Prospects for New Energy Sources

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INTRODUCTION

Man is using energy at an ever-increasing rate. Nearly all of this energy is now coming from the fossil fuels. The convenient and clean fuels, petroleum and gas, will be depleted in the near future and some new sources of energy will then be needed. In fact, new sources will be needed even earlier if these fuels are to be saved in order to be used for more important functions, such as raw materials for chemistry.

Coal is not considered a feasible substitute fuel because it is not as convenient as oil and gas, it is considered dirty, and its distribution is not uniform, i.e. it is concentrated in a few countries. Nuclear power of the fission type is almost ready for large-scale utilization in the form of ordinary nuclear reactors. The fuel for these reactors is not unlimited though, and the new type, the breeder, which is not ready yet, must be introduced if freedom from fuel shortage is to be assured. But nuclear energy of the fission type is increasingly being regarded as undesirable because of the dangers of radioactivity, and it may therefore not be introduced widely. Of the other possible sources of energy, none is yet ready to meet the increasing needs. Below we shall examine each of the possible new sources of energy, its special characteristics, its potential and its chances of success.

NEW ENERGY SOURCES

These new energy sources, both actual and potential, are nuclear (fission and fusion), solar, the winds, the tides, and geothermal power. Some of the traditional sources (wood and plants in general and hydro power) may also be further exploited in the future in new ways or at higher intensity and may therefore qualify as new sources. Other sources also exist, but they are of minor significance.

GEOTHERMAL POWER

It has been estimated that about one percent of the heat stored in the Earth to depths of several kilometers can be withdrawn. At 25% efficiency this would yield an amount of power equal to that which is obtained from all sources today or 3×10^9 kw. Some geothermal plants utilizing steam that leaks out of the ground exist in Italy and New Zealand. Proposals have been made to force water down deep drill holes and remove the heat from the rocks in the crust. It is claimed that in this way the useful geothermal power would be increased 100 times. It is not certain whether this method would be feasible. Hence it may be said that the geothermal energy source is minor.

THE TIDES

The total practical amount of energy that could be obtained annually from the tides in the world is estimated to be equivalent to that which 60 million kw, running continuously, could provide or 550×10^9 kw-hr. Nearly half of this power is in the Bay of Fundy in Nova Scotia. The Bering Sea also has large amounts and recent estimates have revealed that the potential is much higher than previously thought. But its location makes it nearly useless. Thus tidal power is of little importance except perhaps for Nova Scotia.

HYDRO POWER

The total potential in the world is 3×10^9 kw, or about the same as the total power currently being used in the world from all sources. At higher prices for electricity, additional amounts could be added. At present less than 10% is developed, mainly in Europe, North America and the U.S.S.R. Most of the potential hydro power is in Africa, South America and Southeast Asia. Using present technology in the transmission of electricity, power from South America and Africa could be brought to the U.S.A. and Europe, respectively, at a cost of from one to two cents per kw-hr . Total cost to the consumer would then be from two to three cents per kw-hr. This is about double today's prices. Using superconductors for transmission the cost could be reduced, and with superconductors at room temperature the reduction would be drastic. Hydro power could also be used to produce hydrogen fuel on the spot by electrolysis at an efficiency of 70%.

Because the quantities are great and the technology is well-developed, hydro power is considered very important for the future. The main problems in its development and utilization are likely to be political.

WOOD

Each year 60 billion tons of carbon are fixed by photosynthesis on the land areas of the world. It may be possible to utilize upwards of 10% of this as fuel. Improvements may be made by using fast-growing plants and optimizing their harvesting time and by utilizing farm wastes. Reforestation of many deforested areas and perhaps of deserts is another possibility. Thus the total fuel from wood could equal and perhaps exceed the total used in the world today from all sources. Wood has the added advantage of being readily available regardless of the state of technology; man will always have it even if, for any reason, he should lose his technology. Thus wood is a rather large continuous and important source of energy for man's future. However, other needs may limit the use of wood for fuel.

SOME OTHER SOURCES OF MINOR IMPORTANCE

In many parts of the sea there are temperature differences between the upper and lower layers of the water. These could be utilized to generate electricity. The total potential of the seas is large but at present it is not certain whether it can be developed economically.

Ocean waves also contain large amounts of energy, but the technology for its utilization has not yet been developed, and the capital investment needed would probably be very high.

Would atmospheric electricity and lightning be an important source of energy? It has been estimated that one lightning bolt would equal about 5 sacks of coal, if it could be caught. This energy source is obviously insignificant.

THE WINDS

The power of the winds that can be practically harnessed near the ground over the land area of the planet is 60,000 million kw or 20 times greater than the total power used by mankind at present. A small fraction of this power can be converted to electricity at a cost comparable to that of hydroelectric power with present technology at some choice locations. A large fraction of this wind power may become economically attractive as the necessary technology improves and as power from other sources becomes expensive or objectionable for its pollution or other reasons. Wind power is completely clean. Unfortunately, no significant amount of research has yet been done to develop it.

The power of the wind per unit vertical area, near the ground, is on the average of the same order of magnitude as solar power, i.e., about 200 watts/m^2. Wind power can be converted directly to electric power, without an intermediate heat phase as with solar, nuclear or power from fuels, at an efficiency of 60-70%.

Wind power varies as the cube of the wind velocity, i.e.,

$$P = KV^3$$

where if P is kilowatts per m^2 and V meters per sec then K = .006 kw/m^3 at sea level and 25°C.

Two important consequences follow from this:

(a) Large variability at a given location. Therefore wind power cannot supply a steady load directly and an intermediate storage phase must be used. An example of such a phase would be the electrolysis of water and the storage of the hydrogen and oxygen. These in turn could be combined at a steady rate to supply power. There are also other ways to convert the variable wind power into a steady flow of energy.

(b) At a few miles altitude winds of from 50 to 150 miles per hour blow steadily. Hence the power per unit area up there is several hundred times greater than that at the ground. It has been proposed that the power-generating equipment be raised to these altitudes with the aid of helium-filled balloons which could be anchored to the ground. The electricity would be sent to the ground by cable. This is not beyond the capabilities of present-day technology. A large amount of power (several thousand kilowatts) would be derived from each such station. There are problems, e.g., icing, hazard to aviation, maintenance, but none of these is insuperable.

At ground level, it is proposed that the machines be spread over an area like a thin forest. It is well known that the wind recovers its full velocity behind an obstacle after a distance of 10 to 15 times the height of the obstacle. Hence the machines should be no closer to each other than this in that direction. In the other direction also they should be at some distance apart. And at this spacing they will extract a large portion of the wind power. In this manner the windmills will not interfere with agriculture and other activities. A figure of $2V^3$ kilowatts per sq. mile (with 16 machines) is given for this arrangement, when the average velocity V is in miles per hour. In regions of high wind velocities this power is considerable. Wind power will be most useful in areas with no other convenient sources of power. In northern areas with little sunlight, such as northern Canada, the use of wind power is highly probable in the future. Wind velocities are also high in the winter in these areas.

It can therefore be concluded that wind power will be of importance to mankind in the future.

SOLAR POWER

Each year the Earth receives from the Sun the equivalent of 1.88×10^{14} tons of coal in the form of radiation. This is 27,000 times greater than the energy used by man in 1970 and 24 times greater than the energy stored in all the ultimate reserves of fossil fuels. Of this energy, 30 percent is directly reflected back to space by the atmosphere and the Earth's surface, 47 percent is absorbed and converted to heat, and 23 percent is utilized in the evaporation of water. A very small part, 1 in 5000, is trapped by photosynthesis.

These are large quantities of energy, but the conversion of solar radiation into electricity or other energy forms presents a problem. The intensity of solar radiation outside the Earth's atmosphere is 1400 watts per square meter and about two-thirds of this reaches the ground. This is a low intensity for purposes of conversion and therein lies the main problem. An additional problem is the low efficiency of conversion which so far has not exceeded 12% in practical installations. Thus, with present technology, the capital investment needed is uneconomically large. However, the future may hold some promise.

