How to Build 6,000 Nuclear Plants By 2050

by James Muckerheide

A plentiful energy supply is the key to bringing the world's population up to a decent standard of living. We asked an experienced nuclear engineer how many nuclear plants we would need, and how to get the job done. Here are his answers.

In 1997-1998, I made an estimate of how many nuclear plants would be needed by 2050. It reflects an economy that is directed to provide the energy necessary to meet basic human needs, especially for the developing regions.

The initiative required is not unlike what the U.S. government did under Roosevelt to bring electric power to rural areas; to provide transportation by building roads and highways, canals, railroads, and airlines; to develop water supplies and irrigation systems, to provide telephone service, medical, and hospital services; and many other programs that were essential to lift regions out of poverty. That is, to meet the needs of people outside of the mainstream of economic life, even if those people are the farmers providing our food and clothing, miners providing our coal and steel, and so on.

However, as economist Lyndon LaRouche has proposed, we need to do more to meet those needs, both within the United States and for the developing world, to bring those people into the economic mainstream, instead of leaving them just as cheap sources of our labor and raw materials.

At the same time, in the last five years, we have seen greater worldwide recognition that nuclear power is essential. There is increasing support by industry and governments, compounded by recent changes in oil and gas supplies and costs, and there is increasing recognition of the essential role of nuclear energy by some responsible environmentalists. Initiatives in industry and the political environment are gearing up to implement nuclear power. But they are timid and leaderless in the United States and Europe compared to most of the rest of the world.

Unfortunately, current economic concepts expect that such decisions are to be made for individual plants, one at a time, by private interests, only when they are assured that they will be competitive (that is, assured to be profitable). Attempting to make such decisions, even with "guarantees," must therefore compete for private financial resources. But those resources can see greater returns in making movies or reselling mortgages. Such decisions are therefore going to be too little (too little energy), and too late (too little lead time) to adequately address national and international infrastructure requirements.

Government and industry leadership that is directed to meet the national interest must make the public interest decisions to produce essential infrastructure, instead of being limited to providing small, incremental, *ad hoc* profit opportunities. They must enable the critical private interests and industries, which must do the work, to get on with the business of competing to deliver the essential technology and services. The great manufacturing, materials, construction, and services enterprises can produce the infrastructure required to engage the world population in tremendous economic growth, modelled on the U.S. growth of the mid- to late-19th Century, and the mid-20th Century, which would pale in comparison.

The Role of Nuclear Energy

The projections I made for nuclear energy in 2050 simply took the role of nuclear energy to provide for roughly one third of the energy demand in 2050, which was taken to grow by about a factor of 3 from 2000. But, of course, that begs the question: Can fossil fuels continue to provide energy at the same level, or a moderate increase as today, to produce about one third of the energy demand in 2050? And can hydro, wind energy, and other alternatives (for example, tidal and wave energy), provide the other third, also the equivalent of 100 percent of today's total energy use?

We must, however, consider that any significant reliance on

Courtesy of Korea Hydro & Nuclear Power Co., Ltd.

Korea's Yongwang nuclear complex with six reactors.

solar energy runs the enormous risk of another "year without a summer," and possibly longer, following large volcanic eruptions. This occurred twice in the 1800s—Tambora in 1815, and Krakatoa in 1883. Under these conditions, billions of people would die in a world of 9-10 billion people, and dozens of mega-cities of more than 20 million people each, if we don't have adequate nuclear power or fossil fuel supply capacity to provide the "back-up power" required after going weeks or months with the Sun being blocked over the entire northern hemisphere.

So, nuclear power in 2050 would supply about 100 percent of current energy use. Since nuclear energy produces about 6 percent of world energy use today, that is an increase of roughly 18 times current use. This is fewer than the 6,000 plants I projected in 1997, more like 5,100 equivalent 1,000-megawatt-electric (MWe) plants.

But nuclear energy needs to be used for more than just electricity. This includes, for example, desalination of seawater, hydrogen production from water to displace gasoline and diesel fuel for transportation, process heat for industry, and so on. This could also include extracting oil from coal, from tar sands, and/or from oil shales for transportation and other uses, in addition to the use of hydrogen.

Note that, here, nuclear energy does not displace coal, oil, and gas. It just limits the increase in demand. If we need to displace fossil fuels, we need even greater nuclear energy use—along with other alternatives. However, there are limited practical alternatives to provide bulk energy supplies to meet the human needs of the world population, which is growing in numbers, and, to a lesser extent, in improved human conditions. That still leaves the question of how much oil and gas are being depleted, and coal to a lesser extent. If oil and gas production can not be maintained up to about 100 millions barrels per day, this could require an even greater commitment to nuclear energy, especially if nuclear energy is needed to extract oil from tar sands, oil shales, and coal.

This means that about 200 percent of current energy use would still have to come from fossil fuels and alternative sources. This leaves the questions: Is this possible? Can enough oil and gas be discovered, extracted, and refined? Can enough coal, tar sands, and oil shales be converted to displace current oil and gas supplies? If so, how much energy will this use? And how much will this increase per capita energy use?

Policies to reduce carbon emissions may affect this mix of energy supplies, but whether or not that is done, there are pollution-control costs and other cost pressures limiting supply that will make fossil fuels more costly in any event. We need to consider this in the light that nuclear energy can be produced indefinitely at roughly the cost that it can be produced today.

The alternative is to continue "business-as-usual." These conditions are even now producing international conflicts over oil and gas supplies, large environmental pollution costs in trying to increase fossil fuel production, and high costs to try to subsidize uneconomical "alternative" energy sources. This is leading the world into economic collapse, without

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A woman in India prepares cow dung, to be used in place of firewood. To bring the developing sector fully into the 21st Century will require tripling today's energy supply, with one third of the total coming from nuclear.

J.P. Lafonte/United Nations

Nuclear energy will be used for many applications, such as desalination of seawater. This 1960's sketch is of a nuplex, an agro-industrial complex centered on a nuclear power plant. It is located on the seacoast, making possible the large-scale irrigation of farmland.

adequate energy supplies. That will produce a world in which the rich will feel the need to acquire the significant resources of the economy, with the growing disparities in income and wealth that we are again seeing even in the developed world, and frustration in the developing and undeveloped world from limits on their ability to function economically.

Calculating Energy Demand

To evaluate projections of energy demand, I looked at the literature on per capita energy use in the developing and developed worlds: the size of current and projected populations.

World population will increase from today's 6 billion-plus people to an estimated 9 to 10 billion people by about 2050 (unless there are even greater wars of extermination and genocide). The developed world, with fewer than 1 billion people, will have limited population increases. The developing world will add 3 to 4 billion people, with increases from reproduction and with the addition of undeveloped regions to the developing world totals. The current development in China and India, and elsewhere, indicates the enormous growth now in progress. Today, if anything, such development projections may be understated.

The industrialized world can be more energy efficient. Per capita energy use may be 65 to 75 percent of current use. However, there will be greater energy demands for new applications as necessary, such as the use of desalination to produce water, and hydrogen from water, and oil from coal, and so on, using more energy to extract end-use energy.

The developing world will substantially increase per capita energy use, to 40 to 50 percent of current per capita energy use in the developed world. Going from a bicycle to a motor scooter, may require only a few gallons of fuel per year, but it's a large increment over the amount being used with the bicycle. And motorbikes lead to cars. Even in the last 5 to 10 years, there has been an enormous increase in vehicles, in China especially, and in other developing regions. These are large populations, more than 2 billion people, and their need for oil is becoming enormous.

It is virtually inconceivable that world governments have allowed (and even fostered, in the case of Germany and others) this unambiguously devastating condition, known to all, to reach this stage of crisis, unaddressed.

Therefore, if we are to achieve a world that is providing the energy required for developed societies, along with substantial relief of human suffering and deprivation (while limiting the enormous environmental and economic costs of large increases in fossil fuel demand), energy use in 2050 will be roughly three times the level of energy use of 2000.

Why Accelerate Nuclear Power ?

With world energy currently relying on oil, coal, and natural gas, there are limits on the oil and gas that are available. Without fully considering untapped proven and unproven reserves in the ground, in the near- to medium-term we need to increase the current 80 million barrels per day of oil. This will push the competition for oil to dangerous levels in 5 to 10 years, and without more aggressive oil supply development, it will be much worse in 15 to 20 years.

But we aren't taking the actions needed to prevent those conflicts. People talk about wars over oil, including both Iraq wars. China has become a significant player in bidding for oil. Beyond its own region, it is negotiating future supplies from Iran and South America. But large-scale initiatives to meet energy needs in order to limit future conflicts are generally inadequate. China and India have taken major initiatives. Russia will also make significant contributions. There will be an economic war, as well as possible shooting wars. In that war, China already has the substantial leverage of its enormous dollar holdings—more than $600 billion. But if, at some point, U.S. and European monopolies on oil from the Middle East and elsewhere are seen as severely damaging to China's need for oil to maintain its development, we will increase global tensions significantly.

At the same time, fortunately, the United States and China have large supplies of coal. China has enormously expanded coal production and use over the last 20 years. It produces 65 percent of its total energy from coal. It is currently opening about one coal plant *per week*. But this has come with enormous environmental destruction, from using older, cheaper, quicker technologies, both to mine it and to burn it, covering many cities and rural areas with black soot. This has had substantial health consequences, in addition to about 6,000 deaths per year to miners.

China has already expressed its intent to reduce dependence on coal; it is pushing the growth of hydropower—which it is doing with the large dam projects—and nuclear power, and many wind power projects. But because of current high costs, and allowances for intermittent generation, wind power is not now planned to be a significant contribution to China's long-term national energy needs.

Large dams also come with enormous environmental costs, plus the massive relocation of people, and other social costs, in addition to having to move power over long distances. These dams also provide (and must provide) enormous benefits for both flood control and the transfer of large quantities of water from the South to the North of China. These dam projects need to go ahead. There are presently dozens of locations that have been identified as good hydro power dam locations. But, just as in the United States, the Chinese are running out of ideal locations to site hydro power dams. There are also significant losses of arable land, plus the significant social and economic costs of moving and relocating masses of people as land is flooded. So there are fewer benefits to be gained from hydro power, and some costs that must be relieved, instead of being able to depend on dam-building for "renewable" hydro power, to solve its longer-term energy needs.

