UCRL-JC-131306
PREPRINT

Global Warming and Nuclear Power

Lowell Wood
Muriel Ishikawa
Roderick Hyde

This paper was prepared for submittal to the
9th Summer Workshop
Innovative Energy Systems and CO_2 Stabilization
Aspen Global Change Institute
Aspen, CO
July 14-24, 1998

July 10, 1998

Lawrence
Livermore
National
Laboratory

DISCLAIMER

GLOBAL WARMING AND NUCLEAR POWER[*]

Lowell Wood[#]
Hoover Institution, Stanford University, Stanford, CA 94305-6010
and
Muriel Ishikawa and **Roderick Hyde**
University of California Lawrence Livermore National Laboratory, Livermore CA 94550

ABSTRACT

Nuclear fission power reactors represent a potential solution to many aspects of global change possibly induced by inputting of either particulate or carbon or sulfur oxides into the Earth's atmosphere. Of proven technological feasibility, they presently produce high-grade heat for large-scale electricity generation, space heating and industrial process-energizing around the world, without emitting greenhouse gases or atmospheric particulates; importantly, electricity production costs from the best nuclear plants presently are closely comparable with those of the best fossil-fired plants.

However, a substantial number of issues currently stand between nuclear power and widespread substitution for large stationary fossil fuel-fired systems. These include perceptual ones regarding both long-term and acute operational safety, plant decommissioning, fuel reprocessing, radwaste disposal, fissile materials diversion to military purposes and – perhaps most seriously – readily quantifiable concerns regarding long-term fuel supply and total unit electrical energy cost. We sketch a road-map for proceeding from the present situation toward a nuclear power-intensive world, addressing along the way each of the concerns which presently impede widespread nuclear substitution for fossil fuels, particularly for coal in the most populous and rapidly developing portions of the world, e.g., China and India.

This ‘‘design to societal specifications’’ approach to large-scale nuclear fission power systems may lead to energy sources meeting essentially all stationary demands for high-temperature heat. Such advanced options offer a human population of ten billion the electricity supply levels currently enjoyed by Americans for 10,000 years.

Nuclear power systems tailored to local needs-and-interests and having a common advanced technology base could reduce present-day world-wide CO_2 emissions by two-fold, if universally employed. By application to small mobile demands, a second two-fold reduction might be attained. Even the first such halving of carbon intensivity of stationary-source energy production world-wide might permit continued slow power-demand growth in the highly developed countries and rapid development of the other 80% of the world, both without active governmental suppression of fossil fuel usage – while also stabilizing carbon input-rates into the Earth’s atmosphere. The second two-fold reduction might obviate most global warming concerns.

---

[*] Prepared for presentation at the 9th Summer Workshop ‘‘Innovative Energy Systems and CO_2 Stabilization’’, Aspen Global Change Institute, Aspen, CO, 14-24 July 1998. Aspects of this work were performed under the auspices of the U.S. Department of Energy, in the course of Contract W-7405-eng-48 with the University of California. Opinions expressed herein are those of the authors only. None of the authors have any past, present or anticipated future affiliations of any kind with any part of the energy or electric utility commercial sectors.

[#] Visiting Fellow. Permanent address: UCLLNL, Livermore CA 94550.

Global Warming. The prospect of raising the temperature of the terrestrial biosphere by ~1% during the 21st century by the combined direct and indirect effects of anthropogenic injection of "greenhouse gases"[1] has given rise to proposed remedial actions directed primarily to reduction of carbon dioxide injection into the Earth's atmosphere. We note that, while the scientific evaluation of this prospect is still in an early phase,[2] policy deliberations based on its assumed soundness are already well-advanced; thus, it is justifiable to consider cost-efficient technological remediation.

Arguable estimates suggest that increasing the current U.S. wholesale prices of carbon-based fuels by ~40% will suffice to suppress fossil fuel use to levels such that CO_2 injection-rates by Americans will be reduced to 1990 levels.[3] (These 1990 injection-rates are believed in some political quarters to be sufficient to adequately attenuate anticipated global warming, at least for the time being. On the contrary, authoritative scientific studies suggest that perhaps a 6-fold reduction relative to 1990 carbon injection-rates may be required to stabilize eventually the atmospheric CO_2 concentration at its 1990 level.[4])

The economic implications of price-based suppression of fossil fuel use are of very large-scale. For example, a seasonal average of approximately 75 million barrels of oils are presently used per day. The recent 12 month-averaged cost of a barrel of oil is ~$16, so that the world's crude oil bill currently is ~$440 B/year. A 40% increment in this cost would amount to $180 B/year. When other fossil fuels – principally coal and natural gas – are also considered, the total proposed price-burden in order to suppress CO_2 atmospheric injection amounts to ~$320 B/year, at current costs and consumption levels. (Approximately 25% of this fossil fuel price-burden would be borne by fossil fuel users in the United States, at an annual cost of ~$80 B. This amounts to ~1.1% of current U.S. GDP. At the current amortization rate for long-term, low-risk investments, it is equivalent to a one-time expenditure of ~$1.0 T.)

In the spirit of the salient Article of the U.N. Framework Convention on Climate

Change,[5] we inquire in the following for significantly less expensive means of greatly reducing the CO_2 input rate into the atmosphere during the 21st century.

---

[1] Intergovernmental Panel on Climate Change, Climate Change 1995: The Science of Climate Change, JT Houghton, et al, eds. (Cambridge Univ. Press, Cambridge, 1996).

[2] Hasselmann K, ''Are We Seeing Greenhouse Warming?'' *Science* **276**, 914 (1997).

[3] See, e.g., testimony by Janet Yellen (Chair, Council of Economic Advisers to the President of the U.S.) before the House Commerce Subcommittee on Energy and Power, July 15, 1997, and press reports thereof (e.g., Fialka JJ, "Effort to Curb Global Warming Is Tied To Higher Energy Prices in Two Studies," *Wall Street Journal*, 16 July 1997, p. A2), in which estimates of ~40% increases in bulk fossil-energy prices in order to attain price-rationing of fossil fuel-derived energy sufficient to suppress greenhouse emissions below "dangerous levels" were characterized as "mid-level ones." These fractional price increases translate to ~$\$3.2 \times 10^{11}$/year world-wide, or ~$\$0.8 \times 10^{11}$/year in the U.S.

[4] See, e.g., Wigley TML, Richels R and Edmonds J, ''Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations,'' *Nature* **379**, 240-3 (1996), commenting on some salient implications of the IPCC 1995 Report, op.cit.

[5] Article 3 of the Convention states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."