There are various methods for directly capturing and converting solar radiation.

(1) Photovoltaic cells. The silicon cell gives an efficiency of 12% and is used to supply power to satellites. Its cost is from $200. to $300. per watt. To produce electricity competitive with present sources this cost must be reduced by a thousand times. Other types of cells, such as cadmium sulfide, cost less (1/10) per watt, but their efficiency is only 4 to 5%. With large scale production and improvements in technology the cost may decrease, enabling production of electricity at a cost of from two to fifteen cents per kw-hr, according to various estimates. The present cost of electricity from conventional sources is less than one cent per kw-hr. There is some promise therefore that this method may some day provide expensive but limited quantities of electricity.

A fanciful proposal was made recently to place a group of photovoltaic cells with a very large surface area in synchronous orbit with the Earth 23,000 miles above the equator and have the surface always facing the Sun, thus utilizing continuously the maximum solar flux. The electric output of the cells would be converted to microwaves and beamed to the Earth where it would be collected over a (safely) large area and finally converted to 60-cycle power. A satellite area of 25 square miles would be sufficient to supply New York City with 10 million kw. of electric power. This proposal involves several steps that are beyond the capacity of present-day technology, and even if it were attainable the maintenance problems would be anything but simple. The whole scheme therefore is closer to science fiction than to technological reality.

(2) Solar furnaces. Reflectors are used to concentrate sunlight on a small area which is heated to a high temperature. These furnaces are already used in many places for cooking and other small applications. A few larger experimental units exist, but for large-scale power production the problem is the high cost of the reflectors and the associated equipment that is needed to keep them properly oriented. Experimental programs to utilize them in France and the U.S.S.R. have failed.

One recent proposal has been made to focus the light from the reflectors onto a tank high above the ground holding salts or liquid metal which would be heated to 1000°C. The heat would then be used in conventional equipment to generate electricity at high efficiency. No evaluation of the proposal has been given, and until one is made nothing can be said of its prospects except that somewhat similar attempts in the past have not led to success.

It can be said, however, that small furnaces for cooking and other small applications are of considerable importance in highly populated and poor countries such as India and Egypt where no fuel of any kind, not even wood, can be found.

(3) The hot-house effect. This is also used in some places to heat houses and greenhouses. It is possible to use it on a large scale as a partial source of house heating. But because solar heating is either unsteady or inadequate (in cold climates) an auxiliary source of energy must be used along with it. Houses would have to be specially designed for solar heating.

The hot-house effect depends on the filtering ability of certain materials, i.e. their ability to allow more sunlight in than longwave radiation out. An accumulation of heat and a rise in temperature thus results. Some very good filters have been developed recently which can be used in the form of a coating. Their absorptivity to sunlight is as high as 93% and their longwave emissivity is 5%. Research to find even better filters is very active at present.

An exciting and widely-publicized proposal was made in 1971 by A.B. Meinel and (Mrs.) M.P. Meinel of the University of Arizona. A large metal area was to be covered with the coating filters mentioned above. The metal would heat to 560°C and molten salts or liquid metals flowing in channels in the heated metal plate would remove the heat and take it to a central container from which it could be removed and used to produce electric power. An efficiency as high as 30%, even 40%, was claimed for the system. An area of 8 square kilometers, in middle latitudes with mostly cloudless skies, would be adequate for an output of one million kw electric. A cost figure of one cent per kw-hr. was considered possible for this scheme; other estimates give the cost of the solar plant as only a few times higher than the cost of an equivalent thermal or nuclear plant. But a careful calculation by Professor Hottel of M.I.T., an expert in this area, showed that the highest attainable temperature with existing filters would be 295°C, not 560°C, and the overall efficiency using the Carnot cycle would be 11%, not 30 or 40. Thus the cost of power would go up accordingly.

There are also technical problems here that may prove insurmountable, e.g. will it be possible to pump the molten salts or liquid metal over so many square miles? And if it is, will the power necessary to do so be a small fraction of the output of the installation? The great quantities of metal plate needed may also be a problem (e.g. if a stainless steel plate of 1 cm. thickness were to be used the replacement of the present power plants by such solar plants would require several times the known world reserves of nickel).

Special non-corrosive stainless steels or titanium must be used. Other problems include dirtying of the surfaces and the need for large quantities of cooling water to remove the waste heat (where sunlight is plentiful, water is not). Alternative proposals have been made recently, including some by Meinel (e.g. nitrogen gas instead of liquid metal to collect the heat) to overcome some of the problems.

In spite of these difficulties, development of still better filters may make the method promising. A pilot plant will finally be needed to prove feasibility.

The conclusion concerning solar power is therefore that it will be useful for limited and small applications, and its role as a source of large scale power, although uncertain, is somewhat promising.

NUCLEAR POWER

It is generally believed that nuclear power (fission and fusion) is going to be the main source of energy in the future and that it could become so right now if enough money were spent to build the necessary power plants. Neither of these assumptions is completely true. The types of nuclear reactors that will be needed in the long run are not yet ready and they may never be for basic scientific and practical reasons. The types that are now ready still have unsolved safety problems that may limit their use, but even if they had not they could not be used to supply all the demand for new energy because if they did most of the cheap nuclear fuel would be consumed in a few decades and little would be left to serve as initial fuel for the reactors of the future when these become ready.

The Source of Nuclear Energy

Figure 1 is the binding energy diagram for the nuclei of the elements. The ordinate represents the energy, in million electron volts, (Mev), that is needed to remove one nucleon (proton or neutron) from the nucleus. The number of nucleons in the nucleus is plotted as the abscissa. We note that this energy is negative for all elements, i.e., we must lose it in removing the particle. But we also note that if elements on the left combine, or those on the right break up, the movement in either case is downhill. The resulting products will sink lower and lose potential energy. This energy leaves the nucleus and comes out either as kinetic or as electromagnetic energy. The break-up of the elements on the right is called fission. The combination of those at the left is called fusion. We also note that fusion, especially of hydrogen, provides more energy per nucleon than fission, i.e., about 5 Mev for fusion vs. 1 Mev for fission. (Compare with only 4 electron-volts per atom in the burning of coal). This would make fusion look more attractive than fission, but in this case attractiveness will be decided by other factors.

We shall discuss the two cases separately.

Fission

Natural uranium contains two isotopes, one of atomic weight 238, the other of 235. They are written U-238 and U-235. The two isotopes occur in the ratio 140 for U-238 and 1 for U-235. U-235 is the only naturally occuring element that can break up by the absorption of a slow (thermal) neutron. In breaking up, the fragments carry away an amount of energy approximately equal to 200 Mev. Thus if all the nuclei in one gram of U-235 broke up, the energy released would be 8.2×10^{10} joules. This is equal to the heat from 2.7 metric tons of coal or to that from 13.7 barrels of crude oil. A nuclear power plant with a capacity of 1 million kw electric at an efficiency of 30% would consume about 3 kilograms of U-235 per day or 420 kilograms of natural uranium.

