United States General Accounting Office

GAO

Briefing Report to Congressional Requesters

February 1990

NUCLEAR SCIENCE

The Feasibility of Using a Particle Accelerator to Produce Tritium

GAO/RCED-90-73BR

GAO

United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

B-231142

February 2, 1990

The Honorable Brock Adams
United States Senate

The Honorable Sid Morrison
House of Representatives

In your January 30, 1989, letter, you raised questions about the potential for the U.S. Department of Energy (DOE) to produce tritium, a critical material needed for nuclear weapons, using a linear accelerator rather than a reactor.[1] Specifically, you asked us (1) if the option of using an accelerator as a tritium production facility appears feasible; (2) if DOE adequately considered particle accelerator technologies during its examination of future tritium production options; and (3) what cost, safety, and environmental advantages accelerator production of tritium, if feasible, might have over production by a nuclear reactor.

As part of its national defense activities, DOE is responsible for producing tritium, a perishable gas used in nuclear weapons. To date, nuclear reactors are the only successfully demonstrated method for producing the quantities of tritium needed. However, DOE's aging defense production reactors have been shut down due to operational safety concerns, and the timetable for resuming tritium production is uncertain.

In December 1987, the Congress requested that the Secretary of Energy prepare a report on acquiring replacement reactors. In January 1988, the Secretary asked the Energy Research Advisory Board[2] to assess four different reactor technologies for the production of tritium. On August 8, 1988, the Secretary of Energy issued a report to the

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[1]A linear accelerator is a device that uses basic laws of electromagnetism to increase the motion energy of charged particles.

[2]The Energy Research Advisory Board is an independent review board appointed by the Secretary of Energy to provide input to DOE on technical issues such as technologies for tritium production.

Congress recommending that DOE proceed on an urgent schedule to construct two new reactors for tritium production.

In March 1989, however, scientists at DOE's Brookhaven and Los Alamos National Laboratories issued a report in which they concluded that due to technological advances, tritium could be produced using an accelerator. The report contained preliminary designs for a tritium-producing accelerator to be located at DOE's Hanford Reservation, near Richland, Washington.

In summary, we found the following:

-- Accelerator production of tritium appears technically feasible. However, an accelerator with the operating characteristics necessary for tritium production does not currently exist. Engineering development is needed to design and demonstrate the major components, optimize reliability and efficiency, and assure sustained operability of an accelerator with the parameters required for tritium production.

-- The congressionally mandated evaluation of new tritium production reactors did not require DOE to consider technologies other than nuclear reactors. However, DOE looked briefly at alternatives, including accelerator systems. DOE concluded that the alternative technologies were not sufficiently mature to provide new tritium production capacity within the needed time frame, but it is currently reviewing the accelerator concept in more detail.

-- When compared with reactor production, accelerator production of tritium presents fewer safety and environmental concerns. Further, an accelerator could have cost and/or schedule advantages over a new production reactor. In addition, an accelerator could be sized to meet a specific tritium need and then upgraded with relative ease should the need for tritium increase. However, because of the amount of electricity required by a large tritium-producing accelerator, a new electric generating plant may be needed. If this is the case, then the accelerator advantages would be partially offset by the environmental consequences associated with fossil fuel or nuclear power electric generating facilities.

Section 1 contains background information on tritium production, DOE's consideration of producing tritium using an accelerator, and our objectives, scope, and methodology. Section 2 provides details about the concept of a tritium-producing accelerator and the significance of achieving stated parameters through remaining engineering and development. Section 3 compares accelerator production of tritium with reactor production.

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To assess the feasibility of using an accelerator to produce tritium, we interviewed physicists and other scientists--at U.S. and Canadian national laboratories--with expertise in one or more aspects of accelerator technologies. We asked them to identify the potential advantages and/or disadvantages of using an accelerator to produce tritium, compared with using a nuclear reactor. In addition, we discussed these issues with DOE officials in Washington, D.C., and DOE contractor officials in Richland, Washington; Los Alamos, New Mexico; Upton, New York; and Newport News, Virginia. We also interviewed officials of the Bonneville Power Administration, which provides electric power to the Hanford Reservation--a proposed site for an accelerator--to discuss the cost and availability of electric power. Los Alamos officials reviewed the technical information in the report. However, as you requested, we did not obtain formal agency comments on this report. Our review was conducted between February and August 1989, in accordance with generally accepted government auditing standards.

As arranged with your offices, unless you publicly announce its contents earlier, we plan no further distribution of this report until 30 days from the date of this letter. At that time, we will send copies of this report to the appropriate House and Senate committees; the Secretary of Energy; and the Director, Office of Management and Budget. Copies will also be made available to other interested parties who request them.

Should you have questions or need additional information, please contact me on (202) 275-1441. Major contributors to this report are included in appendix I.

Victor S. Rezendes
Director, Energy Issues

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ABBREVIATIONS

DOE	Department of Energy
ERAB	Energy Research Advisory Board
GAO	General Accounting Office
GeV	Giga electron Volt
RCED	Resources, Community, and Economic Development Division

SECTION 1

INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for researching, developing, and testing nuclear weapons for the Department of Defense. These responsibilities include producing certain critical materials required for the weapons. One such material is tritium, a gaseous isotope used to enhance the explosive power of nuclear warheads. Tritium is radioactive, and about 5.5 percent is lost each year through natural decay. Because of this loss, existing weapons must be resupplied periodically with tritium in order to maintain their readiness.

In the 1950s, DOE began producing tritium in nuclear reactors located at the Savannah River Site, near Aiken, South Carolina. Concerns about the operational safety of those reactors led DOE to shut them down in 1988, and it is uncertain when they will resume production. Following a congressional mandate to study and report on new defense materials production reactor capacity, in August 1988 DOE recommended construction of two new defense materials production reactors.

REACTOR PRODUCTION OF TRITIUM

Tritium is a form of hydrogen that occurs naturally in only very minute quantities; hence, it must be "manufactured." Ordinary hydrogen, such as that found in drinking water, is a simple element whose atomic nucleus consists of a single proton.[1] If a neutron is added to the nucleus, the ordinary hydrogen becomes deuterium; if another neutron is added, the deuterium becomes tritium. Thus, tritium is a hydrogen atom whose nucleus consists of one proton and two neutrons.

