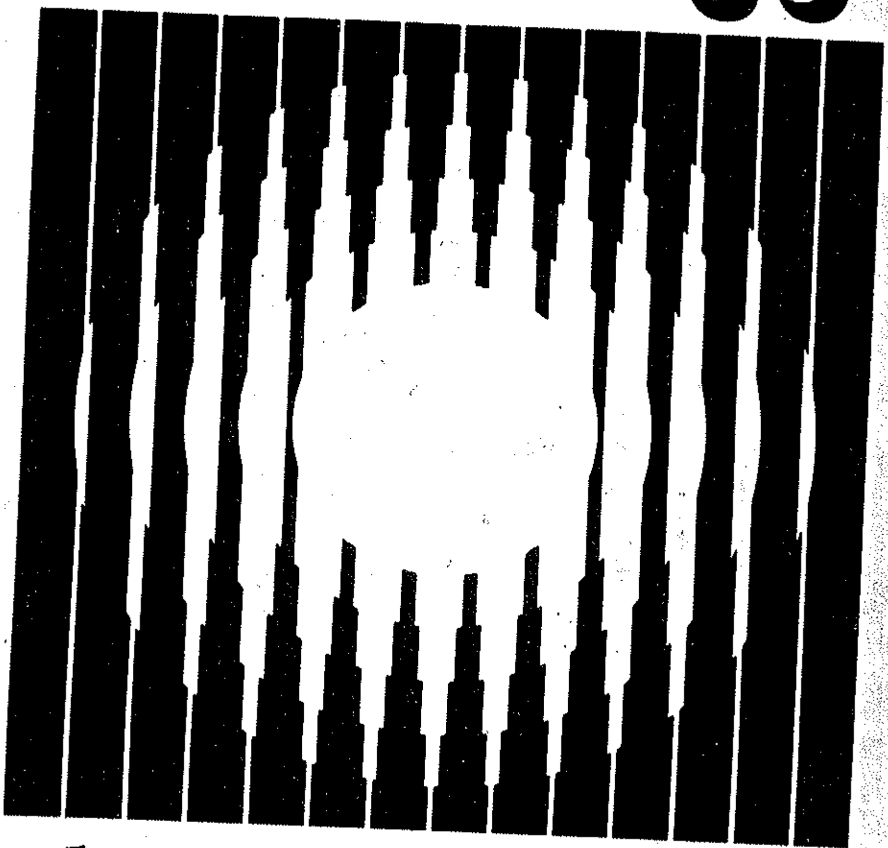
the chemistry of fusion technology



edited by Dieter M. Gruen

THE CHEMISTRY OF FUSION TECHNOLOGY

Proceedings of a Symposium on the Role of Chemistry in the Development of Controlled Fusion, an American Chemical Society Symposium, held in Boston, Massachusetts, April 1972

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PLENUM PRESS • NEW YORK–LONDON • 1972

FUSION ENERGY AND THE FUTURE*

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Today I shall speculate about the future and the role that fusion energy can play in that future. The first part of my talk will illustrate the importance that energy has played throughout man's history and some of the interrelationships that exist among man, energy, and the environment. Then I will project into the future, describe fusion energy, and the chemist's and chemical engineer's part in the future of fusion. Figure 1 shows the history of man and energy. To put this history into perspective the last ten billion years is expanded into the last hundred million, and then into the last million, and then into the last ten thousand and finally into the last one hundred.

The earth was created somewhere about four and one half billion years ago. Its power source was the fusion energy from the sun. That power source created the changes that occurred in the sea and eventually brought about life on land.

During the last hundred million years the dinasour became extinct. Many anthropologists believed they became extinct because they had become too specialized in their use of food energy. There was a shift in the earth's temperature which altered the earth's vegetation cover and caused those animals to disappear. In the last few million years man-like creatures began to appear. There were probably a number of gender and a number of species, but only one gender, homo, and only one species,

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* From transcribed tape of speech

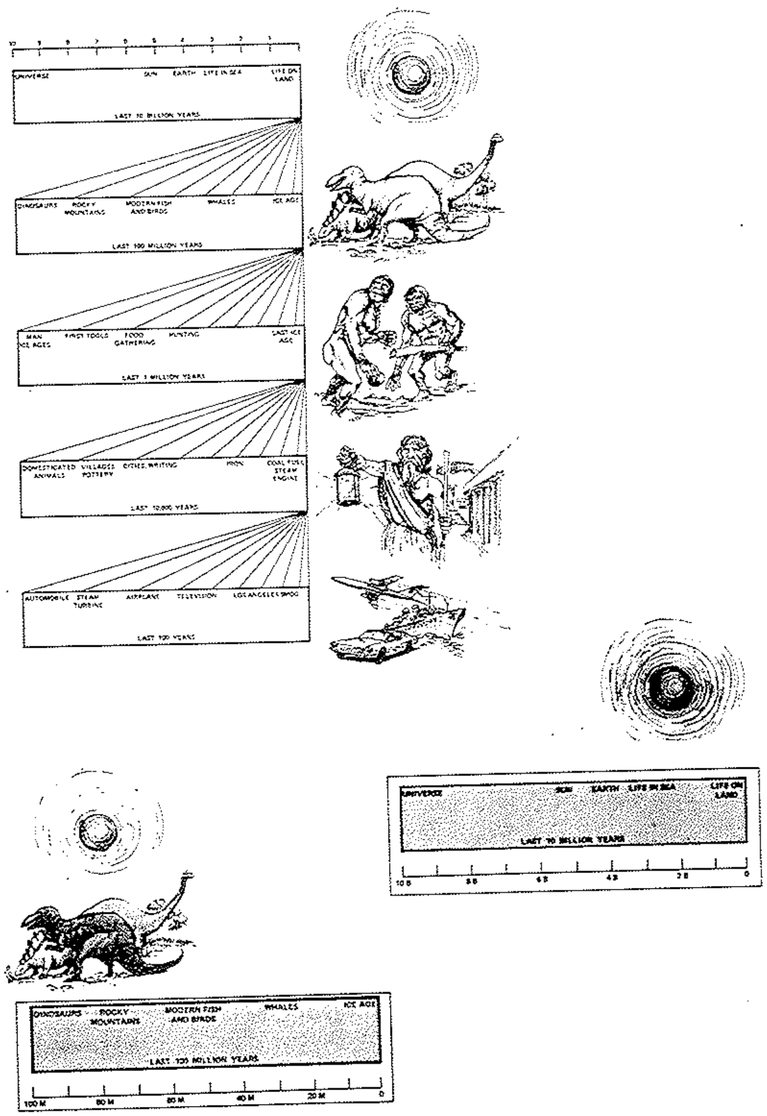
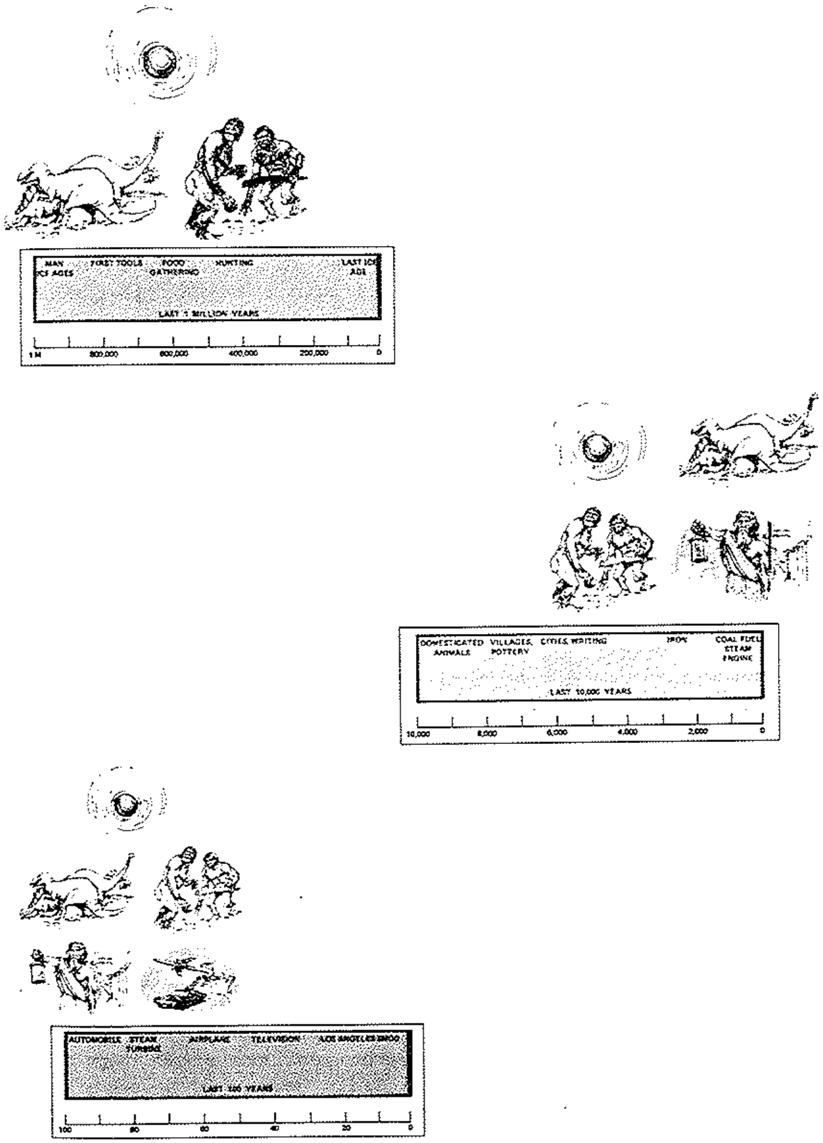


Figure 1 An historical perspective of man and energy.



sapien, survived. During the last million years man as we know him appeared. About 300 to 400 thousand years ago man began to use fire. That was the first harnessing of a concentrated source of energy. It was a contemporary source of energy; the burning of vegetation and wood that is, solar energy stored from the daily sunlight.

During the last hundred thousand years there is an interesting story that is told by anthropologists about one of our relatives.[1,2] He was known as the Neanderthal man. He lived in Europe, and was white, hairless, and intelligent. Few people realize that in addition to our food energy input we are also very much like a plant. We use solar energy directly, in the form of ultraviolet energy, to cause photo-chemical reactions in the skin that produce vitamin D. Vitamin D is essential for the proper use of calcium needed to strengthen the bones. The only way man has of regulating the vitamin D input is by changing skin coloration. These early relatives who lived in Europe received weak ultraviolet from the sun and thus had to adjust to it by being white. Then the ice age came and they had the unfortunate experience of facing up to this last ice age. This changed the temperature-dropped it drastically but did not change the intensity of the ultraviolet. Being intelligent they bundled up their children very carefully, thus cutting off the ultraviolet, and producing an epedemic of rickets. A hunting population with rickets soon dies out. Thus, according to this theory, about 35 thousand years ago, these relatives of ours died out in their attempt to relate to nature.

Now another interesting fact is that man has literally been shaped by his energy requirements. We are warm blooded animals. Such creatures must maintain a constant internal temperature, and they do this by control of their body's surface to volume ratio.[3] Thus for a given species you would have in the colder areas large creatures with a large volume to surface area to maximize energy retension and in the warmer areas you would have smaller creatures with a larger surface to volume area to aid heat dissipation. For example, the artic polar bear is large while the southern brown bear is smaller. In humans, we find Artic people to be more spherical -- to have short limbs and to be a stubbier type of person. In the desert area where it is hot and dry you find linear people -- very tall with a lot of

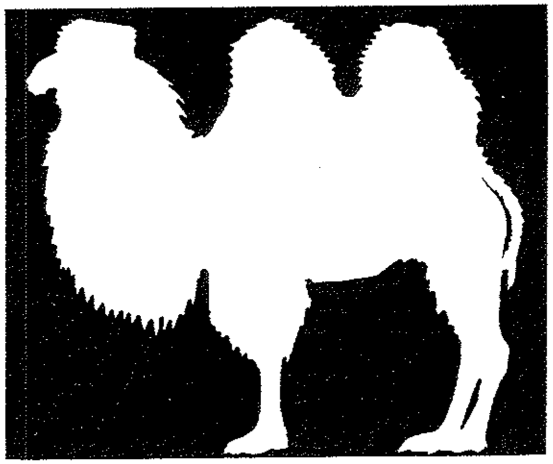


Figure 2 Chemical energy storage in a camel. Source: Carleton S. Coon, The Study of Man, A. Knopt, New York (1962).