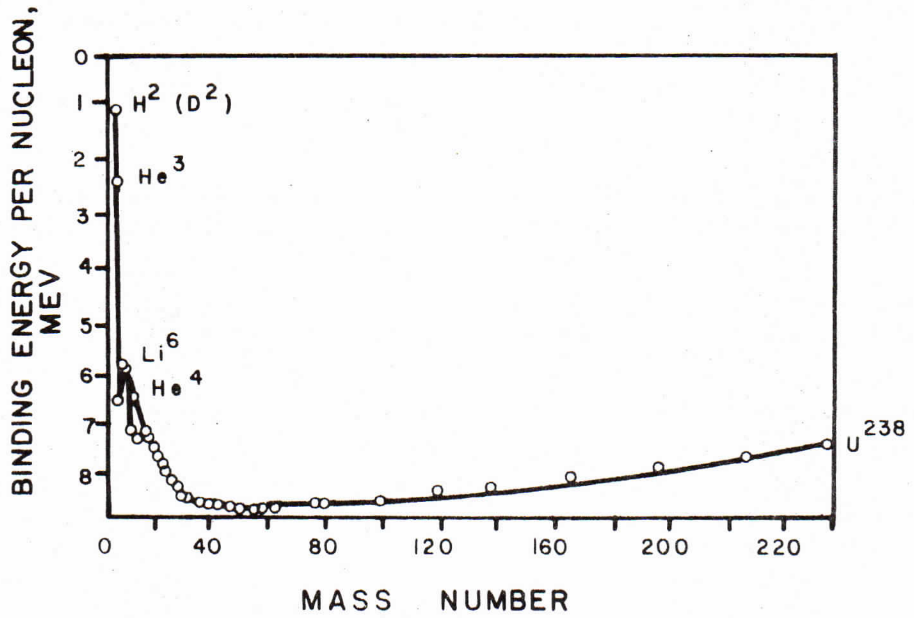


FIGURE 1. NUCLEAR BINDING ENERGY DIAGRAM FOR THE ELEMENTS.

The Chain Reaction

Suppose a U-235 nucleus absorbs a neutron and breaks up, giving off 3 neutrons. These neutrons will wander around and, in the absence of other U-235 nuclei, will enter the nuclei of other elements or even decay into protons and electrons. Nothing happens from the absorption by other elements and that is the end of the event. But if there are other U-235 nuclei in the neighbourhood some neutrons entering them will produce further fissions. If at each step more neutrons are produced than in the previous step, we have a growing chain reaction, a decaying one otherwise.

Only well designed reactors can provide growing chain reactions. This is because many elements absorb neutrons unproductively. Thus if a natural uranium reactor is filled with ordinary water, the water will absorb too many neutrons and only decaying reactions will take place. But if heavy water is used instead, growing reactions will occur because heavy water does not absorb the neutrons. Also if ordinary water is used but more U-235 (2 to 3%) is put in the reactor (i.e., if the uranium is "enriched") growing reactions will again occur. In either case the water serves to slow down the neutrons and pick up their heat. This heat can then be utilized. In all cases the uranium in the reactor is placed in the form of rods. The reaction is controlled by inserting and withdrawing neutron-absorbing rods. The level of the reactions is determined by the external demand for heat. To enrich uranium the U-235 from other natural uranium must be separated by a process such as gaseous diffusion. Most of the nuclear reactors in the world today use enriched uranium and ordinary water (some use graphite). Canada's reactors use natural uranium and heavy water.

Types of Reactors

There are three types: the burner, the converter and the breeder. The burner simply burns U-235. The converter burns U-235 and some of the U-238, which absorbs neutrons and becomes fissionable plutonium. The breeder burns U-235 and U-238 but for each amount of fuel it burns it generates a greater amount of plutonium from the U-238. Because of this the breeder has the ability to convert the entire stock of U-238 into fissionable material. In the converter the amount of conversion is not large; 1 or 2% of the natural uranium is used up, e.g. the Canadian design for Ontario Hydro burns a total of 1%. The pure burner reactor would only burn .7%, (1 in 140) of the total. A pure burner is a very poorly designed reactor. Figures 2 and 3 show schematically the reactions for the burner and breeder reactors for uranium.

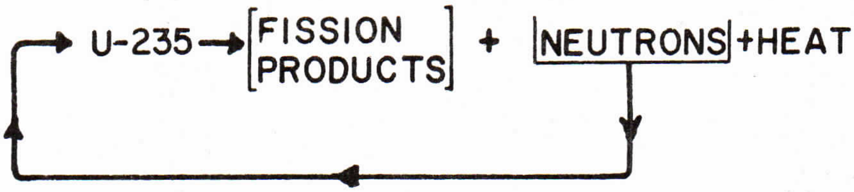


FIGURE 2. CHAIN REACTION FOR URANIUM-235. (From Hubbert, M. King, 1962, *Energy resources: A report to the Committee on Natural Resources*, National Academy of Sciences/National Research Council, Publ. 1000-D, Washington, D.C.).

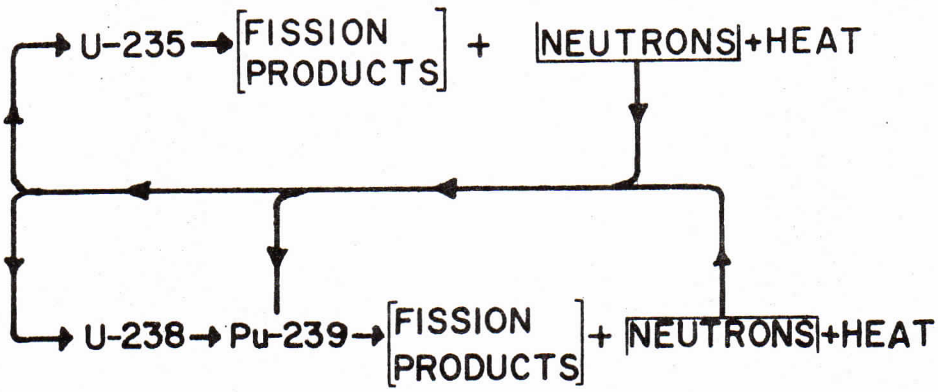


FIGURE 3. BREEDER REACTION FOR URANIUM-238 (From Hubbert, 1962).

Present-Day Reactors

These are of the burner and the converter type and consume slightly more than 1% of the natural uranium. If one could ignore problems of safety resulting from the release of radioactive elements and accept the risk, these reactors would now be ready to provide power.

A number of reactors have been built around the world to a total capacity of about 25 million kw. electric in 1970. One of the most successful and safe designs has been that of Ontario Hydro in Pickering using natural uranium. Figs. 4, 5 and 6 illustrate this installation. Light water reactors using enriched uranium have apparently been less successful, and especially so in the United States where some actual and potential failures have resulted in their being operated at a fraction of their design capacity. Safety is the principal reason for the delayed introduction of nuclear

