PROLIFERATION OF NUCLEAR WEAPONS AND MATERIALS TO STATES AND NON-STATE ACTORS: WHAT IT MEANS FOR THE FUTURE OF NUCLEAR POWER

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ABSTRACT

The irreducible potential contribution of nuclear power to proliferation lies in the field of nuclear knowledge, although nuclear knowledge for nuclear power is far more difficult than for nuclear weapons.

Nuclear power programs have in the past been used as a cover or an introduction to nuclear weapon programs – as in the case of India, and South Africa. In this regard, nuclear power has contributed to proliferation, but it need not.

Reprocessing plants can lead to the separation of plutonium, and although weapon-grade plutonium (more than 90% Pu-239) is preferred for making nuclear weapons, almost any plutonium from a nuclear reactor can be used to make potent nuclear weapons – even those with full yield – with somewhat greater sophistication than the first weapon used against Nagasaki.

Enrichment plants can be used to make high-enriched uranium (HEU) (80% or more favored for nuclear weapons, although 20% is the lower boundary of HEU), and that is also a problem.

But the biggest problem is the transfer of nuclear materials from large stocks in Russia or even in Pakistan to states or non-state actors.

Nuclear power without proliferation can be achieved by deepening the commitment of non-nuclear weapon states, and the resolve of nuclear and non-nuclear weapon states alike, so that all materials and support for the peaceful atom be returned if the state later decides to undertake a nuclear weapon program. Any such support or material used in the weapon program would be in violation of strengthened international undertakings, subject to serious penalties.

Given the commitment to non-proliferation, international security measures need to be introduced to supplement the accounting and reporting systems. Competitive, commercial, mined geologic repositories will reduce the present dilemma imposed by the necessity that each state dispose of its own spent fuel. These would be regulated and approved by the IAEA, as would the waste forms suitable for such disposal. Dry cask storage for 50 to 100 years would augment and reduce the cost of the geologic repositories.

Light-water reactors (LWR) – particularly the once-through approach – would be consistent with non-proliferation measures. Reprocessing would be possible, but additional security and non-proliferation measures would evidently be necessary.

Thorium-based reactors and accelerator-driven reactors would be suitable also, if economically feasible. Uranium from seawater should be seriously explored to determine whether the cost is less than the $750 per kg of natural uranium imputed to the uranium saved by the use in LWRs of plutonium from reprocessed LWR fuel.

Breeder reactors could also be safeguarded and secured, despite the fact that Pu from the breeder blanket is highly suitable for weapons.

The problems with nuclear power are those of affordability and safety. The goal of nonproliferation must be faced, but can be achieved.

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INTRODUCTION

The spread of weapons to potential adversaries has long been a concern of states, and measures have been taken to prevent this. The news as we speak is full of the word "proliferation" and war is impending between the United States and Iraq over the acquisition of "weapons of mass destruction" – WMD – by Iraq in contravention of the UN Security Council resolutions dating from the 1991 Gulf War. Iraq was found to possess chemical and biological weapons and to have an aggressive and widespread program for the acquisition of nuclear weapons. All of these were forbidden to Iraq by the UN Security Council.

"WMD" is a misnomer, since chemical weapons in general are far less effective, per kilogram, than BW or nuclear weapons. But we seem to be stuck with the term.

The consequences of use by terrorist groups of BW or nuclear weapons are detailed in a number of current publications; including some of my own posted at www.fas.org/rlg. Some of these are also available in print form, as in the September 2002 article "The Technology of Megaterror."[1] In particular, the detonation of a nuclear explosive of yield 10,000 tons of TNT (10 kt) in a densely occupied part of Manhattan during the working day could kill 200,000 to a million people. Even a 1 kt weapon would subject almost one-quarter of the area to the same lethal overpressure, and be an unparalleled catastrophe.

BW can be simply infectious as is in large part the case with anthrax, or contagious, as with measles or smallpox. A contagious BW agent such as smallpox has the potential of killing tens of millions or more, and it is fortunate that in this case there happens to be a sufficient number of doses of smallpox vaccine available to protect most Americans. Yet the epidemic would surely spread to the rest of the world, and must be prevented there too.

Our current topic is the proliferation of nuclear weapons, and that in particular is advanced by the Bush Administration as the primary reason for war with Iraq, although the purpose is sometimes cast as "regime change" in order to avoid the possession of WMD by Iraq.

The Bush Administration also objects to the sale by Russia to Iran of one to five nuclear reactors, despite the arguments by Russian officials that Iran would in any case acquire nuclear reactors, and the Russian-supplied power plants would use fuel which would be returned to Russia after being used in the reactor to produce electrical energy.

