Received by OSTI

JUN 2 0 1989

CO_2 AND THE WORLD ENERGY SYSTEM: THE ROLE OF NUCLEAR POWER

CONF-890810--1

DE89 013014

William Fulkerson
John E. Jones, Jr.

Paper to be presented at the 10th International Conference on Small and Intermediate Sized Nuclear Reactors: "Impact of Your Energy Needs on Your Environment" Session.

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so for U.S. Government purposes."

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

The greenhouse effect, and other transnational and global environment, health and safety issues, require energy system planning on an international scale. Consideration of equity between nations and regions, particularly between the industrialized and developing countries, is an essential ingredient. For the immediate future, the next several decades at least, fossil fuels will remain the predominant energy sources. More efficient use of energy seems to be the only feasible strategy for the near to mid-term to provide growing energy services for the world economy while moderating the increasing demand for fossil fuels. In the longer term, nonfossil sources are essential for a sustainable world energy system, and nuclear power can play an important, if not dominant, role. The challenge is to design and implement a safe and economic nuclear power world enterprise which is socially acceptable and is complimentary to other nonfossil sources. The elements of such an enterprise seem clear and include: much safer reactors, preferably passively safe, which can be deployed at various scales; development of economic resource extension technologies; effective and permanent waste management strategies; and strengthened safeguards against diversion of nuclear materials to weapons. All of these elements can best be developed as cooperative international efforts. In the process, institutional improvements are equally as important as technological improvements; the two must proceed hand-in-hand.

Greenhouse Gases

It may be necessary over the next several decades to control the rate of change of greenhouse gases in the atmosphere. Carbon dioxide is the principal greenhouse gas which is increasing. This increase is due to the burning of fossil fuels and the burning of trees in the process of deforestation. Other greenhouse gases increasing in atmospheric concentrations include chlorofluorocarbons (CFC's[1]), methane and nitrous oxide. Manmade chlorofluorocarbons are used in refrigeration systems, for blowing plastic foam insulation, as solvents of various sorts, and as agents in fire extinguishers. Methane in the atmosphere is mainly biogenic and is believed to come primarily from anaerobic processes involving cattle, rice growing, and wetlands. It may also come from forest slash and burn practices, and minor sources are from coal mining and the production and distribution of natural gas. Nitrous oxide is also a greenhouse gas. Sources of nitrous oxide apparently include tropical and subtropical forest soils, oxidation of nitrogen contained in fossil fuel, mainly coal, particularly as a result of efforts to reduce NO_x from the emissions from coal combustion facilities and to a lesser degree, oxidation and/or reduction of nitrogen in agricultural fertilizers. CFCs, CH_4, and N_2O contribute about 35% of the estimated increase in the greenhouse effect since the industrial revolution.

An international agreement to control emissions of CFCs was signed in Montreal in 1987, and it is likely that this effort will continue and that these greenhouse gases will be controlled as a result of concern, not about global warming, but rather for the impact that CFCs have on destroying stratospheric ozone. The increases which have been observed over the past two decades in the concentrations of N_2O and methane in the atmosphere are undoubtedly due to anthropogenic causes but sources and sinks are sufficiently unknown that the control strategies are far from obvious at this moment.