Currently, the only operable reactors capable of producing the necessary quantities of tritium are the heavy water reactors[2] located at DOE's Savannah River Site. These reactors employ uranium fuel elements interspersed with aluminum tubes containing lithium. Neutrons are generated by the fission, or splitting, of the uranium atoms in the fuel. Some of these neutrons are absorbed by the lithium, thus forming tritium. Periodically, the lithium tubes are replaced, and tritium is extracted from those removed from the reactor.

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[1]Protons are particles with a positive electric charge. Atomic nuclei are composed of one or more protons and, with the exception of ordinary hydrogen, one or more electrically neutral particles called neutrons.

[2]Heavy water is water that has been enriched with deuterium. The reactors use heavy water to cool and moderate the nuclear reaction.

PARTICLE ACCELERATORS

First developed in the 1930s for research purposes, particle accelerators are devices that use basic laws of electromagnetism to increase the motion energy of charged particles such as protons. The charged particles gain energy by passing through a series of electrically charged tubes.

DOE has funded the construction and operation of a number of particle accelerators under its high-energy physics and nuclear physics research programs, for example, at the Fermi National Accelerator Laboratory, near Chicago, Illinois, and at the Stanford Linear Accelerator Center, near Palo Alto, California. According to DOE and accelerator facility officials, experiments conducted using DOE's high-energy physics and nuclear physics accelerators have resulted in many important discoveries related to the structure and properties of atomic nuclei and subnuclear particles.

Accelerator designs vary, but all employ certain principal components: a source of particles to be accelerated, a beam of accelerated particles going in a single direction, and a target. In the Fermi National Accelerator Laboratory's main accelerator, the beam is accelerated around a circular tube about 4 miles in circumference. As the name implies, the Stanford Linear Accelerator Center's accelerator is a straight (linear) tube about 2 miles long.

Proposals to use accelerators for tritium production have been made since the 1950s, although no accelerator has been constructed for this purpose. In a March 1989 report, scientists at DOE's Brookhaven and Los Alamos National Laboratories noted that extensive development activities for the Strategic Defense Initiative in the 1980s had produced major advances in accelerator technology. The report concluded that accelerator production of tritium is feasible and contained preliminary designs for a tritium-producing accelerator to be located at DOE's Hanford Reservation, near Richland, Washington.

DOE'S NEW PRODUCTION REACTOR STUDY

Public Law 100-202, December 1987, required the Secretary of Energy to prepare an acquisition strategy for new nuclear production reactor capacity. The report was to be submitted to the Committees on Appropriations and on Armed Services in the Senate and the House of Representatives by May 1, 1988.

The Secretary requested the Energy Research Advisory Board (ERAB), an independent review board appointed by the Secretary, to assess four reactor technologies. Among other things, the

Secretary specifically requested ERAB to assess (1) DOE's proposed selection criteria, (2) the adequacy of each technology to meet the criteria, and (3) the potential technical and schedule risks, costs, and benefits of each of four proposed nuclear reactor technologies.[3]

DOE's report to the congressional committees was issued in August 1988. The report contained the results of the technical evaluation of four reactor technologies under consideration and recommended construction of a new heavy water production reactor at the Savannah River Site and a gas-cooled reactor at the Idaho National Engineering Laboratory, near Idaho Falls, Idaho.[4]

Consideration of Accelerator Production of Tritium

Although the congressional mandate to evaluate new tritium production reactors did not require DOE to consider technologies other than nuclear reactors, DOE's ERAB looked briefly at alternative technologies with potential for tritium production. One alternative was accelerator production of tritium, a subject of research at several DOE facilities.

In February 1988, ERAB officials met to receive presentations on alternatives for new defense production reactor capacity. Los Alamos and Brookhaven officials presented the concept of accelerator production of tritium to ERAB. Officials of the two laboratories stated that their presentations to ERAB lasted about 1 hour each and that ERAB members did not request follow-up information from either. Los Alamos officials stated that accelerator technology was not the ERAB members' primary area of expertise. In addition, Brookhaven officials noted that their presentation occurred during the last part of the ERAB review and that ERAB was operating under time constraints.

ERAB concluded that accelerator technology was not sufficiently mature to provide new tritium production capacity within the needed time frame. However, at DOE's request, ERAB is currently evaluating accelerator production of tritium using the same criteria used to evaluate the reactor technologies. ERAB was specifically asked to determine how soon an accelerator could meet national tritium needs and at what cost. A final report is scheduled for February 1990.

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[3]The four technologies were the heavy water reactor; light water reactor; high-temperature, gas-cooled reactor; and liquid metal reactor.

[4]See our report entitled Nuclear Science: Better Information Needed for Selection of New Production Reactor (GAO/RCED-89-206, Sept. 21, 1989).

The Los Alamos/Brookhaven report[5] on accelerator production of tritium resulted from coordinated research efforts by the two laboratories and the Westinghouse Hanford Company, the operating contractor for DOE's Hanford Reservation facilities. The Los Alamos and Brookhaven laboratories have continued to refine the accelerator concept and explore alternative accelerator design parameters since the report was prepared.

OBJECTIVES, SCOPE, AND METHODOLOGY

In a January 30, 1989, letter, Senator Brock Adams and Representative Sid Morrison asked us about accelerator production of tritium. Specifically, the requesters asked us if

-- the option of using an accelerator as a tritium production facility appears feasible;

-- DOE adequately considered particle accelerator technologies during its examination of tritium production options; and

-- production of tritium by an accelerator, if feasible, would provide cost, safety, and environmental advantages over production by nuclear reactors.

To assess the feasibility of using an accelerator to produce tritium, we interviewed scientists with expertise in one or more aspects of accelerator technologies. To identify such experts, we depended on referrals from (1) the scientists at Los Alamos who prepared the March 1989 report and (2) officials we contacted at the National Academy of Sciences, the Office of Technology Assessment, and the National Science Foundation. In asking for referrals, we sought a balance of opinions; that is, we were interested in talking to scientists who could point out potential problems or uncertainties with using an accelerator as well as those who could identify potential benefits. Because the scientists were not selected randomly, however, their views do not necessarily represent the views of all scientists with expertise in accelerator technologies.