Nuclear Energy is Competitive and Cost-effective

Nuclear power is currently competitive and cost-effective. Numerous pragmatic current and recent construction projects around the world provide a strong basis for cost projections in the United States, Europe, and other locations that do not have current experience. Electricity from available nuclear power plant designs is lower than current costs from recent coal and gas plants, and reasonable projections of electricity costs from future coal and gas plants. But to some extent, nuclear power can be the victim of its own success. In the competitive market, some see new nuclear plants potentially causing electricity prices to come down, possibly to the point that the plant is not competitive, or at least that it reduces the return on investment. This could depress the owner's stock price. In addition, the construction of many new nuclear plants could also reduce the demand for, and therefore the price of, gas and coal, which could also affect nuclear plant competitiveness and stock prices.

There is a popular view that nuclear power is the high-cost option. However, during the 1968 to 1978 nuclear power construction period, there were economic benefits even when there were almost 200 plants ordered, and being procured and constructed, with massive construction costs. Our current 103 operating plants, and more, were ordered between 1967 and 1973. From 1970 to 1978, we were buying and building many more plants that did not get completed. All of those plants established strong competition with oil, gas, and coal. (Burning gas for electricity was prohibited in the United States in 1978, and only went into effect in 1990.) But the competitive pressure brought down the fossil-fuel-generated electricity a great deal. Electric ratepayers in the United States saved billions of dollars in oil, gas, and coal fuel costs over almost three decades.

Of course, the companies building those plants don't see that on their balance sheet. But those are real cost reductions to the ratepayers and the economy as a whole—to the general benefit of the nation—even if the people building the plant do not see a return on their own investment, and even if the oil, gas, and coal companies see these lower prices as a loss, or at least a lost opportunity.

So, without the nuclear option, we lost that competitive pressure. Prices are not constrained by that competition and have been increased, along with increased demand for scarce oil, gas, and coal resources. So, if we build nuclear power plants, even before a significant number of plants are operational, and especially if we have the ability to build a plant in four to five years for large plants, or we have a series of plants of the modular type that can be constructed to begin operations on shorter schedules, we will have an effect of reducing the excessive demand for, and costs of, coal and gas for providing electricity—to the benefit of the whole economy. We must consider that as part of the economic equation that doesn't presently exist, in the way we evaluate nuclear power costs.

We have developed methods to apply "externalized costs" in evaluating alternative energy sources. This is a step toward recognizing that the financial balance sheet does not fully measure the non-monetary values of energy to the economy. But we should also consider "externalized benefits" to evaluate such non-monetary benefits. This includes the benefits of reducing energy prices to the economy, the value of energy security, and so on.

Of course, people still consider the very high costs of the large nuclear plants ordered in the early 1970s. But these suffered the unanticipated effects of high component and labor costs, design changes in process after the Three Mile Island accident, and long construction times with high financing costs.

Westinghouse Electric Corp.

The 600-megawatt Yankee Atomic Electric plant in Rowe, Mass. was the third commercial plant in the United States. Now decommissioned, it operated for 31 years, starting in July 1961. Yankee Rowe was built before high interest-rates and construction delays slowed down nuclear development.

Most of the cost in the 1970s and 1980s was the result of the interest rates hikes instituted by Paul Volcker. But the other side of that coin is in considering the relative financing advantage with demonstrable 4- to 5-year construction schedules and even less, instead of 6 to 7 years in our original *ad hoc* planning and construction experience when we were building them all *de nouveau* on each site. Today, we are prepared to manufacture and pre-build modules, reducing construction schedules to limit that long-term financial exposure, even if there were increases in interest rates.

Then, there were relatively long construction schedules, increases in financing rates, and also delays in construction after the Three Mile Island accident, so that, instead of 6 or 7 years, construction became 10, 12, or 14 years—in some cases, more than 20 years. But we can ignore the outliers. They were delayed for various reasons other than just construction schedules.

Even the plants that took 10 or 12 years were the result of weak engineering and construction management. The good, knowledgeable, hands-on engineering companies during that time, like Duke Power, did not have plants that were excessively delayed. They were able to manage design and construction changes without dropping the ball.

But, in any event, future projects will undertake plant construction with approved designs, with "constructability" incorporated in plans. The current generation of early plants are simply artifacts of the historical first phase of nuclear power plant design and construction, just as the Ford Tri-Motor and the DC-3 are artifacts of the first phases of passenger aircraft.

Mass Plant Production to Follow the Land-Bridge

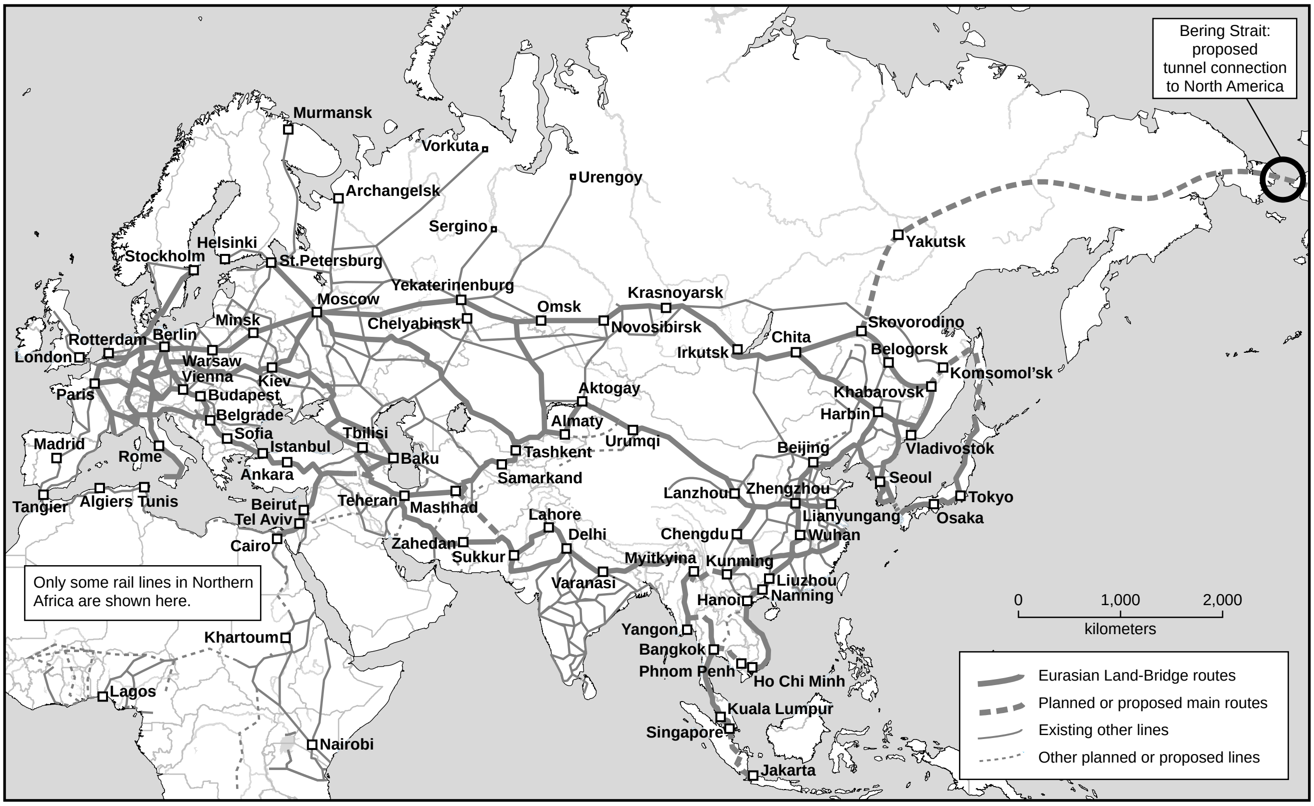
Strategic development and implementation of nuclear plants is like the Eurasian Land-Bridge concept: building networks, not just building out linearly as the United States did in moving to join the East and West in building the transcontinental railroad. It is more like the following period in railroad history, when simultaneous railroad lines were tying together the country; for example, the north and south in bringing Texas cattle to the Chicago stockyards, supported by the telegraph with its ability to implement network communications. The process is explicitly oriented to develop along a strategic path, rather than *ad hoc* plans to develop energy sources and communications around cities that grow as a result of a non-planned, non-networked, model. Or, to be more precise, the city-region is the network, even in large cities where water and power had to be brought from hundreds of miles away. Intercity infrastructure needs to be integrated with intracity-regional systems.

Such strategic plans anticipate growth of large nodes that require substantial infrastructure, which rely on and include power requirements—as in industrial complexes and large cities of more than a few hundred-thousand people. We can consider a little separately the mega-cities of 20-plus million people that are being created. They require an obvious, localized, large energy component, with a primary role for electricity, but with a heavy demand on the transportation capacity to supply the population and industries, and export the products of the cities. The growing cities of an integrated industrial economy are networked by transportation and communications. Electrification of the railways, and non-electric energy for heat, for example, to provide desalinated water, must be considered.

Electric grids also require that power loads be balanced, which further requires planning in a network strategy, instead of linear development as occurred in the early United States, where, even after the beginning of installing electricity, "the grid" was essentially localized to cities.

In building out a network, we can take a manufacturing mode with the construction of nuclear plants to supply the network that is growing an industrial economy, instead of a focus on the major cities as occurred with the original U.S. electric power system development. This fragmented result of *ad hoc* private decisions, responding to individual profit opportunities, had to later be fixed by government, including, for power, government agencies like the great Tennessee Valley Authority (TVA), the creation of the Rural Electrification Administration, and so on, to bring the nation together. As still is true today, this could not have happened effectively by leaving *ad hoc* decisions with the private financial interests, focussing on assured quick-return profit opportunities in individual projects. It could be delivered by corporate America when given the opportunity, just as with the great dam projects, providing power and water for cities and irrigation, and even recreation, with the associated economic development of the American West.

So, nuclear power plant construction should be transformed from the mode of plant-by-plant construction of *ad hoc* projects, into a manufacturing-based strategy. France is a prototype. In 1973-1974, a national decision was made to build nuclear plants in convoy series, to make decisions on designs



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This map of the main trunk lines proposed for the Eurasian Land-Bridge gives an idea of the route, moving west from China's east coast, that nuclear development could follow. Envisioned in the Land-Bridge concept is the building of industrial development corridors along the route, where new cities—agro-industrial and educational centers—would be the vehicle for bringing interior regions out of poverty, developing their human and mineral resources.

and to install those designs multiple times, with evolutionary enhancements in size, costs, and safety for future plants. This puts many plants on line in a manufacturing planning mode rather than constrained by plant-by-plant decision-making and plant construction mode only as individual project profits can be reasonably assured.