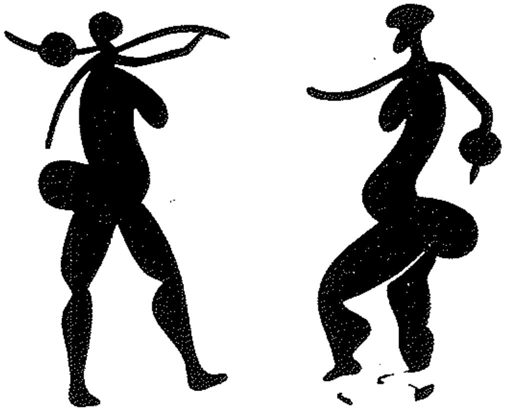


Figure 3 Chemical energy storage in the Hottentots. Source: Carleton S. Coon, The Study of Man, A. Knopt, New York (1962).

surface area to volume.

Figure 2 is a desert camel. The animal is quite linear. But it has an interesting feature -- a chemical energy storage area in its two humps. This fat is fuel for times of food shortages. The humps are nature's way of keeping the linearity and the large surface to volume ratio while providing a location for stored energy. This is also true in humans as shown in figure 3. Here you have the large rumps of the Hottentots and the Bushman. A chemical energy storage area for use during a period of food scarcity. The restricted location results in minimum interference with body heat dissipation.[4]

Now lets look at the last ten thousand years. During this time man begins to domesticate animals so he can control the energy of other creatures and he also uses them to supplement his food energy input. He develops agricultural technologies and thus more efficiently uses the sun's energy. About 800 years ago man began to use coal which is a concentrated source of solar energy stored in the earth over the last half billion years. This is what brings about a real change in our relation with the environment. During the last hundred years, man increasingly used this stored solar fusion energy. With the fossil fuels we have the real source of man's wealth and also his present day problems. As we increasingly used this energy we eventually had the problem of the Los Angeles smog.

I would like to shift from history to the present. Figure 4 represents the world as it is today, as an apartment house with three floors.[5] The top floor is North America, the second floor represents the other developed countries, the third floor, the less developed countries. The population ratio is 1 to 3 to 8. The energy uses are tremendous in the developed countries and are practically nothing in the undeveloped countries. We are rapidly burning up our fuel supplies. Raw materials are flowing from the underdeveloped countries into the developed countries.

Research into the future, carried out at Stanford Research Institute, has found that there is in the United States today a crucial gap between parts of our population. The gap is not really between generations or between liberals and conservatives but between those who anticipate a continuation of present trend and those

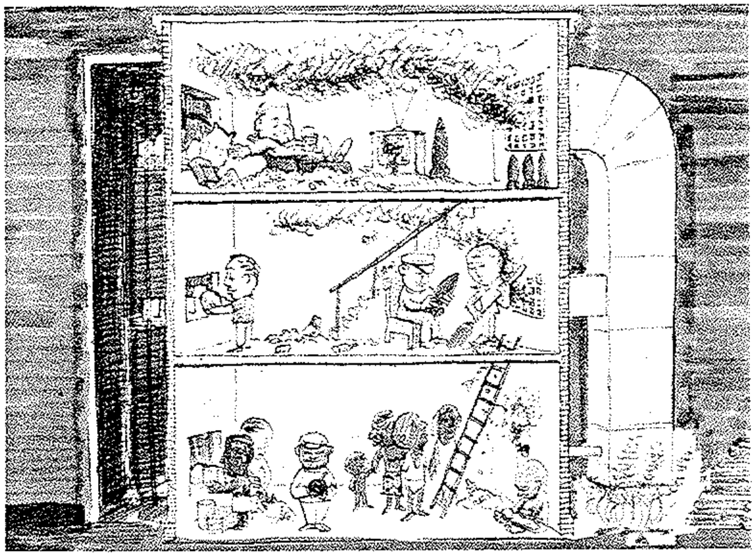


Figure 4 A view of the world as it is today. The apartment house represents the finite size of the earth. The top floor is North America, the second floor is the other developed countries -- primarily Europe, Russia, and Japan; and the bottom floor is the less-developed world---Asia (less Japan), Africa and South America.

who insist that major changes are absolutely necessary. So let's assess these points of view by looking at some of the data. Figure 5 is a per capita plot of energy use and material living standards.[6] The U.S. stands out alone with 6% of the world population using about 1/3 of the auxiliary energy. Most of the people of the world are down in the lower left hand corner of the plot using practically no energy. Our real progress is due to the power subsidiary we receive from concentrated energy sources and our progress would evaporate if these energy sources were unavailable.

Figure 6 is a plot of energy use and materials use.[6] The data used is for steel, which is the best indicator I had of the use of materials in the world. Again the U.S. with 6% of the population is using 1/3 of the materials. We are increasingly becoming dependent on the less developed nations to provide us materials. I estimate that about 3/4 of a ton of every large US car is foreign material.[7]

Now since nothing that we used really disappears, it merely reappears in another form, I have projected in Figure 7 that pollution will also follow the same shaped curve and relate directly to energy use. Of course people in developed countries are more efficient at hiding the pollution -- they use toilets and garbage disposal units.

The reason for the relationships of Figures 5, 6, and 7 is that we are still very heavily dependent on solar energy -- the sun is our basic energy source for the operation of the world. The feedback loops in figure 8 compare an underdeveloped to a developed society.[8] In an underdeveloped society we have a farmer and a family and they essentially raise some crops and feed themselves. They use only the sun's energy. In the developed societies, the advanced societies, we bring in auxiliary fuel. This auxiliary source of energy essentially opens up a gate to allow a more efficient use of the sun's energy. We do this by use of fertilizers, pesticides, tractors, refrigerator cars, and so forth. We now get a much greater food production per person and we can therefore support large populations of people in other types of employment and in cities.

Figure 9 is a log-log plot that shows how the use of energy increases the ability to produce food by orders of magnitude.[8] The top of the figure illustrates that the best you can do is to have gross photosynthesis and algae

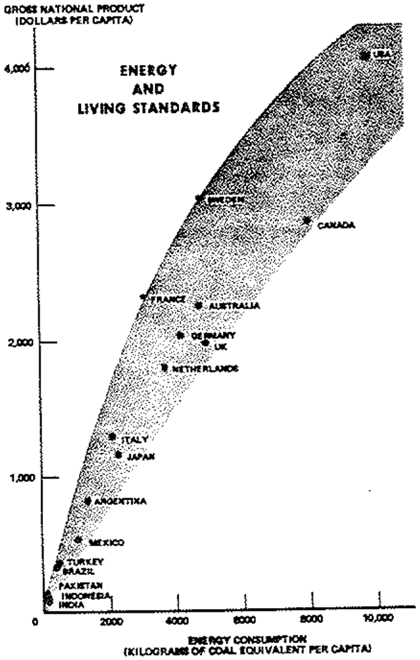


Figure 5 Energy and living standards.

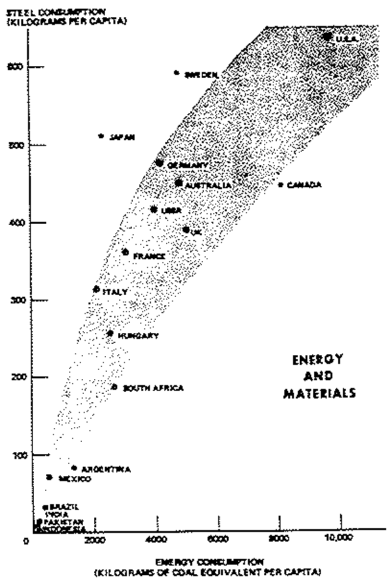


Figure 6 Energy and materials.

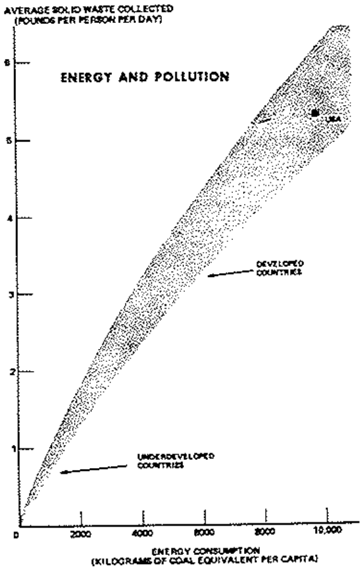


Figure 7 Energy and pollution.

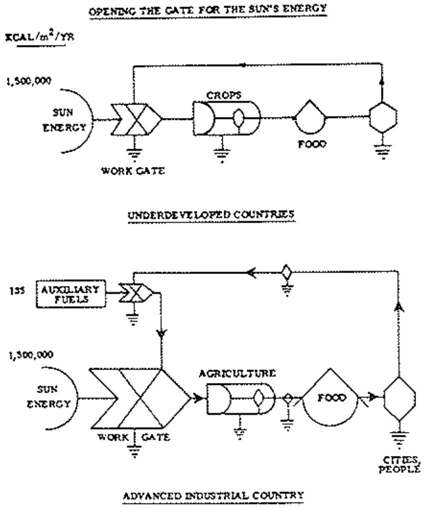


Figure 8 Significance of auxiliary energy.

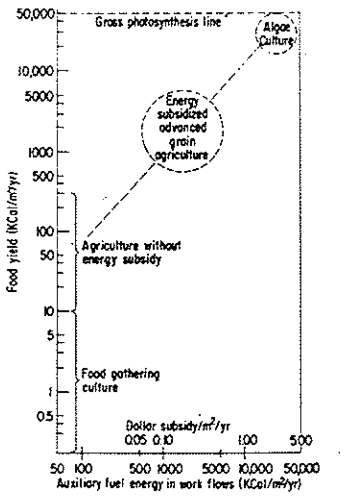


Figure 9 Energy and food.

culture. Thus to increase our food production we have to use energy and the energy is being used in the form of fertilizer and pesticides. However, the use of auxiliary energy in agriculture also brings along questions such as the buildup of fertilizers due to its increased consumption occurring across the world as shown in figure 10. The distribution of world energy reserves is interesting. In figure 11 we note that the world fossil fuel energy reserves are concentrated in the developed countries of North America and Europe. There are far fewer energy reserves available in the less developed countries of Asia, Africa and South America. 90% of that energy reserve is in the form of coal. 5% is in oil and 5% is in gas.[9] We note also that the distribution of wealth in the world relates very closely to the energy reserve distribution with most of the wealth in terms of GNP being in the developed countries. The world population distribution is the inverse of the energy and wealth distributions. One factor in this imbalance is that death control perfected in the developed countries was transported to the undeveloped countries without the necessary accompanying technologies.

I will shift from the present and project into the future. We are all familiar with the exponential growth that is occurring in world population as shown in figure 12. Its the driving force behind many of the changes that are coming up or are projected to come up.

