countries the power from different energy sources is up to 10 kilowatt per person and this is at least 100 times greater than the average muscular power of one man.

The role of energy in economics is well illustrated by Fig. 1 (see[1]). Along the abscissa we have the value (per person) of the gross national product of different countries and along the ordinate the energy resources, also per person. Except for the natural fluctuation, it can be seen that there is a simple proportionality between the two. Therefore, if people are deprived of energy resources, their material well-being will undoubtedly fall.

The obtaining, transformation, and conservation of energy are fundamental processes investigated by physics. The main law established by physics is the law of conservation of energy. On the basis of this law a global crisis in the acquisition of energy has been predicted.[1] The main energy resources currently used are peat, coal, petroleum, and natural gas. It has been established that the chemical energy stored in them was accumulated over millennia by biological processes. Statistical data on the use of these resources indicate that in the coming centuries they will be exhausted. Therefore, on the basis of the law of conservation of energy, man, if he does not find other sources of energy, will be faced with the need to limit his requirements, and this will reduce the level of material well-being of mankind.

The inescapability of a global energy crisis is now fully recognized, and therefore, the energy problem for technology and science has become problem number one. In the leading countries, considerable means are now being devoted to the scientific and technical investigations in this region. These searches are generally carried on in a narrow technical approach, without due allowance for the laws established by physics. Life has shown that the effectiveness of investigations is considerably enhanced if they take into account more fully the basic laws of physics. In this communication, I wish to mention the laws of physics that should play a leading role in the solution of the energy problem.

The energy used by people is now divided into two parts. The first is the so-called consumer energy. It directly guarantees the cultural way of life. This energy is used for illumination, to operate refrigerators, televisions, electric razors, vacuum cleaners, and a large number of appliances used in everyday life. The power used in day-to-day living is usually measured in kilowatts. The other form of energy is industrial energy, in which high powers are involved. It is used in

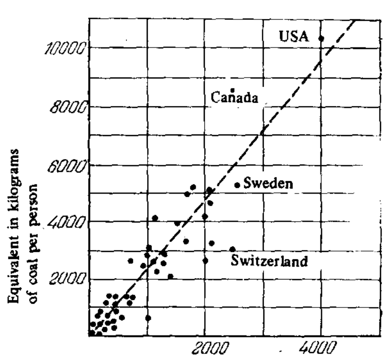

FIG. 1. Energy requirement and gross national product per person. The data refer to 1968 and are based on material of the United Nations Organization and the International Bank for Reconstruction and Development.

[1)]Report at the Scientific Session to mark the 250th Anniversary of the USSR Academy of Sciences on October 8, 1975.

metallurgy, in transport, in mechanical engineering, in mechanization of construction, in agriculture, and in a number of similar fields. This energy is much greater than the consumer energy and is measured in megawatts; its scale and cost determine the level of the gross national product of a country. Of course, the impending crisis will be due to a short fall in the energy resources for only the high-power energy supply, and it is the supply of this energy in sufficient quantity that is the main problem now facing science.

I have already said that the predictions of an impending energy crisis are based on the law of conservation of energy. Of course, another law which also plays a large role in restricting the possible use of energy resources is the law which says that entropy must increase in all energy transformation processes. Both these laws impose a "veto" on the overcoming of the crisis by the creation of perpetual motion machines. The law of conservation of energy "forbids" a perpetual motion machine of the first kind. Entropy forbids the so-called perpetual motion machine of the second kind. It is interesting to note that this second kind of perpetual motion machine is still being suggested today by inventive engineers and it is frequently difficult to refute them. This question relates to thermodynamics; it has been well studied, and I shall not dwell on it.

I shall restrict my consideration to the laws that govern the development of high-power energy sources and are related to the existence in nature of restrictions on the energy flux density. We shall see that these restrictions are frequently ignored, which leads to losses on projects that are definitely hopeless. This will be the main theme of my report.

