LA-UR-96- 3252

Title: **Development of the Accelerator-Driven Energy Production Concept**

Author(s):
Francesco Venneri, LER
Carl Beard, TSA-3
Charles Bowman, LER
John Buksa, TSA-10
Roberto Camassa, T-7
J. Wiley Davidson, TSA-3
Gary Doolen, T-13
Joe Durkee, TSA-10
Robert Ecke, MST-10
Jay Elson, TSA-10
Edward Heighway, LDRD
Michael Houts, TSA-10
Robert Krakowski, TSA-3
Ning Li, MST-10
John Park, NMT-5
Robert Perry, Jr., TSA-10
David Poston, TSA-10
Richard Prael, X-TM
William Sailor, TSA-3
Xiaowen Shan, T-13
Laurie Waters, LER
Stephen Wender, P-23

RECEIVED
OCT 11 1996
OSTI

Submitted to: **DOE Office of Scientific and Technical Information (OSTI)**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Los Alamos
NATIONAL LABORATORY

Form No. 836 R5
ST 2629 10/91

Development of the Accelerator-Driven Energy Production Concept

Francesco Venneri*, Carl Beard, Charles Bowman, John Buksa,
Roberto Camassa, J. Wiley Davidson, Gary Doolen, Joe Durkee, Robert Ecke,
Jay Elson, Edward Heighway, Michael Houts, Robert Krakowski, Ning Li,
John Park, Robert Perry, Jr., David Poston, Richard Prael, William Sailor,
Xiaowen Shan, Laurie Waters, and Stephen Wender

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Accelerator Driven Transmutation Technology (ADTT) offers a means of generating nuclear energy in a clean, safe way that can be attractive to the general public. However ,there are issues associated with the energy story (both at the system level and technical detail) that have to be seriously addressed before the scientific community, the public, and potential industrial sponsors can be compellingly convinced of its cost/benefit.

1. Background and Research Objectives

The world population and economy have grown so much in the last several decades that we have become dependent for our survival, particularly in the western world, on the existence of a sophisticated infrastructure for production and distribution of energy, especially electrical energy. The emerging third world has legitimate aspirations to match the West's energy consumption and the wealth it creates. However, continuing to plunge forward with an energy dependence, primarily based on nonrenewable resources will ultimately fail. Recognizing this reality, scientists have been seeking to develop alternative, clean, renewable energy sources from a spectrum of technologies. Research and development continues toward tidal, solar, wind, and biomass systems. A fusion energy source is still decades from a significant demonstration and longer from actual commercial production of energy. Nuclear reactors, although effective electrical power producers, are having to climb out of a deep depression in public acceptance. Additionally, the public is proving hard to convince of the viability of long-

---

* Principal investigator, e-mail: venneri@lanl.gov

term, high-level geologic disposition of their radioactive waste.

Into this energy arena a new option, or rather a viable development of earlier ideas, has been introduced. Accelerator-driven energy production (ADEP) uses neutrons produced by a high-energy proton beam to drive a blanket assembly containing fissionable fuel and the fertile material thorium. The thorium has several advantages. The first is that it occurs naturally as the abundant element thorium-232. Although not fissionable by the thermal neutron spectrum of the system, it is a fertile material. It is readily transmuted by neutrons to the easily fissionable uranium-233. Higher actinides (such as plutonium, neptunium, curium and americium) are produced in a thorium system in quantities about 100 times less than that for uranium-fueled systems.

The use of thorium in reactor systems has been studied extensively in Canada and experimentally in the United States. The Canadian studies have shown that a thorium-fueled heavy-water reactor system could increase useful fuel burnup by about a factor of three over the natural-uranium system. In the U.S., the Molten Salt Reactor Program at Oak Ridge National Laboratory (ORNL) demonstrated that a self-sustaining thorium reactor is certainly feasible although it would have to operate close to the limits of neutron economy and require fuel processing as well as the addition of enriched material to start the process. That is, it would be difficult to balance the budget between those neutrons needed to induce fission against those lost to other mechanisms. Certainly, there would not be enough neutrons in the reactor to simultaneously produce energy and burn the actinide and fission product wastes. The addition of the accelerator drive not only allows the thorium system to operate in a neutron-economic regime that allows burning of the waste, but it also allows complete utilization of the thorium fuel (akin to what is achievable through breeding reactors). It does this without ever using or producing enriched materials and, therefore, without all the associated proliferation dangers.

