

COMMITTEE VII
Global 2000 Revisited: Re-assessing
Man's Impact on Spaceship Earth

DRAFT - 11/15/86
For Conference Distribution Only

**POSSIBLE REPLACEMENT FOR FOSSIL FUELS
AND COMPARATIVE ENVIRONMENTAL ASPECTS**

by

Jovan Jovanovich
Professor of Physics
University of Manitoba
Winnipeg, CANADA

The Fifteenth International Conference on the Unity of the Sciences
Washington, D.C. November 27-30, 1986



1986, Paragon House Publishers

A. INTRODUCTION

Shall the world always stay divided into rich and poor, into the affluent industrial and primitive agricultural? Will the societies that are presently undeveloped pass through their own industrial revolution and eventually catch up with high income countries of today? Is it realistic to expect that some time in the future all people in the world will be as affluent as people in the United States are today? Can we imagine, sometime in the future, our globe with ten billion people and five billion cars?

In two previous papers (JOVA 86; JOVA 86a) we have discussed this problem and concluded that the world is moving in the direction of global affluence. When, and if, the world achieves this global affluence, assuming that the energy consumption per person will stay the same as it is in the United States and Canada today, and that the world population will stabilize at 10 billion people, the demand for energy will increase tenfold over the present demand. Furthermore, it was argued (JOVA 86, Figure 5) that this tenfold increase in energy demand may be reached as soon as half a century from now.

The object of this paper is to survey the existing and emerging energy technologies, the available resources and the impact such high consumption of energy would have on the environment.

B. ENERGY TECHNOLOGIES

Where can energy needed by an affluent future world come from? An optimist will answer that new technologies using renewable and clean energy sources will provide all that energy, if only enough money is invested into properly selected research areas. It would be great if this statement could be true. Unfortunately, a realistic investigation of the existing commercially feasible and some other scientifically feasible technologies reveals that only two energy sources, coal and nuclear, could provide enough energy needed by an affluent world within the next 50 to 60 years.

B1. EXISTING TECHNOLOGIES

There are essentially only five existing energy producing technologies. They are coal, oil, gas, hydro electricity and nuclear electricity. The contribution of these five technologies, as well as the total world consumption of energy during the last six decades is shown in Figure 1.

Coal. After wood, coal is the oldest fuel used by man. It was used in China for smelting copper at least 3000 years ago. By the end of the 17th century 200,000 tons of coal a year were produced in England (ENCY 74). In the 1920's, well over 80% of energy used in the world was produced by burning coal. At present, coal supplies only 30% of the world energy (c.f. Figure 1).

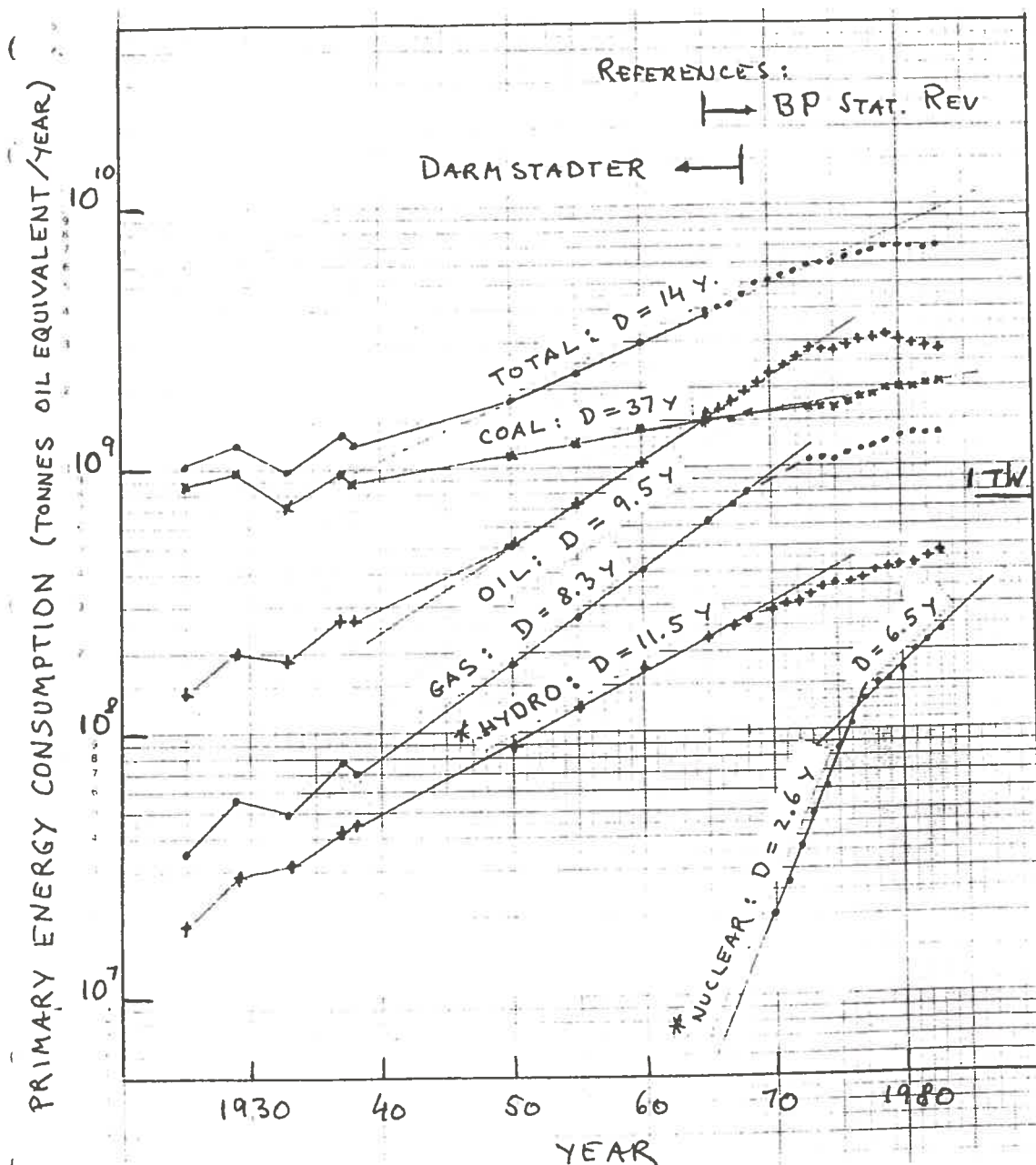


Figure 1. The growth of consumption of industrially produced and commercially sold energy for the period between 1925 and 1983 is illustrated in this graph. The data before 1968 were taken from (DARM 71) and after 1965 from (BPST 84). The heavy black line represents the energy consumption for the whole world. Five thin lines represent consumption of major energy sources, oil, coal, gas, hydro electricity and nuclear electricity. Units used for oil, coal and gas are metric tons of oil equivalent (t.o.e.) per year on the left and terawatt on the right. Hydro and nuclear electricity are shown as amount of oil that would be needed in thermal power stations in order to produce the same amount of electrical energy. This was achieved by equating 1 KWh to 125 grams of coal equivalent. Where data follow a pure exponential, straight lines were drawn and times in years needed to double the amount (called D) are explicitly shown.

Coal is a bad technology because it is dangerous to dig from deep mines, ugly to scrape from the surface, difficult to transport and it produces acid rain which kills lakes, forests and shortens life expectancy of people. The results of some of the recent studies indicate (OFFI 82, page J-7) that acid rain is a contributing factor in 51,000 deaths each year from various heart and lung diseases. Nevertheless, all these difficulties are not the most important difficulties. If we wanted to pay, we could stop acid rain and reclaim abandoned open pit coal mines. The major difficulty with coal, as well as with all other fossil fuels (oil, gas, tar sands, etc.) is the production of carbon dioxide, which cannot be removed from smoke stacks in any feasible manner and which threatens global climate (c.f. Sec. C3).

Oil and Gas. At the present stage of technological development, oil is indispensable as raw material for the production of liquid fuels, so essential in both surface and air transportation. Since 1973 oil is widely being replaced by gas for heat production and by coal and uranium for electricity generation. Figure 1 shows that the world oil consumption has been decreasing since 1979.

Fossil Fuel Resources. Hafele et al. state (HAFE 81, page 40) that the fossil fuel resource base is estimated as follows: conventional oil has perhaps up to 400 TWyr of energy; heavy oil and tar sands another 400 TWyr; shale oil, 60 TWyr; natural gas, 350 TWyr; and coal 2400 TWyr, the total of all being 3610 TWyr. The present rate of energy consumption is about 9 TWyr/yr, thus, at present rate of consumption fossil fuels would last for about 400 years, and at the assumed "saturation" consumption about 40 years. At "saturation", conventional oil would last less than 4 years. From these very crude estimates it follows that even if energy consumption grew at rates as fast as discussed in (JOVA 86), that is increasing by ten times within the next half a century, there would be enough fossil fuels, mainly coal, to power the world to beyond the middle of the next century, but not much longer.

Hydro Electricity. At present about 20 percent of world electricity and seven percent of world energy is produced by hydro power (c.f. Figure 1). Hydro electricity is a very clean and cheap source of energy although the ecological consequences produced by flooding large tracts of land are sometimes very undesirable. Dam bursts have also occurred a number of times in the past with many people being killed (c.f. Sec. C1).

Nuclear Fission. The world resources of uranium are not sufficiently large to provide all the energy needed for the next 50 years if only reactors burning uranium-235 are used. Breeders, which convert 130 times more abundant uranium-238 into fissionable plutonium, will have to be extensively employed. Although the working prototypes of these breeder reactors have been made, they have not yet been commercially exploited. Once breeders are commercially available the nuclear power will be able to provide the world with needed energy for thousands of years.

Unfortunately, even with this scheme there are difficulties.

If the energy consumption in the undeveloped world continues to rise as during the last few decades and if the bulk of this increase should come from thermal and breeder reactors a difficulty with supplies of uranium and plutonium would arise. While the fast breeder reactors would be able to provide enough energy at the assumed saturation for many centuries once the steady state is reached (or almost reached), fast breeder reactors will not be able to convert U-238 into plutonium fast enough to supply fuel for all new breeder reactors. The reasons are that the production of nuclear energy should be doubled every five to six years until "saturation" is reached. The supply of plutonium to be initially loaded into new reactors must grow at the same rate. Unfortunately, present breeders can double the amount of fuel initially loaded only in fifteen to twenty years. Thus, the world supplies of energy could not be bootstrapped by fast breeders alone at a rate which would double the world energy consumption every fifteen years or so. This problem has been considered by World Energy Conference (FOST 78) and the conclusions were illustrated in a diagram which is reproduced in Figure 2.

The anticipated plutonium shortage can be resolved by developing accelerator breeders (DAVI 77) a technology which is scientifically feasible but has not yet been developed. The accelerator breeders are discussed in the next section.

Fission Power Resources. The resources of uranium are estimated by Hafele et al. (HAFE 81, p. 49) to be about 25 million tons of uranium, using only ores with concentrations higher than about 0.1 percent. As one ton of uranium used in breeders could produce, under ideal conditions 2.8 GWyr of thermal energy and present world consumption is 9TWyr = 9000 GWyr, it follows that about 3,000 tons of uranium can power the present world for a year, or 30,000 tons at the assumed saturation. Thus, the estimated resources of "high grade" uranium ores could power an affluent world for about ten centuries. Low grade uranium ores with uranium content between 0.01 percent and 0.001 percent are quite abundant. When thorium resources are added to these uranium resources, it is clear that fission energy can power an affluent world for many millenia.

