NEW APPLICATIONS FOR HIGH-POWER PROTON LINACS*

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Abstract

Advances in high-current rf proton linac technology have made it possible to project credible designs for a new generation of very intense spallation neutron sources for nuclear process applications. Current intest is focused on transmutation of nuclear waste and tritium production. Accelerator production of tritium was proposed recently as a contingency backup to the reactor approach.[1] The concept is based on a 250-mA, 1.6-GeV cw proton beam incident on a matrix of lead (Pb) and lithium-aluminum (Li-Al) rods. Neutrons produced in the Pb are absorbed in lithium to produce tritium. A review by the Energy Research Advisory Board (ERAB) affirmed the technical feasibility of the accelerator concept. This finding stimulated investigation of alternate target/blanket concepts, leading to a separated-function scheme that produces tritium through neutron capture on ^{3}He in a thermal flux level > 10^{16} n/cm^{2}-s. The potential of such high thermal neutron intensities opens an exciting range of new approaches to accelerator transmutation of long-lived actinides and fission products, and to the possibility of reducing time scales for eliminating such wastes from >10^{4} years to human lifespans.

Nuclear Process Applications

Light-ion accelerators have been considerd for more than 40 years for nuclear process applications, including fissile-fuel breeding, fuel-element regeneration, energy production from fertile materials, and transmutation of nuclear wastes. In 1947 a Livermore group proposed a 500-MeV, 320-mA D^{+} cw (50-MHz) drift-tube-linac (DTL) for breeding ^{239}Pu and ^{233}U from ^{238}U and ^{232}Th, using a beryllium neutron-production target surrounded by a ^{238}U multiplier.[2] This project, named the Materials Test Accelerator, was not implemented because of the discovery of large uranium deposits in the western US, but a prototype 33.5-MeV, 12-MHz DTL was built and operated with proton beam currents up to 225 mA (20% duty factor).

In the early 1960s Chalk River Nuclear Laboratories (CRNL) proposed the Intense Neutron Generator (ING), a 65-mA, 1.0-GeV cw proton accelerator for nuclear physics, materials research, and for testing electronuclear fuel breeding concepts. A central motivation was the interest in converting ^{232}Th to ^{233}U to expand fuel resource for the CANDU reactors. Although ING was not funded, an accelerator R&D program evolved at CRNL in the late 70s and early 80s aimed at building a 300-mA, 1.0-GeV demonstration fuel breeder.[3] A high-current 10-MeV cw front end prototype (ZEBRA)[4] was planned, but postponed in 1984 because of the uncertain future of nuclear power in Canada and dropping uranium prices.

BNL also studied accelerator-driven nuclear process concepts during the late 1970s and early 80s.[5] They considered a 300-mA, 1.5-GeV proton linac bombarding a large-volume liquid lead-bismuth (Pb-Bi) eutectic target, surrounded by a blanket of reactor-like fuel elements. Their studies included subcritical assemblies for energy production, fissile fuel element regeneration, production of fissile fuel from fertile material, and also touched on waste transmutation and tritium production. As in the CRNL approach, these schemes employed a fast neutron spectrum (10^{3} - 10^{6} eV) in the conversion blanket, and a relatively low neutron flux distributed over a large volume.

The stagnated growth of nuclear power has eliminated near-term interest in electronuclear fuel production and enrichment. However, waste transmutation and tritium production have different economic and political drivers. There is increasing public concern about accumulating nuclear wastes, and growing disenchantment with the proposed geologic repository solutions. Transmutation using accelerator-driven neutron sources could play the key role in solving the nuclear waste problem, and may be the most promising application area for high-power proton linacs in the near future. Such facilities may also have the potential for electric power generation and tritium production.

