THE ACCELERATOR PRODUCTION OF TRITIUM PROJECT

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Abstract

Tritium is essential for U.S. nuclear weapons to function, but because it is radioactive with a half-life of 12.3 years, the supply must be periodically replenished. Since the last production reactor stopped operating in 1988, tritium has been recovered from dismantled nuclear weapons. This process is possible only as long as many weapons are being retired and will not work indefinitely, thus requiring the United States to bring a new tritium production capability on line. To make the required amount of tritium using an accelerator system (APT), neutrons will be generated by high-energy proton reactions with tungsten and lead. Those neutrons will be moderated, and captured to make tritium. The APT plant design is based on a 1700 MeV linear accelerator operated at 100 mA CW. In preparation for engineering design, scheduled to start in October 1997, and subsequent construction, a program of engineering development and demonstration is underway. That work includes assembly of a 20 MeV, 100 mA low-energy linac plant prototype, high-energy linac accelerating structure protoyping, radio-frequency system improvements, neutronic efficiency measurements, and materials qualifications.

1. INTRODUCTION

Production of tritium in a quantity large enough to supply the needs of the U.S. stockpile can only be accomplished through neutron capture by a stable isotope such as ^{3}He or ^{6}Li. Presently only reactor or accelerator systems can make enough neutrons to produce tritium in the quantities needed. In a reactor, nuclear fission supplies the neutrons. In APT, neutrons are made by proton spallation of heavy metal nuclei. The use of spallation to produce neutrons makes it possible to avoid the use of fissile material, which in turn makes the system design simpler than that of a reactor and provides additional safety and environmental features.

1.1 Project History

The design of an APT system was first considered by the DOE Energy Research Advisory Board (ERAB) in late 1989 and by the JASONs, an independent scientific review panel, in 1992 and 1995. Reviews of APT technology were positive, and endorsed the need for further design and for a technology development and demonstration program. As a result, from 1992 to 1994, the DOE sponsored an APT preconceptual design study using a multi-laboratory and industry team to support a DOE Programmatic Environmental Impact Statement for Tritium Supply and Recycling.

In December, 1995 the DOE announced a decision to pursue a dual track approach to obtaining a new tritium supply. That strategy initiated action to purchase an existing commercial reactor (operating or partially complete) or irradiation services with an option to purchase the reactor for conversion to a defense facility; and authorized work to design, build, and test critical components of an accelerator system for tritium production. The DOE has committed to select one of the tracks to serve as the primary source of tritium by fall, 1998. In addition, the Savannah River Site (SRS) in South Carolina was selected as the location for the APT accelerator.

A critical part of the DOE decision is the fact that the government plans to develop the technology that is not selected for tritium production as an assured backup in the event that the primary technology proves unworkable. For APT that means that the project will continue through engineering design of the plant and include sufficient Engineering Demonstration and Development (ED&D) to ensure low-risk construction and operation.

APT ED&D activities cover areas that have the greatest impact on plant cost and schedule, including an evaluation of alternative designs, and prototyping of key components and subsystems. This work is being performed with the assistance of a Prime Contractor, Burns and Roe teamed with General Atomics, which will be responsible for plant design and construction; and with the Maintenance and Operations Contractor at Savannah River, in order to assure actual plant operations experience.

1.2 Conceptual Design Report

The basis of this paper is the APT Plant Conceptual Design Report (CDR) [1]. The CDR establishes the design, cost, and schedule for the entire project. It also includes technical information on Environment Safety and Health, Operations and Maintenance, Safeguards and Security, and Decontamination and Decommissioning. The report was coordinated by Los Alamos National Laboratory with contributions from Sandia, Brookhaven, and Livermore National Laboratories; the Westinghouse Savannah River Company; the APT Prime Contractor; and supporting subcontractors Northrup Grumman, and Babcox and Wilcox.