Figure 13 gives the relationship between food, land and population. We have in the world a fixed amount of land. About 8 billion acres are considered suitable for agriculture and about one half of this is presently under cultivation. If we assume one acre is required to feed a person and we assume we have to use about 1/5 of an acre for housing, for roads, for the waste handling, for the power and so forth and we assume that the population grows at 2.2% as it has been in the past. We find that we run into rather rapidly a shortage of land for food.[10] Now you can extend the time by doubling or quadrupling your food production per acre but you don't change the estimated time to a land crisis by more than a few decades. The same type of relationship exists for world materials. Figure 14 are curves for copper. The use of copper is increasing more rapidly than the population and is on an exponential curve. Similar curves exist for iron, lead, and other materials. The

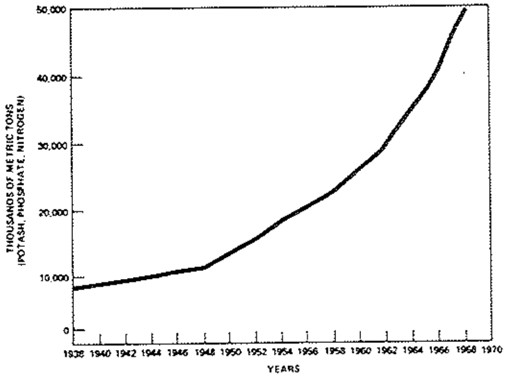


Figure 10 Fertilization consumption (world not including U.S.S.R. and China). Sources: UN Department of Economic and Social Affairs, Statistical Yearbooks, 1955, 1960, and 1970 (New York: United Nations, 1956, 1961 and 1971).

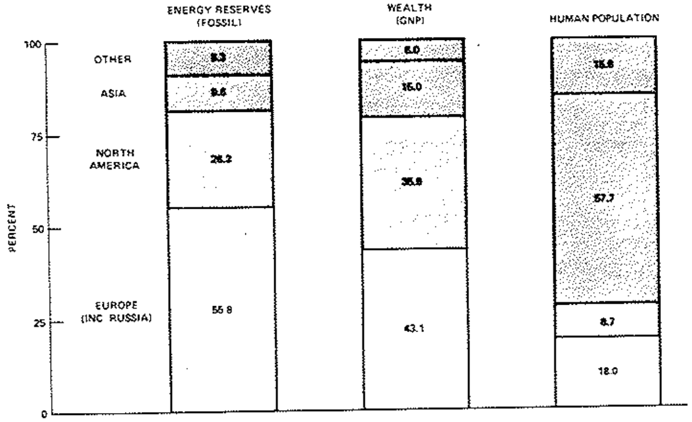


Figure 11 The present distribution of world energy reserves, wealth, and population. Of the world's fossil fuel reserves about 5% is oil and 5% is gas and almost all the remainder is coal.

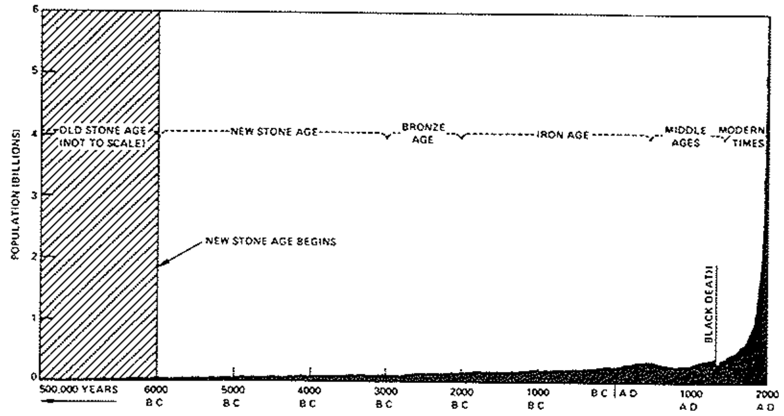


Figure 12 Growth of human population. Source: Population Bulletin, Vol. XVIII, No. 1, Feb. 1962, Population Reference Bureau, Inc.

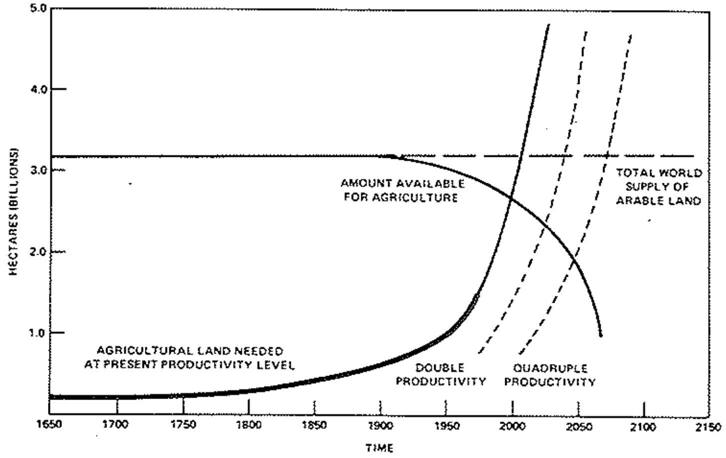


Figure 13 Relationship between food, land, and population. Source: D. H. Meadows, D. L. Meadows, J. Randers, and W. W. Behrens, The Limits to Growth, (New York, Universe Books, 1972).

bottom curve is just for the U.S. It shows that although we once were an exporter of materials we have now become an importer. Similar curves exist for other metals. Almost all of the developed nations are importers of materials.[11]

In figure 15 you can see that although our production of copper remains relatively constant we are decreasing the quality of ores that we are using.[12] Technology has kept the price about the same. In fact, we are depleting in decades the richest mineral deposits, which have been developed by nature over billions of years. Look at some of the materials listed in figure 16. If we keep using iron at the rate the world is now using it, the commercial grades would last approximately 240 years. If, however, we recognize that the world population is growing and that the use of iron is growing 1.8 percent per year, we find that we only have 93 years based upon this exponential growth in usage. Even if we multiply our reserves by a factor of 500%, we find that we only have 173 years.[10] Now iron is one of the most plentiful materials. It's 50 thousand parts per million in the earth's crust, but most of the materials are not that plentiful. There are only three of the metals that are really plentiful -- iron, aluminum and magnesium. Take some of the other elements which are relatively not so abundant in the earth's crust -- copper is 70, lead is 16, silver is 0.1 parts per million.[13] Look at how long they will last using the present rate of consumption and then note how long they will last with an exponential growth rate. Even if you multiply the reserves by a factor of 5 you will be depleting the present commercial grade ores in terms of decades.

Figure 17 illustrates the depletion of U.S. oil reserves. It only covers the continental United States. Actual data for the rate at which we are discovering ore is shown and a curve is drawn through the data points. The production curves lag by about 10 years the discovery curve. Discoveries are increasing and upon this kind of a basis one can predict the reserve available for a given land area.[12] Now we have added a new land area with Alaska and this gives us additional oil supplies.

Most of the materials we are using end up as waste as there is little recycling. We have three sinks for these wastes. One's the ocean. We use river transportation to bring the wastes to the ocean which results in water pollution, or we dump the wastes into the atmosphere

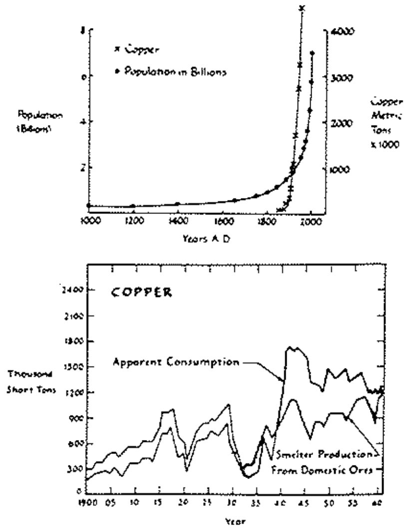


Figure 14 World production of copper (upper curve) and U.S. increasing dependence on imports of copper (lower curve).

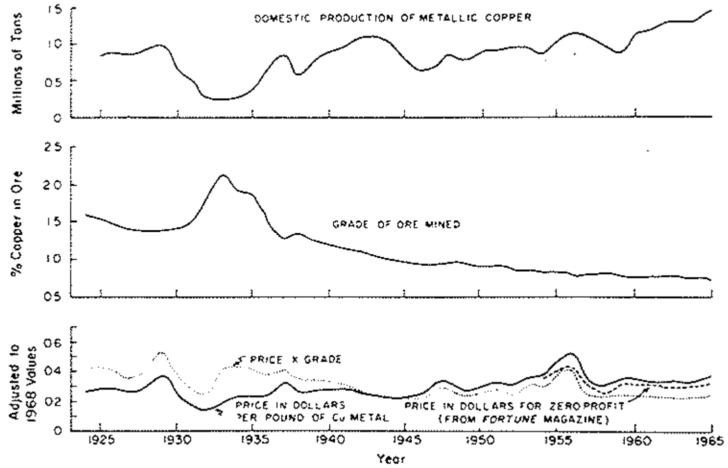


Figure 15 Decreasing grade of copper ore mined in U.S. (Data from U.S. Bureau of Mines).

and we have air pollution. Or we bury them on land where we could produce soil and ground water pollution. Figure 18 is a calculation assuming that all the wastes from 1965 up to the year 2000 were compacted and buried.[14] They would cover a land area about the size of Rhode Island to a depth of 20 feet. Another form of pollution results from putting gas and particles into the atmosphere that can change the energy balance of the earth. Figure 19 shows that about 35% of the solar energy reaching the earth is reflected immediately and about 65% gets absorbed and is reradiated as heat. A trickle of this energy has been stored as fossil fuels. As we burn our fossil fuels, we are burning up this reserve. We are releasing CO_2 into the atmosphere and by so doing are affecting the ability of the earth to release its heat energy and thus you have a world temperature rise possible. At the same time we are putting particles into the air, the particles by reflecting solar energy are affecting the amount of energy that can reach the earth so we are actually cooling the earth by that technique. We really don't know much about maintaining the earth's energy balance. We do know that ice age periods can come on rather rapidly, possibly as the result of a flip flop mechanism.[15] The sun's energy contribution to the earth is 25,000 times what man's present energy production is on earth. Changes in the reflection and absorption of the sun's energy can have a greater effect upon the earth's energy balance than the heat produced through man's use of auxiliary energy sources.

Let's try to see what factors could change the population predictions shown in figure 12. One factor that apparently affects population is the GNP per capita, the wealth of the society as shown in figure 20. The people of Africa, Asia and Latin America all have high birth rates. The developed countries have a much lower birth rate. Counteracting this is another factor shown in figure 21. As you improve the living standards, you improve the nutrition level and you also increase the life expectancy. So you will have a population that lives longer.

I would now like to talk about future research that is presently underway in the U.S. Figure 22 is called a typical tree of alternative futures. This work is being carried out by the Stanford Research Institute.[16] Its an approach which has a maximum scope. They are using a new technique. The underlying philosophy is similar to

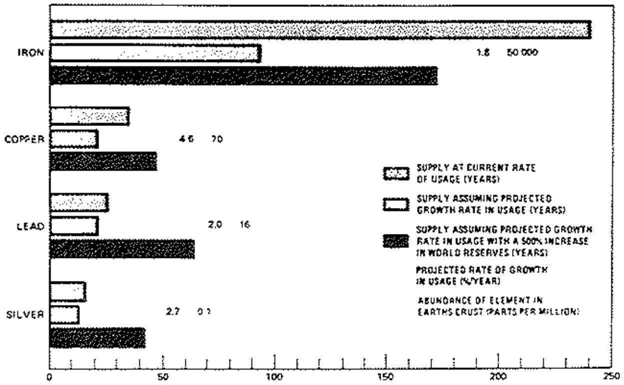


Figure 16 Depletion of world reserves of commerical grade ores.

