NUCLEAR FUSION AS AN ULTIMATE POWER SOURCE

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I. ENERGY, TECHNOLOGY, AND TIME SCALES

If you ask the man on the street what he thought of nuclear energy, most of the time you will get an answer indicating that he is dubious or unenthusiastic about it. I think such a reaction is due to two reasons: some people resent high technology, and other people are afraid of nuclear energy because of the radioactivity that it involves. In my talk today, I will try to relieve some of this anxiety, which is largely unwarranted; and I will try to explain the difference between nuclear fission and nuclear fusion, the latter being a much more environmentally acceptable form of nuclear power.

If there ever was a high technology solution to a problem, it would certainly be nuclear fusion. This is one of the most difficult scientific challenges ever undertaken by man. There is nothing really wrong with high technology; people don't like it only because they don't understand it. Solar power, and even coal, in spite of the problems these sources have, are very popular solutions because people think they understand them. Yet the public has accepted many products of technology which they cannot understand any better than nuclear power. How many have not enjoyed the benefits of watching color TV? Or crossed the continent in four and a half hours by jet? Or made theatre reservations via the computer at Ticketron? Most recently, modern technology has brought us digital watches that are not only much more accurate than mechanical ones, but are also much more inexpensive. The point is that sophisticated technology is here to stay. There is no return to a world of half a billion people and trees everywhere. We need the help of science to survive in a world of increasing population and depleting resources.

The need for new power supplies is shown in the first few slides; I am sure you've seen similar ones before. The first slide (Slide 1) shows the growth of population and of energy consumption as a function of time. If this increase in energy consumption is plotted on a logarithmic scale (Slide 2), we see that the growth of energy use as exemplified by electricity consumption in the United States is such that the demand doubled in only ten years; then it slowed down so that the doubling time was thirty-nine years, and recently it has sped up again to a doubling time of thirteen years. People talk about solving the energy crisis by using conservation, but most methods of conservation will save only between 7% and 40% of our energy consumption. The next slide (Slide 3) shows the effect of an optimistic 30% saving, on the average. You see that this will help only in the short run. When the energy consumption is doubling every few decades, a saving of 30% is not going the solve the long range or even the intermediate range problem. The next slide (Slide 4) shows the projected energy demand and the amount we can get from the usual sources: coal, oil, gas, and hydroelectricity. You see that there is a growing deficit which has to be made up by nuclear energy or other renewable resources.

The so-called energy crisis is not one crisis, but three. The next slide (Slide 5) will make clear the time scales involved. In the near term, that is, the next two to four years, up until about 1983, we will be concerned with the price of oil and gas, and with conservation. The federal government is mainly concerned about this near-term crisis because the term of office of our president is only four years. In the intermediate term, which covers the next thirty years up until about 2010, there will be a period of diminishing fossil fuels and developing technology. In this period, we will depend on increasing our use of coal and of the present form of nuclear energy, that is, in light water reactors or LWR's. We would be very lucky to get through this intermediate period without stumbling and bumbling. We will probably have brown-outs and energy rationing because we will not have had time to perfect new energy sources,and legislation will be too slow to keep up with our increasing needs. However, going through this intermediate crisis would not be so bad if there were something worth looking forward to in the long term. The long term crisis concerns the years between 2010 and 2040 or 2050. This is the main subject of my talk today. In this period, our reserves of fossil fuels and natural uranium will mostly be exhausted. We will have to depend on renewable sources of power: solar power, fission power in the form of breeders, and fusion power.

The time scales involved here are set by the rate of consumption of fossil fuels (Slide 6). For instance, here is a projection of the rate of oil production. You see that it reaches a peak around the year 2000 and will go down to almost zero by the year 2050. The shortness of this time scale can be appreciated if one plots this curve on the time scale of the history of man. The next slide (Slide 7) starts at 2000 B.C. and runs to 6000 A.D. The present time, about the year 2000, is at the center. I have marked various events in history, such as the pyramids, the fall of Rome, the birth of Christ, Columbus, and so forth. This sharp spike marks the period during which we started and stopped using fossil fuels. You see that in this perspective, this is an extremely short period, and we are living in a very privileged era when our legacy of fossil fuels is still available. If mankind is to survive in the future as long as it has in the past, we will need to find an inexhaustible source of energy.

II. FISSION VERSUS FUSION; FUEL SUPPLIES

We can get energy from the nucleus of atoms in two ways: by fission, which is the splitting of large nuclei, and by fusion, which is the combining of small nuclei into larger ones. Let me make clear this difference. In fission, (Slide 8) the nucleus of a large atom,such as this large uranium atom here, is split by a neutron. The atom is made of 235 neutrons and protons,which are the fundamental constituents of matter. After splitting, several neutrons may be left over. And these then may go on to split other atoms and thus promote a chain reaction. A large amount of energy in the form of heat is released in the process. These fission fragments however, are likely to be radioactive, and the neutrons themselves, when they hit the wall material and whatever else is in the reactor, will tend to make the materials radioactive also. (Slide 9) A fission nuclear plant looks like this. The nuclear core, consisting of the fuel and the coolant, is housed in a strong container, and the coolant is then brought through a series of heat exchangers,and ultimately the heat is used to produce steam to drive a turbine that drives a generator to produce electricity. (Slide 10) A nuclear reactor like this works quietly and emits no smoke into the atmosphere. But of course, people worry about accidents which can spread the radioactivity inside, and there is great concern about the disposal of radioactive waste (Slide 11). I shall have more to say about this later.

