

**ACCELERATOR PRODUCTION
OF TRITIUM
(APT)**

EXECUTIVE REPORT

MARCH 1989

Los Alamos National Laboratory

Brookhaven National Laboratory



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ACCELERATOR PRODUCTION OF TRITIUM*

Executive Report

March 1989



Prepared by

Los Alamos National Laboratory

Brookhaven National Laboratory

*This work sponsored in part by the U.S. Department of Energy, Office of Nuclear Materials Production

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SUMMARY

An assured supply of tritium is essential for maintaining the current U.S. nuclear weapons stockpile. Since tritium decays at a rate of 5.5 percent per year, the United States must replenish the tritium supply through production.

The existing U.S. tritium production facilities are reaching the end of their useful life. All production reactors are currently shut down. Additional environmental safety concerns for these aging production reactors and processing facilities could seriously endanger adequate tritium supplies in the near future. New production facilities must be constructed and become operational within the next 10 to 15 years, perhaps even sooner.

To supply tritium for the weapons stockpile, the Department of Energy (DOE) in August 1988 recommended that the nation build new production reactors (NPRs) to replace the aging facilities at the Savannah River Plant (SRP). The specific recommendation was to proceed on an urgent schedule to build a heavy water reactor (HWR) at Savannah River, along with concurrent preparation leading to the construction of modular high-temperature gas-cooled reactors (MHTGRs) at the Idaho National Engineering Laboratory (INEL). We support DOE's decision; reactor construction is currently the lowest technical risk approach to supplying the critical need for tritium. However, we believe it is prudent that DOE pursue other technologies for tritium production to provide potential alternatives as a contingency for the future. One concept that appears to be particularly promising is the Accelerator Production of Tritium (APT).

The APT approach is not a new concept for producing special nuclear materials. Studies in the 1950s, 1960s, and again in the early 1980s concluded that, while the concept was feasible, the technology base for high current, efficient accelerators was not then available. During recent years, extensive development (>\$500 M) in the Strategic Defense Initiative (SDI) neutral particle beam program has produced major advances in the technology of such accelerators. These advances encouraged Los Alamos National Laboratory and Brookhaven National Laboratory to re-examine the potential use of an accelerator to produce tritium for the U.S. weapons stockpile. Westinghouse Hanford company provided support for the Balance of Plant (BOP) and siting.

The APT concept differs from a reactor in that it involves no fissionable materials. The APT target matrix consists of lead-containing neutron production pins interspersed with lithium-containing tritium production pins. Because of the absence of fissionable materials, there are no criticality issues, minimal decay heat safety concerns, no nuclear reactor licensing requirements, and a much smaller amount of radioactive waste. The extensive time required for safety analysis, Environmental Impact Statement (EIS), and licensing activities particular to reactor-based systems would be greatly reduced for the accelerator approach. In addition, it would not involve fuel cycle activities such as fuel fabrication, reprocessing, and disposal of high level process waste.

The capital cost of the reference APT design is estimated to about \$2.3 B, including a \$0.6 B contingency. This is a preliminary estimate, with a more detailed estimate presently being developed. This cost includes the accelerator, target building, and supporting facilities, as well as tritium recovery facilities. Although preliminary, this cost estimate has been subjected to a review and normalization similar to that used for the NPR concepts for a 40-year operating life.

The availability and cost of electric power are major operational issues for the accelerator. We estimate a requirement of 770 MW to operate the facility. Preliminary indications are that such power levels could be made available by the Bonneville Power Administration for the Hanford Site, potentially at 32 mills/kWh. At this rate, the annual cost for electricity is estimated at \$160 M and the total operating cost for the accelerator and peripheral facilities at \$270 M. Doubling the cost of power, for example, would increase the total operating cost by 60 percent.

The reference design is a 0.25 ampere, 1.6 GeV proton linear accelerator, or linac. The concept reference system is described in detail in the accompanying report entitled "Preliminary Assessment of Accelerator Production of Tritium," Los Alamos National Laboratory Report, #DEW-89:20.

The APT concept builds on relatively mature, existing technologies. The linac, in existence for more than 40 years, is a well-developed technology used in many medium and high energy particle physics research facilities. Plant factors for these existing pulsed accelerators have been very impressive—upward of 85 percent of scheduled "on" time. The major differences between the existing accelerators and the accelerator required for APT are the issues of higher current and continuous beam (cw) operation.

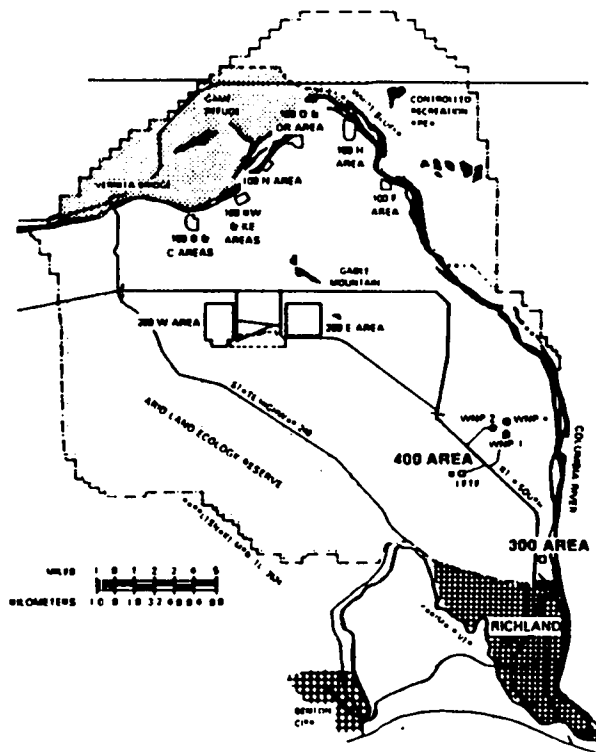
High beam currents and cw operation do not present fundamental problems but will require careful engineering design to ensure that beam spillage within the machine will not cause damage or excessive activation problems. In fact, many of the individual components required for the APT accelerator have been operated under much more stressing conditions (e.g., an H⁺ injector at 300 mA cw, compared to 125 mA cw required for APT). The principal technological issue for APT is the operation of these components in one integrated system for the demonstration of reliable operation and acceptable maintenance procedures.

The target assembly is a conservative, low temperature, water-cooled design. The target lattice consists of banks of water-cooled, vertical pressure tubes, each of which contains a matrix of lead and Li-Al pins. Maximum target assembly outlet temperatures are estimated to be 125°C. Existing Savannah River Li-Al technology and recovery processes have been retained to provide a low-risk approach to tritium production. Two separate target lattice irradiation areas provide capability for continuous tritium production. Structural material radiation damage problems are not expected since the target lattice system will be replaced at the end of each irradiation cycle.

The APT system being proposed should produce annual goal quantities of tritium assuming a 75% plant operational factor. Since APT production rates are a function of the accelerator beam power, any "goal" quantity can in principle be accommodated in the plant design process.

Although the APT can be constructed at any operating DOE facility, the Hanford site offers the potential advantage of low-cost available power, and the grid capacity to power the APT facility. Figure 1 shows the Hanford site map and its desirability. The APT would be located in the 400 area and use the existing Fuel Materials Evaluation Facility (FMEF) for tritium recovery.

Hanford Site Map



The Hanford Location

- Inexpensive electrical power
- Environmental compatibility
- Existing Production Site
- Available technical support
- Involved in Accelerator Programs

Figure 1

Our assessments indicate that neither scientific "proof-in-principle" demonstrations nor basic research programs are required before proceeding. However, an integrated facility with APT parameters does not currently exist; therefore engineering development is needed to design and demonstrate the major components, optimize reliability, improve efficiency, and assure the operability of the integrated system.

It is estimated that this front-end development and demonstration phase will require about 3 to 4 years to complete, given adequate funding. A program plan to define detailed costs and schedules is currently being developed. A phased development schedule, which consists of staged construction of the front-end of the accelerator, is being proposed to guard against unforeseen engineering concerns.

Upon completion of this staged development phase, the major front-end components of the accelerator would be available for use in a full-scale plant. With the successful demonstration of the accelerator front end and the target design, the DOE could commit to the construction of a full-scale system with confidence. It is estimated that it would take an additional 5 years to complete plant construction and attain goal production of tritium, based on an aggressive program.