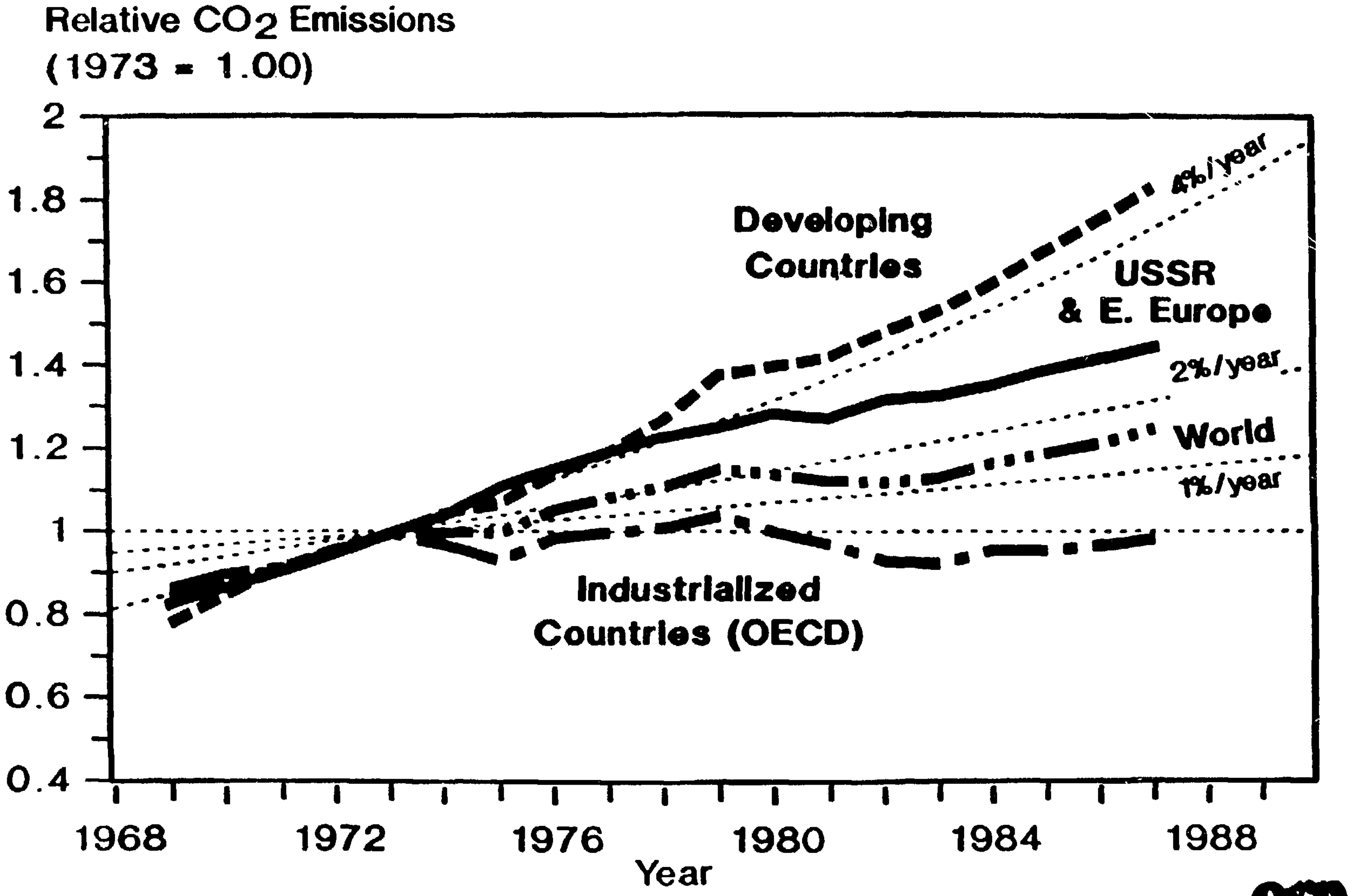
Control of CO_2 by Limiting the Use of Fossil Fuels

This paper will be concerned about the contribution that the energy system of the world makes to the increasing concentration of CO_2. Hence, we are concerned with fossil fuel use. We should begin by noting that it may not be necessary to reduce the emissions of CO_2 from fossil fuels to zero in order to stabilize the concentration of CO_2 in the atmosphere. Tentative indications are that stabilizing the concentration would require at least a 50% reduction in emissions (Firor, 1988 and Perry, 1984). Getting a better understanding of what this maximum allowable emission rate might be under various circumstances is an urgent research priority.

If necessary, how might this sort of reduction be achieved? Actually, the world has already begun to reduce the rate of increase of CO_2. This happened since the Arab Oil Embargo as shown in Figure 1. Worldwide emission rates were rising at about 4% per year prior to 1973, and since 1973, they have been rising

---

[1] We include with CFCs the halons which are bromofluorocarbons and chlorobromofluorocarbons.



ornl

Fig. 1: The Arab Oil Embargo Slowed The Growth Rate of CO_2 Emissions.

at between 1-2%. Principally this is because the emission rates of the industrialized OECD nations have not increased and those of USSR and Eastern Europe have moderated. On the other hand, the rates of emissions of the rest of the world, the developing world including China, have increased as if they had never seen an Arab Oil Embargo, and are currently increasing at about 4% per year.

A simple extrapolation of the behavior of various nation groups for over the past decade, the emission rates of the developing world will exceed those of the OECD industrialized nations by about the year 2000, and thereafter would dominate, as is shown in Figure 2[2]. Thus, the choices made by developing countries will be exceedingly important with respect to controlling future changes in the greenhouse gases. Also, if the increase is going to be kept under control, aggressive actions will be required of industrialized nations to offset the future increases from the developing world.

Can the industrialized world reduce CO_2 emissions? Of course it can if industrialized nations are willing to pay a good deal more for energy than they do presently, and if they will be satisfied with slower economic growth than they have enjoyed over the past several decades. But we are interested in a different answer. Curtailing emissions by moving away from fossil fuels without paying the high energy costs and without drastically slowing economic growth will require much better technology. To illustrate, we use the United States as a surrogate for all the industrialized nations. Two technology improvement strategies are required. The first is to learn how to use and convert energy much more efficiently than we presently do, and the second is to improve nonfossil sources to a degree that they can be economic substitutes for fossil fuels on a large scale and still be socially acceptable from other points of view; e.g., demonstrate high safety and low environmental impact.

