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ACCELERATOR PRODUCTION OF TRITIUM PLANT DESIGN AND SUPPORTING ENGINEERING DEVELOPMENT AND DEMONSTRATION WORK

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ABSTRACT

Tritium is an isotope of hydrogen with a half-life of 12.3 years. Because it is essential for US thermonuclear weapons to function, tritium must be periodically replenished. Since K reactor at Savannah River Site stopped operating in 1988, tritium has been recycled from dismantled nuclear weapons. This process is possible only as long as many weapons are being retired. Maintaining the stockpile at the level called for in the present Strategic Arms Reduction Treaty (START - I) will require the Department of Energy to have an operational tritium production capability in the 2005 - 2007 time frame. To make the required amount of tritium using an accelerator-based system (APT), neutrons will be produced through high-energy proton reactions with tungsten and lead. Those neutrons will be moderated and captured in ^{3}He to make tritium. The APT plant design will use a 1700 MeV linear accelerator operated at 100 mA. In preparation for engineering design, starting in October 1997, and subsequent construction, a program of engineering development and demonstration is underway. That work includes assembly and testing of the first 20 MeV of the low-energy plant linac at 100 mA, high-energy linac accelerating structure prototyping, radio-frequency power system improvements, neutronic efficiency measurements, and materials qualifications.

I. INTRODUCTION

Production of enough tritium 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. At the present time, only reactor or accelerator systems can make enough neutrons to produce tritium in the quantities needed. In a nuclear reactor, fission supplies the neutrons. In APT, neutrons are made principally by proton spallation of heavy-metal nuclei. The use of spallation 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.

A. Project History

An APT system for tritium production was first considered by the DOE Energy Research Advisory Board (ERAB) in late 1989. At that time the Cold War was still underway, requiring more tritium than could be easily supplied in the time thought to be available should an accelerator-based plant be built. With the implementation of START-I, the tritium requirement decreased and the need date moved out, making APT a much more attractive option. As a result, the DOE requested an appraisal by the JASONs, an independent scientific panel, in 1992. Their review of APT technology was 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 in support of the DOE Programmatic Environmental Impact Statement for Tritium Supply and Recycling.

In December, 1995 the DOE announced a dual track plan for obtaining a new tritium supply. That strategy initiated action to purchase an existing commercial reactor (operating or partially complete) or to secure 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 committed to a selection of one of the tracks to serve the primary source of tritium by fall, 1998. The Savannah River Site (SRS) in South Carolina was selected as the location for the APT plant, should it be chosen.

The DOE 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 work will continue at least through engineering design of the plant and will include sufficient engineering demonstration and development (ED&D) to ensure low-risk construction and operation.

ED&D activities are directly linked to the APT plant design schedule. They include evaluating alternative designs, prototyping key components and subsystems, and improving fundamental information needed for the design. This work is being performed mainly at Los Alamos with the assistance of a Prime Contractor, Burns and Roe teamed with General Atomics, which will be responsible for plant design, construction, and commissioning; and with the Maintenance and Operations Contractor at Savannah River, in order to assure actual plant operations experience.

B. Conceptual Design Report

This paper is based on the APT Plant Conceptual Design Report[1] (CDR). The CDR establishes the design,