We asked the scientists about the theoretical aspects of accelerator production of tritium as well as about the uncertainty associated with the engineering, construction, and operation of a tritium-producing accelerator facility. We also asked the scientists to identify the potential advantages and/or disadvantages of using an accelerator to produce tritium compared with using a nuclear reactor. We were assisted in these activities

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[5] Accelerator Production of Tritium (APT) Executive Report, Mar. 1989.

by Dr. George Hinman, a nuclear physicist at Washington State University.

We discussed these issues with officials at (1) the DOE Operations Office in Richland, Washington, which oversees the Hanford Reservation; (2) Los Alamos National Laboratory; (3) Brookhaven National Laboratory; (4) the Westinghouse Hanford Company, the contractor that operates the Hanford facilities; and (5) DOE's Continuous Electron Beam Accelerator Facility, in Newport News, Virginia, a particle accelerator currently under construction. Because a tritium-producing accelerator would require an enormous supply of electricity--potentially affecting its cost, reliability, and/or environmental impact relative to a reactor's--we interviewed officials of the Bonneville Power Administration, in Portland, Oregon, to discuss the cost and availability of electric power.

To determine the extent to which DOE considered accelerator production of tritium, we interviewed officials at Brookhaven and Los Alamos National Laboratories, and the Westinghouse Hanford Company.

Our review was conducted between February and August 1989, in accordance with generally accepted governmental auditing standards.

SECTION 2

FEASIBILITY OF PRODUCING TRITIUM USING AN ACCELERATOR

The consensus of the experts we contacted is that accelerator production of tritium is a sound concept. However, an accelerator with the parameters, or operating characteristics, necessary for tritium production does not currently exist. Engineering development is needed to design and demonstrate the major components, optimize reliability and efficiency, and ensure sustained operability of an accelerator with the parameters required for tritium production.

THE CONCEPT: HOW TRITIUM WOULD BE PRODUCED IN AN ACCELERATOR

As noted in section 1, tritium is produced when lithium atoms absorb free neutrons. Free neutrons are therefore a key "ingredient" for producing tritium. In concept, the accelerator would be used simply to generate the needed free neutrons. Once generated, the free neutrons would interact with the lithium contained in the target assembly, in much the same fashion as in a nuclear reactor. Also, as in reactor production, the target pins containing the tritium would be removed periodically and the tritium extracted.

The conceptual tritium-producing accelerator described in the March 1989 Los Alamos/Brookhaven report is designed to produce 100 percent of tritium goal quantities.[1] The accelerator consists of two major systems: a linear accelerator (linac) and a target assembly. Since publication of the report, Los Alamos officials have proposed modifications to the original design; however, the underlying concepts have not changed. A detailed description of the systems and how they would work follows:

The Accelerator

The accelerator would be used to generate a high-energy proton beam--essentially, a "stream" of protons that strikes the target assembly at nearly the speed of light. As currently conceptualized, the accelerator would consist of five principal components--ion source, radio frequency quadrupoles, funneling device, drift tube linac, and coupled cavity linac--arrayed as in figure 2.1. Housed in a concrete tunnel, the accelerator would be about 3,450 feet long.

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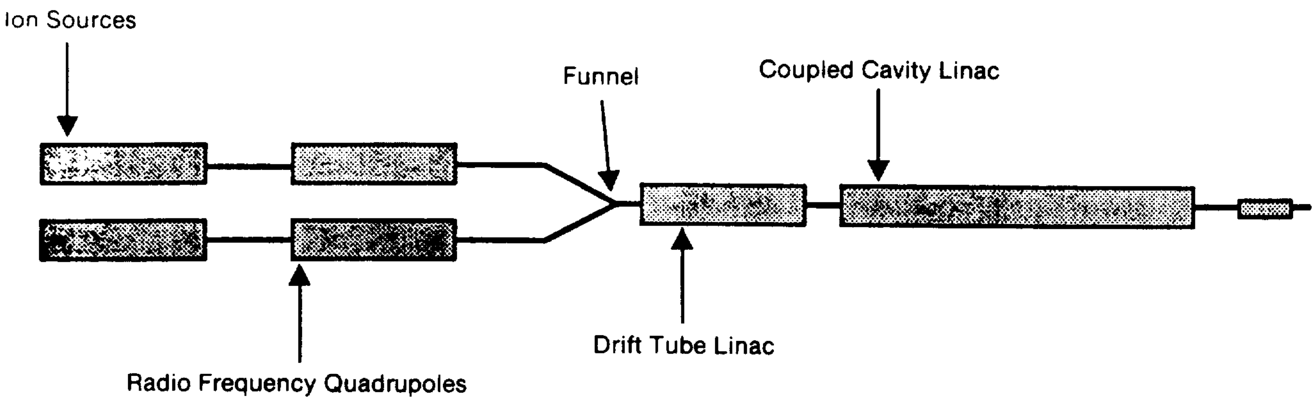
[1]The quantity of tritium needed to meet all national defense needs is referred to as the "goal amount." A tritium-producing facility may be described by the "percent of goal" it is capable of producing.

Figure 2.1: Components of the Tritium-Producing Accelerator



Source: Los Alamos National Laboratory.

For the accelerator to produce the goal amount of tritium, the proton beam must have a very high current. This high current necessitates that two ion sources and radio frequency quadrupoles be used at the initial stage of the accelerator. The ion sources strip electrons from hydrogen atoms, leaving single protons as the particles to be accelerated. The protons are propelled out of the source chamber and into the radio frequency quadrupoles.

Each radio frequency quadrupole would arrange the protons into bunches and accelerate them. Once the two beams are created and initially accelerated, they would be merged in a section of the accelerator called the funnel, which would use magnetic elements to combine them. The number of proton bunches, and thus the current, in the combined beam would be twice that of each beam entering the funnel. The ion source, radio frequency quadrupoles, and funnel total about 56 feet in length.