The bar chart of Figure 3 illustrates that a great deal can be accomplished by improving the efficiency of energy use. The figure compares CO_2 emission rates for two energy forecasts for 2020 and 2040. One is a base case, which is a middle-of-the-road forecast using the Edmonds-Reilly model (Edmonds & Reilly, 1986) and median values for coefficients in that model. The other is a very high efficiency case developed for the year 2020 by Williams (Williams, 1987). Both assume approximately the same growth in the economy and population. In the calculation of emission rates for Figure 3, we assumed nonfossil sources will not increase over the next 50 years from their present levels to show the effect of efficiency improvement alone. Under the base case, the CO_2 emissions double in 50 years. For the high efficiency case, the emission rate could actually decrease by 2020. This case assumes an adoption across the economy of the most efficient technology available that is economical. We consider this high efficiency case to represent a limit, it is the best we could reasonably expect to do. Reaching such a state of universal adoption of more efficient technologies would require aggressive government encouragement, as well as

---

[2] The curves in Figures 1 and 2 labeled "developing nations" include emissions of all the countries of the world not included in the other two categories. Hence they include emissions of some industrialized countries, but the preponderance is due to developing nations.

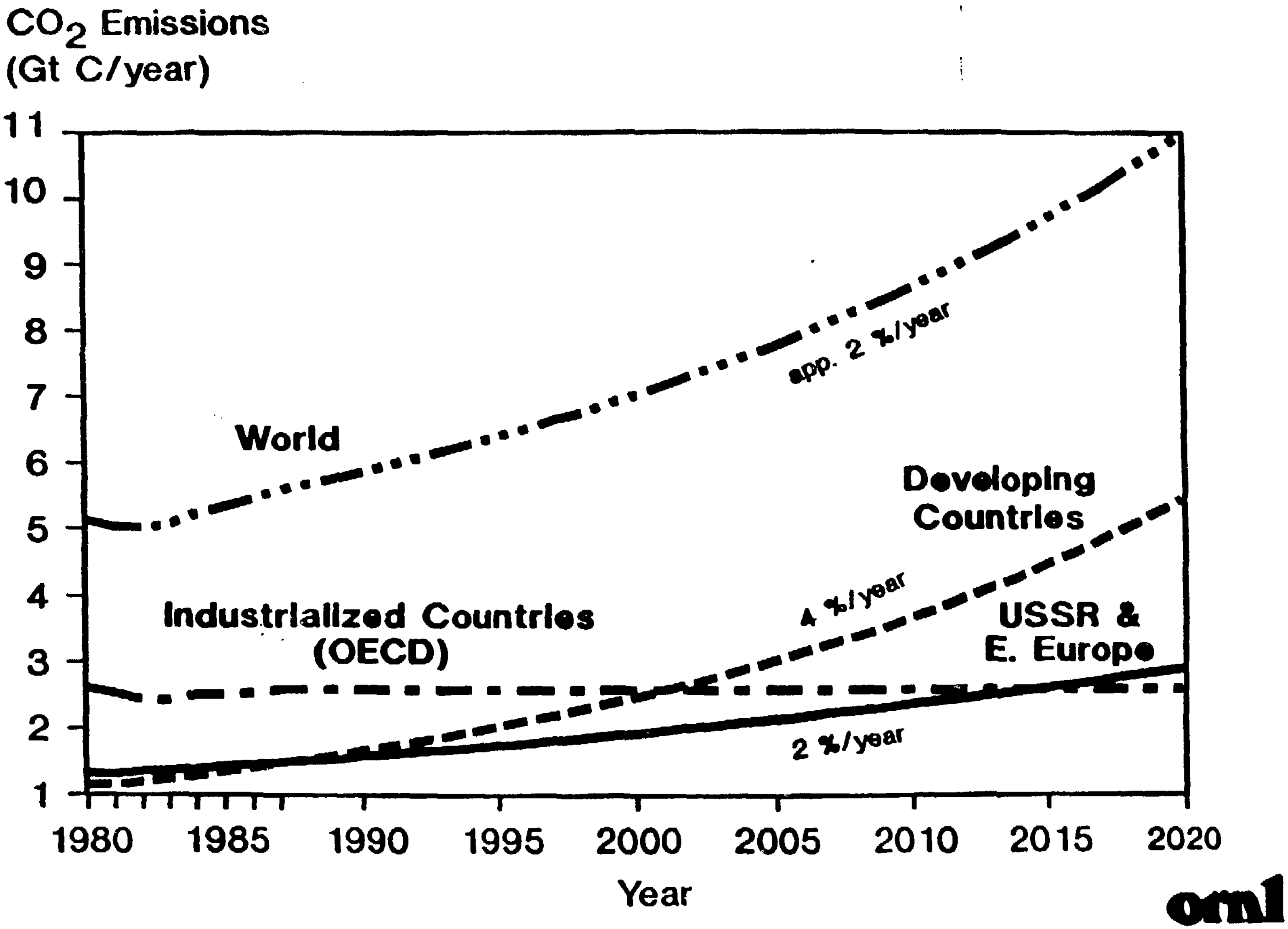
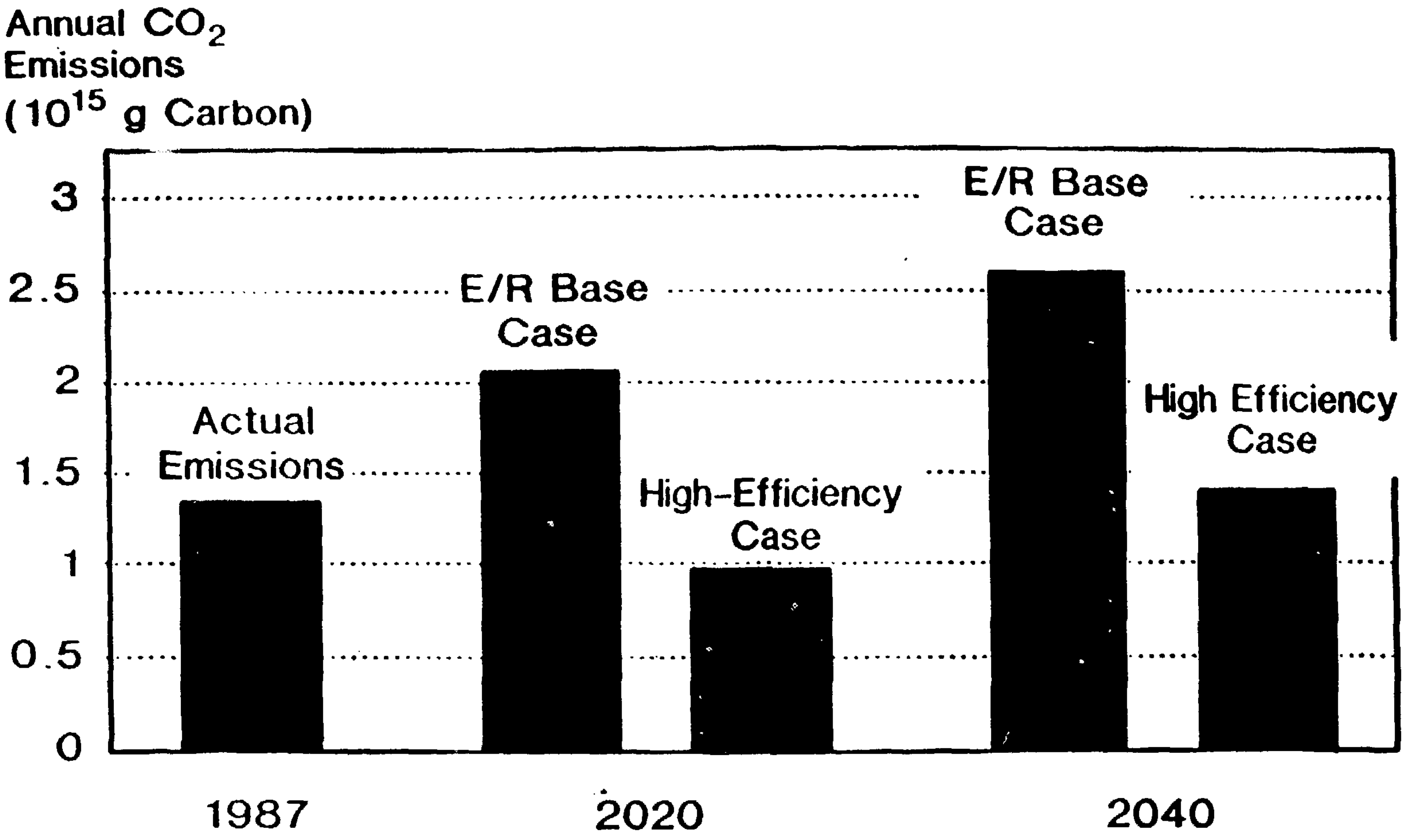


Fig 2: Extrapolating CO_2 Emissions of the Past Decade Shows the Importance of Developing Nations.



ornl

Fig. 3: Curtailing U.S. Emissions of CO_2 From Fossil Fuels Will Be Difficult: Improving Efficiency Can Do A Lot!

continuing improvements in the technologies themselves. Furthermore, efficiency improvement will have diminishing returns. To capture this expectation we assume that technical efficiency in 2040 was the same as for 2020, except that the trend towards less energy intensive industry continues. Of course, the technology assumed for the high efficiency case is by no means pushing the second law limit, so there is still great opportunity for continued improvement. Nevertheless, we think improvements will be at a diminishing rate.

