TARGET DESIGNS FOR ACCELERATOR PRODUCTION OF TRITIUM (APT) UTILIZING LITHIUM-ALUMINUM*

Michael Todosow and Gregory J. Van Tuyle
Department of Advanced Technology
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

A number of accelerator-driven spallation neutron-source target/blanket systems have been developed for the production of tritium under the APT Program. The two systems described in this paper employ a proton linear accelerator, and a target which contains a heavy-metal(s) for the production of neutrons via spallation, and solid lithium-aluminum for the production of tritium via neutron capture. The lithium-aluminum technology is based on that employed at Savannah River for tritium production since the 1950's. In the APT concept, tritium is produced without the presence of fissionable materials; therefore, no high-level waste is produced, and the ES&H concerns are significantly reduced compared to reactor systems.

INTRODUCTION

Recently, accelerator-driven spallation neutron-source target systems have been developed by a team of national laboratories and industrial subcontractors for the production of tritium. With reduced weapons stockpile requirements, Accelerator Production of Tritium (APT) offers significant safety, environmental, and production flexibility advantages compared to reactor systems, and can be developed in time to meet the U.S. defense tritium requirements of the 21st century. In this concept, tritium is produced without the presence of fissionable materials; therefore, no high-level waste is produced, and the ES&H concerns are significantly reduced compared to reactor systems. The APT concept consists of three major elements: 1) a high-powered, proton linear accelerator; 2) the generation of neutrons from proton-induced spallation reactions in a heavy (high-Z) material; and 3) the production of tritium through neutron capture in a suitable target material.

A number of successful and practical APT target designs have been developed over the past ~7 years by Brookhaven and Los Alamos National Laboratories (BNL and LANL) [Cappiello, et al., 1994], [Cappiello, et al., 1994], [Todosow, et al., 1994]. A number of reviews of the APT concept, which have included the DOE's Energy Research Advisory Board (ERAB) in 1989 and JASON panels in 1992 and 1994, were positive about the technology, but pointed out the need for a research and development program.

As a result of these reviews, DOE sponsored a preconceptual design activity beginning in the Spring of 1992 to develop the APT technology sufficiently to serve as a viable alternative to the conventional reactor-based approach for production of needed tritium. The participants in the preconceptual design phase (1992-1994) of the APT program consisted of a multi laboratory team (Los Alamos, Sandia, and Brookhaven), collaborating with several industrial partners (Bechtel, Babcock & Wilcox, Grumman, General Atomics, Maxwell Balboa, and Merrick).

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

Two target systems were developed independently by BNL and LANL during the preconceptual design phase. The baseline Brookhaven design evolved into a Target/ Blanket (T/B) configuration consisting of a neutron-producing array of lead pins cooled by D_2O in a pressure-tube configuration (the Target), surrounded by tritium producing regions (the Blankets) containing lithium-aluminum, and cooled by H_2O; it is referred to as SILC (for Spallation-Induced Lithium Conversion). The lead/lithium-aluminum combination was selected because of the low neutron capture cross section of lead, and the more than 40 years of successful experience with Li-Al at Savannah River for the production of tritium. It is based on the BNL designed lead/Li-Al target that was reviewed by ERAB in 1989.

An alternative to the SILC concept utilizing tungsten and gaseous He-3 for the neutron- and tritium-producing materials, respectively, was developed by Los Alamos beginning in ~1991 [Cappiello, et al., 1994]. The choice of tungsten for the spallation source was based primarily on its high melting temperature (~3000K), and its successful use at LANSCE for ~20 years. The primary advantage of He-3 vs. Li-Al for the tritium-producing material is the ability to continually extract the tritium product from the He-3; this technology is based on the years of successful experience at TSTA at LANL. The continuous extraction from gaseous helium means that there is no accumulation of significant quantities of tritium within the target, and there is no solid waste stream associated with the extraction process as is the case with solid targets such as Li-Al.