APT Concept and ERAB Evaluation

Tritium decays at the rate of 5.5% per year to ^{3}He and must be continuously replenished to maintain the effectiveness of the US nuclear defense. The DOE is proceeding with plans to replace the aging production reactors at the Savannah River Plant (SRP) with two new production reactors (NPR). In 1988 LANL, BNL, and Westinghouse Hanford Company (WHC) proposed accelerator production of tritium (APT) as a backup or contingency production technology, and an initial concept was described in reference 6. A point design of the accelerator, beam transport system, and target/latttice was developed by LANL and BNL during 1989, and was evaluated by ERAB, a high-level technical review panel composed of accelerator, reactor, electric power, and project engineering experts.

The APT system, which is sized for the same tritium production capacity as the heavy-water NPR, is illustrated conceptually in Fig. 1. A cw rf linac delivers a 250-mA beam of 1.6-GeV protons to a large-volume target composed of a matrix of Pb and Li-Al pins. Each proton produces about 45 neutrons in the Pb by spallation and nuclear evaporation. The neutrons produce tritium via the $^{6}Li(n, \alpha)T$ reaction, and the tritium is extracted at intervals by chemical processing of the Li-Al pins. The electric power required to generate the 400-MW proton beam is >900 MWe, and must be supplied externally since no fission power is produced (by design) in the target matrix.

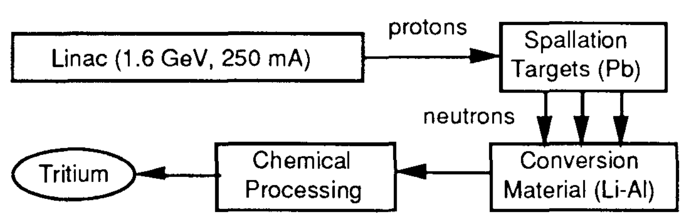

Fig. 1. APT System Concept

The APT has attractive environment, safety, and health features in comparison with a reactor. Since there is no fissile material in the target, there are no pathways to criticality. No transuranic waste is produced, and the radioactive waste stream is small. The process can be shut down rapidly by turning off the beam, and the the taget afterheat is very low. The ERAB Report[7] concluded that there were no serious flaws preventing implementation of the APT scheme, given a suitable development program. The report established the accelerator and beam-transport design concepts as technically sound, and described the target scheme as a conceptual first approach. A major concern was the availability and cost of the required electric power.

High-Power Accelerator

The APT linac can be taken as representative of the class of machines needed for nuclear process applications. Accelerator

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physics design challenges for such a high-power linac are discussed elsewhere[8] and only a summary of the main design points and parameters is presented here. Figure 2 shows the reference accelerator configuration, which consists of a 2-km-long, 700-MHz, coupled-cavity linac (CCL), injected at 20 MeV by a funneled beam-launching system. The launcher is made up of two 100-keV injectors each containing 140-mA proton sources, two 350-MHz radiofrequency quadrupoles (RFQs) providing 125-mA outputs at 2.5 MeV, and two 350-MHz (2βλ) DTLs accelerating beams to 20 MeV. A funnel similar to that tested recently at Los Alamos is used to combine the beams into a 250-mA, 700-MHz bunch train that is then accelerated to 1.6 GeV in the CCL. The

