ON THE POSSIBILITY OF CONTROLLED POWER PRODUCTION USING THERMONUCLEAR FUSION*

By

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The problems of thermonuclear power production are at present dealt with at three different levels.

1. In the National Laboratories of the Great Powers. There is no information available either for the scientific world or for the general public, about the theoretical and experimental work which is being carried on there, which involves large investments of material and mental energies. What we know is the fact only that research is going on and we may guess at its probable directions [1—3].

2. The papers published on the subject up to now are partly the work of scientists not belonging to the above spheres and are restricted to purely theoretical considerations or to the astronomical aspects of the problem [4—8] and partly they contain only to some partial results to the above mentioned laboratories [9—20]. Besides of these only very few articles are to be found which bear any relation to the above problem [21, 22].

3. Owing to the importance of the question the subject has been treated quite often in the daily press as well as in the popular scientific literature in a rather speculative way.

Scientific public opinion seems to be most impressed by the rather pessimistic paper by Thirring [6] in which he reaches the conclusion that owing to the unfavourable balance between fusion power output and radiation losses the realization of controlled thermonuclear reactions does not seem feasible. In the following we want to prove first of all that this balance is more favourable than presumed up to now as the radiation for the realizable plasma dimensions does not follow the assumed black body radiation law. Thus realization is not made impossible by the radiation laws.

Further, we shall make an estimation as to orders of magnitude in connection with some considerations partly suggested earlier by one of us [7, 8].

* The above article contains the lecture of the authors given at the Conference of Physicists at Veszprém (23. 8. 1956). After the manuscript had been finished the papers published in the August 1956 number of Nuclear Science and Engineering by E. Teller, and in the July 1956 number of the Reviews of Modern Physics by R. F. Post came to hand. Some of the statements contained in these papers are in accordance with the results given here.

Let us start from the energy balance of the plasma, i. e. of a gas of finite dimensions, fully ionized because of the high temperature. At a given temperature T the nuclei of deuterium or those of a gas mixture of deuterium and tritium collide. Some of these collisions initiate a nuclear reaction and thus a

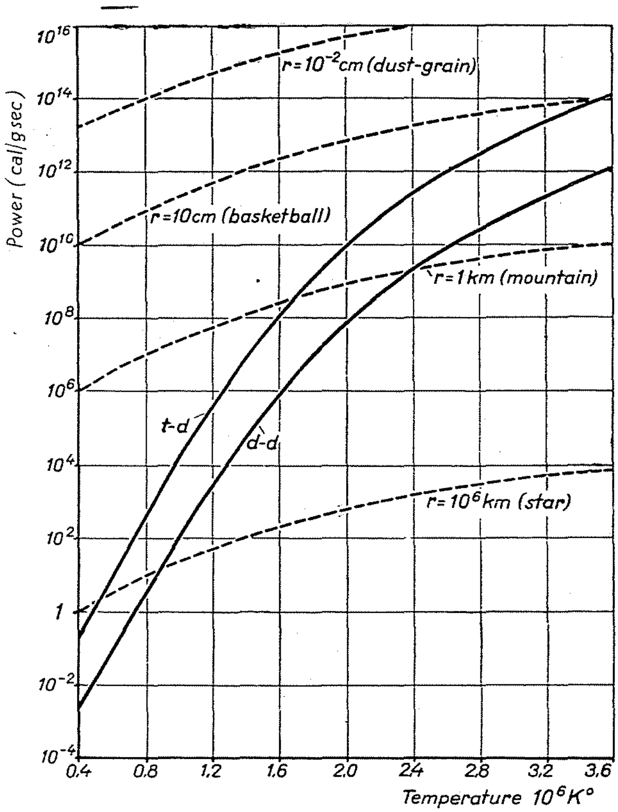

Fig. 1

release of energy. Assuming a gas where the energy distribution follows a Maxwell law, the energy dependence on the temperature is given according to [23] by the following relation :

$$W = a \varrho c_1 c_2 T^{-2/3} e^{-b/T^{1/3}}, \tag{1}$$

where a, b are constants, ϱ is the gas density, c_1, c_2 are the relative concentrations of the two gases, and T is the absolute temperature.

The variation in the specific power output with temperature i. e. the power output per unit mass according to the above equation is shown in Fig. 1 by the solid line with respect to the reactions D—D and T—D. The broken lines in the same figure show for different values of F according to the formula