Figure 2 shows the APT proposed construction schedule. The five-year construction cycle is based on a high priority aggressive project basis. Figure 3 shows the APT normalized 40-year cost projection.

Level 1 APT Schedule

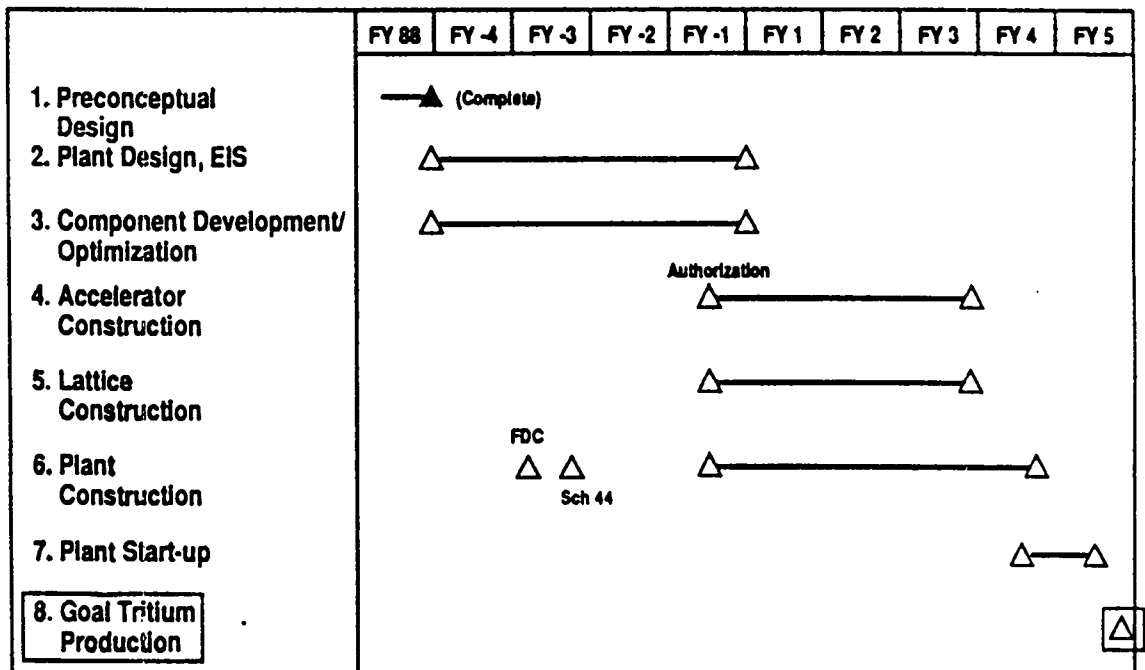


Figure 2

		apnewdel																		12/5/88	
		APT CONCEPT							MILLIONS OF 1986 DOLLARS							HANFORD SITE					
0.04	-8	-7	-6	-5	-4	-3	-2	-1	0	1	35	36	37	38	39	40	41	42	43	44	TOTAL
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	
	1	2	3	4	5	6	7	8	9	10	44	45	46	47	48	49	50	51	52	53	
CAPITAL																					
Des & Const (Dir+All Indr)--ACC				114	190	190	190	76													760
Project Mgt--ACC				11	19	19	19	8													76
Des & Const (Dir+All Indr)--LAT				45	75	75	75	30													300
Project Mgt--LAT				5	15	15	15	5													55
Des & Const (Dir+All Indr)--BOP				100	140	80	40	40													400
Project Mgt--BOP				11	16	8	5	5													45
SUBTOTAL	0	0	0	288	455	387	344	184	0	0	0	0	0	0	0	0	0	0	0	0	1836
Capital Contingency --ACC				50	84	84	84	32													334
Capital Contingency --LAT				22	36	36	36	15													145
Capital Contingency --BOP				39	54	30	18	18													155
TOTAL CAPITAL	0	0	0	397	629	537	480	227	0	0	0	0	0	0	0	0	0	0	0	0	2270
PREOPERATIONS																					
Tech Devt (R&D)--ACC		30	30	10				24	34												128
Tech Devt (R&D)--LAT		18	30	18	2																65
Tech Devt (R&D)--BOP		5	7	10	6	2															30
Preop Contingency		4	4	4	4	4	4	4													24
Training						3	5	7													15
Startup						5	20	55													80
TOTAL PREOPERATIONS	0	54	71	42	12	14	53	96	0	0	0	0	0	0	0	0	0	0	0	0	342
OPERATIONS																					
ACC									18	18	18	18	18	18	18						720
LAT									4	4	4	4	4	4	4						160
BOP									10	10	10	10	10	10	10						400
Elect Power (770 MWe @ .032\$)									162	162	162	162	162	162	162						6480
Target Fab								4	4	4	4	4	4	4	4						160
Target Processing									34	34	34	34	34	34	34	34					1558
Waste Mgt									1	3	3	3	3	3	3	3	2	1	1	1	123
General Support								3	10	17	17	17	17	17	17	12					292
Oper Contingency																					0
TOTAL OPERATIONS	0	0	0	0	0	0	0	7	208	250	252	252	252	252	248	49	2	1	1	1	9893
CAPITAL UPGRADES									17	17	17	17	17	17	17						680
D&D																16	16	16	16		64
CASH FLOW W/O REV	0	54	71	439	641	551	533	330	225	267	269	269	269	269	265	65	18	17	17	1	13249
STEAM/ELEC CREDITS																					
TOTAL PROJ (UNDISC)	0	54	71	439	641	551	533	330	225	267	269	269	269	269	265	65	18	17	17	1	13249
PW OF EXPENDITURES	0	50	63	375	527	435	405	241	158	160	48	46	44	43	40	10	3	2	2	0	5897
DISCOUNTED S/E CREDITS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PW OF PROJ TOTAL	0	50	63	375	527	435	405	241	158	160	48	46	44	43	40	10	3	2	2	0	5897
PRODUCTION																					
PW OF PRODUCTION	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3

BACKGROUND

The potential to produce tritium and other special nuclear materials using a high energy particle beam generated by an accelerator has long been recognized as an attractive approach. Accelerator- or electronuclear-breeding was first proposed in the late 1940s. At that time, the concept was being developed in the U.S. for the production of plutonium. It was abandoned when ample uranium supplies were discovered in the continental U.S. However, development of the Materials Testing Accelerator (MTA) at the Lawrence Livermore Laboratory (LLL) was carried out to the prototype level. In the late 1940s, a low energy cw (100% duty factor), deuteron linac (the A-48) was constructed and operated successfully for over a year. Thus, viability of the concept was demonstrated as early as 1950. In 1952, W. B. Lewis, in Canada, considered the idea for the production of power. That idea was pursued at the Chalk River Laboratory for a number of years leading to the Intense Neutron Generator (ING) proposal and later in the early 1980s to development of high current accelerator components and the studies of nuclear fuel breeding.

The electronuclear breeder was revisited in the late 1970s, early 1980s at Brookhaven National Laboratory. Studies were carried out for the enrichment of commercial nuclear fuels, and production of plutonium and tritium for the weapons program. These studies concentrated on the use of a depleted uranium neutron multiplication target/lattice assembly, driven by a high energy proton linear accelerator.

Subsequent high-current accelerator development in the 1980s was spurred by substantial SDI funding primarily at Los Alamos National Laboratory: The state-of-the-art has advanced to the point where one can have confidence in that the construction and operation of an accelerator required for the production of tritium will be successful. This judgement is further strengthened by the successful operating record of the existing half dozen large linear accelerators located at various national laboratories. These machines have been in operation for more than 20 years with on-line plant factors greater than 80%.

Potential thermal/hydraulics and materials problems encountered in previous studies with the depleted uranium target/lattice assemblies are nonexistent for APT because of the absence of fission neutrons and their resulting high thermal energy deposition.

THE PHYSICS CHARACTERISTICS OF APT

For protons above ≈ 50 MeV, the principal types of interactions with atoms are electron ionization-excitation and inelastic collisions with individual nucleons within the nucleus. Elastic scattering is negligible at these energies. The inelastic collision and ionization-excitation process is usually called the "spallation-evaporation" or "intranuclear-cascade evaporation" process.