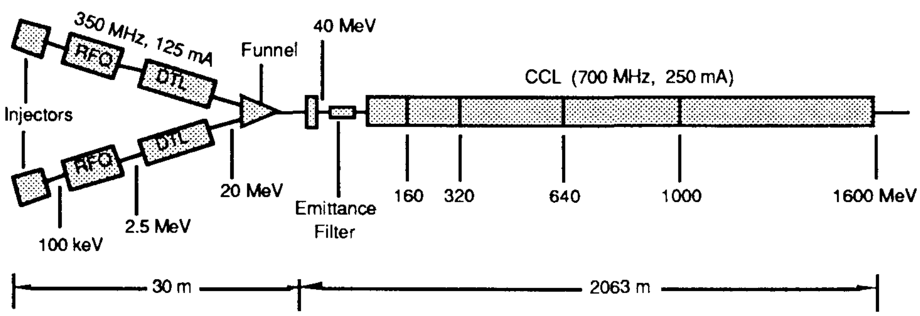

Fig. 2. Reference Accelerator Design for APT

CCL is subdivided into sequences of lattice units, each composed of an n-cell coupled-cavity accelerating module (with n increasing from 2 to 10 as the particle β increases from 0.2 to 0.93), a beam diagnostic and a quadrupole. Figure 3 shows an 8-cell unit. Cavity modules are bridged together in numbers requiring 1 MW of rf input power. The rf tube powering the RFQs and DTLs could be the 1-MW cw 350-MHz klystron developed for the CERN/LEP project. A new 1-MW cw 700-MHz klystron design is needed to power the CCL, which requires about 470 such tubes. Assuming a klystron dc-to-rf efficiency of 0.67, the overall ac-to-beam power efficiency is estimated as about 0.47. Table 1 summarizes the principal parameters of the accelerator; reference 8 provides details on parameter selection, beam dynamics considerations, and the simulations used to predict beam performance.

The overall philosphy governing the linac design is that the low-β beam launcher is optimized to prepare a low-emittance, high-current beam with little halo, and the CCL parameters are selected to assure very low beam loss while maintaining high rf efficiency.

The beam launcher design is very different from the front end of earlier-generation linacs (LAMPF), taking advantage of a decade's advances in the technology of high-current low-β proton linacs. These advances, stimulated partly by the neutral particle beam (NPB) program, include: 1) RFQs replacing high-voltage dc injectors to provide major beam handling improvements in the first accelerating stage; 2) funneling to obtain current doubling with no emittance penalty; 3) higher accelerating-structure frequencies and strong focusing for transverse emittance preservation; 4) ramped accelerating gradients for longitudinal emittance preservation; and 5) proton sources capable of producing high-brightness outputs in the 100-mA range.

Because of the potential for neutron-induced damage to permanent-magnet (PM) materials, the quadrupoles in the DTLs and CCL are radiation-hard electromagnets. Size constraints on the DTL quads then bound the upper frequency limit for the DTL at about 400 MHz. The frequency selection was influenced by the commercial availability of 1-MW cw 350-MHz klystrons. The choice of 20 MeV for the DTL-to-CCL transition is a compromise between the highest practical funneling energy and the lowest practical starting energy for a coupled-cell structure. The low shunt impedance of coupled-cell structures below 100 MeV is relatively unimportant for this design because of high beam loading, and the dominant cost impact of the high-β CCL.

The CCL geometrical layout is similar to LAMPF, with features borrowed from the design of the SNQ linac.[9] The side-coupled linac is in a tunnel buried below 10-15 m of earth shielding. Klystrons, magnet power supplies, and instrumentation are located in a gallery above the linac that is accessible during operation. A non-occupation auxiliary tunnel alongside the linac allows shielding of radiation-sensitive equipment that must be located near the accelerator. The average "real-estate" accelerating gradient is 1 MV/m, a value near a broad minimum in projected facility lifetime costs. The design is driven to this low gradient because of the dominating effects of rf system capital and operating costs. Thermal calculations show that the CCL structures can easily be cooled at this gradient in cw operation, even at the low-β end, where the structure-averaged gradient reaches 2.5 MV/m.

While the average current of the APT CCL is 250 times that of the highest power existing linac (LAMPF), the charge per bunch is actually only 4 to 5 times greater, because the duty factor is 1.0 and all the CCL rf buckets contain protons. Thus the charge-density increase in the bunches compared with demonstrated operating levels is only moderate, and is compensated by stronger transverse focusing. The APT CCL has 4 times the quadrupole linear density of LAMPF, and 50% larger apertures. Given the small beam emittance produced by the modern front end, the ratio of aperture to rms beam size for the APT CCL is 3 to 5 times larger than in LAMPF. This large ratio assures the extremely low fractional beam losses needed to preserve hands-on maintenance of the linac, and has little impact on overall rf efficiency because of the high CCL beam-loading (0.77). An emittance filter may be desirable following the DTL/CCL structure transition to remove residual phase-space tails.