All the energy processes of interest to us reduce to the transformation of one form of energy into another, and this takes place subject to the law of conservation of energy. The most widely used forms of energy are electrical, thermal, chemical, mechanical, and the so-called nuclear energy. The transformation of energy can usually be assumed to take place in a certain volume, energy in one form entering the volume through the surface and leaving it in a different form.

The density of the supplied energy is restricted by the physical properties of the medium through which it flows. In a material medium, the power of the energy flux **U** is restricted by the expression

$$\mathbf{U} < vF, \quad (1)$$

where v is the deformation propagation velocity, usually equal to the velocity of sound, F may be any elastic or thermal energy, and **U** is a vector. In stationary processes, div **U** determines the amount of energy transformation into a different form. The vector **U** is very convenient for studying processes of energy transformation. It was first proposed 100 years ago, in 1874, by the Moscow physicist N. A. Umov. Ten years later the same vector for describing electric processes in the electromagnetic field was found by Poynting. In this country we therefore call it the Umov–Poynting vector.

If the expression (1) is used for a gaseous medium, it takes the form

$$\mathbf{U} = AT^{1/2}p, \quad (2)$$

where A is a coefficient which depends on the molecular composition of the gas, T is its temperature, and p the pressure.

An expression of this form, for example, determines the limiting power that a hot medium can transmit to unit surface of the piston of a motor or the blade of a turbine. It can be seen that this power decreases with the pressure, and the same expression therefore determines the limiting altitude at which a turbojet aircraft can fly.

Using the Umov–Poynting vector, one can also describe processes in which the energy is transmitted by a belt drive. In this case, the product of the belt velocity and its elastic stress gives the transmission power. In the same way one can determine the limiting power transmitted by a band in a van de Graaff generator.

I have encountered in practice a technical problem when the flux of electric energy restricted implementation of a device. This occurred under the following instructive circumstances.

In the forties, my teacher A. F. Ioffe was concerned with developing an original construction of an electrostatic generator, which fed a small x-ray instrument. This generator was simple in its construction and worked quite well. Then Ioffe had the idea of replacing, on a large scale, electromagnetic generators by electrostatic generators and transferring to them the entire large electrical energy of the country. The main justification was the fact that the electrostatic generators were not only simpler in their construction but could give directly a high voltage for the transmission lines. At that time I had to demonstrate that this project could not be implemented on the basis of an estimate of the flux density of electrical energy in its transformation into mechanical energy.

Let us determine in accordance with the expression for **U** the flux density of the energy which is transformed from mechanical into electrical energy and vice versa in the gap between the rotor and the stator of the generator. Then v is equal to the rim velocity of the rotor of the generator. For constructional reasons, this velocity is usually taken to be about 100 m/sec. The tangential forces of the interaction between the stator and the rotor in an electromagnetic generator are determined by the energy of the magnetic field, and we therefore have

$$F = \alpha \frac{H^2}{4\pi}. \quad (3)$$

The coefficient α is determined by the construction of the generator and it is characterized by the cosine of the angle formed by the force F with the velocity v. Usually, α has a value equal to a few tenths of unity.

The magnetic field H is determined by the saturation of iron and does not exceed $2 \cdot 10^4$ Oe. When the flux of the electrical energy is transformed into mechanical energy or vice versa, one obtains about one kilowatt per square centimeter. Thus, for a 100-MW generator the rotor must have a working surface of about 10 square meters.

For an electrostatic generator the energy F is

$$F = \alpha \frac{E^2}{4\pi}, \tag{4}$$

where the electrostatic field E is restricted by the dielectric strength of air and does not exceed $3 \cdot 10^4$ V/cm or 100 esu. Therefore, to obtain the same power of 100 MW one requires a rotor with a surface $(H/E)^2 \approx 4 \cdot 10^4$ times greater, i.e., equal to $4 \cdot 10^5$ square meters or half a square kilometer. Thus, a high-power electrostatic generator requires a virtually unrealizable size.