<u>What Is To Be Done?</u> Renewable energy resources – possibly the first option-set to come to mind – are distributed in quantitatively inadequate and geographically quite uneven manners. Such energy sources – not including hydroelectric generation, whose expandability in most locales is highly doubtful – currently comprise less than 3% of total U.S. generation capacity, after a quarter-century of reasonably intensive government subsidies.[6] Even considering the multi-decadal time-scales upon which large-scale energy systems typically evolve, recent history makes it quite clear that these alternate energy technologies ‘‘aren’t ready yet for prime time’’ with respect to bulk electrical energy supply. Indeed, if <u>any</u> of them were, it manifestly would have enjoyed the exceedingly swift market-penetration which has been <u>demonstrated</u> over the past half-dozen years by combined-cycle gas-fired generation of electricity, a reasonably novel technology of revolutionary impact in the staid electric utility industry.[7]

In marked contrast to ‘’always nearly here’’ renewables, nuclear fission-energized generation is the only large-scale, generally-available source of electricity which doesn't involve the release of large specific quantities of CO_2 (i.e., of the order of 1 kg/kWe-hr, when coal is burnt) into the Earth's atmosphere. If growth in electrical demand over the Earth as a whole is to continue, i.e., if the Third World is ever to attain First World standards of per-capita energy availability, and if at the same time CO_2 emissions into the Earth's atmosphere are to remain relatively low, <u>only</u> nuclear sources of electricity appear to be *actually* available to fill the <u>annual energy gap</u> of *tens of thousands of terawatt-hours* which will be engendered as soon as two decades hence.

We expect that some of the renewables[8] will eventually develop substantial niches in the global energy marketplace, ones of as much as ~10% relative scale, but none of them – or even all of them aggregated – presently appear capable of substituting for fossil fuels on single-century time-scales. We therefore look most seriously at nuclear fission for near-term substitutability for fossil fuel energy sources.

<u>Large-Scale Nuclear Power Supply.</u> Over the past four decades, nuclear fission power reactors have come into widespread usage throughout the world, particularly in the developed countries. Currently, France derives over 70% of its electricity from nuclear reactors, while Japan realizes more than 40% and the U.S. gains 20%. Nuclear-generated electricity in the U.S. presently has a *production* cost which very closely rivals that of the lowest-cost source, coal-fired plants, both of which *produce* electricity for ~$10/MW-hr, or 1 cent/kW-hr, when the best nuclear plants are compared to the best coal-fired ones.[9]

---

[6] For example, wind power, perhaps the most market-ready of the more modern renewables, is critically site-dependent for its economic viability, with relatively very few geographical locations meeting all criteria for wind generation. Its intrinsically variable diurnal and seasonable availability make it innately unsuitable for reliable bulk electric power supply, a basic characteristic it shares with most other (short time-constant) forms of solar-derived energy.

[7] ‘‘Market failure’’ is *prima facie* implausible in this respect, especially in a country such as the U.S., in which ongoing liberalization and deregulation of the market for electric power supply has <u>already</u> ‘‘stranded’’ obsolescent generation technologies having a ‘‘book value’’ of $120 B, *just within the past several years*.

[8] The renewables all represent stellar energy stored for comparatively very short time-intervals – minutes to months, or femto- to nano-Aeons – whereas fossil fuels represent solar energy stored for logarithmically intermediate intervals – centi- to deci-Aeons – and nuclear fusion and fission sources represent stellar energy stored for rather long times – ~5 Aeons.

Nuclear power reactors are almost exclusively of the light water-cooled (LWR) type originally developed in the U.S. for plutonium production during World War II and adapted (e.g., via substitution of water for graphite as moderator) in the subsequent dozen years for raising steam of thermodynamic quality useful for Rankine cycle-based, turboalternator-implemented electricity generation. Other major adaptive steps taken included the use of isotopically-enriched uranium fuel (enriched in the U^{235} isotope from the naturally occurring level of 0.7% to 2.5-4% for greater specific energy production by a given fuel assembly and thus longer intervals between required refuelings) and the elimination of safety deficiencies intrinsic to some early designs.

Nuclear power reactors enjoyed widespread penetration of the electricity-producing marketplace during the first two decades after the advent of the first commercial nuclear plants, over the interval ~1957-77. At the time of the Three Mile Island accident in the U.S., official U.S. government projections were for exponentially advancing use of nuclear power through the year 2000, with ~500 GWe of installed capacity in the U.S. alone being a mid-range estimate for the end of the century.[10] Such high electrical production levels in turn required more *fissile* fuel – e.g.,, the naturally-occurring *fissile* isotope of uranium, U^{235} – for burning in LWRs than could be realized via isotopic extraction from existing reserves of uranium ore. This motivated the development of a breeder-type power reactor, one which could convert *fissionable* fuel (such as the 140-fold more abundant *fissionable* isotope, U^{238}) into *fissile* fuel (Pu^{239}, in the case of converting U^{238}) at a rate at least as great as it consumed fissile fuel.

For a plethora of reasons, major breeder reactor development programs in the U.S., France and Japan have not met with outstanding technical or programmatic success. Furthermore, over the same interval (~1972-85), electrical power demand in the developed countries, which had been increasing rapidly for several decades (e.g., in the U.S. at a ~7% annual rate over 1947-72) dropped quite rapidly (e.g., to a recent ~1.5-2% annual rate in the U.S.), a demand growth curtailment associated with stiffly increased cost of the dominant fuel, oil, over most of the ‘72-’85 interval.

This effect was particularly marked for American nuclear plant vendors, who were also burdened during this interval with a stream of demands issued by U.S. regulators for qualitatively and quantitatively enhanced safety features, demands originated in many minor accidents-and-incidents but strongly focused vis-a-vis public perceptions by the Three Mile Island accident in 1979. These rapidly-escalating economic burdens, accentuated by a peaking in the cost-of-capital in the '75-'85 interval and punctuated by the psychological impact of the major nuclear power reactor accident at Chernobyl in 1986, sharply attenuated the demand for new nuclear power plants – with the notable exceptions of France, Belgium and Japan, which place high valuations on the energy supply-security implicit in nuclear-generated electricity. Taiwan and South Korea are notable examples of rapidly industrializing economies which have also chosen to become nuclear energy-intensive. France, in particular, asserts that economies-of-scale in creation of now-standardized nuclear power plants have rendered these *total* unit energy cost-competitive with the most modern fossil-fueled ones in French circumstances, and seemingly demonstrates this by selling a substantial fraction of all of its nuclear electricity to Western European neighbor-nations at market rates.

---

[9] These results are documented monthly by utility groups and are quite authoritative. Obviously, comparisons of best examples are most relevant.

[10] "A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future, 1976," Vol. 1: "The Plan", U.S. Energy Research and Development Administration report ERDA-76-1, U.S. Government Printing Office (April 1976).

