# Can the World Do Without Nuclear Power? Can the World Live With Nuclear Power?

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## INTRODUCTION

The future of nuclear power and the future of the world are linked. For some the connection has a positive sign, and for some the link is strongly negative-to the extent that they judge that nuclear power and civilization are incompatible. Here I present my views as to the admissibility or the necessity of nuclear power. As will be seen from the analysis, my views are rather positive.

I begin by giving some of my background. Since 1950 I have worked with the U.S. government to build nuclear weapons and also to control them via the Limited Test Ban Treaty, the CTBT, the Nonproliferation Treaty-- NPT-- and more recently the SALT and START Agreements. For more than 20 years, I have been a member of the National Academy of Sciences' Committee on International Security and Arms Control-- CISAC-- which has exerted major efforts to control and to dispose of excess weapon plutonium and uranium.

My own views are that the United States could and should reduce its active nuclear weapon inventory to 1000 warheads in the next couple of years, and should take measures to transfer the materials from other warheads and all weapon-usable materials to the civil inventory. And, of course, Russia should do likewise. The ultimate future of nuclear weapons is in doubt, but questions regarding their prohibition hardly change until the number of nuclear weapons in the world, altogether, falls to 1000 or so.

## A VAST EXPANSION OF NUCLEAR POWER-PROBLEMS AND POTENTIAL.

At least five considerations are important for the adoption of nuclear power:

1. Proliferation of nuclear weapons.
2. Catastrophic accidents.
3. Radiation dose to the public from normal operation and the nuclear fuel cycle.
4. Global warming.
5. Cost, including capital investment and the fuel cycle.

### Nuclear power and nuclear proliferation

Here I summarize widely known aspects of nuclear power, in order to make clear the basis for my judgments. A great negative of nuclear power, to most people, comes from its relation to nuclear weapons. Uranium enrichment plants, which fuel most of the world's reactors, can be used to enrich uranium to the 90+% range, where it is an ideal material for nuclear weaponry. Reactors fueled with uranium create plutonium, which has been the material of choice for nuclear weapons. Nuclear weapon primaries made with plutonium enable the burning of enriched or even normal uranium in thermonuclear fusion secondaries, providing, with enough skill, an essentially unlimited explosive yield.

Even nuclear reactors that burn almost 100% U-235 are potent neutron sources, so that they can be used, in principle, to irradiate normal uranium or depleted uranium to produce Pu-239; and the highly enriched uranium fuel is itself weapon-usable. Reactors fueled with U-233 (and perhaps breeders or near-breeders using the Th/U-233 cycle) evidently involve U-233, also an excellent material for nuclear weaponry. Except that U-233, a couple of years after its production, is contaminated by an intense gamma-ray emitter, necessitating remote fabrication of weapons using this material.

Nonetheless, none of the nuclear-weapon states (NWS) has used so-called reactor-grade plutonium (R-Pu) to any great extent for making nuclear weapons. R-Pu, as is well known to this audience, but I take the opportunity to define it, extracted from normal spent fuel from the typical power reactor, has more than 20% Pu-240 in the plutonium produced, and typically 60% or less Pu-239. The Pu-240 arises from the capture of a neutron on Pu-239, as it remains in the reactor for the long-term, efficient burn-up of the U-235 content in the reactor fuel.

Typically, light-water reactors use fuel enriched to 3.5-5.0% U-235, and the U-238 is a potent sink for neutrons, forming first U-239 and within days Np-239 and Pu-239.

The Soviet Union operated graphite power reactors (RBMK) with very low enrichment, and the resultant plutonium is quite usable for nuclear weaponry. Hence the interest in terminating the operation of those three operating reactors in Russia. Furthermore, although improvements in safety have been made since the 1986 Chernobyl accident, these reactors of RBMK type are regarded as substantially less safe than the LWRs with containment that are more common in the rest of the world.