The selection of the He-3 target in FY95 as the baseline for the APT program, coupled with the development of a modular, target/blanket variant of the original He-3 single-module design [Cappiello, et al., 1996] resulted in an interest in "hybrid" targets. In the new modular design, a heavy-water-cooled tungsten Neutron Source Array (NSA) is surrounded by water-cooled blanket modules containing lead (for additional neutron production) and He-3 in pressure-tubes (for tritium production). The modular nature of the blanket made replacement of the baseline blanket modules with modules containing solid LiAl (or other lithium-based materials) feasible. BNL assumed the primary responsibility within the APT team for evaluating these alternative blanket options, and the performance characteristics/attractiveness of such "hybrid" T/B's.

OVERVIEW OF APT CONCEPT

The APT accelerator/target complex is shown schematically in Figure 1. The proton beam exiting from the linear accelerator passes through a "beam expander" (a system of magnets designed to yield a nearly uniform energy-deposition profile on the target), and then on to one of two identical target stations. When one target and/or blanket have reached their design cycle-life, the beam is moved to the second target, permitting the first to cool, be disassembled, and processed to remove the tritium (if necessary), and then refurbished to serve as a spare, or be available when the second target/blanket has successfully completed an operating cycle. With this approach, availability should be enhanced, especially if a target can be processed and refurbished in significantly less time than a standard operating cycle.

OVERVIEW OF TARGET/BLANKET CONCEPTS

The targets that are described in this paper consist of the following components:

- **A Target Cavity** which contains the target during operation and any shutdown cooling that may be required prior to removal of components (e.g., for replacement, or tritium extraction). The cavity is formed by an appropriate arrangement of shielding sections, and contains the connections to the target cooling systems, shielding, and structural interfaces to the target components. The entire Target Cavity can usually be flooded in the event of a Loss-of-Coolant-Accident to preclude overheating of target components.
- **A Neutron-Source Array (NSA)** where neutrons are generated via spallation reactions induced by protons incident on a heavy metal target. The NSA consists of an array of pressure tubes containing lead or tungsten rods, and are usually cooled by heavy water.
- **Blanket Modules** which surround the NSA. The modules contain the aluminum-clad, lithium-aluminum (in rod or plate form), and are cooled by light-water. The blanket modules may also contain lead to provide additional neutron production. The neutrons leaking from the NSA are thermalized, and captured in the lithium, producing tritium via the $Li^6(n,\alpha)H^3$ reaction.

  (In some earlier designs, the target did not physically separate the neutron and tritium producing material into distinct NSA and blanket regions.)
- **A Beam Expander Duct or Entrance Reflector Unit** containing lithium-aluminum, and/or water. Because much of the neutron production in the NSA is via the evaporation process (which is isotropic), a significant fraction of the neutrons leak out of the source region. This unit captures or reflects these neutrons into regions where they can produce tritium; depending on the

specifics of the design, a significant fraction of the overall tritium production may occur in this region.

The target configurations described here are a result of a complex optimization process involving consideration and resolution of a number of often incompatible objectives. Since one of the major concerns associated with the APT concept is the power required to drive the accelerator (as well as the technological challenges and reliability associated with a high-power LINAC), neutron economy is a major objective. Therefore, the system must have a high production of neutrons, and a significant fraction of the neutrons produced must result in the production of tritium. Consequently, all the structural and spallation-target materials should have capture cross sections as low as possible. In addition, in T/B systems, the NSA is a compromise between being "large" to maximize the neutron production and minimize the power density, yet "small" so as to minimize parasitic capture and maximize the leakage of the neutrons into the surrounding blankets. A corollary to these requirements is that the coolant fraction should be minimized in the NSA, consistent with heat removal requirements, to keep the neutron spectrum hard, and further enhance leakage. Similarly, the blankets should optimize the ratio of Li-6-to-moderator so as to maximize the capture rate of neutrons in the Li-6 and thereby reduce the waste stream per unit of product.