In fusion, two isotopes of hydrogen combine to form helium (Slide 12). This one, with one proton and one neutron, is called deuterium;and this other one, with two neutrons and one proton,is called tritium. Now the product of the reaction, helium, is an inert gas, the same gas that you use to fill birthday balloons. There are no radioactive products, but the neutron activates the materials around the reactor,and tritium is a radioactive isotope which must be contained. Also, tritium does not occur naturally and it must be bred. This is not the only possible fusion cycle--it is the easiest and the dirtiest--but even so, it is much cleaner than fission.

In DT fusion (Slide 13), we need to breed tritium from lithium. The fusion breeder reactions are: deuterium plus tritium gives helium plus a neutron, and the neutron plus lithium gives helium plus the tritium back. So the raw materials are water, from which we get deuterium, and lithium. The main fusion fuels (Slide 14) are shown here. Deuterium is obtained from ordinary sea water by isotope separation, and tritium is obtained from natural lithium, which contains both lithium-6 and lithium-7, by breeding with neutrons. Another fusion fuel which we shall talk about later is the rare isotope helium-3. There are various natural sources of helium-3, but to produce it in quantity we would have to breed it from the DT reaction. The main fission fuels are shown in slide 15. Here we must recognize that there are two distinct kinds of fission reactors. The light water reactor, which is the type that we have today, burns U^{235}, which can be obtained by isotope separation from natural uranium. Only 0.7 percent of natural uranium is the fissile isotope U^{235}. The rest of it is U^{238}. Another fuel that the LWR can use is U^{233}. This can be obtained by neutron breeding from thorium-232. The other type of fission reactor is the fact breeder reactor, or LMFBR. The fuel used there is plutonium, which is obtained by breeding from U^{238}. So the main fission fuels are uranium and thorium. Slide 16 shows the world supplies of these "inexhaustible" fuels. We see that as of 1976, oil resources are about 430 terawatt -years, and all fossil fuels amount to 2,600 terawatt-years. The amount of uranium, if used in LWR's, is equivalent to only 70 terawatt -years. This is because LWR's use only the 0.7 percent of natural uranium which is the isotope U^{235}. If our supplies of uranium are used in LMFBR's, the U^{238} can be used; and this would yield 10,000 terrawatt-years. For fusion, supplies of lithium, if used in a DT reactor, would amount to 11,000 terawatt- years. By way of comparison, the world consumption rate in 1975 was 8.6 terawatt- years per year. And the future consumption rate, assuming a population of 8 billion people, each consuming 6 kilowatts (which is half the present U.S. rate), would be 48 terawatt -years per year. So you see that uranium and lithium will last for several hundred years, even if we assume the present prices. In reality, the supply is much larger than that because we can afford to mine ores that are much less rich. This is because the cost of fuel in these reactors is negligibly small. The main cost is in the capital equipment.

I should point out (Slide 17) that there is also DD fusion, where two deuterons combine to form either helium and a neutron, or tritium and a proton. Since the raw material here is only the deuterium in the oceans, the energy supply is really enormous (Slide 18). In ordinary sea water, there is one atom of deuterium for every 6700 atoms of hydrogen in H_2O. The energy equivalent of the deuterium in one gallon of water is that of 300 gallons of gasoline. The cost of extracting the deuterium is negligibly small. In the oceans of the earth, there are 10^{43} deuterium atoms and this amount of deuterium would give us enough energy at the extrapolated future consumption rate to last one billion years, even if we use it at only 10% efficiency. The supply is really inexhaustible. Even if we could manage to use up all the deuterium in the ocean, the level of the water would drop less than one inch.

The point is that atomic energy is a very concentrated form of energy. If we can learn to use it safely, there would be no supply problem. To give an example for fission: the energy content of natural uranium, if used in a breeder reactor, is worth three million times its weight in coal. Similarly, natural lithium, if used in fusion plants, is worth one and a half million times its weight in coal. This means there needs to be less mining and despoiling of the environment than if we used coal. (Slide 19). One doesn't have to depend on rich deposits uranium or lithium such as are mined today. There is a lot of nuclear energy in ordinary rock. Chattanooga black shale in eastern Tennessee contains 60 grams of uranium per metric ton of rock. This is the energy equivalent of 162 tons of coal or 822 barrels of oil. If you mined 50 km^2 of this rock to a depth of 5 meters, you would get the energy equivalent of all the petroleum deposits in the United States. If you mined 1500 km^2 (that's an area about 25 miles x 25 miles), you would get the energy equivalent of all the initially minable coal in the United States. Here is a story I've heard but have not verified: A piece of coal contains a tiny little bit of uranium. But that little bit of uranium has as much energy in it as the energy you would get by burning the coal. So you could burn the coal, and you would still have the uranium left. (Slide 20) Of course if you were to use low-grade ore, you will not mine it from the earth; you would get uranium and lithium from the oceans. There is a lot of ocean on the earth, as we all learned in elementary school; and the uranium and lithium content of the oceans can supply all of our needs almost indefinitely. We would not have to dig mines at all.

III. FUSION--PHYSICS

Now let me turn my attention exclusively to fusion. Ten or fifteen years ago, it was possible to give only a starry-eyed view of fusion, presenting it as a science fiction type of energy source that was too far off to take seriously. Today, there has been enough progress that we can give some hard facts, including a schedule for putting fusion power on line.

