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Abstract. Tritium is a radioactive isotope of hydrogen essential to the operation of all United States nuclear weapons. Because the half-life of tritium is short, 12.3 years, it must be periodically replenished. In 1995, the U.S. Department of Energy (DOE) initiated a plan for a new tritium supply that examined use of existing commercial power reactors, or construction of a new accelerator-based (APT) system. In 1998, the DOE announced that commercial light-water reactors (CLWR) will be used to provide the primary tritium supply technology. To provide a backup to that approach, the DOE will continue engineering development and preliminary design of a high-power proton linear accelerator-based system to produce tritium, but will not construct the plant. Because the accelerator system represents a substantial advance in high-power accelerator and spallation technology over that currently available, the design and development information is of great value in applications that require an APT-class system such as spent reactor fuel transmutation or clean fission energy production.

I. INTRODUCTION

An adequate defense through both conventional and nuclear arms is an important component of the United States' defense strategy. All U.S. nuclear weapons have tritium as an essential isotope. Unlike other materials used in nuclear weapons, tritium decays at a rate of 5.5% per year, requiring periodic replenishment.

Production of tritium in large enough quantities 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 Accelerator Production of Tritium (APT), neutrons are made by proton spallation of heavy metal nuclei, such as tungsten. Using spallation to produce neutrons makes it possible to avoid the use of fissile material, which in turn makes the system design relatively simple with inherent safety and environmental features.

In December, 1995, the U.S. 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; and authorized work to design, build, and test critical components of an accelerator system for tritium production. In addition, the Savannah River Site, located near Aiken, South Carolina, was chosen as the preferred site for the plant, should APT be selected. In December of 1998, the Department announced a Record of Decision, picking commercial light-water reactor (CLWR) technology as the preferred alternative for tritium production. The Tennessee Valley Authority Watts Barr and Sequoia nuclear power plants will be used through a contractual arrangement to produce tritium. The APT Project will complete preliminary design and engineering development and demonstration of key components, but at a reduced level from that planned had APT been selected for construction.

The backup APT plant will have a design production capacity ranging from 1 kg/year upgradable to 3 kg/year, with a reference design capacity of 1.5 kg/year. The plant design will include a proton linear accelerator, beam transport, target/blanket, and tritium-extraction systems. The balance of the plant equipment design will include all of the structures and conventional support systems.

II. SYSTEM DESCRIPTION

The APT plant design[1] will have a proton linear accelerator[2] producing a continuous-wave beam that will be expanded and rastered to uniformly illuminate a tungsten target surrounded by a lead blanket. Aluminum tubes filled with ^3He gas will be located adjacent to the tungsten target and as part of the structure of the lead blanket. Neutrons created by the energetic protons interacting with the tungsten and lead will be moderated in light water, and create about 20 tritium atoms per incident proton through the $^3He(n,t)H$ reaction. Hydrogen isotopes will be removed from the ^3He gas semi-continuously, and the tritium purified using cryogenic distillation in a tritium separation facility (TSF). The APT plant is being designed to operate in the 70% – 75% availability range. Figure 1 shows the major systems and operating parameters of the APT plant.

A. Linear Accelerator

The APT linear accelerator design was strongly influenced by the need to efficiently use the large amount of RF power required to accelerate 100 mA of proton beam at 100% duty factor to 1030 MeV.[3] Other design issues taken into account included a requirement to keep beam losses low, control of the high-power beam, current-independent tuning and operation, and high availability.

The accelerator system is being designed to provide:

- A 100-mA proton beam at 1030 MeV that can be expanded to provide a current density at the entrance window to the Target/Blanket (T/B) of 28 μA/m^2,
- Beam loss within the accelerator structure low enough to allow unrestricted hands-on maintenance (at 1030 MeV, the loss corresponds to about 0.1 nA/m), and
- Accelerator availability during scheduled operations of ≥ 85%.