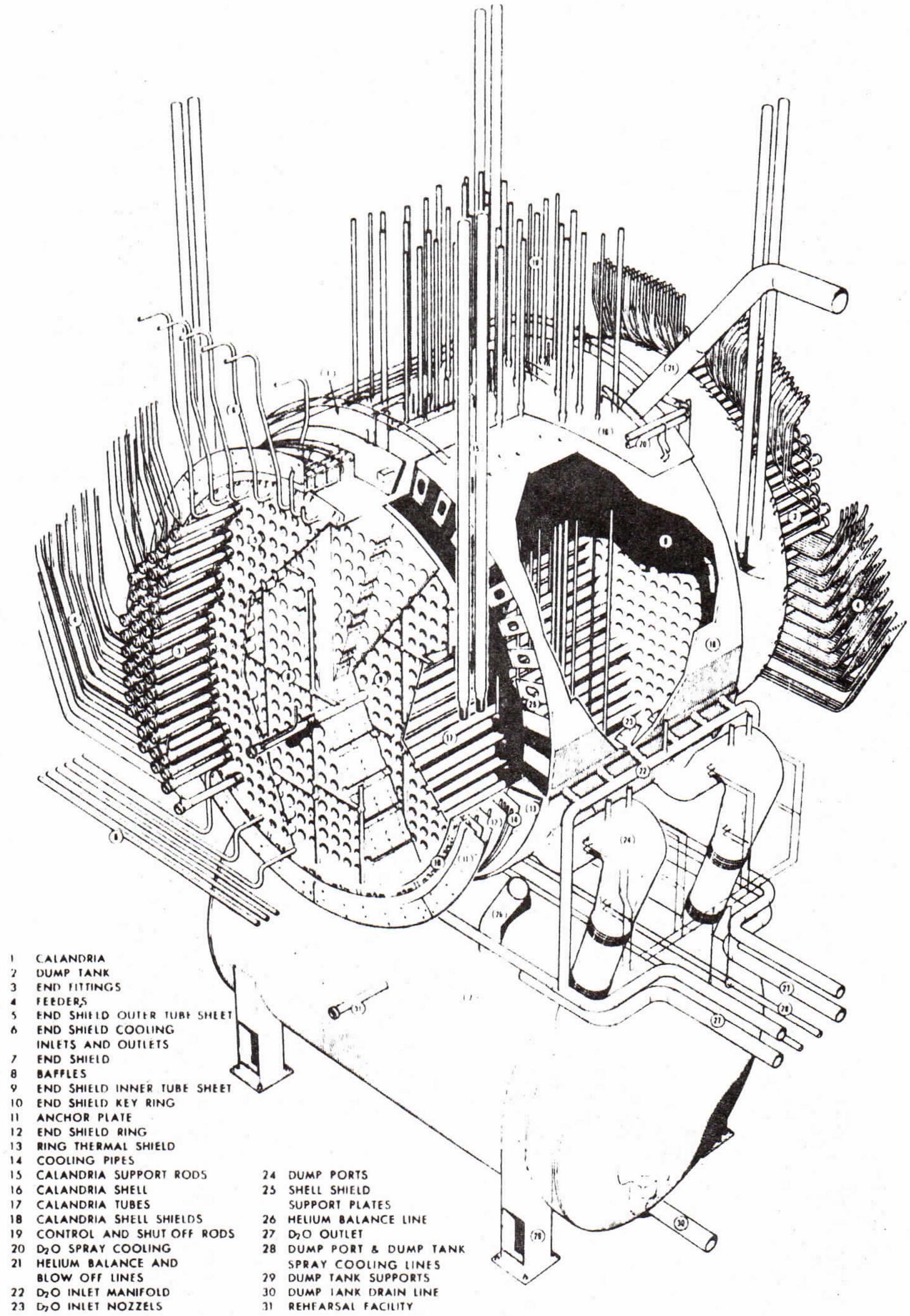


FIGURE 4. ONTARIO HYDRO PICKERING GENERATING STATION: HEAVY WATER REACTOR (Source: Atomic Energy of Canada Limited).

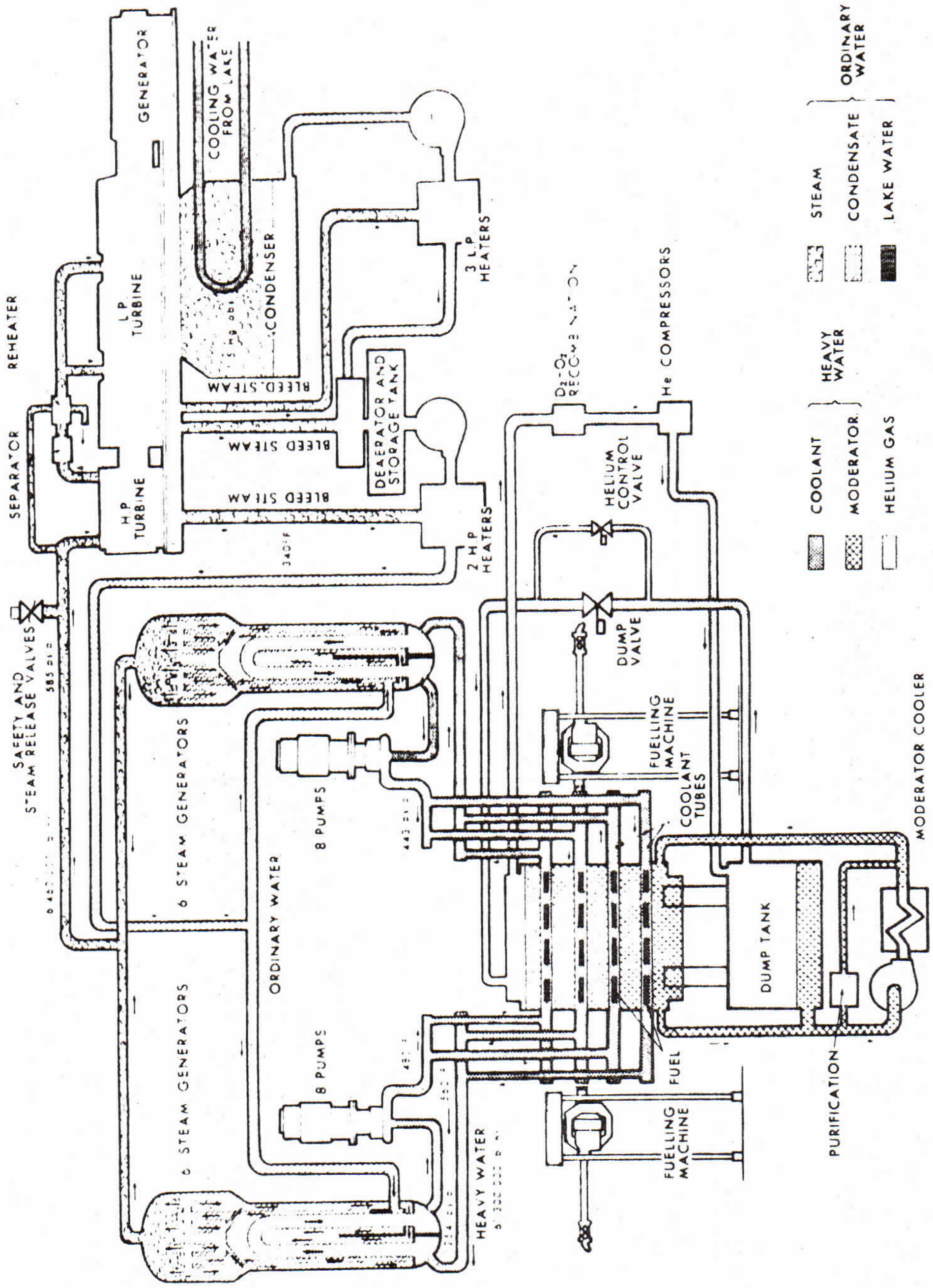


FIGURE 5. ONTARIO HYDRO PICKERING GENERATING STATION: SIMPLIFIED STATION FLOW DIAGRAM (Source: Atomic Energy of Canada Limited).

