The Energy Amplifier

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Introduction

A nuclear reactor producing no long-lived nuclear waste whilst running at subcriticality sounds like a dream come true. Add that the same reactor can use the abundant material thorium as fuel, and you have Carlo Rubbia's proposed Energy Amplifier. In 1993, the Nobel laureate held a talk outlining how such a reactor could be built and has since lobbied for resources to construct a test reactor. [1] The proposed design entails significant technical and economic challenges, involving a particle accelerator to generate the necessary neutrons to drive the nuclear reactions. However, the potential benefit of such a reactor could be vast, providing enough energy for mankind for up to 200,000 years. [2]

Mechanism of Energy Production

Nuclear fission is the process in which a heavy nuclei splits into two smaller nuclei with the release of energy and more neutrons. We distinguish between fissile and fertile nuclei. Fissile nuclei can be split directly by bombarding them with neutrons, while fertile nuclei need to absorb a neutron first, to then decay to a fissile nuclei. In a conventional nuclear reactor, we drive the reactor at criticality, meaning there are enough fissile nuclei in the reactor to achieve a chain reaction where an equal amount of neutrons are generated and absorbed. However, Carlo Rubbia suggested that we can supply the neutrons from a particle accelerator, and thus run the reactor subcritically. The processes occurring after the neutrons are produced are well understood and were tested in CERN in 1995. [3] The neutrons would be generated by bombarding lead with high energy protons. Herein lies the main technological and economic challenge of the design, building a high energy and high power proton source. In his original paper, Carlo Rubbia suggested using a three-stage cyclotron design seen in particle accelerators. [2] However, no cyclotron with as high output power and energy as the one required for the Energy Amplifier has ever been built. Recent developments at Fermilab may make such a cyclotron more feasible. [4]

Reduced Waste

The Energy Amplifier can run on any kind of nuclear fuel, both fissile and fertile. It can potentially be used to reduce plutonium stockpiles, by burning plutonium, but it can also tap into the vast reserves of thorium found on Earth. Thorium is a fertile material that can be transmuted into fissile U-233 by a decay chain after neutron absorption. However, the Energy Amplifier can also incinerate actinides, which are the main components of long-lived nuclear waste. Elimination of long-lived nuclear waste would make long-term geological storage like the Yucca Mountain project unnecessary. The Energy Amplifier has very attractive waste characteristics, assuming the fuel is reprocessed. When reprocessing, fission products are separated from the rest of the fuel, then the remains are reformed with some extra thorium to create new fuel rods. The small amount of actinides created would therefore be recycled and always kept in the reactor. [2] The chemical processes to reprocess fuel from the Energy Amplifier have not yet been fully developed. [5]

Safety Features

A conventional nuclear reactor has a risk of going supercritical, meaning that more neutrons are generated from fission reactions than are absorbed. This leads to an uncontrolled chain reaction, that can lead to disasters similar to Chernobyl. Since the Energy Amplifier runs subcritically, this risk is eliminated. The Energy Amplifier is also designed to use a lead convection cooling system, which would enable cooling of the reactor without supply of power. This would eliminate the risk of loss of cooling power accidents, such as the ongoing accident at the Fukushima Daiichi Nuclear Power Plant in Japan. [2] Through a series of passive safety features, the reactor will shut itself down if it overheats, even with no human intervention Because the fuel efficiency of the Energy Amplifier could significantly reduce the amount of fuel required, it could reduce the demand for mining. The majority of the public exposure to radioactivity due to nuclear power is from mining. The Energy Amplifier would therefore expose the public to less radioactivity than both conventional nuclear power plants and coal power plants. [2]

