Between 2 Devils

Nobel Laureate Burton Richter discusses the promise and the problems of nuclear energy

Nuclear energy is undergoing a renaissance, driven by two very loosely-coupled needs: the first for much more energy to support economic growth worldwide; the second to mitigate global warming driven by the emission of greenhouse gases from fossil fuel.

With the current mix of fuels, growing the economy increases emissions; increased emissions lead to climate change; climate change will eventually harm the economy. Nuclear energy offers one way out of this cycle.

Many forecasts of energy demand in the 21st century all give roughly the same answer. The International Institute of Applied Systems Analysis (IIASA), for example, shows in their mid-growth scenario primary energy demand increasing by a factor of two by mid-century and by nearly another factor of two by the end of this century. By the year 2030 the developing countries are projected to pass the industrialized ones in primary energy use. China alone will pass the United States as the world's largest energy consumer and economic growth in China and India is already higher than assumed in the IIASA Scenario.

Supply constraints on two out of the three fossil fuels are already evident. Oil prices have surged. Demand is rising at an average rate of about 1.5 million barrels per day per year requiring the output of another Saudi Arabia every ten years to keep up with increased demand.

There is a lot of natural gas, but there are transport constraints. Natural gas prices also have risen and now are at the unprecedented level of $9-$10 per million BTU.

The only fossil fuel in abundant supply is coal. However, it has serious pollution problems and expensive technological fixes are required to control environmental problems that have large- scale economic consequences.

Concern about global warming is increasing and even the United States government has finally said that there is a problem. The Intergovernmental Panel on Climate Change (IPCC) forecasts, in the business-as-usual case, an increase in atmospheric carbon dioxide to 750 parts per million by the end of the century with a consequent global temperature rise of 2° to 5° C, less at the equator and more at the poles.

We can surely adapt to this increase if it is at the low end and occurs smoothly. If it is at the high end and accompanied by instabilities in climate, economic and societal disruptions will be very severe.

It is too late to prevent some global warming, but limiting the effect requires a move away from carbon-based fuels. The global-warming issue has caused prominent environmentalists to rethink their opposition to nuclear power. One question to be confronted is which devil would they rather live with, global warming or nuclear energy?

James Lovelock (environmentalist and author of the popular Gaia hypothesis), among others, has come down on the side of nuclear energy. When economic self-interest and environmental self-interest both point in the same direction, things can begin to move in that direction. They now both point to the need for large scale carbon-free energy. Nuclear energy is one such solution.

While nuclear cannot be the entire solution, it can be an important part if the public can be assured that it is safe, that nuclear waste can be disposed of safely, and that the risk of weapons proliferation is not significantly increased by a major expansion.

Nuclear Power Growth Potential

About 440 reactors worldwide supply 16% of world electricity. About 350 of these are in the OECD (Organisation for Economic Co-operation and Development) supplying 24% of their electricity. The country with the largest share of nuclear electricity is France at 78%. To an environmentalist, France should be looked at as a model for the world. Its carbon-dioxide intensity (CO_2 per unit GDP) is the lowest in the world. If the entire world's CO_2 intensity were as low as France's, $C0_2$ emissions would be reduced by a half, and global warming would be much slowed.

Projections for growth in nuclear power are uncertain because of uncertain costs along with the three potential problems mentioned earlier, safety, waste disposal, and proliferation risk.

Safety: The new generation of light-water reactors has been designed to be simpler to operate and maintain than the old generation, and has been designed with more passive safety systems.

With a strong regulation and inspection system, the safety of nuclear systems can be assured. Without one, the risks grow. No industry can be trusted to regulate itself when the consequences of a failure extend beyond the bounds of damage to that industry alone.

Spent Fuel Treatment: Looking separately at the three main elements of spent fuel there should be little problem.

There is no difficulty with the uranium alone, which makes up the bulk of the spent fuel. It is not radioactive enough to be of concern; it contains more U-235 than natural ore and so could be input for enrichment, or could even be put back in the mines from which it came.

There is no scientific or engineering difficulty with fission fragments, the next most abundant component. The vast majority of them have to be stored for only a few hundred years.