DESCRIPTION OF SILC TARGETS

The SILC APT target concept evolved at BNL over a number of years. The designs are predicated on adherence to three major criteria:

- the maximum use of demonstrated technology in terms of mechanical and thermal-hydraulic design, materials, fabrication, and performance in proton/neutron radiation and thermal environments
- a demonstrated physical mechanism for generating the tritium and retaining it *in situ* in a reactor-like radiation and thermal environment
- a demonstrated extraction process for removing the tritium from the target material and subsequent handling

The initial target developed in 1989 (ERAB target) is shown in Figures 2 and 3. The target consists of aluminum-clad, Li-Al and lead rods with an outer diameter of 1.1 cm. which are mixed in a 1:2 ratio ("homogeneously") within each pressure-tube, and cooled by light water. The pressure-tubes are grouped together in banks to form the target. Since the Li-Al is exposed to the direct proton beamt, the tritium inventory is potentially vulnerable to loss as a result of beam upset conditions, as well as being in a region with relatively high decay heat. In addition, prior to use, the performance of the Li-Al in a proton radiation environment would have to be demonstrated to supplement the accumulated experience from the SRS reactors.

In order to remove some of these potential drawbacks, the target was reconfigured into a target-blanket arrangement where the Li-Al was moved well away from the proton beam into separate blanket modules which surround a NSA. The final iteration of this evolution is the SILC target shown in Figures 4, 5a, and 5b. The NSA is based on the original ERAB design with aluminum-clad lead rods (OD=1.1 cm.) in pressure-tubes. The relatively low melting temperature of lead (327 °C) implies a large lead volume to keep the local power density and coolant operating conditions at acceptable levels. Since there is no longer any LiAl mixed with the lead in this design, however, it is neutronically less efficient than the ERAB design, and heavy-water must be used as the coolant to minimize parasitic capture and keep the spectrum hard to enhance leakage into the blankets. The three blanket modules consist of aluminum-clad LiAl plates; the use of plates reduces the cost relative to rods. An additional advantage of this design was that the target (NSA) and blanket modules are configured so as to ease handling, and permit removal of the tritium-producing modules from the target chamber without removing the Neutron-Source Array; this capability makes different operating cycles for the target and blanket feasible, thereby reducing the cost and waste streams.

In the case of the SILC target, the Expander Duct is a significant source of tritium production. The large beam footprint required in order to yield acceptable power densities (and hence operating temperatures) in the lead provides a large leakage path for neutron loss from the system. The Expander Duct approach uses geometry to capture most of the neutrons leaking from the front face of the NSA in LiAl to produce tritium; indeed in this design approximately 50% of the total tritium production is in this region. The alternative would have been to put LiAl in front of the target. While this would significantly reduce the amount of material to be processed, this would raise safety issues and require the qualification effort discussed above.

DESCRIPTION OF HYBRID MODULAR TARGETS

As noted in the Introduction, the current baseline target design for the APT Program is the LANL designed modular He-3 target. (This target is described in detail in [Cappiello, 1996]). The main components of this target are shown in Figures 6-8. The major difference between this target and the SILC targets described above (besides the use of He-3 rather than LiAl for the tritium-producing material) is the use of tungsten for the spallation target material in the NSA, and the presence of lead in the blanket region.

The keys to the success of this design are a number of concepts pioneered by G. Russell of LANL/LANSCE [Russell, 1995], namely: the "split-composite" target concept, and the use of a neutron de-coupler to isolate the NSA and blanket. This approach makes the use of tungsten, with its relatively high capture cross section, feasible by tailoring the geometry and materials of the NSA so as to create and leak the maximum number of neutrons into the tritium-producing blanket, as well as capture them in the decoupler before they can be parasitically captured in the tungsten. Leakage is further enhanced by having a high aspect ratio of 10:1 (height-to-width) for the NSA. This allows the design to take advantage of the high melting temperature of tungsten, and its successful experience as a spallation target.

Two basic variants of the modular target were considered. Since a key objective behind the development of hybrid targets was to take advantage of the "best" features/strengths (including perceived technical risks) of both the SILC and He-3 approaches, the first variant considered a simple replacement of the gaseous He-3 with solid LiAl in the baseline blanket. The second approach was to do a "green field" design for the region external to the NSA, with the only constraints being compatability with the NSA and target chamber, and preservation of the basic hexagonal-module structure for the blanket. Some examples of blanket-module options are shown in Figure 9.