Protection Against Proliferation

A major concern of nuclear power plants today is proliferation of nuclear weapons. The traditional pressurized water reactors allow for breeding of Plutonium which can easily be separated by the chemical PUREX process, thus eliminating the need for expensive centrifuges. In the Energy Amplifier, only small amounts of Plutonium would be generated. Making an atomic bomb from spent fuel rods the Energy Amplifier would be challenging due to the presence of various radioactive elements - both bomb poisons that make bomb yields smaller and very radioactive elements making handling difficult. [2] However, the greatest proliferation danger of the Energy Amplifier seems to be from breeding fissile fuel using the strong proton beam driving the reactor. Rubbia proposed that the Energy Amplifier could be sealed until the fuel rods have to be changed every five years, and then have international teams from the IAEA change the fuel rods. [2] This does not seem to address the main problem, namely that the proton beam would still be accessible. It would be simple to direct the beam into a lead target to generate neutrons for breeding Plutonium from 238U that could then be used to make nuclear weapons. The Energy Amplifier does therefore not solve the proliferation issue.

Challenges

The main challenge of the Energy Amplifier is economic - the great risk of investing a very large sum of money in an unproven technology, where significant problems may occur during development. The main economic barrier seems to be the construction of a high energy and high power proton source to generate neutrons. Rubbia estimated that a prototype would cost $500 million in 1995. [6] The Norwegian company Aker Solutions recently bought Rubbia's patent and is working on raising funding to make a prototype reactor. [7,8] Their cost estimate for a first reactor is $3.2 billion, and they are trying to raise $100 million for the next stage of development. Some parameters have been adjusted from Rubbia's original design to enable use of a smaller and thus cheaper proton accelerator. The new design seeks to run the reactor closer to criticality, thus requiring fewer neutrons from the accelerator to produce power. [8] However, Aker Solutions do not clarify whether running nearer criticality could have a negative impact on the safety of the reactor. It also seems that a conventional Thorium reactor would provide more barriers to proliferation due to the contamination of bred fissile fuel with highly energetic gamma-ray emitters. [5] There are also unsolved problems like corrosion from lead - Rubbia claims that corrosion is not significant until the reactor runs at a higher temperature than the 600C proposed. [2] Further long-term experiments are required to see whether the corrosion problem can be solved or not. The THOREX process for reprocessing spent nuclear fuel necessary to get the full benefits of the Energy Amplifier is also not well-explored, since the Thorium fuel cycle has never been fully implemented. [5]

Conclusions

The Energy Amplifier is certainly a promising prospect for nuclear power as it potentially solves the major problems of both long-term fuel supply and long-lived radioactive isotopes. However, the proliferation problem does not appear to be solved as it should be a simple matter to re-engineer the neutron beam to breed Plutonium for nuclear weapons. There also appears to be significant technical problems remaining, but these seem to be possible to overcome given a substantial one-time investment. 15 years after the original paper by Rubbia, the Energy Amplifier seems to have caught the eye of Aker Solutions and perhaps they can raise the money required for this novel reactor technology.

[1] B. James, "Nuclear Energy: A New, Safer Way?," New York Times, 27 Nov 1993.

[2] C. Rubbia et al, *et al.*, "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier", European Organization for Nuclear Research, CERN/AT/95-44, 29 Sep 95.

[3] S. Andriamonje *et al.*, "Experimental Determination of the Energy Generated in Nuclear Cascades by a High Energy Beam", Phys. Lett. B **348**, 697 (1995).

[4] L. Pham, "Considering an Alternative Fuel for Nuclear Energy," New York Times, 19 Oct 09.

[5] "Thorium Fuel Cycle - Potential Benefits and Challenges," International Atomic Energy Agency, IAEA-TECDOC-1450, May 2005.

[6] C. Rubbia et al, *et al.*, "Some Preliminary Considerations on the Economical Issues of the Energy Amplifier," European Organization for Nuclear Research, CERN/AT/95-45, 29 Oct 95.

[7] A. Evans-Pritchard, "Obama Could Kill Fossil Fuels Overnight With a Nuclear Dash for Rhorium ", The Daily Telegraph, 29 Aug 10.

[8] V. Ashley *et al.*, "Aker's ADS uses Thorium," Nuclear Engineering International, 06 Nov 10.