Table II
APT Linac Parameters

	RFQ	DTL	CCL
Frequency (MHz)	350	350	700
Energy (MeV)	0.1 to 2.5	2.5 to 20	20 to 1600
Synchronous phase (degrees)	-90 to -37	-40	-60 to -40
Radial aperture (cm)	0.4 to 0.3	0.8	1.4 to 3.5
Beam current (mA)	140 to 128	125	250
Length (m)	3.4	11.3	2063
Peak surface field (MV/m)	33	22	7.2
Accelerating gradient (MV/m)		1.1 to 3.1	1.0 (lattice avg)
Copper power (MW)	0.4 (x2)	1.3 (x2)	115
Beam power (MW)	0.3 (x2)	2.2 (x2)	395
Total power (MW)	0.7 (x2)	3.5 (x2)	510
Beam loading	0.43	0.56	0.78
Number of klystrons	1 (x2)	5 (x2)	470
Accelerating structure	4-Vane	2βλ	Side-Coupled
Trans. emittance (π mm-mrad)	0.20 to 0.23	0.27 to 0.58	0.61 to 0.68
Long. emittance (10^{-6} eV-sec)	0.0 to 1.4	1.6 to 3.0	3.0 to 4.4

Technical Issues, LAMPF Experience, and Present Technology Base

In the late 1970s accelerator designers assessing the technology base for nuclear process applications had already identified the major technical issues for a high-power proton linac. These were (and still are): 1) beam-loss activation of machine components, which threatens hands-on maintainability; 2) machine damage from misdirection of the high-power beam; 3) improvement of rf system efficiency and reduction of rf-system unit capital costs; and 4) reliability and longevity of components needed to achieve a 75% plant factor. Some important performance parameters had been demonstrated (300-mA peak current in the FNAL injector linac), and some critical components were available or under development (1-MW cw klystrons). It was recognized that an integrated front end demonstration would be essential to establish the engineering basis for high-power cw operation.

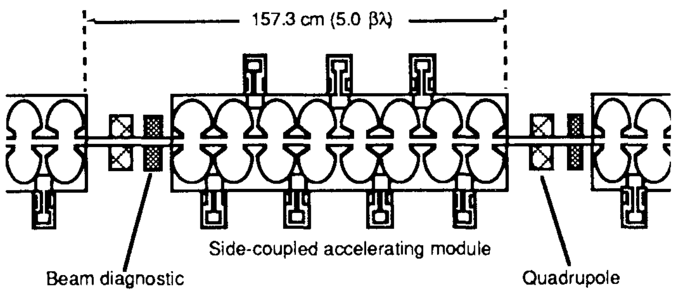

Fig. 3. CCL 8-Cell Lattice Unit

An integrated high-power cw demonstration is still necessary, but accelerator technology improvements and advances in understanding of high-current beam behavior now allow us to project considerably higher confidence that a machine of this class and power can be built and operated. The reference design for APT has taken us a significant step beyond earlier conceptual thinking, and addresses the technical issues point by point. The design includes end-to-end beam simulations with "realistic" matching errors, a machine configuration layout, preliminary engineering analysis of critical components (DTL quads), selection of components to match availability in the existing technology base (klystrons, ion sources), an analysis of off-normal accelerator conditions and beam/target safety arrangements, and a cost and optimization model to confirm parameter choices. The design codes have been benchmarked in the relevant energy and charge-density regimes by simulation of high-current behavior on the NPB Accelerator Test Stand at Los Alamos, and by an end-to-end simulation of LAMPF[10] that confirms measured emittance values as well as beam loss locations and rough magnitudes.