The uranium reactors are a problem for clandestine weapon production during their normal operation, and especially if fuel is reprocessed. Under those circumstances plutonium is separated and stored as PuO in 2-kg amounts, in small welded steel cans. There is no radiation hazard involved in handling these cans, which could, in principle, be stolen or diverted to make nuclear weapons. For a long time, there was a myth that nuclear weapons could not be made with R-Pu, but that was dispelled in the 1994 CISAC report, as well as in a 1997 Department of Energy document.(1) A careful analysis and declassification by the Department of Energy in January 1997, resulted in the following statement in its publicly available report on plutonium disposition:

"At the lowest level of sophistication, a potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapons states......could produce weapons from reactor-grade plutonium having reliable explosive yields, weight and other characteristics generally comparable to those of weapons made from weapons-grade plutonium......Proliferating states of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton range possible with a simple, first-generation nuclear device." and

"The disadvantage of reactor-grade plutonium is not so much in the effectiveness of the nuclear weapons that can be made from it as in the increased complexity in designing, fabricating and handling them. The possibility that either a state or sub-national group would choose to use reactor-grade plutonium, should sufficient stocks of weapons-grade plutonium not be readily available, cannot be discounted. In short, reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states. Theft of separated plutonium, whether weapons-grade or reactor-grade, would pose a grave security risk."

The most accessible early publication on this score is that of J. Carson Mark, who headed the Theoretical Division at Los Alamos for many years. Mark states, as agreed by CISAC, that there are no difficulties of kind and not much of degree in handling R-Pu compared with weapon-Pu (W-Pu), and that using the simplest type of implosion system the R-Pu explosive would always have a yield exceeding one or two kilotons (kt), and that in some cases the yield would, by chance, be substantially more. Aside from the spontaneous neutron production of Pu-240, the somewhat greater gamma radiation from R-Pu would not be a problem for those making relatively few nuclear weapons. The greater heat output would have to be handled by design choices.

The CISAC study states that nuclear weapons of somewhat greater sophistication could be made with substantially higher and reliable explosive yield. It is not my purpose nor am I permitted, to say how this could be done, but I, personally, am thoroughly convinced on this score.

So that is one unique and major potential problem with nuclear reactors. However, that problem exists already, and to an extent difficult to grasp.

In round numbers, nuclear power supplies about 20% of the electrical energy used in the world. Producing electrical energy accounts for about one-third of the world's primary energy consumption, and despite the belief that developed societies can manage with less energy per capita than now, about a doubling of the energy consumption worldwide is generally believed to be desirable to achieve an acceptable standard of living. Despite the fact that much of the world's consumption of energy is not sufficiently concentrated for nuclear power, multiplying these numbers indicates that the present world population of 300 equivalent 1-GWe reactors would need to grow to some 9,000 (or a fraction thereof) if nuclear power were to supply all (or a fraction) of the world's future energy needs.

The amount of weapon-usable material, even from the limited nuclear power industry and the decades of operation thus far, is almost incomprehensible. At present, in excess of 100 tons of Pu has been separated in reprocessing operations, and more than 1000 tons of Pu is still present in spent fuel. None of the spent fuel has been transferred to a mined geologic repository, whether as intact spent fuel or as reprocessed vitrified fission product waste. At the nominal 6 kg of Pu per nuclear weapon, 100 tons of separated Pu would suffice to make 16,000 nuclear weapons, while the thousand tons or more in spent fuel would make 160,000 weapons. Clearly the hazard is not that some terrorist group or emerging nuclear power will capture all of the spent fuel and build a force of thousands or hundreds of thousands of nuclear warheads. Rather, the hazard is that a few tens of kilograms could be stolen, purchased, or diverted, to make a few or a few dozen nuclear weapons that could hold even a large country hostage.

The solution is obviously to account for and to guard the material not as bulk, but as discrete items. In an era of individual empowerment, where a gang of bandits can attack the Millennium Dome in London in an attempt to steal millions of dollars in diamonds from an exhibit, the world needs to rethink questions of security and reinforcement.

It is clear, however, that the hazard does not grow in proportion to the amount of plutonium. If it is all in one vast repository, access to the first tens or hundreds of kilograms poses the hazard, not the vast amount of excess plutonium beyond that. So a key element of protection of weapon usable materials is a strong limitation on the number of storage sites.

There are other possibilities for massive transfer of nominally civilian nuclear materials and capabilities to weapons: What happens with a failed state with a nuclear power system? Can the reactors be maintained safely? Will the world (under the IAEA and U.N. Security Council) move to guard nuclear installations against theft of weapon-usable material or sabotage, in the midst of chaos? Not likely.

