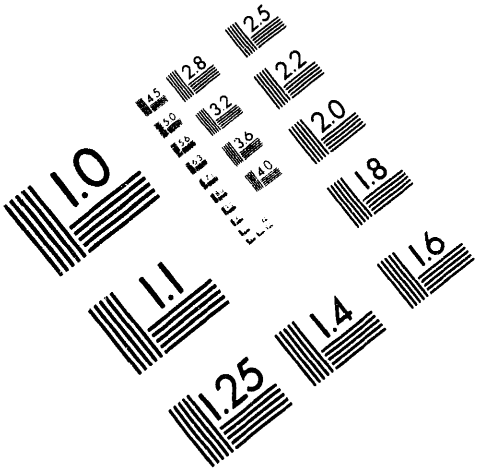

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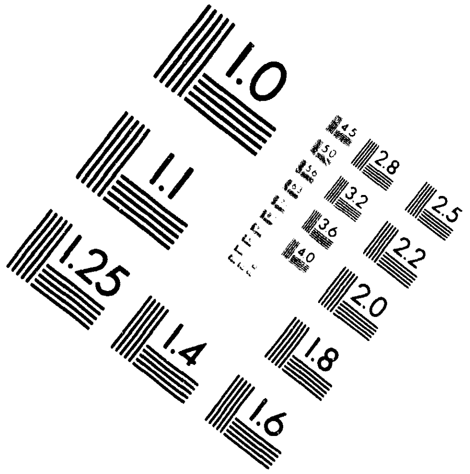

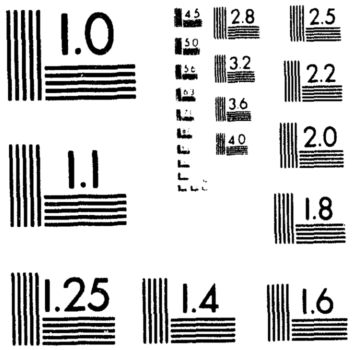

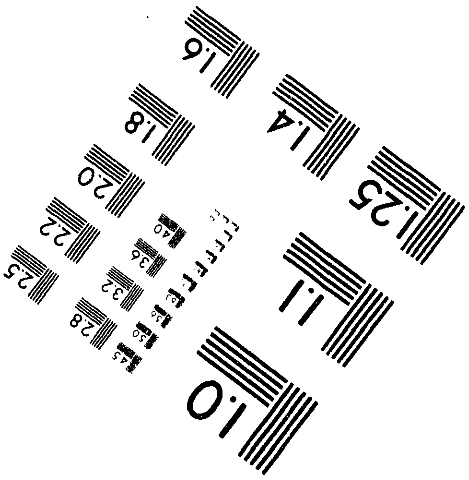

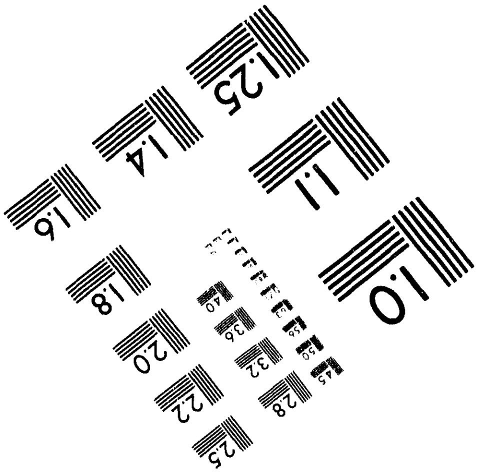

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Technologies Using Accelerator-Driven Targets Under Development at BNL*

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Abstract. Recent development work conducted at Brookhaven National Laboratory on technologies which use particle accelerator-driven targets is summarized. These efforts include development of the Spallation-Induced Lithium Conversion (SILC) Target for the Accelerator Production of Tritium (APT), the Accelerator-Driven Assembly for Plutonium Transformation (ADAPT) Target for the Accelerator-Based Conversion (ABC) of excess weapons plutonium, The PHOENIX Concept for the accelerator-driven transmutation of minor actinides and fission products from the waste stream of commercial nuclear power plants, and other potential applications.