Such a self-sufficient system promises several exciting features. Its operation can extend our existing resources, poses no possibility of a run-away chain reaction, does not require the infrastructure for fuel enrichment and fabrication, and it does not produce a long-term, high-level waste stream requiring attention for thousands of years. The system also has a small inventory of nuclear material, about one-third that in a light-water reactor of similar size and much less than that in a fast reactor. Added to this is excellent resistance to diversion of nuclear material provided by several built-in barriers to proliferation.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The technologies needed for Accelerator Driven Transmutation Technologies (ADTT) are all based on strong competencies at Los Alamos in accelerators, neutronics, materials, chemistry, separations, and others. This project supports LANL core competencies in nuclear and advanced materials as well as earth and environmental systems. It enhances the Laboratory's ability to respond to initiatives involving ADTT.

3. Scientific Approach and Results to Date

The main elements and function of an ADEP system are illustrated in Figure 1 for a system which generates nuclear energy from thorium, avoids the production of plutonium and concurrently destroys its long-lived high-level fission product waste. The system starts with benign thorium-232 in a liquid mixture of fluorides (molten salt) and converts it by neutron absorption into the excellent fissile fuel uranium-233 from which electric power is produced.

Molten-salt technology has been studied and developed by Oak Ridge National Laboratory (ORNL) in the Molten Salt Reactor Program in the 1960s. Molten salt has excellent radiation stability and operates at high temperature (650° C), and hence higher thermal-efficiency, while also operating at low pressure and therefore with increased safety. The salt is primarily a lithium fluoride-beryllium fluoride mixture. It has good flow and heat transfer properties, melts at around 450° C, and is of low chemical activity even at high temperatures. The lithium in the salt has to be nearly isotopically pure lithium-7 to minimize neutron capture losses that occur in lithium-6. The salt and moderator are contained in a single vessel made of a special nickel alloy, Hastelloy-N, suitable for the high-temperature salt operation. The thorium-uranium fuel when mixed in the salt gives a total composition ratio $LiF:BeF_2:ThF_4$ equal to 70:18:12 by mole percent. A small fraction of $^{238}UF_4$ is added to the start-up fuel to isotopically dilute the uranium-233 produced during the blanket power operation so that it can never be used directly for nuclear weapons. The molten-salt liquid-fuel is circulated and the heat transferred to a secondary salt coolant loop. The heat extracted from the secondary loop is used to produce electrical power in conventional steam-driven generators.

In earlier concepts studied by Los Alamos scientists for burning spent nuclear fuel waste, systems of very high neutron-flux, up to 10^{16} neutrons/cm^2-sec, were examined. In contrast, the energy-production design operates at moderate thermal fluxes remaining below 1×10^{14} neutrons/cm^2-sec over the operational life of the system. Also, the system is designed to perform at a low average power-density of 6 W/cm^3, again to place operation in an inherently safe regime. This is at some expense in increased system volume and similar in emphasis to that in recent High Temperature Gas-Cooled Reactor designs.

The entire blanket assembly would be totally enclosed in a containment vessel and any shutdown would be deliberately designed to be passively safe, even under complete loss of coolant or power scenarios. Passively safe implies that the blanket temperature can be controlled without the requirements for either injection of reactivity poisons or emergency circulation of the salt or special cooling. This choice of an inherently safe design, that on shutdown cools by natural convection and conduction, sets the power density, geometry and the total power in the blanket assembly. Studies have concentrated on a 500 MW thermal system, which is a gain of more than 40 times over the power in the driving accelerator beam.

As described earlier, the salt is initially loaded with fertile thorium-232 and a small amount of uranium. Once the accelerator is turned on and neutrons are produced, the thorium-232 captures neutrons to form thorium-233 that quickly beta-decays to protactinium-233. This then beta-decays more slowly with a 27-day half-life to uranium-233 that is a very good fissile material. However, the protactinium-233 lives long enough that it can absorb neutrons and be lost. The thorium-based system is therefore designed for low flux ($1x10^{14}$), since as the flux increases, an increasing fraction of the protactinium is lost and the path to uranium-233 is broken.