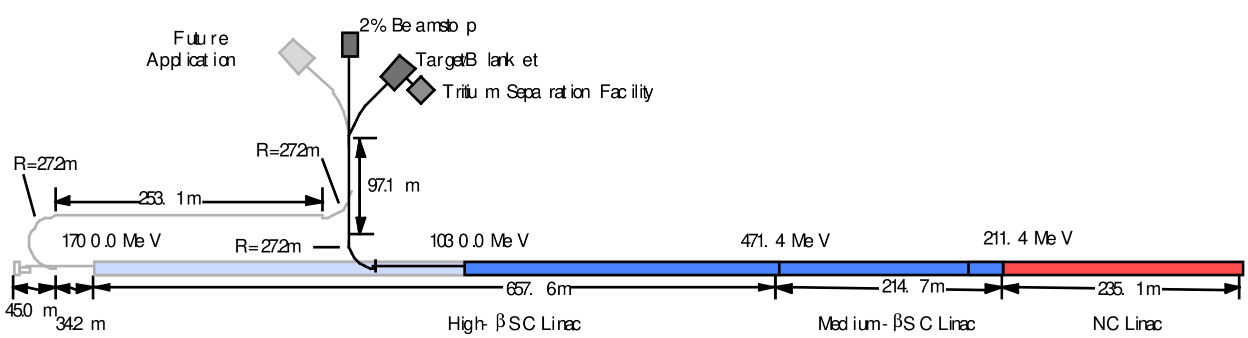

Figure 1. Major Systems and Operating Parameters of the APT Reference Design

The APT linac has a two-stage architecture with normal conducting (NC) water-cooled copper structures to accelerate the proton beam to 211 MeV, and niobium superconducting (SC) accelerating cavities in cryomodules thereafter.[4] A microwave-driven ion source[5] designed to produce a continuous 110-mA proton beam at 75 keV will provide the input beam to the low-energy linac.

The low-energy NC linac design, extending to 211 MeV, consists of a 350-MHz radio-frequency quadrupole (RFQ), a coupled cavity drift tube linac (CCDTL), and a coupled-cavity linac (CCL). The RFQ uses three 350-MHz 1.2-MW klystrons. The CCDTL and CCL accelerating sections use 52 1-MW 700-MHz klystrons. Each klystron distributes power to the accelerating structure through four windows, with each transmitting less than 250 kW.

The high-energy linac design consists of superconducting-cavity linac accelerating structures with two geometries, and an NC magnet focusing lattice.[6] From 211 MeV to 471 MeV, the cavities are optimized for protons with $\beta = 0.64$, and in the section above 471 MeV, for protons with $\beta = 0.82$. Here β is the ratio of the proton velocity to the speed of light. The shapes were modeled after elliptical designs used in electron accelerators, but compressed along the longitudinal axis in proportion to β. Each cavity is designed to have two coaxial RF couplers supplying up to 210 kW of 700-MHz RF power. The design calls for 106 1-MW klystrons for 1030 MeV.

This combination NC/SC accelerator is designed to have strong focusing at low beam energy, and to minimize phase-space transitions after the RFQ to minimize emittance growth and beam halo formation, therefore limiting beam loss. 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 root-mean-square 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 openings in accelerating structures and in the focusing magnets, and by keeping the beam size small using strong beam focusing per unit length. The aperture ratio is about 80 at 1030 MeV, providing a large clearance. Based on operational experience with the Los Alamos Neutron Science Center (LANSCE) 800-kW proton linac, that ratio will keep beam losses low enough to allow hands-on maintenance.[7]

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 but about 50% larger in capacity. This system will provide 2.15° K helium to the superconducting cavities, and a stream of 45° K helium gas for the cryomodule thermal shields. Cryoplant loads are estimated to be 14.5 kW at 2.15° K, and 22.4 kW at 45° K.

The accelerator is housed in a concrete, rectangular-section tunnel 11 m wide and 6.7 m high that is buried under about 7 meters of earth berm for radiation shielding. The tunnel roof is 1.2-m-thick concrete. A building housing the RF amplifiers, magnet power supplies, and controls runs the length of the accelerator and is situated beside the berm. This building can be occupied by operating personnel when the beam is on. A cross section of the beam tunnel in the SC section of the accelerator is shown in Figure 2.