INTRODUCTION

During its long history in designing, building, and operating particle accelerators and nuclear reactors, BNL has explored the application of hybrid technologies, with much of the early work being related to accelerator-driven breeder reactors [1]. More recently, advances in accelerator technologies, fueled largely by the Strategic Defense Initiative of the 1980s, have made viable much larger applications of hybrid technologies. In such applications, one uses the neutrons produced during spallation events, induced by driving charged particles into heavy targets, either to produce or destroy materials that would have previously been produced and/or destroyed in nuclear reactors. In some instances, these spallation neutrons are multiplied in a target containing actinides in some subcritical configuration.

Once one assumes the availability of large quantities of spallation neutrons, a wide array of potential applications becomes readily apparent, based in large part on missions previously undertaken using nuclear reactors. Given the recent difficulties in building nuclear reactors for any purpose, it is indeed tempting to take on any and all missions traditionally fulfilled by the reactors. However, it is essential for the proponent of accelerator-target applications to develop technically credible reasons for moving away from reactor solutions that could, in some cases, be simpler and cheaper. In the applications proposed by BNL, the justifications are generally based on significant environmental, safety, or/and economic or operational advantages.

Accelerator Production of Tritium (APT)

In the case of the Accelerator Production of Tritium (APT), for which BNL is developing the Spallation-Induced Lithium-Conversion (SILC) Target [2], the spallation target material is lead, and the surrounding blankets contain the lithium-6-bearing aluminum plates wherein the neutrons are captured to produce tritium (as is done at Savannah River). In this instance, there are no actinides involved, and the advantages include the avoidance of many reactor safety issues and the lack of high-level waste generation. The disadvantage with respect to reactors is the high electricity requirement, but that disadvantage diminishes with reduced tritium production requirements.

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* This work was performed under the auspices of the U.S. Department of Energy.

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The SILC Target is illustrated in Figures 1 (in exploded form) and 2 (as installed in the target cavity). The SILC Source region is the compact array (about two cubic meters) of aluminum pressure tubes, which each contain about five hundred 1-cm-diameter aluminum-clad lead pins, as well as the heavy-water coolant. Since none of these materials are significant neutron absorbers, most of the spallation neutrons escape the source and penetrate into the SILC Blanket. Once inside the blanket region, the neutrons are slowed by the light-water coolant, and then captured in the aluminum-clad plates of lithium (enriched to 50% Li-6) aluminum. As indicated in Figure 1, the Blanket is composed of three components, the U-blanket that fits below and beside the source region, the L-blanket the covers the top and back of the source region, and the beam-expander duct blanket, which captures most of the neutrons that come back off the front face of the source (towards the accelerator). (Note that a "dog-leg" in the beam transport line prevents these neutrons from ever reaching the accelerator.)