Experience with existing linacs that have operated for years with high availability as multi-program research factories has provided a strong foundation for making extrapolations to the APT performance regime. Because of its high average current, operational experience at LAMPF, is especially relevant, particularly in addressing the important beam-loss issue. For most of the CCL length, LAMPF beam losses are estimated to be < 0.2 nA/m, and radiation levels after shutdown are compatible with unlimited-access hands-on maintenace at nearly all locations. Given the much larger aperture-to-beam-size ratio in the APT CCL and the higher quality input beam, we are able to project high confidence of contact maintainability even though average currents are two orders of magnitude higher. Simulations suggest that absolute losses could be lower than at LAMPF. Klystron longevity, although not in cw operation, has also been partly addressed by LAMPF statistics. Typical lifetime of the 1.25-MW peak-power 805-MHz klystrons (up to 12% duty factor) has been > 50,000 hours, with many tubes having operated for more than 80,000 hours. Another area in which LAMPF experience is relevant has been the demonstrated ability to protect accelerator structures from high peak beam power damage by rapid detection of abnormal beam conditions and fast shutdown (in a few μs).

The technology base for high-power linacs is significantly closer to APT requirements than it was in the late 1970s. The nominal ion source selection for APT is a multiaperture duoPIGatron similar to those being used in the CRNL high-power test program. Other promising candidates are the cusp-field source used for the FMIT prototype and an ECR source under development at CRNL. A 267-MHz proton RFQ at CRNL has operated at 67 mA, cw. Peak (H^-) currents of 100 mA have been demonstrated in a 7-MeV ramped-gradient 425-MHz DTL at Los Alamos, and an 80-mA cw D^- DTL is being built as part of the NPB program. Beam funneling in the relevant current and frequency range has been successfully demonstrated at Los Alamos. High power (0.5 - 1.0 MW) cw klystrons are available at several frequencies, including 352 MHz, 500 MHz, and 1000 MHz. Some have dc-rf efficiencies close to 0.70, and manufacturers believe that further efficiency improvements are possible.

High Energy Beam Transport and Target

The APT linac output is directed to one of two alternate tritium production target assemblies by a high-energy beam transport (HEBT) system depicted in Fig. 4. The HEBT includes an achromatic bend whose $\delta p/p$ bandwidth is ±2% and terminates in a nonlinear optical expander[11] that produces a nearly uniform 4m x 8m rectangular beam distribution at the target face. The expander, which includes two octupoles, eliminates the requirement for beam rastering or sweeping that was a problem in the initial APT concept.[6] The large momentum acceptance of the HEBT makes the APT system relatively tolerant to single klystron failures. The result of a single rf station failure above 320 MeV is that the beam is accelerated to full energy and is transported to the target, but with a momentum deviation up to ±1% of the nominal value. This design feature significantly improves overall machine availability, given an anticipated failure rate of 2 to 3 tubes (out of 470) per week; only 20% of the failures would force immediate shutdown.

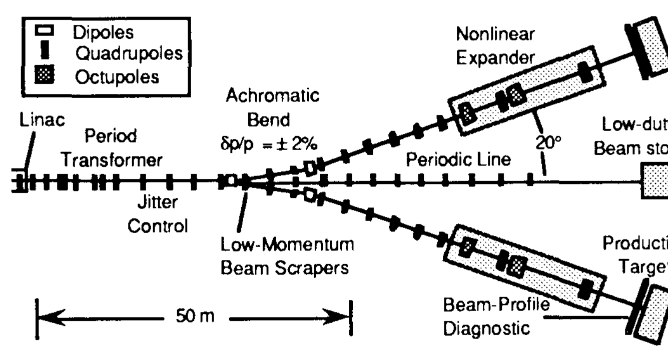

Fig. 4. APT High-Energy Beam Transport

The initial target concept proposed for APT consists of a 4m-high, 8m-wide, 2m-deep rectangular lattice (Fig. 5) of removable 30-cm diameter stainless-steel pressure tubes (7 rows), each of which contains an integral bundle of Pb and Li-Al rods in a 2:1 ratio. The lithium is enriched to 50% ^{6}Li. Light water flowing inside the steel tubes at relatively low temperature (<120 °C) and pressure (<150 PSI) provides cooling and neutron moderation. The entire assembly is designed, in this approach, to look and behave like the core of an SRF reactor, so that SRP fuel fabrication technology and tritium extraction technology would apply with only minor modifications. Neutron flux levels in the lattice are relatively low (< 5×10^{14} n/cm^2-s), and power densities inside the target are comparable to those in an SRP core. Tritium is recovered through processing involving bi-annual removal of the