A High-Energy Beam Transport (HEBT) system is designed to deliver the beam to the Target/ Blanket (T/B) region where tritium is produced. The beam passes through a magnetic switchyard and is directed either to a straight-ahead tuning beam stop rated at 2% of the full-energy power, or into the beam line serving the T/B assembly. The T/B beam line terminates in a beam expander,[8] which converts the small-diameter gaussian-like beam distribution into a large-area rectangular uniform distribution (0.19 m wide ×

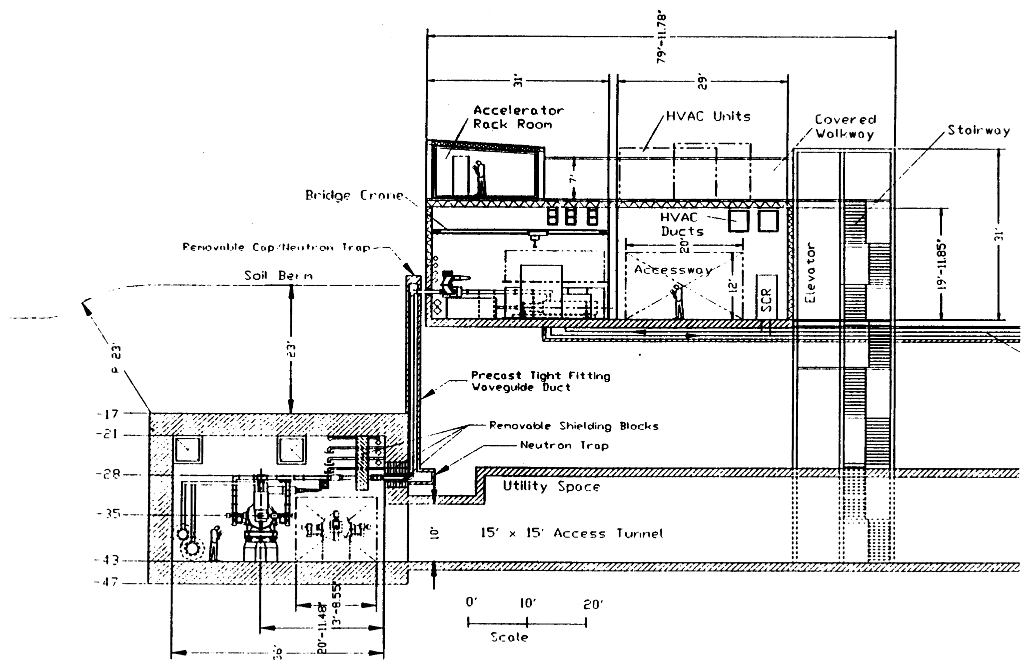

Figure 2. Cross Section of Accelerator Tunnel in SC Linac Region

1.90 m high) at the target. The beam expander uses horizontal and vertical sets of four sweep magnets, driven by triangular waveforms at frequencies near 500 Hz. The frequencies for the horizontal and vertical sweep are slightly different, resulting in a uniform “painting” of the target each 30 ms.

B. Target/Blanket

The Target/Blanket assembly is designed to produce tritium at up to 3 kg/year with a high degree of safety and reliability. The T/B arrangement is shown in Figure 3. Design features include:

- An Inconel beam entrance window to isolate the T/B rough vacuum from the linac high vacuum,
- A tungsten and lead assembly that stops the protons and efficiently produces neutrons,
- A lead blanket containing ^{3}He producing approximately 23 tritons per incident 1030 MeV proton,
- Low-pressure, low-temperature cooling systems with redundant heat removal systems,
- Welded, doubly-contained gas-handling systems to retain the ^{3}He and tritium, and
- Replaceable limited lifetime components.

The tungsten neutron source is designed to maximize the production of neutrons through nuclear spallation, and by allowing those neutrons to leak into the blanket region with minimum loss. It has heavy-water cooled, Inconel-clad concentric tungsten rings mounted perpendicular to the proton beam axis in horizontal Inconel tubes. The tubes are connected to vertical manifold tubes, in a ladder arrangement. To enhance neutron leakage from this source, the tungsten is spread over a large volume. Approximately three neutrons are parasitically absorbed by the tungsten, and therefore, unavailable for making tritium. Surrounding the tungsten neutron source ladders is a ^{3}He-filled, light-water cooled aluminum neutron decoupler that has high transmission for MeV-energy neutrons and other particles, but which preferentially absorbs low-energy neutrons that attempt to return, thereby reducing 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 surrounds the tungsten neutron source and decoupler. The blanket is 120 cm thick and

