LETTER TO THE EDITOR

THE NEED FOR RESEARCH AND DEVELOPMENT IN FUSION: ECONOMICAL ENERGY FOR A SUSTAINABLE FUTURE WITH LOW ENVIRONMENTAL IMPACT

THE SYNOPSIS

Growth in both world population and energy use per capita will force huge increases in energy production in the early to middle part of the next century, even with maximum plausible use of renewable sources and efficiency improvements. Because of the rapidly increasing demand from the developing world and because of depleting reserves and increasing environmental constraints, energy will become considerably more expensive unless new technology can be successfully developed. Fusion, advanced fission,[a] and solar-electric plants are the only unlimited, nonfossil options for a sustainable future, and each requires increased and sustained research and development (R&D) to determine its full potential.

The long-term nature of fusion research means that the required R&D investments will not come from the private sector for several decades. Rather, fusion research is a prime example of a long-term R&D program that warrants investment at the governmental level. As in other long-term research such as cancer research, fusion is an extremely challenging scientific problem, but the payoff for humanity will be immense once fusion is realized commercially. With the judicious choice of low-activation materials, fusion plants would have significantly reduced radioactive environmental burdens, increased safety, and minimal nuclear weapon proliferation concerns compared with any type of fission reactor. Compared with solar, fusion is much more modest in land and material requirements and could supply a dominant fraction of the base-load generation requirements without the need for backup storage.

To be economical and affordable in developing countries, future fusion plants as well as advanced fission and solar-electric plants must produce electrical energy at the output bus bar at ~5¢/kW·h. Continued innovation and diversity of fusion research will be required for fusion to meet this economic goal. To support this research, we suggest that total federal energy R&D at ~1% of all U.S. energy costs, i.e., $5 billion/yr, is prudent and justified to allow pursuit of all three primary energy options for a sustainable global energy future until decisions can be made for large-scale commercialization. The international energy market in the next century, including the use of central power stations to supply electric and hydrogen powered transportation, will be a multi-ten-trillion-dollar industry. The United States can be a major global exporter of energy technology tomorrow if there is adequate R&D investment during the crucial period today.

THE NEED

Current world energy production is dominated by sources based on the burning of carbon-based fuels (oil, natural gas, and coal) with virtually no effort being made to replace them by more benign, long-term sources. This has two consequences: First, and more visible, is the rapid depletion of world resources of low-cost oil and natural gas. Even at the current rate of consumption, these resources will not last longer than ~50 to 70 yr (Ref. 1). This raises the serious ethical problem of leaving our children and grandchildren without vital raw materials. Are we morally wrong to consciously dispossess our descendants by burning these valuable resources *while other potential energy options are apparent*?

The second consequence, though less visible at present, is potentially more grave. By unrestricted burning of carbon-based fuel, we deliver more than 25 billion tons of carbon dioxide to the atmosphere annually.[2,3] Since the beginning of this century, the concentration of atmospheric carbon dioxide has increased by more than 25%. Carbon dioxide has a considerable influence on the thermal balance of the atmosphere and the earth's climate. Because of the high complexity of the atmospheric system, predictions regarding the impact of the resulting "global warming" differ by a factor of 3 or more.[3,4] However, the very uncertainty of these predictions and the justifiable fear that it will be too late once we are able to determine unambiguously that the

[a]By advanced fission, we mean new fission plant designs and fuel cycles (including waste disposal) beyond those currently in use.

trend is irreversible should admonish us to take this very seriously today.

The projection of future energy needs over many decades is inherently uncertain yet forms an important basis for judging both the magnitude and the timeliness of the development of fusion. Energy experts Holdren and Pachauri[1] lay out the implications of two contrasting visions of future energy use, from which Fig. 1 is drawn. The "business-as-usual" scenario in Fig. 1a assumes that the growth in world energy demand continues at the current growth rates and that a free-market world energy supply continues to expand the use of all current energy sources also at current growth rates. Growth in oil and gas use is assumed to slow only as ultimate-recoverable resources (several times current proven reserves) are gradually depleted. The "best-plausible-hope" scenario in Fig. 1b assumes that governments, particularly in developing countries, can manage to increase standards of living while slowing growth in both population and energy use per capita through improved energy-efficient technology. This will require the simultaneous increase in the use of renewables to the maximum plausible level and the reduction of fossil fuel burning to slow greenhouse climate impacts.