The next component, the drift tube linac, would further accelerate the protons and thus add power to the beam. About 167 feet long, the drift tube linac is a necessary intermediate component required to raise the energy of the protons so they can be successfully accelerated by the coupled cavity linac.

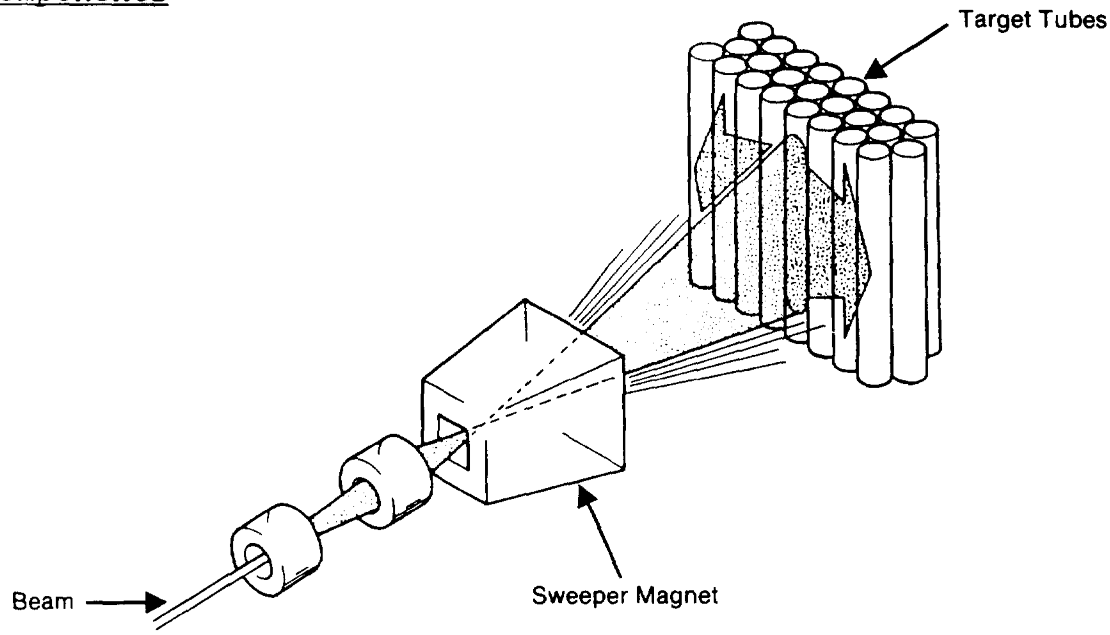
The coupled cavity linac is the last component of the accelerator system. Electron tubes called klystrons would be used to input power to this linac using the designated radio frequency. The coupled cavity linac, about 3,225 feet long, would consist of a series of identical components, which would successively accelerate the protons to a very high energy level and thereby increase the beam power to about 400 megawatts.

The Target System

The target system would consist of "sweeper" magnets and two target assemblies. The design calls for two target assemblies so that the accelerator could continue tritium production with one target while the other target is being replaced.

Between the end of the coupled cavity linac and the target, a vacuum tube would contain a device for switching the beam from one target to the other. As the beam would approach the target area, it would be "defocused" to strike the target assembly. The original Los Alamos/Brookhaven design called for a "sweeper magnet," which would sweep the beam back and forth horizontally across the target, as shown in figure 2.2.

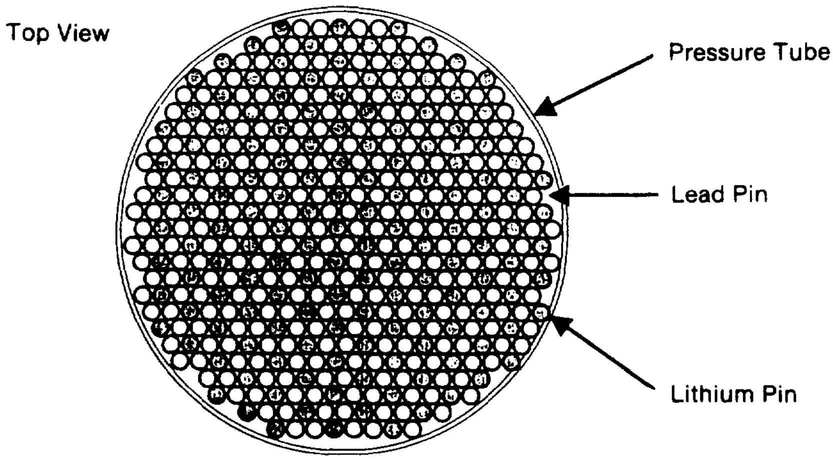
Figure 2.2: Target System, Showing Sweeper Magnet and Other Components



Source: Los Alamos National Laboratory.

Each target assembly would be made up of about 105 tubes, each about 1 foot in diameter and about 9 feet high, contained in a stainless steel vacuum vessel. The tubes would be placed upright in a matrix arrangement, about 15 or more tubes across and about 7 deep. Each tube would contain 570 hollow pins, of which two-thirds would be filled with lead and one-third with lithium (see fig. 2.3). The tubes would be cooled with water, each having its own supply line to the bottom of the tube. The water would circulate upwards and exit via a line at the top of the tube.

Figure 2.3: Cross Section of Target Tube



Source: Los Alamos National Laboratory.

The protons striking the face of the assembly would collide with lead atoms and produce neutrons and other high-energy particles. These particles would interact with other lead atoms to produce still more neutrons in a multiplier effect, so that ultimately many neutrons would be generated from a single proton-lead collision.

Many of the neutrons would eventually be captured by the lithium, which would then be converted to tritium and helium. The first two rows of tubes, which would experience the highest rates of lithium conversion, would be removed after about 6 months of operation. The remaining rows would be removed annually. After the removal of the tubes from the target, the tritium pins would be separated from the lead pins and the tritium extracted using the Savannah River Site standard process. The lead would be disposed of as waste.