The thorium-232 is fertile rather than fissile in thermal fluxes. So, if the system initially contained only thorium-232 at start up, there would be a period of about a year when little or no net power could be produced until enough fissile uranium-233 had been created by the accelerator-supplied neutrons. During this period the system would have to draw power from the commercial grid. However, this start-up dead-time can be eliminated by adding a small amount of uranium seed to the molten salt. This is accomplished by using enriched uranium, e.g. 20% uranium-235 and 80% uranium-238, in the start-up fuel load (about 5% of the thorium inventory). Further, the uranium will always dilute the isotopic purity of the weapons-grade uranium isotopes (233 and 235) present during power production. During the start-up period, the uranium-235 is burned by the fission process while at the same time the uranium-233 is building up to take over the power-producing task. The presence of uranium-238 results in some production of plutonium-239, but in acceptably small quantities. At equilibrium, such plutonium never exceeds a total of about 10 kg and even this is mostly plutonium-240 and 242 with a sizable amount of plutonium-238, coming from the thorium chain, all unattractive weapons isotopes.

The fissionable uranium-233 produced in the blanket is a potential weapons material, but there are three effective barriers to its proliferation from the thorium system. The first is that the fissile material is dispersed as a dilute component of the coolant salt and is never separated as in solid fuel reprocessing or in the ORNL molten-salt breeder design. A significant fraction of the salt inventory would have to be processed to isolate even small quantities of less than ideal weapons material. The second is that, as part of the thorium burning process, the isotope uranium-232 is produced in small quantities. A decay daughter of this isotope emits highly-penetrating gamma radiation. Thus, any attempt to extract the uranium must be done in a special remote-handling facility within a highly shielded environment. The third barrier to proliferation is the deliberate presence of uranium-238 in the start-up fuel. While some of this is burned in the blanket, much of it survives throughout the life of the system, and so enough always remains to dilute the uranium-233. Therefore, even if the uranium were successfully chemically separated from the blanket, the uranium would be mostly uranium-238 and of no value as weapons material.

The backend separation processes are similar to those derived for the Los Alamos systems for accelerator-transmutation of nuclear waste (ATW) and accelerator-based conversion of plutonium (ABC), described in a companion LDRD report.

The cost of the electricity produced using ADEP systems has been analyzed and found to be largely dependent on the size of the accelerator used and on the level of fission-product transmutation performed. Generally, the electricity produced by ADEP will be more expensive than that produced by conventional once-through reactors. However, once factors such as public acceptance and the elimination of fuel fabrication requirements and geologic storage for the waste are taken into account, the comparison might be more favorable to the ADEP systems.

Conclusions

The Accelerator-Driven Energy Producer has been conceptualized. The main components have been broadly characterized and the performance of these systems analyzed. It appears that substantial proliferation and diversion safeguards can be implemented in these thorium-fueled systems. The cost of the electricity produced by these accelerator-driven systems is higher than that produced by the equivalent size critical reactor. However, factors not considered in the analysis, such as the avoidance of geologic storage for the waste, could tilt the balance in favor of ADEP systems.

Publications:

1. Bowman, Charles D., "Basis and Objectives of the Los Alamos Accelerator-Driven Transmutation Project," *Proc. of Intl. Conf. on Accelerator Driven Transmutation Technologies and Applications,* **AIP Vol. 346,** 22 (1995).

2. Buksa, John J., Beard, Carl A., Venneri, Francesco, Elson, Jay S., Park, John J., Prael, Richard E., Waters, Laurie S., and Davidson, J. Wiley, "Conceptual Design of a Thorium Target for Molten Salt Transmutation Systems," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* **AIP Vol. 346,** 332 (1995).

3. Houts, Michael G., Beard, Carl A., Buksa, John J., Davidson, J. Wiley, Durkee, Joe W., Perry, Robert T., and Poston, David, I., "Accelerator-Driven Molten-Salt Blankets: Physics Issues," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications (A-DTTA),* **AIP Vol. 324,** 1109 (1995).

4. Houts, Michael G., Beard, Carl A., Buksa, John J., Davidson, J. Wiley, Durkee, Joe W., Perry, Robert T., and Poston, David, I., "Accelerator-Driven Molten-Salt Blankets: Physics Issues," *Proc. of Conf. on Accelerator-Driven Transmutation Technologies and Applications,* **AIP Vol. 346,** 564 (1995).

