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ABSTRACT

Nuclear power currently reduces CO_2 emissions from fossil fuel burning worldwide by about 8% (0.4 Gt(C)/yr). It can continue to play an important role only if it can grow substantially in the next 50 years. For such growth to occur public confidence will need to improve throughout the world. That might happen if a) other non-fossil alternatives are inadequate to meet electricity demand growth, b) the risks to society from global warming are perceived to be very high, c) nuclear technology improves substantially, and d) an international institutional setting is devised to manage the nuclear enterprise so that the technology is available to all nations while catastrophic accidents and proliferation of nuclear weapon capabilities are avoided. It seems feasible that the necessary technological and institutional advances can be devised and tested over the next 20 years. It is also plausible that the direct costs of electricity produced by the system would be in the range of 50-100 mills/kWhr (1990 dollars) delivered to the grid. In other words, the direct costs of nuclear power should not be greater than they are today. Achieving such an outcome will require aggressive technical and institutional RD&D performed in a cooperative international setting. If rapid growth of nuclear power can begin again in 15-20 years it could supply 30-50% of world electricity in 50 years and cut CO_2 emission rates by up to 2.5 Gt(C)/yr. This would be a substantial contribution to controlling greenhouse gases, but it is not sufficient. Improved efficiency and various renewable energy sources must also grow rapidly if CO_2 emission rates from electricity generation are to be reduced from the current value of about 2 Gt(C)/yr.

INTRODUCTION

Controlling CO_2 emissions,* when it becomes necessary to do so, will be a difficult, protracted, and expensive process. Changing world energy systems from predominant dependence on fossil fuels** to non-fossil sources will take decades to accomplish even if it is pursued vigorously. This would be true because of the slowness and cost of capital stock turnover, even if non-fossil substitutes were competitive. They are not. Each alternative is limited by at least one of 5 factors:

- resource base such as for hydroelectricity and biomass
- geography such as for geothermal and wind
- cost such as for direct solar thermal, photovoltaics, ocean thermal energy conversion and wave power
- technical feasibility such as for fusion, and
- public acceptance of larger scale deployment such as for nuclear fission.

It is fair to conclude, therefore, that we are currently not very well prepared with technology to cope with curtailing the use of fossil fuels (Fulkerson, *et al.* 1989a; 1989b).

There is no single fix for controlling CO_2 emissions. Four major strategies can be important: efficiency improvement; changes in the fossil fuel; recovering and sequestering or recycling CO_2; and substituting non fossil energy sources. In our opinion, all of these strategies should be pursued, particularly to the assessment of the potential and relative costs and effects.

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* Our concern here is control of CO_2, which is the principal greenhouse gas impacted by the world energy system. Already all Organization of Economic Cooperation and Development (OECD) nations (except the U.S. and Turkey) have pledged some degree of greenhouse gas control.

** 89% of world commercial energy is supplied by fossil fuels. Fossil fuels supply probably about 70-75% if non-commercial biomass sources are included. Although these non-commercial, non-fossil fuels produce CO_2 when they are burned, it is possible to manage biomass sources so that their net emissions are zero (or even negative) if as much (or more) carbon is removed by growing plants as by burning them. Most estimates indicate that the world biomass reservoirs are being burned faster than they are growing, so that biomass is a net source not a sink. However, the worldwide imbalance is not known.

Nevertheless, in the near- to mid-term the most effective strategy is to improve the efficiency of fossil fuel conversion and end use. Often this can be done at less cost than the investment in new supply. Furthermore, efficiency is always an attractive strategy. When it can be practiced economically it brings extra benefits of reducing environmental impacts from increasing supply which are generally greater than those of the technologies for more efficient use. Efficiency improvement also lessens the stress on world oil markets and supply, and it can improve the competitiveness of nations which practice it. Not only is efficiency improvement already important, but the potential for continuing improvement through R&D also appears large (Fulkerson, *et al.* 1989a; 1989b) (Carlsmith, *et al.*1990).

Another strategy is the substitution of natural gas for coal which may be a useful approach in some areas of the world, particularly Europe. In the era of Peristroika, we can imagine Europe being able to turn off coal plants by using Soviet gas. The Soviet Union is, after all, the Saudi Arabia of natural gas with resources estimated to be equal to about 60 years supply for the USSR and Europe (East and West) at present use rate plus substituting for all current coal use. Greater use of gas could improve the Soviet economy and the local and regional environments across Europe as well as reducing CO_2 emissions, particularly if gas is used more efficiently than coal, and if methane leakage from the natural gas system is kept very low (< 2%) (Fulkerson, *et al.* 1990).

A third possibility is recovering CO_2 from fossil fuel combustion and sequestering it in biomass reservoirs, the deep ocean, or depleted gas reservoirs. The growing of new forests to offset CO^2 emissions is attractive in this day of deforestation; it is currently relatively inexpensive, but it is likely to be limited by land use priorities. However, growing biomass for energy directly rather than as an offset is likely to be a more productive CO_2 control measure. Recovering CO_2 from large point sources such as power plants appears to be expensive, but some recent calculations (Hendriks, *et al.* 1990) based on an oxygen blown Integrated Gasification Combined Cycle (IGCC) process indicate a much lower cost than previous estimates (Baes, *et al* 1980) (Steinberg and Albanese 1980)

(Steinberg and Horn 1982) (Steinberg 1983) (Steinberg, *et al.* 1984) (Steinberg 1985) (Steinberg 1986) (Steinberg 1987) (Wolsky and Brooks 1989).

The fourth and ultimate strategy is, or course, substitution of non-fossil for fossil sources. This includes R&D to improve the non-fossil sources. Of the non-fossil sources which have the potential to be expanded significantly, nuclear fission is the nearest to realization. It is already used in 26 countries to produce 16% of the world electricity generation (Energy Information Administration 1989). However, opposition to its greatly expanded use is growing and can be found even in countries which are its strongest devotee's.

We do not pretend to understand all of the reasons for public opposition. We suspect opposition is driven partly by concern over the risk of a disastrous accident such as Chernobyl, partly by the fear of radioactivity leading to great concern about the proper handling of wastes not only for this but future generations, partly by the connection between nuclear weapons and nuclear power, and partly by a loss of trust in the institutions constructed to develop and manage the nuclear enterprise (Rayner and Cantor 1987). We know the technology can be improved significantly. Correcting or mitigating weaknesses in the technology is surely a necessary, if not sufficient, condition to gaining a system which enjoys greater public support and confidence. Without that improvement, the possibility for large scale expansion of nuclear power seems remote. A number of papers on this topic have recently been published, and we have benefited greatly from them (Weinberg 1990) (Hafele 1989) (Hafele 1990) (Murray 1990) (Keepin and Katz 1988).

In Section 2 we will review the situation relative to improving nuclear power. Then, in Section 3 we will examine how much impact nuclear power might have over the next 50 years or so if the weaknesses could be reduced to acceptable levels.

TOTAL SOCIAL COSTS OF NUCLEAR POWER

We will discuss improving nuclear power by reducing the total social cost of the fuel cycle. Total social costs include both the direct ones for building, operating, and decommissioning facilities and also those indirect ones such as risks of accidents or environmental impacts. These indirect costs are primarily in three areas: power plant accidents, environmental impacts due to waste management (particularly the inter-generational issue), and proliferation of weapons, including by diversion fissionable materials.