In order to discuss proliferation to states or to terrorist groups, it is a good idea to understand the nature of nuclear weapons. We will be discussing the degree to which proliferation:

- Depends on nuclear power
- Is eased by nuclear power
- Might be hindered by nuclear power

The weapons in the inventories of the nuclear weapon states (in order of acquisition of nuclear weapons: United States, Russia (as the Soviet Union), Great Britain, France, and China) are composed of highly enriched uranium (typically 90% U-235 or more) or weapon-grade plutonium (typically 93% Pu-239 or more). The "fissile material" can undergo fission in the presence of a neutron, liberating on the order of 150 MeV of energy as the fission fragments fly apart and come to a halt in the material. Nuclear fission was recognized early in 1939, after having been produced quite abundantly beginning in 1934 – especially in experiments by Enrico Fermi and his group in Rome. But the phenomenon was so bizarre to those knowledgeable about nuclear physics, that it lay almost totally unsuspected for more than four years.

Fission is a collective phenomenon of the neutrons and protons composing a heavy nucleus. The nucleus is stable against small vibrations, but if provoked by the energy associated with capturing a slow neutron or a fast neutron, the nucleus can be set into vibration of sufficient amplitude that in a long time (on nuclear scales) the two large portions of the nucleus can pinch off much in the way a liquid drop fragments into two. The repulsive electrostatic energy (Coulomb energy) between these separating portions of the nucleus drives them apart, with a kinetic energy which is a large portion of the 150 MeV. In addition, the two fission fragments are left in highly excited states, and these decay by the emission of prompt gamma rays.

Further excitation is removed by so-called beta decay – the emission of negative electrons so that a fission fragment becomes in the course of time the nucleus of an atom with nuclear charge one greater than the primary fission fragment.

Symmetric fission is rare; much more common is for fission to take place producing a heavy nucleus such as barium and a light nucleus such as krypton. From the point of view of the nuclear power engineer, the energy release in fission provides the heat which drives the plant. The energy release in gamma rays and

particularly later beta rays and decay gamma rays is a nuisance, requiring heavy shielding for the plant itself and care for hundreds of thousands or millions of years for the waste from the power plant.

The power plant design is dominated by nuclear physics considerations in keeping the reaction going in a stable fashion, and by thermal considerations, so that the fuel can be cooled to prevent excursions to damaging temperatures. Thus a nuclear power plant is of substantial size, and the fuel is substantially diluted in space and in many cases in quality (typically 4-5% U-235 in U-238 for the fuel of a light-water reactor).

In contrast, a nuclear explosive needs no cooling. It can be very small, although there are lower and upper limits to the size of a fission explosive. In energy terms, the complete fission of 1 kg of U-235 or Pu-239 (or for that matter, of U-238) yields the equivalent of 17,000 tons of TNT. A gram of high explosive is typically taken to yield 4.2 kilojoules (4.2 kJ) of energy, so that one ton of high explosive provides 4.2 GJ of energy.

The characteristic energy (PxV) in the atmosphere corresponds to 0.1 MJ per cubic meter, so that 1 kt of energy would double the energy density in 4×10^7 cubic meters of air – the volume of a hemisphere 270 m in radius or 540 m diameter.

In any case, nuclear explosions are bad news for cities and if detonated close enough, even for missile silos or other very robust structures.

To achieve a nuclear explosive requires that of the 2.5 neutrons from a U-235 fission (3.5 from a Pu-239 fission) more than one remain within the initial mass in order to cause a divergent chain reaction. In a nuclear reactor, precisely one neutron per fission goes on to cause a succeeding fission – in a time on the order of 0.01 microseconds for a fast-neutron reactor, and closer to a millisecond for a thermal reactor. In the fissile metal of a nuclear explosive, a neutron travels only on the order of 7 cm before causing a fission, so the generation time is on the order of 10^{-8} seconds. This is important because if the generation time is very long, a divergent fission reaction only gradually increases the energy density in the material, which will gently disassemble rather than explode.

But with achievable generation times in fissile metal, the energy density rises in a time short compared with the sound transit time across the material, so that it disassembles at speeds in a time comparable with the generation time, but at an exceedingly high energy density.

The efficiency of the plutonium bomb which destroyed Nagasaki in August 1945 was on the order of 20%. It contained about 6 kg of Pu, and yielded almost 20 kt of energy.

The uranium bomb which destroyed Hiroshima three days earlier had an energy release of some 13 kt but contained about 60 kg of uranium. Its efficiency was thus on the order of 2%.

Although other fissile isotopes can in principle be used to make nuclear explosives (in particular, U-233 and Np-237), such materials are not widely available.

So proliferation has usually been taken as concerning the availability of highly enriched uranium or plutonium.

One of the early cooperative measures against proliferation of nuclear weapons was the first Atoms for Peace Conference in Geneva, Switzerland, in 1955. President Eisenhower and his advisors felt that by cooperating with other nations on the peaceful uses of atomic energy, one could reduce the force of the argument that a state needed to acquire nuclear weapons or nuclear reactors in order to obtain the peaceful benefits of nuclear energy – the industrial and medical uses of radioisotopes, and the like. This began an intensive cooperation between the United States and others in education in nuclear energy, and in active collaboration.