If the world would use only present, non-breeder reactors which use uranium roughly 100 times less efficiently than breeders, the world's "high grade" uranium supplies of 25 million tonnes at "saturation" would not last ten centuries, but only ten years!

This very rough calculation clearly shows that from the existing technologies only breeder reactors could supply an affluent world with energy for many centuries.

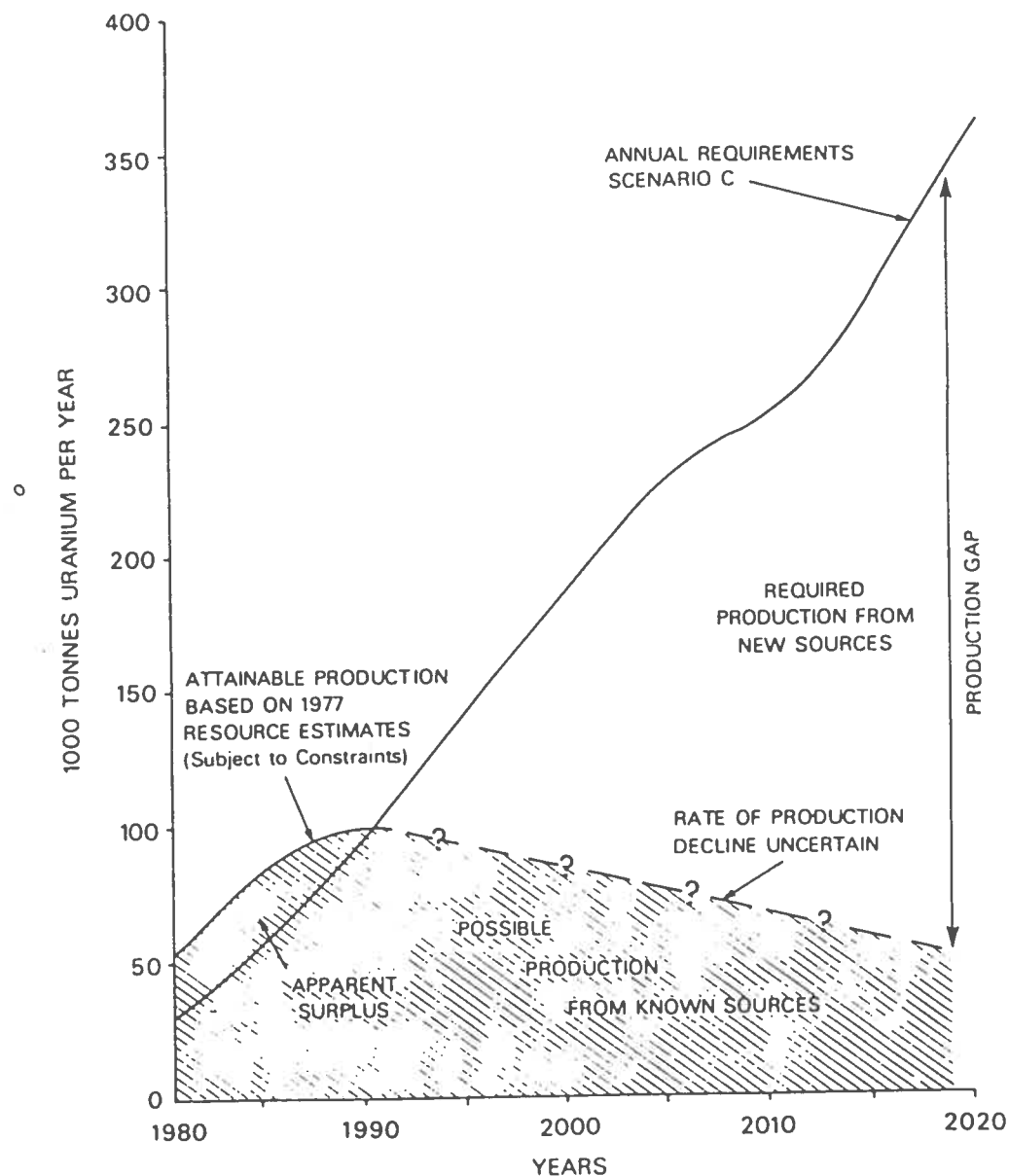


Figure 2. Schematic illustration of world uranium supply problem until year 2020 (reproduced from FOST 78). On the vertical scales is plotted quantity or uranium needed annually for initial fueling of new reactors and refueling of the existing reactors. Scenario C is the one which assumes relatively fast industrial growth in developing nations and use of fast breeders as expected to be economically justified. In fact, this perceived shortage of uranium, as well as perceived difficulty in mining sufficiently large amounts of coal, are main reasons why the study by the World Energy Conference (BL00 78) has considered the historical growth of doubling energy consumption every 15 years as impossible to achieve.

B2. EMERGING TECHNOLOGIES

Renewable Energy Sources. Renewable hydro electricity, wind electricity, biomass fuels, geothermal heat, and OTEC (Ocean Thermal Energy Conversion) electricity could not provide more than a few percent of the total energy needed by an affluent world. A number of studies of these resources have been made (PUTN 53, STAR 71, HUBB 71, HAFE 81). The technical potential of these fuels (HAFE 81, p. 84) on a global scale is illustrated in Figure 3. The practical, economic potentials are naturally significantly lower, and thus, even if these fuels were economically competitive, they could not possibly satisfy the global need for energy.

Solar Energy. The technical potential of solar energy is enormous. Our sun supplies the earth with energy which is several orders of magnitude higher than the presumed "saturation" amount indicated in Figure 3. In spite of this, it is difficult to see how solar energy could provide significant amounts of needed energy during the next half century.

The basic difficulty with solar energy is the Second Law of Thermodynamics. Solar energy is diffused, about one kilowatt per square metre, and so much only when the sun shines. (As a comparison, fission energy is "dense", about 100 megawatts per cubic metre). For most applications we need "dense" energy. To use solar energy for electricity production, it must first be concentrated, and this requires work. Work costs money, thus, the solar electricity is intrinsically expensive. Various engineering designs of solar power stations clearly show this fact (STAR 79). As a result, solar electrical power stations have not yet become commercially feasible and no company in the world is selling them.

Aside from being very expensive, solar electricity has two more disadvantages. One is that the sun shines only during the day, and it is bright if there are no clouds. Therefore, a practical method of storing large amounts of electricity would have to be found before solar electricity could be used day and night, sunshine or rain. The second disadvantage is that densely populated countries would have to use a sizeable fraction of their land to collect enough sunshine. For instance, if the population of India doubled, if each person used as much electricity as we use in North America and Scandinavia today, and if all that electricity was to be produced by solar energy using the only presently available technology, that of mirror collectors, then close to two percent of the Indian subcontinent would have to be covered by mirrors and access paths to these mirrors. In the case of countries with less sunshine, like England, a much greater fraction of the British Isles would be covered with mirrors and auxiliary power-related facilities. This is clearly impractical.

If all the solar power stations were located in various deserts around the world and the electricity generated was used to produce hydrogen gas, then, in principle, the world could get all its energy from the sun. But this scheme is quite expensive and not practical to be fully deployed within the next few decades, if ever.

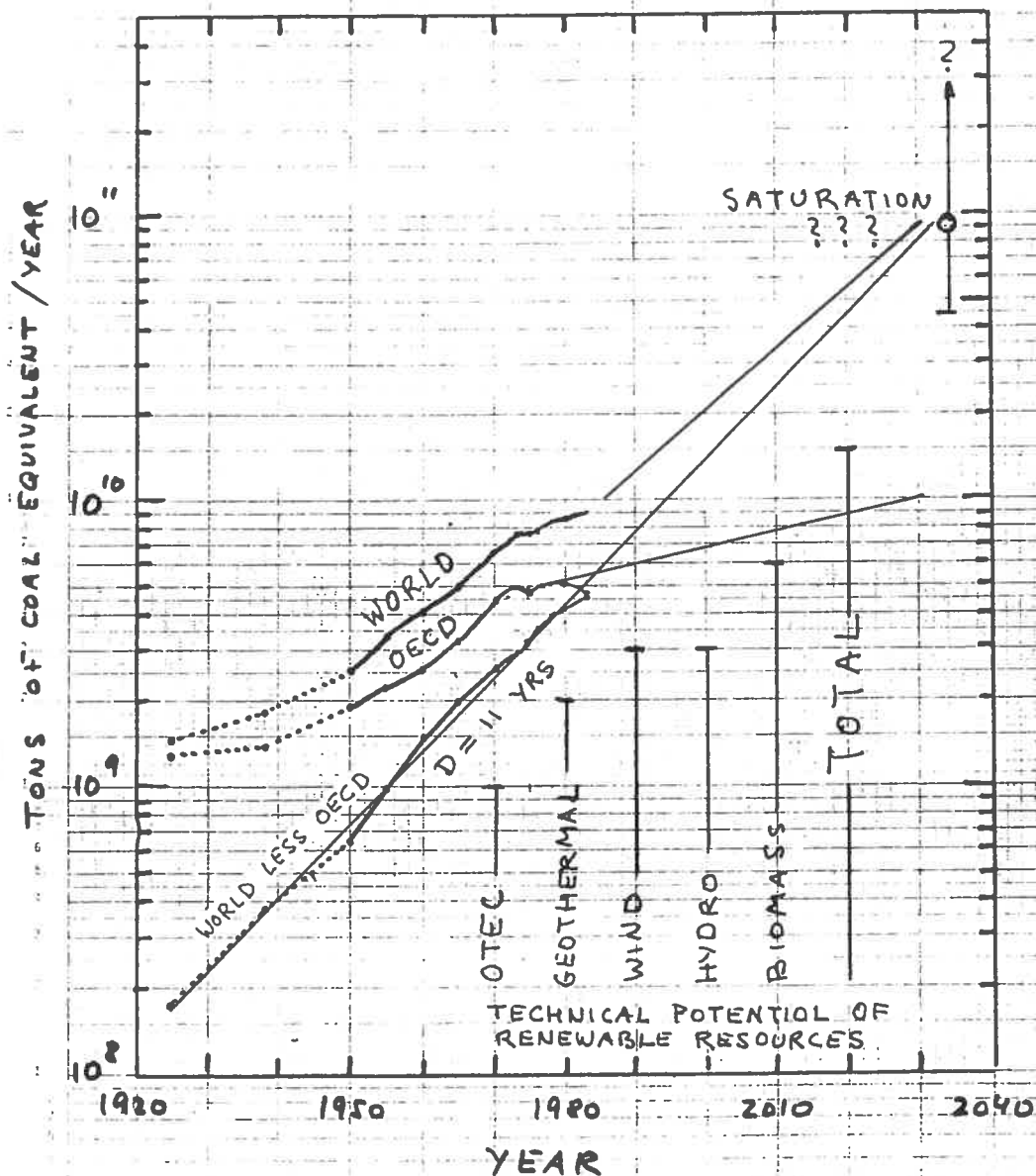


Figure 3. World consumption of commercial energy (top curve) is divided into two world regions, one industrially the most developed and the rest of the world. From 1925 to 1965 the data were taken from (DARM 71) and after 1965 from (BPST 84). In the 1920's the industrially developed world, composed of Western Europe, North America, Japan and Australia, was consumer of over 85% of all energy used in the world. These same countries, with some but not very significant exceptions, form today the Organization for Economic Cooperation and Development (OECD) and consume only 50% of the world energy. It should be noticed that the non-OECD world has been doubling its energy consumption every 11 years, increasing it by 30 times during the last 55 years. Past and projected future energy consumption for the whole world, OECD countries and all other non-OECD countries. Dotted-dashed line is a historical trend for the non-OECD countries. The heavy line is the sum of this line and the low projection for OECD countries in the IIASA study. In the top right hand corner it is indicated what the energy consumption will be a few decades from now, when, and if, the whole world becomes as affluent as the United States and Canada are today. In the bottom right hand corner the upper limits (technical potential) of several renewable energy sources (HAFE 81, page 84) are indicated with arrows and bars.