But let us start with the starry-eyed view. (Slide 21) Our sun is a star that gets its energy from nuclear fusion. The temperature at the center of the sun is about 20,000,000^{o}C. At this temperature, the hydrogen slowly combines to form helium. It takes millions, or even billions, of years for a given atom of hydrogen to undergo a fusion reaction; but the energy released is so great that this slow reaction rate can supply all of the sun's heat. We are trying to reproduce this reaction on the earth. To do so requires heating a hydrogen gas to tremendous temperatures--even higher than in the sun--because we can't wait a million years. A gas at these temperatures, goes into what is called a plasma state--a plasma in this context is a hot gas that is electrified. All the atoms have been broken apart into positive nuclei--or ions--and negative electrons. (Slide 22) As one looks into deep space, all the light that one sees comes from plasmas. Ninety-nine percent of the universe is in the plasma state. On the earth, our atmosphere is too dense for plasmas to exist naturally, and we see plasmas only in such places as the inside of fluorescent lights or in the aurora borealis. (Slide 23)

The reason large temperatures are necessary is that the hydrogen nuclei are positively charged, and like charges repel one another with a strong electrical force. The nuclei must be moving fast enough that they can overcome this force in a head-on collision; otherwise they could not come together to fuse into helium. Fast motion of the particles in a gas means high temperature, because that's what temperature <u>is</u>. Most of the time, the nuclei will be jostling around and bouncing off one another, but once in a while (say, once in a million collisions) there will be a direct head-on collision, and fusion will take place. But temperature is not the only requirement (Slide 24). This slide shows what is required for fusion between the isotopes deuterium and tritium. It takes a temperature of 100,000,000^{o}, a density of 10^{15} particles per cubic centimeter, and a confinement time of 1 second. Each of these requirements has been achieved, but not all simultaneously. Actually, it is only the product of density and confinement time τ that matters; this must be greater than about 10^{15} cm $^{-3}$ sec--a number called the Lawson criterion. We will see later, that the laser fusion approach achieves 10^{15} a different way--using very short confinement times (10 trillionths of a second) and very high densities--about 10,000 times solid density, or about as dense as a white dwarf star. Now, this temperature and this density imply a pressure of 32 atm. We can then appreaiate the difficulty: we must hold this pressure without using any solid materials, which would melt at only thousands of degrees. The sun uses its gravitational field to hold a gas together, but this is not a force that we can control on the earth. We have only two non-material forces that we can use--electricity and and magnetism (or, together, the electromagnetic field). Now, it is clear that an electric field alone will not work because the positive hydrogen ions must be neutralized by an equal number of negative electrons so that the plasma as a whole has no repelling force. This means that both the positive and negative particles have to be confined. An electric field cannot do that since, if it pushes one way on ions, it will push the opposite way on electrons. This leaves the magnetic field.

Now, a magnetic field exerts a very strange and subtle force called the Lorentz force. It acts almost indirectly on a charged particle. Imagine that I am a positive hydrogen nucleus--a proton--and suppose that there is a magnetic field going straight up and down. As long as I don't move, the magnetic field doesn't exert a force. If I move forward, the field pushes me sideways. If I move backwards, it pushes me to the other side. The force never directly opposes my motion. The faster I try to move, the greater is the sideways force. Now, if someone pushes me sideways all the time while I'm trying to walk, I'll end up walking in a circle. My motion will be circular for the same reason that a ball tied to a string will spin in a circle--the force pulling on the ball is always perpendicular to its motion. (Slide 25) So the protons move in circles in a magnetic field as shown here, and are trapped as far as sideways motion is concerned. Since the force acts sideways rather than directly, it works equally well on the negative electrons. Only they spin in the opposite direction. It is only because the magnetic force acts sideways that it is able to restrain the motion of both positive and negative particles. Unfortunately, the magnetic field does not have any effect on the motion in the same direction as the field itself, and the gyrating particles can move at will in this direction. To confine them, one has either to scrunch the field together like this, forming what is called a magnetic mirror, or one has to bend the field lines around so they close on themselves.

This would be simple if plasmas behaved like ordinary gases. The trouble is that the particles in a plasma are electrically charged so they can move and create their own electric and magnetic fields. Every time you try to form a magnetic bottle or magnetic trap, the plasma will wiggle around and find a way to leak out. It has taken more than twenty years to learn how to control the motion of plasmas in magnetic bottles. Some pretty wild configurations have been tried in these years. For instance, the next slide (Slide 26) shows a figure-8 stellarator where the field is twisted up like a pretzel. The next slide (Slide 27) shows a baseball coil where the current flows in a conductor that is shaped like the seam on a baseball. This is a picture (Slide 28) of a modern sculpture we found in downtown Atlanta during a plasma conference. This is a direct copy of the magnetic field configuration in a device called a yin-yang coil at the Livermore Laboratory. Here (Slide 29) is a page from a catalog of different ways to make a magnetic trap. I call this the thermonuclear zoo.

The upshot of all this research is that we have settled on three major approaches (Slide 30). In magnetic confinement, they are the tokamak and the tandem mirror; and in inertial confinement, it is the implosion of a small pellet by using powerful lasers. The tokamak is by far the leading candidate for the first demonstration reactor. It is a Russian invention that looks like this (Slide 31). The magnetic field created by current in these circular coils is bent around in a torus, or doughnut-shaped tube. In addition, the field lines are given a twist by running a large current through the plasma itself. After all, a hot plasma is a good conductor of electricity. This is a drawing (Slide 32) of a large tokamak research device being built at Princeton. You see the large toroidal vacuum chamber where the plasma is to be created, the large coils which produce the magnetic field, and here at the side is the neutral beam injector which is used for heating up the plasma to the proper temperature. To show you some pictures of hardware, here is a large tokamak (Slide 33) under construction in Germany, and here (Slide 34) is a smaller one that we have runnning at UCLA. Tokamak research is being done in many countries around the world.

The tandem mirror (Slide 35) is an approach being followed mainly at the Livermore Laboratory. It consists of a straight magnetic field section plus two plug sections, in which the field lines are squeezed together, and in which a very hot and dense plasma is created. It takes a lot of power to heat the end sections but they are small and they serve to stopper the losses from the large main plasma. A related type of machine called a field-reversed (Slide 36) mirror. This concept is our best bet to make a small reactor that can easily be deployed wherever needed. Small reactors like this are greatly desired by the electric utilities. But we are still very unsure of whether the field-reversed mirror will work.