Indirect Cost

In order to discuss total social costs, we have looked at the contributions of each major element of the fuel cycle. In Table 1, we list the fuel cycle elements and give our judgement of a qualitative estimate of the social costs of each as measured in terms of impacts on the environment, human health, safety, proliferation, and direct costs. For each element in the matrix, we indicate whether we think current plans for improved technology increase or decrease impacts, risks, or direct costs. Comparisons should be made by looking down a particular column of cost, not across a row. These estimates represent the judgement of the authors and are used to suggest a method of analysis rather than the results of any scholarly study. Nevertheless, some interesting features seem to emerge.

Environmental problems of normal operations are centered primarily in mining, milling and processing, and waste management. Human health impacts (from normal operations) tend to be dominated by mining, milling, and processing, whereas safety is dominated by reactor accident risk. Proliferation risks are influenced by enrichment, breeder reactors, reprocessing, and transportation. Direct costs are dominated by the construction and operation of nuclear power plants.

All improved technologies development tend to reduce (or effect neutrally) direct costs, and generally reduce risks or insults with one notable exception. Improved enrichment technologies are designed to reduce the cost of nuclear fuel* and also have lower investment costs and smaller scale than gaseous diffusion (Goldsworthy 1990). Therefore they are likely to be more affordable to a larger number of countries than current enrichment options and tend to increase the risk of proliferation.

However, Table 1 does not represent the whole story. Many of the indirect costs grow as the nuclear enterprise grows. These include the risks of power plant accidents and proliferation by diversion of fissile materials as these become items of international commerce. Hence, to maintain the same overall level of risk would require that the technology or institutional control improve in proportion to system growth (Koomanoff 1981). That is, each new facility in the system must be better. It is plausible to argue that the level of external costs that exist today are about at the tolerable level. This certainly would appear to be the case relative to reactor safety. For some nations such as Sweden,** the limit has already been exceeded, while for others it hasn't; e.g., France, Japan, and Canada. Furthermore, safety is a system-wide problem. An accident anywhere is the same as an accident everywhere.

Following the Three Mile Island accident, the Institute of Nuclear Power Operations (INPO) was formed in the United States by the electric power industry to improve the safety systems and operating procedures across the U.S. nuclear community. This was a voluntary action bolstering the oversight effort of the Nuclear Regulatory Commission. Now INPO is an international organization that aims to avoid reactor accidents everywhere in the world. It is joined now by the World Association of Nuclear Operators (WANO) which fosters exchanges between the USSR and Eastern European countries and the OECD countries.

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* Target reductions in fuel production cost range from 5 to 75%.

** Sweden may be rethinking their decision to phase and nuclear power as indicated in <u>Nucleonics Week</u>, June 21, 1990.

Over the past 12 years there have been two serious reactor accidents. Only one, Chernobyl, caused deaths and significant contamination of the environment; but the other, Three Mile Island, ruined a reactor and cleaning it up has cost more than a billion 1990 dollars (Peach 1982). That is, the world has experienced two serious accidents for some 2000 GW years of integrated power reactor operating experience. It is tempting to divide these two numbers to get a rough measure of the probability of such accidents, but that calculation is statistically unjustifiable. Probabilistic risk assessments (PRA) have been used, however, to obtain a forecast of reactor safety. For light water reactors the probability of an accident like Three Mile Island (i.e., core melt) is in the range 10^{-3} to 10^{-5} per reactor year for the 95th and 5th percentile, respectively (Garrick 1989). That is, the probability of a core melt is $<10^{-3}$ per year with a confidence of 95% and it is $<10^{-5}$ per year with a confidence of 5%. Since worldwide nuclear capacity is about 312 GW(e), this implies an accident every 3 to 300 years if the system doesn't grow. For a world where this capacity has increased by a factor of 10, it would mean a possibility of a serious accident once every 0.3 to 30 years. That appears unacceptably high since the recent experience of two in a decade appears unacceptable. Thus, reactor safety must be improved by at least one order of magnitude and probably two orders of magnitude (a factor of 10 to 100).

Public perceptions about safety are also related to the problem of reliability and the effects of continual operating problems with nuclear power. Although only two serious accidents have occurred, numerous less serious ones occur much more frequently. Even trivial problems at nuclear plants tend to make the national news and this level of visibility serves to reinforce suspicions that the technology is unsafe or poorly managed.

Risk of proliferation or clandestine diversion of weapons grade materials is another external cost which depends on how the nuclear enterprise is operated as a worldwide system. As technology for enrichment and spent fuel reprocessing improves and as their use increases, the risks will grow unless safeguards are also improved. The once-through "throw away" fuel cycle is one approach to reducing the risk because it eliminates spent fuel reprocessing and hence trade in plutonium (or ^{233}U in the case of thorium breeding). On the other hand, fuel reprocessing will be necessary if the breeder is needed to expand the uranium resource base. This circumstance is, of course, more likely if nuclear power is to be a major non-fossil energy source in a greenhouse-constrained society.

For the large scale nuclear system it may be necessary to have breeder reactors co-located with reprocessing plants and to have these centers under international control. In fact, internationalization of enrichment and spent fuel storage is also attractive and may be necessary. The problem of safeguards was recognized since the beginning of the nuclear era (Acheson-Lilienthal Report of 1947). Recently Williams and Feiveson have proposed five criteria they believe must be met to adequately reduce the risk of proliferation (Williams and Feiveson 1989). These are:

1. restrictions on sensitive nuclear technologies and materials shall be nondiscriminatory among nations (i.e., the same restrictions will apply to all nations);
2. fissionable weapons-usable material (outside of spent fuel) and facilities to enrich uranium or to separate plutonium shall not exist outside of international centers;
3. to the extent possible, fissionable weapon-usable material (outside of spent fuel) shall not be produced even at the international centers;
4. spent fuel shall be stored and disposed of in international centers; and
5. reactors under national authority shall be designed so as to reduce to very low levels the production of weapons-usable material in spent fuel (of the order of a critical mass or less per year per gigawatt of capacity).

Meeting criteria such as these would require an extraordinary restructuring of the nuclear enterprise. Before the unprecedented changes in the world triggered by Peristroika in the Soviet Union, such a restructuring was unlikely. Now, however, some of these criteria may be achievable and worth exploring as part of an overall worldwide effort to reduce and control nuclear weapons—particularly criteria 2, 3 and 4.

Although significant strengthening of safeguards may prove necessary, the once-through fuel cycle may well remain the most cost effective way to organize nuclear power for decades even if a rapid growth in reactor deployment occurs. We believe uranium resources are much more extensive than once thought, and economic methods of recovering uranium from very extensive but low grade ores seem probable. Eventually uranium may even be extracted from sea water (Best and Driscoll 1986). We return to the issue of uranium requirements in Section 3.

Total Direct Cost of Nuclear Power – Current and Improved Technology

Although we can't calculate the total social cost of nuclear power quantitatively, we can say something quantitative about the total direct costs and how these may change with advancing technology.