ENGINEERING DEVELOPMENT IS NEEDED TO OVERCOME ACCELERATOR UNCERTAINTIES

During our review, we noted several uncertainties about the ability of the tritium-producing accelerator in the Los Alamos/Brookhaven conceptual design to achieve the stated design objectives. If these parameters cannot be achieved through engineering development, then they would have to be changed. It is likely that such changes would increase the capital and/or operating costs of an accelerator capable of producing 100 percent of tritium goal quantities.

The major uncertainties are

-- the power efficiency factor, that is, the quantity of power delivered to the target compared with the quantity of power entering the accelerator;

-- the ability of the accelerator to operate at a high power level without "activating" the components (activation occurs when a portion of the beam strays and hits the accelerator walls, causing them to become radioactive);

-- the funneling process, which has not been demonstrated; and

-- the neutron yield factor, that is, the number of free neutrons in the target assembly produced by each proton in the accelerator beam.

A discussion of these uncertainties and their impacts follows:

Power Efficiency Factor
for Conceptual Accelerator
May Be Optimistic

The power efficiency factor of a tritium-producing accelerator is probably the most significant of all uncertainties because of its effect on capital and operating costs. For the Los Alamos/Brookhaven accelerator design, the electric power input system represents about 60 percent of the accelerator's estimated capital cost, and electric power consumption represents about 60 percent of the estimated annual operating costs.

The initial design presented by the Los Alamos/Brookhaven report estimated the efficiency factor at 54 percent. According to the report, this design would require about 746 megawatts of electricity; at an efficiency factor of 54 percent, about 400 megawatts would enter the beam. An estimated 400 megawatts would be necessary to produce the required 1.6 billion electron volt (GeV) proton beam.[2] The 1.6 GeV beam deposited on the lead/lithium targets is expected to generate enough free neutrons to produce the goal amount of tritium.

However, the 54 percent efficiency factor may be optimistic. One expert we talked with told us that a 40 percent efficiency factor should be readily achievable, but raising it to 50 percent or higher would be more difficult. The Los Alamos/Brookhaven report acknowledged that due to the need for efficient conversion, development of more powerful klystron tubes and power conversion components will be needed.

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[2]An electron volt is a unit of measure that describes the amount of energy acquired by a particle (such as a proton) as it moves across an electric potential of 1 volt.

The cost impact of the efficiency factor may be illustrated by lowering the 54 percent estimate to 40 percent. At a 40 percent efficiency level, about 1000 megawatts of electricity (rather than 746 megawatts) would be required to provide 400 megawatts of power to the target. Using the same unit costs estimated by the Los Alamos/Brookhaven report, we estimated annual operating costs would increase by about $53 million.[3] In addition, capital cost would increase due to the need for additional power input equipment.

New Conceptual Design May
Alleviate Activation Concerns

The amount of radioactivity created in the accelerator components is important because it can affect costs. If the components become highly activated, remote maintenance, rather than hands-on maintenance, would be required as a safety precaution. In addition, over the life of the accelerator, excessive activation could necessitate replacement of many of the components. In both cases, costs would increase.

The problem arises from the effects of a small number of protons that travel down the linac outside the main proton beam. If too far from the beam, these "halo" protons can be absorbed in the parts of the structure in which the beam travels and make those parts radioactive. An official at Los Alamos told us that not more than one proton in a million can strike the walls of the linac in which the beam travels if activation of the accelerator is to remain at a tolerable level.

Two potential solutions to the activation problem that do not involve changing the accelerator's operating parameters are (1) placing "scrapers" along the beam that would absorb the proton particles on the outer edge of the halo and (2) placing removable covers on critical parts or components. The scrapers or the covers would be replaced as necessary, with the discarded ones becoming waste material.

Los Alamos officials have proposed a design modification in an effort to alleviate the activation problem. The new design employs a larger bore (that is, a tube with a larger diameter) for the beam to travel in, thus increasing the distance between the halo and tube walls. This design modification involves halving the beam's radio frequency and replacing the permanent quadrupole magnets, which could suffer radiation damage, with electromagnets. By making these modifications, Los Alamos officials believe that only 1 in every 10 million protons will reach the accelerator walls.

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[3]GAO computation based on 32 mils (3.2 cents) per kilowatt over 273 days (three-quarters of a year). The Los Alamos/Brookhaven March 1989 report estimated power costs at 32 mils (3.2 cents) per kilowatt hour.

Although increasing the size of the bore through which the beam travels would require a corresponding increase in linac size, a Los Alamos official told us that these modifications would have little effect on cost and schedule. However, the modifications may not entirely eliminate the need for remote maintenance operations.

Funneling Device Has Not Been Demonstrated

Funneling two separate positively charged, high-current beams together to produce a single combined beam is a new technology that has not been demonstrated. Funneling is necessary because of the large amount of current required in the beam as it hits the target. The accelerator designers believe that it would not be possible to keep a single high-current beam from spreading apart too much while at a relatively low energy level. Consequently, to avoid the beam-spreading problem, plans are to use two low-energy systems, each of which will provide half of the necessary current, and then combine the beams using funneling when the beams have acquired sufficient energy.

Los Alamos officials conducted a preliminary test in August 1989 on the funneling device and plan to complete testing within a year. According to a Los Alamos official and other experts we contacted during our review, the concept is sound and the device should perform as expected. However, if technical problems that cannot be solved are encountered, a tritium-producing accelerator would be limited to one-half of the power level estimated in the Los Alamos/Brookhaven report. Since such an accelerator would be capable of producing only 50 percent of the goal amount of tritium, two accelerators would be required to produce 100 percent of the tritium goal.[4]

Total Neutron Yield Is Uncertain

Brookhaven officials have estimated that for each proton striking the lead in the target assembly, a total of 48 neutrons will be produced that can interact with the lithium to produce tritium. According to these officials, this is the number or yield of neutrons necessary to achieve the goal amount of tritium. Since neutron yield tests have not been conducted at the high energy (1.6 GeV) used by the tritium-producing accelerator, Brookhaven's estimate is based primarily on calculations using computer codes extrapolated from information obtained from tests performed at lower energy. Thus, there is some uncertainty about neutron yield.