Throughout this same interval, the stiff economic incentives posed to electrical power plant suppliers selling fossil fuel-fired combustion units by sharply-increased crude oil prices were spurring improvements in the thermodynamic efficiency with which such fuel may be converted into electricity. Stalled for a half-century at 30-35% efficiency in converting thermal energy into electricity, Rankine cycle-based electrical systems slowly crept toward 40% efficiency in this era. However, the introduction of *combined* (Brayton and Rankine) *cycle* combustion heat-to-electricity conversion systems during the last decade has seen conversion efficiencies climb swiftly toward 60%. This is a stunning advance, the more so as it occurred so rapidly relative to the long history of electricity power systems. These *efficiency record-setting* combined-cycle systems also have recently set the *economic pace* in electricity production: they offer a *total unit energy cost* of ~\$0.04/kWe-hr, compared to ~\$0.08/kWe-hr for the current average of U.S. nuclear-generated electricity. (*Total unit energy cost* differs notably from *production cost* by properly including all economic charges involved in the generation of electricity, including amortization of the all of the capital used to create the generation facilities; *production costs* include all regularly-recurring, day-to-day charges, such as those due to personnel, fuel-purchase, materials and maintenance.) As might be expected, essentially all new electric generation being created in the U.S. today is gas-fired, and much of it is combined-cycle technology. Official estimates are that the current annual consumption of 22 T cubic feet of natural gas by the U.S. will increase to 30 T cubic feet by 2010.[11]

These considerations have resulted in the practical cessation of nuclear power plant sales in most developed countries. World-wide, there were 437 nuclear power plants in operation at mid-year 1996, and 39 under construction. Since power-plant lifetimes are ~30 years and construction times are ~5 years, it appears that the Earth's "population" of nuclear power plants will decline to less than half of its current level, if present trends persist. The difference, of course, will be made up by fossil-fired generation. Much of this will be coal-fired, the most carbon-intensive – and generally, the least costly[12] – mode of winning electricity, world-wide.

Therefore, even in the (hypothetical) absence of growing electricity demand, there is a fundamental issue posed by the ongoing nuclear power phase-out, if one assumes that greenhouse gases constitute a major source of global warming and if one rules out *a priori* the technical possibility of offsetting their warming effects by anthropogenic means.[13]

---

[11] American Gas Association estimates, as quoted in the Wall Street Journal, May 15, 1998.

[12] Only in countries which enjoy large natural gas reserves within pipeline transmission range is gas-fired generation the least expensive in total unit energy cost terms. In most of the populous, rapidly developing countries, e.g., India and China, natural gas is not abundant on national energy utilization scales.

[13] We have observed previously that ‘geoengineering’ of the Earth’s atmosphere – increasing by ~1% the incoming sunlight which is scattered back into the space by the atmosphere – offers no-regrets obviation of all possible levels of global warming, for a total annual cost of at most \$1 billion, and possibly as little as \$0.1 billion. See., e.g., Teller E, Wood L and Hyde R, ‘‘Global Warming and Ice Ages I: Prospects for Physics-Based Modulation of Global Change’’, Proceedings of the 22nd International Seminar on Planetary Emergencies, Erice (Sicily), Italy, 20-23 August 1997, and UCRL -JC-128716 (Univ. Calif. Lawrence Livermore Nat'l. Lab., 1997). We again recall that efforts directed to cost minimization of mitigation technologies is specifically supportive of the UN Framework Convention on Climate Change, whose Article 3 states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."

A Societal Requirements-Driven Approach To 21st Century Nuclear Power. In this paper, we inquire as to whether and how nuclear fission-based energy generation can actually contribute to maintenance of a rapidly advancing standard-of-living for people everywhere, in a manner consistent with asymptotic concentrations of CO_2 in the atmosphere not greatly in excess of current ones.

In a fundamental departure from typical practice in the design of nuclear power systems, we look at the complete set of societal requirements on large-scale energy systems – specifically, on ones based on nuclear fission – and only then do we search for technical approaches which may fully satisfy all of these requirements simultaneously in an economically competitive system design.

We emphasize the economic competitiveness of advanced nuclear systems – specifically, the reduction of total unit energy costs of nuclear electricity by at least two-fold, relative to classic LWR values. Similarly, we look only at possible nuclear solutions which aren't at all fuel supply-constrained, for otherwise-"perfect" nuclear solutions which cannot be fueled for intensive, world-wide use for at least a century seem somewhat quixotic.

Our approach involves a "separation of variables" along technological lines. We propose a general developmental track toward large-scale nuclear power supply which can be walked in accordance with local preferences and circumstances, with some features of the approach adopted in some national circumstances and others in other, quite different circumstances. Perhaps a given nation will adopt some minimal set of features early, and add others subsequently. We expect that, ultimately, all large-scale nuclear power systems may share a common, "consensus" set of features which will include (nearly) all of those which we propose.

Features And Their Motivations. We consider each of the following features to be clearly desirable ones for 21st century nuclear power plants:

- **Fuel Supply And Preparation.** Nuclear power reactors which may be fueled with inexpensive, widely-available fuel are the only ones which are likely to be of *general, long-term* interest. We assume for present purposes that any nuclear fuel chosen must be reliably available in sufficient quantity at reasonable extraction costs to give 10 billion people a First World energy standard-of-living for at least 1 century: 10 billion kW-centuries of electrical energy, or ~3×10^{29} ergs.[14]

  Furthermore, we expect that preparation of the fuel for reactor use must involve sufficiently simple operations as to form the basis of a genuinely world-wide free market for fueling services, one inherently resistant to cartel-formation and political restraints-of-trade, in order to preclude either localized coercion or large-scale conflicts over access to energy resources.

- **Economics.** As already noted, both the total unit energy cost and the energy production cost of nuclear electricity sources of present interest should not be significantly in excess of those

---

[14] 1 kW is 10^{10} ergs/sec, and a century is ~$3\text{x}10^9$ seconds, so that $3\text{x}10^{19}$ ergs (about 3/4 kiloton) is a kW-century. Ten billion units of such power-time product then amount to $3\text{x}10^{29}$ ergs, which is the energy-equivalent of $3\text{x}10^8$ grams – 300 tonnes – of mass. Actinide fission converts nearly 0.1% – 1 MeV per nucleon – of mass into energy, so that 300,000 tons of actinides must be fissioned and the resulting energy entirely converted into electricity to satisfy the referenced energy demand. If converted with 60% efficiency, 500 kilotons of actinide fission must ensue, and this mass of fission products – 0.5 million tonnes – will result. This is approximately the same mass as that of isotopically depleted uranium presently stored in the "backyards" of U.S. isotopic enrichment plants.

attainable from the best alternative fossil fuel-fired options, for even a 10% additional cost would impose a present-day annual economic penalty of several tens of billions of dollars, world-wide.