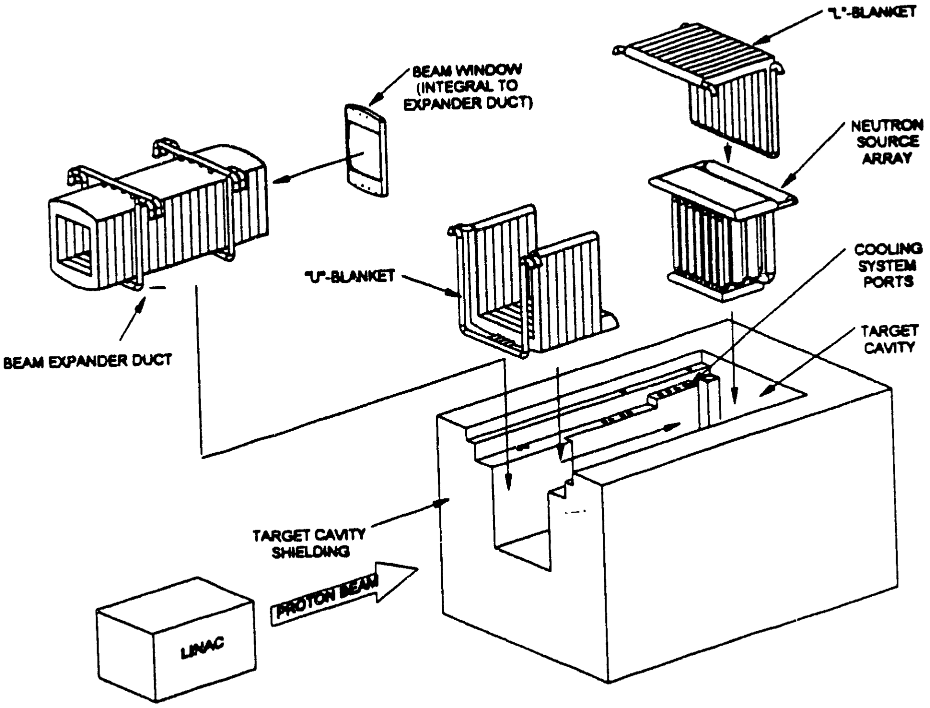


Fig. 1 SILC Target Exploded

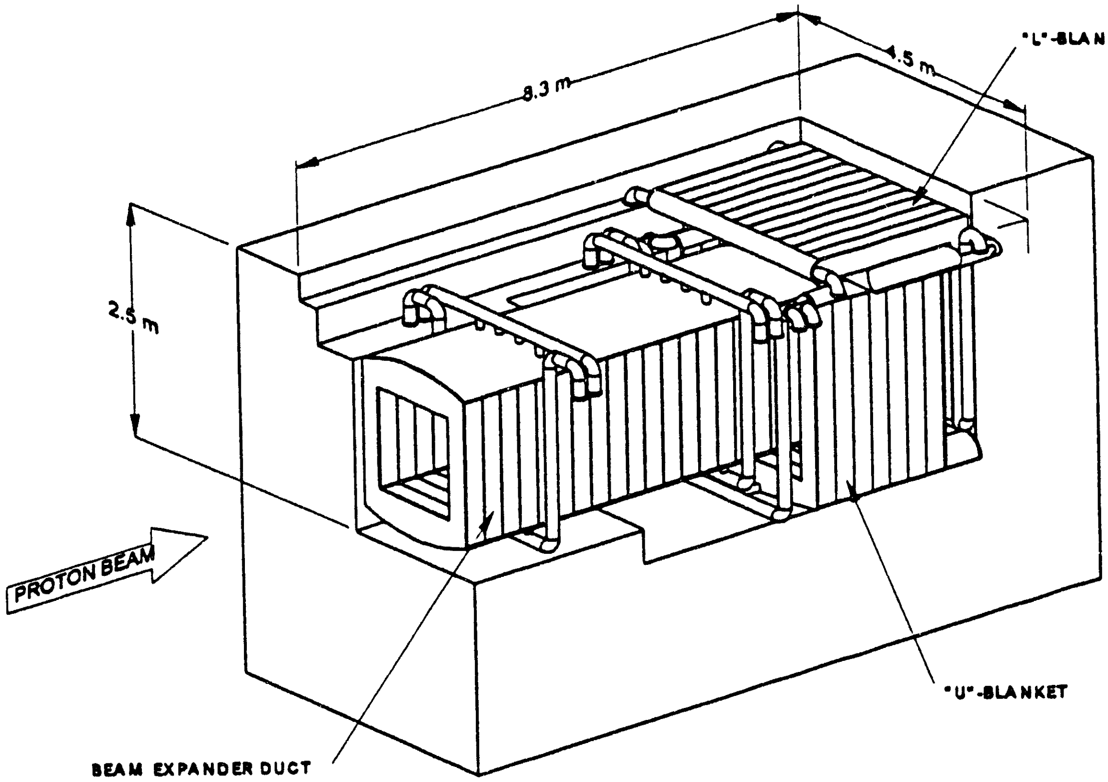
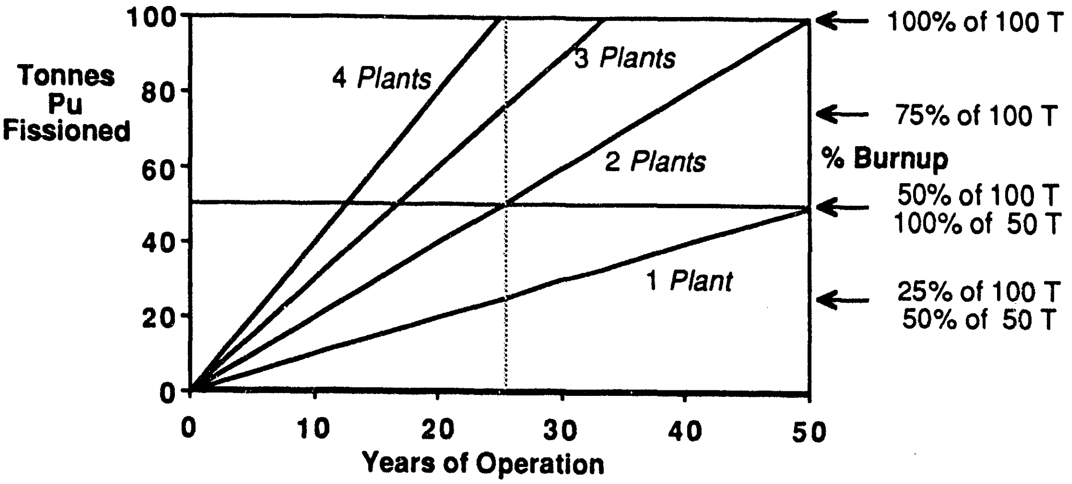