And what about a country in good standing with the NPT and IAEA, acquiring a full-scale, off-the-shelf nuclear power industry and expertise, and later abandoning its membership in the NPT? What action is the world ready to take under those circumstances? More particularly, what is the United States willing to do?

All things considered, including the metric of "comparative risk", I think that the large-scale deployment of LWRs, without reprocessing, is a reasonable approach, but the questions just raised beyond the normal constraints of the NPT deserve urgent international attention.

## Waste disposal

Addressing another parameter of nuclear power, what is to be done with the spent fuel? Here I have a specific and emphatic recommendation-- the creation of competitive, commercial, mined geologic repositories-- CCMGRs-- to be certified by the IAEA for spent fuel and nuclear waste; the acceptable forms of spent fuel and nuclear waste would need also to be certified by IAEA. In the era of globalization, it is ridiculous to insist that Switzerland or Belgium or England each do the research and development and find within its limited territory a site for the geologic disposal of nuclear waste.

Appropriate sites for CCMGR are in western Australia (the PANGEA proposal), China, Russia, and the United States. At 25 tons of spent fuel per standard reactor year, the world's reactors produce some 8000 tons of spent fuel per year. Looking ahead to supplying half the world's primary energy from nuclear power, this would amount to some 120,000 tons of spent fuel per year-each year more than the ultimate capacity of the planned repository at Yucca Mountain. Where and how this can be accommodated needs much more research, but it is premature to opine either way. Ultimately, disposal under the deep seabed may be the solution, with continued surveillance to avoid poaching to obtain long-decayed spent fuel for its plutonium content.

It is clear that the non-proliferation regime needs attention. The nuclear weapon states (particularly the United States and Russia) are claimed by others to have a commercial advantage because their nuclear facilities are not subject to IAEA inspection. And if they were, the IAEA budget would need to be doubled. The NWS should, accordingly, pay the equivalent amount-- but how much?

As I argued years ago at a session in Japan(5) states that configure their nuclear industry in such a way as to ease the burden of inspection should pay less as a consequence.

This recommendation has consequences. For instance, pryoprocessing (or other reprocessing in which a substantial amount of highly radioactive material is kept with the actinides to be recycled) might be more "proliferation resistant" in that it would require less IAEA resources to ensure that material is not diverted, or to respond to a potential diversion. But that is the measure of the benefit of pyroprocessing to nonproliferation. It is not absolute,

Modular high-temperature graphite reactors (MHTGR), whether of the General Atomics design with prismatic fuel elements, or the Pebble-bed Reactor design pursued now by ESKOM in South Africa should also be welcomed-- so far as they meet the other criteria defined above.

Ultimately one comes down to comparative risk. Any state or group dedicated to acquire nuclear weapons can choose the traditional route of building enrichment capability or production reactors that aren't burdened with the high temperatures and pressures of systems that produce electrical power. Or, in the modern era, they can resort to buying or stealing weapon-usable material or nuclear weapons. It is senseless to pay an appreciable amount of the cost of the home to reinforce the back door, if the front door is left open. And these technological approaches become easier with the passage of time.

In contrast, there is always the possibility of buying a full-featured off-the-shelf nuclear power industry, and waiting until the need or opportunity arises for building nuclear weapons. Several countries appear to have been motivated in their nuclear industries by this contingency.

## Catastrophic accidents

Next is the question of catastrophic reactor accidents. I was an author of the Ford-MITRE study in 1977,(6) as well as of the American Physical Society study on the safety of lightwater reactors.(7) Both studies recognized that LWRs or even graphite reactors could not produce a nuclear explosion, with the creation of enormous amounts of radioactive materials, but they could suffer catastrophic accidents which would liberate much of the existing radioactivity that had been produced over years of operation. Since a reactor in one day produces as much radioactivity as a 50-kt nuclear explosion, and fuel in a reactor has typically been there for an average of two years, a typical nuclear reactor has in its core the long-lived radioisotopes from 30 megatons of fission.