The newcomer to the field is laser fusion. (Slide 37) This is a model of the large 8-beam carbon dioxide laser which is operating at Los Alamos. The idea here is not to confine the plasma at all, but to heat it so fast that it reacts before it blows apart. This is called inertial confinement. To do this requires making small pellets (Slide 38) filled with DT fuel. Here is a picture of a pellet sitting on the head of a pin. (Slide 39) This is a glass micro-balloon of the type being used for present day experiments. They have to be perfectly symmetrical. (Slide 40) The pellet is zapped by many laser beams which vaporize the surface, and the plasma which is created expands like a jet exhaust. The counter-reaction then compresses the core of the pellet to 10,000 times solid density, and the fuel burns in the fraction of a billionth of a second that it stays there. The 24-beam Shiva laser (Slide 41) at Livermore can deliver almost one hundred times the total electrical power output of the United States for a billionth of a second. A reactor (Slide 42) would have a vessel that can take the blasts of these micro-explosions set off ten times a second. There would be a problem with materials fatigue. But more serious is the problem of classification. Laser fusion is partly classified. This relation to the weapons program is both a blessing and a curse. The good news is that the ability to simulate weapons effects in these micro-explosions will make it much easier to achieve a nuclear test ban. Using these micro-explosions, we could test defensive weapons without setting off explosions underground. Even if it never produced any power, laser fusion would be worthwhile if it achieved the objective of a nuclear test ban. The bad news is that if laser fusion is used as a power source, there is a danger of proliferation--not of classified materials, as in the case of fission, but of classified knowledge. There are many other ways to achieve magnetic or inertial fusion but these are the main ones.

IV. FUSION--ENGINEERING

To understand the engineering problems of fusion, we must look at a reactor in a little more detail. The next slide (Slide 43) shows diagramatically the different parts of a fusion reactor. This is a tokamak with a donut-shaped vacuum chamber which you see in cross section. The plasma, shown in red, is created and heated inside the torus. These D-shaped coils form a large electromagnet which fills the volume inside them with a strong magnetic field used to hold the plasma. The current in these huge coils is carried by superconductors which must be kept at a temperature below 10^{o} absolute, or -440^{o}F, by immersing them in liquid helium. The plasma, of course, is at a temperture of $100,000,000^{o}$C or $180,000,000^{o}$F. Between the coils and the plasma are these two blue zones. The outer one is a shield to stop neutrons and other radiation from hitting (and heating) the coil. The inner blue zone is a lithium blanket in which pipes carrying liquid lithium carry away the heat generated by the fusion reaction. The lithium serves a dual purpose. It acts not only as a coolant but also as a breeder for tritium. You remember that tritium is not a natural isotope of hydrogen but must be bred by neutrons reacting with lithium; so the lithium must be continuously processed to remove the tritium. Now, lithium is a metal, like sodium, that melts near the boiling point of water and is very corrosive. If lithium comes into contact with water or moisture, such as in air or cement, it burns. This chemical hazard is a serious one for fusion reactors. It can be minimized in less well developed designs using solid lithium compounds and gaseous helium cooling. But the safety studies I will refer to assume the worst case where liquid lithium is used.

These small loops are divertors where escaping plasma is captured and the unburned tritium is pumped out and recovered. The wall of the blanket that faces the plasma is called the "first wall", and it is a matter of great concern. There can be a layer of carbon protecting it from direct x-ray radiation from the plasma, but the first wall will be exposed to a very intense neutron flux. These neutrons, in passing through the wall, can make it highly radioactive and degrade its mechanical strength. The choice of material is a compromise among high operating temperature, long life, and low radioactivity. Every few years the wall will have to be replaced. Old wall material must go into radioactive waste storage. Every day the reactor is shut down for maintenance and repair costs the power company a million dollars. Conservative designs use stainless steel as the first wall material. Other materials such as aluminum, vanadium, molybdenum, or niobium would become less radioactive but each one of them has at least one disadvantage. For instance, aluminum has a low melting point. Molybdenum is hard to weld and fabricate, and vanadium and niobium cannot at present be produced in large quantities. It is likely, therefore, that ordinary stainless steel will be used, at least at first. This will give us a pessimistic estimate on the amount of radioactivity, so we must keep in mind that some day a better material may be found.

The reactor is then enclosed (Slide 44) in a concrete containment structure like this. The tokamak itself would have to be made in pieces that can be taken apart and put together by remote control. (Slide 45) The reactor is but a small part of the entire power plant (Slide 46), which would include heat exchangers from lithium to sodium and from sodium to steam, and then the steam turbines that drive the electric generators. There are many other sub-systems such as the plasma fueling and heating equipment and the tritium processing plant.