Note from Fig. 1 that by about 2030, there is a significant gap between energy supply and energy demand. This gap is similar in relative terms (~20%) *in either vision of the world's energy future* and grows rapidly thereafter. Even under the best-plausible-hope scenario, the energy supply shortfall exceeds 5 TW by about 2030, a staggering amount equivalent to 5000 power plants of 1000-MW(electric) output each! To avoid the risk of exacerbating possibly disastrous climatic changes due to the greenhouse effect, we must develop new major nonfossil sources of energy *and deploy* them to provide >10% of the energy supply within 40 yr. This is a short time given the difficulty and historical timescales of developing any new energy supply on this scale! Energy savings through increased efficiency will not solve this problem alone. Rather, concurrent replacement of the fossil fuel sources themselves is necessary.

There are the renewable energy sources including hydropower, windpower, wavepower, and biomass. However, although potentially useful for meeting local needs, they cannot likely provide more than the limit of 8 TW (i.e., 25%) of the total world energy demand of the next century.[5] Given the vast but unsatisfied energy appetite in the developing world, appeals to cut back on the use of fossil fuels in the next century will have no impact unless alternative options are readily available.

The energy gap in Fig. 1 should, therefore, be viewed as a harbinger of two possible and mutually exclusive futures: one, a multi-ten-trillion-dollar marketplace where developed, advanced energy sources provide tremendous export opportunities for industry or two, the initiation of global conflict between the energy "haves" and "have-nots" of the world. If the latter future should come to pass—and a future in which nuclear proliferants may play no small part—it will be our children and grandchildren who will be left to deal with it.

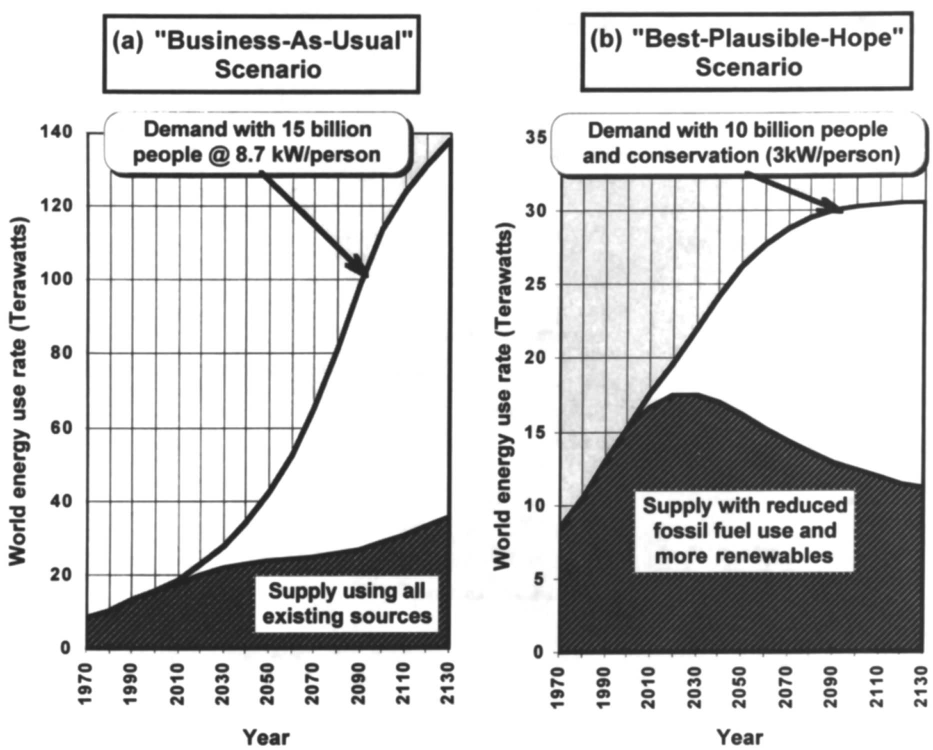

Fig. 1. New nonfossil, unlimited energy options (fusion, fission, and solar-electric) are essential for the post-2030 era, even with different assumptions about growth of future energy needs: (a) business-as-usual scenario and (b) best-plausible-hope scenario.