- **Fueling Operations.** Power reactors of the 21st century shouldn't require re-fueling, once they have commenced operation – for reasons of economics, safety and of suppression of materials diversion. <u>Modern naval nuclear power reactors perform without refueling for the 3-decade operational life of a submarine. There's no basic reason why civilian power reactors can't have this feature also.</u> All the fuel which a power reactor needs during its entire operational life should be built into it, *as it's manufactured*. Reactor design and construction are thereby greatly simplified, due to elimination of the necessity to provide for opening, re-sealing and removing and installing fuel assemblies in an in-service reactor's core. Thus, expensive and hazard-prone periodic (every 1-2 years) refueling is obviated, and costly, risk-prone complications such as spent fuel handling, storage and transport to reprocessing sites are eliminated; the necessity for redundant generation capacity to support refueling outages in a regional power system is obviated, with significant cost savings. Reactor designs involving a minimum of moving parts may be less prone to accidents. Therefore, we have emphasized fuel-breeding reactors in our studies.

  If such fuel-breeding reactors are employed, reprocessing of spent reactor fuel is unnecessary-in-principle. For a nuclear energy economy, reprocessing provides a point at which fissile materials are divertible to military uses. Also, reprocessing burdens nuclear power generation with non-negligible costs, both objective economic and public-perceptual ones. Reprocessing of any type therefore should be avoided to the greatest extent possible. Eliminating refueling during a plant's entire operational life is a major step toward this goal, but it may also be well to avoid end-of-operational life reprocessing of a plant's spent fuel as the plant is decommissioned (even though substantial quantities of fissile fuel having non-negligible economic value may thereby be abandoned).

- **Radwaste Disposal.** Disposal of long-lived radioactivity generated in the course of operation of power reactors of present interest should be performed in a <u>*manifestly*</u> safe manner, so that the <u>exceedingly</u> low likelihood of entry of non-negligible amounts of reactor-generated radioactivity into the biosphere at <u>any</u> future time can be made reasonably clear to the lay public.

- **Materials Diversion.** Fuel for power reactors of present interest during all times in its existence, from manufacture through final-and-irreversible disposal, should be of a nature as to have no immediate utility, regardless of quantity, for any military purposes. That is, it should be essentially as useless in terms of fabrication of nuclear explosives as are uranium or thorium concentrates outputted from classical mining-and-beneficiation processes.

- **Operational Safety.** Power reactors of present interest should be inherently incapable of suffering damage, no matter how seriously their controls might be mishandled by their operators. They should also be incapable of damage due to loss-of-coolant accidents. In addition, they should be highly immune to human misbehavior, ranging from insider sabotage through terrorist attacks to major military actions.

- **End-Of-Operational Life And Plant Decommissioning.** Power reactors of present interest should be capable of inexpensive, low-risk decommissioning at end-of-operational-life, which may be required following three decades of full-power-equivalent operation. Public safety (perceived and actual) and resistance to materials diversion during all phases of decommissioning seem essential in the present context.

- **Public Perceptions.** The *perceptions* of the public regarding the suitability and desirability of nuclear power supply should be respected. In particular, the safety of all aspects of nuclear power generation should be made <u>*obvious*</u> to the general public.

<u>Resulting Basic Design Considerations.</u> We note that these features aren't independent ones, in that more than one may be simultaneously attained by a single design choice and that some particular ways of attaining one may conflict significantly with attaining another. The two large-scale objective issues appear to be the economic and fuel-supply ones, and thus we address them first.

Life-Cycle-Oriented Design. In order to be maximally economical, power reactors of present interest should be designed in a life-cycle-oriented manner, with as much attention given to circumstances at and beyond end-of-operational-life and to initial construction as to the interval of power-producing operation and maintenance. In particular, we believe that ideal power reactors should be viewed as essentially entirely self-regulating; perhaps they should even be regarded as constant-temperature nuclear fission-powered heat sources which, once ignited, operate under fully-automatic, highly-redundant control until either fuel exhaustion or operator-commanded shutdown occurs. We thus suggest that a power reactor should be regarded – and designed – as a pressure vessel-jacketed cladded-fuel assembly with embedded power-regulating features and heat-removal features, supplemented by means for highly-redundant, entirely automatic heat rejection into a "can't fail" heat-sink.

Furthermore, we suggest that an ideal reactor should also be regarded as – and designed to be – the long-term-stable burial cask of all of the radwaste products which it generates throughout its entire operational life, so that once it is emplaced and its fuel charge ignited, *it is not significantly disturbed or removed thereafter* – for tens of millennia. Our design and analyses lead us to believe that this should be possible without large cost increments; indeed, we believe substantial life-cycle *savings* might be realized, relative to the present-day LWR-type nuclear fuel cycle.

Inexpensive, Standardized Construction. Mass production-oriented manufacture and emplacement/construction of standardized, extensively-evaluated nuclear power-plant designs comprise an essential feature of both economic and safe nuclear power systems, in our considered view. Mass production of relatively large-scale, standardized systems appears eminently rational in a world in which about <u>1 GW</u> of electrical generating capacity must be added <u>each week</u> into the foreseeable future.

Minimum-Essential Operator Controls. All of the handful of great accidents in nuclear power plants, without exception, have arisen from maladroit control of the reactor by its human operators; operator errors also may constitute the primary factor in the larger number of much less serious accidents and incidents which have eroded public confidence. This may be intrinsic to prevailing power reactor design and construction practices, for reactor emergencies tend to rise on time-scales of tens to hundreds of seconds, within which small intervals humans do not react aptly to complex, rapidly varying circumstances, particularly if these have not been experienced previously. Therefore, we believe that it is quite desirable that operator controls of power reactors be reduced to the simple and the few, to "minimum essential" ones, and that all possible uses of these should be incapable of inducing catastrophic reactor malfunction. Such a draconian step might be taken more easily if power reactors are designed and constructed with a minimal number of moving parts, and with highly redundant, fully automatic means of controlling power generation by the reactor’s core.

Obviously, the resulting reduction in the usually large staff-complement associated with the nuclear portions of a central generating station will contribute to overall economies.

Underground Siting. The public is rationally concerned about large, abrupt releases of radioactivity into the biosphere by nuclear power systems – and also is somewhat less reasonably worried about very small releases in quasi-steady state. Precluding both of these – but particularly the former – is of great importance and moreover should be accomplished in an obvious fashion. We therefore consider siting of reactors deep underground to be desirable; there should be only "long and slender," automatically-closed passages to the surface – and to the biosphere.[15] That large amounts of radioactivity cannot escape to the biosphere in the course of serious accidents from such locations may be made quite obvious. The underground sites should also be made to be supportive of long-term "housing" of the reactor, after its operational life, in order to facilitate decommissioning and long-term storage of reactor waste.