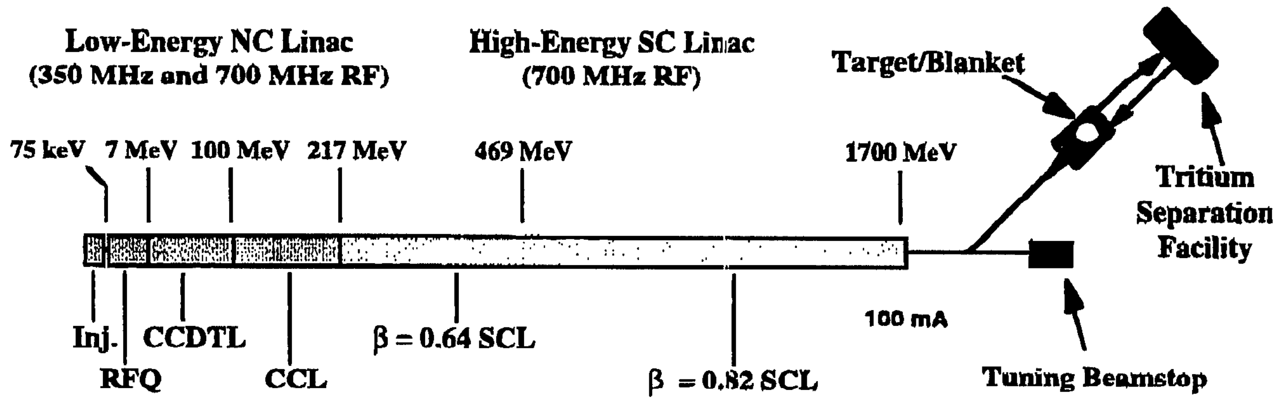


Figure 1. APT Plant Systems and Accelerator Architecture

cost, and schedule for the project and includes information on Environment Safety and Health, Operations and Maintenance, Safeguards and Security, and Decontamination and Decommissioning. The CDR 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.

The design supports DOE requirements for the APT plant including:

- 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 starting no later than 2007,
- Operational lifetime of 40 years, and
- Cost effective, efficient operation in the 2 to 3 kg/yr range.

II. SYSTEM DESCRIPTION

The APT plant will use a proton linear accelerator[2] to produce a 170 MW continuous wave proton beam that will be directed to a tungsten target surrounded by a lead blanket. Aluminum tubes filled with ^3He gas will be adjacent to the tungsten target and within the lead blanket. Neutrons created by the energetic protons interacting with the tungsten and lead will be moderated and create about 41 tritium atoms per incident proton through the $^3He(n,t)H$ reaction. Hydrogen isotopes will be continuously removed from the ^3He gas and the tritium purified using cryogenic distillation in a tritium separation facilities (TSF). The APT plant is designed to operate at 71% or greater availability. Figure 1 shows the major systems and operating parameters of the APT-plant.

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 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.

A. 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 $\mu A/cm^2$ 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 proton beam to 217 MeV, and niobium superconducting (SC) accelerating cavities[6] thereafter.

In order to smoothly and efficiently accelerate the proton beam with acceptable losses, there are several specialized accelerating structures following the injector, each optimized for a specific energy range. The low-energy 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). The CCDTL and CCL accelerating sections 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 linac (SCL) accelerating structures of only two designs with a SC focusing lattice. Here β is the ratio of the proton velocity to the speed of light. From 217 MeV to 469 MeV, the cavities are optimized at $\beta = 0.64$, and in the section above 469 MeV, at $\beta = 0.82$. The shapes were modeled after well-established elliptical designs used in electron accelerators, but compressed along the longitudinal axis in proportion to β. Each cavity will have two coaxial RF couplers to supply up to 210 kW of 700-MHz RF power.

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. This is important in order to minimize emittance growth and beam halo formation and therefore limit beam loss[7]. The clearance between the accelerating structure and the beam core is measured by the "aperture ratio", which is the ratio of the structure aperture diameter to the rms beam size. To ensure low beam loss, the linac was designed to have the largest practical aperture ratio at every energy. The high 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. Based on operational experience at the LANSCE 1-MW proton linac, the ratios[8] will keep beam losses low enough to allow hands-on maintenance.

Because the SC linac can operate with only two different accelerating cavities shapes, 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 at very nearly the same output power following an RF station or cavity failure.

Cooling for the SC linac will be provided by a cryogenic plant consisting of three refrigerators similar in design to the one in use at the Thomas Jefferson National Accelerator Facility. This system will 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] will be used to deliver the beam to a target/blanket (T/B). The beam will pass through a magnetic switchyard and be directed either to a straight-ahead tuning beamstop or into the beam line serving the T/B assembly. The T/B 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 will use two non-linear (multipole) magnets and two quadrupoles, one pair for horizontal-plane expansion, and the other for vertical-plane expansion. After drifting 30 m, the beam will have expanded to a 16 cm by 160 cm uniformly-filled rectangular pattern at the entrance to the T/B.