Fig. 2 SILC Target Installed

Extraction of the tritium from the lithium-aluminum plates is based on the Savannah River technology used in support of the production reactors for several years. Thus, in many respects, the SILC Target is an adaption of reactor technology, but with a different neutron source. However, in this case there are no actinides, which means no high-level radioactive wastes, no reactivity issues, very little after-heat, and a much-reduced "source term" (inventory of hazardous materials that might be released in worst-case accidents).

Accelerator-Based Conversion (ABC) of Weapons Plutonium Using ADAPT Target

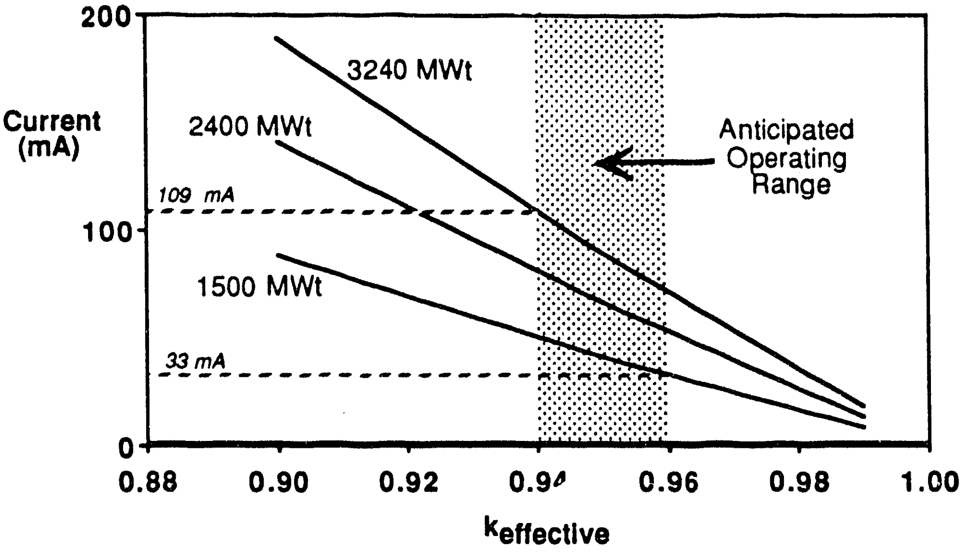
Disposition of highly fissile plutonium from excess nuclear weapons is considered a national priority, and there is a healthy debate ongoing regarding the best candidate technologies for resolving this nontrivial mission. One of the difficulties has been to establish a common basis for comparison, especially regarding throughput and number of machines required. One can best compare options by postulating the complete fissioning of the roughly 50 metric tonnes of weapons plutonium being considered in the U.S (or possibly 100 tonnes). To do so, we postulate a reference *plant* as a 3240 MWt unit running on pure weapons Pu, and operating 75% of the time. Such a *plant* could fission 1 tonne per year, as shown in Figure 3. It is emphasized that this graph applies to both reactors and accelerator targets, as long as one is fissioning only the weapons plutonium and is not making additional plutonium in the process.



- Machine and System Capacity Dictated by Fission Energy, Plutonium Mass, and % Burnup
  - 190 MeV/Fission = 7.66 x 10^{10} MJ/Tonne of Pu (Fully Fission)
  - A 3240 MWt (1070MWe) *Plant*@ 75% Capacity Factor Fissions 1 Tonne/Yr
  - Assumes No New Plutonium Generated During Process