First, we should review what has been the cost experience to date. The direct cost experience of nuclear power in the U.S. today varies widely from plant to plant. As shown in Table 2, the average cost (based on 1988 data adjusted to 1990 dollars) is 65 mills/kWh but the range of experience around that average is very wide (20-200+ mills/kWh for plants with capacity factors greater than 40%). World projections of costs for power from nuclear plants expected to start operation in 1995 to 2000 range from 24-82 mills/kWh, also shown in Table 2. The upper range of costs here may be low since current estimates for the cost of power from the Sizewell Pressurized Water Reactor (PWR) plant in England are now 60-100 mills/kWh or more (U.K. to Finish Sizewell 1990). The largest projected cost variation is in the capital cost component; however, Operation and Maintenance (O&M) and fuel costs also have wide variations. Experience in the U.S. indicates that Operation and Maintenance costs have increased rapidly in the early to mid 1980s (Hewlett 1988).

Advanced reactor technology with passive* safety features holds the promise of not only increasing safety (perhaps by the one or two orders of magnitude needed for a much larger scale nuclear enterprise) but also of reducing costs. The cost reductions are achieved because passively safe systems are inherently simpler than redundant active systems and some passive reactors may not even require secondary containment although they will be located below grade. Such reactors may be forgiving of equipment failures as well as operator errors (Forsberg 1990).

Such concepts now under development in the U.S., Japan, and Sweden include an improved version of the current light water reactor (LWR), a smaller LWR [~600 MW(e)] with passively safe features, the Swedish Process Inherent Ultimate Safety (PIUS) LWR, the Modular High-Temperature Gas-Cooled Reactor (MHTGR), and the Advanced Liquid Metal Reactor (ALMR). Projections of the power generation cost from these advanced concepts are shown in Table 3. The cost estimates shown apply to the technologies once they are fully established. First of a kind (FOAK) plant costs may be significantly greater. In the author's judgement, concept development cost, including FOAK design and licensing costs, are expected to fall in the $250-500 million range for the advanced LWR reactors and $500 million to $1 billion each for the ALMR and MHTGR.** These costs are important deterrents to the introduction of advanced reactors.

The uncertainties in the costs shown in Table 3 at the current level of development are such that no real difference between the various concepts can yet be assigned with any confidence. The estimates are based on detailed vendor estimates, but may be very optimistic at this early stage of development. Furthermore, vendors are likely to use the

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[*] Passive safety means that safety features operate without depending on external input (i.e., external mechanical or electrical active controls). For example, a reactor might suffer a sudden loss of circulation in the core cooling system. In a passively safe reactor, natural conduction of heat to the surrounding ground or to the atmosphere would cool the core sufficiently to avoid reactor damage or release of radioactive materials and the reactor would be shut down without any external mechanical or electrical active intervention.

[**] Estimates based on unpublished ORNL review of vendors' projections.

LWR cost experience as a target ceiling to offer competitive alternatives; therefore, we are not surprised by the clustering in cost estimates.

Developers claim that these passively safe reactors are much less likely to experience a serious accident than the current LWRs which depend on redundant active systems. This remains to be verified by testing and experience, but some critics are skeptical (MHB Technical Associates 1990). Nevertheless, these are the kinds of reactor systems which may achieve one or two orders of magnitude safety improvement over the technology currently in use.

The front end of the fuel cycle should not pose any great technical or economic problem for the advanced LWRs or even the MHTGR. These concepts use enriched uranium fuel just as does the present generation of power plants. Also the fabrication of fuel assemblies is a well established technology even for the MHTGR with its graphite blocks. Enrichment technology is well developed and advanced technology may reduce production costs below $50/Separative Work Unit (SWU) or less than half of today's costs charged by the U.S. Department of Energy (Goldsworthy 1990). Some of the advanced technologies, such as the Atomic Vapor Laser Isotope Separation (AVLIS) process cause proliferation concerns because of the potential to produce highly enriched uranium more easily.

The current DOE reference design for the ALMR is the General Electric PRISM concept which is, or can be, a breeder reactor. This is a metal fueled reactor using plutonium for both the startup and recycle fuel. The concept envisions using an on-site integral recycle facility being developed by Argonne National Laboratory. The costs associated with this fuel cycle are very uncertain, hence the wide uncertainty indicated in Table 3. The source of startup fuel for the ALMR is of concern. Highly enriched uranium can be used, but plutonium is a much better fuel neutronically. On a kilogram basis, less fissile plutonium is required by the ALMR than if ^{235}U were used. The source of this startup plutonium remains a question, with reprocessing of spent LWR fuel the prime candidate, but also the burning of excess weapon material is a possibility.

The backend of the fuel cycle (i.e., reprocessing and high-level waste disposal) continues to be a problem which must be solved if nuclear power is to grow substantially. Of course, the waste problem must be solved whether or not the nuclear enterprise expands. In the United States, spent fuel assemblies are currently stored in pools of water at the reactor sites. Current plans are to transport these assemblies to a repository in Nevada (Yucca Mountain) where they will be permanently sequestered in a volcanic tuff formation deep underground. Entombment is also being pursued by other nations (e.g., by Sweden) where spent fuel may be deposited in a mined rock formation under the Baltic sea. This entombment approach suffers severe political opposition, particularly in the areas where repositories are sited. Concerns range from fear of accidents to uncertainties about the long term integrity of the geologic formations which must survive and remain stable for millennia until the radioactive materials in the spent fuel have decayed sufficiently that they are no longer dangerous.

An alternative to current final storage plans is to keep spent fuel in so-called monitored retrievable storage. Pool storage at reactor sites represent such a strategy, but the mature development would involve a number of carefully engineered, monitored, and protected facilities around the country to which spent fuel would be shipped. Retrievable storage provides more time to develop more permanent solutions without irreversible commitment, and it could become a sort of bank for plutonium to be withdrawn as uranium becomes expensive.

Currently, electric utilities in the U.S. are charged 1 mill/kWh to be paid to the High Level Waste Disposal Fund. This charge may be increased in the future as the cost of ultimate disposal continues to increase. The current cost estimate for the U.S. waste management program is about $30 billion. To this should be added the total cleanup cost attributable to commercial reactors (e.g., the proportionate share of costs of cleaning up at enrichment and fuel reprocessing plants, national laboratories, etc. amounts to a possible addition of $50 billion). If this cost were to be spent over a 20 year period, it could add about 3 mills/kWhr to the current waste disposal fee, and the total costs of waste disposal and clean up would be about 5 mills/kWhr (assuming 100 GW(e) capacity at 75% capacity factor). The range of projections by various nations for the back end of the fuel cycle cost from the NEA/IEA study was about $400-$1700 per kg of heavy metal (HM), which translates to about 1-5 mills/kWhr (NEA/IEA 1989). Some of these back-end costs may include the cost of the reprocessing of the spent fuel.

The cost of reprocessing large quantities of spent fuel is uncertain. The French company, Cogema, reportedly has signed contracts at a price of FF5000/kgHM (about $600-$1000/kgHM depending on exchange rates) for the reprocessing of spent fuel in the post year 2000 period (Cogema Gets Reprocessing Contracts 1990). There is currently no commercial fuel reprocessing in the U.S. nor is any planned.