Brookhaven officials acknowledge the uncertainty by placing a 20 percent accuracy factor on their calculations. If the calculation is 20 percent low, then it will be necessary to

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[4]Downsized accelerators are discussed in sec. 3.

increase the beam energy from 1.6 GeV to about 2 GeV to provide additional neutrons. While this change is possible, it would increase both capital and operating costs. Brookhaven officials plan to conduct, sometime during the next 2 years, more neutron yield tests using high energies.

SECTION 3

COMPARISON OF ACCELERATOR AND REACTOR FOR NEW TRITIUM PRODUCTION

Accelerator production of tritium, compared with reactor production, would be potentially safer and less harmful environmentally. However, these safety and environmental advantages could be partially offset by the accelerator's electricity requirements, particularly if an additional generating facility is needed. Because of the technical uncertainties discussed in section 2, estimates of the schedule and cost for the accelerator are imprecise; therefore, potential cost and schedule advantages of accelerator production depend on the results of engineering development.

ACCELERATOR WOULD AVOID SAFETY AND ENVIRONMENTAL CONCERNS ASSOCIATED WITH FISSION REACTORS

As noted in section 2, a tritium-producing accelerator would employ a multiplier process to generate neutrons rather than employ nuclear fission, the process used in current and proposed new defense production reactors. Although the precise safety and environmental advantages depend somewhat on the final design parameters of a tritium-producing accelerator, the absence of fission avoids two of the principal safety and environmental concerns associated with reactors:

- -- the possibility of a loss-of-coolant accident, resulting in heat buildup and/or the escape of radioactive materials into the environment, and
- -- the need to dispose of high-level radioactive waste material.

Because the absence of fission is inherent in the tritium-producing accelerator concept, safety and environmental advantages would accrue regardless of accelerator size or location.

Loss-of-Coolant Accident Would Pose Less Danger in Accelerator

Nuclear reactors are designed so that fission, the process of splitting atoms, occurs as a self-sustaining chain reaction: When the target fuel (uranium) atoms are split, neutrons are released, which strike other atoms, causing them to split, and so on. The reactions produce heat as well as a host of by-products referred to as fission products, which produce additional heat as they undergo radioactive decay.

To prevent the buildup of heat to excessive levels, a coolant is circulated through the reactor. At the current and proposed new production reactors at the Savannah River Site, the coolant is heavy water. In the new production reactor proposed for the Idaho National Engineering Laboratory, the coolant would be helium, an inert gas.

Reactors are engineered with control systems designed to shut down the fission reaction if the coolant supply is interrupted. However, the shutdown is not instantaneous; the nuclear fuel briefly continues to fission until there are no free neutrons capable of causing a fission reaction. Further, after shutdown the reactor continues to produce heat from the decay of fission products. Although reactors are equipped with systems designed to prevent excessive heat buildup, concerns remain about the possibility of a "meltdown," in which molten radioactive fuel would breach the reactor vessel and escape into the environment.

In contrast, in a tritium-producing accelerator the proton beam could be shut down instantaneously and less decay heat would be produced after shutdown. In normal operation of the accelerator, heat would be produced as the proton beam strikes the lead and lithium/aluminum target assemblies. Cooling would be provided by water circulating through the assemblies. In the event that the coolant supply is interrupted, the accelerator could be shut down instantaneously by turning off the proton beam, and the target assembly would begin to cool naturally. A Los Alamos scientist estimated that if the cooling system should fail, natural convection cooling would be sufficient to prevent melting of the target assemblies.

Accelerator Would Produce Less Radioactive Waste

Los Alamos officials estimate that because of the absence of fission and fission products, the waste produced from an accelerator would be less radioactive, and remain radioactive for a shorter period of time, than that from a reactor. An accelerator would also produce a smaller volume of radioactive waste. Less waste is an advantage because it reduces the threat of environmental contamination.

DOE categorizes different kinds of nuclear waste. High-level waste, generated from the reprocessing of spent nuclear fuel from defense production reactors, has concentrations of radioactivity measured in hundreds to thousands of curies[1] per gallon or cubic foot. Transuranic waste, generated primarily from

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[1]A curie is a measure of the intensity of radiation, is equivalent to 37 billion disintegrations per second, which is approximately the rate of decay of 1 gram of radium.

defense reprocessing and fabrication, is material contaminated by elements with atomic numbers higher than that of uranium. Low-level waste, produced by many commercial, industrial, and medical processes, has lower levels of radioactivity. Low-level waste may require special handling, although extensive shielding is not usually required.

Nuclear production reactors produce all three types of waste noted above. High-level nuclear waste from a production reactor derives principally from the spent nuclear fuel, which contains radioactive fission products and transuranic elements. Some spent fuel elements remain radioactive for thousands of years and require permanent isolation from the public and the environment. Low-level reactor waste includes less-radioactive fission products and items that come into contact with radioactive substances, including tools, gloves, and other items used by workers.

Radioactive waste from an accelerator would arise primarily from irradiation of the lead and lithium/aluminum target assemblies. According to Los Alamos officials, this waste would remain radioactive for a much shorter period of time than would high-level waste generated by a reactor; for example, at the end of 1 year, the total radioactivity from the accelerator waste is estimated to be 25 times less than that from the reactor waste. In reviewing a list that Los Alamos officials provided us of the radioisotopes expected to be generated in the target assemblies, our consultant determined that relatively few of the radioisotopes would have a half-life exceeding 10 years.[2]

The accelerator would also probably produce a smaller volume of radioactive waste than would a comparable reactor. A Los Alamos official noted that the volume of high-level waste generated annually by one Savannah River Site reactor exceeds the accelerator's total designed target matrix volume. If neither the irradiated lead from the accelerator nor the spent reactor fuel were reprocessed, the storage volume of waste from a reactor would be roughly twice that from an accelerator. If the reactor fuel were reprocessed and the lead were not, then the ratio would be less than 2 to 1.