THE PLAN

After ~40 yr of pursuing a medium-scale fusion research program (current expenditure: approximately $350 million for the United States and approximately $650 million for the rest of the world), the fusion scientific community has achieved enormous gains in the plasma confinement figure of merit[b] and has developed a large arsenal of tools and skills. There exists a strong intellectual and technological basis for a broad attack on controlled fusion with parallel approaches to increase the likelihood that an economical fusion energy source will be found. Because energy is so important, prudence also requires parallel R&D on other inexhaustible, nonfossil energy sources as well.

Therefore, as illustrated in Fig. 2, we propose in addition to cost-effective R&D on energy conservation and efficiency, increased and sustained R&D funding of fusion *and* fission and solar-electric from small-scale research through initial commercialization. *Multiple parallel paths are essential* to ensure likelihood of success. In the case of fusion, this necessitates the continuing investigation of alternative, parallel concepts and not simply in refined engineering for any single approach. In particular, R&D should be directed to fusion concepts that promise commercial reactors with lower capital costs, lower complexity, and a lower cost development path. Fission must concern itself with acceptable methods of waste disposal, the minimization of weapons proliferation, and the development of increasingly efficient fuel utilization. Solar-electric must develop economical

[b]The fusion plasma confinement figure of merit is expressed by the product $n \times \tau \times T$, where n is the plasma density, τ is the energy confinement time, and T is the plasma temperature. Over the past three decades, the world fusion program has achieved an increase of approximately four orders of magnitude in this parameter.