A similar analysis shows that the restriction on the energy flux density means that to obtain high power one must rule out a number of very effective energy transformation processes. For example, in gas elements in which there is a direct transformation of chemical energy of oxidation of hydrogen into electrical energy, the process can already be realized with a high efficiency reaching 70%. However, the possibility of using such elements for high-power generation is restricted by the very low rate of the diffusion processes in electrolytes, and therefore in accordance with the expression (1) its energy density in practice is very small and from a square meter of electrode one can take only 200 watt. For a 100-MW power the working surface of the electrodes reaches a square kilometer and there is no hope that the capital expenditure on the construction of such a power station would be justified by the energy it generates.

Another apparently promising direction in which however one cannot repose any hope is the direct transformation of chemical energy into mechanical energy. It is well known that these processes are widely used in nature in the muscles of animals.

To the embarrassment of biophysicists, these processes are still not understood, though it is well known that their efficiency is very high. Even if these processes are in the course of time reproduced outside animate nature, they will nevertheless be of no use for high-power energy sources since here too the energy density is low; it is restricted by the low rate of the diffusion processes that take place through the membranes or the surface of the muscle fibers, and the rate of the diffusion is here no higher than in electrolytes, so that the energy flux density cannot be greater than in gas elements.

The main interest is now devoted to the methods of generating energy that do not depend on the amount of energy stored in the past in fuel of different forms. The principal possibility is here taken to be the direct transformation of solar energy into electrical and mechanical energy—on a large scale of course. Here again a restriction on the practical implementation of this process for high-power energy comes from the restricted energy density. The optimal calculation now shows that the power taken from one square meter of surface illuminated by the Sun will not exceed 100 W on the average. Therefore, in order to generate 100 MW, it is necessary to take electrical energy from an area of one square kilometer. Not one of the hitherto proposed methods of transformation of solar energy can be implemented in such a way that the capital expenditure could be justified by the resulting energy. For the enterprise to be profitable, it is necessary to reduce the expenditure by several orders of magnitude, and as yet one does not even know ways in which this could be done. Therefore, we must assume that the practical direct use of solar energy on a large scale is unrealistic. But, as before, it does remain possible through its transformation into chemical energy, as has been done since time immemorial with the help of the vegetable world. Of course, the possibility cannot be excluded that in time one will find a photochemical process that opens up the possibility of more effective and simpler transformation of solar energy into chemical energy than takes place at present in nature. Such a process of chemical accumulation would also have the great advantage of making it possible to use solar energy irrespective of the change in its intensity during the course of the day or year.

The possibility is also now discussed of using geothermal energy. It is well known that at various places on the Earth's surface where there is volcanic activity this is done successfully, though on a small scale. The advantage of this method for high-power energy supply is undoubtedly very great; the energy reserves are here inexhaustible, and, in contrast to solar energy, which fluctuates not only diurnally but also with the season and the weather, geothermal energy can be generated continuously. As early as the start of this century the brilliant inventor of the modern steam turbine, Parsons, developed a project for its use. Of course, he could not foresee the scale on which energy is now required and his project has only historical interest.

The modern approach to this problem is based on the fact that at any place on the Earth's crust at a depth of 10–15 kilometers one reaches a temperature of several hundred degrees, which is sufficient to obtain vapor and generate energy with a good efficiency. In the implementation of this project in practice we again come up against the restrictions imposed by the energy flux density. It is well known that the thermal conductivity of rocks is very low and to carry heat to the water which must be heated in sufficient amounts with the small temperature gradients that exist within the Earth it is necessary to do this from very large areas, and at a depth of 10–15 kilometers this is very difficult and it is doubtful whether the necessary amount of water can be heated.

In the West a number of interesting propositions are now being advanced. For example, at this depth one could explode atomic bombs and thus produce either a large cavern or a large number of deeply penetrating cracks. The realization of this project would be very expensive, but in view of the importance of the problem and the great advantages of the geothermal method I believe that, despite these expenditures, one should risk the attempt of this project.