Other significant benefits accrue from installing the reactor in a deep underground site, such as a high degree of immunity from natural and man-made disasters on the surface and the availability of gravity to operate innate reactor core-cooling mechanisms, in the event of total power loss.

Salient Features Of An Ideal Point-Design. We have previously tabled a conceptual-level point-design of an ideal nuclear power reactor which we believe satisfies all of the constraints stated above.[16] We recapitulate some of its salient features.

Use of a hard (or fast) neutron spectrum within the reactor's core is essential to simultaneous attainment of the goals of no fuel reprocessing, no reactor re-fueling and use only of abundant fuels; otherwise, strong absorption of slow neutrons by accumulating fission products would pose many difficulties. Also, this fast neutron-spectrum design-choice facilitates the extensive use of high-Z, highly refractory materials in the baseline reactor core design. Such materials have unacceptably large impacts on the neutron economy of any thermal-spectrum reactor, but are eminently affordable in neutronic terms when using a fission-spectrum. Use of such materials permit very high-temperature reactor operation, e.g., coolant exhaust temperatures of $\leq 1200^{o}$ K, which in turn admits the possibility of high-efficiency (~60%), combined-cycle thermal-to-electric conversion of the heat outputted by the reactor. It is also useful for storage of spent fuel at elevated temperatures in high-integrity containers for multi-millennial intervals.

While the reactor's core temperature is high, it must be limited. We therefore designed the reactor core with a high-temperature limit, using a set of liquid-lithium-based thermostats to control the local material temperature via negative feedback on the "local reactivity" which are implemented with liquid Li^6 (a strong neutron absorber). Local fuel temperature rising above the design-point causes the local introduction of additional Li^6 from a neutron-poor region outside the reactor core, thereby reducing the local neutronic reactivity, the local power production – and the local fuel temperature. This is a

---

[15] We note that Andrei Sakharov independently reached this same basic conclusion in the aftermath of the Chernobyl accident, and strongly advocated underground siting of power reactors in his memoirs.

[16] See, e.g., see http://www-phys.llnl.gov/adv_energy_src/ICENES96.html, and Teller E, Ishikawa M, Wood L, Hyde R and Nuckolls J, ''Completely Automated Nuclear Reactors For Long-Term Operation II: Toward A Concept-Level Point-Design Of A High-Temperature, Gas-Cooled Central Power Station System'' Proceedings of the 8th International Conference on Emerging Nuclear Energy Systems (ICENES'96), Obninsk, Russia, 24-28 June 1996, and also UCRL-JC-12708 Pt. 2 (Univ. Calif. Lawrence Livermore Nat'l. Lab., 1996).

‘standard’ negative-feedback effect, although it hasn't been applied previously to nuclear power generation.

This type of nuclear power reactor thus acts as a source of heat at a specified high temperature at any heat-extraction rate, from zero up to its full-power rating, over any time-interval until its initial fuel-charge is exhausted or it is operator-commanded to shut down.

The ability to independently control local reactivity at all points throughout the core on the basis of local material temperature permits use of a (propagating-and-breeding) mode of nuclear fuel burn which is exceptionally efficient in its fuel utilization – and one which functions properly without operator-centered controls. Essentially, a small portion of the reactor’s full-operational-lifetime fuel-charge is initially ‘‘ignited’’ in a nuclear sense, and the fuel thereafter ‘‘burns’’ just exactly as rapidly as heat is extracted from the reactor for electricity generation.

The ignitor produces excess neutrons (relative to those necessary to just sustain the basic chain reaction) which act to convert *fissionable material* – natural Th^{232} or natural U^{238} – into *fissile fuel* in the region adjacent to the initially fissioning fuel. This newly created fissile fuel then fissions in turn, causing the nuclear reaction to very slowly propagate down the axis of the core fuel charge. This "propagating breeding" fuel-burning mode enables very high (>50%) burn-ups of either natural (or isotopically-depleted) uranium or thorium to be attained, thereby guaranteeing nearly as great nuclear fuel utilization efficiency as one may desire – without any reprocessing or other fuel manipulation. One may use a comparatively small "nuclear ignitor" region of moderate (sub-weapons-grade) isotopic enrichment in the center or at one end of the core's fuel-charge. Indeed, the distribution of the Li^6 thermostats throughout the reactor's core ensures that the total thermal power production in the reactor's various portions will be automatically allocated in a proper manner.

Crucially, no weapons-grade materials are used in making the fuel-charge during reactor manufacture. Nonetheless, the entire lithospheric inventory of actinides – all of the uranium and the five-fold larger amount of thorium in the Earth’s crust – can be used highly efficiently, in acute contrast to the ~0.1% of the total crustal actinide inventory which can be utilized by LWRs (as they are presently designed and operated, within the present nuclear fuel cycle). *An actinide fuel supply for the entire human race sufficient for a single decade with LWR usage thus expands into one sufficient for ten millennia with advanced nuclear options of this type.*

We have designed a highly redundant and fully automatic heat transfer system, including cooling by inert helium gas, to prevent all types of anomalous, over-temperature conditions of the reactor core. This system functions properly even when the power system’s above-ground components may be entirely and catastrophically obliterated, e.g., due to natural disaster or military action. Indeed, destruction of the coolant pumps would simply cause the reactor's core to heat up, and thus cause the reactor to shut down, due to thermostat action.

We suggest the use of essentially unenriched, as-mined actinide fuel, operated to high fuel burn-up without refueling or reprocessing. This accesses a huge, near-zero-cost fuel stockpile, one widely distributed geographically and, as noted above, of magnitude sufficient to supply the entire human race at current U.S. levels of energy consumption for ten thousand years. Its highly monolithic, readily-manufactured character and its decommissioning-in-place combine with its high thermodynamic efficiency to yield a potentially quite low-cost nuclear electricity technology.

Moreover, the depleted uranium *already* accumulated in the storage-yards of uranium isotopic enrichment plants world-wide would suffice for more than two centuries of energy production for the entire human race at current American per-capita levels with this novel power reactor technology, and the total fissile material *already* excess to military needs of the two nuclear superpowers would suffice for the ignitors of the corresponding 10,000 power plants, each of 1 GWe capacity.

Mostly as ‘‘Cold War-surplus,’’ ***the human race <u>already has-in-hand all the nuclear fuel</u> needed for more than two centuries’ operation of these advanced power reactors at levels sufficient to give an American standard of per-capita electricity supply to a planetary population of 10 billion!*** (It is widely believed that the depleted uranium would be made available essentially at zero cost to any responsible offer to dispose of it gracefully. In the U.S., the government has sponsored studies of how to employ it industrially in quantity. These inventory-reduction efforts have enjoyed indifferent success through the present time.)