It should be noted that the efforts expended to date on the hybrid concepts have been limited. Therefore, while the tritium production and the acceptability of the thermal environment have been demonstrated, key issues associated with optimization are now being addressed, including waste stream minimization and handling.

NUCLEAR DESIGN

The methodology employed for the nuclear evaluation of the APT target systems includes the LANL-developed LAHET Code System (LCS) [Prael, 1989] and the ORIGEN2 [Croff, 1991] and CINDER90 codes. The LCS consists of LAHET, a modified version of the HETC intranuclear cascade code for evaluations above 20 MeV, and HMCNP, a modified version of the well-known MCNP transport code for calculations from 20 MeV down to thermal energies. Time-dependent calculations to determine the build-up and decay of isotopes produced from spallation and neutron capture, as well as activity and decay power, were performed with a BNL-modified version of the industry-standard ORIGEN2 code or the LANL CINDER90 program.

An extensive validation effort to confirm the ability of these methods to simulate the nuclear performance of the APT target system accurately, and quantify uncertainties, has been an integral part of the APT program. This effort included a series of experiments performed as part of the APT program at BNL and LANL, and included measurements of n/p, T/p, and isotopic production and decay heat vs. energy and target material. Simulations of experiments with the standard design methodology suggest an uncertainty in the predictions in the range of ~10-20% for parameters such as tritium production, and up to a factor of ~10 for the production of individual spallation isotopes (although roughly 50% of the measured vs. calculated isotopes are within a factor of ~2). As the design efforts at both BNL and LANL continue, and new experimental data become available for simple geometries and for more prototypic configurations, the uncertainties should be reduced. Indeed, preliminary interpretation of recent experimental results and calculational simulations suggest that current estimates of uncertainty are too conservative.

COOLING AND HEAT-REMOVAL SYSTEMS

Cooling and heat-removal systems have been designed to provide cooling for the source, blankets, and window of the target system. The detailed designs of these systems were performed by B&W during the preconceptual design phase of the program, with the objective of minimizing any target-specific aspects. The systems contain multiple loops, heat-exchangers, and many redundancies and safety features to provide a high degree of safety and investment protection during normal operations, and off-normal/accident scenarios. Instrumentation to monitor key parameters and provide timely detection of upset conditions, combined with a prompt and highly reliable beam trip at the initiation of accident scenarios, ensure that the cooling system provides adequate protection. A confinement boundary is provided as a further barrier against the release of radioactive species to the environment.

MATERIALS AND FABRICATION

Extensive testing of candidate APT target/blanket materials following proton and neutron irradiation has been performed. While study of the effects on the materials properties continue, no problems have been identified to date. Of particular interest are results from experiments on heated samples of mercury-doped lead which suggest that mercury embrittlement of aluminum cladding should not be a concern at the expected levels of mercury in the Neutron-Source Array for the SILC targets following the present baseline two-year irradiation cycle. In addition, fabrication technologies for Pb rods and lithium-aluminum rods and plates have been identified and evaluated by the Savannah River Technology Center (SRTC) and/or B&W.

TRITIUM EXTRACTION AND WASTE STREAM

Tritium extraction continues to be based on the newest technology recommended by Savannah River. Basically, the lithium-aluminum rods or plates would be cut to appropriate size, placed in crucibles, and heated to drive off the tritium, which is then purified and stored for use; the crucibles containing the residue from the plates/rods are sealed and sent for final disposal.

Waste-stream management should be largely routine with the exception of lead, where one encounters a mixed-waste problem, i.e., the waste issues involve both chemical and radiological restrictions, and thus institutional ambiguities. The current assumption is for disposal of the lead whenever the structural materials (e.g., aluminum cladding and/or pressure tubes) reach the end of their useful lifetimes. However, some reprocessing options are likely available. The bulk of the waste is generated in the tritium extraction process. However, all the waste falls into the low-level, mixed, or hazardous categories; there is no high-level or transuranic waste produced.