$$W_{\mathrm{rad}} = \sigma T^4 F \qquad (2)$$

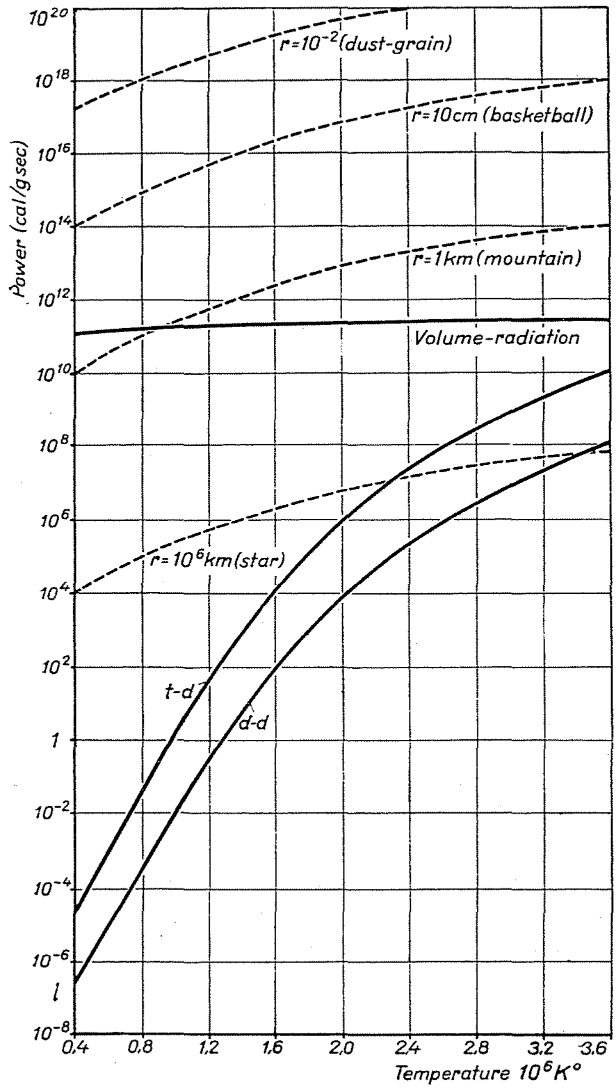

Fig. 2

the radiation output per g for a gas of 1 g/cm³ density. In the formula $\sigma = 5{,}7 \cdot 10^{-5}$ erg/cm² grad sec is the Stefan—Boltzmann constant; F is the surface.

In the following we shall refer to these lines as Thirring curves. A body of small dimensions emits relatively to its mass more radiation than a bigger one having the same density and being at the same temperature, for the Stefan—Boltzmann law implies a radiation proportional to the surface and the quotient surface/volume increases with decreasing dimensions.

The intersecting point of the curves corresponds to the stationary state.

We note [28] in connection with these curves first of all that a material density of 1 g/cm^3 is not feasible as it would require a pressure of 10^8-10^9 *at* at the temperatures occurring at nuclear reactions. Thus we have to consider a lower density. For a lower density the curves of the specific energy production will be displaced downwards and the curves of the specific radiation output will be shifted upwards (Fig. 2). The rate of reactions namely and hence the energy output, too, is proportional to the second power of density. The *specific* power production is therefore proportional to the density. On the other hand the quantity of matter in the given volume is proportional to the density and thus the radiation energy per g of matter in the given volume is inversely proportional to the density.

The density has to be reduced not only because of the high pressure. The fusion of 1 g deuterium-tritium mixture releases an energy of 10^{11} cal. It can be seen from the figure that in case of the given density the power output becomes enormous. With such a high power output the energy of 1 g of gas mixture would not be sufficient even for 1 microsecond and consequently the reactor could not be operated steadily because the material consumed cannot be replaced. Besides, this fast release of energy is comparable to an explosion, the energy of which cannot be put to practical use.

Our second remark is the following [28].

The radiation of a body of a temperature of several million degrees consists mainly of soft X-ray quanta. X-rays penetrate even solid bodies and thus they go much more easily through the much thinner plasma. Therefore the radiation produced in the plasma — if the total volume is not of an extraordinary magnitude — leaves the plasma without having been absorbed and re-emitted, etc. anywhere by it. Thus the plasma, below a given volume, represents *not a surface* but a *volume* radiator. Therefore the Stefan—Boltzmann law cannot be applied and the broken lines in the figures do not represent the real case.

Let us calculate the radiated energy provided the plasma is wholly transparent i. e. all photons produced leave the plasma immediately. Our calculations will not be exact as we are interested in the orders of magnitude only.

The radiation emitted by electrons consists of bremsstrahlung and of radiation occurring at the recombinations.

Energy loss of electrons due to bremsstrahlung. The energy loss of an electron along a path of 1 cm is

$$\frac{dE}{dx} = -NE\Phi, \tag{3}$$

if there are N atoms in 1 cm^3 [24], where E is the energy of an electron (kinetic energy + rest energy) and for non-relativistic energies

$$\Phi = \frac{16}{3} \frac{r_0^2 Z^2}{137} \approx 3 \cdot 10^{-27} \text{ cm}^{-1}, \tag{4}$$

r_0 is here the classical electron radius, i. e. $r_0 = 2{,}8 \cdot 10^{-13}$ cm, and Z the atomic number which has been taken to be 1 as here hydrogen isotopes are being considered.

If the electron travels with a velocity v, it emits a radiation, the energy of which per sec is given by

$$NE\Phi v = 3 \cdot 10^{-27} NEv \,. \tag{5}$$

The number of electrons moving in 1 cm^3 of the plasma be n and the velocity distribution be given by $f(v)$, then the energy leaving the space element of 1 cm^3 per sec is

$$w = \int_0^\infty 3 \cdot 10^{-27} nNEvf(v)\, dv \,. \tag{6}$$

As we deal here with energies of some thousand eV, the kinetic energy of the electrons is negligible compared to their rest energies (0,5 MeV), and thus $E \approx mc^2$ and it follows that

$$w \approx 3 \cdot 10^{-27} nNmc^2 \int_0^\infty vf(v)\, dv \,. \tag{7}$$

Let us assume the electrons to have a Maxwell velocity distribution, then, as is well-known

$$\int_0^\infty vf(v) = \frac{2}{\pi} \sqrt{\frac{2KT}{m}} \,. \tag{8}$$

Substituting (8) into (7) we obtain that

$$w \approx 3 \cdot 10^{-27} nNmc^2 \frac{2}{\pi} \sqrt{\frac{2KT}{m}} \,. \tag{9}$$

If we consider deuterium or deuterium-tritium gas in a fully ionized state we have $n \approx N$. At a density of 1 g/cm^3 — the density the calculations of Thirring are referring to — (9) gives directly the radiation output per 1 g.