V. SAFETY

I know that the question uppermost in most people's minds is: How safe is fusion? After all, it is another form of nuclear power. The question of whether fission--the type of atomic power we have today--is safe and, in particular, whether the plutonium breeder is safe is one that may never be answered. The scientists will maintain that the dangers are insignificant, and the environmentalists will never believe them. The subject is an emotional one. We can, however, ask another question that can be answered scientifically rather than emotionally: How do fission and fusion breeders compare in safety, all else being equal? Even this question will get you a different answer depending on whether you ask a fission expert or a fusion expert. Fortunately, eighteen months ago, a very thorough study of this question was carried out by a team of four experts--two Germans and two Americans--of which two were fission proponents and two fusion proponents. These were Häfele and Kessler from Austria and Germany, John Holdren from Berkeley, and Jerry Kulcinski of Wisconsin. Holdren and Kulcinski were supposed to stand up for fusion. But actually, Holdren is a fission expert who has written critically of both fission and fusion. In spite of this bias, the conclusion of this HHKK study, as I shall call it, was that fusion in a DT tokamak is between ten and one thousand times safer than fission in an LMFBR breeder. The comparison is not straightforward. The next slide (Slide 47) shows the evaluations that have to be made. There is the amount of radioactivity in the reactor plant, the types of radioactive material and their half-lives, the biological hazard potentials (that is, how dangerous each material is to human beings), the ease of dispersal of material (that is, how it can be released to the environment), and finally, how the released radioactivity can be taken up by human beings. There are also several entirely different types of danger from radioactivity (Slide 48). There is the release of radioactivity in routine operation. There are catastrophic releases; that is, accidents. There is a problem of storing radioactive waste. There is the susceptibility to sabotage. And finally, there is the problem of after heat; that is, if cooling is interrupted, the radioactivity in a reactor can cause heating, melting, and vaporization of the nuclear core, giving rise to the possibility of releasing the radioactive materials. I shall now show the results of the HHKK study on each one of these effects.

First, consider the total radioactive inventories (Slide 49) in two plants with the same electrical power output--one a fission breeder (LMFBR), and one a DT fusion reactor with a stainless steel wall. The time axis is logarithmic; that is, each successive number means a ten times longer time. Here is one second, one year, one thousand years. You see that at time zero, when the plants are still in operation, just before they are shut down, fusion has almost a factor of ten fewer Curies/kW_{th} than fission. After the plants are shut down, the radioactivity starts to decay, but at different rates because different elements are involved. In fission, the activity comes from the fuel, the fission products, the activitated structural material, the coolant, and so forth. In fusion, there are no radioactive reaction products, but the stainless steel structure will be activated, as will the impurities in the lithium coolant. But the largest part will come from the tritium inventory, in spite of efforts to circulate it fast and thus reduce the amount stored. After about a year, the two curves actually become comparable. Beyond that, we are talking about the problem of waste storage. After 12 years, the fusion curve drops sharply, mainly because that is the half-life of tritium. In this region, between a hundred and ten thousand years after shutdown, fusion is more than one hundred times safer than fission. To put it another way, fusion wastes have to be stored only one hundred years instead of several thousand years as for fission. After the stuff decays about a million times down to about here, it is safe and no longer a cause for concern. You must remember that stainless steel is a poor choice for this purpose. Fission would be ten times better still if vanadium, molybdenum, or aluminum could be used for the wall material.

Now, a Curie is only a measure of the number of disintegrations per second, the number of clicks per second on a Geiger counter, if you will. A better measure of safety than this inventory is the biological hazard potential, which also takes into account how dangerous each isotope is to human beings. Here (Slide 50) is a plot for those elements that can be inhaled. The hazard is expressed as a number of km^3 of air necessary to dilute the radioactivity down to a tolerable level. You see that fusion is 50 to 1000 times less hazardous than fission. The discontinuous jump in the fission curve is due to the fact that the fission fuel rods are assumed to be sent to a reprocessing plant after one year of operation. Now, a factor of 100 difference looks unimpressive on this logarithmic scale; to appreciate it, one should really plot it on a linear scale. (Slide 51) Here you see the factor of 100 between the I^{131} hazard in fission and the tritium hazard in fusion. If one looks at isotopes that can be ingested (Slide 52), then one has a similar picture, but here fusion is only about ten times better than fission. Now we come to the matter of leakage of radioactivity during normal operation. For fusion, the problem is the leakage of tritium and for the LMFBR it is the leakage of iodine, krypton, and alpha emitters--not from the power plant, but mainly from the reprocessing plant. The HHKK paper concludes that there should not be a severe problem in meeting the acceptance standards of safety here. Of more concern is the question of non-routine releases; that is, of accidents. The business of enumerating sequences of events that could cause an accident and calculating the probabilities is much too complicated for me to explain or even to understand. Let us simply suppose that an accident happens and look for sources of explosive energy that can disperse the radioactivity outside the plant boundaries. In fission, one worries about the loss of coolant, which would cause the reactor to melt. Then the fuel could get compacted and go super-critical. This simply cannot happen in a fusion reactor. In the first place, it is all we can do to make DT burn. If anything happens, the plasma simply cools down. Secondly, there is never enough DT in the reactor at any one time to give much of an explosion. But there are other sources of energy. (Slide 53) Here you see that the energy in the plasma and in the fuel is comparatively small, as we have said. There is a large amount of energy stored in a magnetic field. But this energy cannot be released explosively because of the inductance of the magnetic field. It will come out slowly in the course of many minutes. The largest store of energy is in the chemical energy of the lithium coolant. Here the use of designs which have solid lithium oxide as a breeding medium and have helium gas cooling would have a large pay off. Fusion has another advantage over the breeding and that is, in a breeder economy, there are reprocessing plants and fuel fabrication plants that service many reactors. At each plant there is a large inventory of radioactive materials as you see here, and there is a finite chance of an accidental release. (Slide 54) But more important, the transportation process between plants is especially susceptible to accident and sabotage. In fusion plants, all of the breeding of tritium is done within the plant itself, and no radioactive materials have to be transported.