The commitment to cooperation and peaceful uses was formalized in the Non-Proliferation Treaty (NPT) which entered into force March 5, 1970. The NPT distinguished between nuclear weapon states (NWS) and non-nuclear weapons states (non-NWS), defining a nuclear weapon state as one which had tested a nuclear weapon or other nuclear explosive device prior to January 1, 1967.

The NPT was open for signature by any state and entered into force after a sufficient number had adhered, so that each state could sign up as an NWS (only 5 admitted) or a non-NWS.

Under the Treaty, the NWS committed themselves not to transfer nuclear weapons or nuclear weapon technologies to a non-NWS, and the non-NWS committed not to acquire or accept nuclear weapons.

You will note that other nations now have tested nuclear weapons – namely, India and Pakistan – and South Africa joined the NPT only after revealing that it had made six Hiroshima-type bombs, which had been disassembled and the HEU diluted so that it was no longer directly usable in weapons. Israel is also widely regarded as having **a** substantial number of nuclear weapons. But these states cannot enter the NPT in either NWS or non-NWS category, and that is a problem which needs to be overcome if their nuclear weapons are to

be made as controllable as possible and safeguarded as well as they might be. The NPT gave rise to the Vienna-based International Atomic Energy Agency (IAEA) which operates a system of safeguards by which each non-NWS demonstrates that whatever nuclear facilities it has are not in violation of the commitment not to acquire nuclear weapons.

The IAEA has from the beginning defined a significant quantity (SQ) of plutonium as 8 kg; the SQ for HEU is 25 kg. These numbers are somewhat obsolete, in that the Nagasaki bomb contained only 6 kg of Pu, and it is widely discussed that some 20 kg of U-235 would suffice to make a powerful nuclear weapon if it were used in an implosion device rather a "gun" type nuclear explosive.

TYPES OF NUCLEAR EXPLOSIVE

More detailed information is available in other publications, including a recent book of which I was co-author.[2]

In a gun-type device, U-235 metal is maintained in a sub-critical configuration by having two cylinders or hemispheres separated so that each one is less than a critical mass. Thus, a fission in one from either spontaneous fission of U-238 or a cosmic ray or the action of an alpha particle on a light impurity would give rise to 2.5 neutrons, and fewer than one would go on to cause another fission in the lump. The U-235 might be surrounded by a reflector of U-238 or other material, in order to allow criticality with substantially less uranium than the 60 kg or so which forms a "bare-sphere critical mass." In principle, therefore, a hemisphere of U-235 in its hemispherical reflector could be propelled by ordinary gunpowder down a short gun barrel in order to impact on a similar configuration. A pulse of neutrons timed to occur at the moment of contact would then give rise to the fission chain reaction, doubling every 0.01 microsecond, and leading to a Hiroshima-like yield.

Although the Hiroshima and Nagasaki bombs each weighed on the order of 4000 kg, even a gun-type system (particularly without the weapon case and the ability to be dropped from an airplane) could be much lighter.

Although when the Los Alamos National Laboratory was formed in March 1943 (as site Y of the Manhattan Project), it was planned to use gun assembly for the plutonium weapons, it was discovered in 1944 that Pu-240 has a very high spontaneous fission rate, and enough Pu-240 was present in the Pu from production reactors that the gun-type assembly would be hopelessly "pre-initiated." Self-generated neutrons would induce the chain reaction as soon as the approaching masses exceeded criticality by a slight amount, and only a small amount of fission yield would be required to compensate the tiny energy associated with the propellant assembly of the masses. A Pu gun would thus have a "fizzle yield" far less than 1 kt.

Attention was then focused on much more rapid assembly, requiring much higher kinetic energy per unit mass of the Pu. This could be obtained by the use of high explosive, which in fact does not assemble solid material; the detonation wave in the high explosive and the corresponding shock in adjacent solid material so far exceeds the strength of materials that hydrodynamics rather than structural mechanics is the appropriate model. The initial Nagasaki weapon consisted of a solid ball of Pu (with a cavity at its center for the switchable neutron source) surrounded by tons of high explosive. Thirty-two individual detonation points on the high explosive were each fitted with large explosive "lenses" to convert the diverging detonation waves into a single spherically converging detonation wave to compress the Pu metal.

It may not initially be obvious that compression of a fixed amount of metal can make a sub-critical system supercritical, but the effect is apparent when a child's balloon collapses, and the not obviously dirty skin of the balloon now becomes essentially black as the balloon has shrunk. In fact, doubling the density reduces by a factor four (the square of the compression) the amount of material required to form a critical mass. The implosion technique allowed assembly to be achieved in a time short enough that the pre-initiation probability could be maintained below 10%. And, as detailed in a 1993 paper by J.C. Mark, even a fully pre-initiated system would have a fizzle yield of at least 1 kt – equivalent to 1000 tons of TNT.[3] Later implosion weapons used shells rather than solid spheres of metal, and evidently required less plutonium. In a 1994 report of the National Academy of Sciences, the typical plutonium content of a U.S. nuclear weapon was taken as 4 kg.[4]

THE PRODUCTION OF NUCLEAR MATERIALS

With the advance of industrial technology over the six decades since the first divergent nuclear reaction at Stagg Field in Chicago, the basic knowledge for building nuclear weapons has spread – in part through

declassification by the United States and other governments. Furthermore, explosive technology has become a common tool of industry, and electrical circuitry for timing, detonation, and the like is far more widely available.