We conclude that it is technically possible to stabilize CO_2 emissions over the next 50 years by improving efficiency alone. Sustaining an actual decrease in emission rates rather than just keeping them constant will take increased use of nonfossil sources in addition to higher efficiency. None of these sources, however, is yet ready to substitute economically for fossil fuels at a large scale. The best in the bunch is nuclear power which is presently constrained by concern over a number of issues including cost uncertainty, the problem of waste disposal, operational unreliability in the United States, including a changing regulatory environment, and public and utility concerns about the safety of power lants. Should the nuclear establishment grow internationally to a much larger size, safeguards will become a more pressing concern. Biomass and hydropower are resource limited although they can be increased substantially from present levels. Solar electric and wind technologies are intermittent and costly. Geothermal is geographically constrained and also expensive in most cases.

Figure 4 represents our estimates of the best we might expect from nonfossil sources over the next 50 years assuming that R&D is successful in making them more competitive (Fulkerson et al., 1989). We estimated that by the year 2020, biomass could supply 10 quads of liquid fuels from something like 20 quads of primary biomass fuel, and nuclear power could be increased by a factor of 3 by 2020 based on a new generation of reactors including light water reactors (LWR) which incorporate passive safety features and totally passively safe reactors such as the Modular High Temperature Gas-Cooled Reactor (MHTGR) We estimated furthermore, that nuclear power generation could increase from present levels by a factor of 10 by 2040. That would require maximum annual additions to capacity similar to power plant building rates experienced in the late-60's. Solar, in its various forms and other renewables, could be increased by a factor of 10 by 2020 and a factor of 50 by 2040, thus producing as much by 2040 as nuclear power does today. It may be that this contribution could be much larger if the revolutionary progress in photovoltaics continues. For example, Ogden & Williams, 1989, have postulated that if thin film amorphous silicon photovoltaics become very inexpensive, producing power for about \$.03 to \$.04/kwhr DC in the desert southwest; they could provide a large source of hydrogen pumped around the country. That could change the nonfossil mix substantially. The important conclusion we reach is that both much improved efficiency and much better nonfossil sources will be required for the United States to actually reduce CO_2 emissions assuming, of course, that the economy continues to grow. Also, it is likely that much more aggressive action by the government will be needed to encourage the adoption of better technology.

As nonfossil sources grow, the trend toward electrification will continue since most nonfossil sources are electric. The CO_2 level shown in Figure 4 for

