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Nuclear Power, Nuclear Proliferation, and Global Warming[1]

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Introduction

I address here the nuclear weapons proliferation risks that will be posed by a robust expansion of civilian nuclear power worldwide. By robust, I will take as a benchmark, a global nuclear capacity of 3000 gigawatts-electric (GW) – an eight-fold increase from today's worldwide capacity of 350 GW.

An increase of at least this magnitude will be necessary for nuclear power to make a dent in global warming. For example, under the central business-as-usual projection of the Intergovernmental Program on Climate Change (IPCC), if nuclear power grew to 3000 GW in 2075 (50% of world electricity then projected), and then 6500 GW in 2100 (75% of world electricity), the total carbon emissions avoided cumulatively would be approximately 290 billion tons through 2100 – only about one-fourth the projected cumulative carbon emissions to 2100 projected by the IPCC.

The management of a nuclear system of 3000 GW would be truly challenging. If based on a once-through fuel cycle using light water reactors, such a system would generate roughly 600 tons of plutonium *annually*, and would require on the order of one-half million tons of natural uranium annually. If based on liquid-metal plutonium breeder reactors, it would involve the fabrication into fresh fuel annually of over four thousand tons of plutonium (though the cumulative inventory of plutonium would be much less than for a system based on light water reactors). Is a nuclear future of such magnitude thinkable?

The proliferation risks I have in mind are two-fold:

- That countries or terrorist groups could divert fissile materials directly from the civilian nuclear fuel cycle into nuclear explosives;

- That countries aspiring to obtain nuclear weapons could use civilian nuclear facilities (power reactors, research reactors, reprocessing plants, uranium-enrichment plants, etc.) and trained cadres of nuclear scientists, engineers, and technicians as a cover and/or training ground for the dedicated acquisition of fissile material for nuclear weapons.

A third sort of risk -- that terrorists could use civilian spent fuel or high level wastes for a so-called "dirty" bomb or radiological weapon, or could release substantial amounts of

[1] This paper is based on a longer paper presented at the University of Michigan Workshop on the Future of Nuclear Energy, October 2-4, 2002; and on "The Search for Proliferation-Resistant Nuclear Power," *Public Interest Report*, Federation of American Scientists, September/October 2001.

radioactivity through attacks on reactors, spent fuel pools, dry-store casks, transportation casks, or the like – raises a different class of questions and I do not consider these here.

So let's consider how a nuclear system of 3000 GW would look, and the specific proliferation risks it would pose.

Implications of a Robust Future for Nuclear Power

What countries will have nuclear power?

Nuclear power today is overwhelmingly located in a relatively few industrialized democracies, a few countries in Eastern Europe, Ukraine, Lithuania, and Russia. Of the 350 GW installed capacity worldwide, less than 10 GW are in developing countries. This includes 2.3 GW in India, 2.1 GW in China, 0.9 GW in North Korea, 0.4 GW in Pakistan, and 2.7 GW in South America. For the most part, the countries with nuclear power programs are either already nuclear weapon states or countries which for whatever reason do not aspire to become nuclear weapon states.

An exuberant nuclear future will present a different picture. It is widely recognized that the scene of significant nuclear growth over the next half century will have to be largely in the developing countries. This is where by far the greatest increase in electricity production is projected. The table below shows the top 25 countries by population projected for 2050 by the U.N. I then arbitrarily assumed a 1 kW per capita (1 kW/c) electricity capacity for each country shown, and equally arbitrarily assumed a nuclear penetration of 33 percent. In an article last year in *Physics Today*, Ernie Moniz and Melanie Kenderline note that the knee of a curve plotting the U.N. human welfare index against per-capita electricity consumption is at about 4000 kWh/y.[2] This would correspond to a 1 kW capacity at slightly less than a 50 percent capacity factor.

Rank Order World Population in 2050

Country	Population (millions)	GW at 1 kW/c	GW nuclear at 33%
India	1620	1620	540
China	1470	1470	490
United States	403	403	134
Indonesia	337	337	112
Nigeria	303	303	101
Pakistan	267	267	89
Brazil	206	206	68
Bangladesh	205	205	68
Ethiopia	187	187	62
Congo	181	181	60
Philippines	153	153	51

[2] Ernest Moniz and Melanie Kenderline, "Meeting Energy Challenges: Technology and Policy," *Physics Today*, April 2002. The current average worldwide per capita electricity consumption is about 2300 kwh/y. The idea of using population projections to 2050 was suggested to me by Moniz, private communication.