According to the United Nations Special Committee on the Effects of Atomic Radiation-UNSCEAR-- reports, the 528 atmospheric nuclear tests will contribute 300,000 cancer deaths (according to the International Committee on Radiation Protection-- ICRP-- figure of 0.04 cancer deaths per person-sievert (p-Sv). And Chernobyl, having contributed some 600,000 p-Sv to the global exposure will be responsible, according to the same calculation, for some 24,000 cancer deaths. Although one can find the global exposure of 600,000 p-Sv in UNSCEAR-1993, it is nowhere to be found in UNSCEAR-2000. I fear that this is not only a rewriting of history, but an elimination of the primary data from which hazards or risk could be estimated.

In our 1977 Ford-MITRE book, we judged that 10,000 people might be killed and vast territories rendered uninhabitable at current standards by a single reactor accident in which the core melted down and all of the content was liberated to the atmosphere. The 1979 accident at Three-Mile Island was consistent with our judgment that core melt down was no less probable than the experience thus far achieved in nuclear reactor operations (a contrast with the Atomic Energy Commission's judgment of one core melt down in a million reactor-years); and the 1986 Chernobyl accident (without the containment that is standard on LWRs) had consequences similar to the maximum accident of the 1977 study.

As with the Challenger space shuttle accident, in which the specific failure that actually occurred was ignored because it was "too safe to fail", it became clear that for both the space shuttle and with reactor accidents, these events were instead too horrible to think about.

After TMI-II, Probabilistic Risk Assessment-- PRA-- came into its own, resulting in probability charts that extend to large reactor accidents involving the deaths of 10,000 people.

Ultimately, PRA and the prevention of risk come down to the exchange value of lives for dollars. Half-a-century ago, large construction projects exacted one death per million dollars expended and now in the United States perhaps only one death per $100 million. More recently, many papers have been published about the value of a life spared (or rather of a "premature death" avoided). And something like $10 million is more appropriate.

Reactors such as high temperature modular gas turbine reactors (HTMGTR) can help in eliminating the risk of catastrophic accidents. As this audience knows, one type is under development in Russia at the initiative of General Atomics Corporation, and another, with its encapsulated fuel spheres formed into pebbles in a pebble-bed reactor, in South Africa. Claims are made that this approach is substantially cheaper than the normal light-water reactors.

But how much it is worth to avoid a fatality seems to depend strongly whether upon whether it is your own money or OPM that is involved-- Other People's Money.

One can avoid many of these problems, so far as comparative risk suffices. But when comparative risk has to be evaluated together with comparative cost, the dollar/life coefficient unavoidably enters.

In our Ford-MITRE study, we considered that each reactor-year of operation would involve 1-2 deaths, on the average. The nuclear fuel cycle would contribute, as would normal exposure from reactor operation, and the very small probability of catastrophic accident.

## RADIATION HAZARD FROM NORMAL REACTOR OPERATION AND FUEL CYCLE.

I have recently reviewed these probabilities and found that mining and milling of uranium contributes in many cases substantially more than was estimated in the Ford-MITRE study. And until very recently reprocessing of the spent fuel contributes far more than normal reactor operation in those reactors for which the fuel is reprocessed.

Comparing the expected deaths from a year of reactor operation with that from coal-considering only the ionizing radiation and not the much larger hazard posed by emission of sulfur oxide and heavy metals from coal:

Table 1. Collective effective dose to the public from effluents of the nuclear fuel cycle. (Dose commitment in person-Sv per GWe-yr of operation)

**LOCAL AND REGIONAL COMPONENT:**

| Source | Once-through (1) | Reprocessing and recycle(2) | COAL(3) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Mining | 1.1 | 0.9 | 0.002 Mining |
| Reactor operations (atmospheric) | 1.3 | 1.3 | 20 Power plant |
| Total Local and Regional | 2.4 | 2.2 | 20 |
| **SOLID WASTE AND GLOBAL COMPONENT:** | | | |
| Mine and mill tailings (release over 10,000 years) | 150 | 120 | |
| Reactor operation, disposal of intermediate waste | 0.5 | 0.5 | |
| Reprocessing solid-waste disposal | 0 | 1.2 | 125 Use of ash(4) |
| Reprocessing, globally dispersed radionuclides (to 10,000 years) | 0 | 217 (5) | |
| **Total for Solid Waste and Global Component** | 150 | 339 | 125 |
| **Grand Total** | 152 | 341 | 145 |
| Cancer deaths/GWe-yr (at 0.04/p-Sv) | 6 | 14 | 6 |