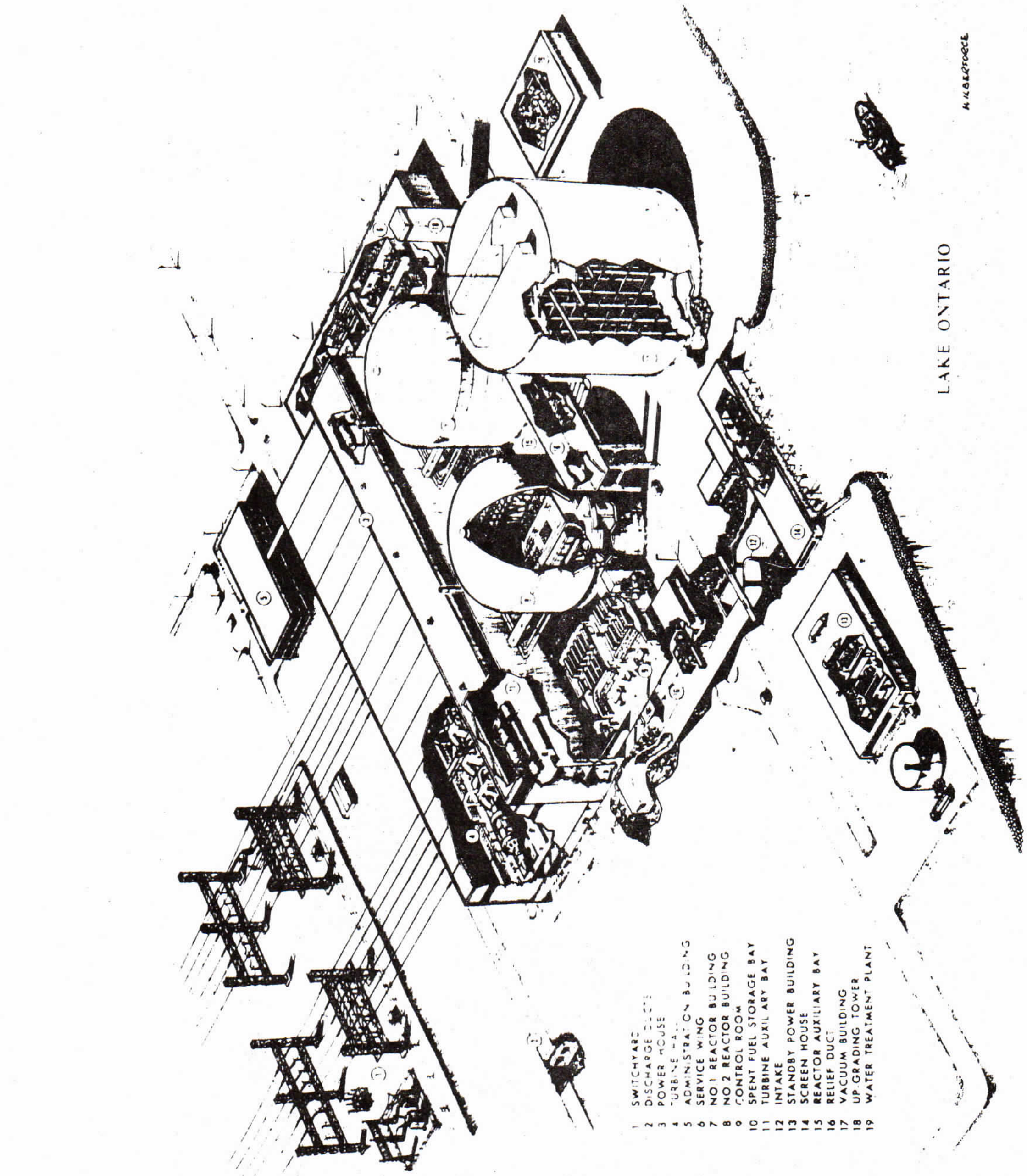


FIGURE 6. ONTARIO HYDRO PICKERING GENERATING STATION: LAYOUT (Source: Atomic Energy of Canada Limited).

reactors, but another factor that could delay them even if they were safe is the limited supply of low-cost uranium. If all the additional demand for electricity were supplied by such reactors the known reserves of cheap uranium in the world could be used up in a few decades. It would then become very expensive to start the breeder reactors of the future which must use U-235 initially in order to produce the plutonium which will be their permanent fuel. Of course plutonium that is presently in bombs could be used to start a large number of breeders. Thus, present day reactors, if actually used, will only be used to fill the gap until the breeder becomes widespread or until some other source of energy that is clean becomes available, such as fusion.[1]

The Breeder Reactor

This reactor differs from the ordinary type in two important respects:

(1) It uses a highly enriched core (50%). Future commercial breeders will contain from 3 to 5 tons of plutonium in their core.

(2) It has no moderator, i.e. water, to slow down the neutrons, but uses a liquid metal or gas to carry away the heat.

The core is surrounded by natural uranium. The fuel in both the core and the rest of the reactor is in the form of rods. Fast neutrons from the core travel out, then enter the U-238 and convert it to plutonium (Figure 3). It is the fast neutrons that can do this job unlike the fissioning of the U-235. The heat in this case is removed from the reactor by circulating liquid metal, sodium or potassium. These do not slow down the neutrons like water, and that is what is wanted. The neutrons travel through the liquid metal and only a small part of their energy is picked up by it before they enter uranium or plutonium nuclei. With liquid metals, the pressure in the reactor is low and safe. Compressed helium gas is also used in place of the liquid metals, at pressures of 100 atmospheres or so. Each alternative has its advantages. Power fluxes in the breeder are more than 2 times larger than in ordinary reactors.

The doubling time, i.e. the time needed to double the fuel in the reactor, is of the order of 10 to 20 years; more enriched fuel produces a faster, but also more dangerous, reaction. The possibility exists that the core may melt (this has already happened in experimental breeders; in Michigan, the core of the Enrico Fermi breeder melted when a beer can blocked the flow of the coolant), and the enriched mass may fall together, form a critical mass and explode in a nuclear explosion. Five tons of plutonium are equivalent to about 110 megatons of TNT. The critical mass

(1) More recent publications suggest that the resources of uranium and thorium, that can be mined economically, are much larger than earlier estimates.

of plutonium is about 5 kilograms, the critical volume being about equal to that of an orange; that of 50% enriched is larger.

Breeder reactors are at different stages of development in various countries. In the United States a commercial model (the Liquid Metal Fast Breeder Reactor or LMFBR) is expected to be ready for general use by 1985-1990. In Britain a commercial model is expected to be put into operation for testing soon, while in the U.S.S.R. a breeder of 350,000 kw. electric was put into operation early in 1972 in the desert east of the Caspian Sea.

Fuel Reserves for the Breeder Reactor

The breeder reactor would consume nearly all of natural uranium (and also thorium) and thus multiply the nuclear fuel reserves by a factor of nearly 100. Not only that, it would then be economical to mine common rock for uranium since 100 times more fuel would be obtained from the same rock. The average concentration of uranium in common rock is 5 parts per million. At this concentration the crust of the Earth should contain 10^{15} (a million billion) tons of uranium, i.e. an infinite supply as far as man is concerned. Even more significant is the fact that many extensive rocks contain uranium in concentrations of up to 60 parts per million. Thus from one ton of rock the equivalent of 162 tons of coal could be extracted. The cost of extraction would probably come to less than one dollar per ton of coal equivalent, i.e. a small fraction of the cost of coal from underground mining.

Objections to Fission Reactors and to the Breeder in Particular

All nuclear reactors produce radioactive wastes which may be very harmful to health. The problem of the final disposal of wastes has not been solved yet. With the breeder, all the problems of ordinary reactors are intensified and some new problems are created. One of these is the possibility of nuclear explosion mentioned earlier. Another arises from the large quantities of plutonium which will be produced. Five to ten kilograms of plutonium can make an atom bomb, and the designs of such bombs are available to the general public. If breeders are widely used, plutonium and atom bombs may become widely available, not only to most governments but also to organizations and even individuals. What may come of this is left to the reader's imagination. This nightmare alone is enough to cause serious doubt about the benefits of nuclear energy from breeder reactors.

Disposal of Long-Lived Radioactive Wastes

The products of fission have half-lives ranging from nearly zero to many years, and even thousands of years in the case of plutonium (which is not a product of fission but is nevertheless produced in all reactors). All radioactivity produces heat. Storage in a high heat transfer medium (water) for a few (about ten) years will allow the intense heat of the components with short lives to dissipate and will leave strontium and cesium, which have half lives of about 30 years. These must be stored for about 30 to 40 half lives or for 1000 years, after which they become harmless. The problem of where to store them for that period arises. It was intended in the United States to place them in large quantities deep in salt beds which were believed to be impermeable. The heat generated by the wastes would raise the temperature and pressure to great values but the salt beds were supposed capable of containing them. Recently, however, this method was declared unsafe. Unknown past (and perhaps future) drill holes and also ground fissures could allow wastes to escape to the ground waters or to the surface. No definite new method has been proposed. The idea of sending them to the sun is not satisfactory. Rockets can fail at launching and they can also melt if too much waste is put into them. The Canadian practice has been to place wastes in a lake in glass containers and to keep a constant watch on them. But who can guarantee a constant watch for 1000 years? The only practical and safe solution seems to be burial near the surface in small quantities and in thick concrete containers. In this manner the concrete may hold the wastes safely for a long time (1000 years?) and the heat may easily flow to the atmosphere. But large areas will be needed for this disposal method. To appreciate the problem let us calculate an example.