DOE requirements for the APT plant include:

- Sustained normal operation at a production rate within the range of 2 to 3 kg of tritium per year,
- Sustained operation at the higher production rate of 3 kg/yr averaged over 5 years,
- Production of 3 kg/yr no later than 2007,
- Operational lifetime of 40 years, and

Cost effective, efficient operation in the 2 to 3 kg/yr range.

2. SYSTEM DESCRIPTION

The APT plant has a CW proton linear accelerator [2] to produce a 170 MW proton beam that is directed onto a tungsten target surrounded by a lead blanket. Tubes filled with ^{3}He gas are located adjacent to the tungsten and within the lead blanket. Spallation neutrons created by the energetic protons are moderated by the lead and cooling

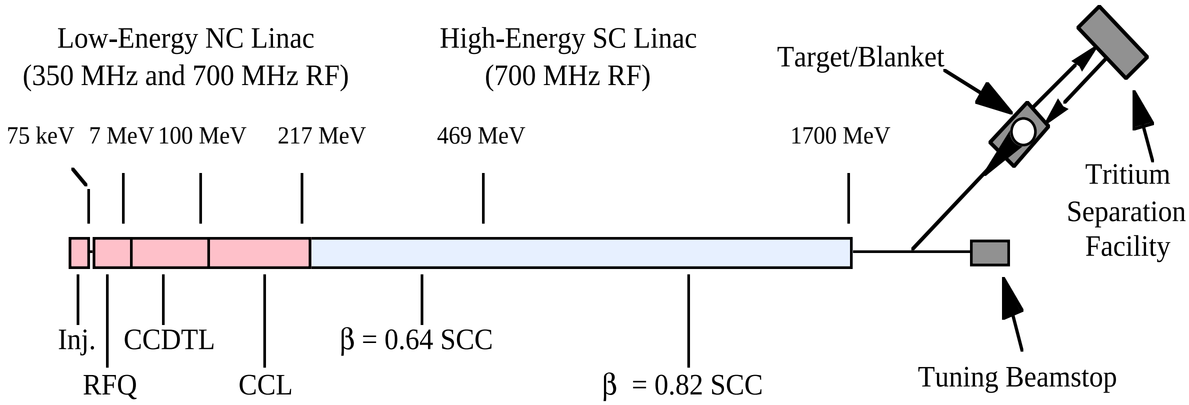


Figure 1, APT Plant Systems and Accelerator Architecture

water and are absorbed by ^{3}He to create about 40 tritium atoms per incident proton. The tritium is continuously removed from the ^{3}He gas. The overall APT plant is designed to operate at 71% or greater availability.

The APT design was strongly influenced by the need for efficient use of the large amount of required RF power [3]. The selection of basic accelerator parameters, such as current, energy, and accelerating gradient, was determined by the required plant production capacity, using a cost-performance model [4]. The model has an energy-dependent parameterization of spallation neutron production in high-Z targets and includes cost estimates for subsystems and consumables such as electricity. The model also includes technical constraints, such as injector current limits and maintenance requirements.

2.1 Linear Accelerator

The accelerator system has been designed to provide:

- A 100-mA proton beam at 1700 MeV that can be expanded to provide a current density at the entrance window to the Target/Blanket that is less than 80 mA/cm^2 and uniform to within ±30%,
- Beam loss within the accelerator structure that is low enough to allow unrestricted hands-on maintenance (At the highest energy, the loss corresponds to about 0.1 nA/m.), and
- Accelerator availability during scheduled operations of ≥85%.

The APT linac uses normal conducting (NC) water-cooled copper structures [5] to accelerate the 100-mA continuous wave (CW) proton beam to 217 MeV, and niobium superconducting (SC) accelerating cavities [6] thereafter.