The total unit energy costs of nuclear electricity derived from such advanced sources might be quite competitive with every major alternative.[17] The relatively modest unit capital cost estimated for such

---

[17] We note that the current economic pace-setting electrical generation technology is natural gas-fired combined cycle, which presently accounts for over 80% of all new generating capacity brought on line in the U.S. during the past few years. Of the ~$0.04/kWe-hr reference total unit energy cost of such electricity, ~$0.010 represents capital costs, $0.004 is attributed to operations and maintenance, and ~$0.025 is expended to buy natural gas fuel. Since the real time-cost of money has returned during the past several years to historic levels of ~3% per annum, a 30-year amortization period for $1000 of capital implies an annual charge of about $55, or a PITI of perhaps $80/year, i.e., 8% of principal; this is a total (PITI-loaded) capital charge of ~$0.01/hour. The 'typical' total capital cost (actual + CWIC) of an LWR-based nuclear power plant is ~$2000/kWe, which has a capital charge-rate – at the current relatively low cost-of-capital – of $0.020/hour; a 'traditional' plant capacity factor for LWRs of 67% thus implies a total capital charge for such plants of ~$0.030/kWe-hr. (Recently, the capacity factor of some of the most modern LWRs has improved to somewhat over 80%. Such improvements, taken together with the return of the real cost-of-capital in low-risk investments to historical levels of ~3% per annum, can be expected to make LWR-derived electricity – the most capital-intensive but one of the lowest in operating costs - competitive in total unit energy cost, as well as in unit production cost, with the best fossil-fired competitors in most parts of the world.)

A unit of electricity from a high-temperature combined-cycle plant with a 60% conversion efficiency requires ~60% of the heat-input as does an advanced Rankine cycle LWR with a 36% conversion efficiency; offsetting this somewhat is a higher cost per unit of heat for more expensive structural materials and construction costs. The plant capacity factor of a *never-refueled* advanced nuclear power plant of the types we consider may be expected to be greater than 90%, or more than a third higher than 'traditional' LWRs. Also, a never-refueled nuclear plant has no requirements for re-fueling equipment or storage pools for spent fuel, or spent-fuel transportation arrangements, or fresh fuel loading and storage areas and equipments, etc., all leading to a substantial percentage savings relative to LWRs. Heat rejection equipment likewise has lower capacity (by a factor of 3.2 per kWe-hr) for 60% conversion efficiency relative to 36%, resulting in additional cost-savings relative to LWRs. Savings in decommissioning charges are offset by the greater costs of deep-underground emplacement (net of land and surface improvements costs) and of the engineered heat-dump. Avoidance of the nuclear fuel cycle (e.g., all aspects of spent fuel transportation, storage, reprocessing and radwaste disposal) generates an additional net saving for the advanced nuclear option, and the net fuel cost differential (in capital-equivalent terms) is also significantly in favor of the advanced option. The bottom line is that the unit capital charges of the advanced nuclear option <u>might</u> be very substantially less than that of the LWR's $0.030/kWe-hr. (Obviously, however, reliable cost estimates may be derived only from careful consideration of a detailed design by cognizant experts; this has not been done for the advanced nuclear options which we discuss.)

advanced-nuclear electricity may be quite significant in the rapid electrification of the Third World, where per capita indigenous capital typically is in short supply and imported capital is expensive in indigenous terms.[18]

<u>An Alternative Design.</u> We consider it likely that <u>many</u> other designs – some significantly different from the one which we've developed – would <u>also</u> provide most, if not all, of the features which we have suggested. This, we believe, will be conducive to universal acceptability of nuclear power during the 21st century. As an example of a quite different approach which still satisfies the basic criteria, consider the following feature-set (relative to the extensively-analyzed point-design just discussed):

- The aspect-ratio of the reactor's fuel cylindrical charge is increased so as to confer greater reactivity control on the surrounding neutron reflector, the set of lithium thermostats are removed, and the core's thermal power generation is regulated by both classic neutron-absorbing control rods and by varying the neutron-reflector's efficiency as a function of axial position along the fuel charge;

- The He coolant temperature is lowered from 1200º to 1000º Kelvin, thereby conferring much greater strength and hot-creep resistance on the reactor core's structural and fuel-cladding

---

When the extensively-documented capital cost of $0.010 of the combined cycle conversion equipment, and a (very generous) total operation-&-maintenance estimated cost for the entire plant of ~$0.010 (allocated 40% for the conversion equipment and 60% for the nuclear heat source), the estimated *total unit energy cost* of the <u>advanced nuclear-combined cycle option amounts to ~$0.03/kWe-hr</u>, vs. <u>$0.04/kWe-hr for the</u> <u>modern gas-fired combined cycle</u> and <u>$0.04/kWe-hr for the LWR option</u> (when the value of $0.010/kWe-hr for fuel services, staffing and other operations-&-maintenance costs demonstrated by the $10/MWe-hr electricity *production* cost of the best current LWR plants are added to the LWR capital charge – at the now-reestablished historic real cost-of-money for low-risk investment of 3% per annum – of $0.030/kWe-hr). The estimated economic margin in favor of the advanced nuclear-combined cycle option thus might be substantial, although the favorable impact of the return of cost-of-money to its historic levels on the economic competitiveness of LWR-based nuclear electricity is itself remarkable.

Finally, it is also obvious that the electricity *production* cost of combined-cycle gas-fired systems can never compete with those of either coal-fired or LWR-centered central stations; natural gas is far more expensive than either coal or uranium, on a BTU-per-dollar basis, as its desirable features command a much higher market valuation of its fuel-value.

[18] To be sure, rapidly developing economies in the Third World – of which the 'Asian Tigers' have been typical, until very recently – may enjoy real per capita GDP growth of 5-10% per year over multi-decade intervals. In such circumstances, imported capital bearing a real cost-of-money of 3% per annum may be viewed as a 'real bargain' by nearly everyone, just as most Americans, then engaged in rapid industrialization, regarded comparably-priced European (mostly British) capital in the second half of the 19th century. (This avidity for imported capital will be seen even when foreign capital owners demand a significant fractional risk premium for investments in developing-country circumstances, as American economic history amply illustrates.) The relative capital intensivity of different bulk electric power supply options in the Third World of the 21st century may be of only secondary importance in such rapid-growth circumstances. The total unit energy cost of bulk electricity, however, is likely to be a primary determinant of national economic competitiveness – i.e., of the comparative advantage of nations – in many reasonably energy-intensive undertakings; thus, few national governments are likely to forget or ignore this fundamental consideration for long.

materials (and permitting extensive substitution of stainless steel for the Ta:W:Re alloy used in the higher-temperature core design);

- The core is operated so as to keep the total neutron fluence seen by any portion of the core's structural materials to a level no greater than 10-15% of that seen by the reference design, i.e., to $\leq 10^{23}$ n/cm^2.