Apart from solar and geothermal energy, with inexhaustible reserves, there is also hydroenergy obtained by damming rivers and exploiting tides. The gravitational energy of the water accumulated in this manner can be very effectively transformed into mechanical energy. Currently, the use of hydroenergy accounts for not more than 5% in the energy balance and, unfortunately, a further increase cannot be expected. This is because the damming of rivers is profitable only in mountainous regions in which there is a large potential energy per unit area of the water reservoir. The damming of rivers when the water level is raised to a small height is usually not justified economically, particularly when this entails flooding fruitful earth since the harvest is usually much more valuable than the energy obtained. Once again the energy density is inadequate. The use of wind is also not justified economically, again because of the insufficient energy flux density. Of course, the use of solar energy, small water streams, and windmills can frequently be useful for everyday needs on a small scale.

But it follows from the above analysis that it does not appear possible to find an economic replacement for the depleted reserves of chemical energy in nature for high-power energy purposes. Obviously, one can and must be more careful about the use of energy resources. For example, it is desirable that they should not be wasted on military requirements. But all this only delays the depletion of the fuel reserves; it does not prevent the crisis.

As is already widely known, all hope for solution of the global energy crisis is based on the use of nuclear energy. Physics gives one every reason to believe that this hope is justified.

Nuclear physics suggests two directions for the solution of the energy problem. The first has already been well developed and is based on using a chain reaction in uranium when its nuclei are split with the liberation of neutrons. This is the same process that takes place in the atomic bomb, but slowed down to a stationary state. Calculations have shown that if it is correctly used there are sufficient reserves of uranium for there to be no danger of their depletion in millennia. Uranium power stations already operate and provide electrical energy at an economic rate. But it is also well known that three fundamental difficulties must be overcome if they are to be further developed and supply the entire energy requirements of a country.

1. Wastes from the decay of uranium are strongly radioactive and their safe storage presents great technical difficulties that have not yet received a generally accepted solution. The best solution would be to dispatch them on rockets into space, but as yet this is thought to be not sufficiently safe.

2. A large atomic power station supplying millions of kilowatts presents a great danger for surrounding nature and, in particular, man. In the case of an accident or sabotage, the radioactivity dispersed could destroy all living organisms over an area of many square kilometers just as effectively as did the atomic bomb on Hiroshima. The danger is now regarded as so great that in the capitalist world not one insurance company is prepared to take the risk on this scale.

3. Wide use of atomic electrical energy also results in the wide dispersal of plutonium, which is a necessary participant in the nuclear reaction. Such dispersal of plutonium over all the countries of the Earth makes it more difficult to control the spread of atomic weapons. This means that the atomic bomb could become a weapon of blackmail for even an enterprising band of gangsters.

Under the threat of the energy crisis people will probably find a way of overcoming these difficulties. For example, the last two difficulties could be overcome by siting atomic power stations on small unpopulated islands in the ocean far from densely populated places. These power stations would be under careful control and the consequences of an accident would not present a great danger for people. The liberated energy could be used, for example, to decompose water and the resulting hydrogen could be transported in liquid form and used as fuel, which does not pollute the atmosphere when it is burnt.

It must however be recognized that the best way out of the dilemma would be to obtain energy by the thermonuclear fusion of the nuclei of deuterium and tritium. It is well known that this process takes place in the hydrogen bomb, but for peaceful use it must be slowed down to a stationary process. When this has been done, all the difficulties that result from the use of uranium will disappear, because the thermonuclear process does not produce radioactive waste in significant amounts, does not lead to great danger in the case of an accident, and cannot be used as an explosive material for a bomb. Finally the reserves of deuterium in nature, in the oceans, is even greater than that of uranium.

But the difficulties of realizing controlled thermonuclear fusion have not yet been overcome. I shall speak about them in my talk because, as it now appears, these difficulties are also mainly related to the formation of energy fluxes of sufficient power in a plasma. I shall dwell on this in somewhat more detail.

It is well known that to obtain useful thermonuclear energy the ions in a plasma must have a very high temperature—more than 10^8 degrees. The main difficulty in heating the ions comes about because the plasma is heated by applying to it an electric field, and virtually all the energy is acquired by electrons, which, on account of their small mass, do not transmit the energy well to the ions in collisions. With increasing temperature, this transfer becomes even less effective. Calculations of the energy transfer in a plasma from electrons to ions in their Coulomb interaction were described in a satisfactory theoretical manner as early as the thirties. Landau[2] gave an expression for this interaction, which is still regarded as correct.