Assume the wastes are buried in the center of a concrete slab lying on the ground. Wide margins of safety would require the slab to be thick (10 meters). Also the temperature in the ground under the slab to great depths will eventually become the same as in the center of the slab. This may have to be kept low for various reasons. Let's assume that it is 50°C. This will allow a temperature difference of 20°C to the outside to remove the heat. The total installed electric capacity in the future is given as 40 times the present, or 50,000 million kw. Assume that it is all nuclear. Using figures for heat generation by the expected wastes (50,000 tons per year and 30 watts per kg 10 years after removal from the reactor) and for the thermal conductivity of concrete we find that a permanent area of 330,000 Km^2 is required. With some space left for passages the required area becomes about equal to that of France. The replacement time is 1000 years in this case. More frequent additions of new waste could be made and the area could be reduced. Also complex structures to improve heat transfer could be built, but these could also collapse and cause overheating.

Some other promising proposals are to bury the waste in the Antarctic ice or deep in stable geological formations (salt domes) on land.

There is also plutonium which has a half-life of 25,000 years and must be kept safely for a million years as a waste. But because its generation of heat is low it could be placed in large quantities (but safely mixed with neutron-absorbing matter!) in the salt beds. No large quantities of plutonium would be wasted since it would be used in the breeder (and be converted to other fission products).

Radioactivity and the Perils of Fission Nuclear Energy

All radioactive fission products that are produced in the reactor are highly harmful to health. Under certain conditions a few micrograms of the long-lived products strontium, cesium and plutonium, if taken internally, can cause death by cancer. This has been proven by experiments on animals. An ordinary reactor of the present type contains several kilograms of these products and a large breeder reactor will contain several tons. Thus an ordinary reactor can give a lethal dose of radiation to nearly everyone in the world - a breeder can do the same a thousand times over. And tens of thousands of such large breeders are expected to be operating in the future. Of course no one is going to take radioactive elements internally if he has a choice. But he may not have a choice, because there are biological processes in nature, some already known, which concentrate these elements in common foodstuffs. The case of strontium in milk that resulted from bomb tests a few years ago is well known. And it is believed that more processes of concentration, not known at present, exist. It is not possible at present to estimate either the quantities of radioactive elements that may be released into the biosphere in the future or the fraction of the released quantities that may end up in foods or in the bodies of man and other animals.

Unlike ordinary chemical poisons, which quickly transform themselves into harmless compounds by chemical reactions when released to the environment, nuclear radioactive poisons will only decay and become harmless with time and the time needed is very long, about a thousand years for strontium and cesium and a million years for plutonium. Theoretically it is possible to transform these elements into harmless forms by nuclear bombardment in specially built reactors, but to prove whether this is feasible in practice may take several decades of intensive research - and even if successful it would only eliminate the problem of final disposal of the wastes, but not accidents and spilling prior to it. Thus none but the smallest quantities may be allowed to leak into the biosphere. This cannot be guaranteed when millions of tons of fission products are to be produced in the future. To expect complete safety in this case is the same as to expect the laws of probability to stop operating in their normal way and to change by miracle so as to act in our favour.

Prospects for New Energy Sources

The experts assure us that so much effort has gone into the design of nuclear reactors that a safeguard has been provided for every conceivable failure. However, the non-expert, relying on his own experience and common sense can see many ways in which the biosphere can be poisoned by radioactive wastes. As the physicist Hannes Alfven put it,

> *"Fission energy is safe only if a number of critical devices work as they should, if a number of key people in key positions follow all their instructions, if there is no sabotage, no hijacking of the transports, if no reactor, fuel processing plant or repository anywhere in the world is situated in a region of riots or guerrilla activity and no revolution or war - even a conventional one - takes place in these regions. The enormous quantities of extremely dangerous material must not get into the hands of ignorant people or desperados. No acts of God can be permitted...If all these conditions (and others) cannot be guaranteed then fission power is unacceptable."*
> *(Bulletin of the Atomic Scientists,* May 1972)

If fission power is so unacceptable, why then are plans being made everywhere for its widespread introduction? The reason is clear. For decades the potential benefits of nuclear energy have been extolled, its harmful effects being either unknown or minimized and ignored, in spite of what happened to Madame Curie. The knowledge that other sources of energy were limited and poorly distributed and nuclear fuels, especially for the breeder, were in enormous quantities, made nuclear energy seem like the saviour of mankind in the moment of need. A powerful public opinion was thus created in its favour, especially in the poor countries where it was expected to transform poverty into riches. Its glamour attracted the best minds who became, and are still becoming, nuclear engineers and scientists dedicated to the "peaceful uses of atomic energy" for the betterment of mankind. Great effort has been devoted to its development and it is now ready to pour out its benefits. (And of course, as usual, those with vested interests are promoting it.)

On the other hand, its possible harmful effects have only recently started to become widely known and it may still take some time before public opinion is fully aroused. In the meantime it is very likely that many nuclear plants will be built and man will start to depend on energy from this source at least for part of his needs. It may take several serious accidents and much harm to prevent its further growth or to stop it entirely.

It is quite possible that the importance of nuclear energy for man has been exaggerated. The world has enough clean energy from coal, wood and plants and from hydro sources to take care of its very basic needs, and more energy can be derived from the winds and from solar radiation. Nuclear fission would supposedly supply those extra quantities of energy that would help improve and beautify life. If this role of nuclear energy is compared with the perils which it involves the conclusion is clear: it is a poor bargain.

At the present it is not possible to make a quantitative estimate of the peril that nuclear energy poses. The best course of action therefore seems to be a slow introduction of the safest reactors and methods of waste processing and disposal. Of the various reactors the breeder is the most perilous and should be opposed outright. Many of the existing types of ordinary reactors are also of unacceptably poor design. In Canada we have the good fortune of possessing one of the (apparently) safest reactors, the CANDU natural uranium reactor. But even with this the move into the nuclear age should be slow and careful. Only time will tell whether the risks are acceptable.

Power from Fusion

Fusion power is heralded to be the inexhaustible cornucopia that will ease the lot of man for as long as he is on this planet. With some reservations one can agree with this statement, provided fusion power ever becomes a reality. Fusion is the process that releases the energy of the sun and of the stars, and fusion energy is clean in spite of the fact that on Earth, man has achieved uncontrolled fusion in the H-bomb. But controlled fusion is a far more difficult problem and after 20 years of work, admittedly at a leisurely pace, man is not yet certain of success.

Reactions of Fusion

The isotopes of hydrogen, deuterium (D^2) and tritium (T^3), can combine to form helium, according to the following reactions:

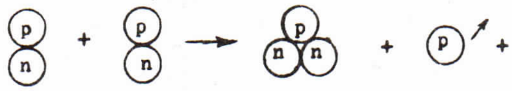
$${}_1D^2 + {}_1D^2 \rightarrow {}_2He^3 + {}_0n^1 + 3.3 \text{ Mev.} \qquad (1)$$

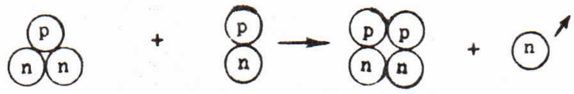
$${}_1D^2 + {}_1D^2 \rightarrow {}_1T^3 + {}_1P^1 + 4.0 \text{ Mev.} \qquad (2)$$

$${}_1T^3 + {}_1D^3 \rightarrow {}_2He^4 + {}_0n^1 + 17.6 \text{ Mev.} \qquad (3)$$

or, expressed in a different way:

+ 3.3 Mev. (1)

 + 4.0 Mev. (2)

 + 17.6 Mev. (3)

where the number on the upper right of the symbol is the atomic mass and that on the lower left is the charge; n is a neutron and p a proton; He stands for helium, D for deuterium and T for tritium. The indicated energy is carried away mainly by the neutrons in (1) and (3) and by the proton in (2). There are other reactions of less interest but the ones shown above are the most promising. In particular the deuterium - tritium reaction (3) is the easiest to achieve.

Fuel Reserves

Deuterium is a naturally occurring element making up 1 part in 7000 of hydrogen. One ton of water contains 35 grams of deuterium with an energy content equal to that from 270 metric tons of coal. Twenty-eight cubic kilometers of sea water contain a quantity of deuterium whose energy content is equal to that from all of the world's coal. The oceans could supply man with energy at the present rate of use for 75 billion years. Hence this is an infinite source of energy for man.