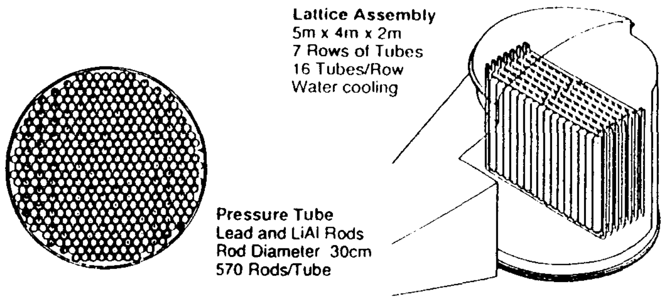

Fig. 5. Initial APT Target Concept

pressure tubes, followed by heating of the Li-Al rods after they are separated from the pin bundles. Neutron yields and spectral distributions in the lattice were calculated using the intra-nuclear cascade code HETC, and tritium production in the lattice was estimated using the point cross section code MCNP with an explicit representation of the lattice rod/tube geometry.

Principal concerns for this target concept are: 1) radiation damage to structural components from the proton beam, which penetrates the entire lattice; 2) formation of highly radioactive ^{24}Na from p,α reactions in the Li-Al , complicating the tritium extraction process; 3) disposal of the radioactive lead waste; and 4) pressure tube failure resulting from an overfocused beam.

^{3}He Target Concept

An alternate APT target concept has been suggested at Los Alamos that may have significant advantages in comparison with the Pb/Li-Al matrix. This new approach employs the reaction $^3\text{He} + n \rightarrow T + p$ (which has a 5300 barn thermal cross section) to recycle the existing ^{3}He inventory. In this scheme (sketched in Fig. 6) the 1.6-GeV, 250-mA proton beam is vertically incident on a 1-m-diameter liquid Pb-Bi eutectic target surrounded by a 4-m-diameter blanket of D_2O moderator. The eutectic flows in the form of a cylindrical fountain, with the liquid pumped upward at the wall (at 150-200 °C), falling through the beam interaction region, and exiting below at 350-400 °C. A NaK cooling loop can be used to remove the heat to a forced-air sink or to recover 25% of the beam power through a steam generator. In this target-blanket configuration the neutron production volume is separated from the conversion region, allowing somewhat higher neutron yield per proton (55 vs 45) than in the Pb/Li-Al lattice, greater design flexibility, and reduced proton radiation damage to structural components. Neutron induced damage in the high flux at the Pb-Bi containment wall may be a concern, but is within the experience range of existing fast fission reactors (EBR II), and is less than in planned fusion facilities. ^{210}Po production from proton capture on Bi would contribute significantly to target afterheat, but can be continuously removed from the liquid metal transport. Liquid Pb and Pb-Bi targets and transport systems have been studied and developed by a number of groups for application to high-power spallation sources[12], and there is a considerable technology base, although not at APT power levels.