Robust containment is simple to build to last the requisite time. (If the Egyptians could build pyramids that have lasted 6,000 years, we should be able to do at least as well.)

The spent fuel problem comes mainly from the last 1%, which is composed of plutonium and the minor actinides, neptunium, americium and curium. For some of the components of this mix, the toxicities are high and the lifetimes are long.

There are two general ways to protect the public from this material: isolation from the biosphere for hundreds of thousands of years, or destruction by neutron bombardment.

Isolation is the principle behind the "once through" system for nuclear fuel as advocated by the United States for weapons-proliferation-prevention reasons. In a world with a greatly expanded nuclear power program, I do not believe the once-through system is workable.

Its problem is a combination of public perception, which I leave to the politicians, and technical limitations. The first technical problem comes from the heat generated in the first 1,500 or so years of storage which limits the density of material that can be placed in a repository. The early heat generated from fission fragments is not difficult to deal with. The decay of plutonium-241 to americium 241 which then decays to neptunium-237 is the main source of heat during the first 1,000 or so years. Limitations on the allowed temperature rise of the rock of a repository from this source determine its capacity.

The second technical problem is the very long-term radiation. Here the same plutonium to americium to neptunium decay chain maximizes the long-lived component, requiring isolation from the biosphere for hundreds of thousands of years.

To use a US example, if nuclear energy were to remain at the projected 20% fraction of US electricity needs through the end of the century, the spent fuel in a once-through scenario would need nine repositories of the capacity of Yucca Mountain. If the number of reactors in the US increases by mid-century to the 300 Gwe projected in the Massachusetts Institute of Technology (MIT) study, the US would have to open a new Yucca Mountain every six or seven years. This would be quite a challenge since we have not been able to open the first one. In the world of expanded use of nuclear power, the once-through cycle does not seem workable.

The alternative to once-through is a reprocessing system that separates the major components, treating each appropriately and doing something specific to treat the component that produces the long-term risks. The most developed reprocessing system is that of France. The French make mixed oxide fuel, or MOX, by separating plutonium (Pu) from spent fuel and mixing it with an appropriate amount of uranium (U). The left over extra uranium will go to an enrichment facility.

The fission fragments and minor actinides are vitrified for eventual emplacement in a repository. The glass used in vitrification appears to have a lifetime of many hundreds of thousands of years in the clay of the proposed French repository.

MOX fuel plus vitrification solves part of the problem but not all of it. The next question is what to do with the spent MOX fuel. The plan is to keep it unreprocessed until fast-spectrum reactors are deployed commercially. These fast-spectrum reactors burn a mix of plutonium and uranium-238 and can, in principle, burn all of the minor actinides as well.

It is possible to create a kind of continuous recycling program where the plutonium from the spent MOX fuel is used to start the fast-spectrum system; the spent fuel from the fast-spectrum system is reprocessed; all the plutonium and minor actinides go back into new fuel, and so forth. In principle, nothing but fission fragments goes to a repository and these only need to be stored for a few hundred years. This sounds good in principle, but there's much work to do before putting it into practice.

Proliferation Prevention: Preventing the proliferation of nuclear weapons is an important goal of the international community. Achieving this goal becomes more complex in a world with a much expanded nuclear-energy program involving more countries. Opportunities for diversion of weapons usable material exists at both the front end of the nuclear fuel cycle, the U-235 enrichment stage; and at the back end of the nuclear fuel cycle, the reprocessing and treatment of spent fuel stage. The more places this work is done, the harder it will be to monitor.

Clandestine weapons development programs have come from both ends of the fuel cycle. Pakistan and South Africa, which voluntarily gave up its weapons in an IAEA supervised program, made their weapons from the front end of the fuel cycle. Libya was headed that way until it recently abandoned the attempt.

There is uncertainty about the intentions of Iran. India, Israel, and North Korea obtained their weapons material from the back end of the fuel cycle using heavy-water-moderated reactors to produce the necessary plutonium.