Notes for Table-(all from UNSCEAR 1993):
(1) From Table 53, page 200.
(2) From Table 53; Table 42 for local and regional; Table 51 for globally dispersed.
This column is per GWe-yr of nuclear plant using reprocessing and recycle.
(3) From page 56, para. 143; page 57, para. 151.
The Reprocessing and Recycle approach is assumed to use 20% less uranium than the once-through option.
(4) Buildings constructed with 5% of the ash from power production.
(5) Recent experience from BNFL shows that by capturing C-14, this number is reduced to 12 p-Sv per GWe-yr of reprocessed fuel, 1997.

I have a major concern with the lack of honest presentation of reactor risk. As mentioned, the 600,000 p-Sv exposure for the global population to be found in UNSCEAR-1993 seems not to appear in UNSCEAR-2000. And at the same time, there is a substantial effort to replace the "0.04 cancer deaths per p-Sv" by zero, simply because no specific cancer deaths can be "attributable" to such disperse radiation exposure. Those interested can refer to my earlier publications on this topic.(8)

In Table 1, I have provided a comparison between the radiation hazard of electrical power production from nuclear plants and that from coal. This, of course, does not include the problem of global warming, nor the much larger deaths in the case of coal due to atmospheric pollution with sulphur oxide and heavy metals. In the Table, one can see that mining and milling is a substantial contributor to the hazard of nuclear power, whether there is reprocessing or not, but reprocessing, in the not-so-distant past has swamped the radiation exposure from normal operation of that same reactor.

Recent information from British Nuclear Fuels Limited-- BNFL-shows that their reprocessing operation at Sellafield now contributes substantially less than the entry in the table, in large part because radiocarbon (C-14) is not liberated to the atmosphere. For 1997, for instance, BNFL reports a ten-thousand-year dose to the world population totaling 12 p-Sv per reprocessed GWe-yr of fuel, in contrast to the 217 p-Sv per reprocessed GWe-yr of Table 1 from UNSCEAR 93(22). The difference between 217 x 0.04 = 9 deaths per reprocessed GWe-yr and 12 x 0.04 = 0.5 deaths per reprocessed GWe-yr is striking. And environmentally conscious mining and milling can reduce the contribution from those operations by a factor 100 below the average shown in the table. Since 100 p-Sv per reactor year, according to the ICRP coefficient is a commitment of 4 cancer deaths worldwide per year, it is worthwhile taking measures to reduce this exposure (only a tiny fraction of which comes from the operation, per se.

## Global warming.

The typical LWR converts 30% of its heat energy into electrical energy. A modern coal-fired plant (or a plant fired by natural gas) converts 40-50% of the primary energy into electrical power. However, the carbon dioxide emitted to the atmosphere from a plant fired with fossil fuel remains there for 40-100 years, and each year thereafter the enhanced greenhouse effect supplies the earth as much heat as was contributed by combustion in the year of operation. So one could build and operate a nuclear power plant for 40 years and contribute less heat to the Earth than is provided by a single year's operation of a fossil-fuel plant.

One can go a bit further in comparative risk, burdening each ton of coal consumed with a carbon tax (to avoid global warming) of $100/ton. To provide 1 GWe by a coal-fired plant requires the annual consumption of three million tons of coal-- hence $300 million in carbon tax-- about equal to the total revenue of a 1 GWe nuclear plant.

Such estimates of the appropriate carbon tax are not capricious, and they ought to enter strongly into the decision to support and expand nuclear power or not. Furthermore, as Bob Williams convincingly shows, carbon sequestration can help convert thousands of gigatons of inexpensive coal into a benign and flexible fuel not only for stationary power plants but also to fuel a hydrogen economy.