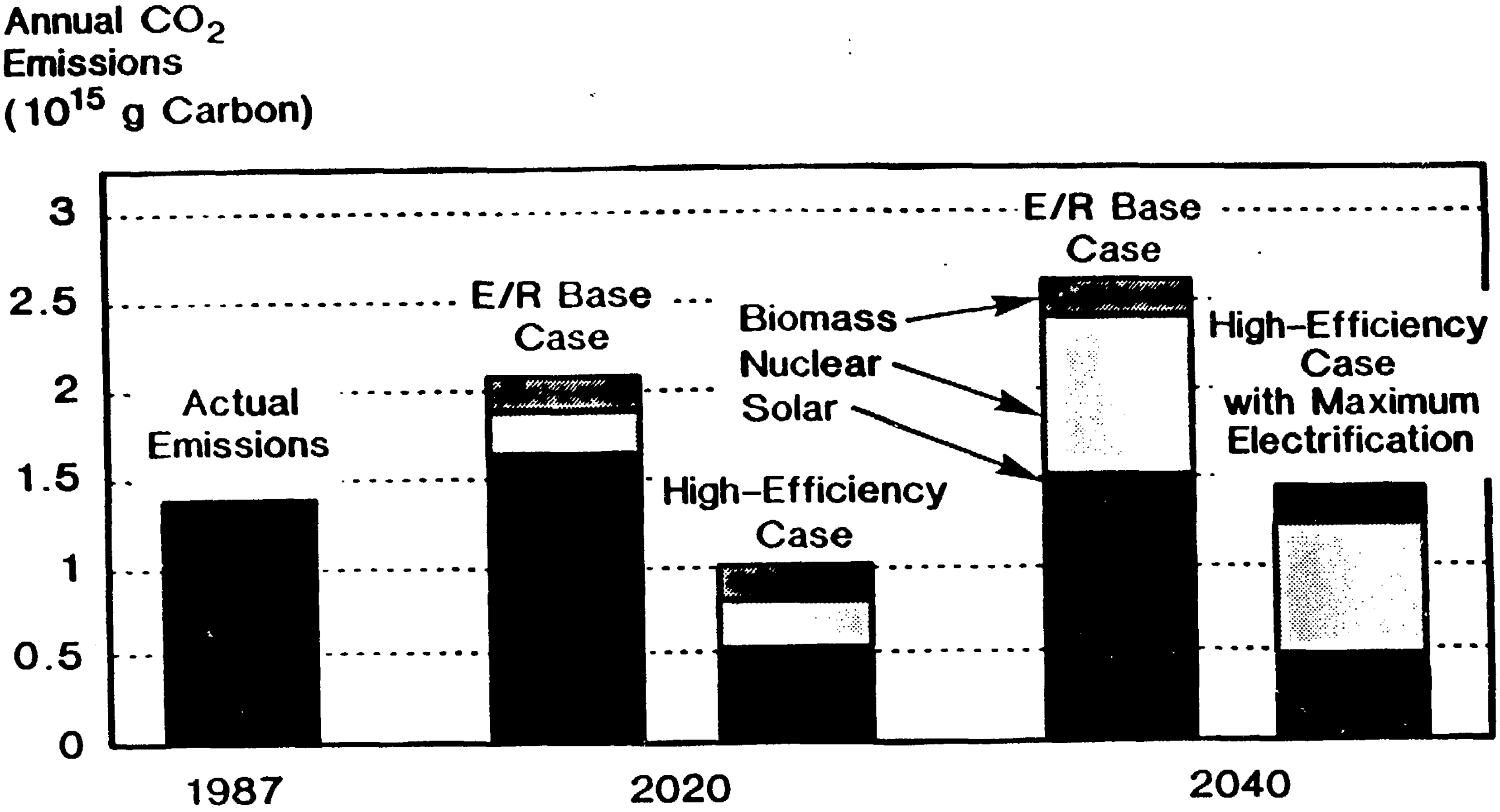


Fig. 4: Curtailing U.S. Emissions of CO_2 From Fossil Fuels Will Be Difficult: Biomass, Nuclear and Solar Are Needed for a Sustainable Reduction.

the 2040 high-efficiency forecast assumes that some nonfossil electricity is used to power electric vehicles and replace natural gas in buildings.

The situation for the world as a whole is qualitatively similar to that for the United States. Assuming that the economies of nations, particularly developing nations, continue to grow and the world population also grows, but at a continually declining rate, the demand for energy services 50 years from now will be much larger than it is today. Based on various forecasts, we might expect demand for primary energy to be in the range of 15 to 25 TWYR/yr. The lower end of the range corresponds roughly to the very high-efficiency scenario of Goldemberg et al., 1987, and the upper end corresponds to the base case Edmonds-Reilly model (Edmonds & Reilly, 1986). This base case total primary energy demand is roughly similar to the lower scenarios of World Energy Conference (WEC, 1983) and International Institute of Applied Systems Analysis (IIASA, 1981). Of course, demand could be much larger. It is hard to believe that it could be much less.

In Table 1 we make some very crude estimates of how this primary energy might be supplied. In order to accomplish the objective of reducing CO_2 emissions from their present value by about a half, we assume a fossil fuel ration for the world between 3 and 5 TWYR/yr. Presently it is about 10. Worldwide we assumed hydropower can produce between 1 and 2 TWYR/yr, biomass 3 to 4, and solar and other renewables, 1 to 2. We then assumed that nuclear power made up the difference between total demand and the sum of our fossil ration plus the other nonfossil sources. In the high efficiency case, this puts nuclear between 2 and 7 TWYR/yr, and in the base case, it is a whopping 12 to 17 which would be very difficult to attain in our judgement.

This shows clearly the need for nuclear power or else one must assume the slack is taken up by some other nonfossil source. It also demonstrates the same point as for the United States. There is no way to control CO_2 emissions without the combination of very high efficiency as well as hefty growth of all the nonfossil sources including nuclear. Both are needed. The EPA analysis for Congress (EPA, 1989) indicates the same thing, except that EPA is much more bullish on biomass and less so on nuclear power. EPA prefers to consider a low economic (Slowly Changing World, SCW) and a higher economic growth scenario (Rapidly Changing World, RCW) rather than very high efficiency versus a lower efficiency base case as we have done. The EPA results for 2040 are shown in Table 1 as are the results of Wolf Häfele for 2030 (Häfele, 1989) whose 16 TWYR/yr scenario is designed for control of CO_2 emissions.