At this density the value of N is for deuterium $3 \cdot 10^{23}$, and for a mixture of deuterium-tritium in equal proportion $2{,}4 \cdot 10^{23}$. Introducing these values in (9), we obtain

$$w_{\mathrm{DD}} \approx 1{,}4 \cdot 10^{20} \sqrt{T} \text{ erg/g sec} = 3{,}3 \cdot 10^{12} \sqrt{T} \text{ cal/g sec}, \tag{10a}$$

$$w_{\mathrm{DT}} \approx 0{,}9 \cdot 10^{20} \sqrt{T} \text{ erg/g sec} = 2{,}1 \cdot 10^{12} \sqrt{T} \text{ cal/g sec}. \tag{10b}$$

If the density of the gas is lower by four orders of magnitude (i. e. if the pressure of the gas is about 1 *at* at normal temperatures) then

$$w_{\mathrm{DD}} \approx 3{,}3 \cdot 10^{8} \sqrt{T} \text{ cal/g sec}, \tag{11a}$$

$$w_{\mathrm{DT}} \approx 2{,}1 \cdot 10^{8} \sqrt{T} \text{ cal/g sec}. \tag{11b}$$

More generally we can write:

$$w_{\mathrm{DD}} \approx 3{,}3 \cdot 10^{12} \varrho \sqrt{T} \text{ cal/g sec}, \tag{12a}$$

$$w_{\mathrm{DT}} \approx 2{,}1 \cdot 10^{12} \varrho \sqrt{T} \text{ cal/g sec}. \tag{12b}$$

Energy loss of electrons due to recombination. It is to be expected that this part of the radiation will turn out to be smaller than the former, as owing to the high temperature the probability of recombination is very small.

Let the number of ions (per cm^3) be N, and that of electrons n, and let the velocity distribution function of the electrons be $f(v)$. The energy loss of electrons per sec due to recombination is then [24]

$$\int_0^{\infty} h\nu n N \Phi' v f(v)\, dv, \tag{13}$$

where, at rather high energies

$$\Phi' = \frac{2\,(h\nu)^2}{m^2 v^2 c^2} \Phi_0 \frac{64 \cdot 137^3}{Z^2} \left(\frac{I}{h\nu}\right)^{7/2}, \tag{14}$$

and

$$h\nu = I + \frac{1}{2} m v^2. \tag{15}$$

I, the ionization energy of the gas, is in case of hydrogen 13,5 eV; $\Phi_0 = 6{,}57 \cdot 10^{-28}$ cm^2. At lower energies, the value of Φ' is less, but as we anyhow want to prove that this term of the radiation is negligible, we may safely calculate with a value higher than the true Φ'. Substituting (14) and (15) into (13) and assuming that the electrons follow the Maxwell velocity distribution, we obtain, by evaluating the integral, for the radiation energy originating from unit volume per sec

$$w_{\rm rec} \approx 2nN \frac{1}{m^2 c^2} \frac{64 \cdot 137^3}{Z^2} I^3 \left(\frac{m}{KT}\right)^{1/2} \left(\frac{1}{2\pi}\right)^{3/2}. \tag{16}$$

In the integration $\left(I + \frac{1}{2} mv^2\right)^{-1/2}$ was substituted by the bigger $I^{-1/2}$. At 1 g/cm^3 density $w_{\rm rec}$ represents the specific energy loss. Substituting the values of the constants and taking into account that here too $n \approx N$,

$$w_{\rm rec\,DT} \approx 2{,}7 \cdot 10^{22} \frac{1}{\sqrt{T}} \text{ erg/g sec} = 6{,}5 \cdot 10^{14} \frac{1}{\sqrt{T}} \text{ cal/g sec}. \tag{17}$$

Comparing this with (10*b*) we may see that at about 1 million degrees (17) is smaller by 4 orders of magnitude and so may be easily neglected.

Thus the radiation of the hot, fully ionized plasma, as far as it can be considered transparent, is given by formula (10) and (11) resp. Its essence is that the radiation is independent of the size of the surface and, therefore, in contrast to the Thirring curves, here only one radiation curve appears. This curve calculated according to equation (11) is plotted in Fig. 2.

Obviously, the plasma can be considered as transparent as long as the surface radiation curve, belonging to its volume, runs above the space radiation curve. At low temperatures — where the emitted radiation is of longer wave-lengths — and in case of larger volume, however, it is opaque. Then the Stefan—Boltzmann law and the considerations of Thirring are becoming valid.

We may state therefore that the construction of a fusion reactor is indeed possible with a plasma of small dimensions, as the energy loss — and at the same time the energy production — is proportional to the volume and not to the surface. *This applies only so long as we consider the energy balance between fusion power production and radiation loss only.* Because of the proportionality of energy production and radiation the point of intersection between the energy production curve and the radiation curve is independent of density and dimension.