Optimistically, the solar energy will be able to provide a certain fraction of electricity in some selected areas of the world, Southern California or Egypt, for instance. The bulk of the energy used by the rest of the world will have to be produced using other energy sources. Pessimistically, the solar produced electricity will never become commercially practical, not even in southern California or Egypt.

Accelerator Breeder. As explained earlier (Section B1) and pointed out during the World Energy Conference (FOST 78), if the use of nuclear energy expands as needed by a world that industrializes itself along historical lines, a shortage of uranium would develop early in the next century. If fast breeders are extensively used, the pressure on uranium supplies would be reduced, but the shortage of uranium and plutonium needed for the first fueling of the breeders would develop again, a decade or two later (see Figure 2). The solution to this difficulty is a new know-how, the technology of accelerator breeders (MYNA 77, DAVI 77, GRAN 77).

A schematic of an accelerator breeder complex is shown in Figure 4. In such a system a very intense beam of protons (say, 300 milliamperes) is accelerated to high energies (about 1000 MeV) in a linear accelerator. This beam then enters a target structure made primarily of uranium and/or thorium. Each high energy proton creates up to 100 neutrons which then either fission uranium and/or thorium and create heat, as in any nuclear reactor, or become absorbed in uranium-238 creating plutonium-239, or in thorium-232 creating fissionable uranium-233. The heat developed in the target is sufficiently large to operate an electric power station, which would supply all the electricity needed by the accelerator. In this way, the accelerator, target and power station would be a self-contained plant producing enough energy out of non-fissionable uranium-238 and thorium-232 to drive itself and, in addition, to convert sizeable amounts of these two elements into easily fissionable plutonium-239 and uranium-233. These two could then be used either in thermal reactors or in fast breeders. As accelerator breeders could produce plutonium as needed, the anticipated shortage of plutonium for the first fueling of breeders would be overcome.

This technology does not exist yet. It is a scientifically feasible technology, but its engineering feasibility has not been demonstrated, as no other but some early design work has been done on it. The development of this technology would enable the fast, worldwide deployment of breeders, as well as the full exploitation of thorium resources. This technology should be of particular interest to India, a country which is relatively poor in any other energy resource but thorium.

Nuclear Fusion. Thermo-nuclear fusion, once harnessed, will provide mankind with almost unlimited amounts of energy. Unfortunately, this process is so complicated that even the scientific feasibility of a fusion reactor has not yet been demonstrated. Thus, it would be too optimistic to expect that this source will provide significant amounts of energy, if any, within the next half a century.

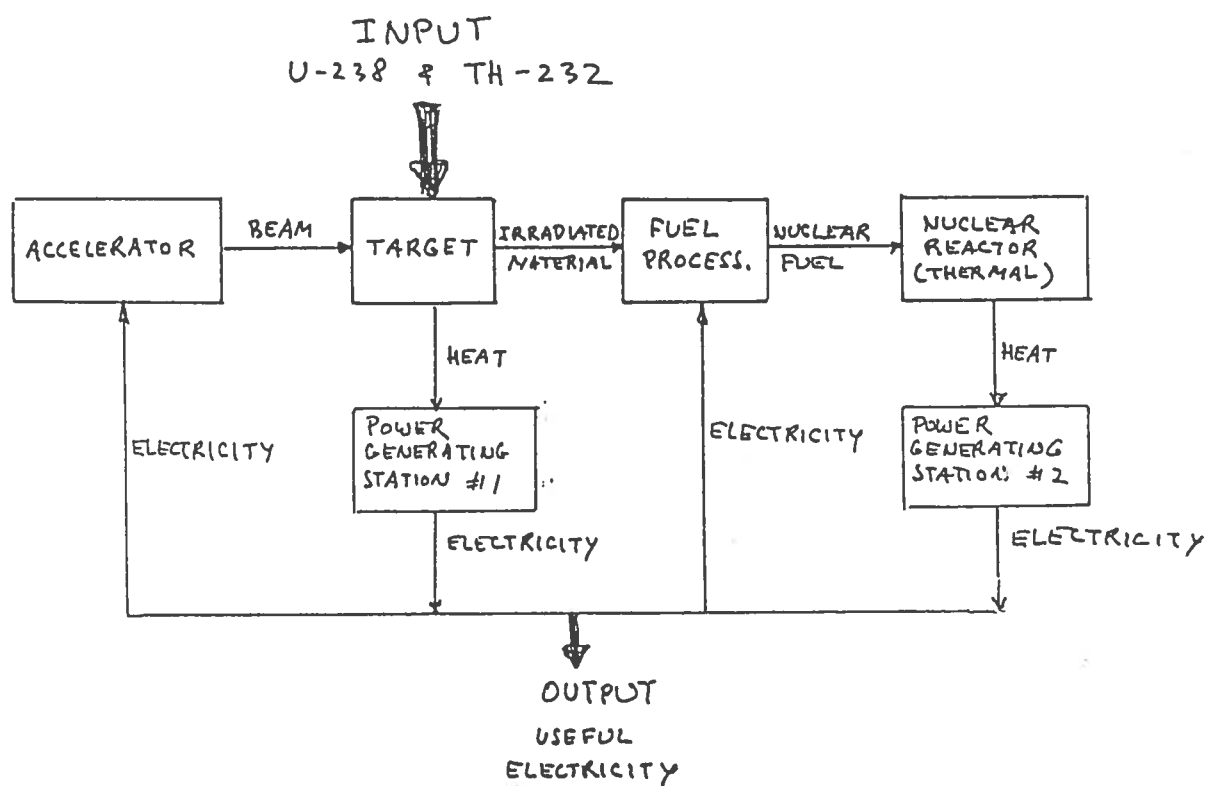


Figure 4. Schematic representation of an accelerator breeder complex designed for the production of fissionable fuels, namely Uranium-233 from thorium and Plutonium-239 from Uranium-238.

Summary. From among all emerging technologies that seem to be on the verge of being practical to use within the next half a century or so, the accelerator breeders seem to be the only ones that have good prospects of being useful, in fact, essential if developing nations continue in their march towards the global affluence.

C. ENERGY AND ENVIROMENT

There exists no ideal technology, a technology that would not present certain dangers to man and the environment. Energy technologies, nuclear power included, are no exception.

All harmful effects produced by various energy technologies can be divided into three broad groups: (1) Local and/or short term effects; (2) Regional and/or medium term effects; (3) Global and/or long term effects.

Under local, we shall understand events whose spatial extent is a few kilometers. Under regional, those events whose extent is up to a few thousand kilometers. Global events affect the whole earth. Short term events will be those whose effects last for a few days or weeks. Medium term would be those whose characteristic times are years and long term events are those that persist for times comparable to or longer than the human lifetime.

The Bhopal disaster, or the collapse of a hydroelectric dam are obvious examples of local effects with short term duration.

Acid rain is a typical example of regional effects whose spatial extent is hundreds and thousands of kilometers. Slow health effects of acid rain, as well as ionizing (nuclear) radiation, have significance on the (medium term) time scale of a decade or more.

There exist only two long term global effects related to energy production. These are the productions of nuclear waste and carbon dioxide. The first problem is, in fact, more regional than global, but it is certainly of long duration. The carbon dioxide problem is truly global in its nature and also of long duration.

The proliferation of nuclear arms does not fall into any of the above three categories. It is the case of a gross misuse of a technology which appears as a result of human relations, rather than the coupling between technology and the environment. A short discussion of this problem was presented in (JOVA 86).

C1. LOCAL/SHORT TERM EFFECTS

Events of local significance and short duration are usually called accidents, sometime disasters. They are of the most direct and immediate concern to people. They usually produce instant injury or death and easily visible damage to the property and environment. Victims of these accidents are either people working with particular technology or the general public.

Non-nuclear Technologies. Every technology has its own type of accidents. The coal industry is well known for its mining accidents which kill anywhere between a few and a few hundred miners. Hydro electricity is known for its high rate of construction accidents and occasional dam failures which sometimes have killed thousands. H. Inhaber (INHA 82) in Table K-3, reproduced in Figure 5, lists numbers of dead due to various major dam disasters and concludes that up to 1980 (including Morvi dam accident) somewhere between 5500 and 7000 people have been killed in this way. Many more examples of energy related accidents could be given.

Nuclear Accidents. A major concern about the nuclear power is the possibility of catastrophic accidents. Although Three Mile Island accident did not kill anybody (KEME 79), the Chernobyl accident did. In 1957, scientists at Brookhaven National Laboratory estimated (WASH 57) that if one half of the radioactive inventory of a 500 megawatt (thermal) reactor were somehow released into the atmosphere in the vicinity of a populated city, and if atmospheric conditions were unfavourable, then 3,400 deaths, 43,000 acute illnesses and tens of thousands of induced latent cancers could occur. Present day power reactors are three to eight times larger, thus, the damage could be much worse.

For several reasons this first and very crude study was too pessimistic. It did not consider what the plausible physical and chemical processes were that could spread half of the reactor core into the atmosphere outside the very strong reactor containment building. Also, this study did not even attempt to estimate how probable such catastrophic accidents may be.

In the Rasmussen report (WASH 75) a set of complex calculations were performed in order to estimate the probability of a nuclear (power) reactor accident that could kill a certain number of people. The results of their study are shown in Figure 6 (reproduced from RUED 75) where they are compared with risks due to other natural or man-made disasters.

It has been hotly debated how good these estimates are (see for instance STUD 75, SHEA 78). The authors of the study themselves did not claim that the results are better than an order of magnitude, that is a factor of ten in either direction.

In recent years, more studies about the safety of certain types of nuclear reactors were made and the conclusions are even less pessimistic than the first Brookhaven estimate and the Rasmussen report (c.f. LEWI 80, LEVE 81, RIPP 84, LEVI 85, LEDE 85, CASE 84).

**Table K-3. Major Disasters Likely Associated with
Hydroelectricity Generation (c)**

<i>Place</i>	<i>Date</i>	<i>Number Dead</i>	<i>References</i>
Vajont, Italy (a)	1963	2600-3000	153, 154 (b)
Gleno, Italy	1923	600	155, 156
St. Francis, United States	1926	426-450	155, 156
Kiev (Babi Yar), U.S.S.R.	1961	145	161
Koyna (Shivaji Sagar Lake), India	1967	180	158
Vega de Tera, Spain	1959	123-150	153, 155, 156
Sella Zerbino, Italy	1935	100-111	155, 156
Oros, Brazil	1960	30-1000	153, 155, 156
Coedty, Wales	1926	20-60	155, 156
Teton, United States	1977	9-11	159, 160
Bhakra, India	1959	10	155
Colorado Dam, Texas, United States	1900	8	155
Necaxa No. 2, Mexico	1909	4	155
		4255-5729	

(a) Dam did not fail, but was overtopped.

(b) Reference 155 indicated 5000 dead, but this may be in error.

(c) Since data on hydroelectricity production are considered only to the end of 1978, the Morvi dam accident of August 1979 in India is not included. This dam had a hydro component (531). A late report (535) placed the number of dead at 1335. This would increase the total associated with hydroelectricity at around 25%. On the other hand, a statement by the president of a local municipality near the dam accident places the number of missing as high as 25,000 (534). In either case, this accident is either the largest or second largest disaster in history associated with energy systems.