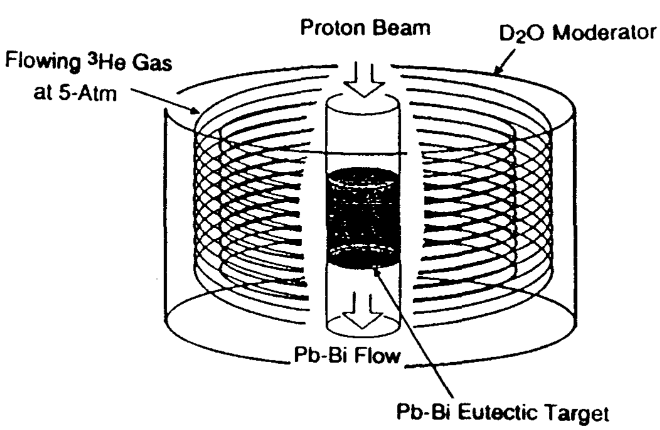

Fig. 6. High-Flux ^{3}He Target/Blanket

Neutron transport calculations show that thermal neutron flux levels >2x10^{16} n/cm^2-s can be achieved in the blanket region near the target wall. ^{3}He at about 75 PSI flows continuously through stainless-steel tubing immersed in the D_2O, and a fraction is converted to tritium on each pass through the neutron field. In a continuous external processing loop similar to that in the Los Alamos TSTA facility , the hydrogen isotopes are first removed by palladium filtering, and then tritium is separated from the other isotopes by fractional cryogenic distillation. The balance of plant for this scheme, which requires a tritium processing capability smaller than TSTA, would be much less costly to build and operate than the SRP process for tritium extraction from Li-Al. Additional advantages of the scheme are that 1) the mixed waste produced is negligible, since the lead target is recycled, and 2) the on-line extraction process greatly reduces the risk of tritium release in an accident.

Nuclear Waste Transmutation

Stimulated by the favorable ERAB evaluation of the APT accelerator concept, preliminary studies at Los Alamos are revealing exciting new nuclear process possibilities for a high-power linac combined with a high thermal-flux target/blanket. These concepts open previously unexplored parameter regimes for transmutation of nuclear waste. It is proposed that the initial application of these ideas would be to the partitioned wastes in the DOE defense complex, and later to the unprocessed used fuel rods currently stored at commercial power reactor sites. There also appears to be interesting potential for energy production without a waste stream, and for tritium production without burdening the electric power grid.

The key to these possibilities is the production of very high (>10^{16} n/cm^2-s) fluxes of thermal neutrons in a useful working volume, which can be achieved with a separated-function target-blanket concept like that described in the previous section, in which a Pb-Bi spallation target is surrounded by a D_2O-moderated conversion volume. Previous accelerator transmutation schemes have required a fast neutron spectrum in the blanket. With the attainment of such high fluxes of low energy neutrons, 100 times greater than in standard reactor designs, significant technical advances are possible. The higher actinides (such as ^{237}Np) are converted by neutron capture to daughter products that are fissioned rapidly by a second neutron interaction before they can decay to non-fissile isotopes. High fluxes of neutrons at thermal energies, where cross sections are large, also permit rapid conversion (to stable isotopes) of long-lived fission products such as ^{99}Tc and ^{127}I . Shorter-lived species, such as ^{90}Sr and ^{137}Cs, can also be converted at rates faster than their natural decay, if the neutron flux is high enough. These processes are shown schematically in Fig. 7. The high flux also provides access to a new, very dilute operating regime that permits high transmutation rates using very low inventories of fissile materials in the blanket. System studies have shown that yearly amounts of transmuted material are similar to those in reactor-based or conventional accelerator-based concepts, but with 100-200 times less resident actinide materials. This leads to positive implications for safety as well as for nuclear safeguards and security.

It is becoming clear that the present plan for disposal of defense and commercial high-level nuclear waste, namely vitrification and very-long-term (10^4 to 10^5 years) storage in geologic repositories, is meeting increasing and deep-seated public skepticism and resistance. Transmutation, while not eliminating the need for short-term storage sites, may offer a way out of this dilemma. Taken together with appropriate chemical processing, there appears to be good potential that a small number of accelerator-driven thermal-neutron transmuters could form the key ingredient in a waste-management system that can destroy accumulated high-level defense wastes within a human lifespan.