This point of intersection defines the minimum temperature necessary to maintain a stationary fusion-power production. From Fig. 2 we can guess by extrapolation its value for the DT reaction to be about 10^7 °K. The power released is about 10^{12} cal/g sec in the case of a density $3 \cdot 10^{19}$/cm^3. We will use in the following in our numerical calculations these values as basic data.

Thus output may be decreased at will by reducing the density without increasing in the temperature. The solid curves of Fig. 2 will be displaced upwards and downwards resp. by varying the density. In this way it seems to be possible to reach very high temperatures on the one hand, and to avoid explosion-like energy release, on the other.

The values quoted below may give an illustration of the fact mentioned here :

n/cm^3	$5 \cdot 10^{19}$	$5 \cdot 10^{15}$	$5 \cdot 10^{13}$
p mm Hg (T = 273 °K)	710	0,07	0,0007
p at (T = 10^6 °K)	35 000	3,5	0,035
ϱ g/cm^3	$2 \cdot 10^{-4}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-10}$
V cm^3/g	$5 \cdot 10^3$	$5 \cdot 10^7$	$5 \cdot 10^9$
P_{DT} MW/g	$6 \cdot 10^6$	600	6
t sec (time of 1 g fuel-consumption)	0,1	10^3	10^5

Up till now, the fact has not been mentioned, that the quantity of reaction products leaving the space of the plasma depends on size and density. The loss of particles may influence disadvantageously the energy balance inside the plasma, but may be useful in view of controlling.

As can be seen from the Fig. 2, the curves of energy output and of radiation are intersecting in such a way that if production increases radiation increases to a smaller degree, i. e. the stationary state is unstable. This difficulty may possibly be overcome with help of the following consideration.

The fusion products arising near the surface may leave the plasma before transferring their energy. Care must be taken that in the stationary case this energy loss should not be significant. If, however, care is taken that, when the reaction intensity increases and the plasma becomes hot, the heat expansion is anisotropic, an increase of the specific surface can be attained with increasing temperature. Larger surface results in greater energy loss and consequently in a cooling-down. The problem can thus be solved in principle and becomes now a technical task.

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The most difficult problem of steady operation is the holding together of the gas at several million degrees. In the natural thermonuclear reactions occurring in the stars a strong gravitational field due to the large dimensions assures the holding together of the plasma and the "wall". By "wall" is here meant the surface layer of a thickness of several thousand kms in which the temperature falls from its internal value of some million degrees to some thousand degrees. A wall of such character although not impossible in principle for terrestrial dimensions is hardly feasible. As the plasma is at this temperature in a fully ionized state, we may hope that it can be hold together in a given part of space by means of an electromagnetic field. In the literature the role the electromagnetic wall plays for the first time mentioned in connection with the name of Richter [6]. We cannot but indicate its possibilities and difficulties.

The notion of an electrostatic potential wall is well-known: it prevents for instance the electrons from leaving the inside of metals. Unfortunately these electrostatic forces have such an effect only upon charges of the one sign and facilitate the departure of the charges of the other sign.

If we produce a static field along an axis according to Fig. 3, the particles of, let us say, positive charge cannot leave in the direction of the axis. Their

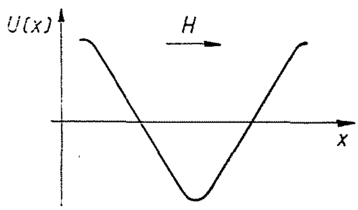

Fig. 3

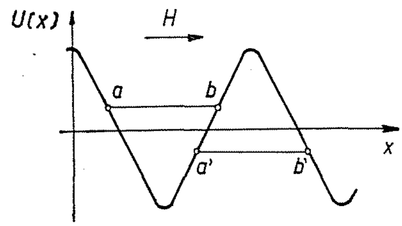

Fig. 4

departure in a radial direction can be reduced by means of a magnetic field in the direction of the axis. In this way the number of escaping charges will be reduced by $1/H^2$ [15]. As the original field deteriorates already through very few enclosed charged particles only very few charged particles can be accumulated. The number of enclosed particles may be increased by the potential shown in Fig. 4: We place charges of alternate signs in the successive potential wells.

With this arrangement the effect of space charge on the outer field will be reduced. Owing to the magnetic field the particles in the potential wall travel, as a matter of fact, mainly in the direction of the axis between the points a and b (Fig. 3), their velocities being smallest in the points of reversal, i. e. in a and b resp. and, therefore, it is here that the density of particles and, consequently, the charge density is the highest. The particles of opposite charge travel between a' and b', their density being also the highest at these points. The regions of the highest charge density overlap and compensate each other so that the outer field will be deteriorated to a smaller degree. This picture is, of course, only approximately true as the charge distribution inside the well changes in case there are particles of opposite charges near to the potential well.

Unfortunately, even so we are able to enclose very few particles only. According to our rough estimation [29] the number of deuterons of an energy of 100 eV which may be enclosed is sufficient only for the production of an energy of $2 \cdot 10^{-2}$ cal/sec.

This example shows that sufficient amounts of charges of one sign can not be accumulated. Therefore — as mentioned before — we have to try to hold together the plasma. As in the plasma, however, there are charged particles of both signs wich are affected by the electrostatic field in opposite ways, we have to look for another "wall".