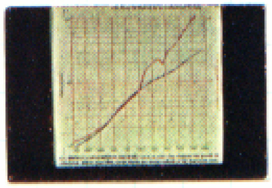
Finally, regardless of natural accidents, which may or may not ever occur, there is always the chance that someone could simply manage to blow up a fission or fusion plant. How many people would be killed by radioactivity in such a catastrophe? For such disasters, it turns out that the critical dose to bone marrow is a good measure of the number of early deaths. (Slide 55) Here, two accidents are compared. One is a large accident of a light water reactor considered in the Rasmussen report, and the other is an accident in a fusion plant releasing its total inventory of one hundred million Curies of tritium. You see that the critical dose to bone marrow is almost a hundred times less for the fusion case than for the fission case. Please do not misinterpret these remarks. I am <u>not</u> saying that fission power is unsafe. Whether it is safe or unsafe depends on what you compare it to and whom you ask. But if you compare fusion with fission on the same basis using the same type of calculation, then it seems that even the worse kind of fusion--DT with stainless steel walls--is ten to one hundred times safer than the fission plutonium breeder.

VI. THE TIME SCALE FOR FUSION

Well, if fusion is so great, how soon will it be ready and why can't we develop it faster? The next slide (Slide 56) shows the progress in achieving high temperatures in experiments all over the world. This point, $50,000,000^{o}$ scheduled for the PLT in 1978, was actually exceeded last August. They achieved 60 to 70 million degrees, and the news made the headlines. The reactor regime is only a little ways away at $100,000,000^{o}$. The next slide (Slide 57) shows the progress in the density-time product. As you see, there has been steady progress through the years. The record now is 2×10^{13}, held by the Alcator tokamak at M.I.T. This is only about five times less than needed for energy breakeven. Both temperature and density-time product are shown in a graph like this (Slide 58), temperature on the horizontal axis and $n\tau$ on the vertical. The reactor regime is up here. These are the achievements of past and future devices. The TFTR is the Tokamak fusion test reactor being built at Princeton at a cost of $239,000,000, scheduled for completion in late 1981. It is to achieve a significant thermonuclear burn, which is more or less a test of scientific feasibility. It will be the first machine that will actually use tritium and therefore become radioactive. There is a chance that TFTR will exceed this line marked "1" which indicates energy breakeven. After that we will need experimental power reactors (EPR's) to test large scale engineering, demonstration power reactors (DPR's) to produce appreciable amounts of energy, and finally commercial reactors. The schedule is shown on the next slide. (Slide 59) For each one of these devices, either built or proposed, the first blue section indicates the number of years required for a preliminary design. The diamond marks the time for a funding decision. After that, there is about a year for the final design. And then, several years for construction. Finally, the red portion indicates the years in which the device is in operation. As you see, the TFTR will be operating starting late in 1981. The EPR's will operate in the early 1990's, and the DPR's in the late 1990's. Although fusion reactors should be well developed by the year 2000, it will be about 2020 or 2025 before commercial reactors will make an appreciable impact on the market. Why is this time scale so long? To give you an example, the next slide (Slide 60) shows the large number of volumes necessary to contain the environmental impact statement for a single reactor. There is a lot of work involved to develop a new technology. Although we are aiming for the late 1990's to make this schedule, the people at Livermore and at Princeton are working two and three shifts as of now. In fact, as of ten years ago. There is no time to waste. Of course, the length of the development period depends on the funding. The next slide (Slide 61) shows the history of funding for fusion. For many years, it was riding along at a level of $30,000,000 a year. Then the funding level increased dramatically as success began to be achieved, and presently the total budget amounts to about $400,000,000 a year, of which three-fourths is for magnetic fusion and one-fourth for inertial fusion. The integrated cost of developing fusion is shown on the next slide (Slide 62). It is estimated that a total expenditure of $15-20,000,000,000 will be necessary to get to the point of a working reactor. This amount of money is enough to run our NASA space program for only about five years.

VII. OTHER POSSIBILITIES

The Carter-Schlesinger administration has put out one position paper on the fusion program. This document was issued by John Deutsch of the Office of Energy Research (Slide 63). The theme of this report is that "The goal of the fusion program is to develop the highest potential for employment of fusion energy." Behind this innocuous statement lies a whole story, because a DT-burning tokamak to generate electricity is not the only way to use fusion, though it is our main aim at the moment. There are other ways that also make sense. For instance (Slide 64) we may be able to develop relatively soon fission-fusion hybrids in which the neutrons from a fusion reactor are used to breed fuel for LWR's; or, in the very long term, we may be able to develop fusion reactors burning clean fuels that do not produce any radioactivity. The next slide (Slide 65) shows these options more clearly. An advanced fuel, pure fusion reactor could use the catalyzed DD reaction or the D-He^3 reaction which produce less radiation that DT, using p-Li^6 to breed the rare isotope He^3; or the clean D-He^3 reaction can be carried out in satellite power plants which are supplied with He^3 from a few relatively dirty plants breeding He^3 from the DD reaction. Note that there is no transportation problem here because He^3 is a perfectly safe isotope. Another possibility is to use a fission-fusion hybrid reactor with a thorium blanket to breed U^{233}. This fuel would then be transported to LWR fission reactors of the type we already have. A single fusion breeder plant can supply enough fuel for five or more LWR's. This is a very attractive alternative because LMFBR's would not be needed and we would not have to change fission technology from the type that we have today to a new type. Remember that if we did not breed fuel for LWR's, they would use up all the natural uranium in a relatively short time. The last of the possibilities I want to mention is this one: We could simply use our present LWR's, but make them burn fuel more efficiently by periodically reactivating or enriching the fuel rods by inserting them into the blanket of a fusion reactor. I would like to end by coming back to the title of my talk. What would fusion be like as an ultimate power source? In the more distant future, we would hope to develop fusion reactors that have very little radioactivity, if any at all. (Slide 66) We at UCLA, and people at TRW and the University of Wisconsin, are working on clean reactions like this one--p-Li^6--which produce no neutrons. The raw materials are ordinary hydrogen and the abundant isotope Li^6. The energy of the reactor comes out in x-rays. There is of course a hitch to this. The temperature required for this chain is $3{,}000{,}000{,}000^{\circ}$--thirty times higher than for DT fusion. This is why I called it a long term or second generation possibility. We are studying the possibility of reactors like this (Slide 67), a multipole with levitated superconducting rings floating inside the plasma. The advantage of a neutronless reactor would be tremendous--(Slide 67) no tritium, practically no radioactivity, no dangerous materials, and no neutron damage to the structure. Perhaps nuclear power will be more acceptable to the public if they would understand that nuclear power could some day be clean, and that fission power or even DT-fusion power may only be temporary solutions on the time scale of the history of human civilzation.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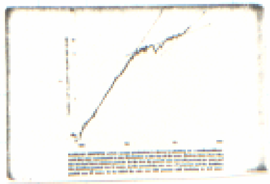
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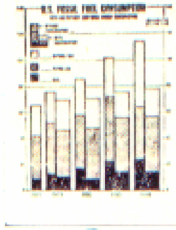