In order to smoothly and efficiently accelerate the proton beam without loss, there are several accelerating structures following the injector, each optimized for a specific energy range. The low-energy normal-conducting (NC) linac, which is used up to 217 MeV, consists of a 350 Mhz radio-frequency quadrupole (RFQ), a coupled cavity drift tube linac (CCDTL), and a coupled-cavity linac (CCL). Within the NC linac, the CCDTL and CCL use 48 1-MW 700-MHz klystrons. Each klystron distributes power to the accelerating structure through four 250-kW windows. The high-energy linac, consists of superconducting-cavity (SCC) cryomodules of only two designs. From 217 MeV to 469 MeV, the cavities are optimized at b = 0.64, and in the section above 469 MeV, at b = 0.82. The shapes were modeled after well-established elliptical designs used in electron machines, but compressed along the longitudinal axis in proportion to b. Each cavity has two coaxial RF couplers to supply up to 210 kW of 700-MHz RF power and uses a SC focussing lattice.

This combination NC/SC accelerator is designed to have strong focusing at low beam energy and to avoid any phase-space transitions after the RFQ that might perturb the beam. Studies [7] have shown that this is important in order to minimize emittance growth and beam halo formation. The amount of clearance between the accelerating structure and the beam core is indicated by the "aperture ratio", which is the ratio of the structure aperture diameter to the rms beam size. In order to ensure low beam loss, the linac has the largest practical aperture ratio at every energy. The ratio is achieved by having large apertures in accelerating structures and in focusing magnets, and by keeping the beam size small using strong beam focusing per unit length. The aperture ratio increases from about 20 at the end of the NC linac, to 80 at the end of the SC linac. The ratios are designed [8] to be large enough to keep beam losses low enough to allow hands-on maintenance.

Because of the SC linac can operate with accelerating cavities having only two values of b the linac output energy may be adjusted over a wide range, providing considerable operational flexibility. For example, output beam energy may be traded for beam current, if necessary, and the accelerator may be retuned for operation following an RF station or cavity failure.

Cooling for the SC linac is provided by a cryogenic plant consisting of three identical refrigerators similar in design to the one in use at the Thomas Jefferson National Accelerator Facility. This system must provide 2°K helium in the superfluid state to the superconducting cavities, 4.5°K helium for the superconducting magnets, a stream of 45°K helium gas for the cryomodule thermal shields, and liquid helium to cool the magnet current leads.

A High Energy Beam Transport (HEBT) system [9] delivers the beam to a target/blanket (T/B). The beam passes through a magnetic switchyard which directs it either to a straight-ahead tuning beamstop or into the beam line serving the T/B assembly. This beam line terminates in a beam expander, which converts the small-diameter Gaussian-like beam distribution into a large-area rectangular uniform distribution at the target. The beam expander has two non-linear (multipole) magnets and two quadrupoles, one pair for horizontal-plane expansion, and the other for vertical-plane expansion. After 30 m of drift, the beam expands to a 16 cm by 160 cm uniformly-filled rectangular pattern at the T/B.

2.2 Target/Blanket

The T/B assembly has been designed to meet tritium production requirements while maintaining a high degree of safety and reliability. Design features include a tungsten and lead assembly that stops the protons, a lead blanket containing ^{3}He that produces approximately 40 tritons per incident 1700 MeV proton, low-pressure, low-temperature cooling systems with redundant heat removal systems, and welded, doubly-contained gas handling systems to retain the ^{3}He and tritium.

Assembled from replaceable modules, the T/B has a beam entrance window, a centrally-located tungsten neutron source, a surrounding lead blanket, a reflector, and shielding. All modules are placed in a cavity maintained at a rough vacuum. A double-wall Inconel window isolates the T/B cavity vacuum system from the accelerator.