Let a particle travel in an inhomogeneous field on a spiral path the axis of which is parallel to the field intensity and which points towards increasing

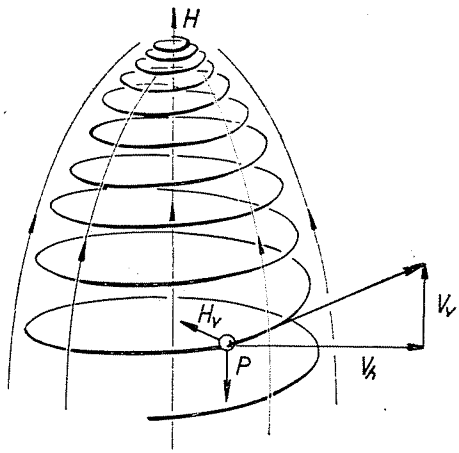

Fig. 5

intensities (Fig. 5). The horizontal component of the field intensity H_ν together with the horizontal component of the particle velocity gives a force oriented vertically downwards which reduces the vertical component of the particle velocity more and more, so that the slope of the spiral path becomes increasingly smaller and the path flattens and turns back and the particle returns on increasingly wide paths [25, 26].

If the inhomogeneous magnetic field is generated between two poles, no particle, of either sign, can leave the field because they always turn round before the poles. Actually, the matter is not so simple. Namely, if a particle starts from the middle in about the direction of the field it is turned back only by a field of very high intensity. If from the middle the same number of particles depart in all directions with the same velocity, half per mille of the particles will pass a surface where the field intensity is $H = 1000\ H_0$ [29]. Furthermore, the particles stray from their original trajectories due to collisions with one another which results in diffusion.

By means of a homogeneous magnetic field, it is possible to build a wall for charges of both signs. According to Fig. 6 the charges may be kept in the inside of a double solenoid and the departure of charges may occur at the two limiting surfaces only. The area of these surfaces can be made negligibly small compared to the total surface by increasing the length of the solenoid. Finally, a completely enclosed field may be produced by a double torus. This field keeps back the constituents of either sign of the plasma, when the plasma is assumed to be very thin. The thinness of the plasma has to be emphasized : it is only in this case that the electrons and the nuclei move like independent particles. Otherwise, we should have to consider the more complicated phenomenon of plasma diffusion. From this point of view plasma may be considered thin

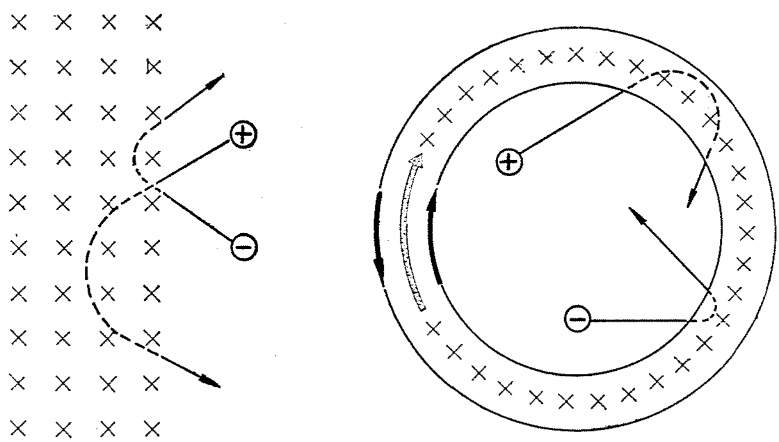

Fig. 6

when the free path of the ions is much longer then the ion orbit in the magnetic wall.

Here only the generally known fact [27] is mentioned that in a plasma carrying big currents, the force produced by the magnetic field of the current itself constitutes a natural coercive force ("pinch effect").

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In order or attain the necessary high temperatures a very high concentration of energy is required. Here a focused explosion wave, or ultrasonic wave [22] may be considered. The sudden discharge of accumulated electrostatic or magnetic energies seems to be most promising [2, 7—20]. Considering that 1 kWs = $0{,}6 \cdot 10^{22}$ eV, it can be seen that with the still realizable energy of $10^2 - 10^3$ kWs each atom of a gas of $10^{-1} - 10^{-2}$ moles could be provided with the required energy of some 100 eV. Of course, the efficiency of the energy transfer constitutes a difficult technical problem.

In principle there is a possibility which is essentially different from the above. Would it not be possible to apply to terrestrial dimensions the analogy of the mechanism of the origin of high-energy cosmic radiation as assumed by Fermi [25]? Let us assume that balls of small but macroscopic dimensions are kept in unceasing motion in a gas mixture. Even their relatively slow motion is connected with a very high temperature according to the relation $1/2\, mv^2 = 3/2\, kT$. If we can assume that a ball behaves like *one* particle, the ball will by colliding with the moleculas transfer their energy to them according to the law of equipartion. Let us assume our gas to be in a fully ionized state. The injected metallic balls collide with and are heated up by the high-energy electrons and ions and possibly evaporate. The actual collision between the positively charged particles and the wall of the balls may be prevented by a positive charge given to the balls. The balls will interact with the particles of positive charge following the law of elastic collisions and until equilibrium