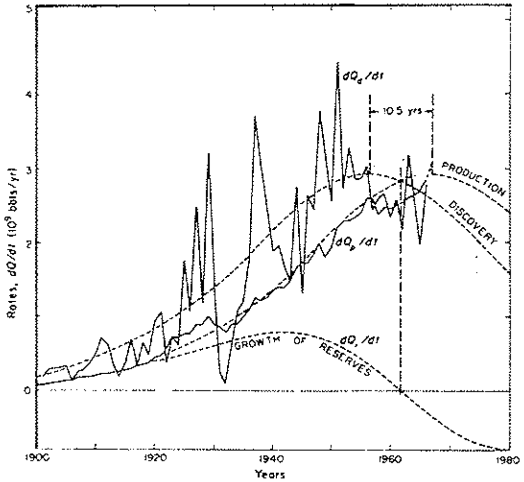


Figure 17 Depletion of U.S. oil reserves. Rates of proved discovery, production, and increase of reserves of crude oil in the United States, exclusive of Alaska. Solid lines are actual yearly data. (M. King Hubbert, U. S. Geological Survey).

YEAR	ACCUMULATED SOLID WASTE (10^9 TONS)	SQUARE MILES OF LAND AT FINAL DEPTHS OF(1) 10 FT	15 FT	20 FT
1965	0	0	0	0
1970	0.85	187.5	140.6	93.8
1975	1.84	406.3	304.7	203.1
1980	2.99	671.9	515.6	343.8
1985	4.31	968.8	726.6	484.4
1990	5.82	1296.9	984.4	656.2
1995	7.55	1687.5	1265.6	843.8
2000	9.49	2125.0	1593.8	1062.5

(1) BASED ON FINAL COMPACTION TO DENSITY OF 32 LBS/FT^3.

Figure 18 Land area required if all refuse produced in the United States is disposed of by sanitary landfill.

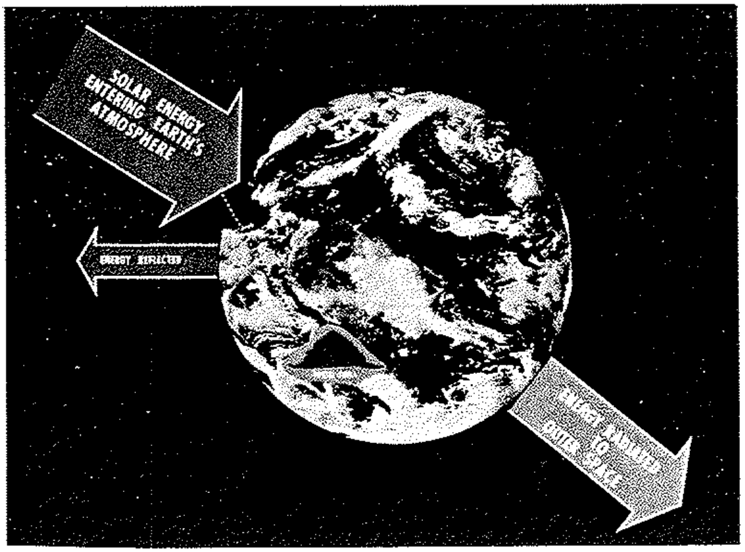


Figure 19 Energy balance for the earth. 35% is reflected and 65% is absorbed, most of which is absorbed on the earth's surface. Over the last half billion years a small trickle of the sun's energy has been stored as fossil fuels.

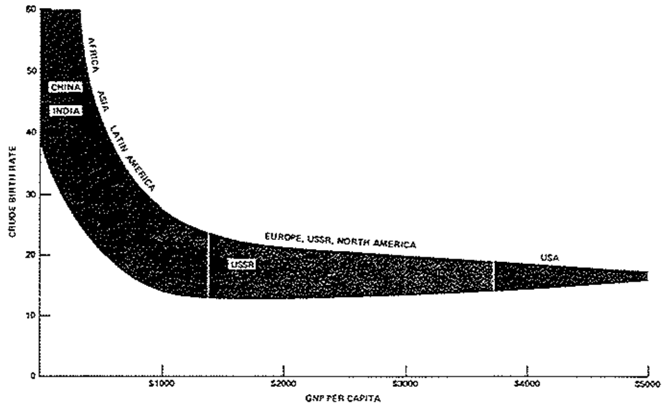


Figure 20 Effect of GNP per capita on population growth. Source: U.S. Agency for International Development, Office of Population, "Population Program Assistance", (Washington, D. C., U.S. Government Printing Office, 1970).

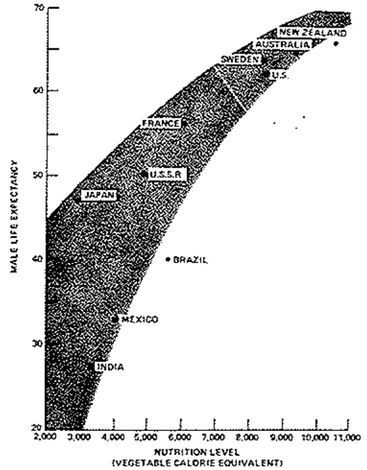


Figure 21 Effect of nutrition level on population growth. Source: M. Cepede, F. Houtart, and L. Groud, Population and Food (New York: Sheed and Ward, 1964).

the relaxation methods of mathematical physics.[17] The result is a series of possible futures which have an internal consistency traceable from the present. Figure 23 is a tree of alternative futuresfor the U.S. These results of course are very tentative and preliminary. The branch points are rather critical, these are the times when crucial choices must be made. Many futures are possible. Now if we take a slice through this tree of alternative futures at the year 2000, we can measure the society in a couple of directions as shown in figure 24. One is the degree to which the society is able to control its own destiny, its motivation and so forth. The other direction is the degree of "openness" within society. This is the flexibility, the trust and the tolance for diversity. In the studies that have been carried out very few futures were found that avoid serious trouble between now and the year 2050. Those that do require a dramatic shift in the values or premises that the society is operating upon. Some of the premises that have been listed at Stanford Research Institute as ones that should be questioned are given in figure 25. These are premises on population growth, the development of new technologies, our responsibility to future generations, the relationship of man to nature, economic growth, and international coordination and cooperation. In essence SRI is saying that the roots of our present problems are implicit in the basic premises of our industrialized culture.

Now in addition to the Stanford studies another futures group is at MIT and has been supported by the Club of Rome.[10] They use a computer simulation of world trends. They started out assuming that our present premises remain essentially unchanged. What they are making are not predictions but projections if we continue on our present trends. They use the method of systems dynamics that is characterized by the feedback loop and they take into account a number of interdependent factors. A sample of their results is shown in figure 26. They predict a rather drastic drop in world population sometime during the next hundred years. Nobody can predict the exact dates. The period over which they are talking however is a period in which our children and grandchildren will be living. They have many assumptions in these models and these assumptions should be questioned. Figure 27 gives the basic interactions in the MIT model.

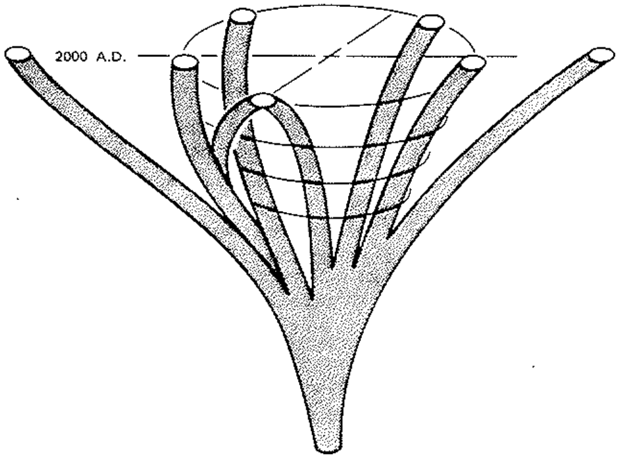


Figure 22 Typical tree of alternative futures. Source: SRI Rept. EPRC 6747-10, February, 1971.

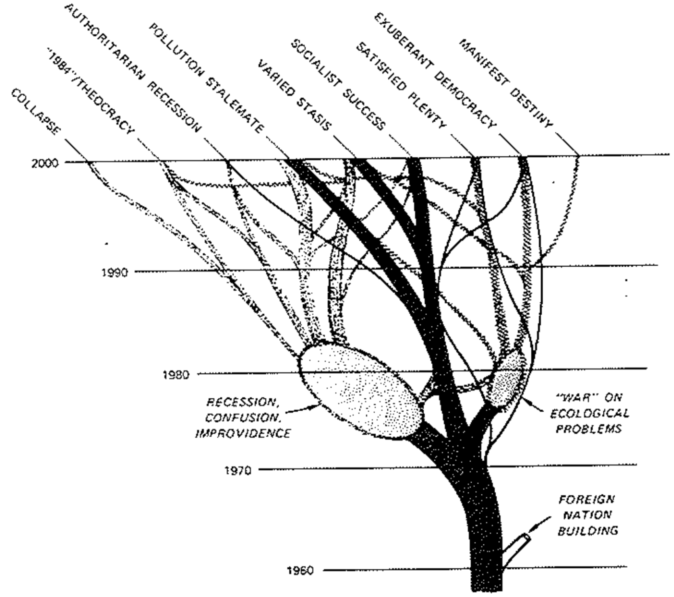


Figure 23 Cross section of tree of alternative futures for U.S.A: Source: SRI Rept. ERDC 6747-6, February, 1970.

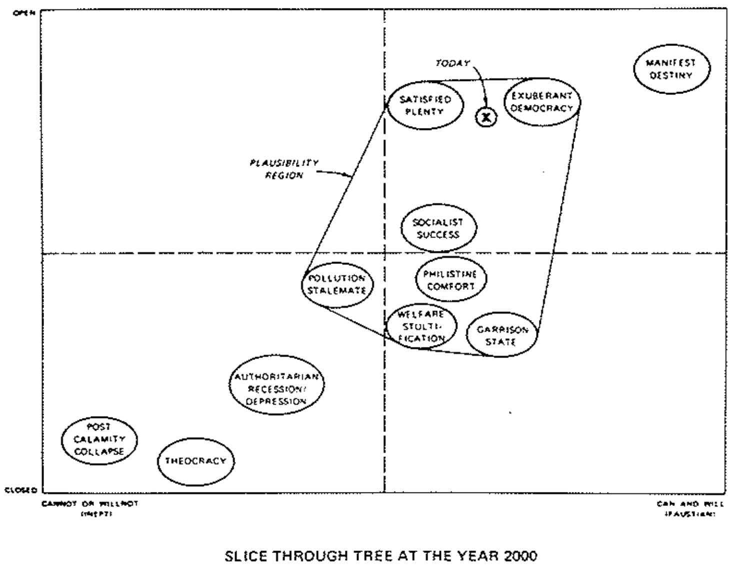


Figure 24 Slice through tree at the year 2000. Source: SRI Rept. ERDC 6747-6, February, 1970.

1. The premise that the pride of families, the power of nations, and the survival of the human species all are to be furthered (as in the past) by population increase.
2. The "technological imperative", that any technology that can be developed, and any knowledge that can be applied, should be.
3. The premise that men are essentially separate, so that little intrinsic responsibility is felt for the effects of present actions on remote individuals or future generations.
4. The premise that man is separate from nature, and hence that nature is to be exploited and "controlled" rather than cooperated with.
5. The "economic man" image, leading to an economics based on ever-increasing GNP, consumption, and expenditure of irreplaceable resources.
6. The premise that the future of the planet can safely be left to autonomous nation-states, operating essentially independently.

Figure 25 Some basic operative premises of our industralized culture as listed by the Stanford Research Institute.

They have included population, food, pollution, natural resources, military expenditures, capital and many others. The overall diagram is, of course, much more complex.