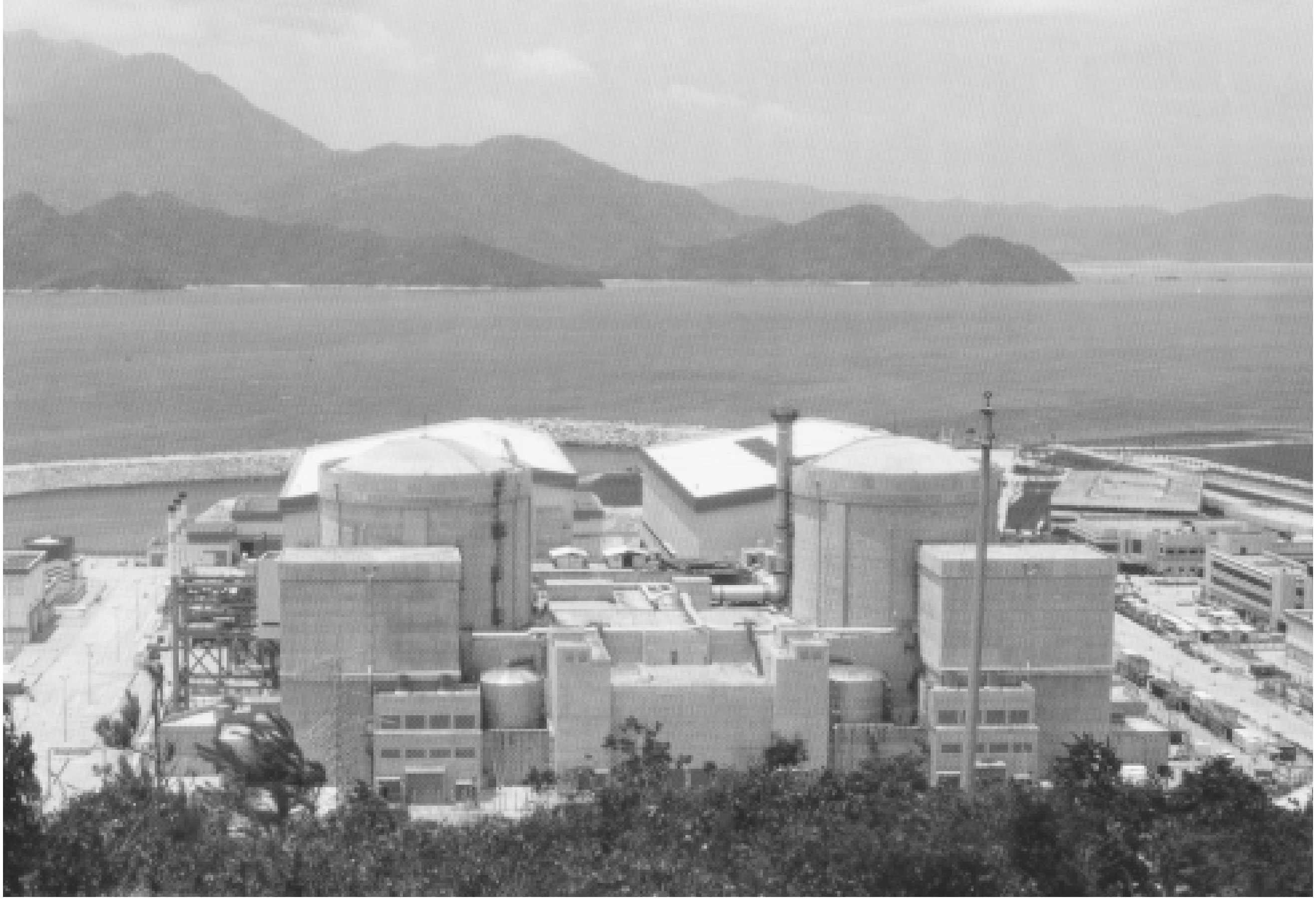
This enables the ability to take advantage of mass production, with programmatic commitments to make the vessels and major components to support a plant assembly approach. Individual plants would be installed to meet the electric power market needs. This is especially true of the modular gas reactors.

There are areas that have high power demands now—southern China for example. In addition, there are developing areas extending inland to produce energy for local development along a Silk Road model. Initial energy demands in such areas are not enormous, so that instead of large light water reactor plants, we could incrementally build dozens of modular units over decades, combined with evaluating power to eventually be fed to, and supplied from, the growth of the larger regional and national grid.

Installation sequences would dynamically respond, to both lead and follow growth. We could build two or four plants in one location, and move down the road 200 miles and build two or four more; then build two or four more at the original location as the demand grows. This would be very responsive to local conditions and growing demand over time, while the central facilities would build units in a long-term planned strategy for a number of pressure vessels per year. Although the 285-MWe GT-MHR (General Atomics' gas-turbine modular helium reactor) modular plants are small, compared to light water reactors, the pressure vessels are as large as 1,200-MWe pressurized water reactors (PWRs). When, 10 or 20 years later, we need to expand the capacity to build pressure vessels, we will work with the manufacturers either to expand existing facilities or to select and develop other locations.

So, we have the railroad model: Start at key nodes, and expand toward other nodes. The railroad development in the United States is a kind of paradigm. It shows that we need a central strategy. But the people doing the work were competing for contracts and building from, and developing, private industrial growth. President Lincoln and the Congress made national decisions to establish routes, public domain issues, incentives, and so on, that were required to support that kind of strategic development. So, governmental direction and vision are needed, with private participation. This has to establish the framework in which the private industries can compete and succeed, to implement that vision in the national economic interest.

We need a similar government vision now on behalf of the nation as a whole, with an orientation to critical infrastructure, that recognizes the human and economic needs, that rely primarily on low-cost energy. This should not be done by government directly, as was done, for example, with the TVA. But



Gabriel Liesse/Framatome

Areas with high power-demands today will need larger plants. This Guangdong Nuclear Power station, at the eastern end of the Land-Bridge in China, has two French-built pressurized water reactors, each 985 megawatts-electric.

it must reflect a vision that enables the private sector and the public to be engaged, to inspire people to see that their future security and opportunities are going to be provided by adequate development and growth in the national and world economies, that are geared to meet human needs. Otherwise, we are all going to be in a real crisis, that will become increasingly visible to the general public, as our lack of adequate economic infrastructure, especially for energy supplies, with associated environmental and financial costs, will be increasingly seen as overwhelming the nation, and the world.

Five Basic Types of Nuclear Plants

We need to implement available plant designs. There are five basic types needed, and there will be more in the future: advanced light water reactors (ALWRs), high-temperature gas-cooled reactors, breeder reactors for the long term, a small packaged reactor for remote and long-term operation without refueling, and small reactors for merchant shipping and other small non-electric-power requirements. The Canadian Advanced CANDU reactor, with a good technology base, is also a candidate to be installed extensively in a large worldwide reactor implementation program.

We clearly have ALWR plants that are well-suited to provide large quantities of baseload power. Because of the inherent safety of these plants, as was documented in the "Policy Forum" in *Science* magazine (Sept. 20, 2002, p. 1997), there are substantial opportunities to reduce the capital costs and construction schedules of these plants over time, as designs can be improved to better reflect safety requirements. However, building one or two units at sites is not very effective. LWR plant sites should be four to six units, and more in many cases. They would be located in areas where large population densities and industrial infrastructure warrant these bulk electric-generation capacities.

At the same time, for high-temperature industrial applications, and relatively remote and developing populations, we need the modular high-temperature gas reactor plants—either the pebble bed modular reactor (PBMR) or the General Atomics prismatic fuel gas-turbine plants (GT-MHR). These modular ceramic-fueled reactors enable incremental planning and flexibility. If we plan on 100 units per year, we can implement that manufacturing plan before deciding the locations of modules, although the primary locations for energy requirements in the network would be known. But implementation over the decades would be able to accommodate demographic and development changes in growth of power, process heat, and so on. At the same time, we can develop the production capacity for the ceramic fuel needed to support that number of plants.

One of the difficulties of the past has been with *ad hoc* decisions of utilities about plant types. In the United States, this was influenced by the light water reactor development technology undertaken for warships by the U.S. Navy, with its need for high power-density reactors, while the utilities did no reactor development to optimize reactors for commercial applications. However, that optimization effort is now being undertaken, in respect to ALWR plants, including the new "passive" designs, and the modular gas reactors, with some limited work ongoing on more advanced reactors under the international "Generation IV" program led by the U.S. Department of Energy.

The gas reactors, the ceramic-fuel reactors that were being built starting in the 1960s, did not have enough plants to optimize fuel production, after orders for the large high-temperature gas reactors (HTGR) plants were cancelled in the early 1970s. The fuel was costly, and there are questions about fuel recycling, although the high burnup of this fuel, including the reduction of plutonium and actinides, limits the inefficiencies that are associated with non-recycled LWR fuel. The HTGR fuel waste greatly lowers disposal costs. However, rational standards and technologies for spent fuel and high-level waste disposal will lead to greatly reduced waste disposal costs in general. There were materials constraints in the 1960s and 1970s, compared to current materials technology. There was more use of CO_2 than helium for reactor heat transfer. In addition, gas turbines today have the advantage of a great deal of large jet engine and combined-cycle turbine technology, which avoids the need to operate with a steam cycle.

The Modular HTGRs

The reactor designs ready to be developed for mass production are the modular high-temperature gas-cooled reactors that have uranium-carbide ceramic-microsphere fuel. The German-designed pebble bed reactor from the Jülich research center was a 15-MWe prototype that operated from 1967 to 1989. It is now being developed for Eskom in South Africa as a 135-MWe pebble bed modular reactor. China also has an operating 10-MWe operating prototype, and is designing a commercial plant. In the United States, the General Atomics design is a 285-MWe prismatic fuel gas-turbine modular helium reactor, the GT-MHR. A prototype plant is being designed with the Russian nuclear agency for construction in Russia, to burn plutonium fuel.

I have long favored HTGRs. I was at Bechtel when the large HTGR plants were ordered by Baltimore Gas and Electric and others in 1971. I also participated in the Department of Energy meetings with industry on the modular HTGR program in the early 1990s.

Of course, in practice, we will initially build the ALWRs that are already designed and now being certified by the U.S. Nuclear Regulatory Commission, and the French-German EPR, and the Russian large PWR, which are being constructed today. These apply where large nuclear power capacities for electric generation are needed, especially in China, India, South America, Russia, Europe, and the United States. But we must also aggressively pursue the gas reactor prototype development, to enable design acceptance for modular gas-cooled reactors, so that they are available for the smaller electric power systems that have less technology and people infrastructure.