Figure 5. A table reproduced from (INHA 82) illustrates often ignored fact that dams are very dangerous structures and that dam accidents have killed many thousands in the past.

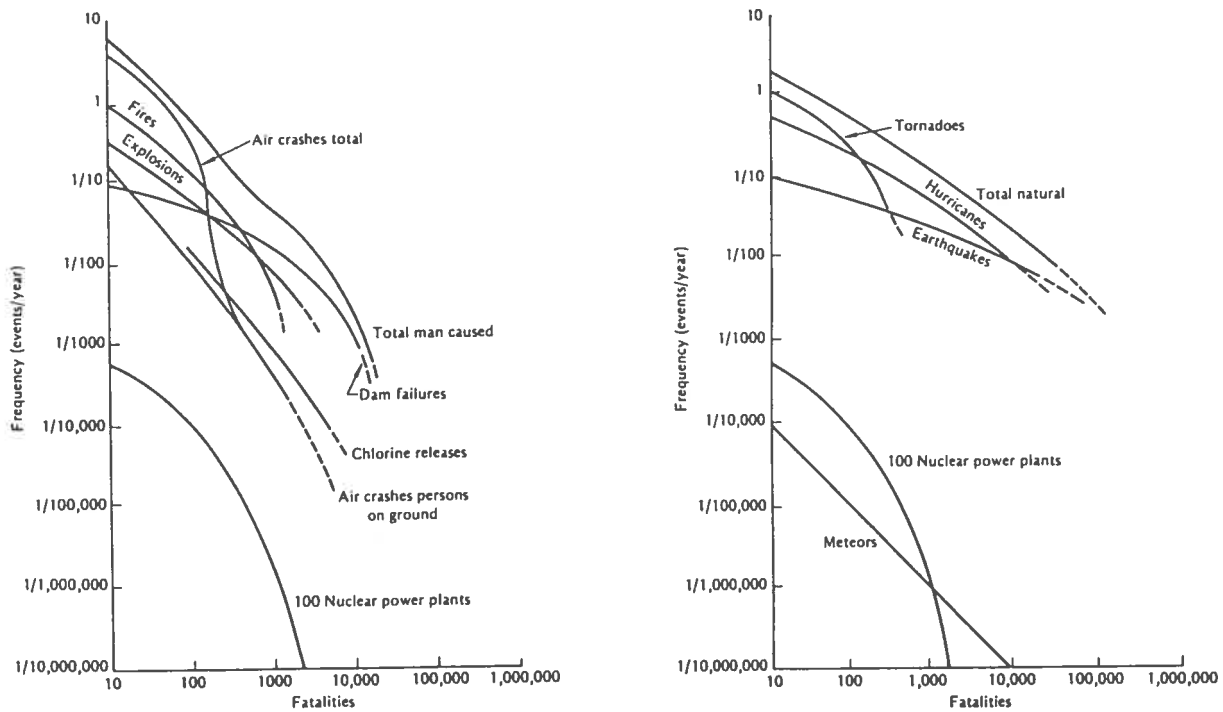


Figure 6. Probability distribution (frequency) of certain events occurring in one year in which more than a certain number of people are killed is plotted as a function of that same number of fatalities. On the left is plotted the frequency of man made disasters and on the right of natural disasters. The curves for 100 nuclear power plants are plotted on basis of theoretical calculations (WASH 75).

It should be also mentioned that the number for dam accidents is an experimental number - this is what has actually happened in the past. The numbers for nuclear reactor accidents are theoretical estimates based on some particular model and a particular set of assumptions. These assumptions may, of course, be wrong, in which case the conclusion would be wrong too, thus making nuclear power either more safe or less safe.

Comparing Nuclear and Other Risks. When all theoretical estimates performed so far are combined with the practical experience in operating existing power reactors, two conclusions emerge.

Until now, all nuclear power stations around the world have produced about 80 PWh, which is about one-sixth as much power as all hydroelectric power stations since the time the first one was built at Niagara Falls. Among the general public there has not been a single fatality yet due to nuclear power reactor accidents. At Chernobyl there were 31 occupational deaths. On the other hand, dam failures occur every few years somewhere, sometimes with thousands of people being killed in a single failure (see Figure 5). Until now, the nuclear power has had hundreds of times less fatalities per unit of electricity produced than the renewable hydro power. (Long term effects of released radiation are unknown and often misinterpreted by assuming that nature obeys the linearity hypotheses. In case on Chernobyl accident, the expected collective dose from external radiation exposure to the population in different regions of European part of the USSR (CHER 86) over the next 50 years was estimated to be 30 million person-rems. Assuming validity of the linearity hypotheses, this would produce about 4000 cancer deaths in a couple of decades. On the other hand, if radiation has a hormesis effect on human body (LUCK 86), then the effects of Chernobyl radiation spill would be beneficial.)

The second conclusion that emerges is that Murphy's law predicts that severe accidents like the one at Chernobyl, or even worse, will happen again sometime in the future. This will be nothing unusual. Other man-made activities and devices have killed in the past many more people.

Could something be done about this risk? Of course, it can. The safety can always be improved--at a price. The safer electricity will be a more expensive electricity. So, the real question is, how much do we want to pay for our own safety, and how should we invest our limited resources in order to get the maximum benefit for the minimum amount of money and effort. This problem was discussed in some detail in (JOVA 86).

Are present day nuclear reactors sufficiently safe? Or could it be that they are over-designed, implying that they have been made unnecessarily expensive? Is the nuclear industry over-regulated or under-regulated? Cohen (COHE 83) presents arguments in favour of the view that the nuclear industry in the United States is unnecessarily over-regulated. At present, there is no way to answer these questions in a conclusive way. The only conclusive way is to do the experiment, that means to operate reactors for thousands and millions of reactor years. While this experiment is going on, it would

presumably be prudent to build reactors far from densely populated areas, particularly when one keeps in mind that transmission of electricity over short distances is relatively cheap. In fact, this was one of the chief recommendations of the Kemeny Commission (KEME 79).

On Figure 7 is reproduced a graph (INHA 82) that relates fatality rates (public and occupational deaths were combined) in various industries per unit of energy produced. According to that study the natural gas is the safest. Nuclear power is the second best.

Summary. Our technological society is a dangerous place to live. There are many ways to get killed in it. But we still live much longer in a high-technology society, than in an underdeveloped society (JOVA 86). If we do not have technology which consumes large amounts of energy, do not have cars and bicycles, electricity and nuclear power stations, we are not going to live over 70 years, we are going to die much earlier due to poor medical care, malnutrition, etc. And, of course, our life is what we value the most.

C2. REGIONAL/MEDIUM TERM EFFECTS

Acid rain. This is one of the effects of energy technologies on man and environment whose spatial extent is a few hundred to a few thousand kilometers and whose effects are felt for periods anywhere between several weeks and several decades. A nice introduction to the topic was presented in (LIKE 79) and a detailed review is given in (OFFI 82).

The following news report illustrates vividly the difficulty with acid rain. In an article "Rain of Troubles", C.K. Groves (GROV 80) writes, "During several recent storms in Wheeling, West Virginia, the rainfall measured 1.5 on the pH scale, a level far more acid than vinegar". Vinegar has a pH level of 3.0, thus, the Wheeling rain was 30 times more acid than vinegar, and about 5 times more acid than lemon juice!

The technology for the control of acid rain exists but it is quite expensive to implement. The report (OFFI 82) states that something like four billion dollars a year would be needed to reduce the acid emissions in the Eastern half of the U.S. to one-half the present value (see Figure 8). This estimate was echoed in a short news report (THIS 83) where it was stated "... the electric industry's research institute (in the U.S.) predicted that cutting (acid producing) emission (from power stations) by 50 percent would raise prices (of electricity) by anything up to 50 percent".

Radiation Effects of Nuclear Power. One of the concerns related to nuclear power is the release of radiation and health dangers associated with it. These dangers have been discussed at some length in several submissions to this conference (TOTT 86, LUCK 86). Also, risks associated with the potential increase in the natural background radiation levels were discussed in (JOVA 86), so, this topic will not be discussed here.

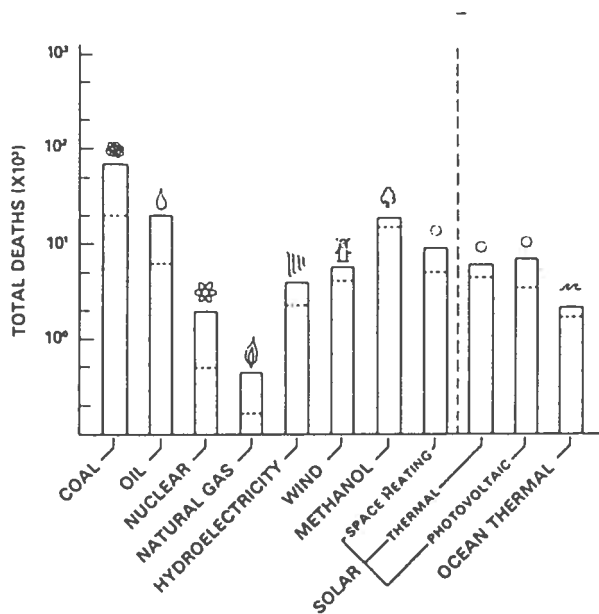


Figure 13. Total deaths, times 1000, per megawatt-year as a function of the energy system. (See explanation in caption to Figure 9.) For this graph, the public and occupational deaths are combined. Natural gas-fired electricity has the lowest value, followed by nuclear.