B. Target/Blanket

The T/B assembly has been designed to meet tritium production requirements and maintain a high degree of safety and reliability. Design features include a tungsten and lead assembly that stops the protons and produces neutrons, a lead blanket containing 3He that will produce 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 3He and tritium.

The T/B will be assembled from replaceable modules consisting of a beam entrance window, a centrally-located tungsten neutron source, a surrounding lead blanket, a reflector, and shielding. All of the modules will be located in a cavity maintained at a rough vacuum. A double-wall Inconel window will isolate the T/B cavity vacuum system from the accelerator.

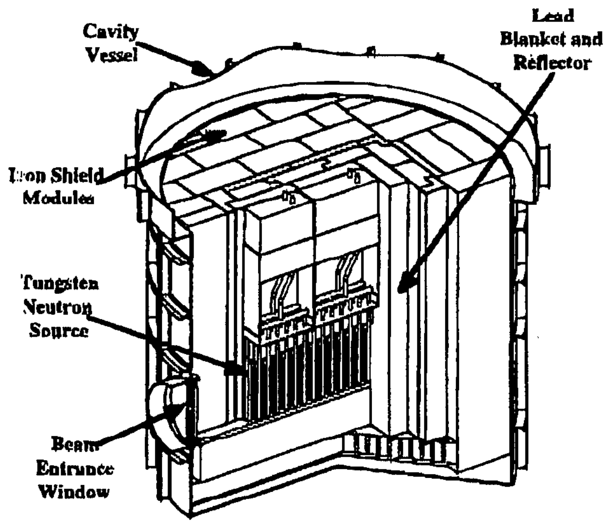


Figure 2. Target/Blanket System

The tungsten neutron source design maximizes the production of neutrons through nuclear spallation and by allowing those neutrons to leak into the blanket region with minimum loss. The tungsten neutron source will have small heavy-water cooled, Inconel-clad tungsten rods mounted perpendicular to the proton beam axis in horizontal stainless steel tubes. The tubes will be connected to vertical manifold tubes, in a ladder arrangement. 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 three neutrons are parasitically absorbed by the tungsten, and therefore, unavailable for making tritium. Surrounding the tungsten neutron source ladders will be a ^{3}He-filled, light-water cooled aluminum neutron decoupler that will allow high-energy neutrons and other particles to leave the central region. The decoupler will preferentially absorb any neutrons in ^{3}He that attempt to return thereby avoiding parasitic losses in the tungsten neutron source. Approximately 36% of the total tritium production occurs in the decoupler.

A blanket of lead, light water, and ^{3}He gas will surround the tungsten neutron source and decoupler. The blanket will be 120 cm thick laterally and extend about 50 cm above the ladders. The lead in this region will increase neutron production by additional spallation and through (n,xn) reactions. Neutrons moderated to low energy by collisions in the lead and light water will be captured in the ^{3}He gas within aluminum tubes to produce tritium.

Tritium inside aluminum tubing will diffuse to a manifold, where it will be carried away by flowing ^{3}He. The ^{3}He/hydrogen-isotope mixture will be transported to a Tritium Separation Facility (TSF) for continuous tritium removal and cleanup. The lead blanket and decoupler will produce an additional 26 neutrons per proton, with approximately 4 neutrons lost to structure and coolant. Fifty-six percent of the tritium will be produced in the blanket.

The blanket will be surrounded by a water reflector holding additional aluminum tubes which contain ^{3}He in order to reduce neutron leakage from the blanket. Of the 170 MW of beam power incident on the T/B, only 130 MW will be converted to heat that must be removed by cooling systems. The outer blanket and the reflector regions produce 8% of the tritium.