The prototypical gas reactor plant has four units with a single control building. But in practice this model is flexible, to be expanded with another control building with another four units going out, or expanding the control building to run additional reactors. There are flexible ways to build out the number of modules at a site, and to sequence modules at more than one site, in case of site installation constraints.

But that's a detail. We need to be able to accept the designs to be able to produce the plants over more than a decade, independent of the commitment of where to build those units, and to plan their associated fuel facilities, pressure vessels, and so on. As noted above, the pressure vessel for the General Atomics 285-MWe GT-MHR is roughly the same size as the pressure vessel for a 1,200-MWe PWR.

Uranium reactors use less than about 1 percent of the energy from the uranium fuel. Breeder reactors use fuel recycling to obtain 60 to 70 times the energy value from the uranium resources. Breeder reactor plants are not needed quickly. However, with a large commitment to nuclear power to meet world energy needs, we must develop breeder reactors and plant designs, and fuel recycling. Fuel recycling will start with the use of mixed plutonium-uranium oxide fuels, with a later introduction of breeder reactors.

The small reactors can be applied to many specific energy applications to replace costly fuel oil for transport; for example, to power oil tankers and container ships. Major industrial applications can be powered by small reactors, not unlike the extensive experience that has been obtained from operating nuclear-powered warships, ice breakers, and power plants for the Antarctic and other remote locations. We need to develop small reactor designs for such commercial applications.

Some power applications can also be met by using radioisotopes that can be extracted from recycled fuel, especially from strontium-90.

The Mass Production Road to 2050

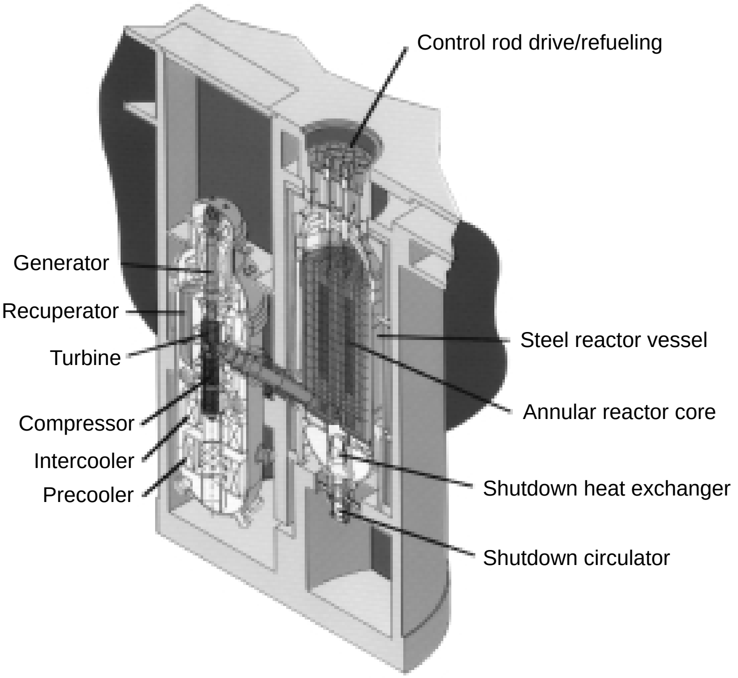
Because the time frames for these construction requirements are long, and we need significant contributions to power supplies by 2020, we can't just follow exponential growth curves to put a lot of the power on line in the decade from 2040-2050. Note that my projections are for a nominal 6,000 units of 1,000 MWe. There would be many more units if there were many modular gas reactors. On the other hand, there may be many 1,600-MWe plants of the French-German European PWR design. This plant design is now being built in Finland, and one is planned in France.

But to produce that number—6,000—plants by about 2050, we can not just increase production exponentially. We need a substantial amount of nuclear electricity before 2030, and we want to install a construction capacity that would also produce a stable plant production rate for the future, to meet both a nominal energy growth and to replace old power and other energy plants. Consider that China is building roughly one new coal plant per week now, and the United States has about 100 coal plants on the drawing board. These plants and hundreds of others will need to be replaced after 2050.

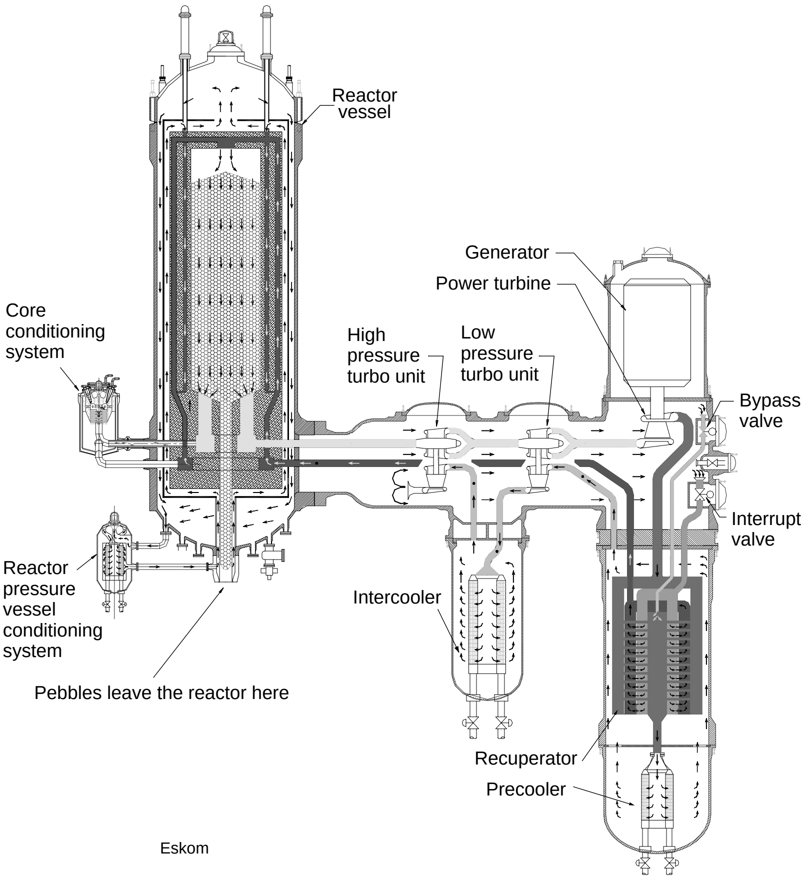
Obviously, we would install much of that capacity between

GT-MHR: GENERAL ATOMICS' MELTDOWN-PROOF REACTOR

The reactor vessel (right) and the power-conversion vessel (left) are located below ground, and the support system for the reactor is above ground, in this 285-megawatt-electric reactor design. This is a gas-turbine modular high-temperature gas-cooled (helium) reactor. Its ceramic fuel particles are embedded in 2-inch-long rods, which are stacked up in columns and inserted into a hexagonal fuel block. Helium can be heated to higher temperatures than water, so the outlet temperature is 1,562° F, compared with the 600° F of conventional nuclear plants.



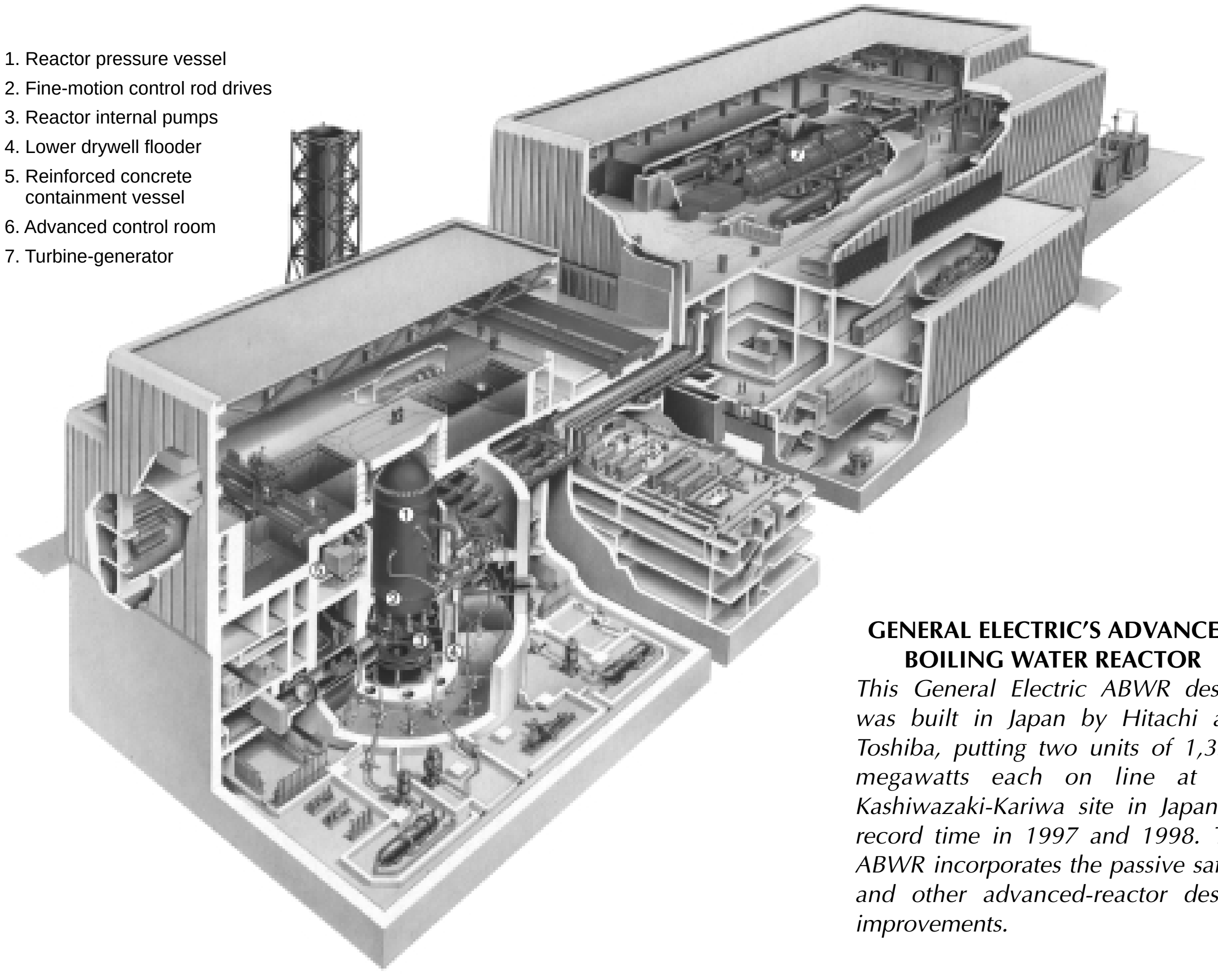
Source: General Atomics



Eskom

PBMR: SOUTH AFRICA'S PEBBLE BED MODULAR REACTOR

This Eskom reactor design is 110-megawatts-electric, and is located below ground. The ceramic fuel particles for this high-temperature gas-cooled (helium) reactor are formed into fuel balls (pebbles), which are about the size of tennis balls. Helium gas is inserted at the top of the reactor, passes among the fuel pebbles, and leaves the reactor core at a temperature of 900°C. It then passes through three turbines, to generate electricity and then cycle back to the reactor.