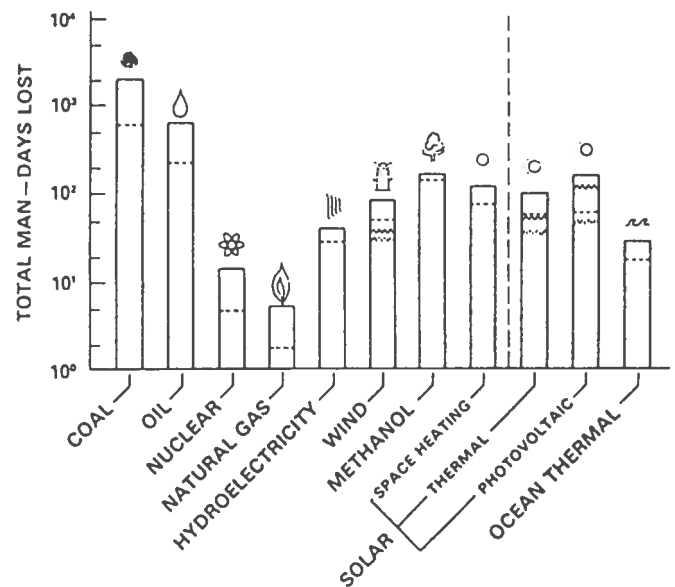
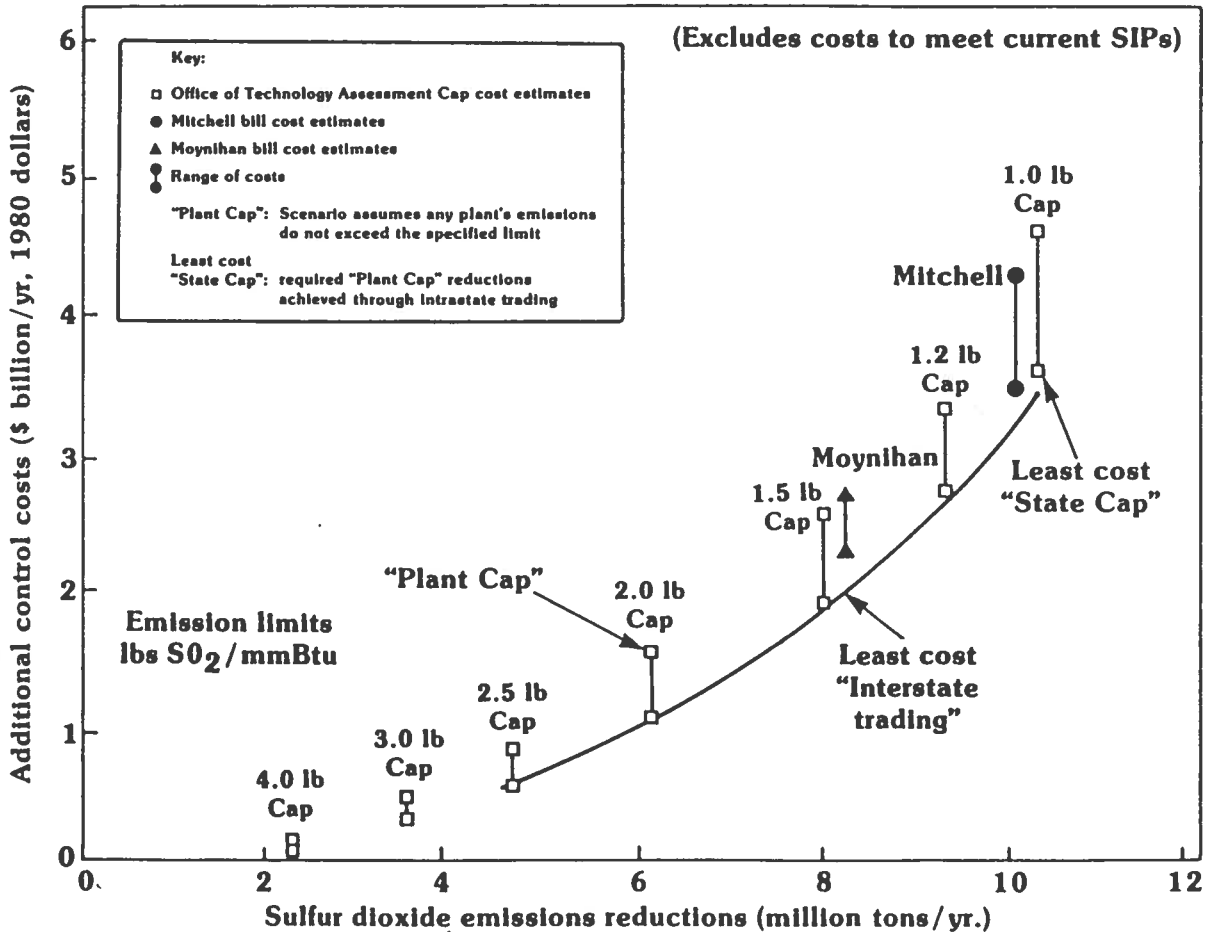


Figure 14. Total man-days lost per megawatt-year net output over lifetime of the system. (See explanation in captions to Figures 9 and 10.) This graph is similar to Figure 13. However, there are some differences in ranking. Natural gas has the lowest values, followed closely by nuclear. Jagged lines imply low risk or no back-up assumed.

Figure 7. Total deaths, times 1000, per megawatt-year as a function of the energy system.

FIGURE B-1

Cost of Sulfur Dioxide Control



SOURCE: Office of Technology Assessment, 1982.

Figure 8. Estimated cost of sulfur dioxide controls in the U.S. coal fired electric power stations (OFFI 82). It has been estimated that the total amount of sulfur dioxide and nitrogen oxide emissions in the 31 states of the Eastern U.S. amounts to 22.4 million tons per year.

C3. GLOBAL/LONG TERM EFFECTS

Radioactive nuclear waste. This topic has been discussed at fair length in Chapters 5 and 6 of Cohen's book (COHE 83) and in his Scientific American article (COHE 77). It is also the topic of a paper submitted to this conference (COHE 86). Only a summary will be given here.

The critics of nuclear power state that the ultimate disposal of nuclear waste has not yet been solved, which is essentially true. No waste from nuclear reactors has yet been irretrievably disposed of and no specific process for its disposal or destruction has been selected yet. All nuclear waste produced until the present time has been temporarily stored in one form or another, usually in the pools at the reactor sites. Why is this done? Briefly, the waste decays all by itself and the longer it is kept, the easier it is to handle it. The temporary storage is safe and cheap, thus, it is better to wait until safer and cheaper disposal technology is developed.

What are the possible technologies that might be used or developed in order to dispose of nuclear waste permanently? A summary of possible options is schematically presented in Figure 9. The full discussion of options indicated in this Figure is given in (JOVA 85, Sections D and E).

Carbon Dioxide Pollution. Our atmosphere contains at present about 340 ppm (parts per million) of carbon dioxide and every year, by burning fossil fuels, we add to it one more ppm (WOOD 78). If we keep increasing our fossil fuel consumption as in the past, doubling it every 15 or so years, we will have, a few decades from now, tripled or quadrupled the amount of carbon dioxide in the atmosphere. If we would continue in this way, the amount would increase even more. In Figure 10, the growth of atmospheric carbon dioxide (LISS 83) is illustrated under various assumptions for the increase in fossil fuel consumption and for the absorption of the released CO₂ by the biosphere and the oceans. If industrial revolution keeps spreading to the presently undeveloped parts of the world as discussed in (JOVA 86 and JOVA 86a), and if this industrial growth is fuelled by coal and other fossil fuels, then the world will be moving along the steepest curve on Figure 10, possibly even steeper. The effect would be quadrupling of the CO₂ concentration in less than a century.

What would be the effects of such a dramatic increase in the carbon dioxide content of our atmosphere? Nobody will know for sure until the "experiment" is done, and then it will be, of course, too late. But, something is known for sure. By adding carbon dioxide into the air, we are warming up the earth due to "greenhouse effect". Again, nobody knows by how much. At present, the best theoretical estimates indicate that, by doubling the amount of carbon dioxide, the average global temperature would increase between two and four degrees centigrades. Higher amounts of carbon dioxide would increase the temperature even more. It has also been estimated that the temperature increase in polar regions would be above the global average (REPO 83). If this warming is sufficiently large, and the existing estimates are that it will be large, all the ice in the polar regions would melt and the

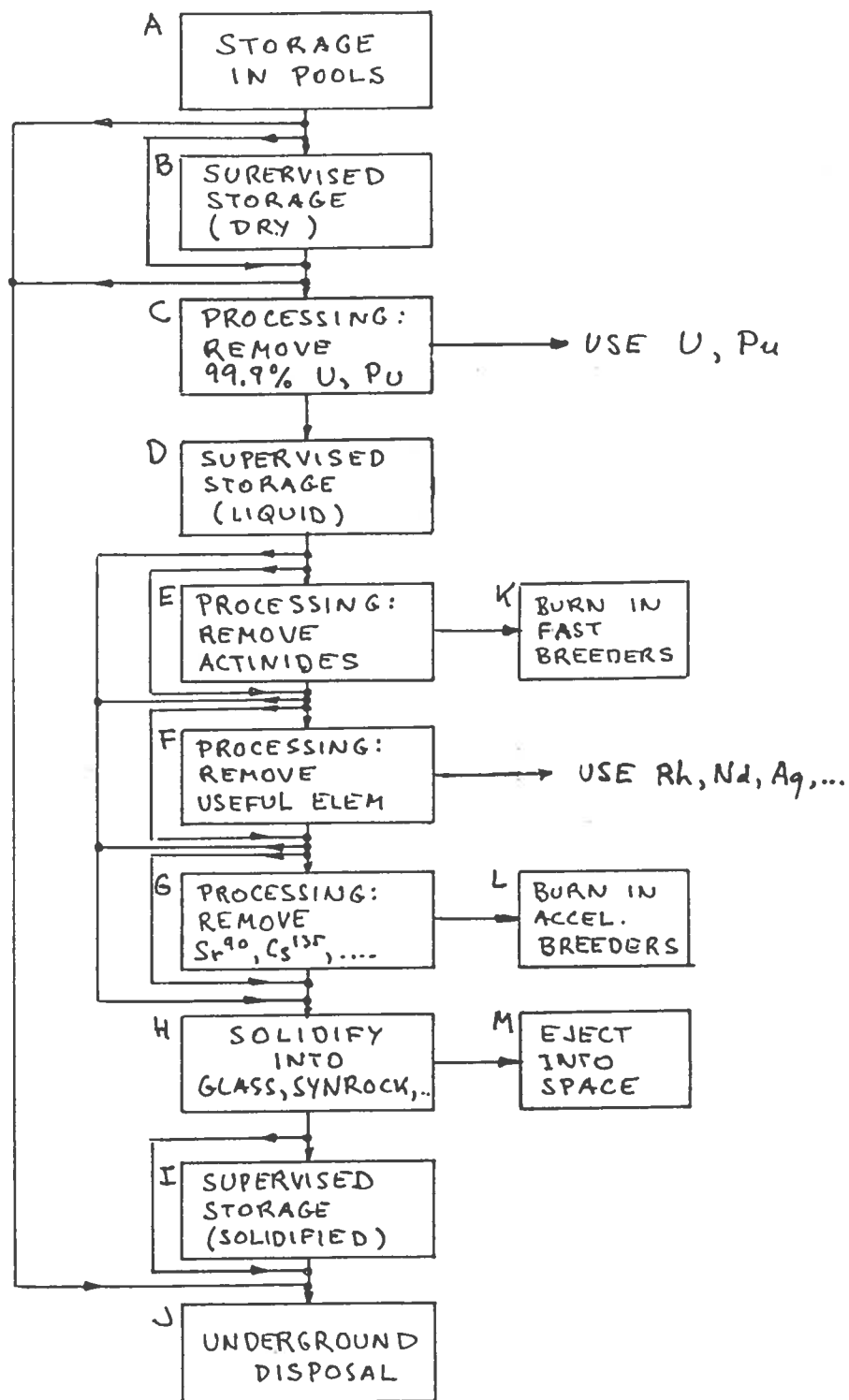


Figure 9. Schematic representation of possible options, present and future, that exist in dealing with nuclear waste.