The level of technical sophistication of these countries ranges from very low to very high, yet all managed to succeed. The science behind nuclear weapons is well known and the technology seems not that hard to master through internal development or illicit acquisition.

It should be clear to all that the only way to limit proliferation by nation States is through binding international agreements that include effective inspection as a deterrent, and effective sanctions when the deterrent fails.

We in the science and technology (S&T) community can give the diplomats improved tools that may make the monitoring that goes with agreements simpler and less overtly intrusive. These technical safeguards are the heart of the systems used to identify proliferation efforts at the earliest possible stage. They must search out theft and diversion of weapons-usable material as well as identifying clandestine facilities that could be used to make weapons-usable materials.

The development of advanced technical safeguards has not received much funding recently. An internationally coordinated program for their development needs to be implemented. Proliferation resistance and monitoring technology should be an essential part of the design of all new reactors, enrichment plants, reprocessing facility, and fuel fabrication sites.

There are technologies not yet deployed that can give real-time results in critical areas. One does not have too wait long to see if uranium-235 is within declared limits in an enrichment plant. One issue that is being revisited is the relative proliferation resistance of the once-through fuel cycle compared to those of various reprocessing strategies.

An analysis has been done by an international group of experts for the US Department of Energy and documented in their November 2004 report, "An Evaluation of Proliferation Resistant Characteristics of Light Water Reactor Fuels." The methodology created in this analysis gives a risk score for every phase of the nuclear fuel cycle and then sums the risks over time.

All of the variants of once-through and reprocessing have about the same score. The increased risk during the phase where plutonium is available in reprocessing scenarios is balanced by the decreased risk of diversion during enrichment, where less enrichment is required, and the increased radiation barrier after the second burn and the increased difficulty of fashioning the weapon from ever-more degraded materials.

These scores should not be read as precision measurements. All they really say is that to sensible people once through is not that different from reprocessing.

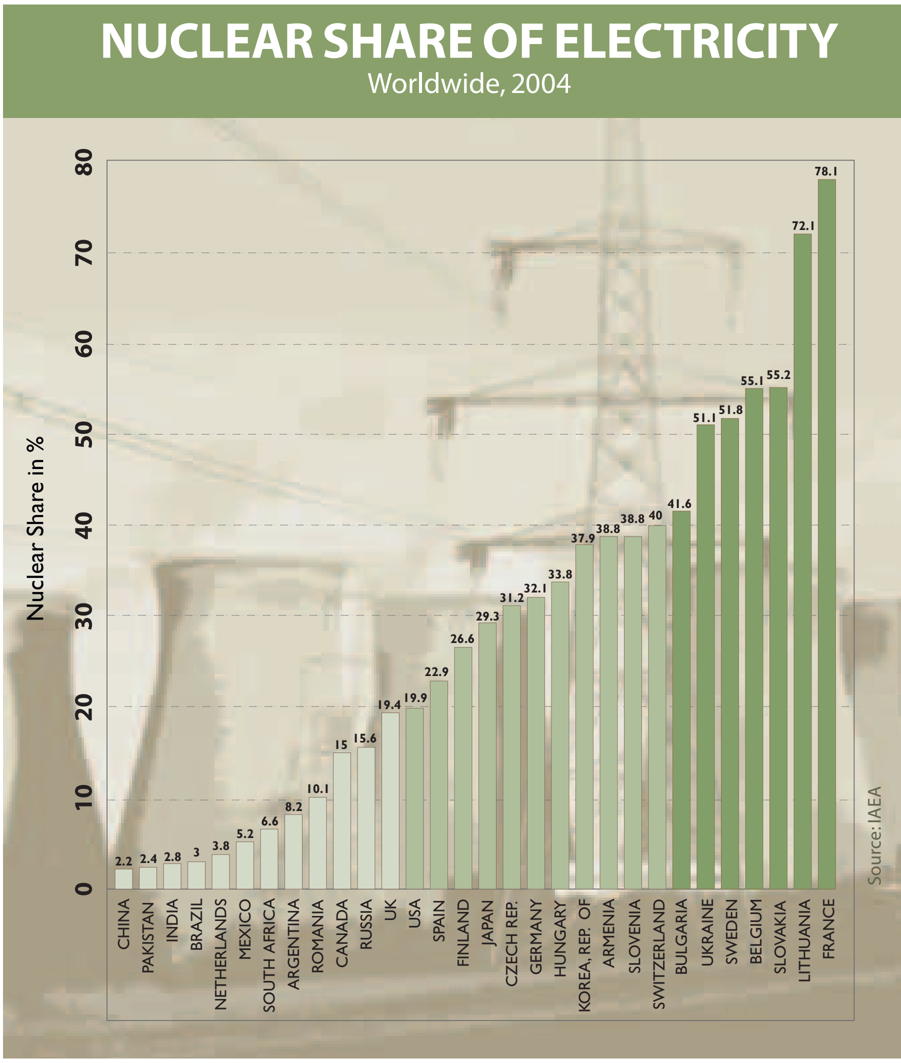
IAEA Director General ElBaradei and US President George Bush have proposed that internationalization of the nuclear fuel cycle begin to be seriously studied. In an internationalization scenario there are countries where enrichment and reprocessing occur. These are the supplier countries. The rest are user countries. Supplier countries make the nuclear fuel and take back spent fuel for reprocessing, separating the components into those that are to be disposed of and those that go back into new fuel.