GENERAL ELECTRIC'S ADVANCED BOILING WATER REACTOR

This General Electric ABWR design was built in Japan by Hitachi and Toshiba, putting two units of 1,353-megawatts each on line at the Kashiwazaki-Kariwa site in Japan in record time in 1997 and 1998. The ABWR incorporates the passive safety and other advanced-reactor design improvements.

2030 and 2050. But to get from here to 2030, we have to re-examine how we plan, and commit, to installing nuclear plants. We need to go beyond the current idea that we would only commit to constructing one plant in the U.S. in 2010, and then, building something like 10 plants in the next 10 years, to 2020, in the United States. That's a long way from 2,000 or so in 2030 in the world.

Fortunately, other countries are doing more to meet the need, as publicly reported in planning announcements, even if that is still inadequate. Hopefully, and I expect that, much more is being done in some key organizations and institutions around the world.

Fuel supply, of course, requires a large expansion of uranium extraction, conversion, enrichment, and manufacturing, along with implementing adequate fuel reprocessing to use plutonium-uranium mixed oxide fuel, and later breeder reactors, to create more fuel than they consume to produce power. This uses the large inventories of depleted uranium created by enriching uranium for power and, especially in the United States and Russia, from building atomic weapons. India is also developing a thorium-based breeder reactor to take advantage of its thorium resources, and limited uranium.

We have to commit to manufacturing the pressure vessels and other large components in mass quantities, contracting now, instead of waiting for future *ad hoc* contracts from individual companies. Even when they decide to build in four-unit plants, there are substantial overheads and delays to develop contracts, which are subject to the *ad hoc* process of integrating such plans into the production capabilities of vendors, with, again, rising costs and/or extended schedules, as negotiations are entered for limited production capacity, with high risks perceived for commitments to expand manufacturing capacity vs. the assurance that the industry will not collapse again.

We must also commit to working on evolutionary designs that can reduce the cost of current and future plants. For example, current requirements for containment pressure and leakage, radiation control, including ALARA (the as low as reasonably achievable standard), and so on, can be based on realistic analyses, while enhancing nuclear power plant safety. In addition to engaging the manufacturing industries directly, we must engage the major national and international standards organizations, and other international non-governmental organizations, in this project.

Such competition in the original nuclear plant construction process in the past led to very high component and materials costs. Individual companies would still have to develop plans and contracts for new plants, but those plants would come from national policies that engage the developed and developing countries to commit to the production and installation of nuclear power plants to produce a large, worldwide plant manufacturing capacity.

To have 6,000 units in 2050, exponential growth would result in building about 400 units per year in 2050, but with fewer in the early decades. But a plan for more rapid growth to a level long-term production capacity to support long-term energy growth and replacement of old plants and fossil fuels, would result in producing up to 200 new units per year. We can plan for 6,000 equivalent units taking our present operating plant capacity as about 300 1,000-MWe equivalent units (from about 440 actual units).

There are about 30 units now in construction in the world, with construction times of five to six years, so we are now building about 6 units per year. This will substantially increase in the next two to three years. So we can take something more than 10 units per year as a current baseline, although we can more rigorously examine pressure vessel capacity. We can plan for a rapid increase in current capacity to a level about 200 units per year around 2040. Current and near-term nuclear power plant construction experience is a sound basis to adopt initial plant designs and major suppliers.

The Production Schedule

The production effort to get to 5,000 or 6,000 plants by about 2050, can be estimated by starting from the existing 300 equivalent 1,000-MWe plants and the plants now under construction, so that there will be about 320 equivalent 1,000-MWe plants in 2010. There is a current production capacity of at least 10 plants per year, which needs to be evaluated as a basis for developing additional capacity.

To build 5,000 plants by about 2050, production can be increased to build an average of about 30 plants per year between 2010 and 2020, which would add another 300 plants, for a total of about 620 plants in 2020. Building an average of about 75 plants per year from 2020 to 2030, adds 750 plants; building 160 plants per year between 2030 and 2040, adds 1,600 plants; and building 200 plants per year between 2040 and 2050, adds 2,000 plants. This results in about 4,970 equivalent 1,000-MWe plants.

To achieve 6,000 plants by about 2050, requires pushing plant production to an average of about 40 plants per year between 2010 and 2020, which adds 400 plants; 125 plants per year between 2020 and 2030, which adds 1,250 plants; 180 plants per year between 2030 and 2040, which adds 1,800 plants; and 220 plants per year between 2040 and 2050, which adds 2200 plants. This results in about 5,970 equivalent 1,000-MWe plants.

This building schedule does not take into account the currently operating plants that would be closed before 2050. That may be about 75 percent of the 440 currently operating plants, but those will be the older and smaller units, at perhaps a loss of about 200 of the 300 current equivalent 1,000-MWe plants. To make up for this loss, about 7 plants per year, in addition to the above schedule, would have to be built between 2020 and 2050.

We would focus primarily on the required fuel cycle capacity and major component manufacturing, and primary materials and infrastructure, including the required people, to produce nuclear units more like the way we build 747s, with parts being delivered for assembly from around the world.

Note that "manufacturing" applies to on-site and near-site support of construction by producing major modules outside of the construction area of the plant itself. The modules built on-site in Japan to construct the two 1,356-MWe ABWRs (advanced boiling water reactors) in about four years each, which came on line in 1996 and 1997, weighed up to 650 tons and were lifted into the plant.

The World War II and TVA Precedents

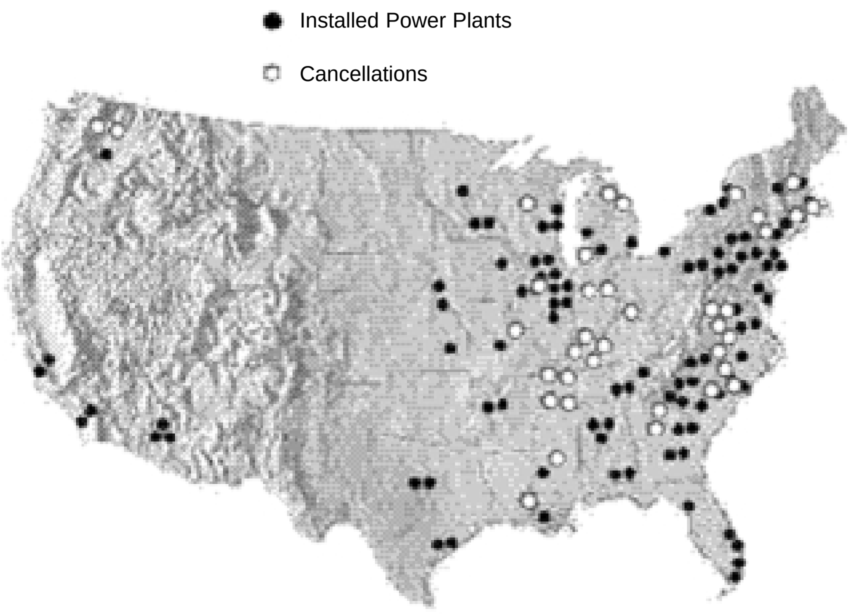
We have the experience of the expansion of production capacity in a few years before and during World War II. President Roosevelt anticipated the need, by engaging industry leaders before the U.S. entry into the war, including earlier production to support U.S. merchant marine shipbuilding, and to supply Britain and Russia using the "lend-lease" program. Henry Kaiser built Liberty ships, which took six months before the war, delivering more than one per day.

The early TVA experience built large projects that integrated production and construction, with labor requirements and capabilities. Unfortunately, as with many large organizations, the later management failed to fully understand and maintain the capabilities that were largely taken for granted as the historical legacy of the organization, with inadequate commitments to maintain that capability. However, there are examples of maintaining those capabilities, in organizations like DuPont and the U.S. Nuclear Navy.

In addition, our original nuclear power construction experience demonstrates that these capabilities are readily achievable. Today there are 103 operating nuclear units in the United States, ordered from 1967 to 1973. Earlier units were the small prototypes that are now shut down. Many units ordered in that period had vessels and major components, and containment construction materials in place or in process. In addition, there are a number of plants that were built in that period that have been shut down, some of which should not have been, if the decisions had been made in the interest of the ratepayers and the general economy, instead of only by and for the utilities, which could then access hundreds of millions of dollars in decommissioning funds.

There were about 200 units in production and construction by the early 1980s. So, even with little management coordination, poor management by many owners and constructors, with plant owners, vendors, and constructors jockeying for position and running up costs in the marketplace, we were building about 20 units per year.

But we got ahead of ourselves. Costs were driven up by competitive bidding for limited production capacity and capital constraints, but, more important, there was much lower electricity growth following the 1973 oil embargo, which had not returned to near pre-embargo rates as had been expected by many in the industry. The then-existing excess baseload plant capacity was sufficient to satisfy the slower growth in demand for two decades, relying primarily on coal, which we have in abundance, and in the 1990s, by building low-cost natural gas-burning plants, when the cost of gas was very low. This provided high



CANCELLED U.S. NUCLEAR PLANTS

The map shows the currently operating 103 U.S. nuclear plants, plus the sites where new nuclear plants were planned, ordered, and then cancelled in the 1970s and early 1980s. We need a national energy plan that will mass-produce standardized nuclear plants now, and site them where power is needed—to supply desalinated water for the drought-stricken areas in the Southwest and West, and to power the re-industrialization of the Midwest, for example.

short-term returns to the electricity-generator companies, but at high long-term energy costs and energy security risks to the nation—and the world. That was an obvious failure to do competent planning, which has clearly exacerbated our current inadequate ability to provide for long-term energy needs of the U.S. and the world, with rising costs that are threatening the world economy.