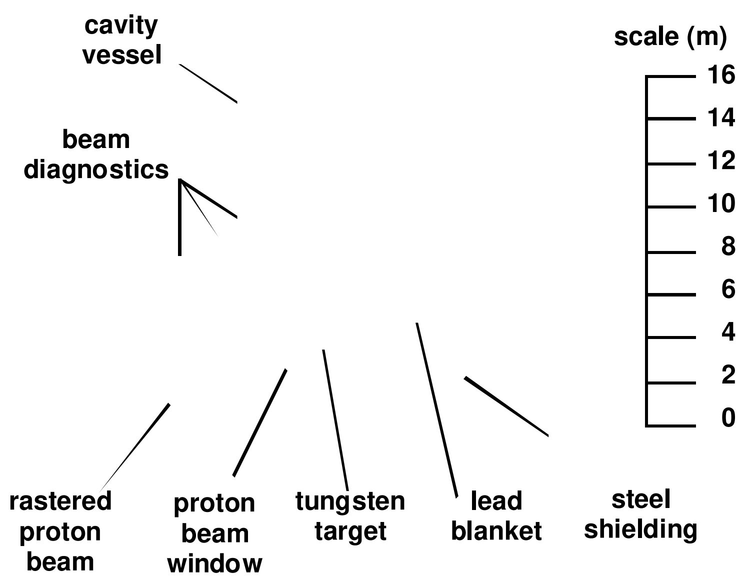

Figure 3. Target/Blanket System

400 cm high. The lead in this region increases neutron production by additional spallation from energetic particles,generated by the incident proton beam striking the tungsten neutron source and through (n, xn) reactions. Neutrons moderated by collisions in the lead and light water are captured in the ^{3}He gas within aluminum tubes to produce tritium. The combination tungsten-lead T/B produces approximately 27 neutrons per 1030 MeV proton. Fifty-six 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 to reduce neutron leakage from the blanket. The outer blanket and the reflector regions produce 8% of the tritium. Of the 103 MW of beam power incident on the T/B, only 80 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, shielded to reduce the radiation dose rate to less than 0.1 mrem/hour for personnel working in adjacent areas. Shielding inside the vacuum vessel is designed to be sufficient to allow it to last 40 years or longer before radiation damage becomes important.

T/B safety is provided by multiple inherent and engineered design features. Inherent to safety is the low amount of heat that evolves 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 cylinders prevents radionuclide release in the unlikely event that water cooling is lost and the cylinders must cool by radiating their decay heat. There is a highly reliable T/B fault detection system, which turns 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 an adjacent spent target storage pool.

C. Tritium Separation Facility

The TSF delivers tritium with purity meeting stockpile production requirements. Any radioactive material in the ^{3}He/hydrogen- isotope gas mixture produced in the T/B is removed before the gas is circulated to the TSF, where hydrogen isotopes are removed. The ^3He is then recirculated to the T/B. Hydrogen and tritium are separated by cryogenic distillation, and the tritium sent to existing Savannah River Site (SRS) tritium facilities. The TSF is designed to 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 determined by the need to meet the requirements of the linac, T/B, and TSF. 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 1.2 km long and bounded by a fence to control access. A view of the reference design plant layout is shown in Figure 4. Incoming ac power from a local utility is converted in an electrical switchyard to a lower voltage for distribution to the accelerator and plant systems, and distributed via a series of substations along the length of the plant. At 1030 MeV, six 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 the size of the cooling load, the T/B facility will have an additional dedicated cooling station.

The APT total electric power requirement for the 1030 MeV configuration will be 312 MWe, consisting of two major loads: the RF and BOP electric power loads of 235 and 77 MWe, respectively. The ac plant distribution system is 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 T/B building has both above- and below-grade structures. Below-grade, the T/B building is reinforced concrete; above grade it is composed of a reinforced concrete bay and a steel frame with metal siding. Remote handling equipment is planned to 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 also contains an Integrated Control System (ICS), which combines accelerator protection and operation, ensures safe running conditions, and controls plant production variables. The complete plant is designed to be operable from the main control room.

Other infrastructure support services 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 APT Project has a broad Engineering Development and Demonstration (ED&D) effort to provide technology information necessary should the plant be built. Through this work, the project is demonstrating and prototyping key components and systems in support of plant design. With the decision to continue APT as a backup, the scope of the ED&D effort has been reduced from what it would have been had APT been built. Nevertheless, there is a substantial amount of ED&D underway, and that effort will continue through the end of September, 2002.