Recently a tie-in with high-level waste disposal and spent fuel reprocessing has been proposed. The ALMR fuel cycle could be modified so as to use mixed actinides (plutonium and trans-plutonium elements) from LWR spent fuel as its initial fuel. By reprocessing LWR spent fuel, with very efficient separation of actinides from the resultant high-level wastes, the job of high-level waste disposal may be made easier and less costly. The ALMR would have its initial fuel, and the stored waste would only be a radioactive threat for hundreds, rather than thousands. Also, plutonium would not be separated in a pure stream, but would remain in a highly radioactive mix with the other actinides and some fission products. The proliferation concerns about reprocessing may therefore be reduced. A large reprocessing plant would be needed for the recovery of the actinides from spent LWR fuel (spent fuel stored at MRS sites). The capital cost of such a plant could be $4-10 billion with unit costs of $250-$1000/kgHM depending on ownership and financial assumptions. The cost of the actinide recovery could be borne jointly by the ALMR and by the waste disposal fund; the latter could be charged to the extent that the reprocessing reduced waste disposal costs. The acceptability, feasibility and economics of such a system remains to be seen, but it is an interesting possibility.

In summary, the direct costs of nuclear power vary widely, but they are probably in the range of 50 to 100 mills/kWh around the world. Advanced technologies hold the promise of providing greater safety and closing the fuel cycle at costs in the same range. In fact, if costs cannot be kept in this range, nuclear power will not be economically viable. Given adequate uranium resources, advanced LWR and MHTGR technologies may permit economic expansion of nuclear power in the immediate future. In the longer term, the introduction of ALMR breeders which can also burn actinides of the spent fuel from thermal reactors is an attractive option to pursue. Nevertheless, these advanced technologies are not fully developed or tested, and accelerated RD&D is needed, as is refinement of the cost estimates.

However, even with favorable evidence on the projected direct costs, a major role for nuclear power in a global strategy to address the greenhouse effect depends on a willing marketplace. There remain a number of considerations regarding international cooperation and coordination that warrant further examination to project this role. We have mentioned the issues of proliferation and safety, but other considerations to be addressed by international cooperation include capital financing, the transfer of technical expertise and equipment, and the transfer of sound operating and siting practices. Unfortunately at this time, there is insufficient research in the area of institutional designs and acceptable large scale nuclear power deployment to suggest the best options for global strategies.

REDUCTION OF CO_2 EMISSIONS

In considering the potential role of nuclear power in limiting future worldwide CO_2 emissions, we focus primarily on the generation of electricity. We do not assume that this is the only useful or potentially-large-scale application of nuclear power. However, it is likely to remain the principal one for several decades and over that period can serve in our analysis as a surrogate for other potential applications such as the use of nuclear heat for producing liquid fuels from coal or methane.

Demand for Electricity

We expect worldwide demand for electricity to continue to increase at nearly the rate of economic growth, even with substantial progress in improving the efficiency of energy utilization throughout the economy. From 1973 to 1987, demand for electricity in OECD countries increased at an average rate of 2.9%/year, in non-OECD countries at 5.9%/year, and in the world as a whole at 4.0%/year (IEA 1988). In a recent report for the U.S. Department of Energy on the potential of energy efficiency (Carlsmith, *et al.* 1990) it was estimated that U.S. electricity demand will increase at 1.8 to 2.2%/year from 1990 to 2010, the lower figure corresponding to full realization of cost-effective conservation based on life-cycle costs. This study assumes no real increase in the price of electricity over the 20 year period; therefore, these demand projections do not reflect the price changes that may follow supply increases.. In calculations using the Edmonds-Reilly energy-economy model (Fulkerson, *et al.* 1989a) (Edmonds and Reilly 1986) a base case approximating the IIASA Low Scenario (IIASA 1981) showed worldwide electricity demand increasing from 1975 to 2025 at an average rate of 2.9%/year, even while overall energy use, relative to gross world economic product, was decreasing by 1%/year. A high-efficiency case designed to approximate the scenario of Goldemberg and colleagues (Goldemberg, *et al.* 1988) showed worldwide demand for electricity increasing over the same period at 1.8%/year.

In the present analysis, we consider a high electricity demand case (HE) and a low demand case (LE) with electricity consumption increasing respectively at 3%/year and 2%/year from a nominal value of 12 x 10^{12} kWhr/year in 1990. Both cases are intended to represent substantial progress in overall energy conservation. By 2040, the total worldwide electricity use would total 53 x 10^{12} kWhr/yr and 32 x 10^{12} kWhr/yr for the HE and LE cases, respectively.

Possible Contribution of Nuclear Power to Electricity Supply

For two decades nuclear power has been, in relative terms, by far the fastest growing component of world electricity supply, averaging about 17%/year (United Nations 1989). However, that period of growth, which (following Alvin Weinberg [Weinberg, *et al.* 1985]) we may call the first nuclear era, is drawing to a close. Planned construction programs in the United States, France, and elsewhere are nearing completion and, in general, few new orders are foreseen in the next few years. Other major programs (e.g., in the U.S.S.R. and Eastern Europe) may soon follow suit, and some earlier reactors (e.g., in Sweden) may be forced into early retirement (although Sweden may be reconsidering such action). Thus, the prospect for the next 10 to 15 years is for generating capacity, now about 312 GWe (mid-1990), to peak at about 390 GWe around the end of the century and then begin a slow decline as increasing retirements overtake declining construction of new reactors. Even with anticipated increases in average capacity utilization factors (currently around 65%) to 70% or 75%, generation of electricity, now at about 1.8×10^{12} kWhr/year, will probably level off at about 2.4×10^{12} kWhr/year in the period 2000-2005.

Of course we don't know what the longer-term future of nuclear power may be. For the purposes of this analysis, we consider two widely divergent scenarios, defining a Low Nuclear (LN) and a High Nuclear (HN) scenario. The former represents the continuing, slow demise of the first nuclear era as a result of scheduled retirements of reactors already in place. We assume service lifetimes of 30 years for reactors built in the early 1970s, rising to 40 years for those built in the early 1980s, and to 50 years for those built in 1990 or later years. We do not assume forced early retirements on a major scale, although that is a possibility.

However, the main point at issue in this paper is how much nuclear power could contribute to reducing future emissions of CO_2. Therefore, our HN scenario is designed to represent a very robust revival of nuclear power in what Weinberg has called the second nuclear era. One condition for such a revival is likely to be the development and demonstration of improved, passively safe reactors such as advanced light-water reactors, modular high-temperature gas-cooled reactors and eventually, advanced liquid metal reactors. We judge that construction of such reactors in numbers comparable to those reached in the 1980s in the first nuclear era (e.g., 20-30 GWe per year) could hardly be expected before 2010. As a simplified representation of this renewed construction activity, we assume a linear increase in annual capacity additions, starting from 0 in 2005 and reaching 100 GWe/year in 2030 (i.e., new additions increasing by 4 GWe each year).

Although such numbers are startling at first glance, it must be remembered that net annual additions of all types of generating capacity averaged 84 GWe/year from 1970 to 1987, that the assumed additions will be to a generating system perhaps 2-3 times larger than at present (5-8 times as large as in 1970), and that the world economy is assumed to be several times larger than at present. In fact, generating capacity of all types must increase at much faster rates to supply total electricity needed for either the low (2%) or high (3%) scenarios we consider.