A more responsible national policy in the 1980s would have acquired some of the abandoned nuclear power plant projects in the national interest (those capable of being maintained to salvage the sunk costs), to be completed when needed to provide new baseload capacity, depending on the costs of coal and gas. In the same way, today, the nation should acquire the bankrupt GM plants from those who have destroyed them, and who would dismantle them, for short-term gain, while losing essential installed national economic infrastructure.

Needed: A National Plan in the Public Interest

There was, and is, no adequate mechanism to make decisions in the public interest based on the value of nuclear power plants to the economy, including environmental and energy security benefits. In a rational world operating in the long-term public interest, it would have been better to have completed many of the plants that were under construction, including mothballing coal plants, and preventing the construction of gas plants instead of overturning the prohibition against burning natural gas for electric power.

But, we hadn't built well-designed nuclear plants, although the later designs of those we built were greatly improved. Those plants are the foundation for the Westinghouse and General Electric advanced LWRs and passive design plants that are being certified by the U.S. Nuclear Regulatory Commission today.

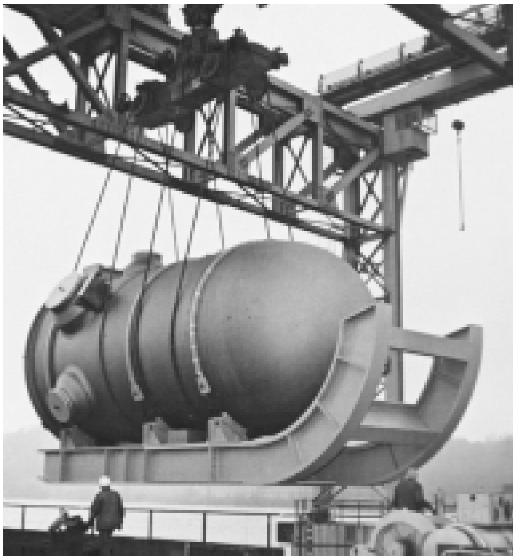
France is the premier example of the alternative model, of making national decisions on both the need to build nuclear power plants (because France did not have the coal or gas that was available in the United States), and the decision to select standard designs to evolve in series, applying the worldwide experience with many early plants.

In contrast, the United States built plants one at a time, because each was a separate contract, for separate owners. Each design was independent, although with some sharing of knowledge and technology. Starting about 1971, as with France, there were initiatives to build "standardized nuclear units" for multiple utilities. But the United States had no institutional capability to make effective decisions in the national interest. This was especially true after the Atomic Energy Commission was dismembered in 1974.

To some extent, we blew up the economic system in competing for massive amounts of capital, as well as the engineering and procurement system, in trying to push all of those plants out at the same time—without national policies and plans that could make that possible. The utility regulatory process that had been in place since the 1930s should have been fixed to meet the realities of future power needs from earnings, when the conditions of lower-cost electricity from new plants no longer applied.

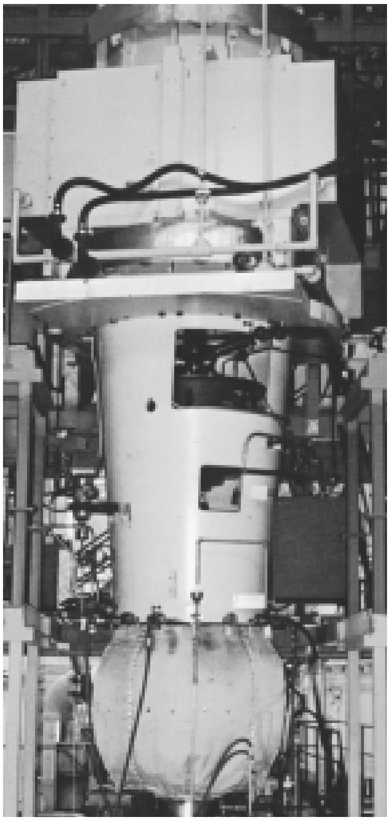
Government needs to put in place the public/private initiative, with national and international authorities to make the requisite strategic and operational decisions on the plant designs to be built, and to make initial commitments to develop the production capacity by the primary vendors. The plants can be put in a manufacturing pipeline. The utilities will identify sites, power needs, and their capability and responsibility to construct and operate the plants, from available plants and positions in the manufacturing pipeline. Volume production would be adjusted to meet demands. This will reduce conflicting demands for resources, including labor, and as with France, enhance high quality designs and production, and reduce wasteful and redundant investment in technology.

Today, an element of that capability exists in the new U.S. Nuclear Regulatory Commission rules that provide for certified reactor designs. This enables a utility to select from "available" regulatory-approved designs. But this general principle needs



Combustion Engineering

◄ *The United States no longer has the capability to build nuclear pressure vessels. This stainless steel pressure vessel was designed and fabricated by Combustion Engineering in the late 1970s.*



Combustion Engineering

▲ *A high-capacity coolant pump, produced by C-E/KSB Pump Company in the late 1970s. The pump was assembled and tested in a full-flow loop at the manufacturing facility, before being shipped to the nuclear reactor site.*

Government of India

Pipes are another component that will be needed in large quantity. Here, the inside of the Tarapur Atomic Power plant in India, which supplies power to two major states. ►

to be applied to complete units, for procurement and licensing, not just to the reactor designs. Current work is developing Construction/Operating License applications for current and in-process certified reactor designs. These are, in effect, the initial standard plants available to be selected for construction. However, private interests have limited ability to plan and commit to develop the production capacity which can provide the cost advantages to establish a productive industry to meet the essential energy needs of the 21st Century.

China's Ambitious Nuclear Plans

It is useful to look at what China is doing. The Chinese have announced a significant commitment—32 new units by 2020. But China is still authorizing the construction of plants proposed by local utilities and requesting tenders for contracts with vendors on a project-by-project basis. Its current tender is for 2 plants with 4 units, for 2 utilities. This approach is reasonable, considering that China is still gaining experience with plants and vendors, including its own plant design and construction capability. The Chinese also have their own successful PWR construction, now in operation, and their own pebble bed gas reactor, with a 10-MWe prototype operating. This is also influenced by the advantages of obtaining foreign financing from vendor countries for plant construction.

I expect that China is evaluating plant designs and vendors, mostly PWRs, with CANDU reactors that were recently completed, and that it will develop its optimum national plans in the next few years, instead of continuing to make separate contracts for each plant and having an *ad hoc* strategy about how many plants it is building. I also anticipate that by 2020 the Chinese will have more than these 32 additional plants that they have announced. They can decide well after 2010 to build plants to be operating in 2020.

Note that China has a contract with France specifically on the French experience with its national nuclear power plant design and construction planning process.

So, building the relatively few plants currently in the pipeline in China should support making decisions on plant designs and development programs, including the pebble-bed gas-cooled reactor. That effort is aggressively promoting the

PBMR as the primary nuclear solution in China. They are undoubtedly planning to produce process heat. I am unaware of plans in China to produce hydrogen to reduce the demand for oil for transportation.

China is where the United States, the United Kingdom, France, Russia, and Canada were roughly 30 years ago. To implement nuclear power, the Chinese need to select and develop standard designs, and decide how to implement them, for example, as in the United States where projects are local utility decisions in participation with a consortium for multiple plants, with engineering and contracting, with vendors competing, to provide those designs. Or they can go the route of France, which abandoned its gas reactors and adopted the Westinghouse PWR design, committed to build many plants, and then to the siting of those plants. Of course, it helped that France had one national utility, EdF, in a national regulatory environment, as opposed to the United States, which had the legacy of *ad hoc* development for short-term profit in hundreds of utilities regulated by each state.

China will likely combine large light water reactors and the PBMRs. This works for most of world nuclear energy needs, where large power centers can readily adopt multiple PWRs, while developing areas and industrial needs are met by gas reactors with many smaller modules. These modular reactors are designed to be simpler to operate and to be implemented to dynamically follow power demands, with four, eight, and even more modules at a given site, while still being a manageable undertaking.

However, the bottom line to this is that this entire enterprise should be the subject of more strategic formal multi-national planning and negotiations to enhance China's ability to develop its nuclear power plant capacity most cost-effectively, as a matter of international support as well as national strategic decision-making. The need to reduce competing demands on oil and gas is in the interest of the world, as well as of China.

The Industrial Gear-up Required for Mass Production

What kind of industries would have to gear up—steel, concrete, new materials, nuts and bolts, and reactor vessel producers?

The cornerstone of manufacturing for an accelerated program is in fuel supplies and reactor pressure vessels, along with steam generators and turbines, and large pumps. Much of the piping and plumbing, power systems, cables, instrumentation and other systems, plus the concrete and steel for the containment and other buildings, are high volumes of materials, but these should be more readily met within the general industrial production of concrete and steel, and other industrial components and equipment.

This also contributes to redevelopment of essential production capacities that need to expand and to be retooled, along with reactivating substantial steel capacity.

The fuel supply is critical. Initially, uranium mining can readily be substantially expanded. However, high-grade uranium supplies will be exhausted, along with surplus nuclear weapons materials, requiring the use of lower-grade ores. But, ultimately, uranium can also be extracted from ocean water, at only about 10 times the extraction costs of lower grade ore, where it is replenished from natural discharges into the oceans. Because, unlike other fuels, the cost of uranium is a relatively small fraction of the cost of producing nuclear energy, such an increase does not substantially affect the costs and advantages of nuclear power. Extraction of uranium might be effectively done in conjunction with desalination plants and hydrogen production. Uranium from seawater, combined with breeder reactors provide redundant pathways to assure supply. This makes it clear that these resources are good for thousands of years.

The need for conversion and enrichment capabilities would be substantial, along with fuel assembly manufacturing, including the need to establish large-scale ceramic fuel manufacturing for the high-temperature gas reactors, and develop reprocessing facilities to extend uranium fuel supplies. Initially, this would be done by making plutonium-uranium mixed oxide (MOX) fuels, and then later developing breeder reactor fuels.

Following the Eurasian Land-Bridge

As to where the facilities would be located: The whole idea of Land-Bridge development applies here. Today, pressure vessels are built in a few locations and transported around the world. But in planning for necessary nuclear power plant construction, it would be rational to locate pressure vessel, steam generator, large pump and valve manufacturing, and other major component facilities relative to the major plant construction and transportation locations, along with steel sources. These decisions would be made with the industries and countries that would produce the components.