Fig. 3 Throughput of Plutonium for a 3240 MWt Plant

The Accelerator-Based Conversion (ABC) approach is categorized as an "ultimate disposition" candidate, and BNL is working on the Accelerator-Driven Assembly for Plutonium Transformation (ADAPT) target technology [3]. The spallation neutron source is similar to that used in the APT SILC Target, but the blanket is a subcritical reactor containing the 96% fissile plutonium contained in coated graphite beads (0.5 cm diameter). This fuel is based on a similar fuel developed for a Particle-Bed Reactor (PBR) that was to operate at much higher power densities and temperatures [4]. The degree of subcriticality is a key design issue, and will depend on the safety analysts assessment of the vulnerability to reactivity accidents. While much work must be done, some difficulties are expected due to a natural tendency for plutonium to give positive reactivity feedbacks, especially when overheated. Once the vulnerability has been assessed and the necessary safety margins have been quantified, one can set a suitable criticality limit, probably between 0.9 and 0.99. This would then determine the subcritical multiplication in the blanket, and the required accelerator current, as indicated in Figure 4.



- Current Requirement vs. Subcriticality (vs. Power)
  - #Fissions = #Source Neutrons * [k/(1-k)] / #Neutrons per Fission, ($k=k_{effective}$)
  - # MegaWatts = 1.9 * I (mA) * [k/(1-k)], Assuming N/P=25 and 2.5 Ns/Fission

Fig. 4 Beam Current Required vs. K_{eff} for Candidate Power Levels

With a high power density and high throughput, this target is designed to convert the plutonium to fission products in a form ready for disposal, without producing new plutonium and with safe management of the difficult reactivity characteristics of plutonium. The formal design work (see Figure 5 and 6) is just beginning, with a reference or "Preconceptual" design expected by late 1995.