SUMMARY

An accelerator-based system, Accelerator Production of Tritium (APT), is now being considered by the DOE as an alternative to a reactor for the production of needed tritium. BNL and LANL have developed a number of target options that have attractive performance, safety, ES&H, and economic benefits. The systems do not use fissile material, and therefore, reactor-related issues such as reactivity transients, nuclear criticality, and disposal of high-level radioactive spent fuel are not concerns in the design and operation. In addition, the inherent rapid-shutdown capability of the accelerator, combined with the low decay-heat rate of the APT target and blanket, greatly diminish many of the traditional safety concerns associated with a reactor facility.

ACKNOWLEDGEMENTS

The following individuals contributed to the successful design effort for the APT/SILC target: C. L. Snead, D. M. Cokinos, C. Czajkowski, E-M Franz, G. A. Greene, P. Kroeger, N. Tutu, R. Youngblood, N. Tsoupas, E. Schmidt, A. Hanson, J. Heiser, B. Boyer, M. Zucker, and G. Bozoki at Brookhaven National Laboratory; R.V. DeMars, S. M. Trepanitis, D. W. Bell, D. Hildreth, D. Mensink, B.E. Bingham, and T. L. Lotz at Babcock & Wilcox; E.L. Albenesius, C.B. Goodlett, P. Grand, and O.A. Towler at Amparo Corporation; and L.K. Heung, and J.H. Owen at the Savannah River Technology Center. Individuals that were instrumental in developing the original BNL APT target designs included J. Powell, H. Ludewig, P. Grande, M. Steinberg, R. Cerbone, and F. Horn. The design effort at LANL for the He-3-based targets, including the current APT baseline modular target approach which includes both He-3 and the LiAl backup options described above is led by M. Cappiello.

REFERENCES

Cappiello, M., et.al.,"Target/Blanket design for the Los Alamos APT System," International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, July 25-29, 1994.

Prael, R.E., and Lichtenstein, H.,"User Guide to LCS: The LAHET Code System", LA-UR-89-3014, Los Alamos National Laboratory (September, 1989).

Croff, A.G.,"ORIGEN2.1-Isotope Generation and Depletion Code, Matrix Exponential Method," CCC-371, Radiation Shielding Information Center (1991).

Cappiello, M., et.al.,"APT Target/Blanket System Design," International Conference on Nuclear Engineering (ICONE-IV), New Orleans, March 10-14, 1996.

Todosow, M., et.al., "SILC Target Design for Accelerator Production of Tritium (APT)," International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, July 25-29, 1994.

Russell, G., "APT 3He Target/Blanket Topical Report, Rev. 1.5", LA-UR-95-2071, Los Alamos National Laboratory (March, 1995).

Table 1
Comparison of SILC and Hybrid Modular Target/Blankets

	ERAB	SILC	Hybrid Modular
• **Neutron Source Array**			
Spallation Material	Lead	Lead	Tungsten
Structural Material	Stainless Steel	Aluminum	304 Stainless Steel
Geometry	Clad Rods	Clad Rods	Bare Rods
Coolant	Light-Water	Heavy-water	Heavy -water
Beam footprint (height/width)		1.4 m X 1.4 m	1.4 m X 0.14 m
• **Blankets**			
Tritium-producing Material	Lithium-Aluminum	Lithium-Aluminum	Lithium-aluminum
Spallation Material	(integrated with Pb rods	None	Lead
Structural Material	within each target tube)	Aluminum-6061	Aluminum-6061
Components		5-Large Modules	Ganged Hex-Modules
Geometry		Clad Plates	Clad Rods
Coolant		Light-water	Light-water
• **Window**	None	Aluminum	Inconel-718
• **Target Cavity Environment**	Vacuum	He @ atmospheric	Rough Vacuum
• **Accelerator Parameters**			
Beam Energy (GeV)	1.6	1.0	1.0
Beam Current (mA)	250	200	100
Beam Power (MW)	400	200	100
• **Tritium Production Goal**	"Goal"	"3/8-Goal"	"3/16-Goal"