Characteristics of the assumed nuclear scenarios are shown in Figure 1. Our HN scenario reaches an installed capacity of 1458 GWe in 2030 (1300 GWe of new reactors and 158 GWe remaining from the first nuclear era) and reaches 2600 GWe in 2040, which is approximately equal to total world generating capacity of all types in 1987. For comparison, Häfele (Hafele 1990) assumes an increase of nuclear capacity to 2000 GWe in 2030. Our HN scenario represents a very aggressive program (if not a maximum), and is suitable for estimating the potential displacement of fossil-fired plants and consequent reduction of CO_2 emissions.

Potential CO_2 Reductions. At this point, we would like to estimate the reductions in CO_2 emissions made possible by following the HN scenario rather than the LN scenario. To do this, however, we need an estimate of the CO_2 emissions from fossil-fired stations generating the same amount of electricity. This is not a fixed characteristic of these stations, but varies with the mix of fuels and with the efficiency of the stations. These factors will not be the same for all possible future scenarios, of course. Nevertheless, we adopt a single trend line of CO_2 emissions from fossil-fired stations (GtC/10^{12} kWhr), based on a 2% annual growth in output. To satisfy this increased demand, we assume a more rapid growth in gas-fired units than coal or oil; i.e., 2.8%/year for gas vs 1.7%/year for coal and oil. We also assume significant improvement in the efficiency of new units, reflected in an assumed linear increase in the average efficiencies of all operating units, reaching 40% in 2040 for coal-fired units, 47% for oil and 47% for gas. (The best new units may have higher efficiencies than these, e.g., greater than 50% for gas-fired turbines, the assumed efficiencies given above represent nominal averages for all units in operation, new and old.) These assumptions yield a two-fold increase in coal and oil consumption for electricity and nearly a three-fold increase for gas. They also yield a trend in CO_2 emissions decreasing approximately linearly from 0.23 GtC/10^{12} kWhr in 1990 to 0.16 GtC/10^{12} kWhr in 2040.

Reductions in CO_2 emissions, calculated under these assumptions, are shown in Figure 2 for the HN and LN scenarios and for the difference between them. The difference (HN-LN) is shown to indicate the potential contribution of the advanced nuclear technologies expected to supersede current technologies. Nuclear power already reduces CO_2 emissions by about 0.4 GtC/year. (For comparison, worldwide CO_2 emissions associated with electricity generation are now approximately 1.8 GtC/year and, without the nuclear reduction, would be about 2.2 GtC/year.) However, it may also be seen that a renewed commitment to nuclear power is likely to make very little difference in CO_2

emissions before about 2010. Thereafter, it could become an increasingly important tool for limiting CO_2.*

Figure 3 indicates how much of the total electricity requirement can be met by the high nuclear case. For the low electric scenario nuclear could supply up to 50% of electrical requirement worldwide by 2040 and about 30% for the high electric scenario. The remainder must be supplied by renewables and fossil fuels.

Estimating the penetration of renewable sources is beyond the scope of this paper but a recent analysis in the United States (SERI 1990) indicates they could produce as much electricity as nuclear for our high nuclear case if RD&D paid off and/or fossil sources were severely penalized. The SERI report details a very aggressive scenario, at least as aggressive as our high nuclear scenario. On this basis, if both high nuclear and high renewables were developed, fossil fuel sources needed to supply electricity would remain at about present levels for the High Electric demand scenario, but fossil sources could be phased out altogether for the Low Electric case.

Thus, an important conclusion is that neither nuclear, nor efficiency improvement, nor renewables separately can significantly reduce CO_2 emissions from electricity generation. All three will be required to do that. They are complementary, not in competition.

Uranium Requirements. The HN scenario is an ambitious one and would require a large amount of uranium if it were restricted to the once-through fuel cycle for light-water reactors (or fuel cycles of comparable material efficiency in other reactor types). In Figure 4, we display the cumulative uranium requirements for the HN scenario, based on the once-through fuel cycle, in three different ways: (1) the actual cumulative consumption of uranium up to a given year; (2) cumulative uranium consumption up to a given year plus

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* Weinberg 1990 points out that while nuclear plants do use fossil fuel during construction and preparation of fuel, this added CO_2 burden is far less for a nuclear plant than a coal plant of the same capacity. A 1000 MWe nuclear plant (PWR, with no recycle) releases at most only 13% as much carbon as the same size coal plant for lifetime operation.

forward commitments for 20 full-power years (FPY) of operation for each reactor at the time of startup; (3) cumulative consumption plus forward commitments for 20 FPY at the time the reactor is ordered, here taken to be ten years prior to startup.

If we argue that prospective reactor owners will be hesitant to order new reactors unless they are reasonably assured of a lifetime supply of fuel, then it would appear from Figure 4 that even a resource base of 20-25 Tg of natural uranium* would not be sufficient to sustain our HN scenario much past 2040 and that steps would be required, even prior to that date, to assure a larger supply of uranium or to make much more efficient use of the 20-25 Tg, e.g., via breeding. Breeding, however, should multiply uranium productivity by at least a factor of 50.

Other Considerations. In this crude analysis, we have not examined many of the geographical problems with the expansion of nuclear power. For example, much of the growth of electricity demand will be in the developing world. Penetration of nuclear in these nations is constrained by availability of capital and trained people. Equity and practical considerations may require very drastic reduction of CO_2 emissions by the industrialized world (90% or more) so that developing nations can use increasing amounts of fossil fuels. We assume in any event, that nuclear must be an internationally controlled enterprise and that it will be accessible to all nations under the conditions that all accept international regulations. It is, or course, not obvious that such a world system can be established at reasonable costs, but if it can't, the role of nuclear for controlling CO_2 is likely to be very constrained.

CONCLUSIONS

From the preceding discussion, we derive the following conclusions regarding the nuclear power contribution to limiting CO_2 emissions over time:

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* OECD/IAEA projections at $130/kg ($60/lb) are: 6 million metric tons reasonably assured and estimated additional resources, and 24 million metric tons of speculative resources (OECD/NEA 1983).

- Nuclear power certainly can help reduce CO_2 emissions; in fact, it has already. However, even if nuclear power grows substantially in the next 50 years it can be only part of the means to reduce CO_2 emissions. Both much improved efficiency of electricity use and aggressive deployment of renewable energy sources are also essential.

- For nuclear power to continue to be an important factor, a much larger-scale enterprise worldwide will have to evolve (larger by a factor of 5-10 in 50 years). Such an enterprise will require:

  a) Safe operation of the present system (no serious accidents).

  b) For the next generation, much safer reactors which are forgiving of equipment failure and operator error and which can be used by developing nations as well as industrialized countries.

  c) Strengthened international institutions to control nuclear materials perhaps by putting enrichment, fuel reprocessing, and breeders (when they are needed) in centers under international control as well as the transportation and monitoring of reactor fuel assemblies new and spent. However, as yet, we have limited information of the kinds of international arrangements and institutions that would be the most effective to deploy a larger-scale nuclear enterprise.

  d) Developing better methods to dispose of waste, perhaps by burning actinides as part of breeder and reprocessing technologies.

- These requirements are not likely to come easily. They can be met only by the most concerted efforts of international cooperation. This cooperation should include joint RD&D on both hardware and institutional arrangements.