Inelastic scattering reactions between complex nuclei and protons, neutrons, or mesons possessing energies large compared to nucleon binding energies in the target nucleus occur by direct collisions between the projectiles and the individual nucleons in the nucleus setting off an intranuclear cascade of nucleon-nucleon collisions. If the collision energy within the nucleus is sufficient, meson production may occur, setting off a subsequent intranuclear cascade of meson-nucleon collisions. Some of the intranuclear cascade collisions result in protons, neutrons, or mesons escaping, or being "spalled-out" of the nucleus. Ultimately, the incident particle energy not carried away by the escaping particles is shared by the remaining nucleons in the target nucleus, leaving it in a highly excited state. A statistical "evaporation" process occurs in which nucleons and gamma rays are emitted until the residual nucleus is de-excited. The energy of the spallation products may be sufficient to induce further intranuclear cascades in other target nuclei. Thus, neutron multiplication occurs as a result of these intranuclear processes in any target material. High atomic mass nuclei will result in larger neutron yields than low mass nuclei.

Even at high energies, incoming charged particles, which lose energy through the intranuclear cascade process, also lose part of their energy through electron ionization. As the proton slows down, energy transfer by electron ionization becomes more important. Below ≈ 100 MeV, it becomes predominant and sets the total range or stopping length of the incoming charged particle in the target material. The energy lost through ionization remains in the target and is converted to thermal energy.

The yield of neutrons produced in the spallation-evaporation process by energetic protons has been measured. It is interesting to note that the neutron yield from U^{238} is about twice that obtained from Pb. The difference is due to neutron induced fast fission in uranium. However, Pb is the target element of choice for the APT, because it avoids fission waste. Computational models for the spallation-evaporation process agree closely with the measurements.

As part of the APT design, the tritium production rates have been calculated using the Monte Carlo Transport Code HETC and the discrete ordinates transport code ANISN. The calculation was based on a primary target of lead, lithium-aluminum and H_2O coolant. The neutrons generated in the target are followed by HETC down to 15 MeV. Below this energy they are tracked by ANISN until they are captured in Li^6 or otherwise lost.

These calculational results indicate that the goal quantity of tritium required to satisfy our national security needs can be produced by this process with little technical risk. Production calculations are accurate to $\pm 20\%$, with the principal source of uncertainty being high energy nuclear cross sections.

Tritium (^3H) production using the APT process in a lead/lithium target is described simplistically in the schematic of Figure 4.

The APT Process

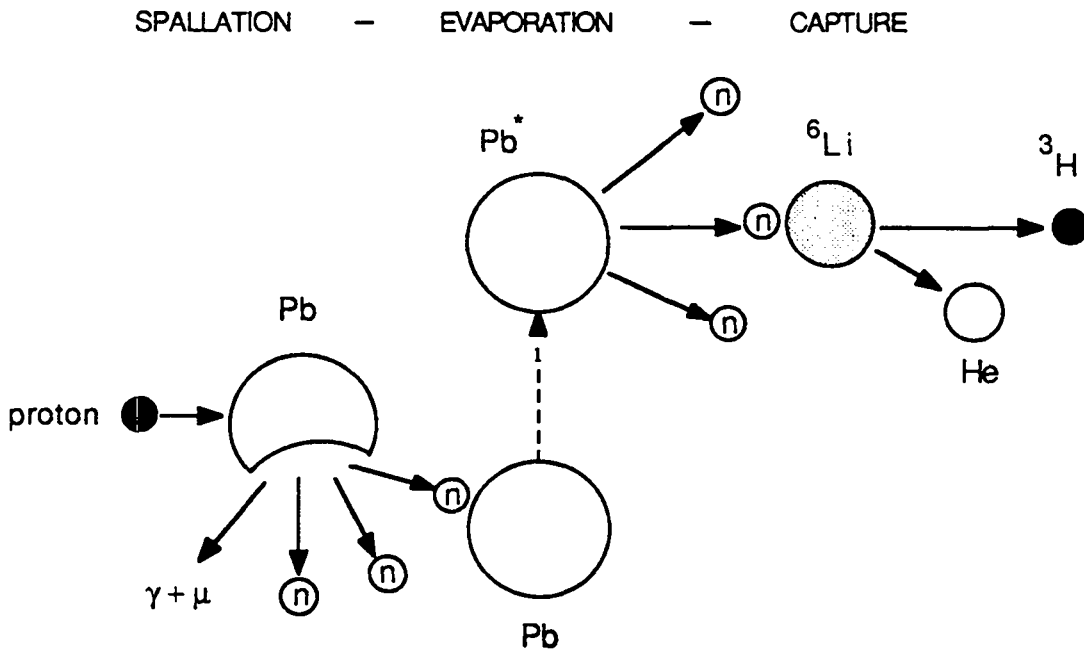


Figure 4

THE APT CONCEPT AT HANFORD

The APT consists of two principal systems: the linear accelerator generates the high energy proton beam, and the target assembly stops the beam, converts it, and multiplies it into neutrons that are moderated and absorbed in the lithium to produce tritium. The two systems are coupled via a beam transport of arbitrary length. The beam transport also provides beam switching from one target system to another. The proposed concept has two identical targets to provide for reliability and to minimize the downtime during target lattice removal.

Of the total facility capital cost of about \$2.3 B, two thirds is for the accelerator system and one third for the target system. Similarly, the operating cost for the facility of about \$270 M/year is two thirds for the purchase of electricity (based on 32 mills/kWh) and one third for the operation and maintenance of the accelerator, target fabrication, and tritium processing. Reduction in tritium requirements would correspondingly lower the electricity cost for operation, as well as the construction costs.

Figure 5 shows an overlay of the APT concept at the Hanford 400 area site.

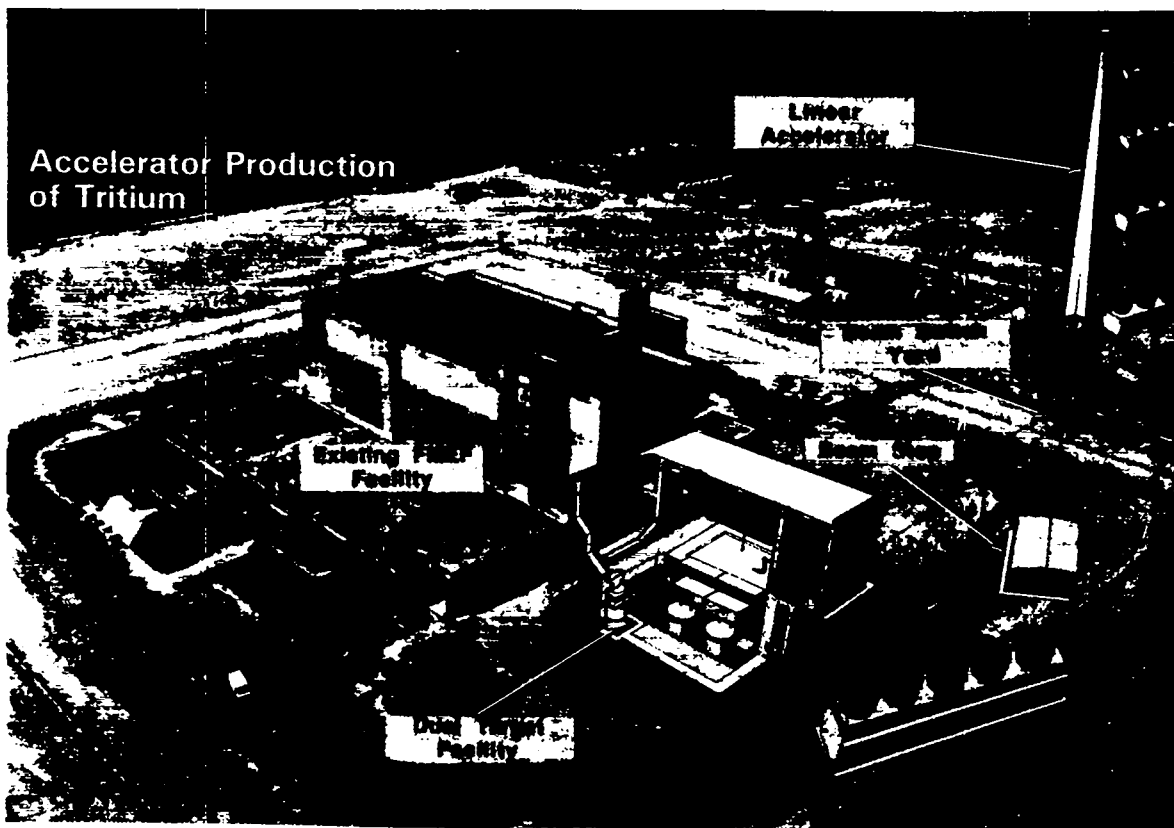


Figure 5

THE ACCELERATOR

The linear accelerator, or linac, is the only type of accelerator capable of accelerating a steady, continuous beam of over 100 mA. With linear accelerators, proton currents of 300 mA have been accelerated to 200 MeV, albeit in a pulsed mode, and even higher currents appear possible. Besides its unique capability of accelerating high currents, the linac has the added advantages of: a) providing the most efficient means of energy conversion (electrical energy to beam energy) and b) having the lowest beam loss factor (particles lost during the acceleration process). Minimizing beam losses is an important criterion for this application. At the high beam power needed for this application, even the lowest fractional beam loss can be detrimental.

