Accelerator-based nuclear systems: their potential for civilian and military applications[*]

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June 23, 1998

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[*] Briefing paper prepared for the European Parliament hearing "Plutonium Choices, and Novel Actinide Engineering" on 24 June 1998.

1 Executive summary

Accelerator-driven spallation neutron sources are the most effective method for producing large quantities of neutrons.

While this method has been known for decades, it has only recently become economically attractive for breeding large quantities of nuclear materials, such as tritium or plutonium, or for driving subcritical reactors that may possibly produce electricity or burn plutonium and radioactive wastes.

Since accelerator-based systems are roughly ten times more productive than reactors of a similar size, their use is now planned by nuclear weapon States for the large scale production of tritium.

However, this increased productivity makes such systems also highly attractive to potential nuclear proliferators to breed plutonium and tritium. The latent nuclear proliferation and terrorist threat of tritium is that it dramatically facilitates the use of reactor-grade plutonium for making highly efficient nuclear weapons. Only a few grams of tritium are needed to boost a warhead.

In other possible applications (electricity generation, actinide burning, and high-level waste transmutation) the potential advantages of accelerator systems include some added flexibility in reactor control and possibly a higher productivity than critical reactors. However, these advantages are marginal rather than radical, especially considering the additional cost, complexity, and proliferation risks associated with using accelerators.

Overall, accelerator-based systems are not better than fast-breeder systems. Moreover, they do not overcome the fundamental problem that all feasible actinide and high-level waste transmutation schemes pose: greater environmental and political risks than the "once through" nuclear fuel cycle.

In principle, the irreversible withdrawal of plutonium is an intrinsic quality of any plutonium burner. However, whatever the method, there are fundamental limitations: in particular, unavoidable contamination and process losses will be in the percent range, which imply that deep geological disposal cannot be eliminated. These conclusions are in agreement with a recent assessment by the U.S. National Research Council [1]. Moreover, a factor substantially less than one hundred times reduction of plutonium stocks over several decades is not acceptable from the nonproliferation point of view.

Concerning the disposal of plutonium, accelerator-driven technology has the disadvantage that it can readily be used for plutonium production and would then be ten times more productive than reactor-based systems. Finally, the development of high-current accelerators is fostering the proliferation of nuclear weapons and of new types of weaponry such as beam weapons and antimatter weapons.

2 History

Plutonium was first produced in 1941 by irradiating uranium by neutrons obtained by bombarding a target with deuterons accelerated in a cyclotron. From this time until Fall 1943, particle accelerators were the sole source of plutonium.

In the United States, the first attempt to use an accelerator to produce special nuclear materials in large quantities was made in the early 1950s under a classified project called MTA (materials testing accelerator). The objective was to produce plutonium and tritium for the weapons programme using coal-generated electricity. At the time, the uranium was mostly bought from the Belgian Congo and South Africa. However, the project was abandoned when substantial uranium deposits were discovered in western United States. Construction of the MTA had already begun, and part of the accelerator had operated successfully.

Extensive investigations on the possible use of accelerators in the nuclear fuel cycle resumed in the late 1970s under the U.S. Department of Energy Nonproliferation Alternative Systems Assessment Program (NASAP). The conclusion was that ordinary nuclear reactors using the "once through" (i.e., no reprocessing) fuel cycle were best from the point of views of economics and nonproliferation.

Accelerator-based concepts were revived in the mid 1980s as an alternative for producing tritium to supply military needs. It is in this context that the idea of coupling an accelerator to a subcritical nuclear power reactor was revived as well (e.g., at Los Alamos, by Bowman, et al.). When publically announcing in 1993 his "energy amplifier" concept, Carlo Rubbia created much confusion because his project was a dream machine, which combined many attractive options (e.g., spallation, sub-criticality, passive safety, liquid lead, thorium, reprocessing, etc), and which assumed that all these features would work perfectly and be compatible with one another.

Since then, there have been many critical appraisals of the "rubbiatron" and of similar concepts. Moreover, an extensive comparison of reactor- and accelerator-based systems for the transmutation of nuclear wastes has been published by the U.S. National Research Council [1].

3 The key advantage of accelerators: spallation

The physical process used with accelerators is called “spallation”. Spallation takes place when a high energy particle hits a complex nucleus, and neutrons are ripped, or spalled, from it.

The first advantage of spallation is that it generates in the target ten times less heat per neutron that fission does in a reactor:

- fission of uranium: about 500 MeV per useful neutron;
- spallation of lead: about 50 MeV per useful neutron.

Second, spallation produces at least ten times less nuclear waste than fission. Disposal of heat and nuclear waste are major cost drivers in any neutron production facility.

Third, spallation enables one to reach neutron fluxes higher than with critical reactors.

For these reasons, modern neutron research facilities tend to use spallation neutron sources.

Similarly, such sources are used by the military for simulating nuclear weapons effects, for studying nuclear weapons physics, and for neutron-radiography of nuclear weapons components. These uses, however, are only part of the nuclear proliferation implications of spallation.