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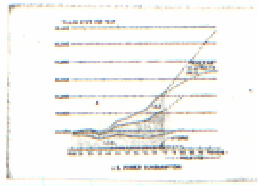

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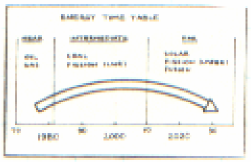

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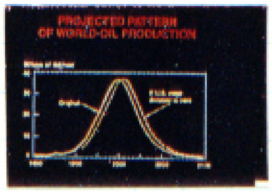

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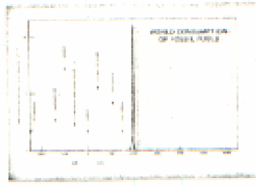

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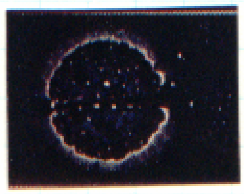
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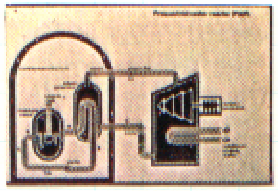
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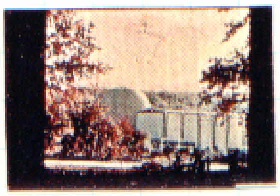
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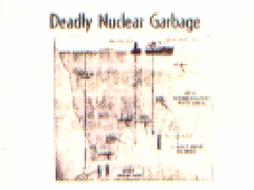

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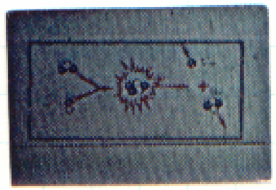
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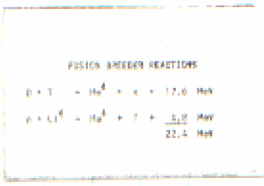

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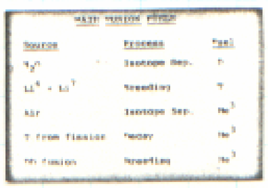

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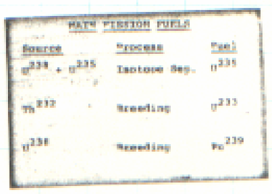

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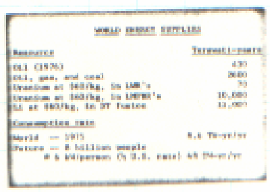

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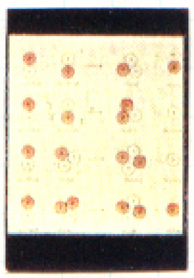
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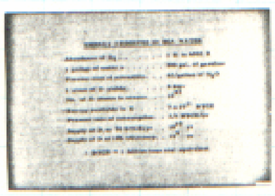
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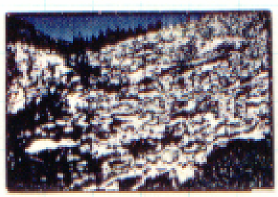
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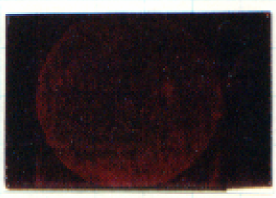
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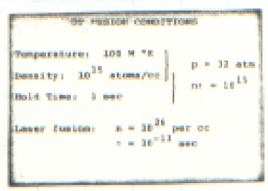

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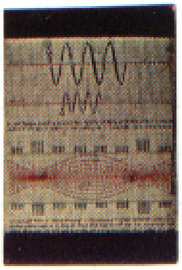

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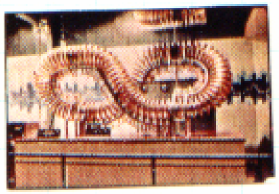

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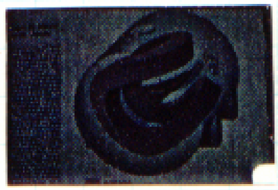

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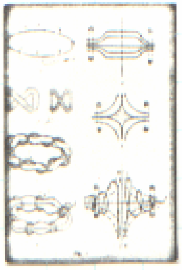

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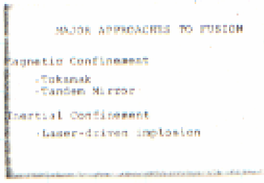

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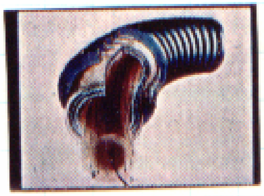

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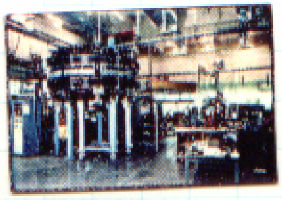