- The will to make such efforts will depend in part on the extent of the perceived need. That is, it will depend on how seriously nations perceive the need to reduce CO_2 emissions and the cost, limitations, and other aspects of social acceptance of alternatives to the nuclear option. These other energy options are also the subject of this conference. As we said in the beginning, no single option is likely to emerge as a panacea. At this stage, it is prudent to pursue all options vigorously, including nuclear. The eventual outcome will be determined by the relative success of RD&D.

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NUCLEAR POWER SCENARIOS

HIGH NUCLEAR (HN) AND LOW NUCLEAR (LN)

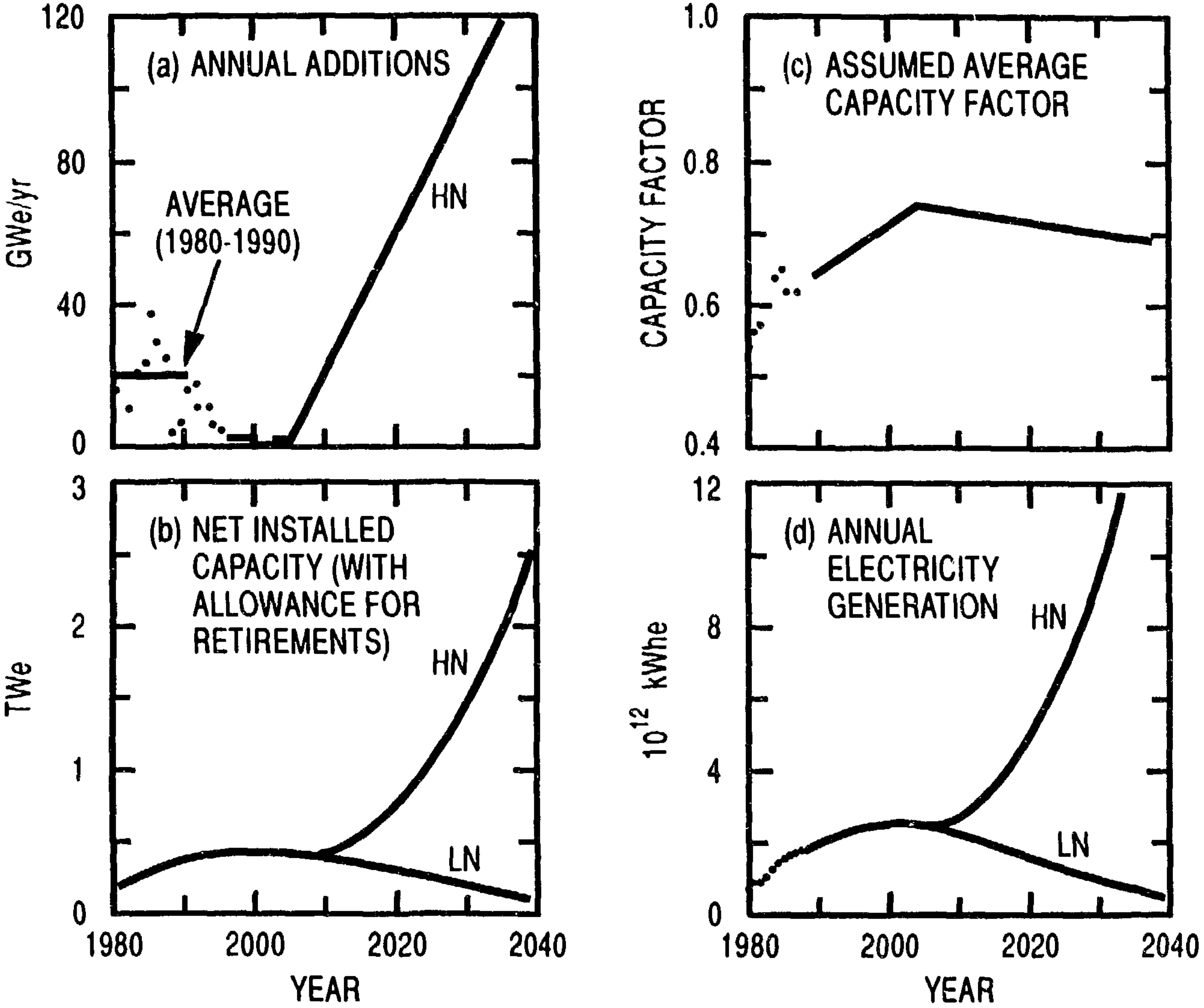

Fig. 1 Nuclear power scenarios; high nuclear (HN) and low nuclear (LN): (a) assumed annual additions of second generation passively safe nuclear plants; (b) net installed capacity with allowances for retirements; (c) assumed average capacity factors worldwide; (d) annual electricity generation for HN and LN.