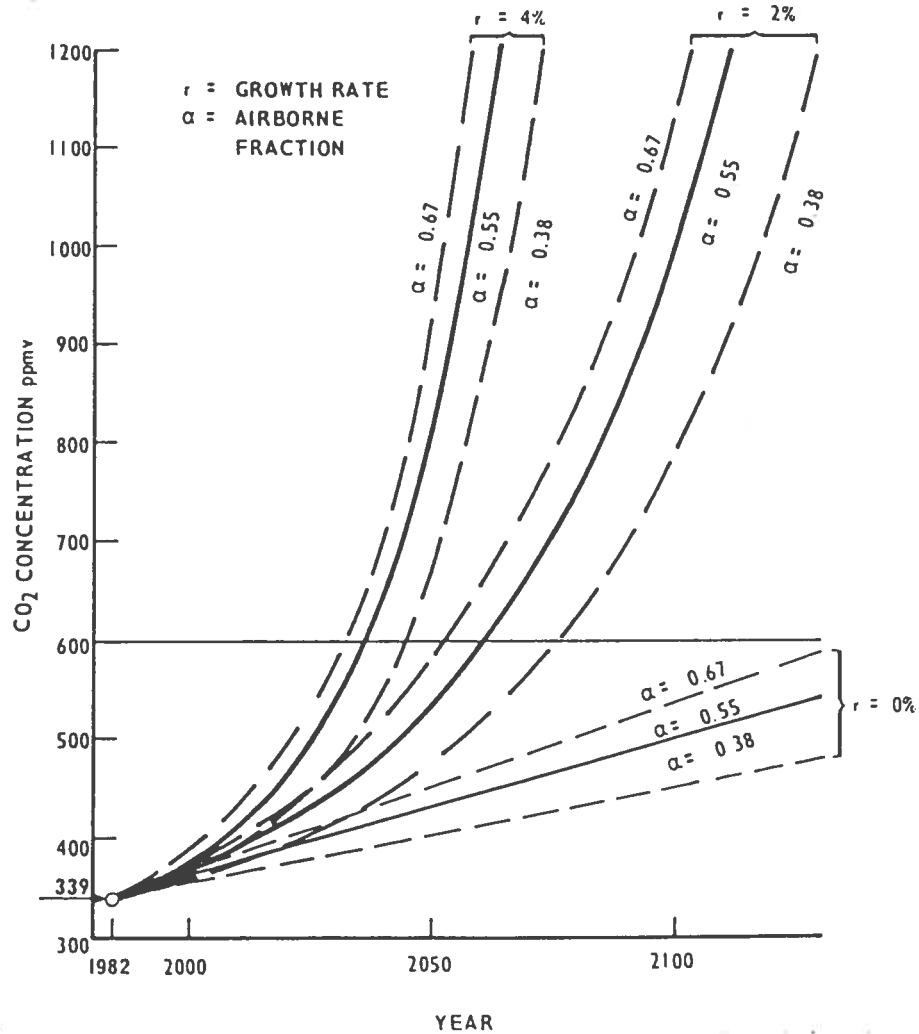


Figure 10. Predicted growth of atmospheric carbon dioxide concentration over the next 150 years assuming indicated growth rates in carbon dioxide emissions and fractions which remain airborne, that is not absorbed by the biosphere and the oceans. These emissions are directly related to the amount of fossil fuels burned.

level of all seas and oceans would rise at first, within the next few decades or centuries, by five to six meters, and then, probably after several millenia by about 70 meters (MERC 78, BART 84).

In addition, a higher average global temperature would certainly produce large changes in regional climates. Deserts and fertile regions would move about. How much, where and how quickly would these changes occur nobody can predict for certain (BERN 80, HANS 81, REVE 82, ROTT 84). It is reasonable to expect that some changes will be beneficial and others catastrophic. There will be winners and losers.

The Earth's climate is a very complicated system and relatively sudden changes are possible. We can only speculate on the consequences of a global warming of two, four, or more degrees centigrade. For instance, it would be reasonable to ask what would happen to one billion people living in India if the monsoon rains shifted farther east and if the Indian Thor desert shifted, in a period of few decades, over a sizeable portion of the Indian subcontinent? What would happen if the North American bread basket, the Midwest, would turn into a desert? While, of course, there is no way claiming that such a terrible shifts in rain patterns would occur, the atmospheric science cannot prove that something like that would not happen. By changing the content of carbon dioxide in the atmosphere we are gambling with the earth's climate and human lives on a grandiose scale.

It may not be necessary to speculate about the future in order to convince ourselves of the gravity of the problem. It may be sufficient to look at the present. In the beginning of the last century, the carbon dioxide (LISS 83) content was about 280 ppm, thirty years ago 315 ppm and today 340 ppm. Therefore, this very important component of the atmosphere, a component that has a very strong effect on the regulation of the temperature of the globe, has been changed by about 20% during the last 150 years, and by 8% during the last 30 years. During the last decade or so, sub-Saharan Africa has been hit with a series of severe droughts. It has been reported (CROS 83) that the Sahara has been extending Southward at the rate of 10,000 square kilometres per year and that contributing factors to this fast desertification are overpopulation, overgrazing and poor agricultural practices (CROS 83, CROS 84). But, as Elssaser pointed out (ELSS 85), could it be that the movement of the Sahara desert is the first effect of our changing of atmospheric carbon dioxide content by 20%? We, of course, do not know. The present atmospheric science can not give us an answer to this question. But the possibility is clearly there. We have changed the environment in a significant manner without knowing whether the climate will be affected or not. Our inability to predict climatic changes raises another very important question.

If we are able to change our environment in an appreciable way and do not know what are consequences going to be, should we change it? Or, putting it another way, on whom is the burden of proof, on those that are changing the environment to show that the changes are harmless, or on those that eventually get affected to prove that changes are harmful and ask for compensation?

Clearly, the first should be the rule.

Drought and flood have always been among the worst calamities that could befall people. The large increase in the fossil fuel consumption will almost certainly induce them on an unprecedented scale.

Summary. In some respects nuclear waste is similar to carbon dioxide. When fossil fuels are burned, carbon dioxide is produced. When nuclear reactor operates, nuclear waste is produced. Both products are unavoidable and when produced in large quantities and released into the environment, they both represent a threat to the environment and the human race on the time scale of centuries and millenia. Carbon dioxide will trigger climatic changes and nuclear waste will increase the background level of naturally occurring ionizing radiation. We do not know how harmful these effects are, and if they are harmful at all, thus it is reasonable to be on guard against them. Unfortunately, we are protecting ourselves from these two environmental effects very selectively. We keep contained nuclear waste and make every possible effort to achieve its absolute confinement. On the other hand, we routinely dump carbon dioxide into the atmosphere and simply ignore its possible detrimental effects. Is this attitude reasonable? Clearly, no. Just as we do not release nuclear waste into the environment, we should not do that with carbon dioxide either.

D. SUMMING IT ALL UP

D1. THE LEAST BAD OF ALL TECHNOLOGIES

An "ideal" technology does not exist. Each of the technologies is "bad" in some respects. Thus, a question which technology is "good" and which one is "bad" is a meaningless question. The only meaningful question to ask is which technology is "the least bad".

The major criticism of hydro power are that there is not enough of it, that it often makes more environmental damage than benefit, and that it is very dangerous for those who live downstream from power dams.

The major criticisms of fossil fuels are the creation of acid rain, which can be controlled at a price, and the production of carbon dioxide, which cannot be controlled in any known manner. It is virtually certain that the increase in the carbon dioxide content of the atmosphere will change global climate in some way, but we do not know in which way. We expect that there will be "winners" and "losers". For "losers" the change may be, or likely will be, catastrophic.

The major criticisms and fears of nuclear power are due to the intentional and accidental releases of radioactive substances into the environment and the proliferation of nuclear weapons. By some, the nuclear

power is considered as an unacceptable technology due to these undesirable effects. The implication is that other technologies are better.

The first issue to be resolved is just how do radiation dangers compare with dangers of other technologies, for instance, danger due to releases of sulphur dioxide, pesticides, various chemical substances (Bhopal!), etc. What are the appropriate comparisons? Only a brief discussion will be given here.

Long term effects of low levels of ionizing radiation on human body are not known. Often, the linearity hypotheses is used to estimate the number of people "killed" in a specific radiation release, like those at TMI and Chernobyl. It has been pointed out before that such statements are incorrect and deceiving and that the effects of low levels of radiation on human health should be compared with effects of smoking (see for instance, MARS 82). Marshal points out that, according to the linearity hypotheses, the risk of death from exposure to one rem of radiation is about equal to the risk of death from smoking 78 cigarettes over 30 year period. This comparison is certainly better than the one which calculates the number of "killed", but it also suffers from two weaknesses. It assumes the validity of the linearity hypotheses for low radiation effects and a similar linearity hypotheses for the health effects of smoking. (Smoking of a few dozen of cigarettes a day has been related to the lung cancer incidence, but not smoking of one twentieth of a cigarette per week.) We believe another comparison is more appropriate.

The cosmic component of natural background radiation is responsible for about 25 millirem of exposure per year at the sea level and it doubles at about the 1200 meter level. Therefore, receiving one rem of radiation once in a lifetime, or about 14 millirem every year during somebody's lifetime (assume 70 year life expectancy), is equivalent to moving about 800 meters up the hill. In the Soviet report (CHER 86) it was estimated that 75 million people will be exposed to about 30 million person-rem of radiation during the next 50 years as a result of the Chernobyl accident. This means that, on the average, each person will receive additional 7.8 mrem per year, the same as if he moved 470 meters up the hill. (1 mrem of additional exposure is equivalent to moving up for 68 meters, that is onto the 16-th floor of a high rise building.) The advantage of this comparison is that it is free from any assumptions, and it is also very descriptive.

When one speaks of nuclear accidents, a comparison ought to be made to accidents caused, say, by hydro dam failures. Such a comparison was discussed earlier in this paper and the conclusion was reached that the nuclear power (with Chernobyl accident included) has in the past caused much less fatalities per KWh than hydro power, although it may have produced more material damage.

Comparisons of potential damage due to radiation releases and production of nuclear wastes should be compared with the potential dangers due to carbon dioxide. For instance, we should ask the following question: Is it better to double the carbon dioxide content of the atmosphere, or to double the background radiation in the whole world? As discussed by Luckey (LUCK 86) it

is not clear how dangerous ionizing radiation is, and whether it is dangerous at all, or maybe even beneficial. If carbon dioxide doubles, rain patterns may change and millions may starve. Thus, the question is not whether it is acceptable to us to increase radiation background for a certain amount, but which of the two risks we wish to choose from, to change climate or "move up the hill". In fact, even in an all nuclear world there is no need to increase the world background radiation by a factor of two, while we have already increased CO₂ content of the atmosphere by 20%, and are on our way to double, even quadruple it. Apparently, the risks due to possible climatic changes are much greater than those due to the radioactivity released from nuclear power stations or leaking from nuclear waste depositories.

Disposal of nuclear waste should be compared with the disposal of fossil fuel wastes, namely acid rain and carbon dioxide (coal ashes are relatively easy to handle). Sulphuric and nitrogen oxides which produce acid rain do not have to be dumped into the environment--technically it is possible to contain them at the source, but the cost of some fossil fuel produced electricity would be increased significantly, by a quarter, possibly more. But, as far as carbon dioxide is concerned, there is no known way how to contain it, it must be dumped into the atmosphere. So, by comparing the problem of nuclear wastes with the problem of acid rain and carbon dioxide, one concludes that nuclear waste is less troublesome.

The potential connection between the development of nuclear power and the proliferation of nuclear arms is generally considered to be a very serious problem and unique to the nuclear power. This problem, however, is more political than technical in its nature and thus it should be compared with political problems that would be created if a severe world shortage of energy developed and various nations would have to agree on how to share the available energy. These risks have been discussed in (JOVA 86) and will not be repeated here.

In summary, it is fairly obvious that nuclear power is "the least bad" of all energy technologies.

D2. A DESIRABLE SCENARIO

At present more than 90% of the commercial energy consumed in the world is produced by burning fossil fuels. If undeveloped and developing countries continue expanding their economies until they catch up with the United States, as apparently they are doing it (JOVA 86, JOVA 86a), the enormous increase in the energy consumption could come, for all practical reasons, only by burning coal or splitting uranium. Ideally, due to greenhouse effect, the burning of fossil fuels should be kept at the minimum with nuclear power producing the bulk of the rest. How fast should the use of nuclear power grow in such an ideal case?