The power P_a given up by the electrons at temperature T_e to the ions at temperature T_i in a volume v is[3]

$$P_a = vnk\frac{T_e - T_i}{\tau_{eq}}, \quad (5)$$

where k is Boltzmann's constant and n is the density of the plasma. The relaxation time τ_{eq} is calculated by Landau on the basis of Coulomb interactions, and it is found from this expression that for the high ion temperatures $T_i = 10^8 - 10^9$ °K at which the thermonuclear reaction can give useful power the flux of energy transferred from the electrons to the ions is very small.

The expression (5) shows us that when the ion temperature is $T_i = 0.6T_e$ the transferred power has a maximal value. The maximal power transferred from the electrons to the deuterium ions is[3]

$$P_{max} = 1.57 \cdot 10^{-34} v \frac{n^2}{\sqrt{T_i}} \text{ W}. \quad (6)$$

In a plasma at one atmosphere and with electron temperature $T_e = 10^9$ in one cubic meter the energy transmitted by the electrons to the ions is about 400 W. This is a small quantity since one can readily calculate that about 300 sec are required in order to heat a cubic meter of plasma to $6 \cdot 10^8$ degrees when energy is supplied in accordance with the expression (6).

The smallness of the amount of energy transmitted to the ions is manifested in particular in the thermonuclear devices that are now most widely developed—the tokamaks. In them, the ions are kept in a restricted volume by a strong magnetic field and the heating process is performed by electrons, which are first heated by a short current pulse to very high temperatures and then transfer their energy to the ions by Coulomb collisions. Under the conditions assumed in the modern designs of the tokamak, the time during which the electrons give up their energy to the ions reaches 20–30 sec.[3] It is found that during this time the major part of the electron energy is lost through bremsstrahlung. Therefore, one is now looking for ways for the effective transmission of energy from the electrons to the ions over a prolonged period.[4] This may be achieved either by high-frequency heating or injection of fast neutral deuterium atoms, or by the dissipation of magnetoacoustic waves.[5] It goes without saying that all these methods of heating the ions make the construction of tokamak reactors much more complicated.

It can be seen from the expression for P_a that the efficiency of energy transfer between the electrons and ions increases with the density. We therefore suppose that in the case of heating by a laser pulse of solid condensed tritium or deuterium the initial density will be very high, by several orders of magnitude higher than in in the tokamak, and that it will be possible to heat ions by pulses in a short time interval. But calculations have shown[3] that although the heating time is indeed shortened to 10^{-8} sec it is still inadequate since the plasma bunch, which is no way confined, will have expanded to a considerable size during this time.

For a laser-pellet reactor[4] one is now looking for methods of collective interaction of electrons and ions—for example, the creation of shock waves which, by adiabatic compression, can raise the ion temperature faster than the Coulomb interaction.

At the present time, the principal obstacle is that the physical processes in plasmas have not yet been sufficiently well studied. The theory, which is here well developed, applies only to a nonturbulent state of the plasma. Our experiments[6] on a freely evaporating plasma filament obtained in a high-frequency field have begun to show that a hot plasma in which the electrons have a temperature of several million degrees is in a turbulent state in a magnetic field. Even in ordinary hydrodynamics turbulent processes have not yet been given a complete quantitative description, and essentially all calculations are based on similarity theory. In a plasma the hydrodynamic processes are undoubtedly much more complicated, and we are therefore forced to proceed in the same manner.

As yet there are no reasons to assume that the difficulties of heating ions in a plasma will not be overcome, and I believe that the thermonuclear problem of obtaining high power will be solved in the course of time.

The main task facing the physicist is the deeper experimental study of the hydrodynamics of a hot plasma as is needed for the realization of a thermonuclear reaction at high pressures and in strong magnetic fields. This is a large, difficult, and interesting problem of modern physics. Its solution is intimately related to the solution of the energy problem, which has become the central problem of our epoch. Naturally, this is problem number one of physics.

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