## Cost of nuclear power

The various other categories of hazard and benefits discussed thus far-- proliferation or nonproliferation, reactor accidents, disposal of spent fuel, and global warming-- are all hypothetical, probabilistic, or long delayed. What affects decisions most is the cost of nuclear power, in comparison with the cost of other approaches to providing the same end-- electrical energy or heat.

Since the TMI accident in 1979, not a single nuclear plant has been built in the United States that was ordered before that time. However, many have been built in the world at large, and at a cost of perhaps $2-4 billion per GWe. The cost of nuclear power is largely the capital investment. The cost of fuel and operation is on the order of 10-20% of the annual cost due to the initial investment. Nevertheless, conventional uranium reserves have appeared to be inadequate for a vast expansion of nuclear power using reactors of existing types; from the beginning of the nuclear era, the prospects of breeding additional fissile material (Pu-239) from the 99.3% of natural uranium that is U-238 has been a vision of plenty-in contrast to the 0.71% fissile U-235 content of that same uranium.

In regard to the fast-neutron breeder reactor, which has always been associated with the long-term future of nuclear power, Edward Teller has this to say:

"I have listened to hundreds of analyses of what course a nuclear accident can take. Although I believe it is possible to analyze the immediate consequences of an accident, I do not believe it is possible to analyze and foresee the secondary consequences. In an accident involving a plutonium reactor, a couple of tons of plutonium can melt. I don't think anybody can foresee where one or two or five percent of this plutonium will find itself and how it will get mixed with some other material. A small fraction of the original charge can become a great hazard."(9)

In fact, the cost of expanding and continuing nuclear power may be far less than has been supposed by nuclear power technology enthusiasts. They have usually jumped to the consideration of breeder reactors because of the "shortage" of uranium fuel. With proven reserves of some three million tons of natural uranium, and a consumption of some 200 tons per year per 1-GWe reactor, this resource would last for only about 15,000 reactor years-- 50 years at a consumption of 300 reactors equivalent, and a mere two years if reactors are to supply half of the world's future total energy needs.

Of great interest are the terrestrial "reasonably assured resources" of uranium, which are likely to amount to 100 to 300 million tons of uranium at a price of $350 per kg (in comparison with the current spot market price of $20-30 per kg)(21).

Of course, nobody of right mind would buy uranium at $350/kg when the same material is available at $30/kg, but it is of primary importance to note that at $350/kg these high-cost terrestrial resources would still be cheaper than the cost of recycling fuel in an LWR (perhaps $700/kg of natural uranium avoided) or of building a breeder reactor with a capital cost that might be double that of an LWR.

Ultimately, we may have safe, economical breeder reactors, but we can take centuries to perfect them. Because in addition to the 200 million tons of terrestrial high-cost uranium, there are four billion tons of uranium in the oceans-2000 years of operation of a population of 10,000 LWRs. Half of this seawater uranium could be harvested without substantial increase in cost above that of harvesting the first seawater uranium in bulk. And that might cost from $100-$1000/kg-- probably still cheaper than recycle and breeders, but even at the higher figure the cost of fuel is still affordable.

If all enrichment costs and tails fraction remain the same, to buy 200 tons of uranium at $1000/kg to fuel a typical LWR for a year would involve costs of $200 million. This would approximately double the cost of power from an LWR, but the additional cost per kWh would be some 2 cents per kWh-- easily affordable in comparison with the 10 cents or 20 cents per kWh charged to the consumer and the 40 cents or 70 cents per kWh recently experienced in California.

Seawater uranium is available in principle to any producer and would be an article of commerce. The estimates of $100 to $300/kg come from French and Japanese groups,(10) but a recent paper provides an estimate of $1000/kg.(11) More such analyses are needed, and I comment on this paper by Kato, et al, not to attack it but to motivate additional work. A sounder estimate, whether it supports a high cost or a low cost for seawater uranium, is important to the evolution of nuclear power in the next half century. Kato, et al, consider as a unit a plant capable of extracting 200 tons of uranium per year from seawater-enough to supply fuel continuously for a single 1 GWe power reactor (at current tails fraction). At 100 yen per dollar, the investment cost for an Ashore Facility is $269 M, of which $16 M is for chelating resin to retain uranium, and $253 M for equipment; Transport Ships amount to $66 M; and Ocean Facilities to $1,721 M (of which $1045 is for an Ocean Floating Facility). The primary absorbent in the ocean facility total amounts to only $82 M.

