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Chap. I

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PROJECT SHERWOOD: ORIENTATION LECTURES PRESENTED AT OAK RIDGE NATIONAL LABORATORY, NOVEMBER-DECEMBER, 1955

Chap. I. Nuclear Fusion and the Energy Resources of the Earth

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I. NUCLEAR FUSION AND THE ENERGY RESOURCES OF THE EARTH

Project Sherwood is the official name for the American project which has as its objective the controlled release of energy from nuclear fusion. Major research efforts in this field are being carried out at Princeton, Los Alamos, and Livermore. Smaller scale efforts are underway at Oak Ridge and at New York University. The essential features of the problems involved will be described in the lectures to follow. In its utmost simplicity, however, it might be described as the problem of containing and controlling a gas at temperatures comparable to those of the sun for a time long enough to achieve sizeable nuclear reactions. The three major research centers named above are working on specific schemes for a device. Oak Ridge and NYU are concerned more with fundamental research and development.

Before considering the possible schemes for a Sherwood device, it is probably most sensible to look at the role which fusion (or thermonuclear) energy would play in the over-all resources of this earth. The discussion which follows is based upon data published by Palmer Putnam.[1]

Putnam defines a convenient energy unit called the Q. The Q has a value equal to 10^{18} Btu. In terms of this unit, one can summarize the energy that has already been used on this earth to the present day and can also characterize the availability of the remaining energy in the usual forms. Some interesting numbers are listed in Table 1.1.

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1. P. Putnam, Energy in the Future, Van Nostrand, Princeton, N. J. (1953).

Table 1.1

Burnup to 1850	6-9 Q
1850-1950	4
Total to 2000	25
Total to 2050	100
Present rate is 10Q per century	
Available Coal	32
Oil	6
	38Q
Nuclear	575

The first two numbers represent burnups of all energy resources which have occurred in the relevant periods. The next two items are the estimated totals to the years 2000 and 2050. These figures are based on an extrapolation of both the population growth of the planet and of the rise in energy requirements per capita.

The second part of the table summarizes the major energy resources remaining on this planet. These estimates consider only those available reserves of coal and oil which can be economically marketed -- that is to say, marketed at a basic price that is not over twice the present average cost. The total reserve in nuclear fuel includes uranium and thorium and assumes complete breeding. This last number is perhaps the most uncertain of Putnam's estimates and, in fact, there is a great deal of evidence that it is an appreciable underestimate. Thus it is clear that there is no immediate and pressing urgency for the development of a fusion reactor, while there is good reason for a large scale effort in the fission field. It is also clear, however, that there is certainly something less than an unlimited supply of energy in uranium and thorium, even assuming complete breeding. If the power requirements of the earth should rise appreciably above their present levels, it is conceivable that all other energy sources - that is other than fusion and solar energy - will be exhausted in a few hundred years.

What then is the energy reserve which is available in light element fusion processes? To evaluate this, consider the reactions listed in Table 1.2 which, as will be seen later, comprise the most feasible reactions for a fusion reactor. The most promising is the D-D reaction which yields a neutron or proton with about 50% probability. Next most promising is the D-T reaction which yields a neutron. The energy of the reaction products are listed in parentheses in the table.

Table 1.2

D + D	$\rightarrow$ He^3(0.8 Mev) + n(2.5)
	$\rightarrow$ T(1.0) + p(3.0)
D + T	$\rightarrow$ He^4(3.5) + n(14.1)
n + He^3	$\rightarrow$ T(0.2) + p(0.6)
D + He^3	$\rightarrow$ He^4(3.6) + p(14.7)
n + Li^6	$\rightarrow$ He^4(2.0) + T(2.6)

The energy release in the burning of deuterium may be estimated by following a deuterium atom through all the burnings which will occur, even in a reactor which is initially of pure deuterium. It is clear from the reactions which have just been listed that He^3 will be produced as a by-product half of the time and tritium as a byproduct half the time. These charged particles will not escape from the system, but may be expected to burn once again in a D-T or a D-He^3 reaction. Table 1.3 lists the sequence of these events.