POTENTIAL COST AND SCHEDULE ADVANTAGES DEPEND ON ENGINEERING DEVELOPMENT

The estimated capital costs for each of DOE's proposed new production reactors and for an accelerator capable of producing goal quantities of tritium do not differ significantly. The

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[2]The half-life is the time required for a radioisotope to lose one-half of its activity.

estimated life-cycle cost for the accelerator is somewhat less than for either reactor. However, the cost estimates for both the reactors and the accelerator are surrounded by substantial uncertainty. Further, direct comparisons are complicated by the fact that the proposed heavy water reactor and the Los Alamos/Brookhaven accelerator are designed to produce goal quantities of tritium, while the proposed gas-cooled reactor is designed to produce only 50 percent of goal quantities.

The estimated schedules for the reactors and the accelerator suggest that the accelerator may be constructed more quickly. DOE estimated that about 11 years would be needed to construct and start operating the heavy water reactor and 12 years would be needed for the modular high-temperature, gas-cooled reactor. However, we concluded in our September 1989 report[3] that a minimum of about 12-1/2 years for the proposed heavy water reactor and about 16 years for the gas-cooled reactor would be required to realize tritium. Even these estimates are uncertain, due in part to technical questions and to safety and environmental considerations. Schedule estimates for a tritium-producing accelerator range from 8 to 12 years. While these estimates could be increased by technical uncertainty, environmental and safety issues should have little effect on the accelerator schedule.

Estimated Capital Costs Do Not Differ Significantly

DOE estimated a $3.2 billion capital cost for the proposed heavy water reactor at Savannah River and $3.6 billion for the modular high-temperature, gas-cooled reactor at the Idaho National Engineering Laboratory (both in 1988 dollars). However, in our September 1989 report we found that DOE used unrealistic assumptions in developing some of its reactor cost estimates, and that the cost would probably increase.

The Los Alamos/Brookhaven report estimated the capital cost of the accelerator at $2.3 billion in 1988 dollars. A more detailed cost estimate performed for Los Alamos by Grumman Aerospace Corporation in May 1989 estimated this cost at $2.4 billion in 1989 dollars. However, this estimate does not include buildings and tunnels to accommodate the accelerator, nor does it include the cooling system for the target assembly. These items are estimated by Los Alamos officials to cost an additional $600 million, for a total estimated capital cost of $3.0 billion.

We did not assess the accuracy of the accelerator cost estimates. However, we noted that most of the accelerator components have been produced and demonstrated, albeit under

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[3]Nuclear Science: Better Information Needed for Selection of New Production Reactor (GAO/RCED-89-206, Sept. 21, 1989).

different operating conditions, thus providing a reasonable basis for the estimates. For example, the coupled cavity linac and the radio frequency power input system have been manufactured and operated at accelerator sites. These components represent about 60 percent of the estimated capital cost for a tritium-producing accelerator. In addition, the injector system, radio frequency quadrupoles, and drift tube linac have been manufactured and operated.

The accelerator cost estimate may be affected significantly by the outcome of remaining engineering development work. Uncertainties about the power efficiency and neutron yield factors, as discussed in section 2, could result in either increased costs or an accelerator capable of producing less than goal quantities of tritium.

Life-Cycle Cost May Be Less for Accelerator

While the estimated capital costs for the heavy water reactor; modular high-temperature, gas-cooled reactor; and tritium-producing accelerator are not significantly different, our computations of life-cycle costs show the accelerator to be significantly less costly than the reactors.

DOE estimated life-cycle costs for the heavy water reactor and the modular high-temperature gas-cooled reactor at $19.7 billion and $18.6 billion (1988 dollars), respectively, based on a 40-year life. Our computations for the accelerator show an estimated life-cycle cost of about $10.8 billion (1989 dollars) for an accelerator with an efficiency factor of 54 percent and about $12.9 billion (1989 dollars) for one with an efficiency factor of 40 percent.

In computing the life-cycle cost estimate for the accelerator, we used the estimated annual operating costs of $270 million, which Los Alamos and Brookhaven officials presented in their March 1989 report. This estimate assumes that the accelerator achieves the stated parameters needed to produce goal quantities of tritium and that the cost of electrical power is 32 mils (3.2 cents) per kilowatt hour. A Bonneville Power Administration official told us that 32 mils per kilowatt hour is a reasonable estimate for planning purposes because it is based on their wholesale power rate projections for years 1989 through 2010.

Accelerator Schedule Compares Favorably With Proposed Reactor Schedules

In our September 1989 report, we concluded that DOE's estimated schedule of 11 to 12 years to complete, operate, and realize tritium from the proposed new production reactors was understated and probably would increase. We concluded that the heavy water reactor would take at least 12-1/2 years to yield tritium and the modular high-temperature, gas-cooled reactor would take about 16 years. The report pointed out several uncertainties that could further lengthen the estimated schedules, such as technical problems, environmental challenges, safety review processes, and the availability of an industrial base for first-of-a-kind reactors.

The Los Alamos/Brookhaven report estimated that it would be 8 to 9 years before tritium would be available from an accelerator. An estimate prepared by Westinghouse Hanford officials placed the completion time at 12 years. The primary difference in the two estimates is the time allotted to develop and demonstrate the front-end components of the accelerator under a phased construction approach.

The Los Alamos/Brookhaven report estimated that 3 to 4 years would be required to develop and demonstrate all of the accelerator components up to and including the first section of the coupled cavity linac. However, for the same work, Westinghouse officials believe that about 7 years are necessary. Both Los Alamos and Westinghouse agree that 5 years are necessary to complete development and demonstration of the last stage, which is the coupled cavity linac.

According to Westinghouse officials, the development and demonstration of the front-end components of the accelerator are important because these present 80 to 90 percent of the engineering uncertainties. These officials stated that the Los Alamos/Brookhaven schedule does not provide sufficient time to test certain components before proceeding with development of others in the front end of the accelerator.

ELECTRICITY REQUIREMENTS ARE A POTENTIAL DISADVANTAGE

The Los Alamos/Brookhaven accelerator designed to produce the goal amount of tritium would require at least an estimated 746 megawatts of electrical power if all accelerator parameters are achieved. This is equivalent to the output of some electric generating plants. The electrical requirements could at least partially offset the accelerator's safety and environmental advantages over a new production reactor, particularly if the accelerator is considered responsible for the construction of new generating capacity.