Deuterium can be separated rather easily from water and this is now being done on a commercial scale (heavy water). Tritium does not occur in a natural state and must be produced from lithium by neutron bombardment. The total world deposits of lithium are estimated at 7 million tons. The tritium that can be produced from these could provide an amount of energy equal to 3-4 times the energy of the fossil fuels. Common rock also contains 22 grams of lithium per ton, and this could be mined economically. It is also believed that if the D-T (deuterium-tritium) reaction (3) succeeds, the D-D (deuterium-deuterium) reactions (1) and (2) will also succeed. Thus no problems concerning the availability of cheap fuel will arise.

Theory of Fusion

If the particles are to fuse together they must be made to approach each other to a short distance. At that short distance the nuclear attractive force, which is short-range but much larger (100 times) than the repulsive electrostatic force, takes over and the particles fuse. The energy required to overcome the electrostatic force is about 5,000 electron volts for the D-T reaction and twice this for the D-D reaction, for head-on collisions. Note that 1 electron volt is equivalent to 12,000 degrees Kelvin; the corresponding temperatures are therefore 60 and 120 million degrees Kelvin. These are not very high temperatures. In accelerators a million times higher energies are achieved.

In order to carry out the reaction a quantity of the material must be heated to these temperatures. The resulting "gas" is a plasma, i.e. a mixture of nuclei and electrons. The problem of containment arises immediately. Since the plasma cannot be allowed to touch anything, for it would cool if it did (nothing would melt, the density is too low for that), it must be confined in free space and this can be done by a magnetic field. It will be recalled that a moving charged particle in a magnetic field describes a curved path because the force on the particle is perpendicular to the velocity, This is the common force of electric motors and generators. Typical particle paths are shown in Figure 7. Thus particles are compelled to move helically along the magnetic field lines and are prevented from escaping if the field is strong enough and some other conditions are also satisfied. The very strong magnetic fields that are needed are created by very large electric currents flowing in superconductors. Various devices now exist for containing plasma. Heating the plasma is another problem. It can be achieved by resistive heating with an electric current or by compressing the magnetic field.

If the plasma is heated enough and is held together for a sufficient time at high enough density, reactions will occur and energy will be released. If this energy is large enough to overcome the losses, we have scientific feasibility. If it is about 10 times larger, we have practical feasibility. At the present time scientific feasibility has been approached. For scientific feasibility the Lawson relationship must hold above the ignition point, i.e.

$$nt \geq 10^{14}$$

Where n, the particle density, is in particles per cm^3 and t is the confinement time in seconds, for devices that condense plasma in pulses.

Devices

Two main types exist: the linear and the toroidal. In the linear device the plasma travels back and forth, usually between two magnetic coils which are often called "mirrors" (Figure 8). This device has advantages and disadvantages, compared to the other. The main disadvantage is that particles escape through the coil. At present the big hopes lie with

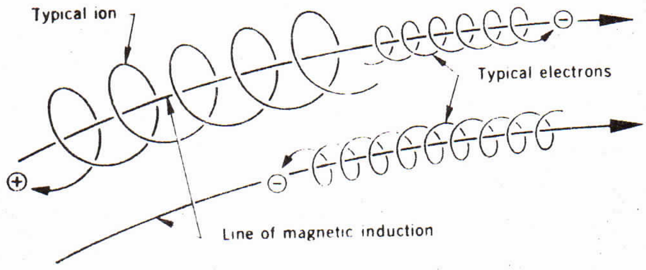


FIGURE 7. ORBITS OF IONS AND ELECTRONS IN A MAGNETIC FIELD (From David Rose, 1971, Fig. 1, Page 798, with permission. Copyright 1971 by the American Association for the Advancement of Science).

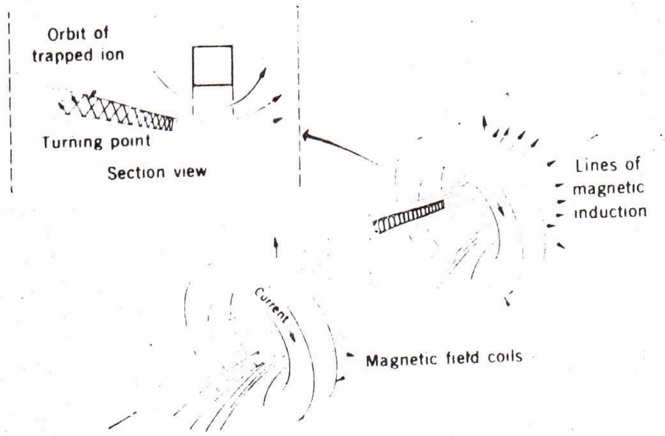


FIGURE 8. MAGNETIC MIRROR PARTICLE (AND PLASMA) CONFINEMENT CONFIGURATION (From David Rose, 1971, Fig. 3, Page 799, with permission. Copyright 1971 by the American Association for the Advancement of Science).

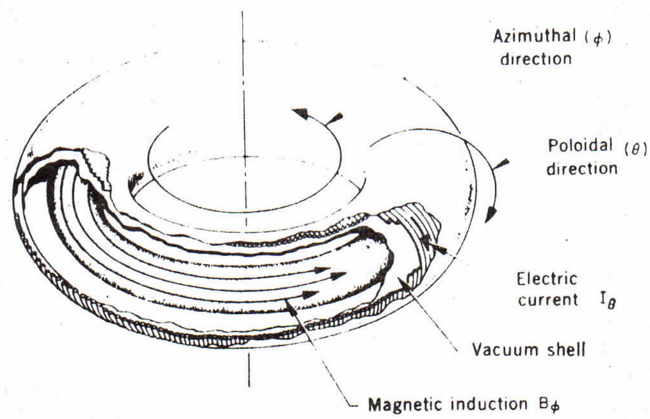


FIGURE 9. TOROIDAL MAGNETIC FIELD MADE BY POLOIDAL ELECTRIC CURRENTS (From David Rose, 1971, Fig. 2, Page 798, with permission. Copyright 1971 by the American Association for the Advancement of Science).

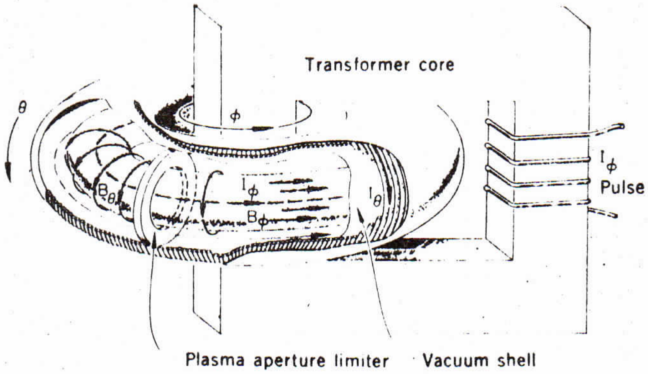


FIGURE 10. THE TOKAMAK PLASMA CONFINEMENT SCHEME (From David Rose, 1971, Fig. 4, Page 799, with permission. Copyright 1971 by the American Association for the Advancement of Science).