Unfortunately, the manufacturing of a gun-type device is quite simple and within the capability of many terrorist groups – if they had the U-235 metal.

The production of U-235 is a difficult but now well established process. Most enrichment capacity at present is used to provide fuel for LWRs, and enriches from the 0.7% U-235 in natural uranium to 4 or 5% in the material to be used to make LWR fuel. Early enrichment techniques were the electromagnetic separation (Calutron in U.S parlance) as practiced at Oak Ridge, TN; and gaseous diffusion by which a porous "barrier" is used to permit UF_6 containing U-235 to pass at a speed which slightly exceeds (by the inverse square root of the molecular mass) the seepage rate of UF_6 gas containing U-238. Very many stages of such a "cascade" can be used to enrich to 90% or more U-235.

Although the United States still uses gaseous diffusion, much of the remainder of the world's production capacity is in the form of gas centrifuge capacity, using the same UF_6. To provide a given enrichment capacity (measured in Separative Work Units – SWU) the gaseous diffusion plants require about 40 times as much power as does the centrifuge.

A SWU costs about $100 on the market, and 1 kg of weapon-grade HEU contains about 220 SWU – so has a separative work value on the order of $22,000. To make 500 tons of HEU such as the United States is purchasing from Russia in the "Megatons to Megawatts Program" is clearly expensive ($11 billion), but to make 120 kg in order to have two gun-type bombs would correspond then only to about $3 million. And simply reckoning amortization of plant, it would require an investment of less than $30 million in centrifuges if such could be copied and manufactured locally.

THE PROLIFERATION HAZARD FROM EXCESS WEAPON MATERIAL

But the proliferation problem in the modern world is exacerbated by the presence of very large stocks of weapon usable material no longer prized for nuclear weapons.

The United States had a peak of 33,000 active nuclear weapons in 1967 and the Soviet Union some 45,000 in 1986. Nuclear weapon holdings in each country are now down to about one-third of that level, but many of the nuclear weapons and essentially all of the nuclear weapon material still remains. HEU from weapons can be diluted cheaply to form feed for producing reactor fuel, and about half of the SWUs now represented in low-enriched uranium (LEU) sold annually by USEC (United States Enrichment Corporation) come from diluted Russian weapon HEU. This 500 tons of excess weapon HEU is being purchased from Russia over a period of 20 years for about $12 billion, and more such material is available.

Evidently, having many tons of excess weapon HEU around for more than 20 years is not a good idea, and it would be both urgent and practical to pay Russia up front to dilute the HEU to the upper bound of LEU – 19.9% – to reduce the possibility that such materials could be stolen or otherwise diverted into proliferant nuclear weapons.

IMPLOSION WEAPONS CAN BE MADE FROM REACTOR-GRADE PLUTONIUM

Although Pu-239 is fiercely radioactive, the decay scheme is essentially all alpha particles, so that Pu metal, usually shielded by an inert metallic coating – can safely be picked up in the bare hands. I have done it, with two hemispheres such as those used in the Nagasaki bomb. Early production from the Hanford reactors corresponded to some 500 megawatt-days per ton of uranium in the reactor, and thus produced very little of the second-order capture material – Pu-240 The Pu in the spent fuel from an LWR irradiated at 40,000 megawatt-days per ton of uranium has far more Pu-240 – typically on the order of 25%, so that the pre-initiation probability for a Nagasaki-type bomb is substantial. This was the burden of the 1993 Mark paper, where he showed that there would still be a significant probability of obtaining full yield and a high probability of obtaining partial yields in the range of 5 kt, and that the yield would in no case fall below 1-2 kt.

This point was addressed also in the 1994 NAS document.[5] The conclusion is that the reactor-grade Pu, although containing Pu-240 with a high rate of spontaneous fission and the highly penetrating gamma rays from Am-241 do not prevent the fabrication of nuclear weapons from R-Pu, although the heat generated by Pu-238 and Pu-240 require "careful management of the heat in the device." And the Committee concluded:

"In short, it would be quite possible for a potential proliferator to make a nuclear explosive from reactor-grade plutonium using a simple design that would be assured of having a yield in the range of one to a few kilotons, and more using an advanced design. Theft of separated plutonium whether weapons-grade or reactor-grade, would pose a grave security risk."

We are now ready to look at the nuclear fuel cycle to identify points of proliferation hazard.

THE NUCLEAR FUEL CYCLE AS SEEN BY A POTENTIAL PROLIFERANT

The product of an enrichment plant producing LEU for LWRs is hardly more usable than natural uranium for nuclear weapons. About half the SWU content has been invested, but this is not a major step toward weapon uranium. However, almost any enrichment facility could be reconnected to produce HEU, and this could be done not only in continuous fashion, but in a batch or "campaign" mode. Thus IAEA inspects enrichment facilities to ensure that they do not produce HEU.