From all these estimates the point is clear, nuclear is an essential ingredient, but, it is not the only ingredient nor even the predominant one. How important it will become depends on how effective the industry is at solving the problems that face the nuclear enterprise on a worldwide basis; on the progress of competing sources; and on how urgent the CO_2 problem becomes.

Conditions of Acceptance of Nuclear Power

In order to expand nuclear power significantly, a number of technical and institutional issues will need to be resolved to the satisfaction of the public and utilities. The job is made more difficult, of course, because we have no

Table 1: COMPARISON OF VARIOUS WORLD FUEL MIX PROJECTIONS YIELDING LOW FOSSIL FUEL USE, I.E., LOW CO_2 EMISSIONS (TWYR/YR)

		Nonfossil Sources			
Total	Fossil Sources	Hydro	Nuclear	Biomass	Solar and Other Renewables
1987					
12.1	9.6	0.7	0.5	~1.3	<0.1
2020					
Goldemberg *et al*., 1987/88					
11.3	8.7	0.4	0.7	1.4	0.2
2030					
Häfele (1989)					
16	7	0.8	3.7	1.3	1.2
2040					
High Efficiency Case (This paper)					
15	3-5[a]	1-2	7-2[b]	3-4	1-2
Base Case (This paper)					
25	3-5[a]	1-2	17-12[b,c]	3-4	1-2
EPA-SCWP (1989)					
14	8	2	1	2	1
EPA RCWP (1989)					
20.5	9	2	2	5.5	2

[a] Estimated fossil fuel ration

[b] Obtained by difference

[c] This enormous quantity of nuclear power seems implausibly high indicating that if demand is as high as 25 TWYR/YR, fossil fuel could not be constrained to 3-5 TWYR/YR.

accurate measurement or even unit of measure of what constitutes the condition of public or utility acceptance. Clearly scale may be a factor. For example, it may be acceptable if the probability of a core meltdown is one in a hundred years, but not at all acceptable if the number is one in ten years. If the probability of such meltdown were 10^{-4} per reactor year, the nuclear enterprise would have to be limited to something like 100 reactors. A thousand reactors would clearly be too many because it would cause the probability of one meltdown in ten years. Furthermore, the conditions of acceptance may be fickle, they may change with circumstance. As global warming becomes a greater concern, the public's acceptance of a greater commitment to nuclear power may increase. But the public doesn't necessarily think in terms of probabilistic risk assessment. In the case of nuclear power, Steve Rayner and Robin Cantor (Rayner & Cantor, 1987) have suggested that TLC is much more important to the public than any probabilistic risk assessment. "T" is <u>trust</u> in the institutions which are running the nuclear enterprise, "L" stands for <u>liability</u> (who will pay the cost of an accident), and "C" means <u>consent</u> emphasizing that the potentially affected publics must have some voice in agreeing to the arrangements of the technology application.

Elizabeth Peelle (Peelle, 1988) has argued that in certain circumstances community involvement and public participation in decision-making is the best way of obtaining consent, and indeed it may have a good deal to do with arranging for institutional fixes which provide the necessary trust as well. As poorly as we understand the conditions of public acceptance, we have a sort of faith that improvements in the technology can help, and we know now that the technology can be made considerably better.

There are five important areas where improved technology can make a difference. The first area is to improve the performance of existing operating power plants. A variety of state-of-the-art technology is available for making operating power plants more reliable with many fewer unscheduled outages. The objective, of course, is to increase the capacity factor of the existing stock of operating plants and to ensure that they are operated in such a way that no major incident, similar to TMI, occurs. In fact, the best thing for nuclear power is for it to become invisible to the public--simply chugging away producing power in a very reliable and highly productive way.

The second area relates, of course, to safety of power plants which can be improved by LWR designs which have more effective passive safety features. Alternatively, new reactor concepts, such as the MHTGR or various liquid metal reactor (LRM) designs may be required to achieve acceptance for a very large scale nuclear enterprise--not only in this country but worldwide. We know how to develop technology much more forgiving with regard to safety than the present LWR. Forsberg (1989) has suggested that the next generation of reactors be what he calls "PRIME reactors." PRIME stands for <u>P</u>assive safety, <u>R</u>esiliant operation, <u>I</u>nherent safety, <u>M</u>alevolence resistance, and <u>E</u>xtended safety. Examples he sites are the PIUS light water reactor being developed by ASEA Brown Boveri in Sweden and the MHTGR.

The third area is to manage waste to public satisfaction. Substantial, but very slow, progress is being made in this area, and innovations include both improved technology for handling both low level and high level radioactive waste, and all sorts of institutional innovations between and among states as a result of the Nuclear Waste Policy Act. It remains to be seen how this will actually evolve to the solution of the problem with respect to high level radioactive waste. Perhaps reburning would help.