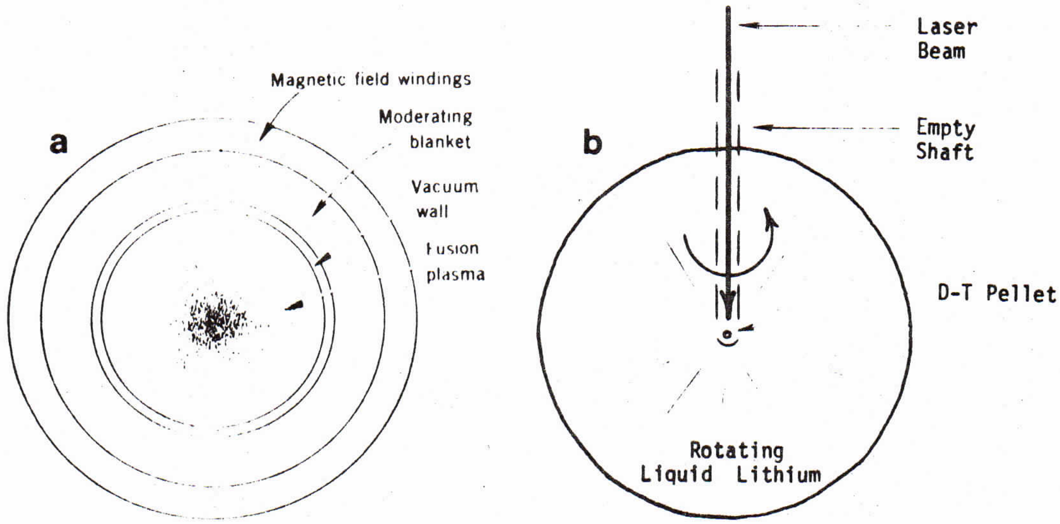


FIGURE 11. SCHEMATIC DIAGRAMS OF FUSION REACTORS (a) PLASMA TYPE (b) FUSION OF SOLID PELLET BY LASER.

the toroidal device.

A simple toroidal device is shown in Figure 9. The plasma here travels around in the torus. The most successful of these devices yet is the Tokamak shown in Figure 10. It is a simple device in which the heating of the plasma is done by a transformer. Thirty million degrees Kelvin have been achieved in this. The next generation of Tokamaks now being built in the U.S.S.R. (where it was developed) is expected to reach fusion temperatures. Somewhat similar devices known as stellarators have been built in the United States. Several Tokamak devices are now being built in the U.S. and in Germany.

Fusion by Laser

If a powerful laser beam is focused on a solid particle of deuterium-tritium the temperature may be raised enough to cause fusion. The heating must be sudden to cause fusion before the particles have a chance to scatter. Pulsed powerful lasers can achieve this. Fusion in this case will result in an explosion and in a practical reactor there would be a continuous sequence of periodic explosions. The energy might be absorbed by a surrounding liquid that should be bubbly to absorb the shock. At present the effort is concentrated in achieving fusion. The problem of designing the reactor, which may prove more difficult in this case than in the case of plasma, will come later.

Fusion by laser will also have its unpleasant aspects. It may lead to what has been called "the poor man's H-bomb". This H-bomb will probably be cheaper and easier to make than fission bombs, and its construction may take place in any case since the availability of fuel does not depend on the existence of power plants based on laser fusion. If nuclear proliferation of either the fission or the fusion type is inevitable, fusion is by far the lesser evil. Fusion bombs will produce very little radioactivity and their damage will be mechanical and thermal and highly localized.

A Practical Reactor

Technical feasibility will not automatically follow scientific feasibility. In fact it may never come. In the case of fusion by laser the difficulties are obvious. With plasma the energy is carried away mainly by neutrons which have no electric charge. A fluid must therefore be used to remove the neutron energy by ordinary heating. From the fluid the heat may be removed with conventional equipment. In a few cases the energy is carried away by protons and it may be possible to use magnetohydrodynamic methods to convert their kinetic energy directly into electricity. The walls of the reactor must fulfill some very strict requirements. They must allow huge magnetic fields to pass in and large neutron fluxes to pass out, and suffer heavy bombardment without failing too often. What materials will perform these tasks is not known at present. Figure 11 shows schematically the bare elements of some hypothetical fusion reactors of the future.

On the other hand, fusion reactors will not have the safety and pollution problems of the fission reactors. No explosions can take place with them since the amount of fuel in them at any time will be negligible and any disturbance would immediately stop them. Some radioactivity will be created by neutron bombardment but its amounts will be of the order of a million times smaller than in fission reactors. It will even be possible to locate them within cities.

Present Activity

The total effort applied to the development of fusion in 1971 was of the order of $200 million, involving about 2500 full-time scientists. Its distribution was as follows: U.S.S.R. 38%, West Germany 17%, U.S.A. 16%, U.K. 7%, Japan 6%, others 16%. This effort is really very small in view of the great potential benefits of fusion power. The magnitude of these benefits is indicated by the value of electricity produced in 1971: over $50 billion.

The important role of fusion power in the future has been indicated by some recent developments. These promising developments and the perils of the fission reactors have turned the attention of many countries towards fusion. In the United States the Director of the fusion program declared that his main problem was not a shortage of funds but of trained manpower. In Western Europe, where no significant energy reserves exist, the disillusionment with fission is opening the way for great efforts towards research on fusion. Fusion power is the number one technical problem of today.

Probability of Success

As a result of the promising recent developments the probability of success is often given as "fifty percent or better". The optimists, among whom are the Soviet experts, think that fusion power is almost certain to become a reality. As for the timing it is believed that with somewhat greater than today's efforts, scientific feasibility will be demonstrated within the next 10 years while technical feasibility may take from 20 to 40 years (or perhaps never), depending on the effort. Economic feasibility is very likely to follow technical feasibility unless materials that are scarce or have become depleted by then are required.

THE PROBLEM OF THE NEW ENERGY SOURCES

The realization that man is faced with an energy shortage has come quite suddenly. This has been the result of the exponential growth in the rate of use of petroleum and gas and the recently acquired certain knowledge that their remaining reserves can only last for a relatively short time. The problems associated with fission power have intensified this realization. Research to develop new energy sources has been slow or even neglected. Oddly enough, the U.S.S.R., which among the major countries least needs new energy sources, has put the largest effort into this research. This may be due to its larger scientific force and the lesser preoccupation with short-term problems of the competitive type that is more typical of private enterprise. But it may still be possible to develop new energy sources and have them ready when they become badly needed. The world has more than 10 million engineers and scientists and almost 3 million of them are occupied in research and development. It would only be proper, and not very difficult, to direct a larger fraction of them to the search for solutions to the energy problem and other major environmental problems in order to find solutions within the next few decades. If the numbers are not sufficient, many more can be trained in the next few decades. It should be stressed that, in a sense, research costs nothing or very little. It uses few non-renewable resources and utilizes human intelligence which is renewable and plentiful and would be wasted if not used in this way. Intelligence is a resource that should be used to the maximum.

THE WORLD WITHOUT NEW ENERGY

If the probabilities of success of deriving large amounts of power from fusion, wind and solar radiation are 50, 25 and 20 percent respectively then the probability that none of these methods will succeed is 30 percent. If in addition fission reactors are not used because of their health hazard, what energy is there left for man to use?

There is enough coal to last for several centuries even if the present rate of energy use in the world were doubled or tripled. In addition there are continuous sources of indefinite duration. They are, mainly, hydro power and wood. Smaller quantities from solar radiation can be derived for space heating, while energy from the wind is uncertain but could be significant. Hydro power could be developed more thoroughly to add roughly 1500 million kilowatts to the estimated 3000 million kw at present costs. Part of it could be used directly as electricity, part could be converted to a fuel, possibly hydrogen. Wood and plants could be efficiently managed to provide perhaps 6 billion tons of coal equivalent per year. All these quantities are listed in Table 1.

TABLE 1: CONTINUOUS SOURCES OF ENERGY FOR THE WORLD (Billion tons of coal equivalent per year)

Source	Present	Additional Possible	Total
Hydro	4.5 ($3x10^9$ kw)	2.2 ($1.5x10^9$ kw)	6.7
Wood, plants	-	6	6
Solar space heat	-	1-2	1-2
TOTAL	4.5	9+	14+

We might assume that the population of the world may lie between 7 and 20 billion. At 7 billion there would be 2 tons of coal equivalent per capita. This is somewhat below the level of Italy. At 20 billion there would be .7 tons per capita, which is above the level of China. Since the Chinese can maintain good physical and mental health on a smaller amount it should be possible to do even better, especially if intellectual and cultural activities are developed to a high level to compensate for the losses in the material field. However, with a world population of 20 billion there will be other problems to worry about besides energy.

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