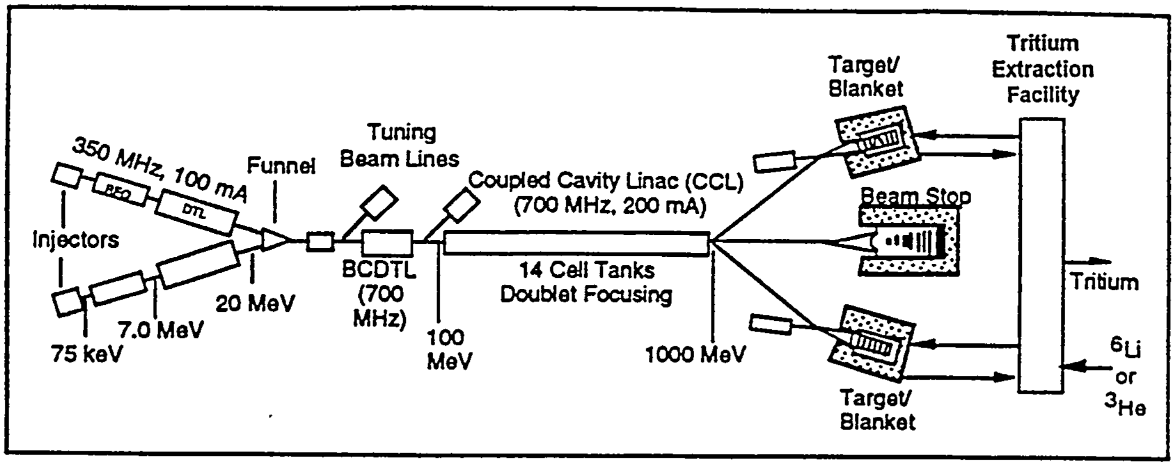

Figure 1. Schematic Diagram of the APT System (not to scale)