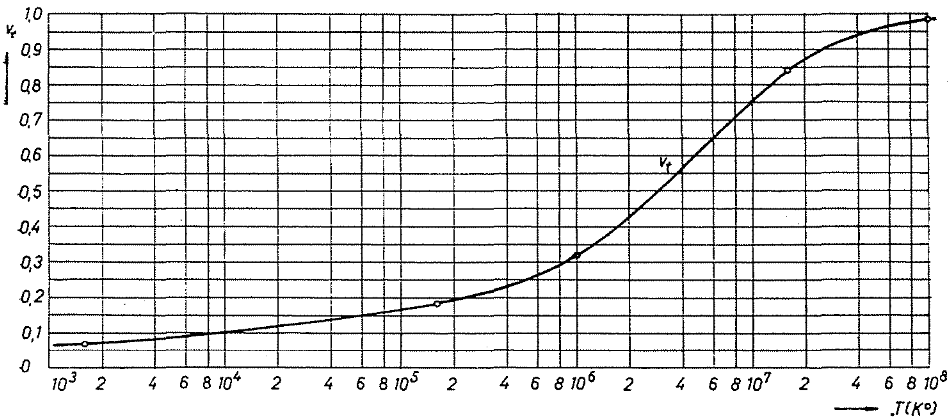

Fig. 7

state is reached the balls will impart — on the avarage — excess energy to the ions.

It would be possible to bring about a similar interaction between balls and the electrons, too, by magnetizing the metallic balls into dipoles. The magnetic field in this way will, namely, prevent the electrons from reaching the balls, in the same way as the magnetic field of the earth prevents the low-energy cosmic particles from reaching the Earth. The result of our detailed calculations [30] basing ourselves on this analogy is shown in Fig. 7. Here the fraction of electrons reaching a ball is shown for a ball of realizable magnetic momentum and of such dimensions that even if a potential is required to repulse the positive ions, a field intensity which is not too high will be produced. It can be seen that even at relatively low temperatures our ball cannot be effectively protected from the impacts of electrons.

There is a further difficulty: neither the electric nor the magnetic field prevents radiation from reaching the balls. Thus the balls will be heated not only by the electrons colliding with them, but also by the photons impinging on them. The latter difficulty may be overcome if the balls can be regarded as transparent.

In practice the energy transfer described here is hardly feasible. However, the balls provided with charges and dipoles may perhaps play the part of a moving electromagnetic wall and thus decrease diffusion of the plasma. The balls heated to a very high temperature are removed from the plasma.

Collisions with a "dematerialized" magnetic fields may lead out of these difficulties. Similar collisions increasing the energy may be realized by the motion of the magnetic walls as shown in Fig. 6. An energy transfer of this character is mentioned by Soviet research workers, too [15, 16]. A more effective energy transfer may be effected by keeping the magnetic walls vibrating for longer periods by means of an external force.

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Accelerators may also have a part to play in power production. According to [7, 8] the condition of excess energy production is

$$v = \frac{E_r}{E_0} > \frac{1}{\eta_n \eta_t} - 1 , \tag{18}$$

where v is the probability that a reaction will occur; E_r is the energy of the reaction; E_0 the energy of the injected particle; η_n accelerator efficiency and η_t is the thermal efficiency of the re-transformation of heat into energy. The probability v that a reaction will occur, has been calculated [8] from the curves of the effective cross section $\sigma(E)$ and of the range $R(E)$ for a tritium target bombarded by deuterium, based on the relation

$$v = N_T \int_0^\infty \sigma(E) \frac{dR}{dE} dE , \tag{19}$$

and with this the excess energy produced by the reaction D-T is obtained as

$$\eta = v \frac{17.6}{E_0} . \tag{20}$$

This excess energy is too small to be of practical use, it is, however, measureable by macroscopic means. From Fig. 8 the importance of an increase of range is to be seen. At a given density of the gas this increase is only possible by reducing the energy transferred to the electrons. In the following we shall investigate whether there is any possibility of doing this effectively.

We proceed first to determine the upper limit of the energy gain [28].

Let us assume first that the electrons for some reason do not participate in the energy transfer. In this case the deuterium or tritium gas loses its energy exclusively by the elastic collisions with the nuclei. Now, the question arises as to the probability of a reaction occurring during the slowing-down of the deuteron to thermal energies. The problem is similar to that of the slowing-down of neutrons and, accordingly, the integral equation applied in our considerations will be similar to that known from reactor physics.

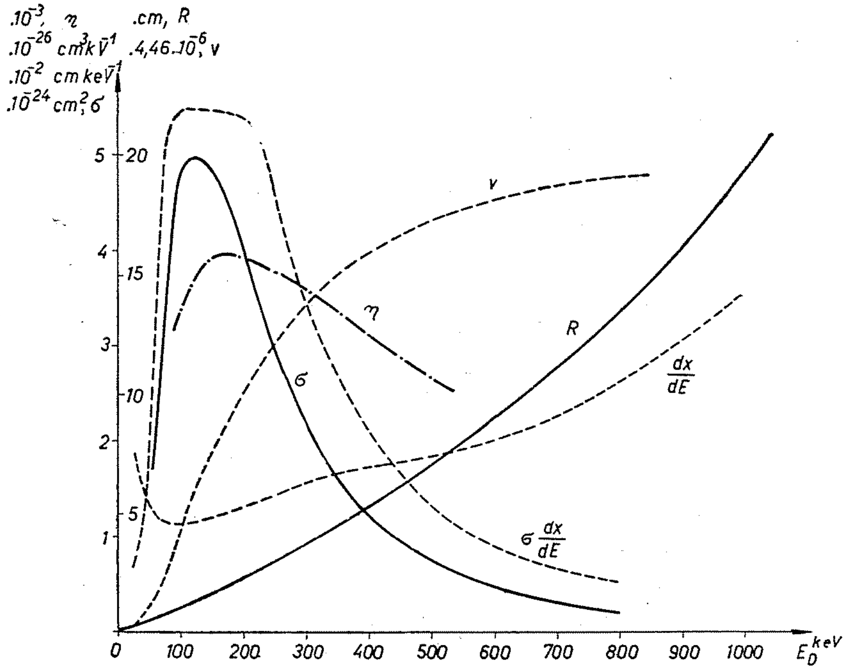

Fig. 8

Let us assume a deuteron gas of infinite dimensions, in the unit volume of which a given number of fusions is initiated continuously by means of some external effect — for instance by tinjections from an accelerator. The energy of the reaction products is transferred to the nuclei. In this way a certain energy distribution $n(E)$ is obtained, which satisfies the following integral equation