Mexico	153	153	51
Vietnam	119	119	40
Russia	118	118	40
Egypt	113	113	37
Japan	101	101	37
Iran	100	100	33
Saudi Arabia	91	91	30
Tanzania	88	88	29
Turkey	86	86	29
Sudan	84	84	28
Uganda	84	84	28
Germany	79	79	26
Yemen	71	71	23
Thailand	70	70	23

This list includes several countries which today have essentially no or a negligible amount of nuclear power: Indonesia, Nigeria, Pakistan, Bangladesh, Ethiopia, Congo, Philippines, Vietnam Egypt, Iran, Saudi Arabia, Tanzania, Turkey, Sudan, Uganda, Yemen, and Thailand. No doubt, several of these countries (and many others down the list) will, in the event, not actually develop nuclear power on a large scale. And, of course, it is a real question how these countries will obtain the capital and technical expertise required. But let's not kid ourselves. If, as we are positing here, nuclear power comes to play a substantial role in the world energy economy, it will have to be located in many of these countries – and on a substantial scale. After all, in the illustration shown, nuclear represents just one-third of electricity posited, and electricity overall is likely to be no more than about one-third of total energy consumption. Thus, even in this exuberant extrapolation, nuclear represents a relatively small fraction of total energy – on a lesser scale, it would make little dent in the greenhouse problem.

This immediately provokes several concerns.

States of Concern. Today, Iran and, in a somewhat different category, North Korea, raise special problems. These countries are parties to the NPT, and in the case of Iran at least have accepted full IAEA safeguards. But both countries are suspected of harboring nuclear weapon programs (in the case of North Korea admitted) and raise vexing issues for the international community. As the table above suggests, in the future, there are likely to be several countries whose nonproliferation credentials will be suspect, and some of these may be tied to terrorists. Because of this, there will be temptation for the international community to indulge in a two-class system of nuclear power, with certain technologies and fuel cycles denied to one class of countries, while permitted in "safe" countries. It seems unlikely that such a system could be maintained over decades.

Latent Proliferation. Whereas today it is fair simply to demand that civilian nuclear power remain a less attractive route to acquisition of weapons-usable material than a dedicated route, that is not the way to think about a robust nuclear future. For in this case, we are talking about scores of countries which do not today have any substantial nuclear power program at all obtaining both nuclear facilities and the infrastructure in technology and expertise under the guise of a civilian purpose that would eventually allow a dedicated weapons program. Today, we have to be realistic in admitting that in many countries the nuclear technology genie is well out of the bottle; but this does not in itself justify letting genies everywhere out of the bottle.

There would be a large expansion of safeguards. If safeguards' efforts are calibrated roughly by the number of facilities in non-nuclear-weapon states, the nuclear future envisioned would involve a many-fold increase in numbers of inspections and in the inspection budget as compared to today.

What happens today if a state withdraws from the NPT? While its NPT International Atomic Energy Safeguards (IAEA) agreement would then also expire, in many – in fact, in most – cases other obligations would remain in place from pre-existing safeguards agreements that were suspended when the NPT came into force, or from back-up safeguards demanded by nuclear suppliers at the time of the export. The legal situation is somewhat murky and has to be examined country by country; but it appears that facilities and materials produced indigenously might not carry back-up safeguards obligations. This could be troubling in a robust nuclear future where over time one imagines an increasing number of countries will be able to develop nuclear power independently of outside suppliers.

Pressures for reprocessing and recycling of plutonium

Nuclear power today is operated predominantly on once-through fuel cycles in which the fuel for the reactors is either natural uranium or low-enriched uranium which cannot be used for weapons, and the spent fuel discharged from the reactors is not reprocessed – that is, where the plutonium contained in the spent fuel is not separated from the highly-radioactive fission products. Thus, the once-through fuel cycles are reasonably proliferation resistant. A country could, of course, seek to enrich low-enriched uranium fuel to weapons levels (from 4-5% U-235 to over 90% U-235), or alternatively to build a quick and dirty reprocessing plant to recover plutonium. But in general safeguards should be adequate to discover such activities so that any attempt at diversion could not be done clandestinely. Still more important, such enrichment or reprocessing appears out of reach for sub-national groups.

However, even today not all nuclear power is operated on once-through fuel cycles, the UK, France, Russia, and to a lesser degree Japan are reprocessing spent fuel. Large commercial plants in the UK and France are reprocessing both their own spent fuel and spent fuel from other countries, notably Japan and Germany. At present, about one third of the spent fuel discharged from reactors each year worldwide is being reprocessed. The plutonium separation is currently roughly 20-24 tons per year, though this may decrease some during the next few years. Most of the plutonium that has been separated remains stored at the reprocessing plants.