Although the Kato study is more detailed and perhaps more realistic in its costing than previous estimates, in my judgment it has analyzed the wrong system. It has an ashore facility because the authors reject the environmental hazard of a 2000-ton ship with a load consisting largely of 15% hydrochloric acid. Yet far more dangerous loads are carried every day over the seas. So we clearly need a cost and absolute risk analysis of what would be a much cheaper system such as that sketched by Foos, et al, with the processing aboard ship. This would enable uranium farming in vast ocean areas far from shore.

In his book, "The Mythical Man-month," Fred Brooks-the architect of the IBM-360 computer line of the 1960s-wisely counsels that one should "plan to discard the first one." That is, the first large project (computer operating system, for instance) should not be put into production, but should be a training exercise. The design should by analyzed, criticized, and used as a stepping stone to a second version, which might be brought to market. And that is exactly what is needed in the design of seawater uranium farms. In particular, even if one were to depend on Ashore Facilities, it seems unnecessary and costly to have Ocean Floating Facilities on the surface of the sea. Instead, the buoyed adsorbent structures should approach no more closely than 30 m to the surface, and the vertical strings of adsorbent beds could be loaded vertically into the ship either for processing aboard or for transport to a structure in the neighborhood. Since even at a cost of $300/kg-U, the investment per reactor in uranium farm will amount to about $700 M, it is worth planning substantial R&D and design refinement to arrive at minimum cost. Of course, specialized design of the lift system to bring aboard the adsorbent bed strings is one candidate a prospect in the longer run is to use a non-standard small-waterline-area ship that would be largely immune to heavy seas and would improve the fraction of the time the ship can operate. And it must be recognized that an annual compensation rate of 10 million yen per person-year for Japanese workers will make uranium farming attractive for organizations with much lower labor costs. Japan buys its uranium now of terrestrial origin; it is likely that Japan will buy its seawater uranium as well, and be richer for doing so.

## CONCLUSIONS AND RECOMMENDATIONS.

So my recommendations for the future of nuclear power are:

- To prepare authorized competitive, commercial, mined geologic repositories.
- To reinforce and further increase support to the IAEA and the U.N. Security Council to provide not only an accounting function but a protective function to safeguard nuclear reactors and the nuclear fuel cycle. Internalize costs.
- To provide honest evaluations of accident probabilities and risks, in order to evaluate nuclear power and to reduce accident hazards.
- To recognize the benefits of nuclear power in comparison with the 40-100 times larger contribution to global warming per unit of electrical energy produced from fossil fuel without CO2 sequestration.
- For governments to spend good money now to determine and reduce the cost of acquiring uranium from seawater, in order to guide future nuclear power and energy decisions.

My recommendations for fossil and renewable power are:

- Adopt regulatory framework encouraging distributed generation-including wind, solar energy, and combined heat and power-co-generation.
- Plan for massive transport of electrical power from sources to consumers, with transmission (e.g., superconducting power transmission lines) contributing to load leveling.
- Take seriously storage-especially compressed-air energy storage (CAES).
- Demonstrate options for carbon sequestration for clean use of coal for production of electrical power and hydrogen.

Although the topic of this conference is not directly nuclear weapons, which have been and can be produced independently of nuclear power, it is essential to reduce nuclear weapons and to provide negative and positive security assurances so that the remaining much smaller number of nuclear weapons can be seen as contributing to the security of all and not to the security of a few at the expense of the many. To this end should be considered guarantees of nuclear weapon use on the part of international coalitions and of the United Nations itself.

Can the world so without nuclear power? Yes, with carbon sequestration until coal is largely exhausted.

Can the world live with nuclear power? Yes, if the risks and benefits are honestly acknowledged and organizational and financial resources committed to ensure against catastrophic accidents and nuclear weapons proliferation from the nuclear power system.

In a word, my judgment is an emphatic and unequivocal "maybe".

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# The Garwin Archive

## 2000-07 | 1990-99 | 1980-89 | 1970-79 | 1960-69 | 1950-59 | 1947-49

Richard L. Garwin was born in Cleveland, Ohio, in 1928. He received the B.S. in Physics from Case Institute of Technology, Cleveland, in 1947, and the Ph.D. in Physics from the University of Chicago in 1949.