Of course clandestine enrichment facilities are, by definition, not inspected. Yet there is available a lot of intelligence information which might identify such clandestine plants, and they would be of substantial size if the requirement were to produce HEU for hundreds or thousands of nuclear weapons. They would not be so large for a few nuclear weapons.

The spent fuel from reactors is fiercely radioactive, although it can evidently be processed (reprocessed) to obtain the plutonium. This was done first in the production reactors, and is routinely practiced at La Hague, France, and Sellafield, England. Japan is also building a large facility at Rokkasho, modeled after the COGEMA plant at La Hague. Two facilities at La Hague, UP2 and UP3, each handle 800 tons of spent fuel per year and thus each separate about 8 tons of Pu annually. Sellafield produces also about 8 tons of Pu per year. At both plants the Pu is held in the form of oxide, which for criticality reasons is welded into steel cans each containing about 2 kg of Pu.

A state setting up a so-called "closed" fuel cycle requiring the separation of Pu could quite readily store a lot of this oxide for the fabrication of mixed-oxide fuel (typically 5% Pu and 95% U-238).

It is, unfortunately, a simple matter to reduce plutonium oxide to plutonium metal, as was done in the early days of the nuclear weapon program. For the production of a few nuclear weapons, even with R-Pu with its more intense radiation field, such activities could be done in an ordinary glove box.

RESEARCH REACTORS

Unfortunately for the prospect of proliferation, dozens of research reactors the world over were built to use HEU. Fresh fuel for these reactors could be processed chemically to obtain HEU metal, for nuclear explosives. A reduced enrichment program for research reactors has been in existence since the 1970s but needs to be reinvigorated. The recent transfer of Vinca research reactor HEU (instigated and paid for by Ted Turner's Nuclear Threat Initiative) is a case in point.

A state desiring nuclear weapons could perfectly well set up enrichment facilities or a production reactor without any connection to a commercial nuclear power program. It would require nuclear expertise, but this is a lot easier in the case of production reactors or nuclear weapon design than is required for high-performance power reactors. Hence the acquisition of nuclear weapons is in no way dependent on having a nuclear power sector.

But every state with nuclear power to some extent facilitates the acquisition of nuclear weapons by another, if the materials are not properly safeguarded and physically protected. Unlike safeguards for NNWS, which are the joint responsibility of the state and the IAEA, physical protection is almost totally the responsibility of the state.

Can nuclear power hinder proliferation? The idea behind Atoms for Peace and also the NPT is that cooperation between NWS and NNWS on the peaceful uses of nuclear energy can reduce the incentive to have a dual-use program. In principle, nuclear power can be used to reduce the stocks of weapon-usable material. Some 34 tons of excess weapon plutonium have been identified by the United States, and extensive discussions and negotiations between the United States and Russia have taken place to organize the disposition of excess weapon plutonium on the two sides. Russia has insisted that because a great deal of money and blood went into the acquisition of this plutonium, it is too valuable to dispose of in any way which does not obtain the energy value of the plutonium. The United States takes a more reasoned view, considering that "sunk costs" are just

that, and should not enter into the valuation of the material. Together with John Holdren**,** I have participated for many years in these discussions and was a member of the five-person U.S. team of the U.S.-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium which studied such things six years ago or so.[6]

In fact, those who make MOX fuel have now publicly stated that they would not accept excess W-Pu even if it were given to them without charge, because it costs more to make MOX fuel from free plutonium metal than it does to make the equivalent UOX fuel from scratch-mining and milling uranium, purifying and enriching, and fabricating the fuel.

As for the energy argument regarding excess weapon plutonium, precisely the same energy is locked up per gram in the depleted uranium reject from the enrichment plants, of which there is a thousand times more than there is plutonium. Of course, it costs money to release this energy from U-238 (investment in the form of a fast breeder reactor), just as it costs money to release the energy from Pu-239.

But the commitment of Russia to the use of excess W-Pu in reactors persists and has diverted the U.S. program from the cheaper approaches of vitrification of excess W-Pu together with fission products to a program to use MOX in U.S. reactors.

So although the nuclear power industry in principle can burn both W-Pu in LWRs and also even more effectively in fast breeder reactors, the costs are very substantial.

WHAT IS TO BE DONE?