Medium energy linear accelerators (200-800 MeV) have been operating for almost 20 years with a remarkable service record. The BNL and Fermilab 200-MeV linacs have experienced less than 7% unscheduled downtime. The 800 MeV LANL linac (LAMPF) averages less than 15% overall unscheduled downtime.

Over the last 20 years, there has been considerable progress in furthering the understanding and development of the technology. A massive investment by SDIO is pushing the state-of-the-art of linac technology well beyond the specifications required for the APT. The SDI effort to develop a flight qualified Directed-Energy Weapon based on a proton linac puts extremely stringent requirements on accelerator performance which are not necessary for this application. On the other hand, the quasi-commercial application of the APT requires a developmental effort in improving components and system efficiency and reliability to lower operating costs.

The linear accelerator design proposed for the APT takes a conventional, conservative approach. It consists of an ion source coupled to an injection system, a 100-150 MeV drift tube linac and a "coupled cavity" linac, of the type used at LAMPF. The frequencies chosen allow the use of klystron amplifiers throughout.

The Injection System: The injection system starts with a duoplasmatron- or duopigatron-type ion source. These sources are well developed and have produced upward of 600 mA dc beams of protons. The beam extracted from the source at 125 kV will be injected into a Radio Frequency Quadrupole (RFQ) accelerator to adiabatically bunch and accelerate the beam to 2.5 MeV which is the injection energy of choice for the drift tube linac. Two ion sources and RFQs would be operated in parallel to relieve beam loading in the RFQs. The two RFQ beams are then funneled into a single beam line.

Extensive experience has been gained in the design of injection systems over the last ten years. Los Alamos has designed, constructed, and operated a 100 mA, 2 MeV deuteron system for the Fusion Materials Irradiation Facility (FMIT) program, as well as a 100 mA,

3-MeV proton system for the SDI program. Both systems rely on RFQ acceleration. The experience gained with these test stands give complete confidence that an APT injector can be built to meet the required performance. This front end of the accelerator is by far the most demanding technology for the entire accelerator system. It should be noted that an injector with the characteristics required for APT has been operated successfully at the Chalk River Laboratories.

Drift Tube Linac: The drift tube linac (DTL) will be a conventional Alvarez, or drift tube structure operating at about 700 MHz. This type of accelerator, invented about 50 years ago, has been in use in all high current machines to date. It is well understood and well developed. To optimize operating costs, the accelerating gradient will be relatively low, reducing the technical risk even further.

Drift tube linacs have accelerated 300 mA pulsed beams at Fermilab and have reached 12% duty factors at LAMPF, Los Alamos. A 100% duty factor, 3 MeV DTL has been operated at the Chalk River Laboratories. A cw (100% duty factor) deuteron drift tube linac (CWDD) is being built by Grumman Corporation for SDI and a 100 MeV machine (GTA) is being constructed at Los Alamos, also for the SDI program. The design performance requirements of these SDI projects are much more demanding than that of the APT.

Coupled Cavity Linac: The coupled cavity linac (CCL) developed at Los Alamos in the 1960s is the structure of choice for proton energies above 100 MeV. This transition to the CCL is predicated by its increasing efficiency with higher beam energy and its ability to provide acceleration at higher rf frequency. The coupled cavity linac structure operating at 1400 MHz comprises the bulk of the accelerator, from 100 to 1600 MeV. It is a simpler structure than that of the drift tube linac. It lends itself to monolithic assemblies with low technical risk. In fact, experience at LAMPF has demonstrated zero failure of the structure during its 17 years of operation. The LAMPF CCL consists of 5000 cells and is 730 meters long. This same coupled cavity structure has also been successfully developed at Los Alamos to operate cw at 2380 and 2450 MHz in accelerators constructed for the National Bureau of Standards and the University of Illinois.

Radio Frequency Systems: High power rf systems using klystrons have been used for pulsed accelerator applications with good success. High power klystrons are available commercially. These tubes give output powers of 1 MW average with more than 50,000-hr lifetimes. However, because of the amount of rf power required, and the incentive for high conversion efficiency, tubes and power conversion components expressly developed for this application will be needed. The development effort will be focused on obtaining high ac-to-rf power conversion efficiency and high output power. The capital cost of rf systems decreases with increasing output power per amplifier unit; therefore, power tubes with output power of 1 to 2 MW should be feasible.

The capital cost of the radio frequency system represents about 60% of the total accelerator cost. The same can be said for operation; the cost of electricity is about two-thirds of the annual operations cost. Thus, any improvement in the rf system efficiency and/or decrease of capital cost will be a major driver in the overall cost of the facility. A large effort will therefore be devoted to improve the rf power system technology with these goals in mind.

Compared with current operating pulsed linacs, continuous wave operation brings tremendous simplifications to parts of the rf system. Energy storage requirements are minimal, and feedback control of cavity amplitude and phase is greatly simplified. However, fast crowbar and other protection features may be more difficult. These must be investigated in detail and provided in the design.

Control and Diagnostic Systems: Computer control systems for accelerators are well developed on existing machines. In fact, the SDI program is developing the technology for remote operation in space of accelerators much more complex than that proposed for APT. Distributed intelligence systems, where peripheral minicomputers or microprocessors carry out control functions at the location of the device and control is distributed by a central processor, appear to be the most promising of many possible configurations. Fast control for protection against beam loss and control of the cavity phase and amplitude levels, must be accomplished locally with analog systems. Adequate designs for these systems have been demonstrated on existing accelerators. Similarly, beam diagnostic instrumentation, which allows monitoring of the beam parameters during accelerator operation, has been developed for cw beams. Continuous information on beam position, size, and phase relative to the cavity rf phase is essential for reliable operation. The general technology is available for instrumentation to perform these functions.

Figure 6 shows the Brookhaven 200 MeV drift tube linac, and Figure 7 the Los Alamos 800 MeV coupled cavity linac. Both machines have been operating successfully for almost 20 years, with no major failure.

Figure 8 describes the accelerator parameters used to develop the APT conceptual design and cost estimate. Although not optimized, the design calculations of the cavity structure and beam dynamics were carried to the extent necessary to meet the APT specification.

Figure 9 shows a cross section of the proposed accelerator system. The accelerator proper and its rf final power amplifier (klystrons) will be housed in a tunnel covered by earth shielding. A "light construction" building at ground level will house all the services required for the machine. This typical accelerator housing construction would extend for about one mile in length.