Table 1.3

$$D + D \longrightarrow T(1.0) + p(3.0)$$
$$D + D \longrightarrow He^3(0.8) + n(2.45)$$
$$D + T \longrightarrow He^4(3.5) + n(14.1)$$
$$D + He^3 \longrightarrow He^4(3.6) + p(14.7)$$

$$6D \longrightarrow 2He\ (7.1) + 2p(17.7) + 2n(16.55) + (1.8)$$

The over-all effect is the burning of six deuterons. The products are two protons, two neutrons, and two alpha particles. The quantities in parentheses indicate the energies with which these are produced, and it must be remembered that the energy deposited in the charged particles is put back into the gas since charged particles will not be expected to escape. Adding up the energy in charged particles and dividing by six shows that the energy deposited in the gas per deuteron is 4.4 Mev. Similarly, dividing the energy which escapes in the form of neutrons by six yields an additional energy contribution per deuteron of 2.76 Mev. The total energy output per deuteron burned is approximately 7.2 Mev.

It is instructive to use this figure to calculate the available energy on the surface of the earth in the form of sea water. Deuterium occurs in sea water in a ratio of about 1 part in 5000. The amount of energy in a gallon of sea water is easily found to be of the order of magnitude of 10^4 kw-hr. Speaking very roughly, 1 gal of water has the energy equivalent of 300 gal of gasoline. The cost of separating the amount of deuterium found in a gallon of water from sea water is approximately 10 cents. Hence, the separation cost is completely negligible. An estimate for the amount of surface water on the earth is about 10^{21} gal. Therefore, the total energy available from sea water is readily calculated to be about 5×10^{10} Q. Hence, if one could burn deuterium cheaply in a controlled thermonuclear reactor (or CTR), the energy problems of the earth would be solved for an essentially infinite time.

Over and above the energy resource argument for Sherwood, there exist at least two other reasons for working on this project. The first is the possibility that a Sherwood device may actually supply electric power at a cheaper rate than conventional methods. The reason for this is the possibility of direct conversion of the energy output of the system into electrical energy. As will be seen later in these lectures, the working fluid of a Sherwood device is a completely ionized plasma at a temperature of 100,000,000 deg. It may not be too difficult to find some means of separating the charges in the plasma (at least up to a potential difference equal to kT, which is 10^4 ev) and actually obtaining a DC potential which can be used directly. Alternative schemes involve use of inductive action in expanding plasmas.

The second reason is the competition angle. It is known that the USSR and the UK are working on such devices. If these devices are successful, they could prove an important economic, political, or psychological achievement. Hence, it is in the national interest not to fall behind in this field of research.

It is to be noted that the list of possible reactions of the light isotopes included tritium. If one attempts to design a reactor which operates mainly on the burning of deuterium and tritium in a D-T reaction, careful heed must be paid to the problem of the replacement of the tritium. Since tritium does not occur naturally, it can only be obtained in large quantities from nuclear reactors operating on the fission principle. The coupling of a thermonuclear economy to a uranium economy is an undesirable prospect and hence, it is extremely desirable that the tritium be recovered in some fashion and be put back into the proposed CTR. A possible way to accomplish this is to make use of the neutrons which result from the D-T reaction by absorbing them in a lithium blanket. The n-α reaction in Li^6 yields a triton which can then be recovered by some chemical means and fed back into the system. Hence, the problem is one of neutron economy and perhaps of neutron multiplication.

The calculation below is indicative of the magnitude of the problem. If C is defined to be the fraction of neutrons which are recovered in the device, Eq. (1.1) then gives the situation at steady state for no net triton gain or loss.