5. Krakowski, Robert A., "Cost-Based Optimizations of Power Density and Target-Blanket Modularity for Th-232/U-233-Based ADEP," *Proc. of Global 1995: Intl. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems,* **Vol. 2,** 1896 (1995).

6. Li, Ning, "A Brief Summary on Specifications and Performance of Centrifugal Separation System Concept for ADTT," Los Alamos National Laboratory report LAUR-95-1374 (1995).

7. Perry, Robert T., Buksa, John J., and Houts, Michael G., "Kinetics of Accelerator Driven Devices," *Proc. of Conf. on Accelerator Driven Transmutation Technologies and Applications (A-DTTA),* **AIP Vol. 324,** 1083 (1995).

8. Venneri, Francesco, Bowman, Charles D., and Wender, Stephen A., "The Physics Design of Accelerator-Driven Transmutation Systems," *Proc. of Global 1995: Intl. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems,* **Vol. 1,** 474 (1995).

Papers published in FY95 Conference Proceedings by Russian scientists under contract to the International Science & Technology Center for Project 17 Sponsored by the United States and *Monitored by the LANL ADTT Project Office Using FY95 LDRD Funds*

ADEP-Related Work

Institute for Theoretical and Experimental Physics, Moscow

1. Bergelson, B. P. and Balyuk, S. A., "The Concept of the Double-Purpose Electro-Nuclear Facility," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 770-776 (1995).

2. Kochurov, B. P., "The Influence of External Source Intensity in Accelerator/Target/Blanket System on Conversion Ratio and Fuel Cycle," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 777-783 (1995).

Russian Research Center "Kurchatov Institute", Moscow*
Joint Institute for Nuclear Research, Dubna[a]
Institute of Nuclear Physics, Novosibirsk[b]
Kharkov Physical Technical Institute, Kharkov, Ukraine[c]

3. Alekseev, P. N.*, Ignatiev, V. V.*, Men'shikov, L. I., Prusakov, V. N.*, Ponomarev-Stepnoy, N. N.*, Subbotin, S. A.*, Krasnykh, A. K.[a], Rudenko, V. T.[a], and Somov, L. N.[a], "Subcritical Enhanced Safety Molten-Salt Reactor Concept," *Proc. of Global 1995: Intl. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems*, vol. 2, pp. 1500-1507 (1995).

4. Novikov, V. M.*, "The Results of the Investigations of Russian Research Center - "Kurchatov Institute" on Molten Salt Applications to Problems of Nuclear Energy Systems," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 138-147 (1995).

5. Abalin, S. S.*, Alekseev, P. N.*, Ignat'ev, V. V.*, Kolyaskin, O. E.*, Men'shikov, L. I.*, Mostovoi, V. I.*, Prusakov, V. N.*, Subbotin, S. A.*, Krasnykh, A. K.[a], Popov, Yu. P.[a], Rudenko, V. T.[a], Somov, L. N.[a], Dikansky, N. S.[b], Novokhatsky, A. V.[b], and Dovbnia, A. N.[c], "Conception of Electron Beam-Driven Subcritical Molten Salt Ultimate Safety Reactor," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 527-534 (1995).

Institute of Physics and Power Engineering, Obninsk

6. Shubin, Yu. N., Ignatyuk, A. V., Konobeyev, A. Yu., and Lunev, V. P., "The Analysis of Long-Lived Radioactivity in Lead and Lead-Bismuth Targets," *Proc. of Global 1995: Intl. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems*, vol. 2, pp. 1522-1529 (1995).

7. Gai, E. V., Rabotnov, N. S., and Shubin, Yu. N., "On the Radiology of Thorium-Uranium Electrobreeding," *Proc. of Global 1995: Intl. Conf. on Evaluation of Emerging Nuclear Fuel Cycle Systems*, vol. 2, pp. 1966-1970 (1995).

Institute of Nuclear Power Engineering, Obninsk

8. Korovin, Yu. A., Artisyuk, V. V., Konobeyev, A. Yu., Pereslavtsev, P. E., Plyaskin, V. I., and Stankovski, A. Yu., "Neutron Data Library for Transactinides at Energies up to 100 MeV," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 834--835 (1995).