ED&D activities are based on design data need (DDN) requests from plant de-signers that are directly linked to the plant schedule.

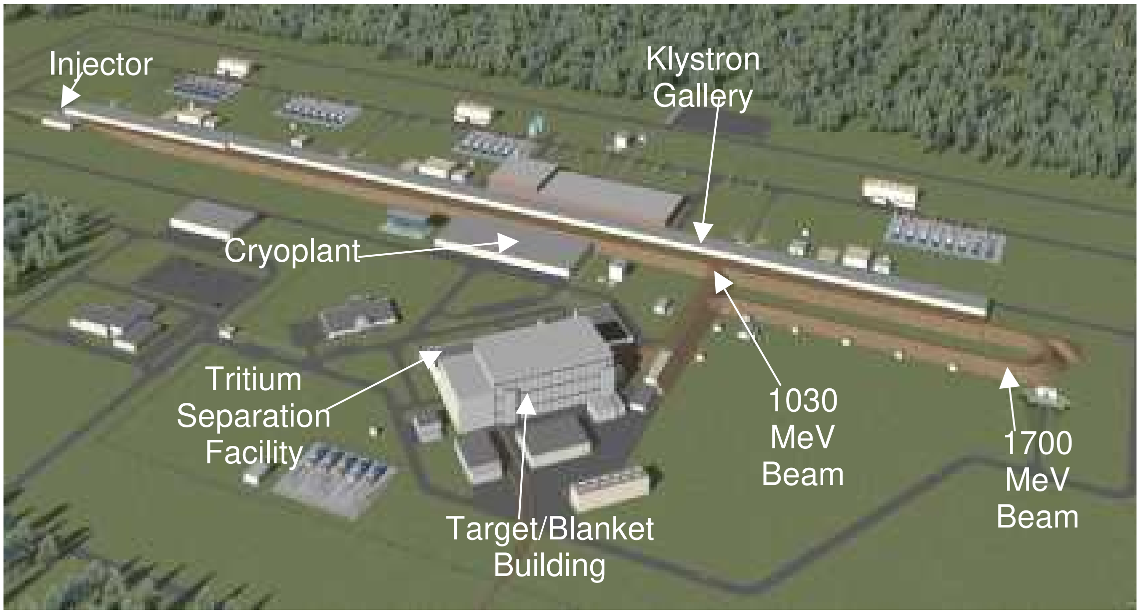

Figure 4. Reference Design APT Layout

DDNs include evaluating alternatives, prototyping key components and subsystems, and improving fundamental information needed for design.

The ED&D program has five major technical activities underway:

A. Low-Energy Demonstration Accelerator (LEDA);
B. Normal-Conducting Accelerator Structure Prototyping, Beam Raster, and Advanced RF Power Development;
C. High-Energy Superconducting Accelerator Structure Prototyping;
D. Target/Blanket performance and Materials Studies; and
E. Tritium Separation Demonstrations.

A. Low-Energy Demonstration Accelerator

LEDA activities[9] are underway to progressively demonstrate integrated high-power operation of the low-energy linac. Those activities and their status are listed below:

- Installation and testing of a 75-keV, 110-mA proton injector. The Injector is completed and fully operational meeting plant requirements.
- Fabrication and testing of 350-MHz RFQ accelerator to accelerate a 100-mA CW proton beam to 6.7 MeV. The RFQ has been completed, installed, and is under commissioning.[10] As an interim step in LEDA, the injector was successfully modified and operated with a 1.25-MeV RFQ obtained from another program.[11] That test demonstrated plant-level beam current and transmission (100 mA, 85%) as predicted, validating the codes used to design the APT RFQ. Figure 5 shows the LEDA configuration at 6.7 Mev.
- Addition of a 700-MHz CCDTL to further accelerate the 100-mA CW proton beam to 8 MeV. The CCDTL components have been designed and are in fabrication.
- Operational testing and measurement of beam characteristics under conditions that will intentionally create off-axis or “halo” beam to fully benchmark the beam physics design codes in the APT operating regime at 8 MeV.

B. Normal-Conducting Accelerator Structure Prototyping, Beam Raster, and Advanced RF Power Development

- A prototype of the highest energy NC CCDTL section, near 100 MeV, will be fabricated and tested at full RF power. It is at this energy that thermal performance is critical and the test is planned to ensure that the design is adequately cooled. An aluminum cold model of the accelerator structure has been completed prior to fabrication of the copper prototype.