Let us see if we can better understand what is happening by putting things into the perspective of thousands of years. We are entering now what has been called the great transition.[18] We are in a period of very rapid growth and change. Probably the most abnormal in human history, and probably the greatest ecological and biological upheaval that the earth has ever seen. Now the operating premises that we started with were very valid for making the rapid rise shown in figure 28 but are probably not valid for the stationary state or equilibrium state that the world must eventually reach. We see that the power source to get us onto this rise has been fossil fuels. But fossil fuels are just a blip as far as time goes and can be depleted rather rapidly. We'll then have to depend on fission, fusion or solar energy to power the world. Now the traps that you can fall into are population (food), entropy (depletion of resources and energy, and pollution), and the war trap. There are three states that you can go into -- 1) a successful transition, 2) the overshoot that has been predicted by the Club of Rome study, and 3) a complete disaster with nuclear war.

The war trap has been ranked at the top for its imminence in total danger to present and succeeding generations and to our making a successful transition. Figure 29 shows the buildup of nuclear weapons in the United States and the Soviet Union on a log scale.[19] Its in the thousands now. There are about twenty tons of TNT equivalent per man, woman and child in the world. Figure 30 illustrates the use of world public resources, and gives the world public expenditures for the year 1967. By 1969, the major item of military expenditures had reached 200 billion dollars.[20] Education, i.e. training the next generation, is second and the remaining are much smaller. The question is "Can we make the transition with the world's existing resources without a reallocation of world resources?" Figure 31 gives a picture of what the danger is. This is a computer simulation of a nuclear attack on the United States[21] and of course could be carried out many times over. But all of the war trap is a man made problem and it can be solved by man. It requires changes in values and changes in technology

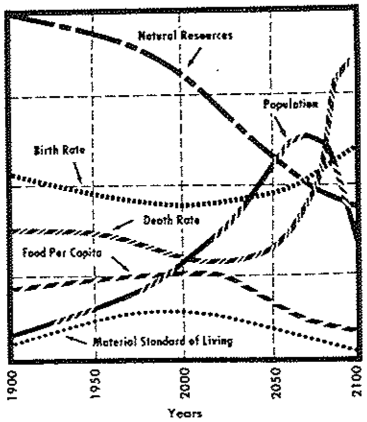


Figure 26 Computer simulation of world trends. Used with the permission of the World Future Society, P. O. Box 19285, 20th Street Station, Washington, D. C. 20036 (The Futurist, August, 1971).

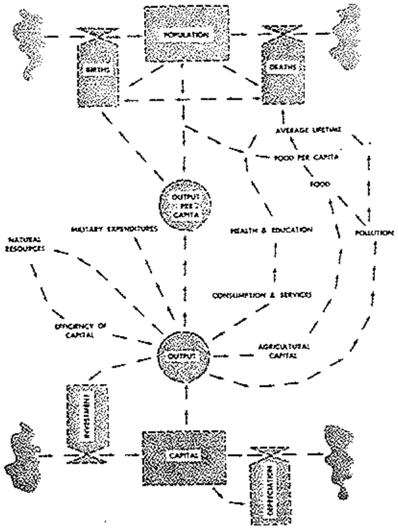
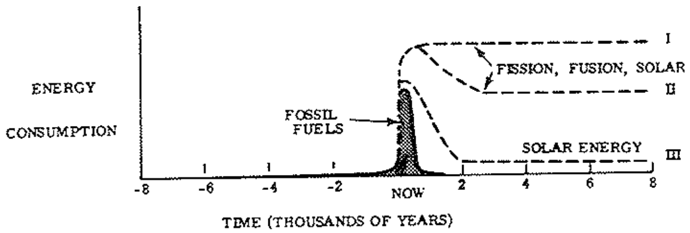


Figure 27 Basic interactions used in global model. Used with the permission of the World Future Society, P. O. Box 19285, 20th Street Station, Washington, D. C. 20036 (The Futurist, August, 1971).



THREE TRAPS:

1. POPULATION (FOOD)
2. ENTROPY (RESOURCES, ENERGY, POLLUTION)
3. WAR (HUMAN NEEDS AND BEHAVIOR)

THREE ASSUMPTIONS

I. SUCCESSFUL CONTROL - AVOIDANCE OF TRAPS
II. SERIOUS OVERSHOOT OF POPULATION - TEMPORARY STATE OF CHAOS
III. SERIOUS FOOD, RESOURCES, AND ENERGY SHORTAGES - CONFUSION AND CHAOS - NUCLEAR WAR

Figure 28 The great transition.

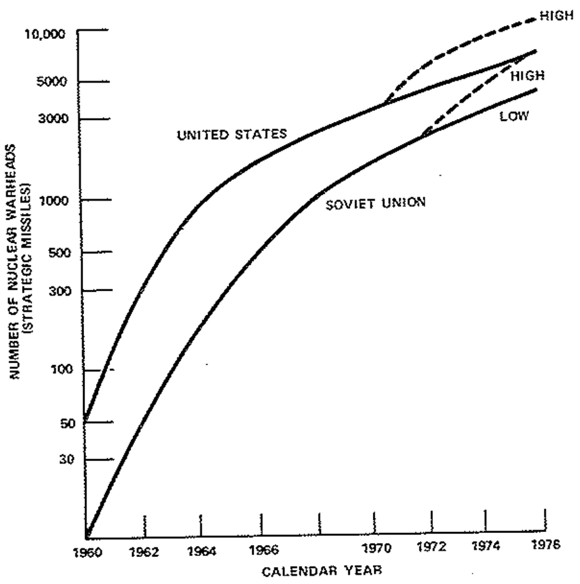


Figure 29 Build up of weapons. Source: Ralph Eugene Lapp, Arms Beyond Doubt, (New York, Cowles Book Company, 1970).

and probably a rather long lead time. The Salt Talks are under way and we appear to be going in the right direction.

If we look at births we find that a very small portion of the population is controlling the population rise as shown in figure 32. 90% of the births occur from women between 16 and 35. We have literally a man-woman made problem here. Again its a question of human values and technology. The U.S. population's rate of growth is now decreasing and we can set an example for the world. However, we must not forget the U.S. population of 200 million is essentially equal to the error with which we know the total world population.[22]

Figure 33a illustrates the way the economy is presently working. It is essentially a linear economy. We are depleting resources, and we are building up wastes. The measure of success is how fast one can push items through the system. The tendency is to decrease the quality. We have an energy source driving the system which is very polluting. Eventually we will have to have a constant world population, of course, but also we will need a closed materials economy as shown in figure 33b. The economics for such a system have been studied by people like Herman E. Daly, Kenneth E. Boulding, and further back, by John Stuart Mill.[23] Underneath such a system the criteria becomes one of how to maintain an item in the system the longest possible period of time. There are questions on distribution of resources, distribution of leisure time, and distribution of wealth. Apparently you can lower GNP under such a system, since it's no longer the most meaningful measure of a successful society. To do this would require new economic premises and new technologies because you would need new technologies of energy, of recycling, and of industrial production to achieve a closed materials economy. There will be long lead times involved for such a conversion.

Let us explore the question of energy use and fusion energy reserves.[24] As shown in figure 34, U.S. electrical generation in terms of Q is 0.015 where Q is equal to 10^{18} Btu. Our total energy consumption is .06 Q, hence only 1/4 of our energy is electrical at the present time. The world energy consumption is 0.17 Q. Thus we represent about 1/3 of the world's consumption. And if the world had 10^{10} people and if they all lived at our standard of energy consumption, it would require almost 3 Q. Now if

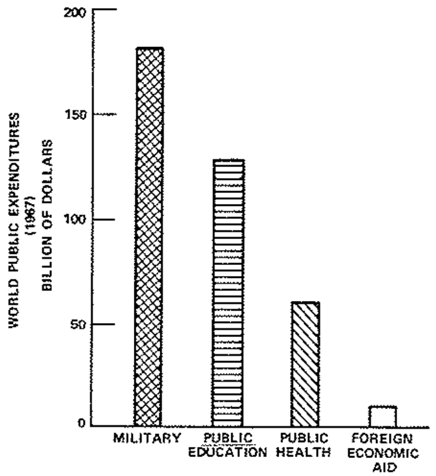


Figure 30 Use of world public resources. Source: World Military Expenditures (Arms Control and Disarmament Agency, March 1970).

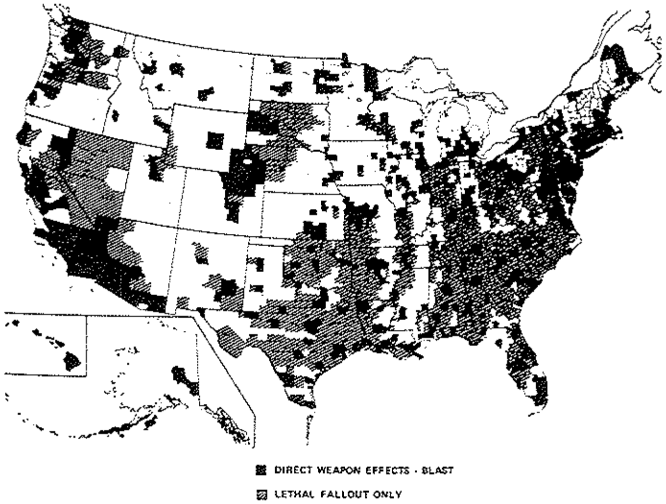


Figure 31 Computer simulation of nuclear attack on the United States. Source: Proceedings of the Symposium on Post Attack Recovery from Nuclear War, November 6-9, 1967, AEC-DTIE 671135.

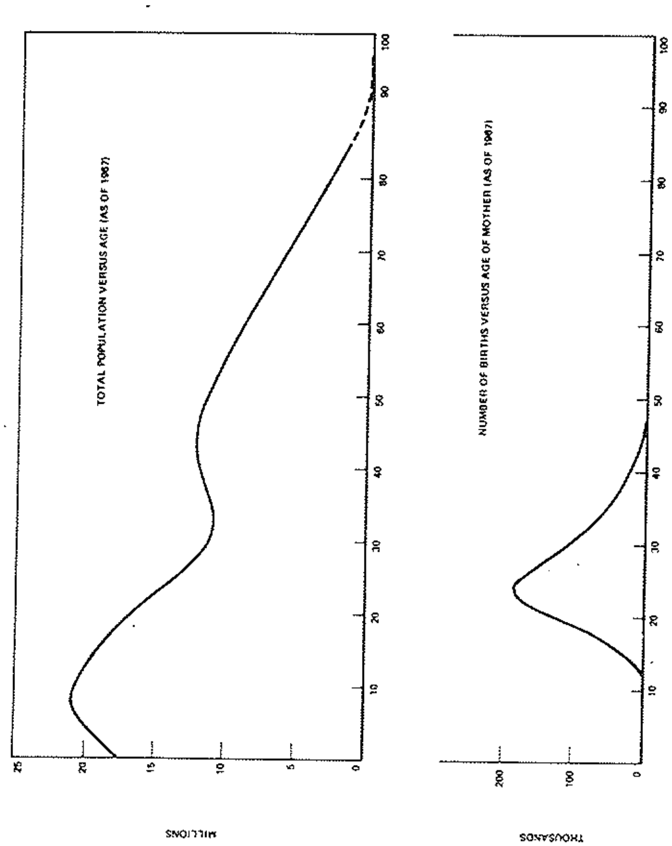


Figure 32 Total population versus age and number of births versus age of mothers for the United States in 1967.