It is inadequate to protect just the easiest proliferation targets, because, unlike earthquakes or volcanos, the proliferators can shift his attention. Therefore, there are a number of points which need to be covered in guarding the commercial power reactor against proliferation:

- Competitive mined geologic repositories will consolidate much of the fuel both underground and in interim above-ground dry storage. But these will need to be regulated by the IAEA for adequacy, as will the acceptable spent fuel and high-level waste forms to be stored there.
- Security must be provided in addition to accounting, and security should be guaranteed by an international organization.
- Interim dry cask storage should be consolidated and provided on a competitive commercial basis, with both safeguards and physical security provided IAEA and the United Nations.
- Reduced enrichment for research reactors should be pursued, although this is less important than the other items on this list.
- New types of reactors should be considered, through an internalization of nonproliferation and security costs. Reactors and fuel cycles which require the separation of plutonium will cost more to secure than those which process plutonium and higher actinides together into highly radioactive fuel. Some candidates are:
    - The integral fast reactor with pyro processing takes advantage of the fast reactor's tolerance for modest amounts of fission products and the ability to burn higher actinides. Fission product removal is necessary for the fast reactor (or, for that matter, for the LWR). But for the LWR, higher actinides accumulate and tend to poison the reactors.
    - Thorium reactors have benefits for periods up to 100,000 years in reduced activity of the waste.
- Any reactor must prevent irradiation of uranium or even thorium to make a weapon-usable material.
- Enrichment facilities need also to be safeguarded.
- Reprocessing, together with the storage of the fuel; MOX fabrication, the storage of MOX fuel and its transport and storage at reactors must all be safeguarded and protected, if reprocessing and MOX play a role in the chosen solution.

CONCLUSION

The problems with nuclear power are those of affordability and safety. The goal of nonproliferation must be faced, but can be achieved. But "must be faced" means that eliminating the contribution of nuclear power to proliferation of nuclear weapons is a requirement–not an option.

NOTE ON THE PRESENTATION BY PATRICK LEDERMANN

During the session of October 4, 2002, Patrick Ledermann presented a discussion which included a substantial portion on the benefits of reprocessing and on reducing the volume of waste which must go to the repository.

His slide showed the progress made in reduction of volume and was clearly labeled "per ton of uranium." In 2002, the total "long-lived waste after conditioning" amounts to about 0.5 cubic meter per ton of uranium. In contrast, Ledermann shows "direct disposal option (estimation)" as 2 cubic meter per ton of uranium.

But in his presentation, M. Ledermann referred to this 0.5 cubic meters as being the volume of the waste from "8 fuel elements." Since there are 200+ fuel elements containing about 100 tons of uranium in a normal PWR, 8 fuel elements should contain 4 tons of uranium, and not a single ton.

During the presentation itself, however, I questioned the validity of these small waste volumes. Recalling a recent report done for the Scientific and Technological Options Assessment of the European Parliament. I searched the web and found the information on page 75 of the report, which I excerpt:[7]

POSSIBLE TOXIC EFFECTS FROM THE NUCLEAR REPROCESSING PLANTS AT SELLAFIELD AND CAP DE LA HAGUE PE 303.110

8.1.2. Final volume of waste

Reprocessing requires the final disposal of vitrified wastes plus the direct disposal of some spent fuel, and various additional wastes produced through reprocessing, such as bituminised waste, hulls and nozzles, technological waste, and most separated plutonium and uranium which is not re-used. Not only does the direct disposal option produce fewer waste categories, it also produces smaller volumes of final waste. Spent MOX fuels have much higher heat outputs than spent uranium fuels, and thus require much longer storage times before disposal and/or much larger volumes in any final repository[a49]. These factors imply much larger costs for handling spent MOX fuel than ordinary uranium fuel.

According to preliminary specifications defined by ANDRA in 1998 for final disposal in a deep ground repository in clay[b50], the same type of small galleries -- only with different lengths -- could be used to store either canisters of vitrified waste, or UOX or MOX spent fuel. One gallery could receive 8 canisters of vitrified waste, or 4 so-called S3U packages, each containing 3 assemblies of spent UOX, or 2 SM packages, each containing 1 assembly of spent MOX. The respective length of the galleries would be around 20, 28 and 17 m; the volume of one package (including overpack of the canister) is around 0.5, 4.1 and 1.9 m^3 . Assuming that the reprocessing of one UOX assembly in La Hague produces around one canister of vitrified waste, these ANDRA concept lead to the following volume orders:

- *Disposal of vitrified waste from the reprocessing of 1 UOX assembly: 0.5 m^3 of package, 12.5 m^3 of package plus structure;*
- *Direct disposal of 1 spent UOX assembly: 1.4 m^3 of package, 11.5 m^3 of package plus structure;*
- *Direct disposal of 1 spent MOX assembly: 1.9 m^3 of package, 42.5 m^3 of package plus structure.*

These results can be used for a basic comparison of the two options: (a) the direct disposal of 8 UOX and (b) the reprocessing of 7 UOX plus the direct disposal of 1 MOX[c51]. For 8 assemblies, the reprocessing option only produces 5.5 m^3 of HLW, while the direct option produces 11 m^3 . But, if including the volume of the structures in the

calculation, the ratio is of 92 m³ for direct disposal against 130 m³ for reprocessing. Again, this is not taking into account the additional waste in the reprocessing option, like unrecycled uranium, technological and process ILW from reprocessing, etc.