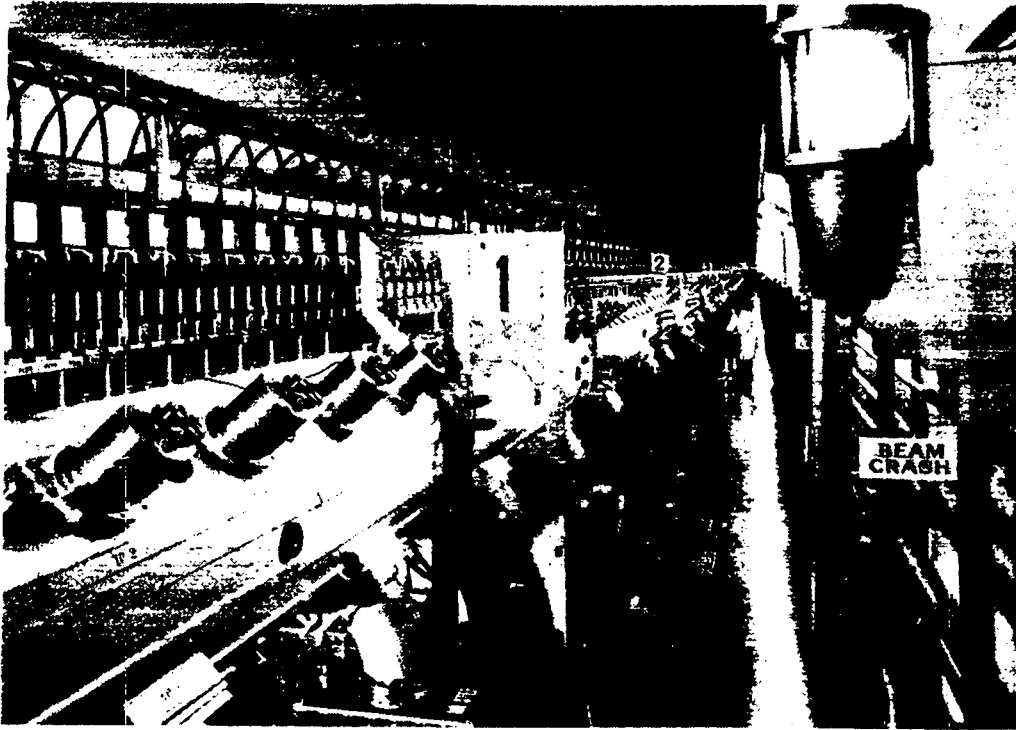


Figure 6

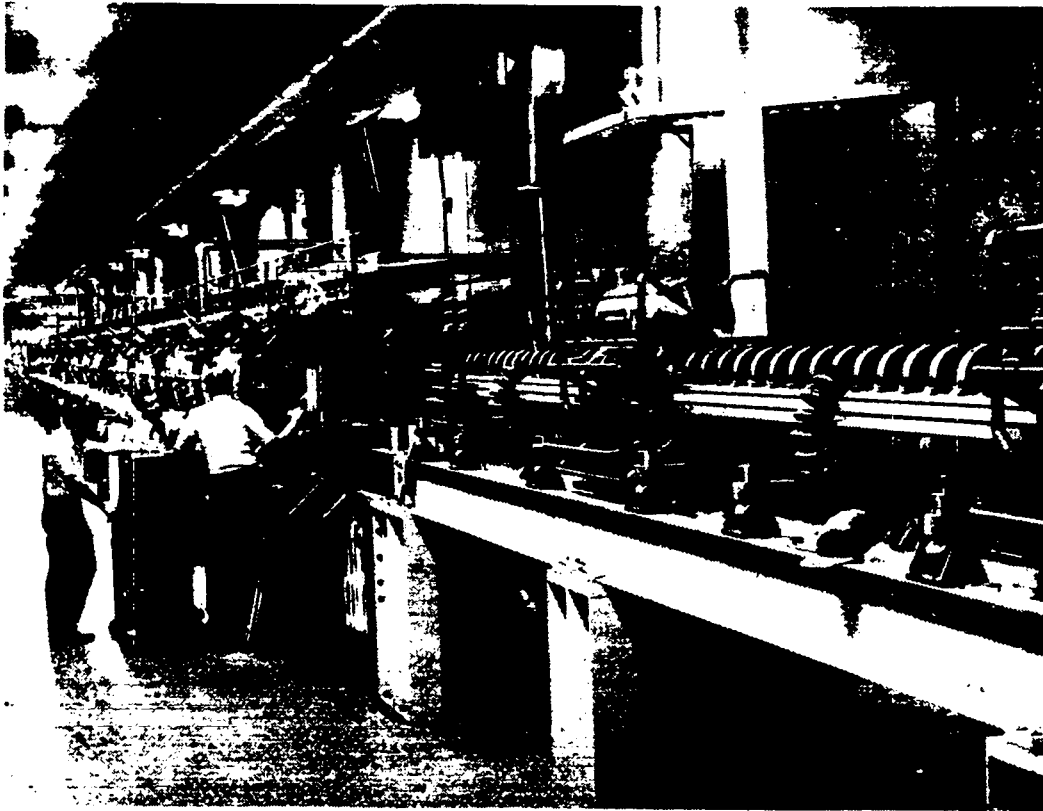
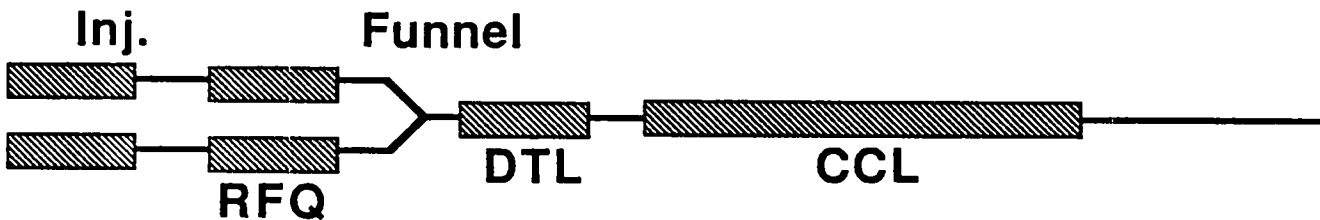


Figure 7

Reference Accelerator Parameters

- 0.125 MeV Injector
 - 350 MHz, 4 m RFQ
 - 3 m Funnel
 - 700 MHz, 51 m DTL
 - 1400 MHz, 983 m CCL
- Two at 140 mA
 - Two for 0.125 to 2.5 MeV (125 mA)
 - 350/700 MHz, magnetic elements
 - 2.5 to 100 MeV (250 mA)
 - 100 to 1600 MeV (250 mA)

-
- Output energy/current
 - Length
 - Beam power
 - AC power
 - Efficiency
- 1600 MeV/250 mA
 - 1051 m
 - 400 MW
 - 746 MW
 - 54%



		Inj.	RFQ	Funnel	DTL	CCL	Total
Energy Out	MeV	0.125	2.5	2.5	100	1600	1600
Current	Amp	2 x 1/8	2 x 1/8	2 x 1/8	1/4	1/4	1/4
Frequency	MHz	DC	350	350/700	700	1400	
Length	m	10	4	3	51	983	1051
Beam Power	MW	0.03	0.6	0	24.4	375	400
AC Power	MW	0.2	2.6	0.7	46	696	746
Efficiency	%	15	24	0	49	54	54