If such a scheme were to be satisfactorily implemented, there would be enormous benefits to the user countries, particularly the smaller ones. They would not have to build enrichment facilities nor would they have to treat or dispose of spent fuel.

Neither is economic on small scales and repository sites may not be available with the proper geology in small countries. In return for these benefits, user countries would give up potential access to weapons usable material from both the front end and the back ends of the fuel cycle.

If this is to work, an international regime has to be created that will give the user nations guaranteed access to the fuel that they require. This is not going to be easy and needs a geographically and politically diverse set of supplier countries.

Reducing the proliferation risk from the back end of the fuel cycle will be even more complex. It is essential to do so because we have seen from the example of North Korea how quickly a country can "break out" from an international agreement and develop weapons if the material is available. North Korea withdrew from the Nuclear Non-Proliferation Treaty at short notice, expelled the IAEA inspectors, and reprocessed the spent fuel from their Yongbyon reactor, thus acquiring the plutonium needed for bomb fabrication in a very short time.



NUCLEAR SHARE OF ELECTRICITY
Worldwide, 2004

Supplier countries that should take back the spent fuel for treatment are not likely to do so without a solution to the waste-disposal problem. In a world with a greatly expanded nuclear power program there will be a huge amount of spent fuel generated worldwide. The projections mentioned earlier predict more than a terawatt (electric) of nuclear capacity producing more than 20,000 tons of spent fuel per year.

This spent fuel contains about 200 tons of plutonium and minor actinides and 800 tons of fission fragments. The once-through fuel cycle cannot handle it without requiring a new Yucca Mountain scale repository every two or three years. Reprocessing with continuous recycle in fast reactors can handle this scenario. Only the fission fragments have to go to a repository and that repository need only contain them for a few hundred years rather than a few hundreds of thousands of years.

In summary, nuclear energy is an important component of a strategy to give the world the energy resources it needs for economic development while reducing consumption of fossil fuels with their greenhouse-gas emissions. If this is to happen on a large scale, advances in both physical S&T and political S&T will be required.

We on the physical side can produce better and safer reactors, better ways to dispose of spent fuel, and better safeguards technology. This can best be done in an international context to spread the cost and to create an international technical consensus on what should be done. Countries will be more comfortable with what comes out of such developments if they are part of them.

While the physical development can best be done in an international context, the political S&T can only be done internationally. The IAEA seems to be the best place to start and the first baby steps have already been taken. I look forward to larger steps of both kinds in the future.

Burton Richter is on the faculty of the Stanford Linear Accelerator Center (SLAC), Stanford University, and served as SLAC Director from 1984-99. He was awarded the 1976 Nobel Prize in physics with Samuel C. Ting "for their pioneering work in the discovery of heavy elementary particle of a new kind." E-mail: brichter@slac.stanford.edu

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