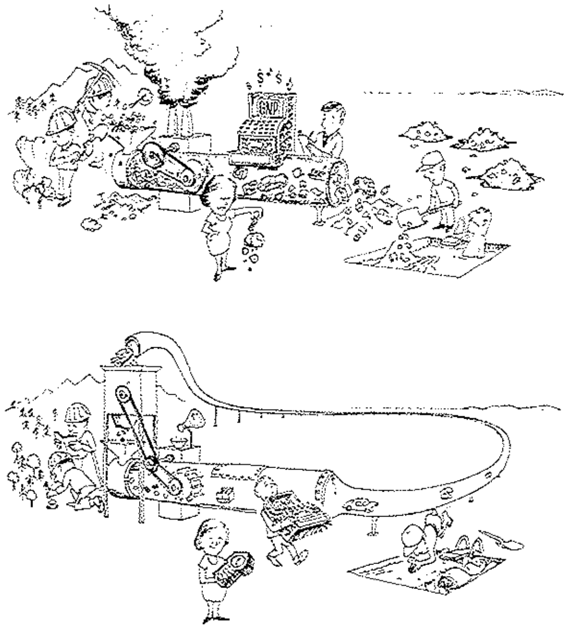


Figure 33 The top figure illustrates an essentially "linear" or open materials economy. Input for production must be taken from the environment, which leads to depletion of materials. An equal amount of matter in the form of wastes must be returned to the environment, leading to pollution along with the pollution of the energy sources driving the systems. The objective is to increase annual production (GNP) by maximizing the flow of materials. The natural pressure, therefore, is to decrease the life or quality of the items produced. The bottom figure illustrates a circular or closed materials economy. Limits on the total amount of materials or wealth will depend upon the availability of resources and energy and the earth's ecological, biological, and physical system. Within these limits, the lower the rate of material flow, the greater the wealth of the population. The objective would be to maximize the life expectancy and hence quality of items produced.

you look at the reserves of energy for fusion systems, in the "known" and "inferred" U.S. lithium reserves we have 500 Q. The world's probable lithium reserves are 8300 Q. The lithium content of sea water is 21 million Q and the deuterium in the ocean is 7 1/2 billion Q, that would be sufficient to run the earth for billions of years almost until the sun expands and absorbs it.

For this transition period that we're entering we have certain resources available. We have the planet Earth with its materials and its ecosystem. We have man made fixed capital -- the stored materials that we have in the form of machinery and buildings which includes the knowledge that is stored in this fixed capital plus the energy that was used to produce it. We have two expandable resources -- knowledge and energy. Energy will be needed to reconstitute the materials and to organize the society. Knowledge will be needed to guide the transition.

Let's look at our energy sources. Figure 35 shows that right now we have fossil fuels, which are limited resources that have many other applications plus some unknowns as far as environmental effects. We have the present fission water reactors which are essentially burning U^{235} -- a very small part of natural uranium and thus they use uranium at only 1 to 2% of its potential efficiency. Our uranium reserves and thorium reserves, if used at this very low efficiency, become costly rather rapidly because the reserve of very high grade ore is limited. In figure 36 we have what I have called "infinite" energy sources. If we could use the uranium far more efficiently such as in the breeder reactor, we would be able to transmute the U^{238} with neutrons into plutonium which burns easily. We would thus have essentially an infinite energy source. Most questions are of an environmental and safety nature. Solar energy is certainly plentiful but we do not have the technology to concentrate such a diffuse energy source as yet. For fusion the primary question is whether our understanding of the plasmas will be sufficient to convert them into a usable energy source. Other infinite energy sources are water power, tidal, geothermal, and wind, but none of these can meet the demands which will be coming up in the future. Thus, our options are few, all have problems, and none are ready to meet our energy needs without extensive research and development.

ENERGY USE

	Q (10^{18} BTU)
U.S. ELECTRIC GENERATION	0.015
U.S. ENERGY CONSUMPTION	0.06
WORLD ENERGY CONSUMPTION	0.17
10^{10} PEOPLE AT U.S. PER CAPITA CONSUMPTION	2.9

FUSION ENERGY RESERVES

KNOWN AND INFERRED U.S. LITHIUM RESERVES	500
PROBABLE WORLD LITHIUM RESERVES	8,300
LITHIUM CONTENT OF SEA WATER	21,000,000
DEUTERIUM CONTENT OF SEA WATER	7,500,000,000

Figure 34 Energy use and fusion energy reserves.

FOSSIL FUELS:

CONCERN: A LIMITED AND IRREPLACABLE NATURAL RESOURCE

QUESTION: ATMOSPHERE CO_2 BUILDUP - EFFECT ON WEATHER, PH OF OCEAN, PHOTOSYNTHESIS

FISSION WATER REACTORS:

CONCERN: USE OF IRREPLACABLE U-235 "SEED - CORN" - ONLY 1-2% EFFICIENCY FOR RECOVERING FUEL'S HEAT CONTENT

QUESTION: FUEL AVAILABILITY AT LOW COST

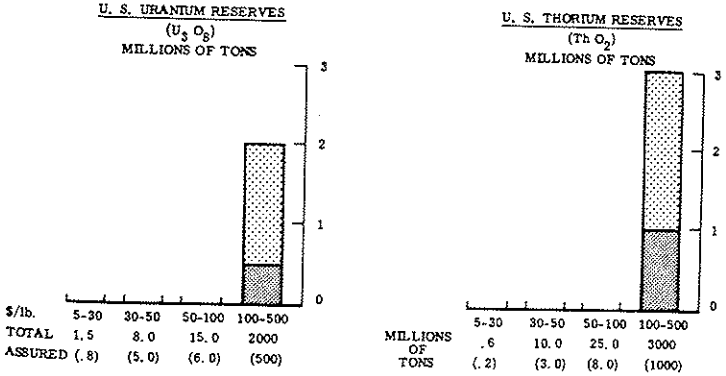


Figure 35 Limited energy sources.

Figure 37 gives the principal fusion fuel cycles. We are burning isotopes of hydrogen--deuterium and tritium in the DT cycle, deuterium and deuterium in the DD cycle. Deuterium and helium three, and proton (hydrogen) and lithium six are also possible fuel cycles. The ignition temperature required increases from DT fuel cycle which is the easiest to obtain as far as temperature goes, and the energy released is quite high. The sun operates at about 20 million degrees so we are above the temperature of the sun. In fact we have achieved all of these ignition temperatures in various experiments. We already have fusion energy on earth in the form of the hydrogen bomb. Actually we have generated in our controlled experiments small amounts of fusion energy. For instance in the Scylla IV about 370 watts for 3 microseconds have been produced in the plasma. Although in experiments we don't normally use tritium fuel, if we had, something like 180 kilowatts for 3 microseconds would have been produced. This is, however, far from the break-even energy.

The wastes that come from fusion reactors are either hydrogen or helium. There is some regeneration of fuel. There are no radioactive wastes. Neutrons are produced. The neutrons from the DT cycle are needed to breed tritium, through reactions using lithium six and lithium seven. The neutrons, also, since they must interact with materials, cause an activation problem by producing a radioactive structure. The degree of radioactivity depends upon structural materials chosen. Of the fuels, the only radioactive fuel is tritium. It will also be generated in the DT and DD cycles and in the deuterium helium three cycles, and this needs careful control. The DT cycle needs a blanket to breed the tritium. None of the other cycles require a tritium breeding blanket although they will be extracting energy from the neutrons in a blanket.

Fusion systems are inherently safe from any kind of nuclear runaway. There is not enough fuel in the system to cause any such problem. Figure 38 shows results from some fusion experiments. You can see that we have exceeded in our experiments the ignition temperatures for all four fuel cycles. We are working over a wide density range, many tens of billions. And we can have fusion reactors over a range of one billion in density. The diagonal line cutting across the figure is the dividing line for the use of external field coils for magnetic

MAJOR:

FISSION BREEDER REACTORS:
QUESTION: FISSION PRODUCTS, SAFETY, AND RADIOECOLOGICAL CONCENTRATION PROCESSES, PROLIFERATION OF NUCLEAR MATERIAL

SOLAR ENERGY:
QUESTION: TECHNOLOGICAL ABILITY TO ECONOMICALLY AND EFFICIENTLY CONCENTRATE THE LOW RADIATION ENERGY DENSITY

FUSION REACTOR:
QUESTION: ADEQUATE SCIENTIFIC UNDERSTANDING OF PLASMA PHYSICS (CONFINEMENT AND SCALING LAWS)

MINOR:

OTHER ENERGY SOURCES:
INSUFFICIENT TO MEET FUTURE DEMANDS

	WORLD POWER CAPACITY THOUSANDS OF MW
WATER	2,900
TIDAL	1,100
GEOTHERMAL	10
WIND	NEGLIGIBLE

BUT: WORLD ENERGY REQUIREMENTS BY YEAR 2000 = 30,000

Figure 36 "Infinite" energy sources.

FUSION FUEL CYCLE

	IGNITION TEMPERATURE
$D + T \longrightarrow He^4 + n + 17.6$ Mev	50,000,000°C
$D + D \longrightarrow He^3 + n + 3.2$ Mev $D + D \longrightarrow T + H + 4.0$ Mev	300,000,000°C
$D + He^3 \longrightarrow He^4 + H + 18.3$ Mev	500,000,000°C
$H + Li^6 \longrightarrow He^3 + He^4 + 4.0$ Mev	900,000,000°C

TRITIUM BREEDING

$n + Li^6 \longrightarrow T + He^4 + 4.8$ Mev

$n + Li^7 \longrightarrow T + He^4 + n - 2.5$ Mev

Figure 37 Fusion fuel cycles and tritium breeding reactions.

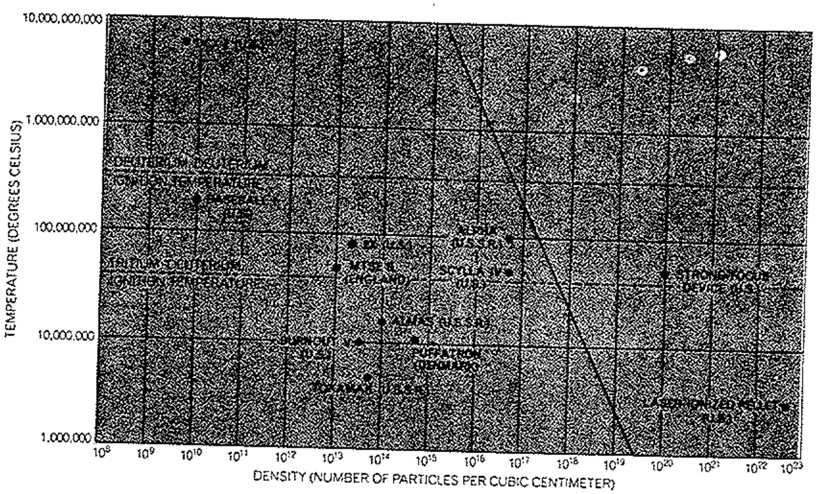


Figure 38 Plasma experiments that have achieved temperatures near or above the fusion ignition temperatures of a deuterium-tritium fuel (bottom horizontal line) and a deuterium-deuterium fuel (top horizontal line) are identified by the name of the experimental device and the country in which the experiment took place. The diagonal colored line represents the limit beyond which the materials used to construct the magnet coils can no longer withstand the magnetic-field pressure required to confine the plasma (assumed to be 300,000 gauss). Beyond this limit only fast-pulsed systems (in which the magnetic fields are generated by intense currents inside the plasma itself) or systems operating on entirely different principles such as laser-produced, inertially confined plasmas are possible. (From "Prospects of Fusion Power" by Gough and Eastlund. Copyright 1971 by Scientific American, Inc. All rights reserved.)