4 Production of plutonium, U-233, tritium, etc.

When neutrons are absorbed in natural uranium, they produce plutonium. When absorbed in thorium, they produce uranium-233, and when absorbed in lithium or helium-3, they produce tritium. All three products are essential materials for nuclear weapons. Moreover, accelerators can be used to breed large amounts of plutonium that could be burnt as mixed oxide fuel (MOX) in ordinary power reactors.

Accelerator-based systems are roughly ten times more productive than reactors of a similar size for making large quantities of special nuclear materials for military or other needs. However, compared with reactors burning inexpensive nuclear fuel, the technique has only recently become economically attractive. Moreover, the required technology (which could have been developed earlier) is coming to fruition only now, mainly as a result of developments made under the U.S. Strategic Defense Initiative and of the construction of large accelerators at laboratories such as CERN.

In the United States, the "Accelerator production of tritium" (APT) and "Accelerator transmutation of waste" (ATW) projects are based on technology developed for the "Ground test accelerator" (GTA), a prototype particle beam weapon.

TRISPAL, the French project to produce tritium by spallation, plans to use accelerating cavities similar to those developed at CERN for the LEP accelerator.

CERN-type superconducting accelerating cavities are now under consideration for use at both the APT and TRISPAL.

Production of special nuclear materials is the only application in which the advantages of accelerators are fully used, i.e., high productivity with considerably less heat and nuclear waste.

5 Military importance of tritium production [2]

Tritium is the essential ingredient which enables the construction of compact and light-weight nuclear weapons. Tritium also insures that such weapons are reliable and extremely safe. The recent nuclear tests by India and Pakistan demonstrated this fact: most of the explosions were specifically designed to test "boosting," i.e., the use of tritium to enhance the efficacy, reliability, and safety of the warheads.

Tritium has a half-life of only 12 years. A permanent supply of tritium is therefore needed as long as there are nuclear weapons. In the United States, for example, 5-10 kg of tritium must be produced every year. The current plan is to use an accelerator for this purpose.

The latent nuclear proliferation and terrorist threat of tritium is that it dramatically facilitates the use of reactor-grade plutonium for making highly efficient nuclear weapons. Only a few grams of tritium are needed to boost a warhead.

6 Electricity production (Energy amplification)

Instead of breeding nuclear fuels, accelerators can be used to produce energy directly. For instance, they can be coupled to a subcritical reactor in which the accelerator-generated neutrons induce nuclear-fission reactions. The resulting "energy amplifier" produces "after-heat" and nuclear waste just like an ordinary reactor. The potential advantages (fast shut-down, larger burn-up of fuel, use of natural uranium or thorium, etc) derive from the added flexibility provided by the accelerator. In practice, however, all of these advantages are marginal rather than radical: none of them lead to any truly decisive improvement over critical reactors.

About 20% of the construction costs and electricity output must be dedicated to the accelerator. In existing power plants, the reactor typically accounts for about 35% of the total cost. Therefore, to produce electricity competitively, the subcritical reactor must be substantially less expensive than a conventional reactor, which is unlikely.

Moreover, the accelerator and the spallation target create a number of safety problems which do not exist with critical reactors.

Finally, accelerator-based electricity generation technology enhances rather than decreases the proliferation of nuclear weapons.

7 Disposal of plutonium

The idea of using an accelerator-driven subcritical reactor to dispose of plutonium faces the same kind of criticism as the energy amplifier. Moreover, the possibility of burning plutonium as MOX fuel in ordinary reactors makes the rubbiatron redundant for this purpose.

Several nuclear weapon States have large stockpiles of excess plutonium that must be disposed. The urgency of this problem favors a more conventional approach, for example, mixing the plutonium with high-level waste in order to make its recovery at least as difficult as the reprocessing of spent fuel from ordinary power reactors (i.e., the "spent-fuel standard").

From the perspective of an abolition of nuclear weapons (or of a universal ban on plutonium recycling) the safe disposal of both military and non-military plutonium is essential.

Any kind of separated plutonium can be used for making nuclear explosives. Moreover, if tritium is available, boosting can be used to make excellent bombs with low-quality plutonium. The purification of plutonium from "reactor-grade" to "weapon-grade" quality (e.g., by laser enrichment or by conversion in a reactor blanket) is only important for making nuclear weapons that can be stockpiled and stored indefinitely.

In principle, the irreversible withdrawal of plutonium is an intrinsic quality of any plutonium burner. However, whatever the method, there are fundamental limitations: if a system is designed to convert 99% of plutonium-239 in ten years, the other isotopes will be converted by only about 90%; one burner will have to operate 20–40 years to fission the full actinide production of a few power reactors; multiple-pass conversion implies losses that are in the percent range; etc. A factor of less than one hundred times reduction of plutonium stocks over several decades is not acceptable from the nonproliferation point of view.

The plutonium disposal option itself should be proliferation-resistant. This is not the case of accelerator-driven technology because it can be used for plutonium production and would than be ten times more productive than reactor-based systems.