Figure 8

Typical Accelerator Building Layout

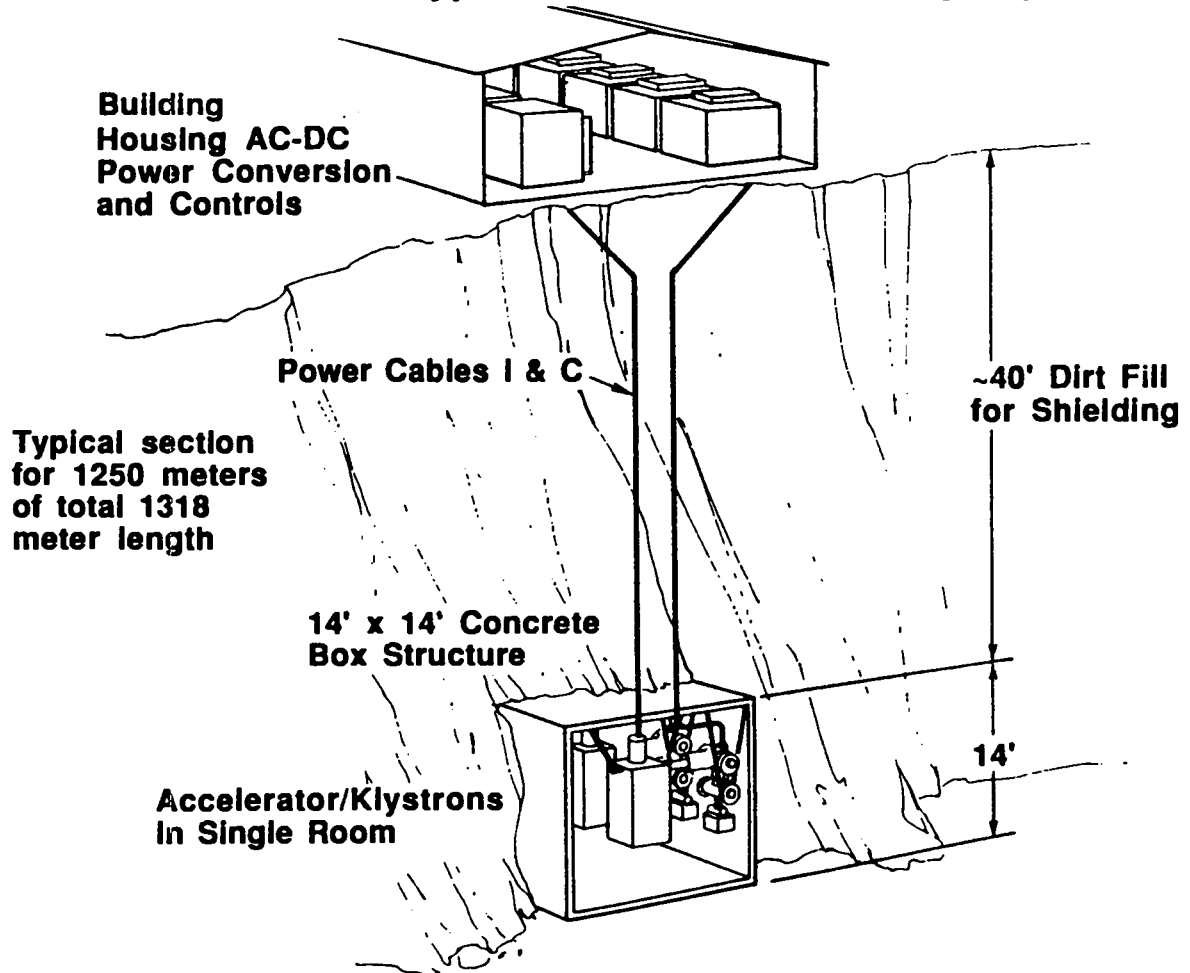


Figure 9

BEAM TRANSPORT

From the accelerator exit to the target systems, the beam is guided in a vacuum tube with quadrupole and dipole electromagnets. The design of the beam line is conventional, and its length and geometry can be set to suit the particular site.

In the context of flexibility and potential future applications, the beam transport system will allow for possible expansion, leaving space for branch-off switching magnets for additional target stations.

For the APT, the beam line will contain an instrumented beam dump in line with the linac. This beam dump is required for facility commissioning and linac tune-up. From this straight line, the beam will be diverted into a secondary line leading to the two target stations. A switching magnet in this line will provide the capability of directing the proton beam into either of the two target stations.

The design of the last section of the beam transport to the target is a critical element of the APT. To maintain and control target temperatures, the beam is first defocused and given a uniform power distribution in the vertical plane with the use of quadrupole and octupole magnets. It is then swept horizontally with a dipole magnet in a sawtooth wave shape at a rate of 10 Hz. Defocusing and sweeping the beam on target is designed to cover a 2×4 meter area (8 m^2) and lower the beam power density on target to about 5 kW/cm^2 average or $<100 \text{ watts/cm}^3$ in the lead pins.

Design of the beam delivery system utilizes conventional technology. The dipole sweeper magnet will be operating in a high radiation field requiring radiation hardening; this technology has been developed over the last decade to satisfy similar situations in accelerator facilities.

Figure 10 describes the beam shaping and sweeping system. Design studies are needed to optimize sweep rate vs magnet supply power as well as the potential effects of thermal cycling.

Beam Shaping and Rastering System

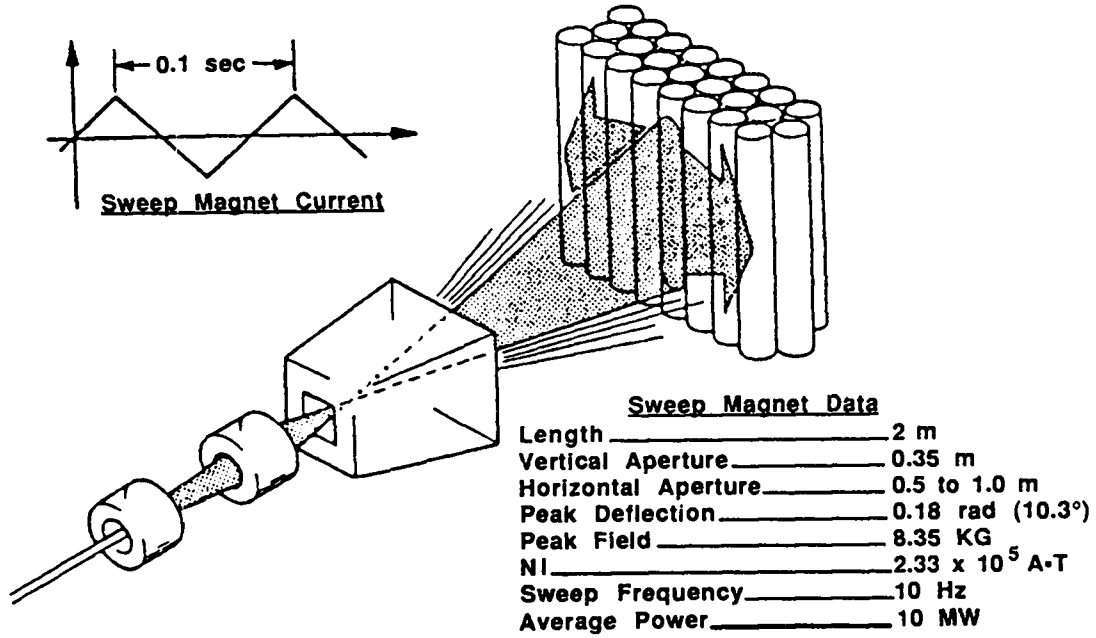


Figure 10

THE TARGET SYSTEM

The target system consists of a matrix of primary target lead pins (the neutron converters) and of lithium-aluminum pins (the neutron absorbers which produce tritium). The pins are arranged in a matrix fashion and the interspace is used for cooling water which also acts as neutron moderator. This large matrix or lattice of about 60,000, 3-meter long pins is divided into 105 modules or pin assemblies, each mounted in a thin wall, vertical pressure tube to contain the water coolant. These pressure tubes are arranged into 7 banks of 15 or 16 tubes each, and the entire assembly is installed in a large vacuum vessel.

The target lattice system conceptual design approach, besides satisfying and optimizing the physics of tritium production, is aimed at a very conservative, reliable, long-life system. To that effect, from the onset, two identical target lattice systems will be constructed, providing minimum scheduled downtime for tritium removal, as well as improving system reliability. Thus, while one target lattice is being serviced and replaced, the other can be operating at full power.

Lead was selected as the material for the primary spallation neutron source because it is inexpensive, available in abundant supply, and is easy to use in the fabrication of pins. Furthermore, the neutronic, mechanical, and heat transfer properties of lead are well known.

Lithium-aluminum with about 3 wt% lithium, 50% Li^6 enriched, was selected as the tritium producing material because of the availability of a large data base developed for heavy water reactor (HWR) technology at the Savannah River Plant (SRP). A possible improvement and simplification of the system might be to integrate the lithium directly into the lead pins resulting in a simpler, more homogeneous target system. However, until this new approach is thoroughly studied, the standard SRP technology is the lowest risk approach.

The pressure tubes are replaced either semiannually or annually, depending on their location relative to the incident proton beam. The first two rows of the array will be changed every six months, the other rows on an annual basis. The optimum replacement cycle is a trade-off between maximum tritium yields and acceptable material irradiation limits due to proton and neutron fluences.

Mechanical and Thermal Hydraulic Design: The use of the existing SRP Li-Al technology sets the limiting thermal constraints for the APT target system. Based on these limits, 125°C maximum for the Li-Al pins, leading to 175°C maximum for the lead, the maximum power density allowable in the target is 100 watt/cm³. This, in turn, dictates the proton beam delivery parameters.