Some of the separated plutonium is being fabricated into mixed-oxide fuel (MOX) at four plants in Europe. In 2000, these plants produced somewhat less than 200 tons of MOX, incorporating 10-12 tons of plutonium, with the MOX production capacity expected roughly to double in the next few years. The MOX is being burned in approximately 32 light water reactors (LWRs) in France, Germany, Belgium, and Switzerland. Another 18 have been licensed to use MOX. Japan is planning to use MOX in one-third of its reactors by 2010. In almost all these cases, MOX is being used or is planned on being used in one-third of cores.

The proliferation risks of reprocessing and recycling are clear. First of all, the reprocessing has generated a tremendous quantity of separated plutonium which has to be very carefully accounted for and guarded. Much of the separated plutonium – in the form of plutonium oxide – is France and the UK, and reasonably secure one believes. But a large quantity is in Russia under less certain security, and there are appreciable quantities in Japan. Second, the use of MOX in reactors means that there will be supplies of fresh plutonium fuel at MOX fabrication plants, at reactor sites, and in transport from reprocessing plants to fabrication plants to reactors.

For a time, many in the nuclear industry maintained the belief (or unexamined hope) that the plutonium being separated and recycled could not be used for nuclear weapons. They believed this because the plutonium recovered from civilian spent fuel – so-called "reactor-grade plutonium" -- has a relatively high fraction of the isotope Pu-240, around 25% for plutonium from LWR spent fuel, compared to less than 6% for weapons-grade plutonium. Pu-240 fissions spontaneously, emitting large amounts of neutrons, leading to the possibility that one of the neutrons could initiate a chain reaction before the bomb assembly reaches its maximum super critical state and thus creating a fizzle yield. Indeed, the prospect of such pre-detonation rules out the use of gun-type designs employing even weapon-grade plutonium. Unfortunately, it is now clear that reactor grade plutonium can be used for weapons. The issue was addressed in a 1994 in a National Academy of Sciences study and later described in a January 1997 U.S. Department of Energy Release[3]:

"virtually any combination of plutonium isotopes … can be used to make a nuclear weapon. … In short, reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states. Theft of separated plutonium, whether weapons-grade or reactor-grade, would pose a grave security risk."

So, in short, reprocessing and recycling already present risks. However, with the recycling activities so far restricted to Europe, the standards of security and safeguards applied to the MOX are probably high. But this cannot be counted on in a vastly expanded nuclear industry worldwide. Whatever the risks today, they will be multiplied if ever a real market develops for MOX, with middlemen and agents arranging for the purchase and sale of MOX.

And in the robust future envisioned, there will be marked pressures on countries to reprocess and recycle. First of all, the uranium demand for nuclear power relying mostly on a once-through fuel cycle will be enormous. It will be on the order of 600,000 tons of natural uranium per year. Even if eventually hundreds of millions of tons of uranium could be obtained from so far unexplored terrestrial sources and/or from seawater, there will exist strong incentives for countries to use uranium resources more efficiently.

Perhaps even more significant will be the pressure put on spent fuel disposal. If repositories are limited by heat output at time of the closure of the repositories, reprocessing could increase effective repository space by a factor of 3 or so if only

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[3] U.S. Department of Energy, *Non-Proliferation and Arms control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, January 1997.

plutonium and uranium are separated, and ten-fold or more if the separation includes Americium and the lesser actinides. It seems unwise to base our fuel cycle choices on repository availability given the high costs of reprocessing and transmutation that would be involved – and especially so if the difficulties of finding repositories is due more to politics than science. But concerns with spent fuel disposal will certainly give strong support to those who wish to reprocess and recycle, and in fact are already doing so.

No plutonium recycling – continued reliance on once-through fuel cycles

Let us say, nevertheless, that the world can keep to once through fuel cycles. How proliferation resistant would such a world be?

For sake of specificity, let's assume a 3000 GW nuclear capacity comprised half by pebble-bed high temperature gas reactors of the kind now under study in the U.S. and South Africa, each of 100 MW, and half by light water reactors (LWRs), each of 1 GW. In such a world there would be 15,000 pebble-bed reactors and 1500 LWRs, and an enrichment capacity worldwide of about 400 million SWUs per year. If one takes 2 million SWUs per year as a nominal capacity of one enrichment plant – about the size of a URENCO plant – 200 such plants would be required. A 2-million SWU plant could make about 600 bombs per year starting with natural uranium. It could make 3500 bombs per year starting with 8% uranium, the fuel enrichment of the gas-reactor fuel.

Although arguably enrichment plants could be highly centralized with capacities much greater that 2-million SWU, the wish of countries to diversify and not to put too many eggs in one basket will place some limits on centralization. And in any case, a nuclear system based on a once-through fuel cycle will involve massive flows of natural and low-enriched uranium, lots of separation plants, and lots of incentive for innovation to make isotope separation cheaper and quicker. This is especially of concern in that terrorist groups could far more readily make a nuclear weapon from highly enriched uranium than from separated plutonium.