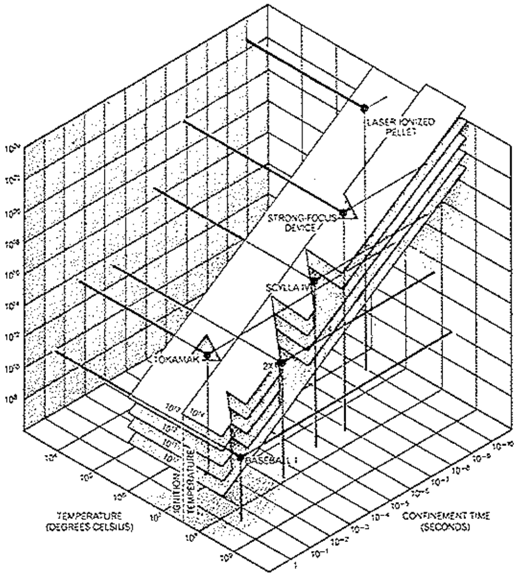


Figure 39 Basic criterion for determining the length of time a plasma must be confined at a given density and temperature to achieve a "break-even" point in the fusion-power balance is represented in this three-dimensional graph for a deuterium-tritium fuel mixture in the temperature range from 40 million degrees C. to 500 million degrees C. The product of density and confinement time must be close to 10^{14} seconds per cubic centimeter to achieve the break-even condition (based on an assumed energy-conversion efficiency of 33 percent). This corresponds to the top layer in the stack of planes in the illustration. The lower planes, which correspond to successively smaller values of density times confinement time are included to give some idea of the positions of the best confinement results from several experimental devices with respect to the combination of parameters needed to operate a full-scale fusion reactor. (From "Prospects of Fusion Power" by Gough and Eastlund. Copyright 1971 by Scientific American, Inc. All rights reserved).

confinement to keep the hot plasma off the walls. For experiments on the left hand side of the line we can use magnetic confinement coils. For those experiments just to the left of the line these coils must be pulsed. When the densities get to the right of the line we can not use magnetic confinement coils because of the structural problems of magnets. Instead we can use self magnetic fields and inertial confinement.[25]

The goal of fusion plasma research as shown in figure 39 is to move three criteria to break even energy conditions -- they are confinement time, temperature, and density. By working over the large range in densities, we can trade off density and confinement times and end up with a surface that has to be above a certain temperature. Thus the program is moving towards a break-even surface. The figure shows where our experiments were one year ago. Figures 40, 41 and 42 are three pictures of fusion experiments.

The first is a toroidal experiment (closed experiment) at Princeton University known as the ST Tokamak. The second is the 2X mirror machine, an open ended device, at the Lawrence Livermore Laboratory. The third is the arc section of the Scyllac experiment at the Los Alamos Scientific Laboratory. This is a pulse experiment with high plasma density. In pulse experiments the diameter of the plasma chamber is much smaller because the gas is at a very high density.

Figure 43 gives an indication of the progress we have been making in the basic understanding of plasmas.[24] It is a measure of the discovery rate of plasma instabilities as a function of time. The instabilities in plasmas causes the plasma to cross the magnetic field and be lost. If we are losing plasma too fast we can't have net power. New instabilities were being discovered at a fast rate in the late 1950's and early 1960's. This was rather discouraging. But we were identifying the losses -- the major sources of trouble in fusion. We have now essentially learned what most of these losses are. We have been finding no new instabilities. We have been learning how to inhibit the growth of instabilities and their effects on the plasma. Thus we have been steadily moving towards the break-even experiments. Figure 44 is a schematic of a DT fusion power plant. It shows the location of the hot plasma, the vacuum, the first wall

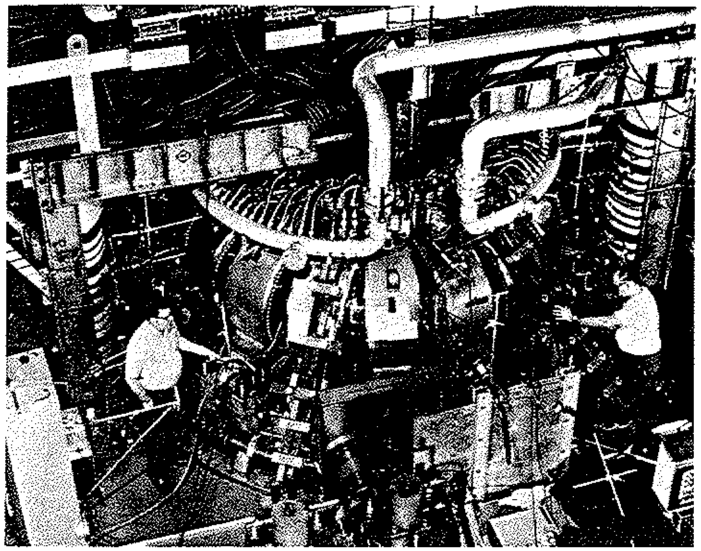


Figure 40 The Model ST Tokamak at the Plasma Physics Laboratory, Princeton, New Jersey.

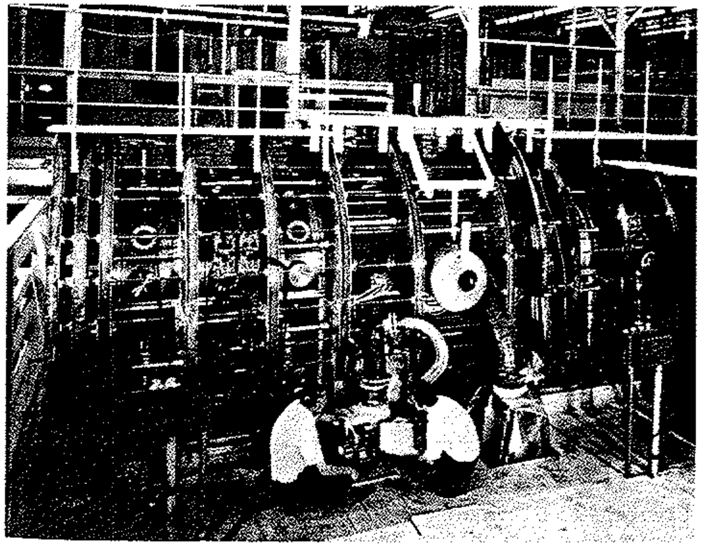


Figure 41 The 2X-II Mirror Experiment at the Lawrence Livermore Laboratory, Livermore, California.

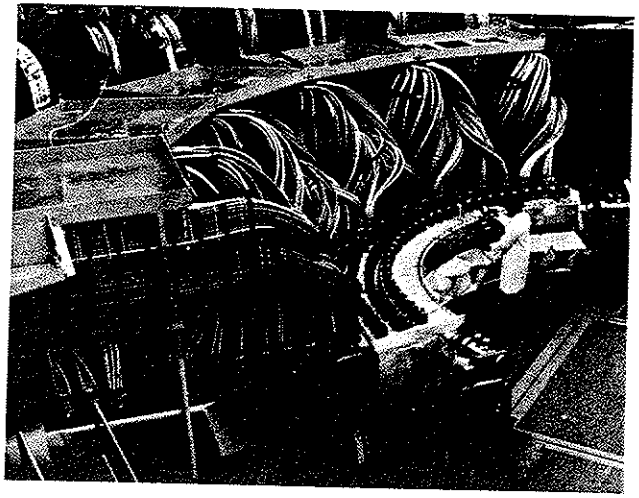


Figure 42 The Scyllac Experiment (arc section) at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

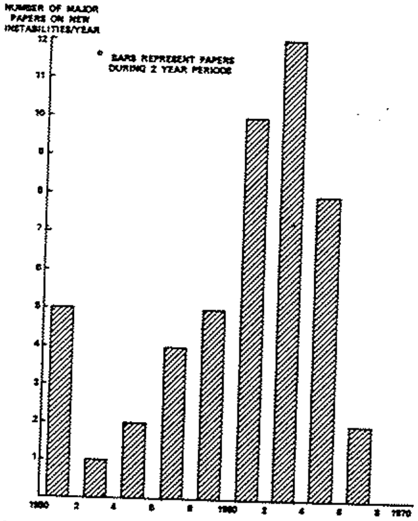


Figure 43 Discovery rate of plasma instabilities as a function of time.

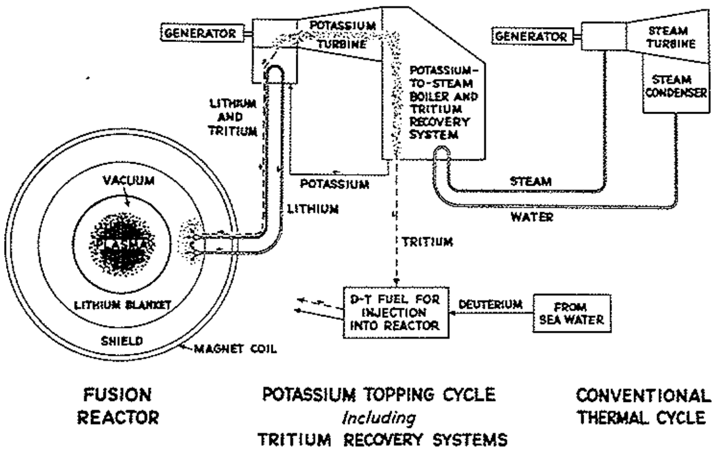


Figure 44 D-T fusion power plant. Thermal energy conversion would be most effective in a fusion reactor based on a deuterium-tritium fuel cycle, since such a fuel would release approximately 80 percent of its energy in the form of highly energetic neutrons. The reactor could produce electricity by absorbing the neutron energy in a liquid lithium shield, circulating the liquid lithium to a heat exchanger and thereby heating water to produce steam and thus drive a conventional steam-generator plant. The reactor core could be either linear or toroidal.

material, the tritium breeding blanket, the lithium coolant, the potassium topping cycle, the tritium separation, and the injection of the tritium and deuterium fuel. The conventional thermal cycle appears on the right.

Figure 45 is a fusion reactor using a fuel cycle that doesn't require a breeding blanket. It uses a direct energy converter, in other words the charged particles of fusion are being converted directly to electricity. Such energy converters may be able to achieve 80% or 90% efficiencies. The fuel cycles chosen should maximize the number of charged particles and minimize the number of neutrons. Any neutrons would be captured in the blanket-shield and converted to electricity by the less efficient thermal cycle.

Figures 46 and 47 are R&D flow charts for a DT fusion reactor, specifically they are for a toroidal system using liquid metal coolant. About 95% of our effort in the fusion program is concentrated on plasma research to achieve the necessary plasma parameters and to develop plasma scaling laws. Using our plasma information we move outward towards the reactor and establish requirements for the magnetic field, the tritium handling, and the heat removal. This is where the chemists and chemical engineers make their entrance. As soon as such requirements are set we must obtain information on the interaction due to the plasma on reactor components. You will be hearing papers on the surface chemistry at the first wall, tritium breeding rates, the permeation of hydrogen through metals, and the handling of tritium. To reach a fusion reactor you not only move outward by setting requirements we have to move inward.