8 Disposal of long-lived wastes (actinides and fission products)

The disposal of high-level fission products by transmutation requires the development of special nuclear reactors and of complex chemical processes to recirculate the materials until they are completely destroyed.

Transmutation requires a very high neutron flux which may be achieved in a blanket surrounding a fast reactor or an energy amplifier burning actinides. In theory, one such reactor would be enough to burn the plutonium and to generate the excess neutrons needed to transmute the high-level waste of 5-20 power reactors. Consequently, an actinide and/or waste burner will have to be at least 10 times safer than an ordinary reactor.

A first fundamental limitation of transmutation is that waste reduction by a factor of about 100 requires an increase in neutron flux by 100 over existing technology, which poses extraordinary engineering and materials challenges.

A second fundamental limitation is the difficulty of achieving the required degree of chemical separation and concentration of the highly radioactive materials.

Besides, isotopes such as Sr-90 and Cs-137 will be difficult to transmute, and overall process losses will be in the percent range.

A third fundamental limitation is that risk analysis shows that transmutation is hardly favorable under most circumstances [3]. Possible improvements in geological disposal technology may render transmutation even less attractive in the future.

Under ideal conditions, plutonium burning and fission-product transmutation might only reduce the *quantitative* aspect of the waste disposal problem. The method does not dispense of geological storage. The dilution of the remaining waste after separation, transmutation, and reprocessing may even make final disposal more complicated.

Finally, a "waste transmuter" is readily usable as an "activator" [4], which could be used to produce nuclear weapons materials.

There are potentially better solutions than transmutation to safely dispose of all nuclear wastes and separated nuclear materials over a time span of 30 to 50 years: entombment under the sea bed, deep repositories under the South pole, etc. Such radical solutions can be promoted as active steps towards the global elimination of nuclear weapons and latent proliferation.

9 Nuclear proliferation and other military implications [5, 6, 7, 8]

Accelerator-based systems provide a new path to nuclear weapons because they enable plutonium, uranium-233, and tritium production without the need of building a nuclear reactor or an enrichment plant.

The nuclear proliferation problem with accelerators is that they are more flexible to use than fission reactors (e.g., the source and target are separated) and easier to hide because they produce much less heat and nuclear waste per unit output.

At present, commercially available accelerators could be used to produce about 100 g of plutonium per year. The next generation machines will have to be put under IAEA safeguards [8].

Practical uses of particle accelerators form a bundle of technologies with mostly military applications:

- particle beam weapons;
- synchrotron radiation and free-electron lasers;
- neutron generators for nuclear weapon simulation and stewardship;
- inertial confinement fusion drivers;
- production of tritium, plutonium, and antimatter.

However, accelerators and spallation are excellent tools for scientific research. Moreover, for the production of industrial and medical isotopes, they provide an efficient method which is compatible with a nuclear-free world because it does not use fissile materials.

10 Conclusions

1. The future of nuclear energy depends on the discovery of radical solutions to three fundamental problems: reactor safety, nuclear waste and nuclear weapons proliferation. Accelerator-based systems do not offer such a solution to any of these.

2. The only current application which fully exploits the advantages high-current accelerators have over reactors is the production of tritium. Future military applications may include the production of new nuclear explosive materials, such as antimatter.

3. In the other proposed applications (energy amplification, actinide burning, and high-level waste transmutation) the potential advantages of accelerator systems include some added flexibility in reactor control and possibly a higher productivity. However, these advantages are marginal, especially considering the additional cost, complexity, and proliferation risks associated with the use of an accelerator. Overall, accelerator-based systems are not better than fast-breeder systems.

4. Straightforward risk analysis shows that the reprocessing, separation, and transmutation options are hardly more favorable than the "once-through" nuclear fuel cycle. Moreover, possible improvement in geological disposal technology will render these options even less attractive in the future.

5. For scientific, industrial, and medical applications, spallation has the advantage of not involving the use of a critical reactor using fissile materials.

6. Concerning the disposal of plutonium, accelerator-driven technology has the disadvantage that it can readily be used for plutonium production and would then be ten times more productive than reactor-based systems. Moreover, the development of high-current accelerators is fostering the proliferation of nuclear weapons and of new types of weaponry, such as beam weapons.

11 Policy recommendations

1. Nuclear weapon nonproliferation implies that everything should be done to avoid using particle accelerators as a new path to proliferation (e.g., tritium production).
2. Accelerator-based systems should be discarded as an energy option.
3. International laboratories dedicated to fundamental research, such as CERN, should not work on nuclear energy related applications of particle accelerators.
4. Such laboratories should be converted to international pure-science parks, which would totally refrain from any type of direct or indirect collaboration with weapons laboratories.
5. Future large spallation neutron sources for scientific research should be confined to such international pure-science parks.
6. Legislative bodies such as the European Parliament should establish forward looking committees to openly assess the long-range military impact of emerging technologies such as: particle accelerators, antimatter, superlasers, etc.

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