Relative to the reference design, the practically-attainable heat-to-electricity conversion efficiency drops from ~60% to ~50% as the coolant temperature decreases, albeit with the offsetting gain of greater structural margins. The five-fold lower fuel burn-up efficiency involves a negligible increase in fuel cost, though fuel-cladding and structural costs increase somewhat – and the maximum neutron fluence seen by core structural materials moves much closer to fast reactor operating experience widely known to be satisfactory. The reactor's fuel charge becomes roughly an order-of-magnitude longer (for a constant total energy output during the three-decade reference full-power operational lifetime of the core), but the incremental cost is probably minor. The greater surface-to-volume ratio of the higher aspect-ratio core facilitates heat removal from it, both under normal operating conditions and during possible emergencies. Due to their smaller diameters, cores of this type may adapt more gracefully to smaller-capacity power plants.

This alternate design may therefore represent a substantially lower-risk initial approach toward the ideal system – and thus may be preferable in many circumstances. It shares with the point-design the features of a fast neutron spectrum, a lifetime-averaged fuel-breeding ratio far greater than unity, a propagating nuclear burn-wave moving through a fuel-charge, inert gas coolant outputted at high-temperature (i.e., in a format well-adapted to combined-cycle conversion), and relatively high burn-up of naturally-occurring fuels (i.e., excellent utilization efficiency for the actinide inventory in the Earth's crust). While its ultimate cost advantages might not be as large as those of the point-design, its initial engineering and development costs may be expected to be substantially lower. It is thus a highly attractive alternative, overall, in the search for nuclear power sources adapted to addressing global change on a world-wide basis.

A Path Forward. We recognize that not all features of either the point-design or the alternate design will have universal appeal, moreover at the present time, when much of the world’s population has little if any electrical service at all. We therefore consider a possible set of paths leading from the present state-of-affairs toward the highly ideal one of exceedingly low-risk, per-capita-intensive nuclear electrification. In particular, we now examine briefly how a Third World nation – perhaps one of the populous, electricity-hungry 'nuclear states' – might proceed in a step-wise manner toward such an ideal nuclear power system.

The earliest implementations of nuclear power reactors of the types sketched above might emphasize great safety and, to the extent immediately feasible, economy of construction and operation. It thus would focus on winning high-grade nuclear heat with strictly minimized cost. Relative to the design-concept just discussed, such a maximally-economized version might:

- *Be located sufficiently far below the Earth’s surface*, to eliminate an attractive target for military operations and terrorist actions, as well as to greatly minimize the biospheric impact of even low-likelihood accidents;

- *Have a single primary coolant-loop and a single emergency coolant-loop*, in order to obviate the additional cost of multiple, redundant loops in the just-discussed conceptual design;

- *Employ forced-convection emergency core cooling and a surface heat-sink for afterheat*, accepting the associated additional costs and risks of high-quality forced-convection and surface heat-dumping in order to avoid dependence on the yet-unproven gravitationally-driven passive cooling potentially available with deep-underground emplacement;

- *Use both control rods and (e.g., lithium-based) thermostating technology both for power-leveling and overall core power control*,, in order to provide completely duplicative manual <u>and</u> automatic control of the reactor (including propagation of the fuel-breeding and -burning process).

In summary, this initial-phase advanced nuclear power reactor might have a relatively large and comparatively highly-enriched uranium nuclear ignitor module in order to swiftly launch a full-scale nuclear deflagration wave into a thorium fuel-charge. Basically, it will look from outside its pressure-vessel like a very long-endurance (never-refueled) LWR reactor which, however, is able to output ~1200^{o} K high-pressure He for high-efficiency combined-cycle generation, in addition to being able to raise ~600^{o} K pressurized water/steam for traditional Rankine cycle-based generation.

Shortly after the plant’s end-of-operational-life, the reactor's core presumably will be extracted and reprocessed, with its half-dozen tonnes of U^{233} dispatched to be fabricated into a few dozen other nuclear ignitor modules and its fission products-&-residual actinides sent to long-term storage. The long-term spent-fuel management and plant decommissioning issues innovatively addressed in the ideal design-concept discussed above thus are given rather conventional solutions. Feeding high-pressure core-cooling He gas *directly* into parallel arrays of combined-cycle turbogenerators, perhaps initially imported from the most technologically advanced nations but thereafter domestically mass-produced, would complete the generation of electricity in a manner likely to be *highly competitive* economically with all other options.

This nuclear power reactor concept may be the one of choice for many present-day Third World circumstances, which may emphasize economy of electrification, just as the ideal system discussed earlier may be superior for many Western circumstances which emphasize greatest possibly attainable safety and absolutely minimized environment impacts and which are correspondingly comparatively cost-insensitive. This initial-phase reactor would be remarkably straightforward to design and implement, and not significantly more difficult or hazardous to operate. The point-design variant is very nearly at an EBR-1 level of nuclear engineering sophistication; only its high fuel-burnup and associated structural transmutation feature is relatively novel, and the alternate design lacks even these latter features.

The use of high-temperatures construction materials, combined with initially relatively low-power and low coolant temperature operation of a prototype reactor, supported by obvious diagnostic measurements and simple computer-based modeling, would permit the adequacy of both outside-the-reactor power-leveling and power-control control-loops to be fully evaluated, moreover quite readily and rapidly; much of this would be unnecessary for the alternate design. As confidence in the correctness of the prototype reactor’s design and implementation was thereby gained, the core of the point-design could be ramped up to full power and full peak-power-density operation and could be operated at ever-larger fractions of maximum design-rated coolant temperature. Modules of 20-30 MWe combined-cycle electrical generation capacity (e.g., GE’s already-famous H series units) could be added periodically. The first point-design prototype thus could evolve, continuously and prudently, into a full-scale power-plant, over perhaps a half-decade interval: a 21st century Shippingport, albeit with full operational legacy. The alternate design might make this transition significantly more quickly.

All of this considered, we expect that advance to ever-greater per capita wealth in the Third World will result in ever-greater emphasis on the greatest possible – and most obvious – safety measures for all types of large-scale energy systems, just as it already has in the First World. Thus, we expect that location of the reactor core underground and introduction of core thermostating will be among the first steps taken, both in order to enhance safety margins and to minimize requirements on reactor operators. Emphasis on ever more efficient fuel utilization – attained via propagating breeding – will occur naturally, as actinide usage accelerates and prices rise. We are confident that the ideal system which we have sketched will be the one which likely predominates toward the end of the coming century, after several generations of convergent technological evolution from a varied set of initial-phase systems.