- The beam raster system described earlier has been fabricated at full plant scale and is undergoing long-term reliability testing.
- Development of a 1-MW higher-order mode inductive output tube continues. Design and fabrication are complete and the tube is nearing readiness for initial testing.

C. High-Energy Superconducting Accelerator Structure Prototyping

The SC accelerating cavities designed for APT are based on elliptical shapes used in electron accelerators but with a modified geometry to take into account the fact that protons have lower velocities.[12] For proton applications, the DDNs are addressed by the following activities:

- Fabrication and high-gradient testing of several single-cell intermediate velocity proton beam Nb cavities. Performance of 5-cell $\beta = 0.64$ cavities has been confirmed to exceed the APT accelerator design requirements (peak electric field of 18 MV/m) by more than a factor of two.
- Evaluation of radiation damage of a prototype Nb cavity and Nb samples. Measurements have been completed and the results analyzed showing that no degradation in superconducting properties was observed for proton losses exceeding those expected for more than 40 years of plant operation.
- Fabrication and testing of high-power couplers for SCRF medium-velocity cavities. Couplers have been designed and are under fabrication. The SC windows have been procured and are undergoing testing.
- Fabrication and high-field testing of SC cryomodules. Design is underway. Due to the downselect decision, plans for performance testing are under revision.

D. Target/Blanket Performance and Materials Studies

These ED&D activities address issues connected with the spallation neutron target and the surrounding lead blanket.[13] In general all measurements in the three main areas have been completed and the data are under analysis.

- Materials and corrosion activities address performance in the radiation environment unique to high-energy spal-

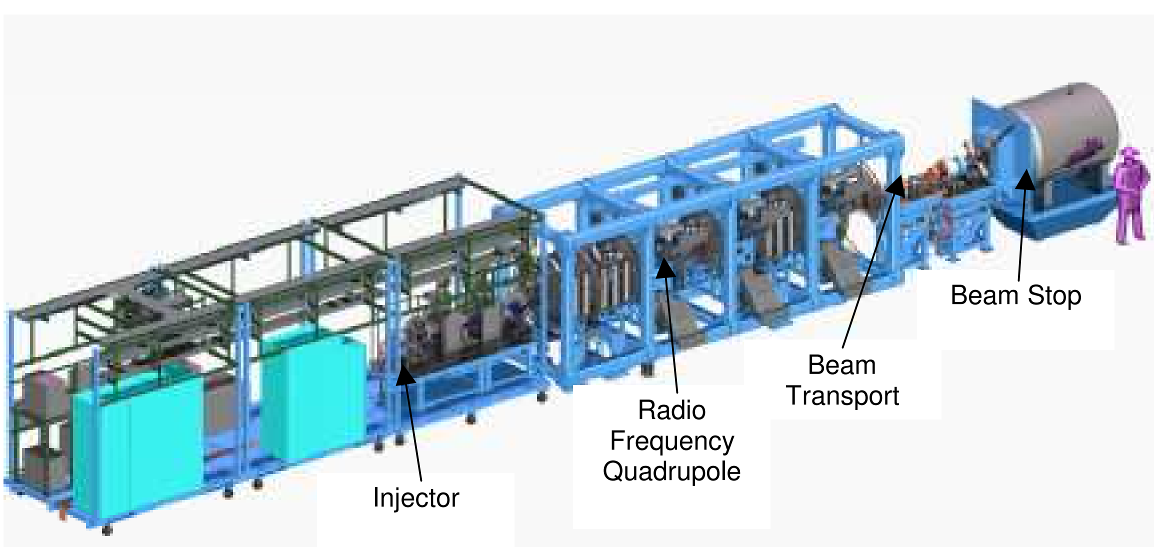

Figure 5. Low-Energy Demonstration Accelerator Layout at 6.7 MeV

lation applications. Irradiation of over 5000 mechanical test samples has been completed at the LANSCE 800-MeV accelerator, providing prototypical proton and mixed proton-neutron fluences in the maximally exposed samples of 3×10^{21} p/cm^2 (10–12 dpa). The samples are under examination and testing; results will be compiled in a Materials Handbook. Corrosion effects have been investigated simultaneously with the materials irradiations by using electrical impedance probes and by making weight-loss measurements following irradiation.