He is IBM Fellow Emeritus at the Thomas J. Watson Research Center, Yorktown Heights, New York. After three years on the faculty of the University of Chicago, he joined IBM Corporation in 1952, and was until June 1993 IBM Fellow at the Thomas J. Watson Research Center, Yorktown Heights, New York; Adjunct Research Fellow in the Kennedy School of Government, Harvard University; and Adjunct Professor of Physics at Columbia University. In addition, he is a consultant to the U.S. government on matters of military technology, arms control, etc. He has been Director of the IBM Watson Laboratory, Director of Applied Research at the IBM Thomas J. Watson Research Center, and a member of the IBM Corporate Technical Committee. He has also been Professor of Public Policy in the Kennedy School of Government, Harvard University. From 1994 to 2004 he was Philip D. Reed Senior Fellow for Science and Technology at the Council on Foreign Relations, New York.

He has made contributions in the design of nuclear weapons, in instruments and electronics for research in nuclear and low-temperature physics, in the establishment of the nonconservation of parity and the demonstration of some of its striking consequences, in computer elements and systems, including superconducting devices, in communication systems, in the behavior of solid helium, in the detection of gravitational radiation, and in military technology. He has published more than 500 papers and been granted 45 U.S. patents. He has testified to many Congressional committees on matters involving national security, transportation, energy policy and technology, and the like. He is coauthor of many books, among them Nuclear Weapons and World Politics (1977), Nuclear Power Issues and Choices (1977), Energy: The Next Twenty Years (1979), Science Advice to the President (1980), Managing the Plutonium Surplus: Applications and Technical Options (1994), Feux Follets et Champignons Nucleaires (1997) (in French with Georges Charpak), Megawatts and Megatons: A Turning Point in the Nuclear Age? (2001) (with Georges Charpak), and "De Tchernobyl en tchernobyls," (with Georges Charpak and Venance Journe) (2005).

He was a member of the President's Science Advisory Committee 1962-65 and 1969-72, and of the Defense Science Board 1966-69. He is a Fellow of the American Physical Society, of the IEEE, and of the American Academy of Arts and Sciences; and a member of the National Academy of Sciences, the Institute of Medicine, the National Academy of Engineering, the Council on Foreign Relations, and the American Philosophical Society. In 2002 he was elected again to the Council of the National Academy of Sciences.

The citation accompanying his 1978 election to the U.S. National Academy of Engineering reads "Contributions applying the latest scientific discoveries to innovative practical engineering applications contributing to national security and economic growth." He received the 1983 Wright Prize for interdisciplinary scientific achievement, the 1988 AAAS Scientific Freedom and Responsibility Award, the 1991 Erice "Science for Peace" Prize, and from the U.S. Government the 1996 R.V. Jones Foreign Intelligence Award and the 1996 Enrico Fermi Award. In 2003 he received from the President the

National Medal of Science.

From 1977 to 1985 he was on the Council of the Institute for Strategic Studies (London), and during 1978 was Chairman of the Panel on Public Affairs of the American Physical Society. He is a long-time member of Pugwash and has served on the Pugwash Council.

His work for the government has included studies on antisubmarine warfare, new technologies in health care, sensor systems, military and civil aircraft, and satellite and strategic systems, from the point of view of improving such systems as well as assessing existing capabilities. For example, he contributed to the first U.S. photographic reconnaissance satellite program, CORONA, that returned 3 million feet of film from almost 100 successful flights 1960-1972.

He has been a member of the Scientific Advisory Group to the Joint Strategic Target Planning Staff and was in 1998 a Commissioner on the 9-person "Rumsfeld" Commission to Assess the Ballistic Missile Threat to the United States. From 1993 to August 2001, he chaired the Arms Control and Nonproliferation Advisory Board of the Department of State. On the 40th anniversary of the founding of the National Reconnaissance Office (NRO) he was recognized as one of the ten Founders of National Reconnaissance. In June, 2002, he was awarded la Grande Medaille de l'Academie des Sciences (France)-2002.

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