The tungsten neutron source, decoupler, reflector, and blanket will be mounted inside a cylindrical steel vacuum vessel that will be 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 will be provided by multiple inherent and engineered design features. Inherent to safety is the low amount of heat that will continue 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 of the tungsten rods prevents radionuclide release in the unlikely event that the water cooling is lost and the rods must cool by radiating their decay heat. There will be a highly reliable T/B fault detection system which will 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 from the spent target storage pool.

C. Tritium Separation Facility

The Tritium Separation Facility (TSF) will deliver tritium in quantity and purity meeting stockpile production requirements. Radioactive material in the ^{3}He/hydrogen-isotope gas mixture produced in the T/B will be removed before the gas is circulated to the TSF where hydrogen isotopes will be removed. ^{3}He will then be recirculated to the T/B. The hydrogen and tritium will be separated by cryogenic distillation, and the tritium sent to existing SRS tritium facilities. The TSF will recover 99.9% of the tritium transported from the T/B assembly, and chemically and isotopically purify it to a minimum of 99% tritium.

D. Balance of Plant

The Balance of Plant (BOP) design was 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 km long and bounded by a fence to provide access control. A plan view of the plant layout is shown in Figure 3.

Incoming ac power from a local utility will be converted by an electrical switchyard to a lower voltage for distribution to the accelerator and plant systems, and distributed via a series of sub-stations along the length of the plant. Nine cooling towers and their associated heat exchangers will be 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 will have an additional dedicated cooling station.

The APT total electric power requirement will be 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 will be housed in a concrete tunnel, with seven meters of earth covering the linac section for shielding.

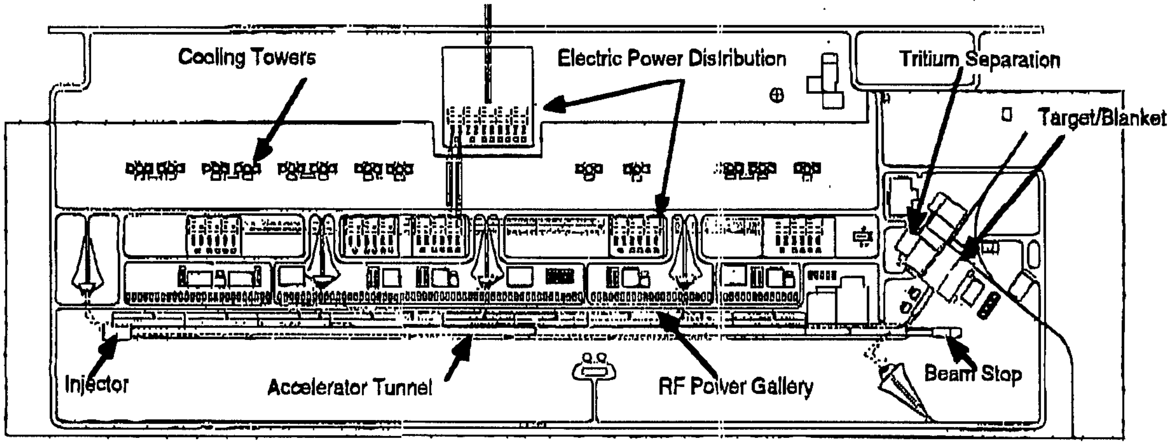


Figure 3. APT Plant Layout

Located at grade and offset from the linac tunnel will be a steel frame, metal building that will parallel the accelerator tunnel and house the RF generation equipment. A section of the accelerator tunnel in the SCL section is shown in Figure 4.

The T/B building will have both above-and below-grade structures as shown in Figure 5. Below-grade, the T/B building will be reinforced concrete; above grade it will be composed of a reinforced concrete bay and a steel frame with metal siding. Remote handling equipment will be used where contact handling is not practical or not permitted by personnel hazards, such as during replacement of used T/B components. The BOP will contain the Integrated Control System, which will integrate accelerator protection and operation, ensure safe running conditions, and adjust 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.