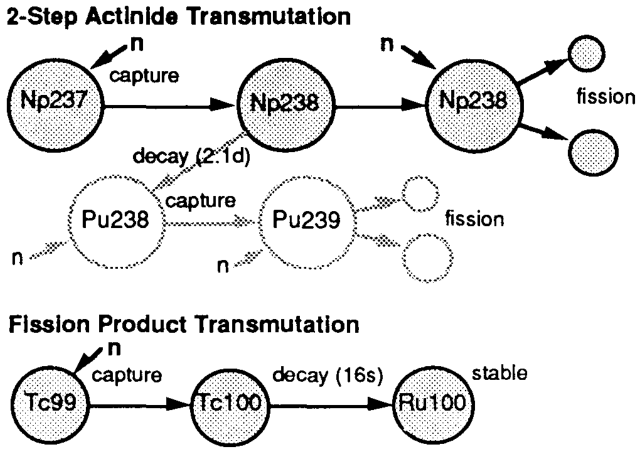

Fig. 7. Transmutation in Thermal Neutron Flux

Figure 8 provides an overview of a full-scale transmutation system currently being studied at Los Alamos, in which a 1.6-GeV, 250-mA proton beam falls on a Pb-Bi target surrounded by a D_2O moderated blanket in which the material to be transmuted is carried in a dilute solution of molten fluoride salts. The molten salt flows continuously in a loop at high temperature, using technology similar to that developed at ORNL years ago for the experimental molten salt reactor program.[13] Higher actinides or Pu in the salt multiply the spallation neutron flux, producing sufficient fission power to run the accelerator. Advanced continuous fluoride chemical partitioning and processing methods appear to be capable of separating stable products from material that is recycled through the transmuter.

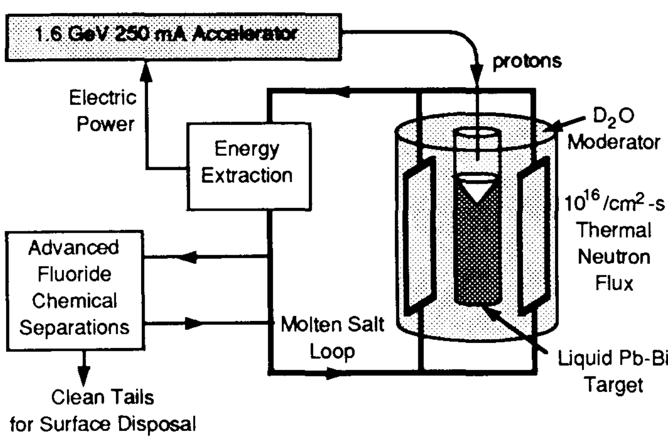

Fig. 8. Los Alamos Transmutation Scheme

Two-dimensional neutron transport calculations for an unoptimized target-blanket geometry show that a single APT-class (250-mA) facility could transmute waste actinides and fission products at a rate of 500 kg/year. Given present inventory levels, the accumulated defense wastes could be converted in 20 to 30 years. While these numbers show what can be done, this first calculational model is far from ideal, with about 50% of the accelerator-produced neutrons being absorbed in structural materials. Very general neutron economy arguments applied to similar systems show that the potential for performance optiimization is large. If, for example, a 13% neutron loss is assumed (consistent with molten salt reactor experience), then the beam current required to attain similar performance is much lower, and we could expect 500 kg/yr transmutation rates with a 30-mA accelerator.

Using this neutron economy picture, we can show that one APT-class accelerator can burn the waste discharge of about eleven 1000 MWe light-water reactors (not including U and Pu to be recycled), while providing enough power to run itself. Using the high temperature molten salt concept, overall thermal-electric efficiencies of about 30% appear feasible, if the accelerator-driven system is used to generate power from Th or U fertile material feed, and enough neutrons would be left over to burn the fission products made in this process. This last concept could eventually lead to a new regime of nuclear energy production with minimal requirements for long-term radioactive waste disposal.

Acknowledgement

The material discussed in this paper represents the ideas, contributions and efforts of a large group of people at Los Alamos National Laboratory, drawn from several technical Divisions.

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