[a49] *Belgian radioactive waste management schemes envisage 3 times the volume in final storage for spent MOX than for spent uranium fuels. The costs are correspondingly higher.*

[b50] *Communication by ANDRA, 2000.*

[c51] *This is assuming that the reprocessing of 7 UOX produces the right amount to produce 1 MOX, that 7 UOX + 1 MOX deliver as much energy as 8 UOX and that in the reprocessing option all UOX and none of the MOX is reprocessed.*

In preparing this note, I wrote P. Ledermann on 10 October, 2002, to obtain from him the volume of storage ANDRA would consume for the options of direct disposal and the disposal of vitrified waste, and met with him and Philippe Leconte of CEA Saclay on November 29, 2002. However, I had sensed an error in the STOA document and confirmed with WISE-Paris staff that they did indeed err in assigning 0.5 m³ of conditioned volume to the product of a single fuel assembly, instead of two assemblies.

Thus, according to WISE-Paris, the relevant volume "of package plus structure" per fuel assembly should be 6.25 m³ for the processed waste. One UOX assembly in direct disposal will require 11.5 m³ in package plus structure. If, as seems likely, the MOX assembly is not reprocessed but is subject to direct disposal, this one MOX assembly's 42.5 m³ of "package plus structure" would correspond to 42.5/7 or about 6.2 m³ of "package plus structure" apportioned to each of the 7 UOX assemblies which have been reprocessed.

Then the grand balance for UOX direct disposal would be the 11.5 m³ previously stated, in contrast to (6.25 + 6.1) m³ for the reprocessing route—no benefit for reprocessing, even in the largely irrelevant measure of underground volume required. I communicated this information to Ledermann and looked forward to the CEA response.

At Saclay we discussed a 28 November paper by Philippe Leconte, "Comparative Dimensions of a Disposal Facility." This paper assumes that MOX will ultimately be burned to the same GWj/t as uranium oxide fuel (UOX3); notes that WISE-Paris used the uncompacted rather than the compacted volume for hulls and end-pieces; that bitumen is no longer used, but that the materials previously incorporated in bitumen now go to the CSD-V-- that is, glass.

CEA's position is that, although MOX spent fuel is not presently reprocessed, "the most probable case is reprocessing which must be considered first." That may or may not be true, but in any case, we have both numbers. For the unreprocessed MOX, the total for eight fuel elements is 4.35 cu.m. The total for eight UOX, according to CEA numbers, is 10.46 cu.m.

CEA declines to quote any volumes for the repository (e.g., overpack and structures) because ANDRA has not completed its studies. But CEA maintains that "... it is the excavated volume which should matter in terms of cost." The argument is that repository volume is very scarce, and that this is a critical element in the acceptability of nuclear power, and that it is not the cost of excavation but the scarcity of repository volume in France which is dominant.

CEA assumes that the long fuel assemblies require a large amount of excavation for turning from the vertical to the horizontal, or in the horizontal plane. And that different volumes of excavation are required for the different diameters of packages, and must be taken into account.

In any case, I learned that the plan is to have only a single layer within the clay formation, and not multiple layers of tunnels and that the plan area required per package is determined by limiting the temperature at the package surface to 100°C.

In response, I stated that it is not acceptable to have no estimate at all of the total volume, and that CEA should make such an estimate, based on current ANDRA papers. Furthermore, one should evaluate the two approaches: one of automated handling of the packages, so that one does not need a biological radiation shield; and the alternative of emplacing packages with their shields, which might be done with workers underground or with automation

In particular, the rotation of the long fuel assemblies can be accomplished with a narrow cut at the mid-height of the tunnels (for horizontal rotation about a vertical axis), or a similar approach for the rotation from a vertical shaft to the tunnel (about a horizontal axis).

As for the ultimate limit governed by a 100°C temperature-- 225 sq.m per UOX assembly vs. 22-45 sq.m for glass from UOX1, supporting analysis is needed.

MY JUDGMENT: Despite the impressive progress made by CEA and COGEMA in reducing the volume of waste packages at La Hague, no waste or spent fuel has yet been emplaced in a repository. Packaged waste exists at La Hague using bitumen and much larger volumes per fuel element. MOX may or may not be reprocessed; The interesting and valuable data provided by CEA is inadequate to guide COGEMA and nuclear power activities in France or the world, because the overall program cost is determinative, and not the volume of the waste packages without overpack or structure.

This discussion emphasizes the benefit of the availability of commercial, competitive, mined geologic repositories to supplement and in many cases to supplant the insistence on disposal of waste or spent fuel in a repository within the state producing the nuclear energy.

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The following pages contain the text for the transparencies used by Richard Garwin during his presentation at the symposium *Energy and the Environment: The Role of Nuclear Power* at the University of Michigan on October 4, 2002.

Proliferation of Nuclear Weapons and Materials to States and Non-State Actors:

What it Means for the Future of Nuclear Power

by

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A presentation in the seminar series
Energy and the Environment:
The Role of Nuclear Power

October 4, 2002

We will be discussing the degree to which proliferation

- o Depends on nuclear power
- o Is eased by nuclear power
- o Might be hindered by nuclear power.