$$\int_{E-E_{\min}}^{E_{\max}} \sigma(E', E-E')\, n(E')\, v'\, dE' + \int_{E}^{E_{\max}} \sigma(E'', E)\, n(E'')\, v''\, dE'' = \tag{21}$$
$$= \{\Sigma(E) + \varphi(E)\}\, n(E)\, v,$$

where $\sigma(E_1, E_2)$ is the effective cross section of that process in which a particle of energy E_1 loses an energy E_2 and where

$$\Sigma(E) = \int_{E_{\min}}^{E} \sigma(E, E')\, dE' \tag{22}$$

represents the total effective cross section of the particles of energies E scattered anywhere. E_{max} is the energy of primary deuterons to which the energy of the reaction products is transferred directly; E_{min} is the assumed minimum of energy transferred in elastic collision; $\varphi(E)$ is the effective cross section of fusion. By means of a rough estimation this integral equation may be simplified and thus the function $n(E)$ determined. With this the number of further fusions per one initial fusion can be obtained. This number is found to be 3—4. This means that leaving the electron gas out of consideration with respect to the energy balance, a divergent energy-producing process would be obtained. It seems thus to be worth while to investigate the possibility of such neglect.

It is obvious that in case of normal ionization, that is when the temperature of the plasma is some thousand degrees the electrons may still be considered cold as compared to the injected deuterons which have a temperature of 10^7—10^8 °K. Thus the energy transfer will occur in the known manner.

It might be suggested that an *ordered* motion of the electrons knocked on away from the deuteron beam may reduce the energy transfer in case of a target current of high intensity.

Elementary calculations [29] show that if heavy particles arrive successively, the energy of each being transferred to the electrons knocked on by the preceding one, the energy transferred by the n-th heavy particle will be

$$\Delta E_n \approx \Delta E_1 (1 - 2\varkappa)^{n-1}, \tag{23}$$

where ΔE_1 is the energy transferred to the electron at rest by the first heavy particle and

$$\varkappa = \frac{\ln\{1 + (b_{max}/\Lambda)^2\}}{(b_{max}/\Lambda)^2}. \tag{24}$$

b_{max} is the maximal impact parameter and

$$\Lambda = \frac{e^2}{m_r c^2},$$

where c is the velocity of the heavy particle, the reduced mass m_r being about the same as that of the electron. As the value of $\varkappa$ is very small, there is no considerable decrease in the energy transfer.

Thus we see that although the increase of range is possible in principle, cannot expect a rate of increase which would change the energy balance corresponding to (18). The combination, however, of a plasma, having an energy comparable to that of the accelerated particle and an accelerator may be of importance.

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From the above it seems possible to design, at least in principle, a reactor and all equipment — if only in rudimentary form — required to start it up and control it and to ensure its stability (Fig. 9).

This model serves two purposes: first to show the interdependence of the problems envolved and to formulate them clearly, and further it shows the order of magnitude of the physical quantities playing a role in fusion power production. It does not aim at being the prototype of a real reactor. We are of course aware of the fact that it might hardly possible to build a

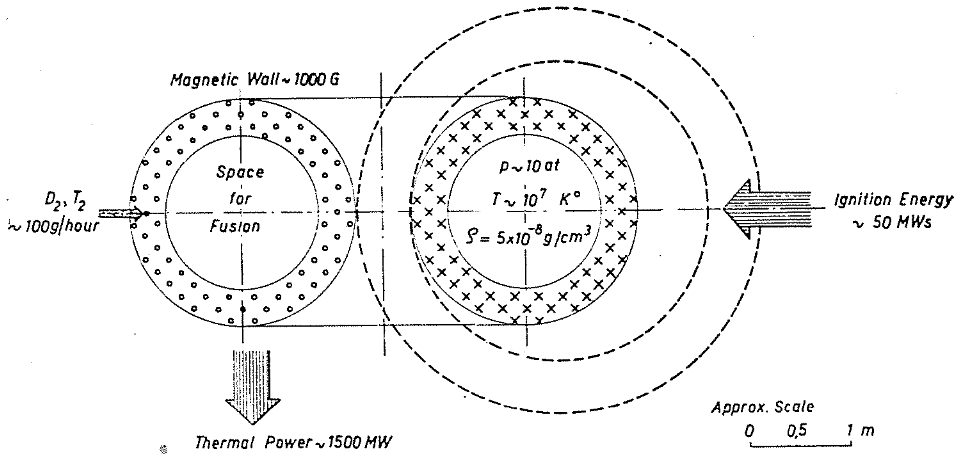

Fig. 9

reactor using the ideas developed here and that a completely different way might have to be followed.