The fourth area is the necessity of extending fissile material resources. A very large scale operation necessary to contribute substantially to preventing global climate change will require the adoption of resource extension technologies, perhaps by the middle of the first part of the next century. The most likely technology is of course the LMFBR, but can it be made passively safe at a reasonable cost? There are other resource extension technologies which may need to be investigated, including uranium from sea water, and even the fusion/fission hybrid.

The fifth area of concern is the area of safeguards. Safeguards against clandestine diversion of nuclear fuel to weapons (e.g., by terrorists) or against proliferation of weapons through the use by a country of its nuclear power facilities will be an area of heightened attention as the scale of the nuclear enterprise increases. Increasing safeguards may require better institutions and more cooperation between nations. Solutions are <u>not</u> primarily technical, except for technologies to detect diversion activities or changes in the power system required to produce weapons.

This leads us to our final point, and that is that we must think about nuclear power as a world system. We are all in it together. Whatever goes wrong with the system in any part of the world goes wrong with the system everywhere, as Chernobyl so readily demonstrated. We must think in terms of institutions which can manage a global enterprise. A global enterprise must include the developing nations, and we should think very carefully about the technologies we will be developing over the next two decades to ensure they meet the needs of both the industrialized world and the developing nations as well and be designed specifically for that purpose.

It is interesting to note that the three largest contributors to the greenhouse effect among the developing countries are China, India, and Brazil. These three countries are not signatories to the Treaty on the Non-proliferation of Nuclear Weapons, but all three countries already have a burgeoning nuclear enterprise, and of course two of them possess weapons. Promoting the expansion of nuclear power in these countries hardly constitutes much of a risk with regard to nuclear war or the use of nuclear weapons. Nuclear power is likely to grow in developing countries regardless of what we do in the United States, but we can have an influence on that growth. We have a better chance of influencing the choices made by developing countries if we work closely with them to develop institutions and technologies which they will find attractive.

References

Edmonds, J., and J. Reilly, 1986. *The IEA/ORAU Long-Term Global Energy--CO_2 Model, Personal Computer Version A84 PC*, ORNL/CDIC-16, CMP-002/PC, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Firor, J., 1988. "Public Policy and the Airborne Fraction," *Climatic Change* 12, 103-105.

Forsberg, C. W., "New Developments in Reactor Design," paper presented at WATTEC '89 Meeting, Knoxville, Tennessee, February 1989.

Fulkerson, W., S. I. Auerbach, A. Crane, D. E. Kash, A. M. Perry, and D. B. Reister, *Energy Technology R&D: What Could Make a Difference?*, ORNL-6541/V1, 1989.

Goldemberg, J., T. B. Johansson, A. K. N. Reddy, and R. H. Williams, *Energy for a Sustainable World*, Wiley Eastern, Ltd., New Delhi, 1988; also *Energy for a Sustainable World*, World Resources Institute, Washington, D.C., 1987; and *Energy for Development*, World Resources Institute, Washington, D.C., 1987.

Häfele, W., "Energy Systems Under Stress," invited paper prepared for the World Energy Conference, Montreal, September 1989, cited by permission of author.

IIASA (International Institute of Applied Systems Analysis), 1981. *Energy in a Finite World: A Global Systems Analysis*, Report by the Energy Systems Program Group of the International Institute of Applied Systems Analysis; Wolf Häfele, Program Leader, Cambridge, Mass.: Ballinger.

Ogden, J. M. and R. H. Williams, 1989. *Hydrogen and the Revolution in Amorphous Silicon Solar Cell Technology*, PU/CEES Report No. 231, February 15, 1989.

Peelle, E., 1988. "Beyond the NIMBY Impasse II: Public Participation in an Age of Distrust," paper presented at Spectrum '88, International Meeting on Nuclear and Hazardous Waste Management, Richland, Washington, September 11-15, 1988.

Perry, A.M., 1984. *Atmospheric Retention of Anthropogenic CO_2: Scenario Dependence of the Airborne Fraction*, EPRI EA-3466, Electric Power Research Institute.

Rayner, S. and R. Cantor. "How Fair Is Safe Enough? The Cultural Approach to Societal Technology Choice", *Risk Analysis*, I, 3-9, 1987.

United States Environmental Protection Agency, "Policy Options for Stabilizing Global Climate," draft report to Congress, February 1989, (eds. D. A. Lashof and D. A. Tirpak).

Williams, R. H., 1987, "A Low Energy Future for the United States," *Energy 12*, 929-44.

REFERENCES (Continued)

World Energy Conference, 1983. Energy 2000-2020: World Prospects and Regional Stresses, ed. J. R. Frisch; Graham and Trotman.