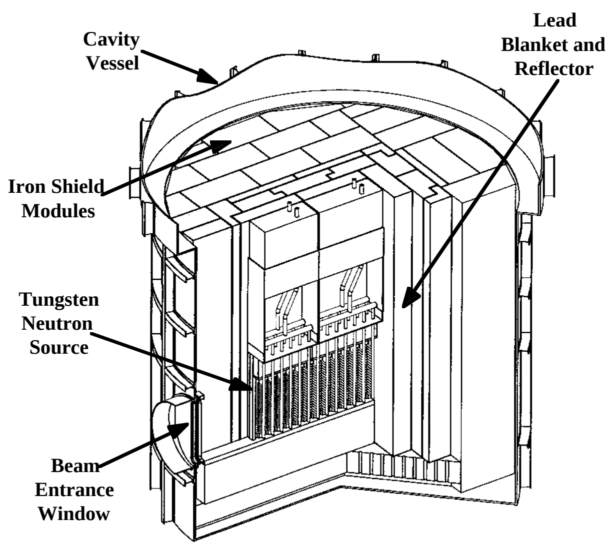


Figure 2, APT Target/Blanket System

The physics design of the tungsten neutron source maximizes the production of neutrons through nuclear spallation and allows them to leak into the blanket region with minimum loss. The tungsten neutron source consists of small heavy-water cooled, Inconel-clad tungsten rods mounted perpendicular to the proton beam axis in horizontal stainless steel tubes. The tubes are connected to vertical manifold tubes, in a ladder arrangement that is about 2 m tall. To enhance neutron leakage from this source, the tungsten is spread over a large volume. The tungsten neutron source produces approximately 21 neutrons per 1700 MeV proton. Approximately 3 neutrons are parasitically absorbed by the tungsten, and therefore, unavailable for making tritium. Surrounding the tungsten neutron source ladders is a neutron decoupler which allows high-energy neutrons and other particles to leave the central region. The decoupler also preferentially absorbs any neutrons in ^{3}He that attempt to return. The decoupler has several layers of light-water cooled, ^{3}He -filled aluminum tubes. Approximately 46% of the total tritium production occurs in the decoupler.

A blanket of lead, light water, and ^{3}He gas surrounds the tungsten neutron source and decoupler . The blanket is 120 cm thick laterally and extends about 50 cm above the ladders. The lead in this region increases neutron production by additional spallation and (n,xn) reactions. The neutrons are moderated to low energy by collisions in the lead and light water, and are captured in ^{3}He gas contained in circular aluminum tubes to produce tritium. Tritium produced in the ^{3}He diffuses to a manifold, where it is carried away by flowing ^{3}He. The ^{3}He/hydrogen-isotope mixture is transported to the Tritium Separation Facility (TSF) for continuous tritium removal and cleanup. The lead blanket and decoupler produce an additional 26 neutrons per proton, with approximately 4 neutrons lost to structure and coolant. Fifty-four percent of the tritium is produced in the blanket. The blanket is surrounded by a water reflector holding additional aluminum tubes which contain ^{3}He for reducing neutron leakage from the blanket. Of the 170 MW of beam power incident on the T/B, only 130 MW is converted to heat that must be removed by cooling systems.

The tungsten neutron source, decoupler, reflector, and blanket are mounted inside a cylindrical steel vacuum vessel that is shielded both inside and outside to reduce the radiation dose rate to less than 0.1 mrem/hour for personnel working in adjacent areas.

Target/Blanket safety is provided by multiple inherent and engineered design features. Inherent to safety is the low amount of heat that continues to evolve from the tungsten target and other components after the beam is removed. Unlike fission-based systems for tritium production, there are no delayed neutrons and no criticality concerns. Inconel cladding on the tungsten rods prevents radionuclide release in the unlikely event that the cooling water is lost and the rods must cool by radiating their decay heat. There is a highly reliable T/B fault detection system which would turn off the proton beam should an upset condition occur. Backup safety features include natural circulation heat removal, an active residual heat removal system, and the ability to flood the cavity.

2.3 Tritium Separation Facility

The TSF delivers tritium in quantity and purity meeting production requirements. Spallation products in the ^{3}He/hydrogen-isotope gas mixture produced in the target/blanket are removed before the gas is circulated to the TSF. There hydrogen isotopes are removed, and ^{3}He is recirculated to the T/B. The hydrogen isotopes are separated by cryogenic distillation, and the tritium is sent to existing SRS tritium facilities. The TSF recovers

99.9% of the tritium transported from the T/B assembly, and chemically and isotopically purifies it to a minimum of 99% tritium.