Consider 1 g of D-T mixture. We may consider a simple deuterium gas, too, the conditions will not differ essentially, only the equilibrium temperature will be higher. Enclosing this quantity of gas in a volume of 20 m^3, the value of the density will be $5 \cdot 10^{-8}$ g/cm^3 ($n = 1{,}2 \cdot 10^{16}$ particles/cm^3), and that of the pressure 0,2 mm Hg at room temperature. The power output by fusion of a gas of this density which is equal to the radiation output at equilibrium temperature is $4 \cdot 10^8$ cal/s $\approx$ 1500 MW according to equations (12). It is a rather high value but it can be conducted from the boundary area of the given volume. 1 g fuel supplies this energy for a period of 10^2 sec, thus the fuel consumed may be replaced.

If we decrease the density by one order of magnitude, we get the power of a usual electrical power station i. e. about 150 MW. But in this case other difficulties mentioned below will be increased.

This gas which for a D-T mixture has a temperature of about 10 million degrees may be enclosed in the torus coil mentioned above. For a magnetic field intensity of H $\approx$ 1000 G a homogeneous field, of an 50—100 cm width, constitutes practically an impenetrable wall for all particles of thermal energies. The rate of particle leakage and consequently the inner temperature may be controlled by varying the thickness of the magnetic wall. At a given thickness the rate of departure of high-energy particles will increase with increasing temperature. This phenomenon may insure in principle the realization of stable operation.

The electrons and deuterons, assumed to be of the same energy, penetrate to different depths into the magnetic wall. Thus, in contrast to the internally neutral plasma, negative charges are found on the inner edge of the wall and positive charges on its outside. Placing two electrodes in a suitable position we may obtain useful electric power immediately on account of the fusion energy. The energy leaving in form of radiation may be re-transformed into heat and used, for instance, to produce electric power in the usual way.

The radiation energy appears in the form of soft X-rays. Thus, it is possible to convert it directly into electrical energy using appropriate semi-conductors.

The pressure of the gas at the equilibrium temperature is approximately $p \approx 10$ at. This means a force of some tens of tons for the solenoid if there are ten windings on 1 m length of the torus. Fig. 6 shows, how a ring current is formed by the electrons and ions scattered back by the magnetic wall, the current attracting the inner solenoid and repulsing the outer one.

It is a rather surprising fact that all the quantities we have been dealing with up to now are of an order of magnitude which is common in engineering praxis. But there are grave counter arguments against its feasibility, too, which may compel us to abandon this way of approach. Some are listed below.

What will be the behaviour of the electromagnetic wall when interacting with the plasma instead of with individual particles. The physical picture given here may be considered as an asymptotic approximation only. The above-mentioned ring current carries millions of Ampers. The distortion of the magnetic field cannot be neglected so that the equations of magnetohydrodynamics must be solved.

In order to prevent the charged reaction products from escaping we have to increase the strength of the wall by at least one order of magnitude.

The free path of elastic collisions of the nuclei and even more so the free path of the reaction products, especially that of the neutrons, is too long. They collide frequently with the walls, than with one another. Therefore, the probability of colliding with the windings of the solenoid is great. Thus, the area of these windings must be as small as possible. On the other hand these have to carry ten thousands of Amperes and to withstand tens of tons. They must be cooled, too, although the power per unit area is not too high and the field distortion in the direct neighbourhood of the windings may decrease the number of particles colliding directly with the windings. This is the greatest difficulty which can hardly be eliminated in this construction. All these considerations show the importance of a magnetic wall without windings. Such a wall is e. g. realized in the pinch effect.

The energy carried by the neutrons is entirely lost. The equilibrium temperature will thus be higher and the pressure increases, too.

The possibility of control can be determined only by a quantitative analysis of the dissipation of power through radiation taking into consideration the effect of diffusion, too.

To initiate the process of fusion, i. e. to impart to each particle an energy of a few keV, an energy of the order of magnitude of 50 MWs is required. In the Soviet experiments energies of 0,5 MWs were involved. The energy transfer is feasible in principle by discharging the condenser batteries charged up to the given energy through a ring coupled to the torus, or discharging the magnetic energy stored up. But it is very difficult to realize it.

We conclude that there are quantities, like balance between power production and radiation, pressure and size fitting well ordinary engineering praxis ; but there are discouraging aspects like the problem of confinement, ingnition, regulation which are yet to be solved and possibly in another direction than that discussed here.

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The consideration of the possibility of fusion power production is of importance at present, also in view of the solution of several interesting problems in physics, which are connected with this subject. It is important even if in time a law similar in character to the second law of thermodynamics would be proved : The fusion reactor is not feasible in terrestrial dimensions. Let us remember the proof of the second law of thermodynamics : certainty of this fundamental law is given just by the many unsuccessful experiments to realize the perpetuum mobile. Everybody who deals with the problem of the realization of fusion-reactors nowadays does it in the belief that his experiments either help its realization or at worst are required to support a law of the above-mentioned character.

Summary

In this paper a formula is derived which differs from the Stefan—Boltzmann law in respect of the plasma radiation. According to this the specific radiation output is independent of geometrial dimensions. Fusion power production and radiation reach equilibrium at a well-defined temperature independent of geometry and even of density.

The possibilities of power production by accelerators are also discussed with an essentially negative result.

The sketch of a scale-drawn reactor is reproduced here which helped to formulate the problems to be solved.

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