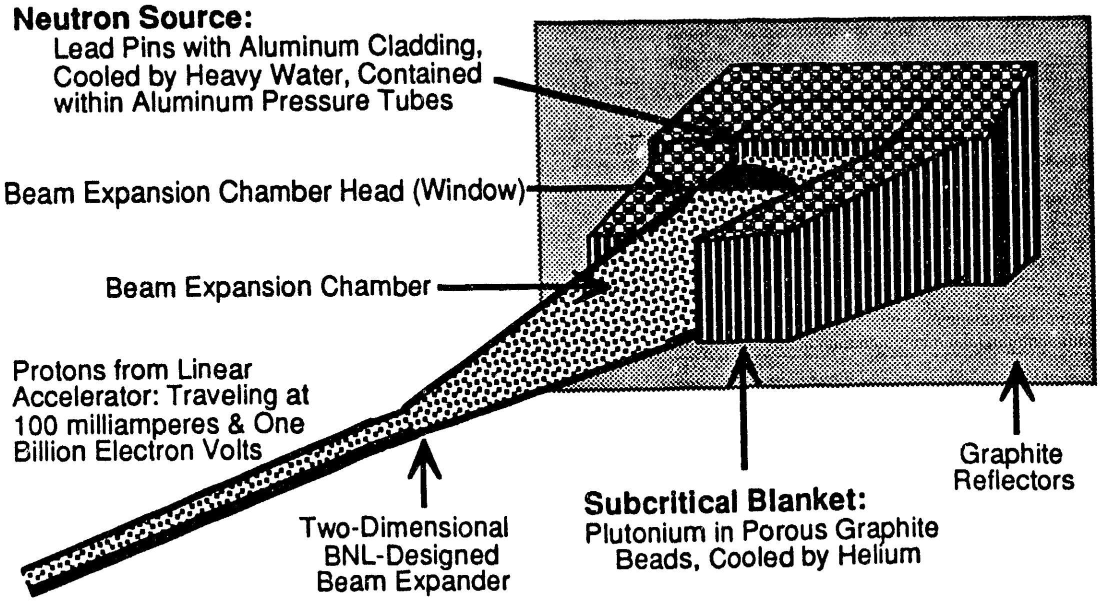


Fig. 5 ADAPT Target to Dispose of Excess Plutonium

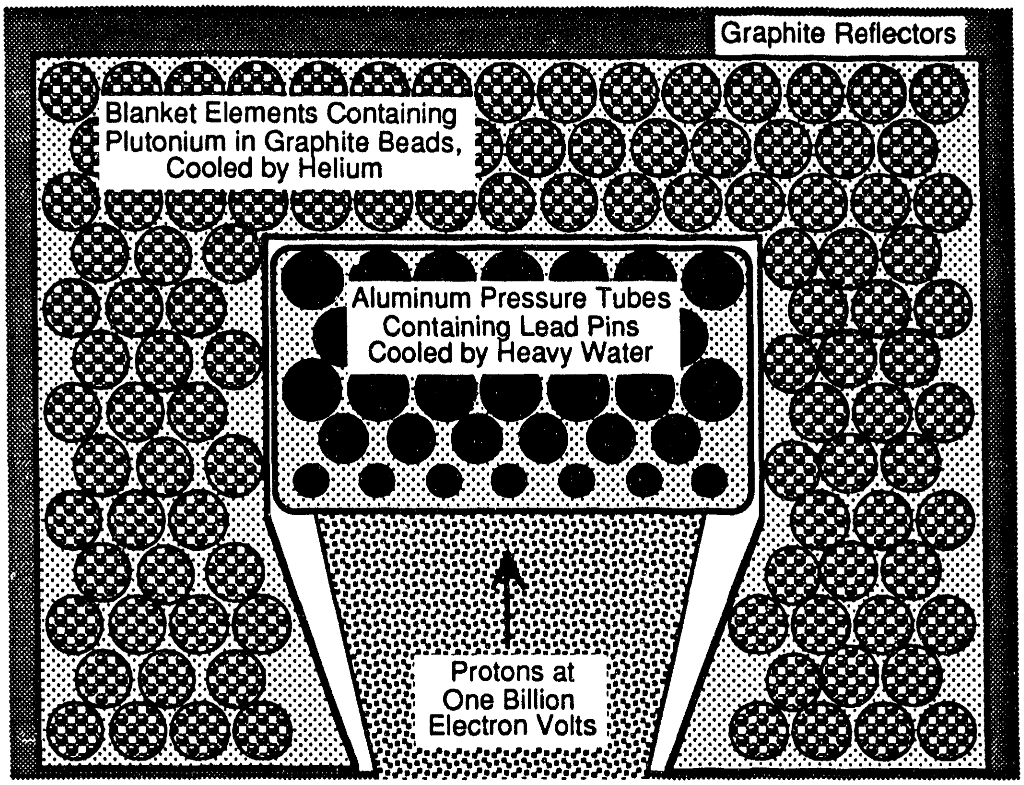


Fig. 6 ADAPT Target - Top View

The PHOENIX Concept

A few of the long-lived radioactive wastes in commercial spent fuel, including the plutonium, minor actinides, and a handful of fission products, cause most of the technical difficulties in assuring the adequacy of proposed waste repositories. The predicted mass flows from one hundred 1000 MWe nuclear power plants (slightly exceeds U.S. production levels) are shown in Figure 7 [5]. As shown, about 95.6% of the waste is 0.8% fissile uranium and 3% is either short-lived or stable fission products, with the remaining 1.4% containing long-lived actinides and fission products. While the LANL ATW Concept [6] attempts to transmute all of the components within the problematic 1.4%, BNL envisions the plutonium and technetium components being recycled back into power plants, due to the scope of this mission (the plutonium throughput could run at least seventeen 1000 MWe power plants). As a result, BNL has focused on the design of one or two machines to transmute the troublesome minor actinides and iodine, and assumes interim storage is the best option for the 30-year-half-life strontium-90 and cesium-137.