Initially, two or more major pressure-vessel facilities might need to be developed to be able to produce about 20 vessels per year. These would be massive facilities. With an initial target to ultimately produce 200 plants per year in the 2040s, we would decide later whether to develop 10 to 20 such facilities around the world, or to make larger and fewer facilities. This will reflect the capabilities of the various companies that must do the work. We can get that capability into simultaneous production. We can construct the large PWRs in four to five years, even three-and-one-half years or so, and down to two years for the gas reactors, using factory production, and on-site manufacturing production of modules. On-site plant construction is therefore more of an assembly process, as well as the construction process that we normally think of in building large concrete and steel structures and facilities.

Manufacturing facilities would be located with consideration of the known and anticipated locations of future power plants, steel suppliers, transportation capabilities, and so on. A constructive competitive environment can be established to keep the system dynamically improving and reducing costs, with necessary elements of competition and rewards to the companies and people producing the components.

We have done this to some extent in the past in building the railroads and the TVA, the Nuclear Navy, and other major programs such as the space program. Of course, there have also been many poor and costly government program decisions that were made to satisfy political and private interests in developing facilities and services. Some of this is also "necessary overhead," as long as it falls short of outright corruption, and the building of "roads to nowhere" that do not contribute to the national purpose, to the productivity of the economy, and to meet essential human needs.

Our experience with the railroads, and the Interstate Highway system, and economic infrastructure development growth in general, is that it's not just a matter of providing transportation from point A to point B, as it is with marine shipping. Here, the development created is more from developing the track-side part of the world than just meeting the needs of transporting goods around the world.

The Political Framework

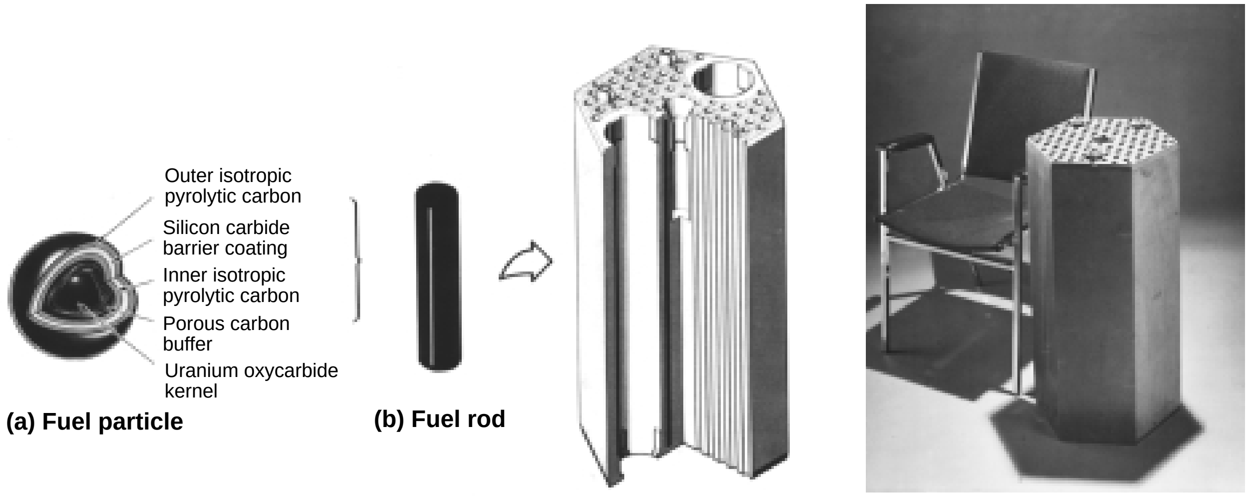
So, how do we proceed with this ambitious building and development program? We need both top-level direction and authorization, and private-sector initiatives.

Certainly, the fundamental decisions can only be made at the top. An organization must be created that has the resources and authority to make plans and commitments. But just how centralized that would be beyond the essential commitments and responsibilities for infrastructure planning and financing, how it works as a government/private sector implementation program, is flexible.

Private initiatives can be authorized, directed, and supported by government, more like the transcontinental railroad development. It was justified by national needs for mail delivery and military purposes, which also supported stage coaches and early airlines development, providing guarantees and funds for services. Or it can be a more centralized government role, like the TVA development, but thinking of this like Admiral Rickover thought of it, in using the private sector and competition to build the U.S. Nuclear Navy: Get the private sector to develop and deliver the technology, while government makes major strategic and programmatic decisions, contracting to undertake production capacity to meet demanding specifications and performance requirements.

The COMSAT/INTELSAT model was advocated by President Kennedy to engage the private sector to interconnect the world through a for-profit organization with substantial participation by the private-sector communications companies. This was done even though AT&T was prepared to implement its own system based on its successful TELSTAR satellite, which would have required tracking antennae to follow medium-orbit satellites across the sky, providing service to the most lucrative markets. COMSAT provided for geosynchronous satellites to cover the whole world, and INTELSAT supported the formation of satellite communications companies in many nations, to avoid having to patch world communications together after *ad hoc* projects to provide communications satellite service to the most lucrative markets (as AT&T had been prepared to do).

We need a dynamic, competitive, management-driven



(a) Fuel particle

(b) Fuel rod

(c) Fuel block element

(d) Fuel block element

Source: General Atomics

FUEL PELLETS FOR THE MODULAR HELIUM REACTOR

The fourth generation ceramic fuels, pioneered by General Atomics, will stay intact up to 3,632°F (2,000°C), which is well above the highest possible temperature (2,912°F or 1,600°C) of the reactor core, even if there is a coolant failure. The tiny fuel pellet (a) is about 0.03 inch in diameter. At the center is a kernel of fissile fuel, uranium oxycarbide. This is coated with a graphite buffer, and then surrounded by three successive layers, two layers of pyrolytic carbon and one layer of silicon carbide. The coatings contain the fission products within the fuel kernel and buffer. The fuel particles are mixed with graphite and formed into cylindrical fuel rods about 2 inches long (b). The fuel rods are then inserted into holes drilled in the hexagonal graphite fuel-element blocks, (c) and (d). These are 14 inches wide and 31 inches long. The fuel blocks, which also have helium coolant channels, are then stacked in the reactor core.

The particle containment is similar for both the General Atomics GT-MHR and the Eskom PBMR. In the PBMR, however, the fuel particles are embedded in graphite and formed in tennis-ball-size balls, called pebbles. In both reactors, there are hundreds of thousands of fuel particles.

enterprise, to prevent becoming trapped or captured by either private interests or self-serving government bureaucracies that don't, or don't continue to, perform well, either on the technology side or on the economic side. Such failures leave the national interest hostage to self-serving organizations and financial interests, whether private or governmental.

Consider the building of the transcontinental railroads in the United States, where the Union Pacific and Central Pacific were chartered to do the job, with subsidies, but they had to raise their own money, with government direction and guarantees. This was compromised in many ways, however, including buying Congressional support with Credit Mobilier stock for changes favorable to the owners, and so on. That was not a clean process.

But after false starts with little progress, while self-serving work was being done, primarily in land-grabbing with the 10-mile track-side lands given to the Union Pacific owners, President Lincoln and the Congress created incentives that led to progress. Eventually the companies had to compete as to how far they were going to build out to where they would meet, and be rewarded for how much of the intercontinental connection they had respectively built. And for many years it was a substantial competition that had them going "hammer and tong," as we would say, to build out from San Francisco and from the Missouri River at Omaha, Nebraska. Lincoln had to pick the starting point, which was itself a political reward for electoral support.

Learning from Other Great Projects

This job is even more vast. But there are lessons to be learned from the railroads, the TVA, and other great projects to implement essential public purposes. The railroad conditions, before and after the Civil War had the complications of procuring and delivering materials to Nebraska and California, with most of the financial and corporate interests in New York and Philadelphia, and government participants in Washington, along with involvement by some states. They had a problem getting labor, until the Chinese were recruited by the Central Pacific, and Union and Confederate Army soldiers were recruited to do the job by the Union Pacific after the war. Pay and conditions were poor, which is part of the down-side of relying on private interests to do the job, before labor standards had been established.

Thomas Durant, who headed the Union Pacific effort, saw that most of the wealth would be generated from developing the track-side land and resources. The companies weren't making much progress on actually building the railroad, so Lincoln worked to shift incentives to have to build so many miles of track, and the company with the most miles of track at the end was going to make more money. Without that, the Union Pacific would have built out only slowly, focussing more on developing the more valuable track-side land resources. When they were building out, the Central Pacific was trying to get past Salt Lake City, Utah, to the coal deposits in the Wasatch mountains. They failed to do that when they could only get to Promontory Point, where the railroads joined up. But construction was being driven by rewards in obtaining such resources.

So, there are lessons from considering where the interests and values are in developing an economy, beyond just thinking of it as a point A to point B transportation construction project, unlike ocean shipping. Or the need to have airlines serve smaller cities as well as the large cities.

In the final analysis, the world will work by people maximizing their financial rewards. The question is, are they doing it consistent with the larger objectives of the economy in serving the public interest, whether that is by using a more centralized government program to develop the TVA, or by engaging the private sector more directly, as with the railroads. This is as opposed to corrupt actions by financial interests or government agencies that steal the public treasure for self-serving purposes.

The early development of the airline industry is another model of combining private and government interests, but with inadequate government responsibility to meet the national interest since airline deregulation.

The Interstate Highway system is another model, where government directly funded construction. This was, and is, of enormous economic value, but it was also not done with an adequate balancing of the effects on railroads and cities by the financing models established by the Congress, rather than by a responsible government transportation agency, for example, in establishing and allocating fuel taxes. There was no one competing for ownership and profits, other than those doing the engineering or pouring concrete, nor were there rewards for building the most highway miles. On the other hand, there were many local interests working politically to influence routes and highway interchange access that were always at work. Those were government program decisions rather than private interests licensed to build highways between points A and B, to profit on being given roadside land and resources, and owning and selling interchanges to the highest bidding communities.

But historically, the transcontinental railroads, originally championed by Stephen Douglas, even with the major scandals, were a great and economically important success, as a national economic and political achievement. They captured the imagination of the country. When looked at closely, we find that it's like making sausage, or laws—we may not want to see how it's done, and who is just self-serving in the process, whether they are just normally biased by personal and local political advantage, or they are committing outright fraud. But programs today can generally control any significant fraud.