But plutonium will also be a matter of concern in this ostensibly once-through nuclear world. Consider the scope of the spent fuel (and contained plutonium) that will be generated in such a once-through world. The spent fuel would be on the order of 50,000-70,000 tons of heavy metal per year, approximately the capacity that has been planned for Yucca Mountain (70,000 tons). So nominally we can imagine one "Yucca Mountain" being constructed every year worldwide. And each one will have to be guarded indefinitely, since after several decades, the radioactivity surrounding the plutonium will decay substantially making the spent fuel repositories prospective "plutonium mines."[4] Each repository (using the Yucca Mountain scale) would contain some 1400 tons of plutonium-239.

[4] Per Peterson, "Issues for Detecting Undeclared Post-Closure Excavation of Geologic Repositories," *Science and Global Security*, Vol. 8, No. 1, 1999; Per Peterson, "Long-term Safeguards for Plutonium in Geologic Repositories." *Science and Global Security*, Vol. 6, No. 1, 1997; Edwin Lyman and H.A. Feiveson, "The Proliferation Risks of Plutonium Mines," *Science and Global Security*, Vol. 7, No. 1, 1998.

Proliferation Resistance of New Generation Reactors and Fuel Cycles

Advanced nuclear technologies and fuel cycles under study could in principle improve the proliferation resistance of nuclear power, but whether they could do so to the extent necessary under an exuberant nuclear future must be doubted.

The concepts being examined by nuclear engineers and scientists in the U.S. and abroad include: reactor-types and/or new fuels which allow very high burn-up and produce less plutonium than do current reactors (such as, for example, the pebble-bed high temperature gas-cooled reactor); breeder or particle-accelerator driven reactors that, to the extent possible, co-locate sensitive processes (such as reprocessing) with the reactor, and do not separate the plutonium from other actinides; and schemes that restrict nuclear power to large, international energy parks that would then export to individual countries, electricity, hydrogen, or small, sealed reactors. The reactors envisioned in this last scheme would be say 40 or 50 MW and would be fueled at some central nuclear park and then sealed and sent out to client countries. The reactors would have lifetime cores, not requiring re-fueling, and at the end of the core life (say 15-20 years) would be sent back to the central facility unopened. Let's call this a hub-spoke configuration.

All these ventures are worthy of study. However, so far none of the concepts appears altogether satisfactory. The high-burn-up reactors require higher enriched fuels than light water reactors, and as indicated above, if deployed on a grand scale, would lead to vast flows of uranium and a great expansion of enrichment activities. And it is also questionable that such reactors maintained in a once-through mode could sustain a nuclear capacity of 3000 GW. The breeder and closed fuel cycle concepts generally imagine a world where the breeder reactors are restricted to "safe" countries while off limits to much of the developing world. As noted earlier, I am skeptical that such a two-tier nuclear world can long be sustained.

The third concept of large, centralized international parks appears to me the most attractive of the new proliferation resistant ideas being examined. But are international energy parks realistic alternatives on political and economic grounds? Politically, international energy parks run against the strong wish of many countries to become energy independent. Countries will also be wary of concentrating too much of their energy future in a few places, with their attendant risks of common-mode failures, disruption of transmission lines or shipping, etc.

Conclusion

All in all, it may be that nuclear power can limp along for years, maybe decades, at roughly current levels and with almost all nuclear power located in a relatively small number of highly industrialized countries, with tolerable proliferation resistance. And this possibility would be further enhanced if new-generation reactors can be deployed in the next twenty years or so. Certainly, in the margin, a few more or a few less reactors in the nuclear weapon states, in Japan, and in Europe would hardly seem to matter at all. But, in this case, we have to ask the question whether such a limited nuclear future is really worth all the attendant aggravations and real (albeit contained) risks. If not, perhaps the time has come for many countries to begin plotting a determined phase out of nuclear power!

In my view, the risks associated with a robust nuclear future are essentially irreducible even if some of the so-called "proliferation-resistant" concepts now being explored by the international community are implemented. The concept under study that holds the most promise is the development of a hub-spoke arrangement where all sensitive activities are performed at a central, perhaps international, facility with sealed nuclear reactors, electricity, or hydrogen then sent out from the central facility to the "client" states. But such a strategy faces enormous political and practical obstacles. And all the more so does the extreme of this strategy – to place all nuclear power under international control. A nuclear power system worldwide of a scope to address global warming will pose unacceptable risks of nuclear proliferation without a drastic lessening of national control either over nuclear energy or over nuclear weapons.

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