- Radiation transport simulation code improvements are underway to improve the underlying physics and to increase the extent of the fundamental nuclear data libraries from 20 MeV to 150 MeV. A merger of the intranuclear cascade code, LAHET, and the transport code, MCNP, into a single code known as MCNPX has been completed and is in testing.

Target/Blanket characterizations to benchmark important observables, such as total neutron production, decay heat, and proton beam energy deposition have been completed and are under analysis. Measurements of total neutron production as a function of energy were completed for targets of lead and tungsten from 0.4 to 2.0 GeV are in excellent agreements with calculated values over the entire energy range. Preliminary decay heat measurements for tungsten show agreement with calculation to better than 10%. Proton energy deposition measurements at 800 MeV, 1200 MeV, and 1500 MeV for tungsten and lead are complete using thermistor probes and analysis is underway.

E. Tritium Separation Demonstrations

Efforts underway in this area include work to determine tritium processing and separation efficiencies under APT plant operating conditions. Experimental quantification of spallation product production and removal efficiency was completed at the LANSCE accelerator facility in 1998.

IV. PROJECT PHASES AND COST

The Integrated APT project plan was initially developed to support key DOE and project-specific milestones, from Critical Decision 1, “Approval of Mission Need,” to Critical Decision 4, “APT Plant Acceptance.” It had five major phases: Engineering Development and Demonstration, Conceptual Design, Preliminary and Final Plant Design, Procurement and Construction, and Operational Testing and Commissioning. Of these, the Conceptual Design has been completed and the Engineering Development and Demonstration activities are more than half done. Preliminary plant design was initiated in November, 1998, following approval of Critical Decision 2 by the Secretary of Energy. With the designation as backup by the DOE, the Project has developed a new baseline to support completion of the preliminary design and ED&D activities. This work is planned to follow the following strategy:

- Advance the design of major systems,
- Advance the design and underlying ED&D elements to resolve issues with components or systems of the highest cost or technology risk, and
- Document the preliminary design and ED&D work in a Preliminary Design Summary report that includes a roadmap to all project documentation and a summary of activities and priorities needed should the DOE decide to restart the project.

V. SUMMARY

Although the DOE has not chosen to implement APT as the tritium production technology for the U.S., substantial progress has been made in developing the technology. That work will continue through 2002 in order to fully obtain the benefits of the ED&D work and to complete the preliminary design.

VI. REFERENCES

1. APT Conceptual Design Report, Los Alamos Report, LA-UR-97-1329, April 15, 1997.
2. G.P. Lawrence "High-Power Proton Linac for APT; Status of Design and Development," Proc. XIX International LINAC Conference (LINAC98) (August, 1998).
3. M. McCarthy, *et al.*, "Overview of the APT RF Power Distribution System," *ibid.*
4. J. Tooker, "Overview of the APT Accelerator Design," Proc. 1999 Particle Accelerator Conf., New York (March 1999).
5. J. D. Sherman, *et al.* "Status Report on a d.c. 130 mA, 75 keV Proton Injector," Rev. Sci. Instrum. 69 (2) (1998) 1003.
6. F.L. Krawczyk, *et al.*, "Superconducting Cavities for the APT Accelerator," Proc. 1997 Particle Accelerator Conf., LA-UR-97-1700, Vancouver, Canada, May 1997.
7. T.P. Wangler, "Basis for Low Beam Loss in the High-Current Linac," Proc. XIX International LINAC Conference (LINAC98) (August, 1998).
8. S. Chapelle, *et al.* "Testing of a Raster Magnet System for Expanding the APT Proton Beam," Proc. 1999 Particle Accelerator Conf., New York (March 1999).
9. J. L. Anderson, "Technology Development for the Accelerator Production of Tritium," *ibid.*
10. J. D. Schneider, "Operation of the Low-Energy Demonstration Accelerator: The Proton Injector for APT," *ibid.*
11. GO. Bolme, *et al.*, "Proton Beam Verification using RF Power Measurement Data for a CW Radiofrequency Quadrupole Linac," *ibid.*
12. K.C.D. Chan, *et al.*, "Progress of Superconducting Linac Engineering Development," *ibid.*
13. L. Waters, "APT Target/Blanket & Materials ED&D: Performance Verification and Validation," Proc. AccApp98 Conf., Gatlinberg, TN, August, 1998.