In Figure 11, in a schematic manner is outlined a desirable, although probably not a very realistic, scenario for the future. The past world energy consumption is shown together with curves due to hydro and nuclear produced electricity and the sum of the two. The difference between that sum and the total electricity curve, multiplied by about three, gives approximately the amount of fossil fuels that is burned in order to produce the remaining amount of electricity. A simple extrapolation of the total electricity consumption into the future is made on the assumptions discussed before (JOVA 86). The scale for electricity is on the right hand side, units used represent the energy content of electricity as used. The curve for hydro electricity is fairly arbitrarily extended into the future until a reasonable saturation is reached, a saturation which assumes that most of the economically feasible hydro sites will be developed. The curve for non-fossil electricity has been extended so as to intersect the total electricity curve at the year 2020. This procedure effectively assumes that by 2020 almost all electricity will be produced by nuclear power. By that time it is also assumed that the world will be an almost all-electrical world. The curve labeled fossil fuels was obtained by multiplying the non-fossil electricity curve by three and subtracting it from the curve for total energy consumption.

This exercise was performed in order to see what should be done in order to minimize the further growth in fossil fuel consumption and at the same time to allow for the expansion of economies in undeveloped and developing world along the historical lines. The assumption of no fossil-fueled electrical power stations by 2020 essentially implies an immediate ban on new construction of these stations - in 35 years presumably all of the stations that are now in existence will be retired from service as old and obsolete. The curve on nuclear electricity then shows that nuclear power stations should be built at a rate doubling nuclear capacity every six years, which is about the same as the growth rate since 1976 (c.f. Figure 1). In this scheme by the year 2030 there will be something like 50,000 nuclear reactors, each of 1000 MW(e) capacity operating in the world. Even under these assumptions the fossil fuel consumption, that is carbon dioxide production, would double by the year 2000 and stay constant or decrease slowly afterwards. A crude comparison with Figure 11 would indicate that the carbon dioxide concentration in the atmosphere might not in that case increase over 450 ppm or 500 ppm by the end of the next century. Climatic consequences of such an increase are not known, but they would certainly be much smaller than if carbon dioxide content increased to 1000 ppm, or even higher.

The above desirable scenario is technically feasible only on the assumption that the technology of accelerator breeders can be developed on time. There are enough uranium and thorium resources in the world to sustain such a growth in nuclear electricity production, if accelerator breeders would be used to create enough plutonium for the first fueling of breeder reactors. An affluent world 50 years from now will almost certainly have difficulty with liquid fuels for transportation, but liquifaction of coal, use of ethanol, non-polluting electric car for short trips and trolley-trucks for long trips, should probably be able to make up for the shortage of oil that would likely develop well before 50 years are up. Whether such a desirable and optimistic

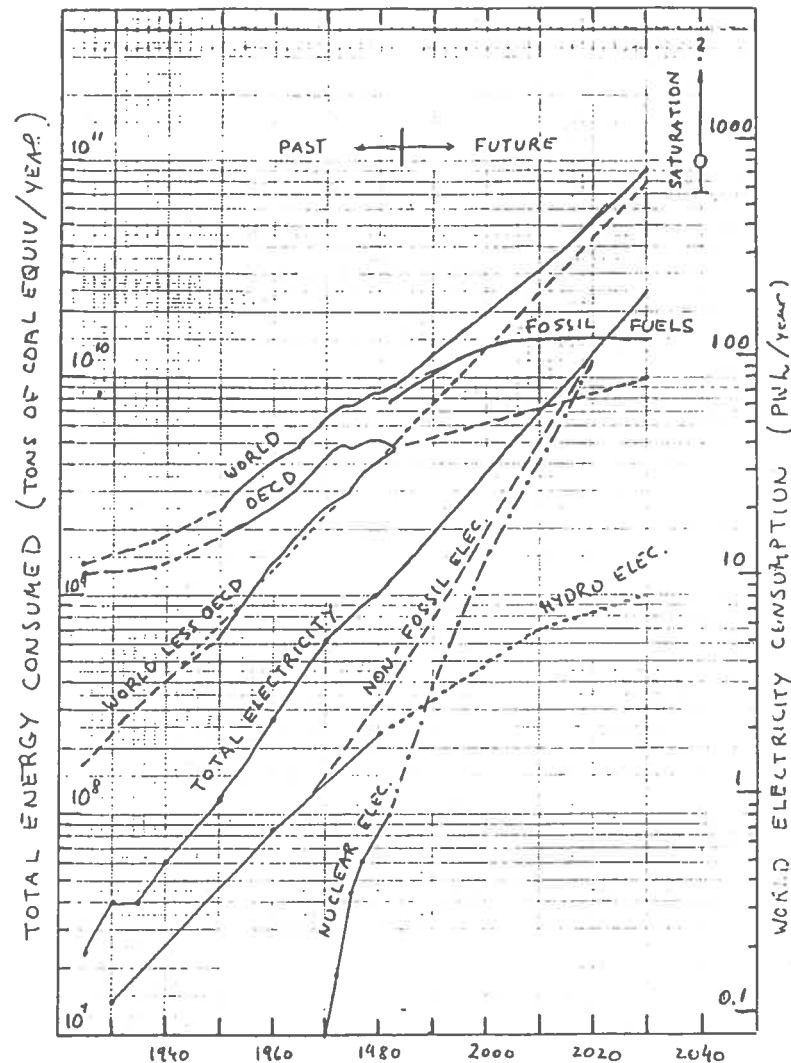


Figure 11 Past and assumed future world energy consumption and electricity production are shown in a simplified manner. The scale for the electricity consumption is shown on the right in conventional units. The assumption is made that the growth of total energy and electricity consumption will continue as in the past until a saturation level of twenty times present energy and forty times present electricity consumption is reached. Present production of hydro and nuclear electricity which is also shown accounts only for about one-quarter of all electricity produced, the remaining three-quarters coming from the burning of fossil fuels. A postulated growth of nuclear electricity with doubling times of five years, was chosen so as to assume only the modest growth in use of fossil fuels, a growth which may produce some climatic changes, but hopefully not the catastrophic ones.

scenario is feasible from the point of view of political and economic conditions in the world is, of course, another matter.

D3. SOME OPINIONS

If we are able to change our environment in an appreciable way and do not know what are consequences going to be, should we change it? On whom is the burden of proof, on those who are changing it to show that the changes are harmless, or on those that eventually get affected to prove that changes are harmful and ask for compensation? Clearly, the first should be the rule. Therefore, we should reduce carbon dioxide pollution of the globe before the first effects show up, or at least until we learn enough about climate to know what we are doing. And if we do that, then the only source that could provide more energy to the energy-hungry developing world within the next few decades is nuclear (fission) power.

The world needs more energy. Trying to stop further expansion of nuclear power, as the anti-nuclear movement is trying to do, is unrealistic, dangerous, and risky. It is unrealistic because some countries, like France, India or Japan, have neither enough coal nor oil. For these countries the only alternatives are nuclear power or a heavy dependence upon imported energy. As the second alternative is in the long run unacceptable, these countries simply cannot afford the luxury of not using nuclear power. It is dangerous because a world without adequate supplies of energy is an unstable world, a world in which devastating wars could easily break out. And it is risky, because carbon dioxide pollution due to increased use of coal would have unpredictable and, in some world regions, catastrophic effects on the climate.

The undeveloped world badly needs more energy. While intensive conservation efforts in the developed countries can slow down, and possibly even stop, the growth in energy consumption, in developing countries such measures cannot be successful, as there is simply so little to use and nothing to conserve. Nuclear power stations are very capital intensive and can be purchased only in a few developed countries. The developing countries simply cannot afford to import this technology at commercial prices and at inflationary interest rates, which effectively transform all long term credits into short term credits. So, for them, the only possible way of increasing energy consumption is through heavy reliance on indigenous sources of fossil fuels, since the associated technology is simple enough and could be developed relatively easily domestically. On the other hand, a further increase in fossil fuel consumption is in nobody's interest. The only escape from this impasse is for the developed countries to provide generous financial and technical help to the developing countries to enable them to expand their energy supplies using nuclear energy. As some increase in fossil fuel consumption in developing nations is inevitable, even if they use exclusively nuclear power for the production of electricity, the developed nations should reduce the use of fossil fuels wherever it could be replaced with nuclear power. Whether such a scenario is politically feasible or not, is, of course,

another question.

The world as a whole should invest more effort and monies into the research and development of all energy-producing technologies, and into nuclear power in particular. The opponents of nuclear power complain that nuclear power is too heavily subsidized through research. Is this charge justified? In 1982, the world produced close to ten trillion KWh of electricity. If each KWh was sold for five cents, the total value of the electricity produced was about one half trillion dollars. Five percent of that amount, namely, twenty-five billion dollars, is a very small fraction indeed. Would it not be reasonable if at least so much money were invested into the research and development of new sources of electricity? The International Energy Agency reported (NULC 83) that in 1982 the governments of all industrialized nations together, excepting France and the Soviet Union, spent seven billion dollars on nuclear energy research, and over three billion dollars on non-nuclear energy research. If the Soviet Union, France, and all other countries in the world are included, one can estimate that only about two percent of the value of the world electricity is spent on all, and not just nuclear, energy research. If the world introduced a two percent research tax on the electricity sold, which is not very much, the amount of money used in both nuclear and non-nuclear research would be doubled. As a comparison, it should be mentioned that reducing by half the acid rain emissions from coal-fired power stations would increase the price of electricity by ten times as much. Clearly, all energy research, nuclear and non-nuclear, is a bargain.

Will there be anything wrong with an almost all-nuclear world operating tens of thousands of nuclear (breeder) power reactors?
 p; The answer is NO, if it is used wisely. Nuclear power is abundant and, if handled properly, is environmentally very clean. Thermal pollution, which is not much different from what the fossil fuels would produce, and can be easily absorbed by the environment. Nuclear power stations emit no carbon dioxide or gases producing acid rain. Some radioactivity is released during regular operations, and although there is much concern about it, it is negligible both locally and globally. Nuclear waste, which accumulates in relatively small (by weight and volume) quantities, is extremely dangerous if released in large amounts into the biosphere but with proper care it can be satisfactorily controlled. The mining of uranium and thorium for these breeder reactors should be no major problem as breeders would use uranium and thorium hundred to a thousand times more efficiently. At present about 10% of world electricity is produced by nuclear power, thus twenty-fold increase in electricity would require 200 fold increase in consumption of uranium fuel. But as breeders would be more than a hundred times more efficient than presently used thermal reactors, in an all electrical, all nuclear world, uranium (and thorium) mining should increase only two to three times over present amounts and all coal mining would be closed.

This is the reason why scientists and engineers around the world have been and still are enthusiastic about nuclear power. This is the reason why politicians have agreed so easily to provide money for research and development of nuclear power. No other technology has ever shown so much

promise.

Unfortunately, the so called Murphy's law, which is so popular among scientists and engineers, states that if something can go wrong with a device, one day it will. Thus, we have also to consider what can go wrong with nuclear power, what would be the consequences and what can we do in order to reduce the risks. Here are some opinions.

The management of the nuclear industry should be improved, just as the management of many other technologies should be improved. The accidents at Three Mile Island and Chernobyl would not have happened if the reactors had been better designed and managed. Similarly, the oil rig 'Ocean Ranger' would not have sunk with 84 people aboard if it had been better managed, and the Bhopal disaster would not have occurred if the plant had been better managed. The real problem is how to assure a better management of all these technologies, in fact, of any technology. Strong and continuous public pressure could help greatly in this direction. The present anti-nuclear movement is misguided. The energy problems of the world cannot be solved by stopping nuclear power, they can only be further aggravated. The opponents of nuclear power would provide a much greater service to the society if they concentrated their pressures on mismanagement, rather than attempting to shut down the nuclear power industry altogether.