ORNL-DWG 90Z-15285C

THE POTENTIAL OF NUCLEAR POWER TO CONTROL CO_2 EMISSIONS

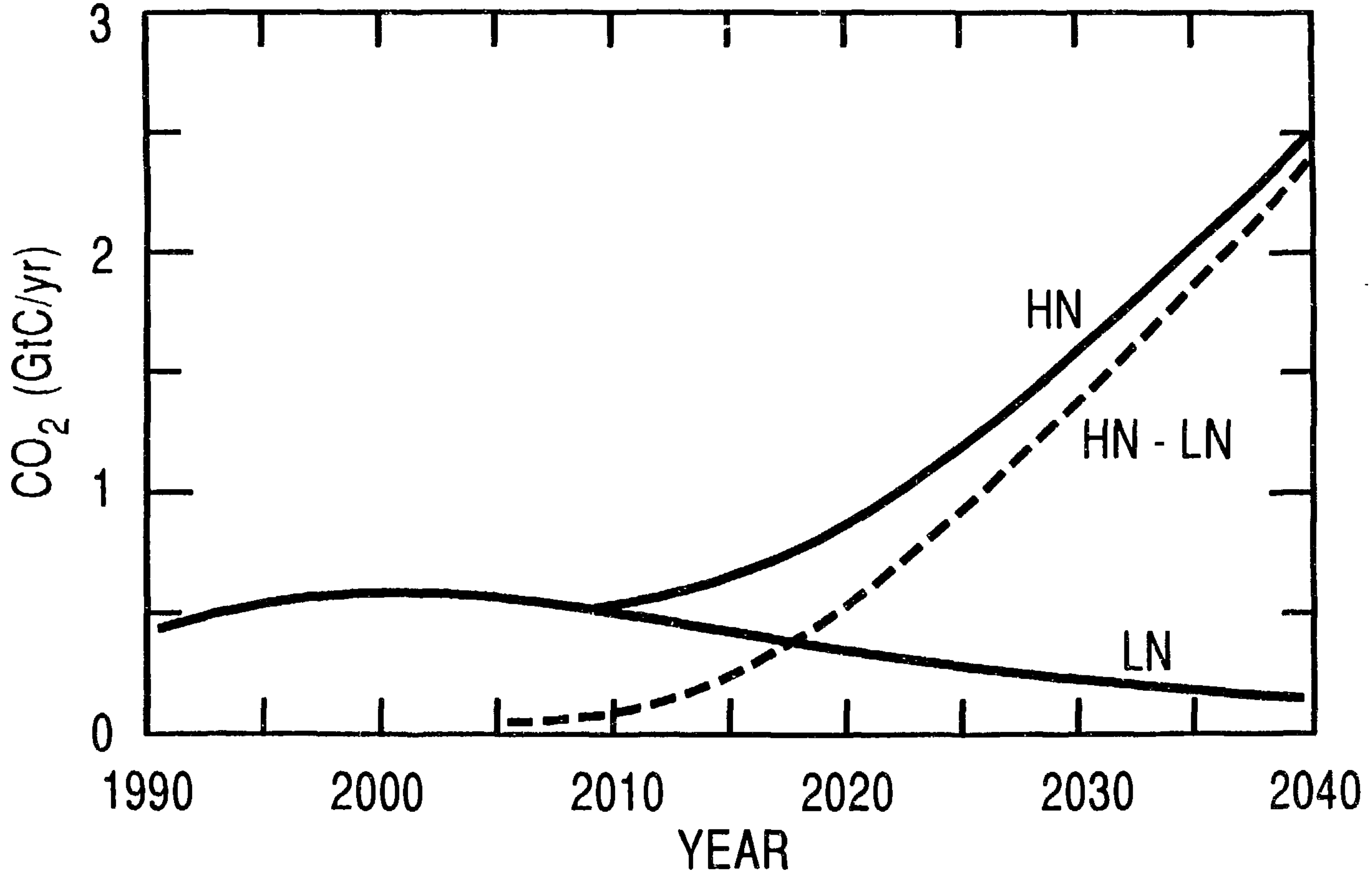

Fig. 2 CO_2 emissions avoided by use of nuclear power by high nuclear (HN) and low nuclear (LN) cases.

ORNL-DWG 90Z-17201C

HIGH NUCLEAR GROWTH MIGHT SUPPLY 1/3 TO 1/2 WORLD ELECTRICAL NEEDS

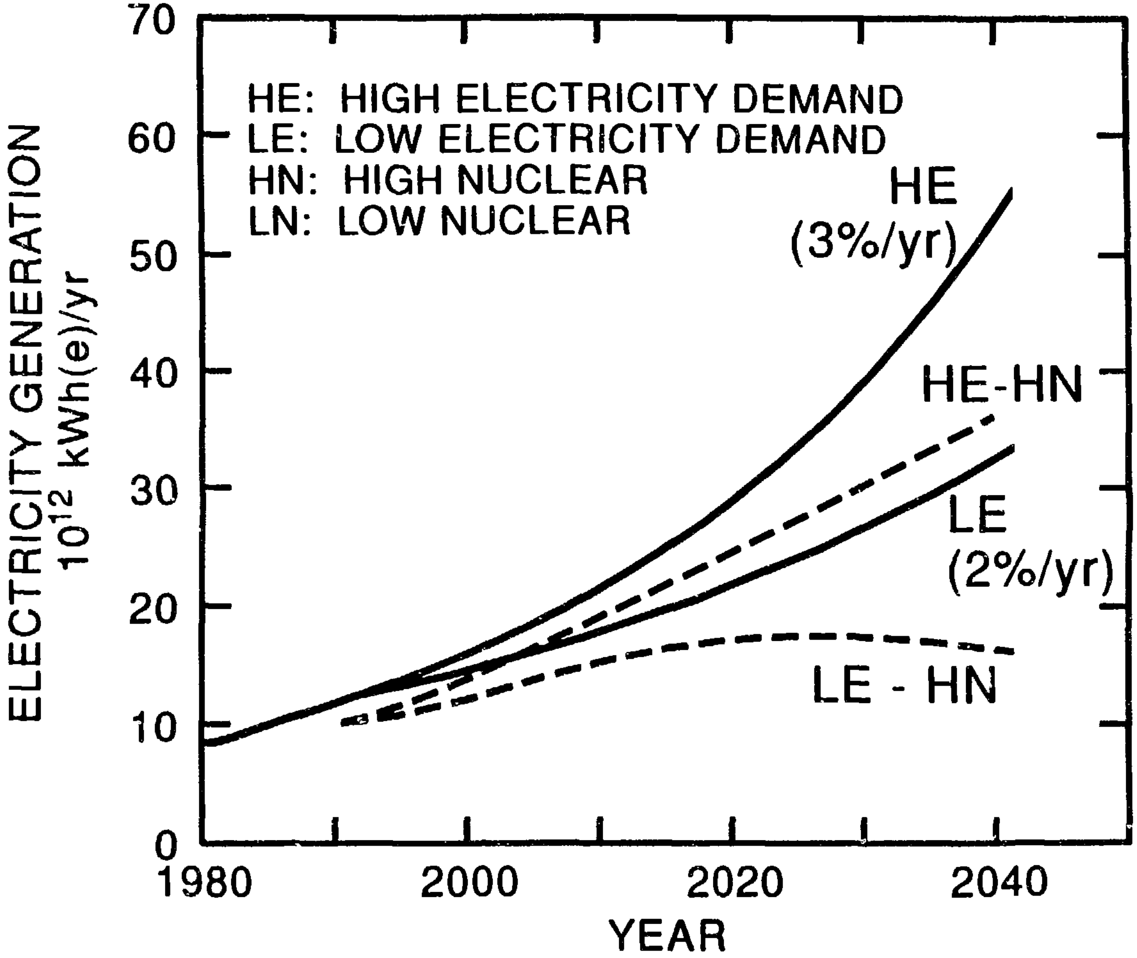

Fig. 3 Nuclear power under the high nuclear scenario could supply up to 50% of world electricity needs by 2040 [low electric case (LE)] or 30% [high electric case (HE)] The remainder indicated by the dashed curves must be supplied by renewables and fossil fuels.