2.4 Balance of Plant

The Balance of Plant (BOP) design is driven by the need to meet the requirements of the linac, target/blanket, and tritium separation facilities. Those requirements include input electric power, waste heat to be removed, distributed utilities within the plant, shielding requirements, and remote handling of radioactive materials. About 10^6 square meters of land area is needed to accommodate the APT plant which will be 1.5 kn long and bounded by a fence to provide access control.

Incoming ac power from a local utility is converted by an electrical switchyard to a lower voltage for distribution to the accelerator and plant systems, and is distributed via a series of sub-stations along the length of the plant. Nine Cooling towers and their associated heat exchangers are located above ground along the accelerator tunnel to serve the accelerator and its power supply components. Because of its major cooling load, the T/B facility has an additional dedicated cooling station.

The APT total electric power requirement is 486 MWe, consisting of two major loads: the RF and BOP electric power loads of 377 and 109 MWe, respectively. The ac plant distribution system will be supplied by two 100% capacity overhead lines from the local utility. Loads that must meet safety requirements are fed from both normal and three 800-kW power generators and several uninterruptible power supply (UPS) backup systems.

The accelerator tunnel and high energy beam transport buildings are housed in a concrete tunnel, with seven meters of dirt covering the linac section for shielding. The klystron gallery is a steel frame, metal building that parallels the accelerator tunnel.

The T/B building has above- and below-grade structures. Below-grade, the T/B building is reinforced concrete, while above grade it is composed of a reinforced concrete bay and a steel frame with metal siding. Remote handling equipment is used where contact handling is not practical or not permitted by personnel hazards, such as during replacement of used targets.

The BOP contains the Integrated Control System (ICS), which integrates accelerator protection and operation, ensures safe running conditions, and adjusts plant production variables. The plant will be completely operable from the main control room.

Other infrastructure support services considered within the BOP include radiation monitoring and protection, heating, air conditioning and ventilation, water supply, fire protection, communications, interfaces to SRS infrastructure, and safeguards and security.

3. ENGINEERING DEVELOPMENT AND DEMONSTRATION

The operation of all essential APT systems, structures, and components has been demonstrated, sometimes on a smaller scale and in different environments than will be present in the production plant. However, because the DOE dual-track approach has a critical decision in 1998, the APT Project plans to develop and demonstrate several key technologies and components at prototypic scale before that decision. These planned activities are identified in a Core Technology Plan which forms the basis for the ED&D component of the APT project. They will be carried out with the assistance of the Prime Contractor, and with the Maintenance and Operations Contractor at Savannah River, in order to assure actual plant operations experience. ED&D has substantial breadth, but there are four major technical activities underway:

- Low Energy Demonstration Accelerator (LEDA)
- Target/Blanket and materials ED&D
- Tritium separation
- High-energy accelerator ED&D

3.1 Low Energy Demonstration Accelerator

LEDA activities [10] will be conducted in five stages to progressively demonstrate integrated high-power operation of the low-energy linac.

- Installation and testing of a 75-keV, 110-mA proton injector;
- Addition of a 350-MHz RFQ accelerator to accelerate a 100-mA CW proton beam to 7 MeV;
- Addition of a 700-MHz CCDTL to further accelerate the 100-mA CW proton beam to 20 MeV;
- Addition of CCDTL modules to raise the final energy of the 100-mA CW proton beam to 30-40 MeV; and
- Optional phase addition of a second parallel apparatus similar to that of Stage III, and a beam combiner to merge two 350-MHz, 100-mA, 20-MeV proton beams into a single 700-MHz, 200-mA, 20-MeV proton beam. This beam would then be accelerated with CCDTL modules to an energy as high as 40 MeV.

Of these, the first item has been completed, while construction and assembly of the RFQ [11] in the second item is underway.

3.2 High Energy Accelerator

Although the high-energy linac accelerating structures are based on well proven designs, RF coupling, manufacturability, and thermal performance will be demonstrated by building and testing a prototype of the 100 MeV CCDTL section.