Achieving a great project transcends such details, and provides for the generation of great wealth for the economy as a whole, for the nation and the world. This wealth is greatly out of proportion to the costs from any such malfeasance.

I also like to be philosophical, considering that any such perpetrators of fraud, if not stealing from such great projects, would likely be stealing elsewhere, perhaps from our pension funds, and so on, that are much more of a zero-sum game.

We can also learn from the ongoing national economic development that was stopped by the 1873 financial collapse created by the international bankers, after they had failed to stop American development by instigating the secession of the South.

And we can learn from the subsequent role of Thomas Edison, and his aversion to the Wall Street financiers, to make an enormous individual contribution to overcoming that interruption in American development.

What a Nuclear Energy Initiative Can Bring to the World

First, even though such a nuclear power enterprise is an enormous project to salvage the world energy lifeline and to limit conflicts, while being a primary economic development engine, it is just the core of the larger decisions to provide adequate energy from coal and other technologies, plus other critical infrastructure required to provide for the human needs of the developing and undeveloped world, and expanding productive wealth in the developed world.

In addition, such a nuclear power and/or energy technology development initiative is also a foundation of common science and technology, and common purpose, for the world. It can be a model. It is a national and international enterprise, founded on government and private industry participation. It has the power to limit the non-productive machinations of both government and private financial interests that are in conflict, and constrain responsible government and private interests from working for greater general wealth and constructive progress for both the developed and developing world.

Nuclear power also has the advantage that it currently has a high international profile, and substantial, if relatively non-productive, ongoing national and international government organizations. For example, the United Nations, especially with the International Atomic Energy Agency, the International Energy Agency, and the Non-Proliferation Treaty, is essential to our need to safeguard uranium enrichment and plutonium production, plus many other institutional components. The major industry organizations are also more coordinated, with compatible technologies and capabilities that are more complementary than other equivalent

It's Not 'Waste': Nuclear Fuel Is Renewable

The first thing to know about nuclear waste is that it isn't "waste" at all, but a renewable resource that can be reprocessed into new nuclear fuel and valuable isotopes. The chief reason it is called "waste," is that the anti-technology lobby doesn't want the public to know about this renewability. Turning spent fuel into a threatening and insoluble problem, the anti-nuclear faction figured, would make the spread of nuclear energy impossible. And without nuclear energy, the world would not industrialize, and the world population would not grow—just what the Malthusians want.

The truth is that when we entered the nuclear age, the great promise of nuclear energy was its renewability, making it an inexpensive and efficient way to produce electricity. It was assumed that the nations making use of nuclear energy would *reprocess* their spent fuel, completing the nuclear fuel cycle by renewing the original enriched uranium fuel for reuse, after it was burned in a reactor.

When other modern fuel sources—wood, coal, oil, gas—are burned, there is nothing left, except some ashes and airborne pollutant by-products, which nuclear energy does not produce. But spent nuclear fuel still has from 95 percent to 99 percent of unused uranium in it, and this can be recycled.

This means that if the United States buries its 70,000 metric tons of spent nuclear fuel, we would be wasting 66,000 metric tons of uranium-238, which could be used to make new fuel. In addition, we would be wasting about 1,200 metric tons of fissile uranium-235 and plutonium-239. Because of the high energy density in the nucleus, this relatively small amount of fuel (it would fit in one small house) is equivalent in energy to about 20 percent of the U.S. oil reserves.

Ninety-six percent of the spent fuel can be turned into new fuel. The 4 percent of the so-called waste that remains—2,500 metric tons—consists of highly radioactive materials, but these are also usable. There are about 80 tons each of cesium-137 and strontium-90 that could be separated out for use in medical applications, such as sterilization of medical supplies. Using isotope separation techniques, and fast-neutron bombardment for transmutation (technologies that the United States pioneered but now refuses to develop), we could separate out all sorts of isotopes, like americium, which is used in smoke detectors, or isotopes used in medical testing and treatment.

Right now, the United States must import 90 percent of its medical isotopes, used in 40,000 medical procedures daily. These nuclear isotopes could be "mined" from the so-called waste. Instead, the United States supplies other countries with highly enriched uranium, so that those countries can process it and sell the medical isotopes back to us!

How Fuel Becomes 'Spent'

The fuel in a nuclear reactor stays there for several years, until the concentration of the fissile uranium-235 in the fuel is less than about 1 percent at which point, the nuclear chain reaction is impeded. A 1,000-MW nuclear plant replaces about a third of its fuel assemblies every 18 months.

Initially, the spent fuel is very hot, and is stored in pools of water which cool it and provide radiation shielding. After one year in the water, the total radioactivity level is about 12 percent of what it was when it first came out of the reactor, and after five years, it is down to just 5 percent.

Unlike other poisons, radioactive isotopes become harmless with time. This decay process is measured in terms of "half-life," which refers to the amount of time it takes for half of the mass to decay. Although a few radioisotopes have half-lives on the order of thousands of years, most of the hazardous components of nuclear waste decay to a radioactive toxicity level lower than that of natural uranium ore within a few hundred years.

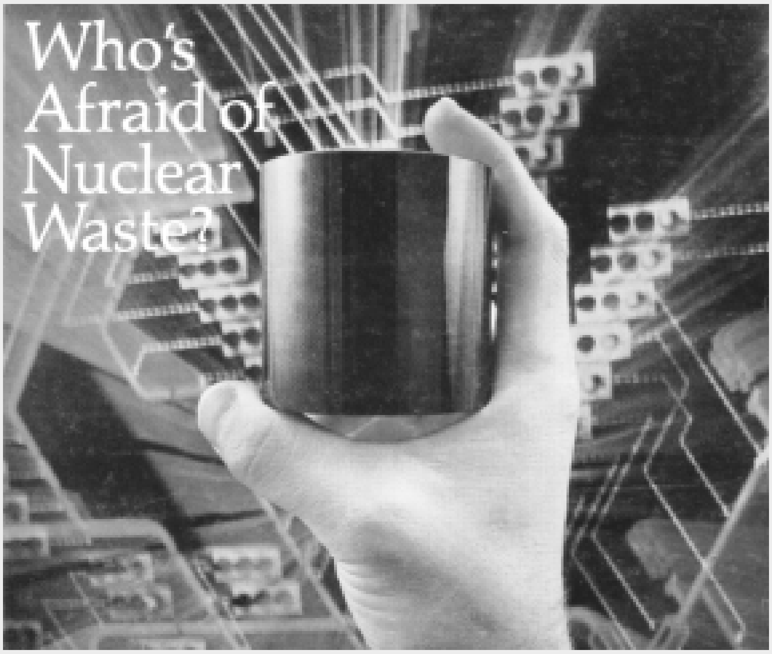
The spent fuel includes uranium and plutonium, plus all the fission products that have built up in its operation, and very small amounts of some transuranic elements (those heavier than uranium) or actinides, which have very long decay times. If this spent fuel is not reprocessed, it takes hundreds of thousands of years for its toxicity to fall below that of natural uranium.

What are we really wasting? The spent fuel produced by a single 1,000-megawatt nuclear plant over its 40-year lifetime, is equal to the energy in 130 million barrels of oil, or 37 milindustries.

In addition, such actual public/private mechanisms can transcend some of the destructive national conflicts and destructive financial conditions, to meet actual worldwide energy needs, and to actually implement essential nuclear power energy supplies to prevent world conflicts over energy—in the real world. This can provide an initiative with a productive purpose that can push current non-productive governmental and non-governmental organizations to replace non-productive dialogue and make actual progress in meeting the human needs of the world.

With any success, these mechanisms can also contribute to models that can address other substantial national and international purposes, to engage the developed and developing nations to enable solutions, beyond current "policy discussions." These mechanisms can enable productive cooperation, along with healthy competition, that can enhance relevant technologies, and lower costs, instead of seeing little actual progress in major projects. This can include basic infrastructure, health care, and drug delivery, education and communications, and so on. These initiatives can constrain costs, and preclude destructive financing costs on developing and undeveloped nations.

The nuclear power enterprise can reduce the coming world energy conflicts, create wealth, and be a model to address the inability to deliver technology and services to the developing and undeveloped world and bring these societies into the economic mainstream. This can be the primary economic engine, the wealth-generating machine, for the 21st Century.



Battelle Pacific Northwest Laboratories

A glass cylinder illustrating the total amount of radioactive waste generated for one person if his lifetime electricity needs were supplied by nuclear energy.

ESTIMATED ELECTRICAL ENERGY FROM DIFFERENT FUELS

Fuel	killowatt hours of electricity from 1 kilogram of fuel
Hardwood	1
Coal	3
Heavy oil	4
Natural gas	6
Natural uranium	50,000
Low-enriched uranium	250,000
Uranium with reprocessing	3,500,000
Plutonium with reprocessing	5,000,000

This comparison of the approximate electricity that can be derived from currently available fuels, indicates why nuclear energy was viewed as such a breakthrough and came under such attack from the Malthusians. When electricity is cheap and plentiful, populations can prosper.

Source: John Sutherland, "Nuclear Cycles and Nuclear Resources," June 27, 2003.

lion tons of coal, plus strategic metals and other valuable isotopes that could be retrieved from the high-level waste.

Why We Don't Reprocess

The United States, which pioneered reprocessing, put reprocessing on hold during the Ford Administration and shut down the capability during the Carter Administration, because of fears of proliferation. This left reprocessing to Canada, France, Great Britain, and Russia (plus the countries they service, including Japan, which is now developing its own reprocessing capability). In addition, new methods of isotope separation using lasers, such as the AVLIS program at Lawrence Livermore National Laboratory, were shut down, or starved to death by budget cuts.

As a result, today we have 40,000-plus metric tons of spent fuel safely stored at U.S. nuclear plants, which the anti-nuclear fear-mongers rail about, even though they are the ones who created the problem. The plan to permanently store the spent fuel at the Yucca Mountain repository in Nevada, has become bogged down in what looks like a permanent political battle.

Technologically speaking, we can safely store nuclear waste in a repository like that of Yucca Mountain. But why should we spend billions of dollars to bury what is actually billions of dollars' worth of nuclear fuel, which could be supplying electricity in the years to come?

The commercial reprocessing plant in Barnwell, S.C. shut down in 1977, but we could start reprocessing at the national nuclear facilities at Hanford in Washington State, and at Savannah River in South Carolina. And we could have a crash program to develop more advanced technologies for reprocessing.

—Marjorie Mazel Hecht