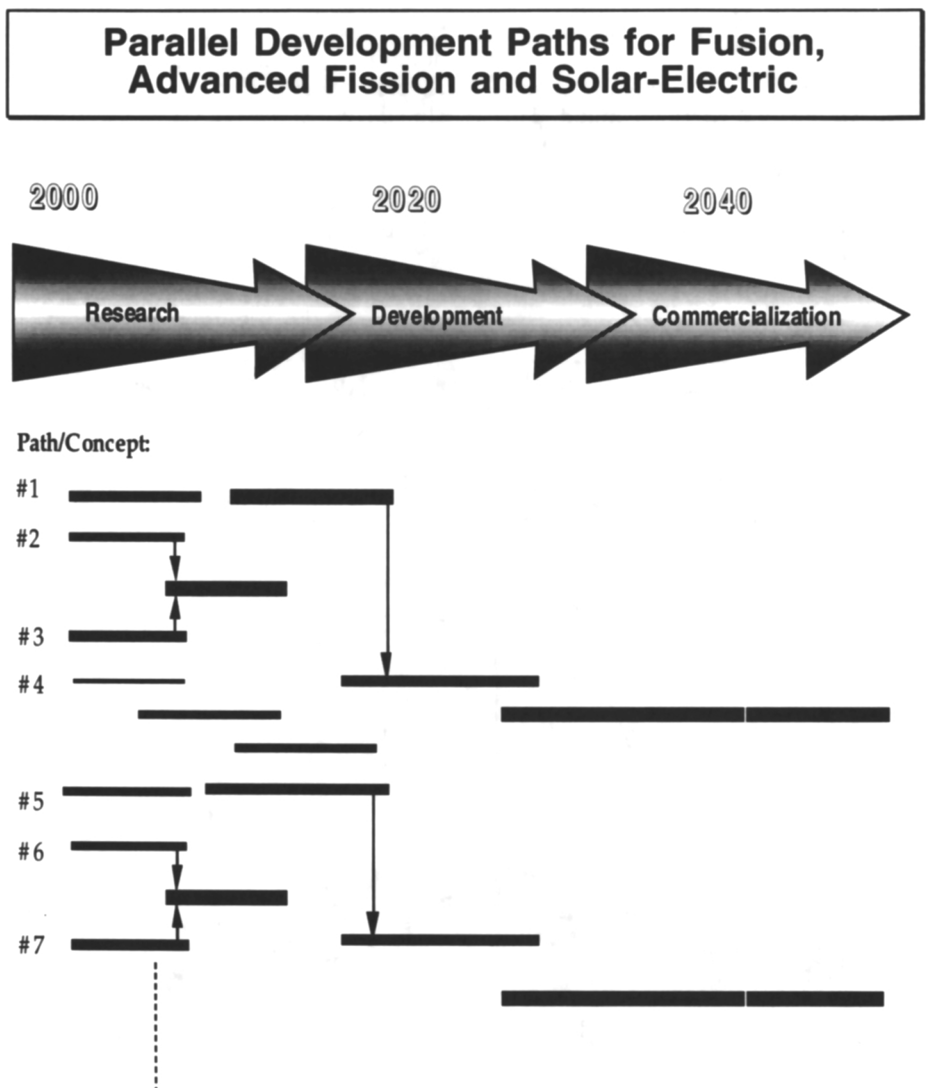

Fig. 2. The R&D paths for energy commercialization for fusion, advanced fission, and solar-electric. Federal investment at $5 billion/yr (~1% of U.S. energy costs) is prudent and justified to allow pursuit of all three primary energy options for a sustainable future. Parallel paths are essential to ensure likelihood of success.

methods of energy storage for periods of no sunshine and for reductions in the usable winter solar flux; it must also improve efficiency to minimize land use and must lower capital costs. Program development plans and options for all three energy sources will be discussed in the full paper.[6]

In 1990, the world expenditure on energy was approximately $2000 billion/yr with approximately $500 billion/yr for the United States alone.[1] This suggests that reinvestment of, for example, 20% of net profits taken as 10% of gross, i.e., reinvestment of 2% of gross, is reasonable for all private and government energy R&D, excluding reinvestment in maintaining and expanding the existing energy production infrastructure. This R&D level amounts to approximately $40 billion/yr worldwide or approximately $10 billion/yr for the United States. In view of the potential seriousness of the future energy gap, the government share should be ~50% of the energy R&D total, i.e., approximately $5 billion/yr, and should primarily emphasize the long-term research needs, especially that of fusion. Government support is essential in the early research phases "R," with more industry support in the later development stages "D." As an additional rationale, $5 billion/yr was the federal level in 1980, which fell to approximately $2.5 billion in 1990, and is now under $2 billion in 1995. Even this level is now threatened with further major reductions in the U.S. Congress.

THE CONCLUSION

Fusion, advanced fission, and solar-electric plants are the only unlimited nonfossil options for a sustainable energy future for the world. Fusion poses the only indigenous fuel reserve that will last as long as the earth itself lasts. However, continued innovation and diversity in fusion R&D will be required to meet its economic goal. The long-term nature of fusion research means that the required R&D investment will not come from the private sector. However, once fusion is realized commercially, the dividend for humanity will be profound in terms of the welfare of the global community. We should also not underestimate the huge potential export opportunities that would then open up for industry. Federal energy R&D at ~1% of U.S. energy costs is prudent and justified to allow pursuit of all three primary energy options for a sustainable energy future. Multiple parallel paths are essential to ensure success. The projected timescale for significant shortfalls in world energy supply to become apparent is ~30 to 40 yr depending on assumptions. The time to develop fusion from near-term R&D through significant commercial market penetration is *at least* of the same order, so its development must not be delayed. As evidenced by the Apollo Program and the eradication of smallpox, we are capable of supreme achievements. However, these were only realized through immense dedication, significant initial parallel approaches, and the commitment of sufficient R&D resources. Could energy self-sufficiency for humanity be the next grand challenge and supreme achievement?

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