III. 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. Because of the nature of the DOE dual-track approach, the APT Project plans to develop and

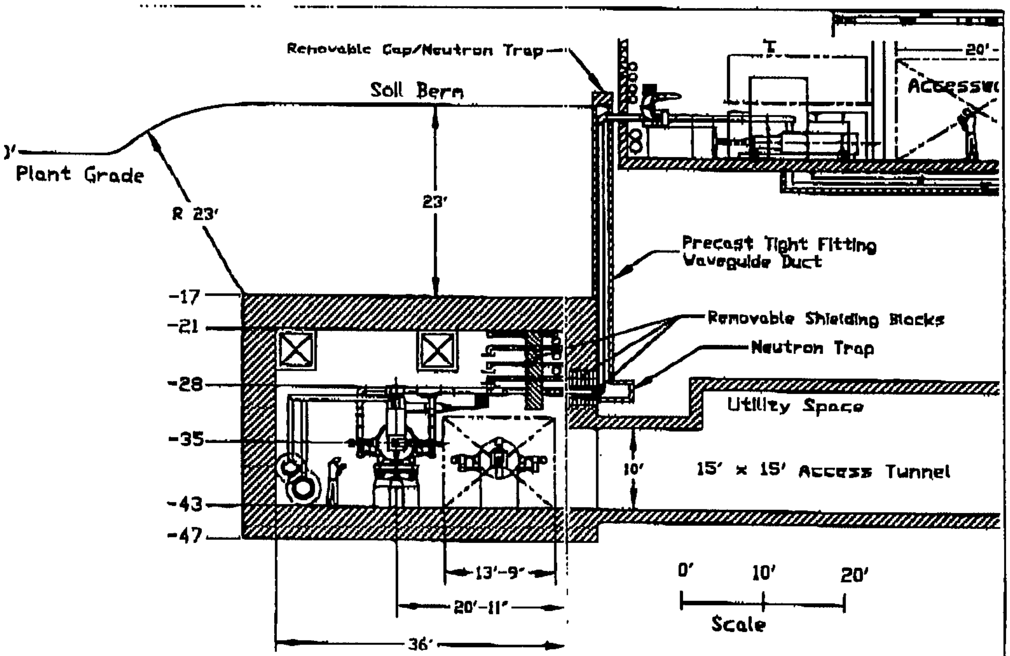


Figure 4. Accelerator Tunnel Section in $\beta = 0.64$ Structure Region.

demonstrate several key technologies and components in support of plant design. The 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)
- High-energy accelerator ED&D
- Neutron and Tritium Production
- Materials Performance
- Tritium separation

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, and construction and assembly of the RFQ in the second item is underway[11].