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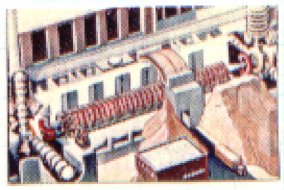

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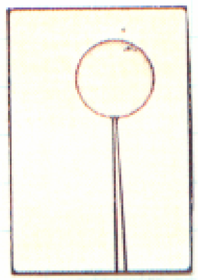

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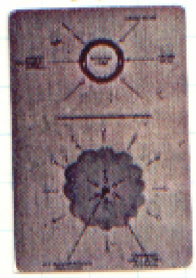

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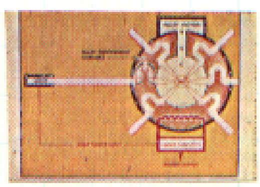

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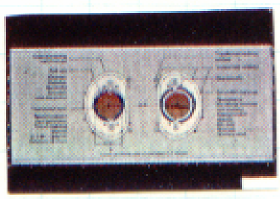

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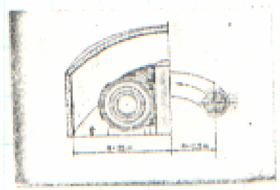

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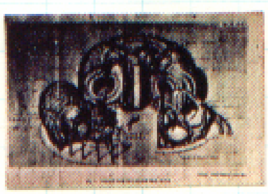

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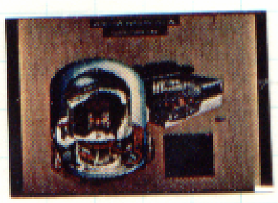

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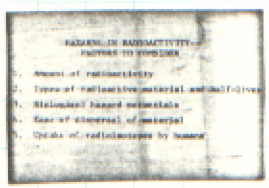

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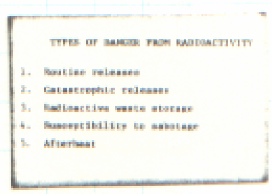

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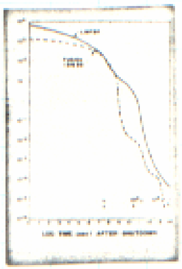

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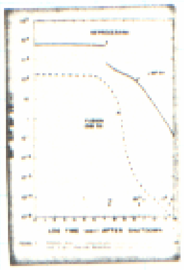

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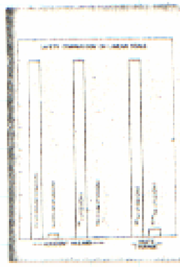

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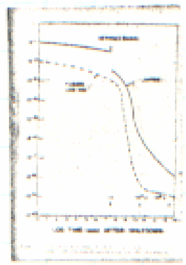

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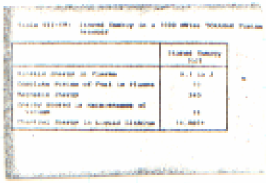

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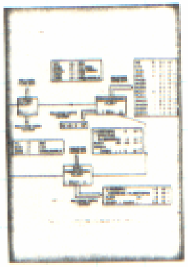

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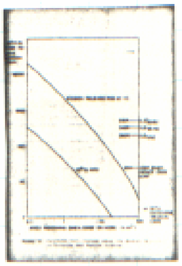

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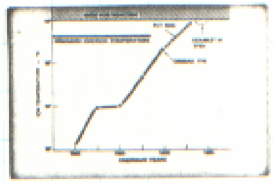

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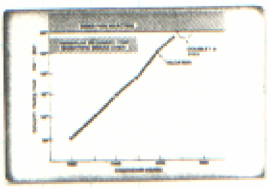

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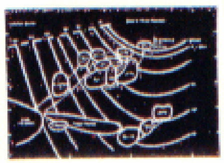

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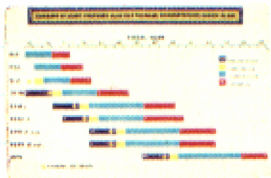

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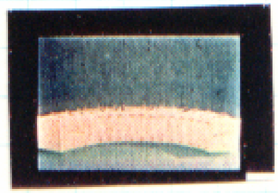

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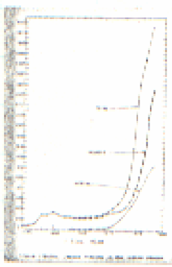

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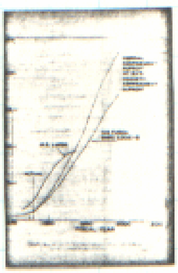

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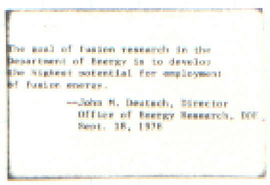

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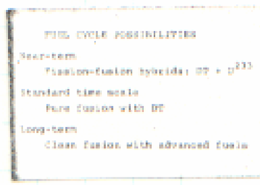

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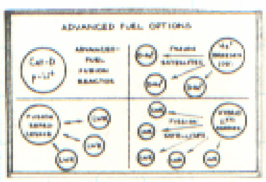

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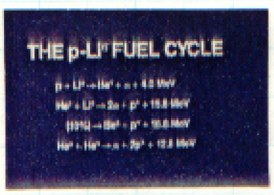

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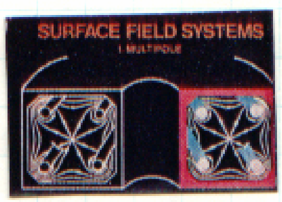

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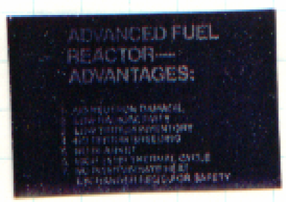

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