Progress will be made by moving from the technologies as shown in figure 47 because these technologies are setting constraints and they have to be coupled with the scientific constraints that are being set by the plasma. There are a number of technologies, cryogenics, superconductivity, divertors for toroidal systems, fuel injections, tritium recovery and energy converters. Papers on liquid metal coolants will be given. Other coolants could be used such as helium, and you will hear a paper on molten salt as a coolant. You'll hear a discussion on superconductors, the tritium recovery

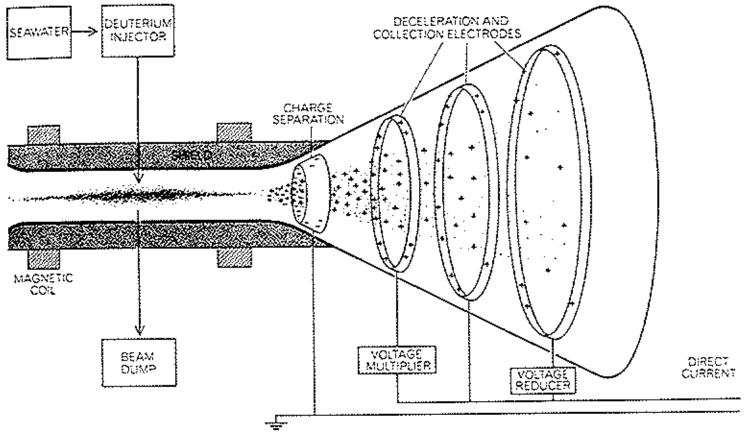


Figure 45 Direct energy conversion would be more suitable for fusion fuel cycles that release most of their energy in the form of charged particles. The energetic charged particles (primarily electrons, protons, and alpha particles) produced in the core of a linear fusion reactor would be released through diverging magnetic fields at the ends of the magnetic bottle, lowering the density of the plasma by a factor of as much as a million. A large electrically grounded collector plate would then be used to remove only the electrons. The positive reaction products (at energies in the vicinity of 400 kilovolts) would finally be collected on a series of high-voltage electrodes, resulting in a direct transfer of of the kinetic energy of the particles to an external circuit. (From "Prospects of Fusion Power" by Gough and Eastlund, Copyright 1971 by Scientific American, Inc. All rights reserved.)

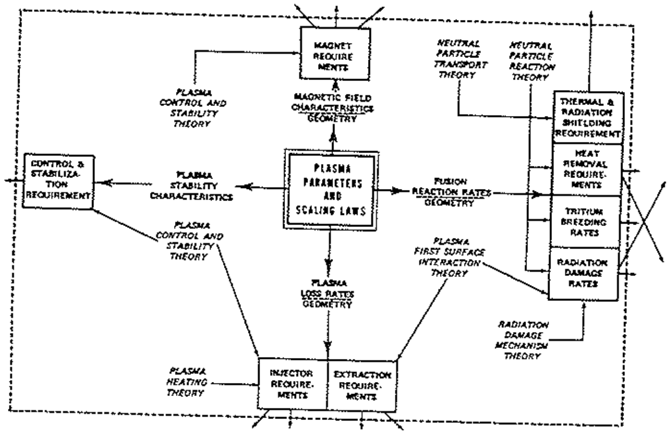


Figure 46 Partial R&D flow chart for a DT fusion reactor showing how system requirements are established from the plasma outward.

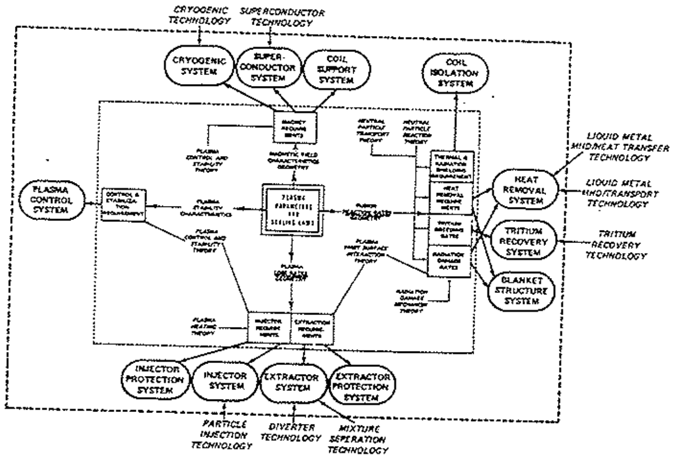


Figure 47 Complete R&D flow chart for a DT fusion reactor showing how available technologies interact inward on the system requirements.

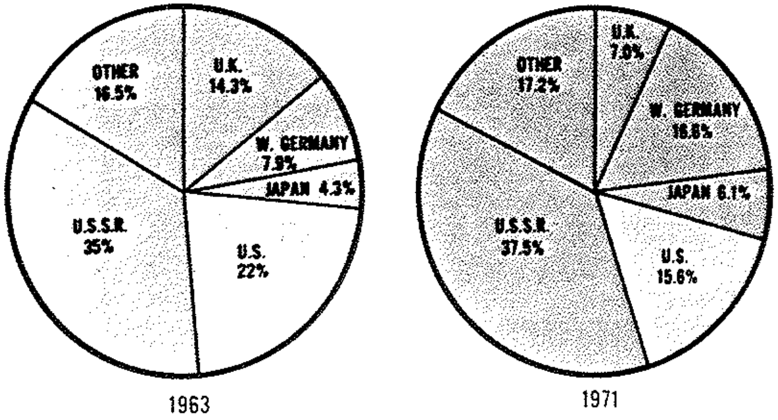


Figure 48 Distribution of the world effort in controlled fusion research.

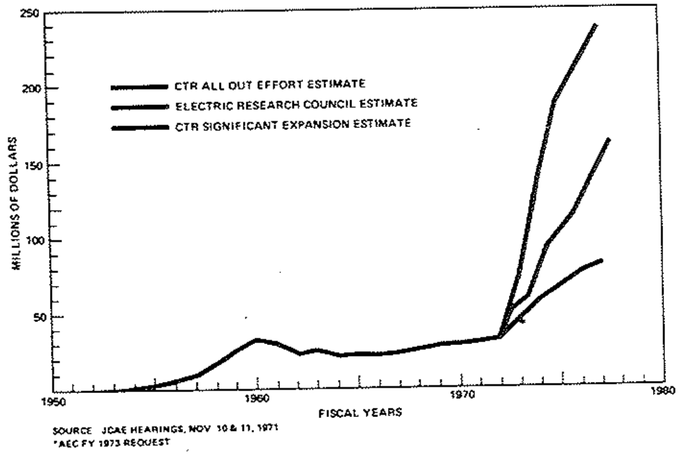


Figure 49 U.S. controlled fusion program (operating and equipment costs). Actual costs are given through FY 1972, estimated costs beyond that date. Source: JCAE Hearings, November 10 &11, 1971.

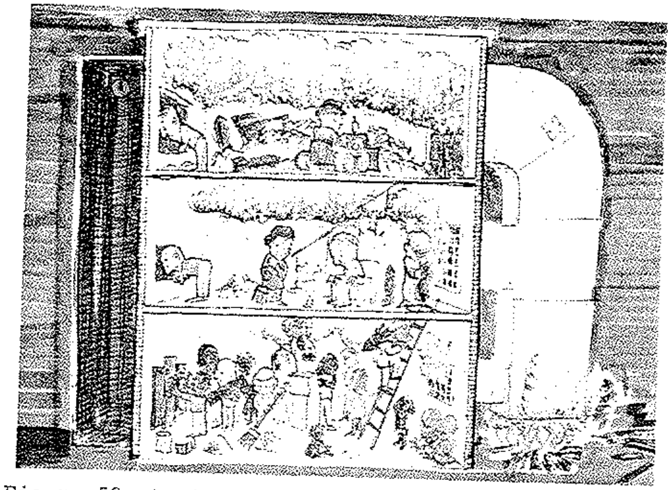


Figure 50 A view of the world as it may be at the beginning of the next century.

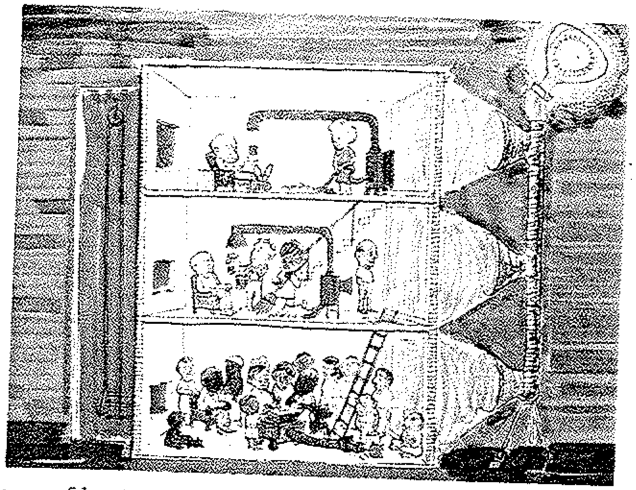


Figure 51 A view of the world as it hopefully could be at the beginning of the next century.

techniques, and direct energy converters. These are all areas where the chemist and chemical engineer will contribute.

If we look at the time scale for fusion, the first thing that we note is that the U.S. fusion program represents slightly over 15% of the total world program, as shown in figure 48.[24]

Our present operating budget is 31 million in fiscal year 1972. Figure 49 gives the actual costs since the program's inception. They represent approximately the cost of one moon shot; something in the 400 million dollar range. We can't bring fusion on in five years and we can't bring it on in ten, at least we can't have commercial fusion. It will require a considerable effort to have commercial systems in twenty to thirty years. So we are entering a transition stage now.

Varying cost estimates for the future were presented at a recent Congressional hearing before the Joint Committee on Atomic Energy.[24] There are two major elements that have to be considered. One is the physics. In the plasma physics there are unknowns that still remain. Because of these physics unknowns, a broad plasma program gives the maximum probability of success in the shortest timescale. This appears desirable since costs during the R&D stage are relatively low when compared to later costs. The second element is the fusion reactor technologies that are involved. We know many of the problems that have to be solved. We know them now and the question is to what extent do we start to work on these problems because technological developments are expensive.

The top curve of figure 49 constitutes an all out effort. It would attempt to bring fusion on in the shortest time with minimum risk. One would have an expanded physics program and would start immediately upon extensive technology developments required for fusion reactors. The Edison Research Council estimates assume commercial fusion sales by the year 2000 developed under a broad based physics program with a sizeable technology effort. The last curve is called a significant expansion. It maintains a solid physics program, but postpones expensive technologies until after scientific feasibility. It would attempt to have an operating fusion reactor by the year 2000 at minimum cost. These estimates are being refined in a study now underway for the Office of Science and Technology.

I would like to conclude with figure 50 and 51. If we take projected population growth, we'll have a ratio of people in North America, to the other developed countries, to the underdeveloped countries of 2:4:16 in the year 2000. Our energy supplies will be depleting. Our sources of raw material may be cut off. Pollution will be building up. Weapons will be proliferating. But man is a self evolver at this moment and he is responsible for his own evolution into the future.

Evolution means selecting and we must choose and decide and develop the values which will assure our survival. Thus although this is one possible future, it need not be our choice. The last figure shows a much happier situation in which we will have the ability to recycle materials, and we will have abundant energy available. Hopefully the world will go in this direction. In many ways we are like a disorganized crew trying to sail a ship, and our navagational aides, poor though they may be, are indicating that there is a storm ahead. We don't know exactly how far ahead. The capability to build good navagational tools, fusion being one of them, exists, but the crew is going to have to work together as human beings. The question is will we? and when?

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TRITIUM BREEDING AND DIRECT ENERGY CONVERSION

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ABSTRACT

Tritium breeding and direct energy conversion are key technological problems in the development of practical fusion reactors. Lithium in some form is needed for tritium generation, but certain chemical problems must be overcome. Alternatives to lithium metal should be considered. Better methods must be developed for efficiently recovering the tritium and safely disposing of the unwanted byproducts. Separation of the fusion fuel and waste products will be especially challenging for mirror machines with direct energy conversion. Hopefully, in the long run, these machines will employ the DHe^3 fuel cycle, but this will impose additional demands for efficient helium isotope separation and, possibly, tritium storage in some manner that allows for recovery of the He^3 decay product.

INTRODUCTION

To realize the promise of fusion, we must resolve many questions deriving not only from the basic problems of plasma physics but also from the peripheral technology. The plasma physics problems are, of course, of paramount importance. However, the technological aspects are of growing significance, particularly as they relate to the solution of the basic physics problems.