Electric generating plants may raise environmental and/or safety concerns. For example, plants that burn fossil fuel have caused concerns about their contribution to acid precipitation and global climate change. A nuclear (fission) power plant providing the accelerator's electricity could raise the safety and environmental concerns associated with fission reactors that would be avoided by the accelerator itself. As a consumer of a large amount of electricity, the accelerator could be viewed as responsible for contributing to these concerns.

Also, additional electric generating capacity in a given area can affect the costs of electric service to ratepayers served by the utility. Electric utilities are generally allowed rate structures that enable them to recover the cost of producing and distributing electricity and enable a return on the investment. Therefore, additional generating capacity that increases the utility's total cost of supplying power to its customers may result in an increase in the customers' rates.

It is important to note that an accelerator may not be the only cause for a utility to increase its generating capacity. Utilities base decisions about constructing new electric generating facilities in part on the projected future demand for electricity in their service area. Many factors--such as population growth patterns or economic trends--can affect this demand. For a given area, demand projections may suggest that additional electric generating capacity will be needed at some point in the future.

If a tritium-producing accelerator is constructed in an area where projected electricity demand is already increasing, then the accelerator may not be the sole reason for increasing generating capacity. In such an area, however, the accelerator could result in increasing generating capacity more than it would have been increased otherwise or increasing it sooner.

The Los Alamos/Brookhaven report was based on a full-size tritium-producing accelerator at the Hanford Reservation, with electricity to be purchased from the Bonneville Power Administration. Bonneville officials were uncertain about the source of power that would be used to supply such an accelerator. However, one official commented that the accelerator's electrical requirements might hasten the need for a thermal (coal or nuclear) power plant. The official stated that the cost of a new power source would probably be incorporated into the overall rates, so the cost of electricity would increase for ratepayers. However, in contracting for such a large amount of electric power, the federal government is likely to have to make concessions. Such concessions would include not incorporating part or all of the cost in the ratepayers' base. If this occurs, the cost of the electricity to the government could possibly double, which could nearly double the operating costs of the accelerator.

DOWNSIZED ACCELERATORS OFFER ADVANTAGE OF FLEXIBILITY

An accelerator designed to produce less than 100 percent of the goal amount of tritium would require less electric power than one designed to produce the full goal amount. Thus, building several smaller accelerators in different locations offers flexibility in meeting electrical needs and may avoid the need to construct an additional generating plant required to power a full-size accelerator. Such a strategy could also provide greater security by dispersing tritium production among several locations. In addition, within certain limits downsized accelerators could be subsequently upgraded with relative ease to produce greater amounts of tritium if needed. However, several downsized accelerators capable of producing the goal amount of tritium collectively would have higher capital and operating costs than would a single large accelerator capable of producing the goal amount of tritium.

Immediate Electrical Needs Would Be Smaller

The principal factor affecting the production capacity of a tritium-producing accelerator is beam power--the quantity of power that the beam deposits on the target assembly. (Beam power determines the neutron production rate, that is, the number of free neutrons that will result from each proton.) In turn, beam power is the product of the electric current (amperage) times beam energy (electron volts). Reducing amperage, voltage, or both would lessen the electric power requirements of the accelerator.

A Los Alamos report[4] states that accelerators to produce less than 100 percent of the goal amount of tritium could be designed and constructed with less beam power by reducing either the amperage or the voltage delivered to the target. According to the report, an accelerator producing one-fourth of the goal amount of tritium would require about 260 megawatts of electricity, while an accelerator producing one-tenth of tritium goal amount would require about 150 megawatts. In comparison, DOE's proposed Superconducting Super Collider, a high-energy particle accelerator to be built in Texas, will require about 200 to 250 megawatts. One of the site selection criteria for the Super Collider was the ability of the site to provide sufficient electric power.

Constructing a series of smaller accelerators in different locations could thus lessen the impact on local electric power systems. However, the operating costs of this option could be higher than for a full-size accelerator, because the small accelerators collectively could have a higher overall electrical need. An accelerator capable of producing 100 percent of tritium goal quantities is estimated to require a total of about 746 megawatts. Using the Los Alamos estimates, we calculated that 4 accelerators capable of producing one-fourth goal each would collectively require about 1,040 megawatts, while 10 accelerators

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[4] Production of Reduced Goal Amounts of Tritium Using the APT Concept, Apr. 1989.

capable of one-tenth goal each would collectively require about 1,500 megawatts. In addition, Los Alamos estimated the capital cost for an accelerator capable of producing one-fourth goal at $1.7 billion, not including the cost of tritium extraction facilities. We estimate that the capital cost would be $6.8 billion for four accelerators that collectively would produce the goal amount of tritium, assuming a capital cost of $1.7 billion for each. This compares to $3.0 billion for one large accelerator capable of producing the goal amount of tritium.

Downsized Accelerators Could Be Upgraded to Meet Tritium Needs

According to the Los Alamos report, accelerators capable of producing 10 and 25 percent of goal could be upgraded to produce larger quantities of tritium by the addition of more electrical power to the beam. The report noted that during the construction phase, space along the linac would be provided for additional electric power input components. If it would become necessary to produce more tritium, then the components could be added.

In addition, the Los Alamos officials pointed out that the downsized accelerators, capable of producing up to 50 percent of goal quantities, would eliminate much of the engineering work required on the front end of a full-size accelerator. The smaller accelerators would require one-half of the current in the initial stage. Also, in this case, only one beam would be necessary, thus eliminating the funneling of two beams into one.

MAJOR CONTRIBUTORS TO THIS BRIEFING REPORT

RESOURCES, COMMUNITY AND ECONOMIC DEVELOPMENT DIVISION, WASHINGTON, D.C.

Robert E. Allen, Jr., Assistant Director
W. David Brooks, Evaluator-in-Charge

SEATTLE REGIONAL OFFICE

Julianne H. Hartman, Evaluator

(301852)

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