Conclusions. If global warming is recognized as a phenomenon with large-scale environmental impacts and if suppression of CO_2 emissions is the means chosen to palliate its effects,[19] then either world-wide energy production will decrease or else some major source of central-station generation – of heat and/or electricity – will be employed to fill the ever-expanding gap between growing energy demand (mostly in the rapidly-developing Third World) and diminishing fossil fuel-based energy generation. At the present time, only nuclear fission-based central station technology is sufficiently developed and operationally performance-proven to be a credible candidate for this major gap-filler role.

Nuclear power systems of current design, construction and operational practices have a substantial set of significant issues facing them. The aggregate effect of these issues has halted – indeed, has even reversed – the penetration of electricity markets by nuclear fission power reactor technology in most of the developed countries. These issues must be satisfactorily addressed if nuclear power is to be other than a niche player in the 21st century energy picture, i.e., if there is to be any suitably low-risk gap-filler between rising energy demand and fossil fuel-fired energy production which diminishes swiftly relative to the characteristic near-century-duration time-scale on which major energy systems have risen and fallen historically. However, we recognize that satisfaction with the characteristics of any energy supply may be strongly geography- and time-dependent; any one-size-fits-everyone-for-all-time approach to bulk energy supply seems likely doomed to irrelevance.

In this paper, we have sketched what we believe to be satisfactory responses to these issues in the context of large-scale nuclear electric power supply. We have given two quite different examples of how these responses may result in actual designs for 21st century nuclear power reactors: an initial-phase one suitable for employment in capital-limited circumstances presently prevailing in much of the Third World and an ideal one suitable for the capital-intensive, risk-adverse circumstances of the present-day First World which we expect will prevail throughout the world by the end of the 21st century. Notably, this solution could be an enduring one: proven reserves of actinides in the Earth's crust can thereby deliver energy to the entire human race at levels currently enjoyed by Americans for intervals greater than ten millennia and, as observed above, the quantities of uranium *already* processed for American and Russian nuclear weapons stockpiles are sufficient for more than two centuries of such (relatively) lavish nuclear energy-supply.

---

[19] Teller, et al, op. cit.

We believe that <u>all</u> issues facing large-scale nuclear fission power – including the compelling economic and public perceptual ones – may be simultaneously addressed in a manner which we expect will see near-universal adoption in the latter portion of the 21st century; we likewise believe that these design approaches may be employed as a set of building-blocks for realizing large-scale nuclear power systems tailored to local circumstances – e.g., variable safety concerns and price-sensitivities – quite early in the coming century.

Success along these lines could have large implications for addressing global change. Substitution of nuclear heat for that currently derived from combusting fossil fuels at large stationary energy-generating installations can reduce by two-fold the world-wide rate at which carbon is presently inputted to the Earth's atmosphere. Quite importantly, it will also serve to conserve remaining lithospheric reservoirs of hydrocarbons for uses by future generations of natures and significance presently unknown to us.

If such a two-fold reduced carbon input rate to the atmosphere were maintained, the asymptotic atmospheric concentration of CO_2 would be approximately three times that of a century ago, or roughly twice that of present, i.e., possibly tolerable from the standpoint of presently forecast environmental impacts. If cheap, abundant nuclear power of the type which we contemplate were further leveraged to provide moderate-to-large-scale industrial process heat and energy-supplies for half of the present mobile consumption of hydrocarbons,[20] a further two-fold reduction in rate of carbon input to the atmosphere would result. If maintained thereafter, a reduction of this magnitude would result in an asymptotic atmospheric concentration of CO_2 in the neighborhood of its present value – i.e., of real concern to essentially no one. Remaining crustal stores of hydrocarbons could then be largely reserved for truly non-substitutable, highest-and-best uses, e.g., creation of petrochemicals – rather than for firing large, stationary boilers(-equivalents) and loading of the atmosphere.

<u>Epilogue Regarding Properly Proportioned Resource Expenditures.</u> It should not be forgotten that resource levels currently committed to focused exploration of practical, large-scale electricity supply alternatives are mis-matched by literally orders-of-magnitude relative to those of the problem itself, as well as to alternate means of addressing it.

It must be emphasized that many proposals for advanced nuclear power options are currently lying on the table, from authors in Japan, Russia, Europe, the U.S. and elsewhere; the foregoing represent merely a few of these. There is assuredly no shortage of technical creativity and invention in the advanced nuclear power area. There may be a deficiency of follow-through.

---

[20] The use of large, high-temperature nuclear reactors to thermally decompose – to ''catalytically crack' – water and thereby generate streams of oxygen and hydrogen gases has been proposed for a few decades now. Oxygen, obviously, can be released to the atmosphere or employed for other industrial processes; hydrogen may be used to reform CO_2 into H_2O and most any hydrocarbon-of-choice, e.g., CH_4: $4H_2 + CO_2 \rightarrow 2H_2O + CH_4$. In lieu of CO_2 sequestration or crustal re-injection, one might consider ''carbon re-cycling'', in which the existing high-pressure gas transmission-line infrastructure is employed to transport methane so manufactured from a central facility to various large, stationary use points (e.g,. power plants), with another, parallel portion of the same pipeline infrastructure being used to ship to the resulting CO_2 back to the central facility for reforming back into CH_4. In such a 'carbon re-cycling' energy economy, carbon could be regarded as a 'wrapper' or container for hydrogen – which is what it largely is, for primary energy-generating purposes – and the pipelines as conveyances. While such an approach might adapt quite readily into the existing energy infrastructure, its competitiveness relative to simply pipeline-shipping high-pressure hydrogen gas from a large nuclear reactor-powered water thermolysis facility located in present-day natural gas fields isn't obvious.

From the economic perspective, we recall that, in the U.S. alone, price-rationing sufficient to significantly reduce fossil fuel usage is estimated by some to involve costs to the American GDP of the order of $80 billion annually, which is a 40% surcharge on an annual U.S. fossil fuel bill of ~$200 billion. However, the combination of public and private American expenditures directed toward focused searches for practical alternatives clearly is less than $1 billion annually. As long as such a profound, two order-of-magnitude mis-match exists between technological opportunity and rational economic wherewithal, the basic issue of environmentally acceptable bulk electric power supply seems likely to persist. Only sustained, properly proportioned expenditures directed to development of practical alternatives to fossil fuel-fired electricity generation appear likely to result in public policy success.

In the political economics of large-scale energy supply as in physical thermodynamics, "There ain't no such thing as a free lunch!"

Acknowledgments. We thank our many colleagues with whom we've discussed these matters over the past few decades. No claim, explicit or implied, is made for originality of any of the concepts reviewed in this paper, many of which may well be due to others in either the present or some similar form.

We are particularly grateful to Edward Teller and John Nuckolls for several recent, very helpful and extensive discussions on many of the topics discussed in this paper, as well as for critical reviews of drafts thereof. Their many comments, some seminal and others provocative, resulted in many substantial improvements. Those imperfections which remain are our exclusive responsibility.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Technical Information Department **• Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551