Moscow Radiotechnical Institute, Russia Academy of Sciences, Moscow

9. Batskikh, G. I., Fedotov, A. P., Murin, B. P., and Vassil'kov, R. G., "Accelerator-Based Transmuter-Breeder and Energy Producer from Transuranic Actinides and Thorium," *Proc. of Intl. Conf. on Accelerator-Driven Transmutation Technologies and Applications,* AIP Vol. 346, pp. 738-744 (1995).

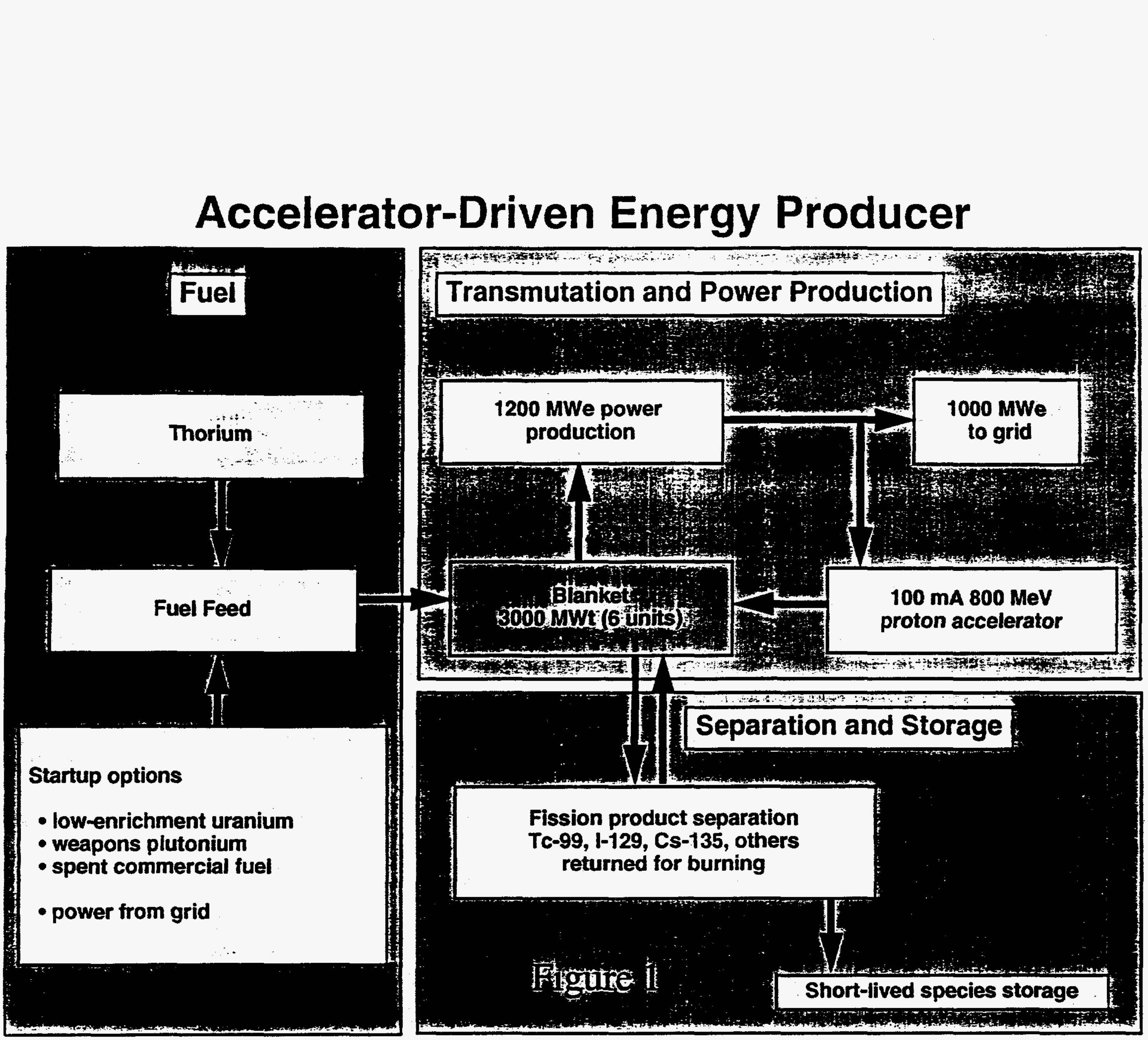

Fig.1. Schematic functional diagram of the Los Alamos concept for the Accelerator-Driven Energy Producer based on the thorium cycle.