The 1.6 GeV proton beam deposits approximately 400 MW in the target lattice. The

first two pressure tube rows see the maximum power deposition. The 100 watts/cm³ in the front rows corresponds to an 8 m² proton beam irradiation area.

To meet the expected heat load, each pressure tube is water cooled. Inlet temperature and pressure conditions are 45°C and 150 psig. The average outlet manifold conditions will be 120°C and about 120 psig. The required water flow is 660 gpm for each tube, with the water flowing upward in the tube.

The lead and Li-Al pins (1.10 cm diameter and 3 meter long), are set in a triangular pattern with a pitch to diameter ratio, $P/D = 1.075$. This corresponds to an equivalent hydraulic diameter of 0.302 cm. The 0.215 water volume fraction in the hexagonal lattice results in a water flow velocity of 9.0 ft/sec and produces a pressure drop of 15 psi.

A manifold connects the pressure tubes to headers carrying cool inlet water to the bottom of the target assembly. A similar arrangement at the top discharges hot outlet water. The total pressure drop between the inlet and outlet headers is estimated at 30 psi.

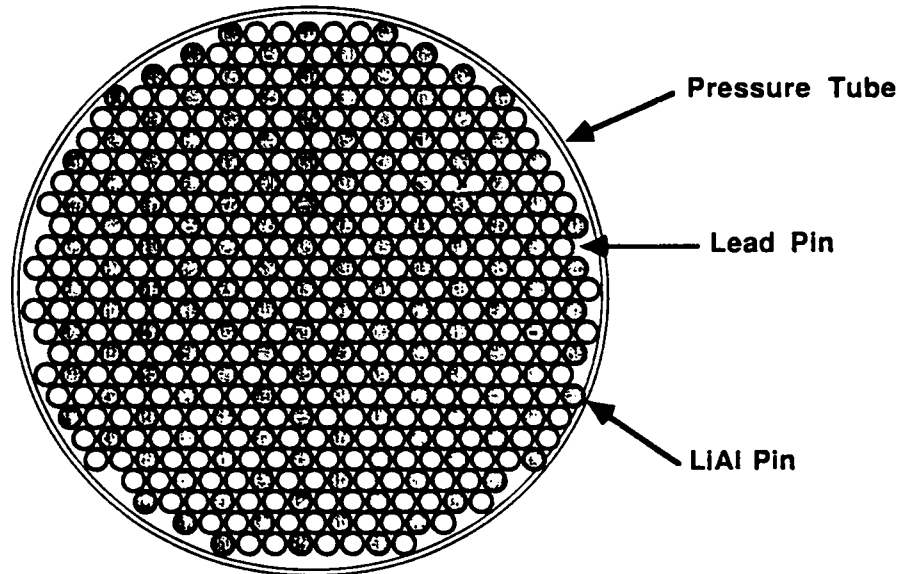
Materials: The pins forming the lattice, both lead and Li-Al will be aluminum clad. Aluminum was chosen because of its low neutron absorption properties and its ease of fabrication. The pressure tubes and all associated piping and hardware will be 316-L stainless steel.

Because of the low operating temperatures and periodic replacement, radiation damage to the target lattice assemblies is not a problem. The combined proton and neutron damage to the structural materials (pressure tubes) is not enough to cause loss of ductility. The maximum helium and hydrogen concentrations in the stainless steel have been estimated at 80 appm and 600 appm at the end of the irradiation cycle. This small concentration should not cause any swelling.

The low pressure, vacuum vessel surrounding the target lattice is the only structure which might be affected by radiation damage since it must last for the full lifetime of the facility. However, the combination of modest stress and low temperature it is subjected to, and proper attention to shielding protection will be more than adequate to guarantee longevity, especially in view of the fact that the target assemblies will be irradiated for less than six months per year.

Figure 11 shows a typical pressure tube cross section with its lead and Li-Al pin lattice. Hexagonal pressure tubes can potentially minimize neutron leakage and improve the matrix geometry. Figure 12 shows a cutaway view of the target lattice assembly in the vacuum vessel. The vessel is connected directly to the accelerator via the beam transport system.

Cross Section of Pressure Tube



Tube Diam.-30 cm
Pin Diam.-1.1 cm
No. of Pins-570
Pb/Li Al Pins-2:1

Figure 11

Target Assembly Beam Expander and Vacuum Vessel

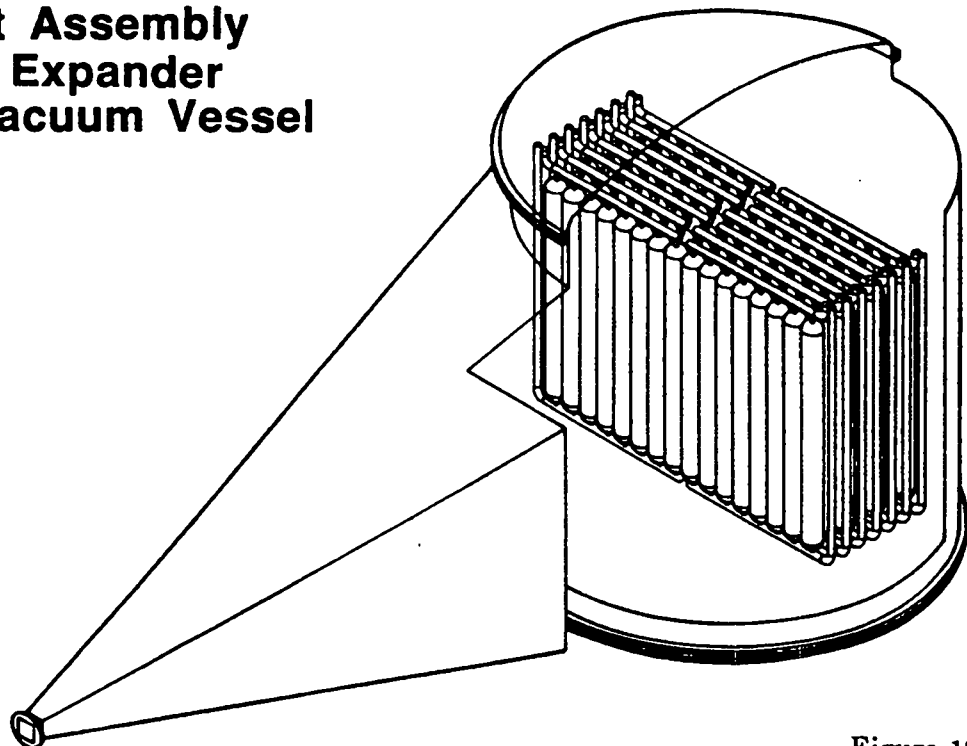


Figure 12

Safety: Safety of the APT target lattice is assured by a combination of inherent and engineered safety features, including: rapid shutoff of the proton beam ($<10^{-3}$ second), very low decay heat, non-fissile lattice, low residual radioactivity, and natural convection cooling.

The proton beam can be turned off in a very short time ($\approx 10^{-5}$ second) by turning off the ion source and the rf power. Protons still in transit will arrive within a millisecond so that an upper limit on the turnoff time is 1 millisecond.

The most important safety issue for reactors, that of removing decay heat in a loss of coolant accident (LOCA) condition, is not an issue for the APT because of the very low inventory of decay products. Preliminary analysis indicates a maximum decay heat power of ≈ 14.5 MW immediately after shutdown, falling to ≈ 8 MW within 100 seconds. The thermal inertia of the target assembly is more than sufficient to survive such a complete loss of coolant accident without releasing tritium.

In the same context, the complete absence of transuranics and fission products removes a whole class of safety and environmental issues. Residually active materials and low level waste, as well as potential tritium contamination, will, of course, still exist. However, these do not cause the same kind of technical and societal difficulties that are present with fission products.

Tritium Extraction and Processing: The proposed two APT target stations are housed in heavily shielded vaults inside a large hot cell. This shielded building will contain all necessary remote handling equipment for the assembly and disassembly of the irradiated banks of pressure tubes. The shielding will be sufficient to have one vault open for target removal while the other target is being irradiated at full power.