   Power plant design is dominated by nuclear physics considerations in keeping the reaction going in a stable fashion, and by thermal considerations, so that the fuel can be cooled to prevent excursions to damaging temperatures. Thus a nuclear power plant is of substantial size, and the fuel is substantially diluted in space and in many cases in quality (typically 4-5% U-235 and U-238 for the fuel of a light-water reactor).

In contrast, a *nuclear explosive* needs no cooling. It can be very small, although there are lower and upper limits to the size of a fission explosive. In energy terms, the complete fission of 1 kg of U-235 or Pu-239 (or for that matter, of U-238) yields the equivalent of 17,000 tons of TNT. A gram of high explosive is typically taken to yield 4.2 kilojoules (4.2 kJ) of energy, so that one ton of HE provides 4.2 GJ of energy.

The characteristic energy (PxV) in the atmosphere corresponds to 0.1 MJ per m^3, so that 1 kt of energy would double the energy density in $4x10^7$ m^3 of air-- the volume of a hemisphere 270 m in radius or 540 m diameter.

With achievable generation times in fissile metal, the energy density rises in a time short compared with the sound transit time across the material, so that it disassembles at speeds in a time comparable with the generation time, but at an exceedingly high energy density.

The efficiency of the plutonium bomb which destroyed Nagasaki in August 1945 was on the order of 20%. It contained about 6 kg of Pu, and yielded almost 20 kt of energy. The uranium bomb which destroyed Hiroshima three days earlier had an energy release of some 13 kt but contained about 60 kg of uranium. Its efficiency was thus on the order of 2%.

Atoms for Peace Conference in Geneva, Switzerland, in 1955.

The Non-Proliferation Treaty entered into force March 5, 1970. The NPT distinguished between nuclear weapon states (NWS) and non-nuclear weapons states (NNWS), defining a nuclear weapon state as one which had tested a nuclear weapon or other nuclear explosive device prior to January 1, 1967…

The IAEA has from the beginning defined a significant quantity-- SQ-- of plutonium as 8 kg; the SQ for HEU is 25 kg. These numbers are somewhat obsolete, in that the Nagasaki bomb contained only 6 kg of Pu, and it is widely discussed that some 20 kg of U-235 would suffice to make a powerful nuclear weapon if it were used in an *implosion* device rather than in a *"gun"* type nuclear explosive.

Pu can be used *only* in an implosion system. And not only "weapon-grade" Pu (>90% Pu-239), but also "reactor" Pu with 25% Pu-240.

Hiroshima and Nagasaki weapons each ~ 4,000 kg. Current simple weapons might be 500-1000 kg. Some <50 kg.

Unfortunately, the manufacturing of a gun-type device is quite simple and within the capability of many terrorist groups-- if they had the U-235 metal.

Enrichment: "electromagnetic" (Calutron); gaseous diffusion; gas centrifuge.

One SWU costs ~$100. One kg of 95% U-235 contains 220 SWU. US-Russian "HEU deal" for 500 tons HEU ~$12 B…

But 120 kg of HEU contains $2.6 M in separative work.

WHAT IS TO BE DONE?

One cannot just protect the easiest proliferation target, because, unlike earthquakes or volcanos, the proliferator can shift his attention. Therefore, there are a number of points which need to be covered in guarding the commercial power reactor against proliferation:

o Competitive mined geologic repositories will consolidate much of the fuel both underground and in interim above-ground dry storage. But these will need to be regulated by the IAEA for adequacy, as will the acceptable spent fuel and high-level waste forms to be stored there.

Security must be provided in addition to accounting, and security should be guaranteed by an international organization.

As indicated, interim dry cask storage should be consolidated and provided on a competitive commercial basis, with both safeguards and physical security provided IAEA and the United Nations.

o   Reduced enrichment for research reactors should be pursued, although this is less important than the other items on this list.

o New types of reactors should be considered, through an internalization of nonproliferation and security costs. Reactors and fuel cycles which require the separation of plutonium will cost more to secure than those which process plutonium and higher actinides together into highly radioactive fuel. Some candidates:

-    The integral fast reactor with pyro processing takes advantage of the fast reactor's tolerance for modest amounts of

fission products and the ability to burn higher actinides. Fission product removal is necessary for the fast reactor (or, for that matter, for the LWR). But for the LWR, higher actinides accumulate and tend to poison the reactors.

-    Thorium reactors have benefits for periods up to 100,000 years in reduced activity of the waste.

-    Any reactor must prevent irradiation of uranium or even thorium to make a weapon-usable material.

-    Enrichment facilities need also to be safeguarded, as must be reprocessing, together with the storage of the fuel of the MOX fabrication, the storage of MOX fuel and its transport and storage at reactors.

IN GENERAL

- **The nuclear fuel cycle in *all* states must be safeguarded and provided adequate physical security, backed by international rights and security forces.**

- **Costs of security must be included in choice of fuel cycle and will favor those approaches which do not have weapon-usable material such as highly enriched uranium or separated Pu of whatever isotopic composition.**

- **Localities or regions for which adequate security cannot be provided must limit their nuclear facilities to those most resistant to diversion or proliferation.**