B. 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.

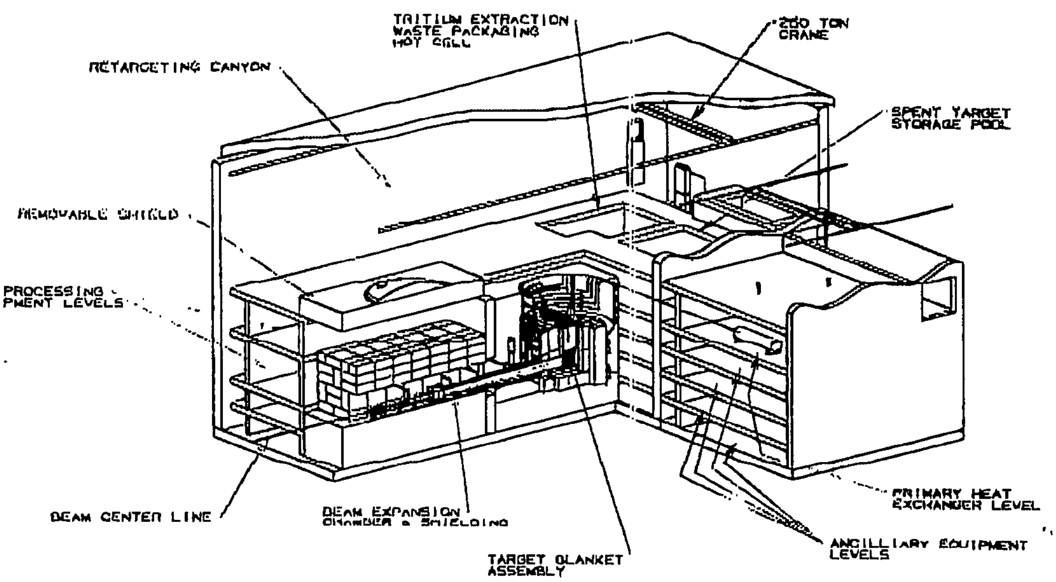


Figure 5. APT Target/Blanket Building

A. 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 addition of a second parallel apparatus up to 20 MeV, and a beam combiner to merge the two 350-MHz, 100-mA, 20-MeV proton beams into a

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.

C. Neutron and Tritium Production

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 at the SATURNE accelerator in France. Those data confirm the predicted neutron and tritium production are shown in Figure 6. The 10% errors at energies above 800 MeV are due to uncertainties in the aluminum activation cross section used to measure the proton flux. Measurements are planned at Brookhaven National Laboratory to obtain more accurate data and thereby reduce the uncertainty to 3-5%. Work in the planning stage involves a operation of a protoypic power density system to investigate the engineering performance of a 1-MW tritium-producing ^{3}He loop at the LANSCE accelerator.

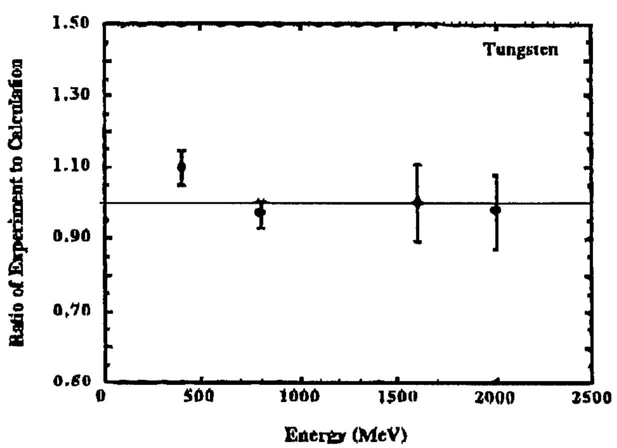


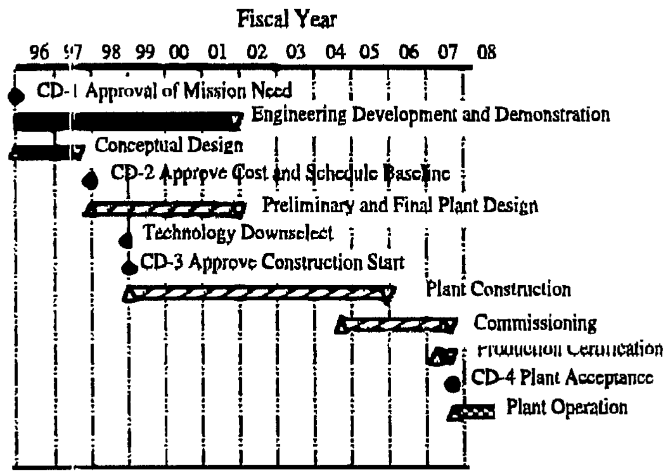
Figure 6. Tungsten Total Neutron Leakage

D. 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.

IV. 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 links key deliverables from the ED&D program to final design and procurement activities. The APT Project summary schedule shown in Figure 7, shows 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 7. 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) include the costs of Engineering Development and Demonstration, Conceptual Design, Environmental Safety and Health program, start-up, and all of the associated project management and administration costs for OPC activities. Annual operating costs for 3 kg/yr production are $150M.

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