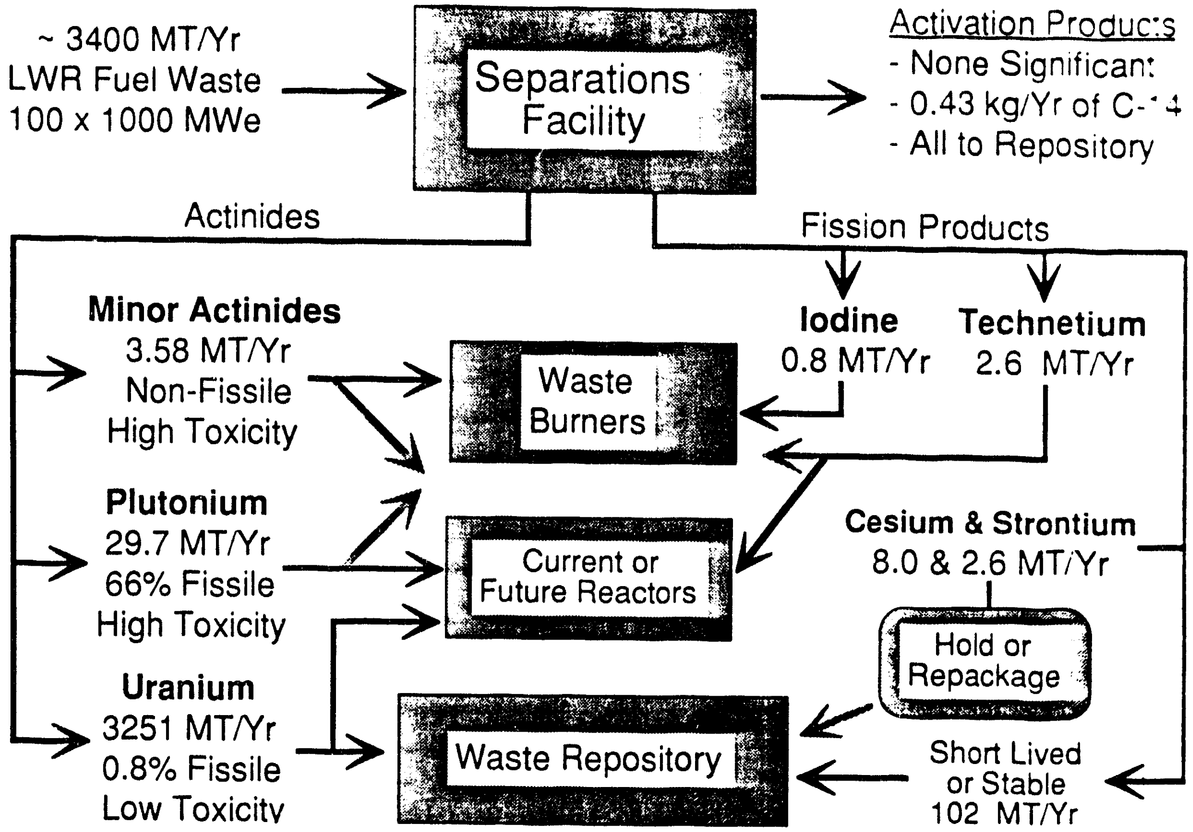


Fig. 7 Approximate Mass Flows From All U.S. LWRs in 1991
(Predicted, Not Measured)

The PHOENIX Concept [7] is illustrated in Figure 8. For this "waste" application, it is nearly impossible to make an assembly of minor actinides critical (initially the isotopes are all fertile, not fissile), even using a fast-spectrum, so the accelerator is essential to keep the target/blanket "source-critical". The eight modular targets closely resemble the Fast Flux Test Facility [8], except the fast reactor demonstration fuel is replaced by minor actinide oxide fuel, with the mix of neptunium, americium, and curium dictated by the composition from the LWR waste stream and the recycle flow from the PHOENIX fuel cycle. The machine would process 2.6 MT of Minor Actinides and about 300 kg of Iodine per year, producing 1.05 MT of fission products (mostly stable or short-lived, but with some recycling of iodine, etc.), 300 kg of stable xenon, and 1.55 MT of plutonium that is largely (about 85%) Pu-238. While NASA uses Pu-238 for deep-space missions, most of the Pu-238 produced by the waste burner would contain too much Pu-236 to be useful to NASA. However, the mix could be useful for blending with excess weapons plutonium, since it would make the mix hot (thermally) enough to make weapons design difficult [9].