The safety of nuclear reactors is of paramount importance, and more research should be done in this field. No comprehensive world-wide study comparing safety aspects of various reactor types has ever been performed. For instance, no comparative study of Soviet RBMK and PWR reactors, Canadian CANDU's and American PWR's and BWR's has ever been made. The need for such a study was clearly demonstrated after the Chernobyl accident, when everybody asked "could it happen here?". In fact, there exists no institution in the world that has the task of making such a study. Any national study comparing reactors produced by different countries would be suspect, so such a study would have to be performed by an international organization. The International Atomic Energy Agency in Vienna could, in principle, perform such a study, if it had funds and authority to do so.

Finally, the question of nuclear arms proliferation must be resolved in a satisfactory manner if the world is to avoid small, or large, nuclear wars. The processing, storage, and use of fissionable plutonium must be strictly controlled. At present, these controls are too weak. The United Nations and its organ, The International Atomic Energy Agency should play a much stronger role.

E. CONCLUSION

Energy resources and technological know-how to use them essentially exist. If they are used wisely, an affluent world with ten billion people can be fueled without producing unacceptable insult on the environment and the

people themselves. Whether food resources, mineral and other raw materials exist to sustain an affluent world of ten billion people and five billion cars has not been discussed in this article. On the other hand, if enough energy and know-how exists, in principle, all other non-energy raw materials could be replaced by something else.

For above reasons, the nuclear breeder power is not the only choice, but it is both economically and environmentally nearly an ideal choice. Nuclear breeders would be able to provide needed power, whenever and wherever needed, in an environmentally acceptable manner and at a reasonable price for the next few thousand years. What else could one ask for?

Unfortunately, the world is not introducing nuclear power as fast as it should be desirable to avoid risks due to CO₂ induced climatic changes. Every country is solving its own energy problem in its own way without any regard for the effects on the globe as a whole. Such attitudes should not continue much longer. The production of energy in general, and carbon dioxide pollution in particular, have become of world wide importance. They should be tackled at an international level.

REFERENCES

- (BART 84) Michael C. Barth and James G. Titus, "Greenhouse Effect and Sea Level Rise - A Challenge For This Generation", Van Nostrand Reinhold Company (1984).
- (BEIR 80) Committee on the Biological Effects of Ionizing Radiations, "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980". National Academy Press, Washington, D. C. (1980).
- (BERN 80) Harold W. Bernard, Jr., "The Greenhouse Effect." Harper and Row (1980).
- (BLOO 78) I. J. Bloodworth, et. al, "World Energy Demand to 2020 - The Full Report to the Conservation Commission of the World Energy Conference", Published for the World Energy Conference by IPC Science and Technology Press (1978).
- (BPST 84) BP Statistical Review of World Energy, June 1984.
- (CASE 84) W. R. Casey, V. P. Bond and C. B. Meinhold, "The Disparity Between the Amount of Emergency Preparedness for Nuclear vs Other Rare Catastrophic Events", Health Physics, Vol. 47, No. 4 (1984)
- (CHER 86) USSR State Committee on the Utilization of Atomic Energy, "The Accident at the Chernobyl's Nuclear Power Plant and Its Consequences", Information compiled for the IAEA Experts' Meeting,

25-29 August 1986, Vienna, Translated by the US Department of Energy as a Working Document for the Post-Accident Review Meeting.

- (COHE 77) B. L. Cohen, "The Disposal of Radioactive Wastes from Fission Reactors", Scientific American, June, 1977, p. 21.
- (COHE 83) B. L. Cohen, "Before It Is Too Late", Plenum Press (1983).
- (COHE 85) B. L. Cohen, "Putting 'Risk' In Perspective", Fusion, Vol. 7, No. 2, page 37 (March-April 1985).
- (COHE 86) Jerry J. Cohen, "Nuclear Waste Disposal: The Nature of the Problem", submitted to this conference.
- (CROS 83) Michael Cross, "Last Chance to Save Africa's Topsoil". New Scientist, 28 July 1983, p. 289.
- (CROS 84) Michael Cross, "UN Admits Failure to Halt Deserts." New Scientist, 10 May 1984, p. 3.
- (DARM 71) J. Darmstadter, "Energy in the World Economy", published for Resources for the Future, Inc. by The John Hopkins Press (1971).
- (DAVI 77) John Davies, "Conserving Uranium Without the Fast Breeder", Nature, Vol. 270, p. 376 (Dec 1, 1977).
- (ELSS 85) Hugh W. Ellsaesser, "The Sahelian Drought--First Evidence of a CO2-Induced Climatic Change?", UCRL-92499 preprint (1985).
- (ENCY 74) Encyclopedia International, Grolier, Inc., New York (1974).
- (FOST 78) J. S. Foster, M. F. Duret, G. J. Phillips, J. I. Veeder, W. A. Wolfe and R. M. Williams, "Nuclear Resources - The Contribution of Nuclear Power to World Energy Supply, 1975-2020", Published for the World Energy Conference by IPC Science and Technology Press (1978).
- (GRAN 77) P. Grand, K. Batchelor, J. R. Powell and M. Steinberg, "The Accelerator Breeder, An Application of High Energy Accelerators to Solving Our Energy Problems", IEEE Transactions on Nuclear Science, Vol. NS-24, No. 3, p. 1043 (June 1977).
- (GROV 80) C. K. Groves, "Rain of Troubles", Science, July/August 1980, p. 76.
- (HAFE 81) Wolf Hafele et al, "Energy in a Finite World: Paths to a Sustainable Future", Report by the Energy Systems Group of the International Institute for Applied Systems Analysis, Ballinger Publishing Company (1981).

- (HANS 81) J. Hansen, D. Johnson, A. Lacir, S. Lebedeff, P. Lee, D. Rind and G. Russell, "Climate Impact of Increasing Atmospheric Carbon Dioxide", Science, 213, 957 (1981).
- (HUBB 71) M. King Hubbert, "The Energy Resources of the Earth", Scientific American, Vol. 224, Sept. 1971, p. 60.
- (INHA 82) H. Inhaber, "Energy Risk Assessment", Gordon and Breach (1982) .
- (JOVA 86) J. V. Jovanovich, "Future Energy Consumption in Less Developed Countries and Associated Macro-Risks", to be published in the Proceedings of the International Symposium on Total Risk and Benefit Impact of Energy Alternatives held at the University of Waterloo, Waterloo, Canada, May 20-23, 1986.
- (JOVA 86a) J. V. Jovanovich, "Energy Needed For Continuing Industrialization of Developing Countries", Proceedengs of Energy and Developement, International Scientific Conference, Zagreb, Yugoslavia, 29 September to 3 October, 1986, Yugoslav Scientific Forum, Beograd, Yugoslavia, page 913.
- (JOVA 86b) J. V. Jovanovich and R. M. Rotty, "A Plausible Future of Rapid Energy Growth in China", Energy--The International Journal, in press.
- (JOVA 86c) J. V. Jovanovich, "Spent Nuclear Fuel - A Waste or a Resource", Unpublished lecture note, March, 1986.
- (KEME 79) Report of The President's Commission on the Accident at Three Mile Island, the Need for Change: The Legacy of TMI, John G. Kemeny, Chairman, October 1979, Washington, U.S. Government Printing Office, Washington, D.C. 20402.
- (LEDE 85) Luis Lederman, "Probabilistic Safety Assessment: Growing Interest", IAEA Bulletin, Autumn (1985), page 51.
- (LEVE 81) M. Levenson and F. Rahn, "Realistic Risk Estimates", IAEA Bulletin, Vol. 23, No. 4 (1981).
- (LEVI 85) Barbara G. Levi, "Radionuclide Releases from Severe Accidents at Nuclear Power Plants", Physics Today, May (1985), page 67.
- (LEWI 80) Harold W. Lewis, "The Safety of Fission Reactors", Scientific American, March 1980, p. 53.
- (LIKE 79) G. E. Likens, R. F. Wright, J. N. Galloway and T. J. Butler, "Acid Rain", Scientific American, October 1979, p. 43.
- (LISS 83) P. S. Liss and A. J. Crane, "Man-Made Carbon Dioxide and Climatic Change: A Review of Scientific Problems", Geo Books, Norwich

(1983).

- (LUCK 86) T. Don Luckey, "Hormesis and Nurture With Ionizing Radiation", submitted to this conference.
- (MARS 82) Walter Marshall, "Talking About Accidents", Paper presented at the IAEA Int. Conf. on Nuclear Power Experience, Atom, 312, 210, (October 1982).
- (MERC 78) J. H. Mercer, "West Antarctic Ice Sheet and CO2 Greenhouse Effect: a Threat of Disaster", Nature, Vol. 271, p. 321 (1978).
- (MYNA 77) F. R. Mynatt, "Preliminary Report on the Promise of Accelerator Breeding and Converter Reactor Symbiosis (ABACS) as an Alternative Energy System." Oak Ridge National Laboratory, Report ORNL/TM-5750 (Feb 1977).
- (NUCL 83) Nucleonics Week, Nov. 10, 1983, p. 11.
- (OFFI 82) Office of Technology Assessment, Congress of the United States, "The Regional Implications of Transported Air Pollutants", July 1982.
- (PUTN 53) Palmer Cosslett Putnam, "Energy in the Future", D. Van Nostrand Co. (1953).
- (REPO 83) Report of the Carbon Assessment Committee, "Changing Climate". Board on Atmospheric Sciences and Climate, National Research Council, National Academy Press, Washington (1983).
- (REVE 82) Roger Revelle, "Carbon Dioxide and World Climate", Scientific American, August 1982, p. 35.
- (RIPP 84) Simon Rippon, "Accident Source Terms--Cause for Less Concern", Atom 327, January (1984), p. 2.
- (ROTT 84) Ralph M. Rotty, "The Nature of the CO2 Problem: Certainties and Uncertainties", Environmental Progress, Vol. 3, No. 4, 253 (1984).
- (RUED 75) The draft of the Summary Report of the Reactor Safety Study directed by N. C. Rasmussen, U. S. Atomic Energy Commission, reprinted in "Perspectives on Energy", edited by L. C. Ruedisili and M. W. Firebough, Oxford University Press (1975), pp. 224-237.
- (SHEA 78) R. F. Shea, "Prose and Controversy"; Clamshell Alliance, "Nuclear Accidents: A Look at the Record", IEEE Transactions on Nuclear Science, Vol. NS-25, No. 5, Oct. 1978, p. 1098; W. H. Arnold, "Perspective on Nuclear Accidents: A Look at the Record", ibid., p. 1101.
- (STAR 71) Chauncey Starr, "Energy and Power", Scientific American, Vol. 224,

Sept. 1971, p. 36.

- (STAR 79) Chauuncy Star, "Current Issues in Energy - A Selection of Papers", Pergamon Press (1979).
- (STUD 75) The Study Group on Light-Water Reactor Safety, "Nuclear Reactor Safety--The APS Submits its Report", Physics Today, July 1975, p. 38.
- (THIS 83) This Week Report, "US Study Says Acid Rain Can Be Beaten", New Scientist, 7 July 1983, p. 9.
- (TOTT 86) John R. Totter, "Cancer: A Result of Incidental Exposures or of Senescence, or Both?"
- (WASH 57) Technical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants. WASH-740, U.S. Atomic Energy Commission (1957).
- (WASH 75) Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400, U.S. Nuclear Regulatory Commission (1975).
- (WOOD 78) G. M. Woodwell, "The Carbon Dioxide Question", Scientific American, January 1978, p. 34.