The target lattice will first be disassembled in steps. Modules of 7 or 8 pressure tubes (half bank) are removed as a unit. Each module will then be separated into individual pressure tubes to be transferred to hot cells at other locations. There they will be dismantled and the tritium-containing pins removed. The irradiated lead pins, cladding, and structural materials will be disposed and tritium will be extracted from the Li-Al pin, using standard SRP practice.

This tritium extraction and processing technology has been used for the past 40 years at the SRP reactors. Retention of this technology greatly reduces the technical risk of any new production facility. The APT target assemblies will be housed in a shielded building adjacent to the existing DOE Fuel Materials Evaluation Facility (FMEF) at Hanford. This new \$250 M facility is ideally suited for the entire hot cell operation and tritium processing and provides substantial savings in the implementation of the APT.

Figure 13 compares the decay heat of an HWR reactor to that of the APT. This low residual decay heat of the APT, as well as the complete absence of criticality, are the two factors which make the safety issue easier to approach. Figure 14 describes schematically the inherent safety features and the engineered safety devices which will be part of the APT.

Comparison of HWR and APT Decay Heat

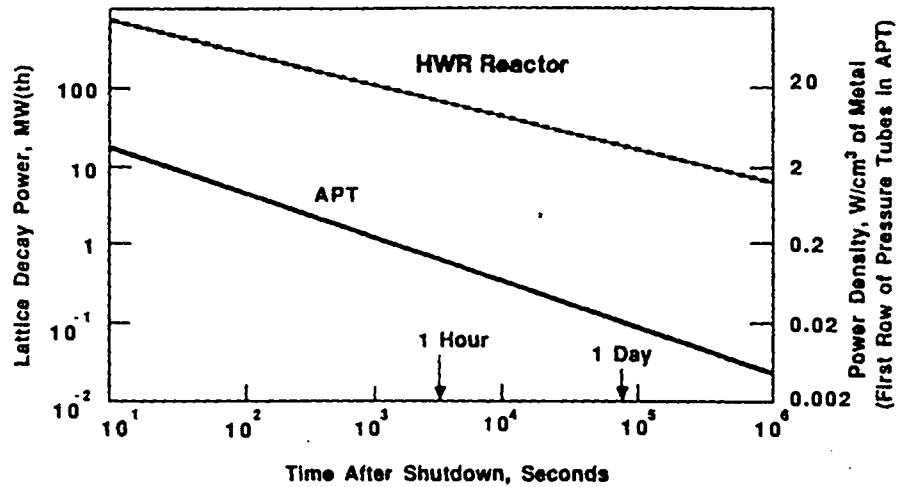


Figure 13

Lattice Safety Features

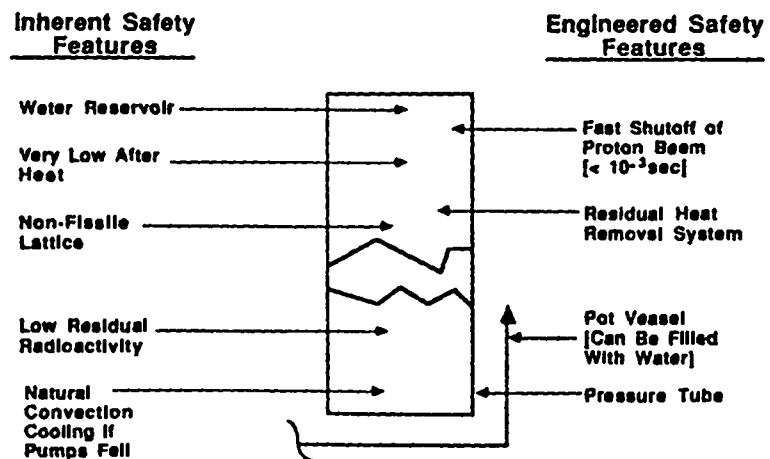


Figure 14

Figure 15 shows a layout of the two target vaults and Figure 16 shows the location of the target system with respect to the Fuel Material Evaluation Facility (FMEF) building at the Hanford 400 area. The target stations and the FMEF will be arranged to maximize the utilization of the existing facilities.

Lattice Vault Building

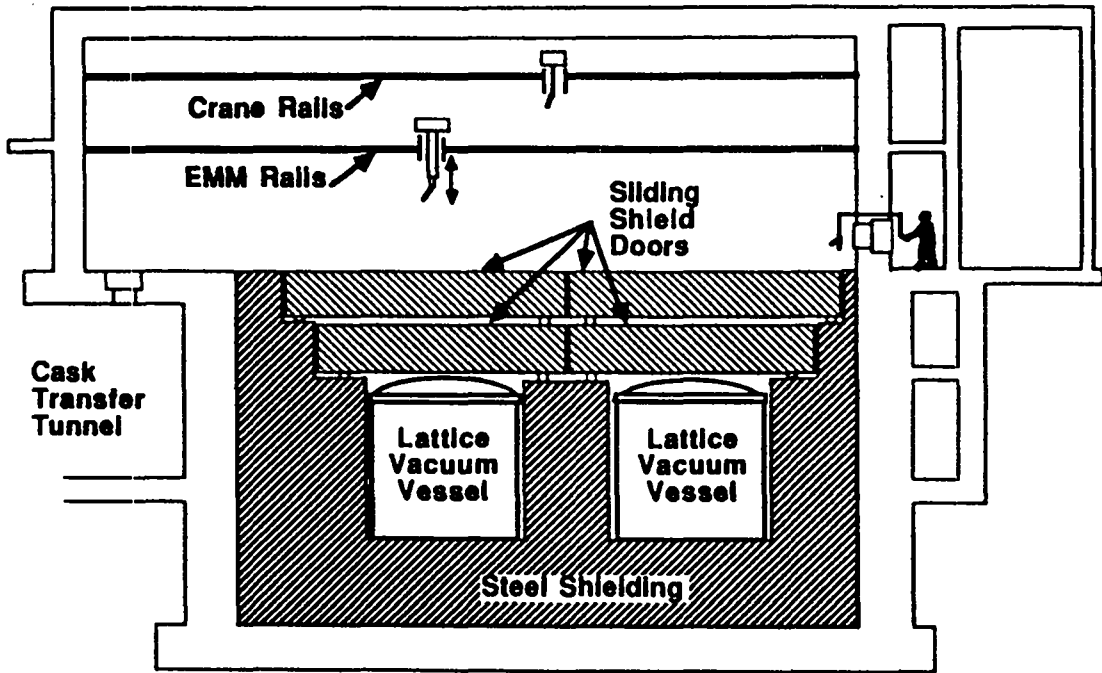


Figure 15

FUELS AND MATERIALS EXAMINATION FACILITY BOP IN FMEF

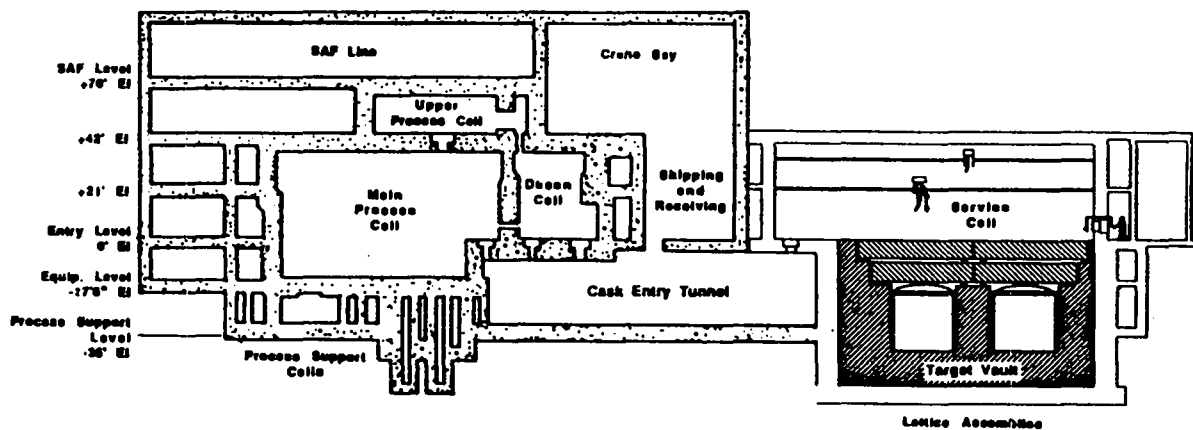


Figure 16

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