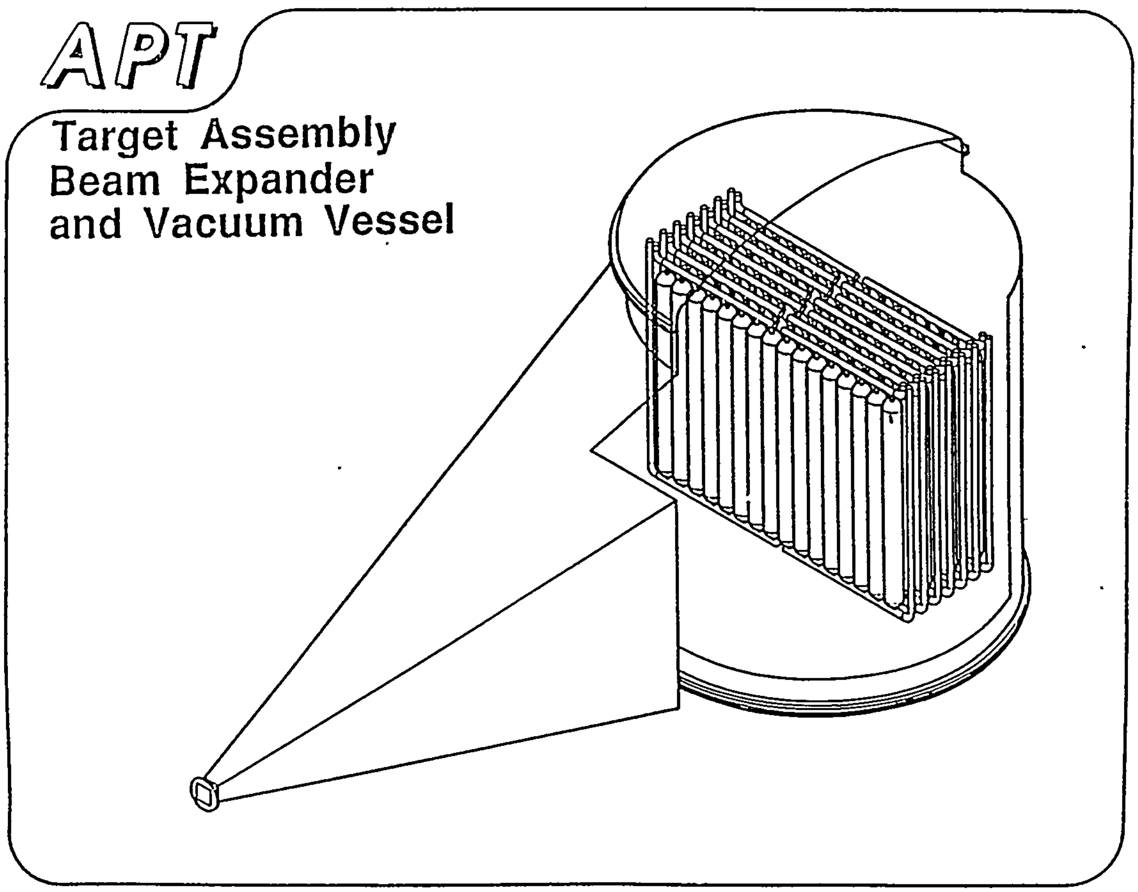

Figure 2. APT ERAB Target

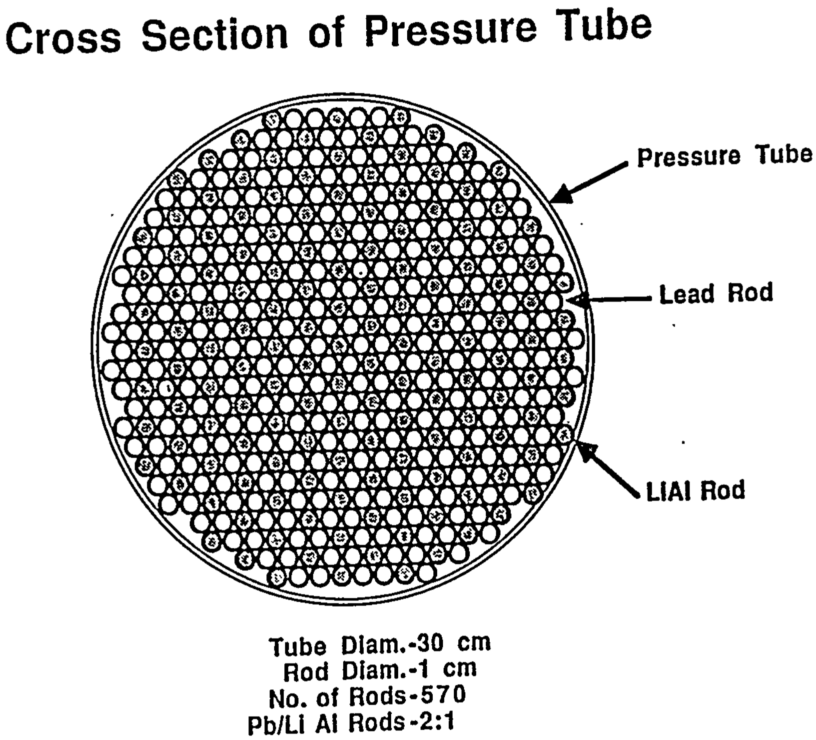

Figure 3. APT ERAB Target