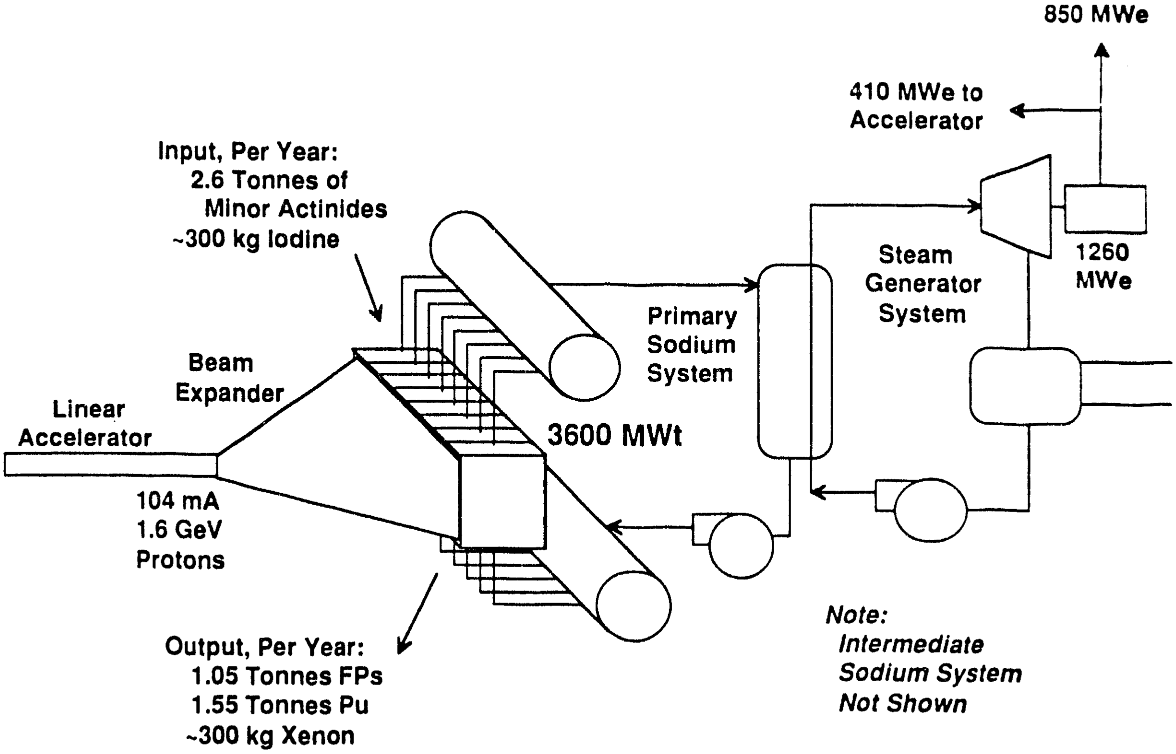


Fig. 8 The PHOENIX Concept

Other Accelerator Applications

Others accelerator-target applications envisioned and/or under development at BNL include spallation neutron sources [10] and isotope production facilities. In these instances, it is the difficulty and costs involved in building and operating reactors to perform these missions that drives the interest in looking at alternatives. Since some of these missions require modest beam power, it is possible to use smaller circular ("ring") accelerators, which would reduce the capital cost significantly. It is also possible to combine missions, and the addition of some isotope production to a tritium or weapons plutonium mission would not be technically difficult, although the programmatic aspects of such multiple missions could be challenging.

One intriguing mission would be the production of the Pu-238 needed by NASA, with the goal production being in the range of 15 kg/year. A major challenge would be the unavailability of americium 241 and the limited inventory of neptunium-237 in the U.S. (more of these materials would be available if the commercial wastes were to be reprocessed), especially when coupled with NASA's requirement for very low Pu-236 (about 2 ppm) content. (The decay chain of Pu-236 leads to Tl-208, which gives off a problematic 2.6 MeV gamma.) If Americium-241 were to be available, neutron capture and the subsequent alpha decay would yield highly pure Pu-238. However, Np-237 has a binding energy of 6.8 MeV, so neutrons or gammas above that energy are likely to produce Pu-236. So even though most Np-237 would capture lower energy neutrons and produce Pu-238, the Pu-236 must be carefully minimized. This would mean positioning the Np-237 out of the direct beam, and avoiding the use of structural materials that might introduce high-energy gamma decays in the proximity of the neptunium. At this time, BNL has not performed detailed calculations for Pu-238 production, although some design features are readily apparent. Because neptunium and plutonium are relatively hazardous and toxic materials, the use of uranium in the spallation target / neutron source poses little additional safety burden, and provides neutron multiplication (subcritical) that could reduce the requirement for accelerator beam. However, as the target begins to function more and more like a reactor, the safety systems will evolve toward comparability, and the advantages associated with the accelerator driver would become significantly diminished.

SUMMARY

Several accelerator-driven target concepts are under evaluation at BNL, with the two largest efforts associated with tritium production (APT/SILC) and weapons-plutonium disposition (ABC/ADAPT). The availability of spallation neutrons opens up options to assume missions previously fulfilled using nuclear reactors, although the neutron economics are quite different. In general, the accelerator option is more economical when fewer neutrons are required, with reactors maintaining an advantage when many neutrons are necessary. Other potential advantages include better environmental, safety, and health characteristics (as for APT), potentially better safety and control characteristics (ABC), and additional operational options such as subcriticality (needed for transmuting minor actinides).

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