ORNL-DWG 90Z-15290D

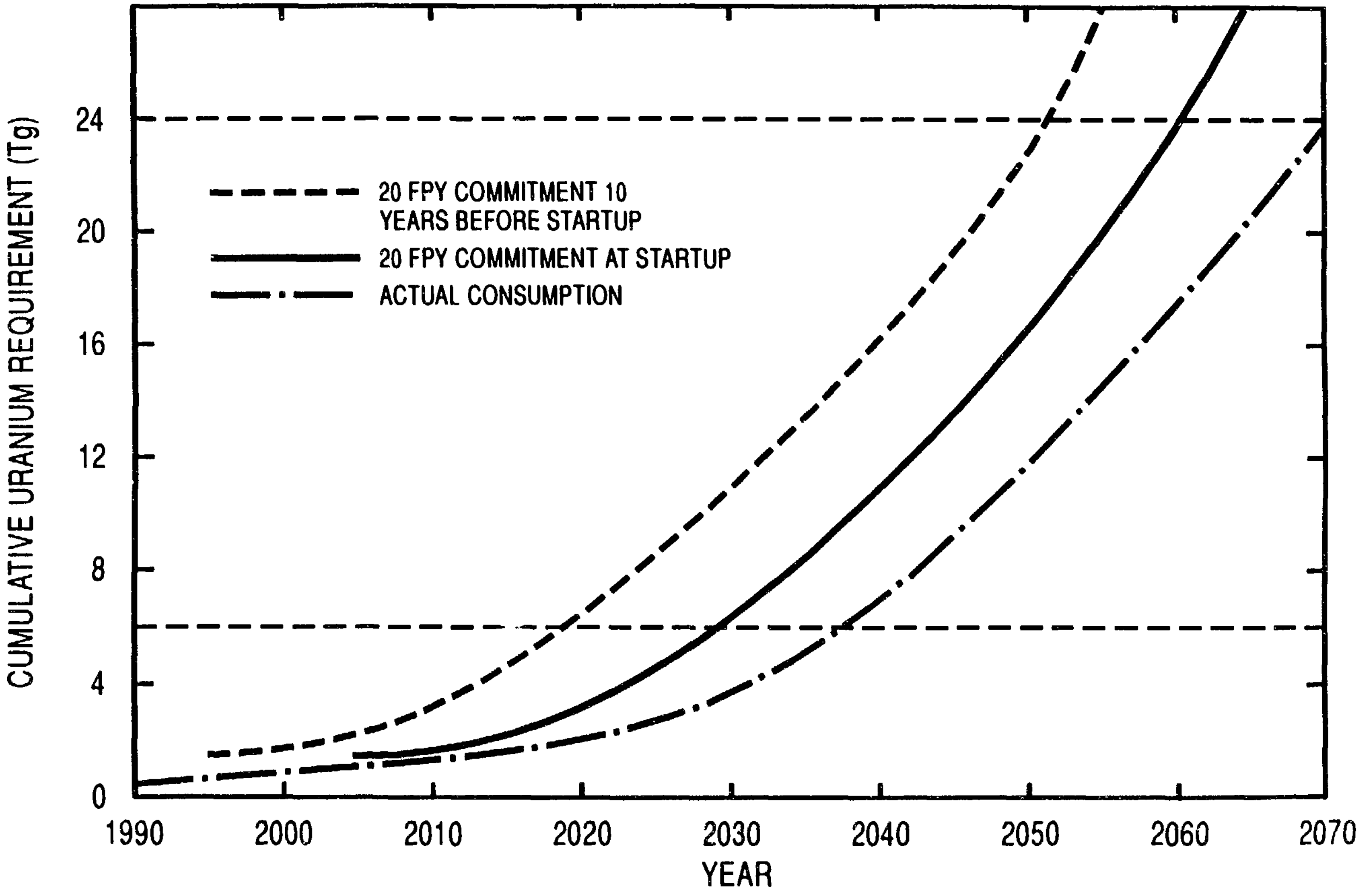

Fig. 4 Cumulative uranium requirements for the high nuclear scenario and a once through system. The lower curve is actual cumulative uranium consumption; the middle curve adds 20 full power years (FPY) of fuel forward commitment and the upper curve allows for 20 FPY commitment made 10 years before startup. The horizontal dashed lines indicate current OECD/IAWA uranium resource projections of 6 and 24 million metric tons. The former is reasonably assured resources at $130/kg whereas the latter represents speculative resources.

TABLE 1. AUTHORS' JUDGEMENT OF CONTRIBUTIONS TO INDIRECT OR EXTERNAL AND DIRECT COSTS OF NUCLEAR POWER AND THE POTENTIAL FOR IMPROVED TECHNOLOGY TO REDUCE COSTS BY VARIOUS STAGES OF THE FUEL CYCLE

	Indirect or External Costs				Direct Costs
Fuel Cycle Elements	Environmental Impacts (normal operations)	Human Health Impacts (normal operations)	Safety (accidents)	Proliferation	
Mining, Milling, and Ore Processing	xxx(+)	xxx(+)	x(+)		x(o)
Enrichment	x	x	x	xxx(-)	x(+)
Fuel Fabrication	x	x	x	xx(?)	x
Nuclear Power Plant Operation					
Burners	x	x	xxx(+)	x	xxx(+)
Breeders	x	x	xxx(+)	xxx	xxx(+)
Spent Fuel Reprocessing	xx	xx	xx	xxx(+)	xx(+)
Spent Fuel or High Level Radioactive Waste Storage/ Disposal	x(+)	x	x	x	x
Other Waste Disposal	xx(+)	x	x		x
Decommissioning and Decontamination	x	x	x		x
Transportation	x	x	xx(+)	xx(+)	x

Improved Technology
- (+) reduces impact, risk, or direct cost
- (o) neutral
- (-) increases impact, risk, or direct cost
- (?) uncertain

Fuel cycle elements should be compared down any column not across a row. Then, for each column, the fuel cycle element with the highest cost under that column is ranked to have a triple x (xxx) cost and other elements are compared on a relative basis. If a fuel cycle element has no score, it is judged to have no cost in that cost category.

TABLE 2. DIRECT COSTS FOR CURRENT GENERATION NUCLEAR PLANTS

[1990 dollars Mills/kWh(e)]

	Current U.S.[a]		Projected World Range[d] for 1995-2000
	Average[b]	Range[c]	
Capital	43	8[e] - 146	16 - 53
O & M[f]	14	7 - 37	4 - 13
Fuel[g]	8	5 - 20	4 - 16
Decommissioning[h]	0.5	0.3 - 1	
Total	65	20 - 200	25 - 75

[a] Based on internal Oak Ridge National Laboratory analysis of actual 1988 industry data for all operating nuclear power plants with capacities greater than 400 MW(e). Data were adjusted to 1990 dollars.

[b] Average defined as the sum of the total cost divided by the total energy generated.

[c] Based on actual cost range adjusted to 1990 dollars. Plants with capacity factors less than 40% removed from data set.

[d] NEA/IEA study, "Projected Costs of Generating Electricity from Power Stations for Commissioning in the Period 1995-2000," Range of national responses adjusted to 1990 dollars.

[e] Some early plants with subsidized construction cost removed from data set.

[f] Includes the cost of low level waste disposal.

[g] Includes the cost of mining and milling of uranium ore, conversion to UF_6, enrichment, fuel fabrication and high level waste disposal.

[h] Decommissioning cost range of $100 million - $300 million based on projected costs for U.S. plants.

TABLE 3. POWER GENERATION COSTS FOR ADVANCED NUCLEAR PLANTS

[1990 dollar Mills/kWh(e)][a]

Plant Units x MWe/Unit	Current[b] LWR 1 x 1144	Improved LWR 1 x 1280	Passive LWR 2 x 600	MHTGR 2 x 538 (module block)	ALMR[c] 3 x 465 (modular block)
Capital	37	27	27	32	24
O & M	10	10	11	8	8
Fuel[d]	6	6	6	9	12[e]
Decommissioning	0.5	0.5	1	1	1
Total	54 (50-110)	44 (35-57)	45 (39-67)	50 (42-75)	45 (36-72)

[a] Range shown in parentheses indicates authors' best guess adjustment for uncertainties.

[b] Current LWR based on U.S. construction and operating experience with best plants.

[c] General Electric PRISM concept.

[d] Includes cost of mining, milling, conversion, enrichment, fabrication, and disposal.

[e] *Initial actinide fuel from LWR fuel reprocessing plant at cost of $37/gram fissile Pu.*

Key Words:

Nuclear Power
Social Costs
Direct Costs
Social Acceptance
High Growth
Advanced Reactors