The SCRF development program has as its basis the successful cryomodules for electron accelerators. For proton applications there are several engineering development activities leading to pre-production prototypes suitable for manufacture that will be addressed by the following activities:

- Fabrication and high-gradient testing of several single-cell intermediate velocity proton beams Nb cavities;
- Fabrication and testing of high-power couplers for SCRF medium-velocity cavities;
- Fabrication and high-field testing of multi-cell SCRF cavities;
- Tests of multi-cell prototype SCRF cavities and couplers in beam cryostats at full power, using resistive loads to simulate the beam; and,

- Evaluation of radiation damage of a prototype Nb cavity and Nb samples.

Of these activities, the first and fifth have already been successfully accomplished.

3.3 Tritium and Neutron Production Efficiency

The technology associated with generation and moderation of neutrons produced by energetic proton beams on tungsten and lead targets has been demonstrated at neutron sources worldwide. The efficiency of tritium production for an optimized T/B has a proton energy dependence very nearly the same as that of the total neutron production for range-thick targets. Measurements of tritium production from simplified prototype targets at 800 MeV and for neutron production over the proton energy range of interest for APT have been completed, confirming the predicted neutron and tritium production. Additional work is in the planning stage involving a protoypic power density system for investigating the engineering performance of a tritium-producing ^{3}He loop at the LANSCE accelerator.

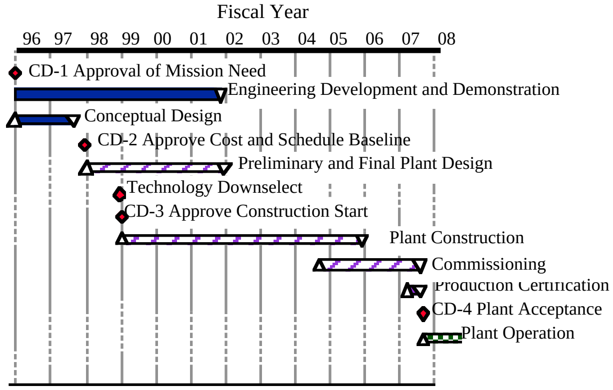
3.4 Materials Performance

Candidate Target/Blanket structural materials, including Inconel, stainless steel, aluminum alloys, lead, zircaloy and tungsten, are being irradiated in the high power proton beam at 800 MeV at LANSCE. The irradiations are planned to achieve a fluence corresponding to about one full-power APT year. Included with the materials irradiation samples will be a corrosion study to determine on-line and in-situ water chemistry in which an instrumented closed-loop coolant system exposes candidate materials to a prototypic proton flux. The materials work will lead to fundamental information on the response of proposed materials to prototypic radiation environments as a function of fluence, material lifetimes, water radiolysis and spallation product mitigation requirements, and water chemistry requirements.

4. PROJECT COST AND SCHEDULE

The Integrated APT Project Schedule was developed to support key DOE and project specific milestones, from Critical Decision 1, “Approval of Mission Need,” to Critical Decision 4, “APT Plant Acceptance.” The schedule is also based on key deliverables from the ED&D program that interface with final design and procurement activities. The APT Project summary schedule shown in Figure 3, presents the major phases of the project: Engineering Development and Demonstration Conceptual Design, Preliminary and Final Plant Design, Procurement and Construction, and Operational Testing and Commissioning.

Figure 3 APT Project Summary Schedule



The APT cost estimate includes all costs to develop, engineer, construct, commission, operate, and decommission the APT plant. The Total Estimated Cost ($3.5B, with contingency and escalation) includes Preliminary and Final Design, construction costs, and all associated supporting activities such as systems and construction engineering, construction management (including inspection and testing), and all project management. Other Project Costs (OPC) ($1B ,with contingency and escalation) includes costs of the Engineering Development and Demonstration program, Conceptual Design costs, Environmental Safety and Health program costs, start-up costs, and all of the associated project management and administration costs for OPC activities. Annual operating costs for 3 kg/yr production are $150M.

5. REFERENCES

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