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$$\left[n_D n_T(\sigma v)_{D-T} - \frac{n_D^2}{2}(\sigma v)_{D-D}\left(\frac{1}{2}\right)\right] = \left[\frac{n_D^2}{2}(\sigma v)_{D-D}\left(\frac{1}{2}\right) + n_D n_T(\sigma v)_{D-T}\right] C \quad (1.1)$$

The terms on the left-hand side represent first the loss of tritium by D-T reactions, and secondly the gain of tritons from the D-D reactions which are going on. The term in the brackets on the right-hand side represents the rate of neutron production in the device. Equation (1.1) may be solved for C as a function of the ratio of the concentration of tritium to that of deuterium and also as a function of the cross sections for the D-T and D-D process.

$$C = \frac{\left(\frac{n_T}{n_D}\right)\frac{(\sigma v)_{D-T}}{(\sigma v)_{D-D}} - \frac{1}{4}}{\frac{n_T}{n_D}\frac{(\sigma v)_{D-T}}{(\sigma v)_{D-D}} + \frac{1}{4}} \quad (1.2)$$

It will be seen shortly that the D-T cross section is about 100 times the D-D cross section in the region of interest.

It may be seen from Table 1.4 that the percentage of neutrons which must be recovered is extremely high, even for a reactor which has a 50% mixture of tritium and deuterium, and only becomes a rather easily achieved number when one goes to reactors which are almost pure deuterium.

Table 1.4

C	% T	% D
0	0.25	99.75
0.60	1.0	99.0
0.78	2.0	98.0
0.995	50	50

Hence, in any D-T device it will be a very serious problem to conserve neutrons so as to be able to recycle the tritium. This is an important factor in the economics of the machine and in the design of the blankets, coils, and shielding. Undoubtedly, use will be made of beryllium in the blanket to take advantage of the multiplication resulting from the (n,2n) reaction. In fact, at least one proposed working thermonuclear device has the feature that it may actually succeed in being a tritium producer -- that is, more tritium will be produced than is burned up in the device. This is an additional factor which is favorable to the over-all economy of the device.

One final calculation should be done before the study of the characteristic parameters of a sensible thermonuclear device begins. This calculation is to find what the critical dimensions of a highly simple thermonuclear reactor -- namely a critical mass of deuterium -- would be. It is implied that enough deuterium has been assembled so that the radiation lost from the surface is less than or equal to that being produced by the thermonuclear reactions going on inside the deuterium mass, even at room temperature. As a result, this system will begin to heat up. As it heats up, the cross section for the reactions increases strongly and one would expect the device to lift itself by its own boot straps to a reasonable operating temperature. A calculation of such a system by Heitler many years ago has been reported in the Sherwood literature.[2] Since the original reference has not been located as yet, it may be instructive to

2. J. L. Tuck, Classified Conference on Thermo-Nuclear Reactors Held at Denver on June 28, 1952, WASH-115 (1952).

describe the following calculation which is highly simplified and, furthermore, quite inconsistent. Nevertheless, the order of magnitude which results may not be completely meaningless.

Equation (1.3) below describes the steady state balance between black body radiation and energy production in an opaque isothermal sphere of deuterium with a radius r and at a temperature T.

$$4\pi r^2 \sigma T^4 = \frac{4}{3} \pi r^3 \frac{n^2}{2} (\sigma v)_{D-D} E \qquad (1.3)$$

The quantity E corresponds to an energy release of about 14 Mev resulting from the burning of two deuterons. The solution of this equation for the radius is given in Eq. (1.4).

$$r = \frac{6\sigma T^4}{n^2 (\sigma v)_{D-D} (14 \text{ Mev})} \qquad (1.4)$$

Next, from the behavior of the D-D cross section with temperature (see Chap. II), it is readily recognized that $T^4/(\sigma v)$ has a <u>minimum</u> value in the neighborhood of $T = 10^8$ deg (1 ev = 1.16×10^{4} °K, hence roughly 10^{8} °K = 10 kev). With this assumed temperature and an assumed <u>maximum</u> reasonable density of 10^{22} particles per cubic centimeter, the following result is obtained:

$$r \geq \frac{(6)(5 \times 10^{-5})(10^{32})}{(10^{44})(10^{-19})(2 \times 10^{-5})} = 10^8 \text{ cm} = 10^3 \text{ km} \qquad (1.5)$$

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The final size of the device would be of the order of the radius of the moon! Obviously, such a system is impractical.