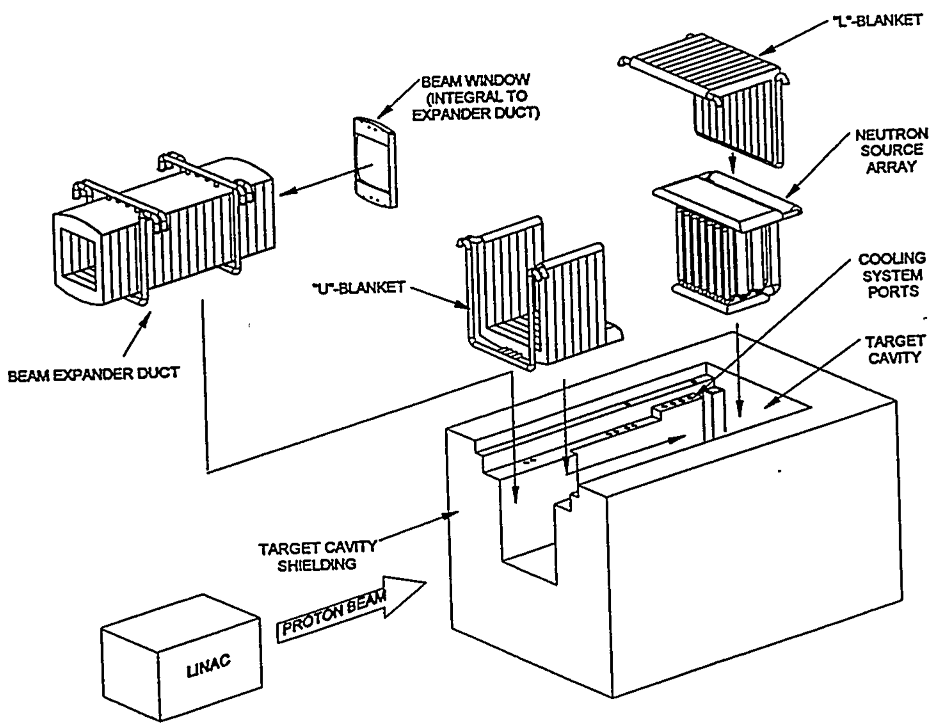

Figure 4. SILC Target Exploded View

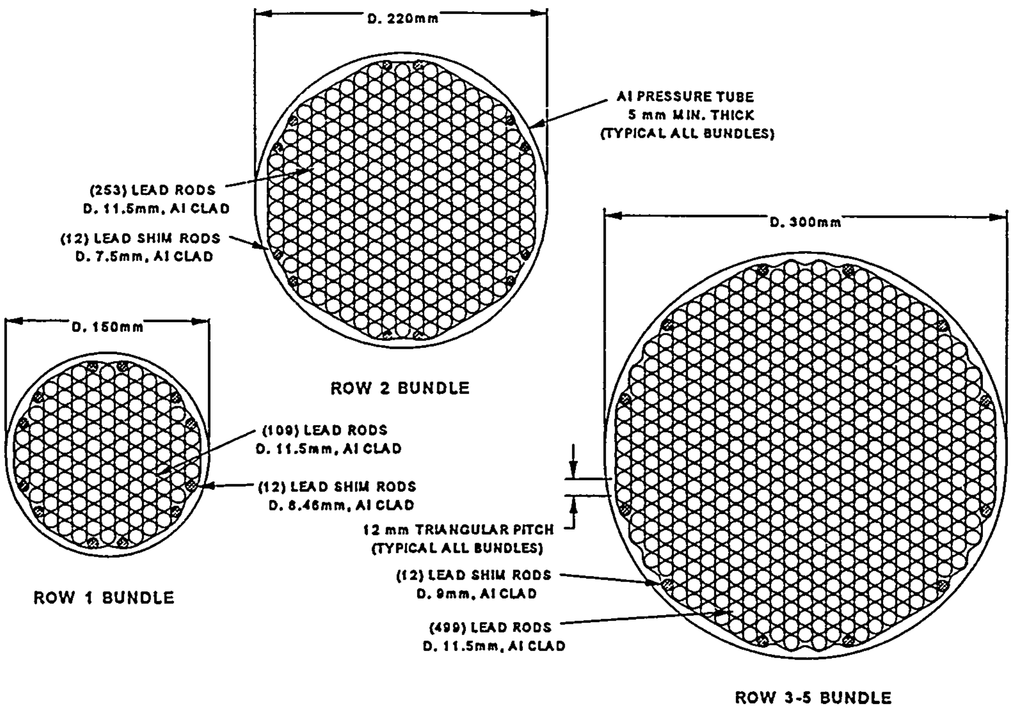

Figure 5a. Source Rod Bundles for APT SILC Target

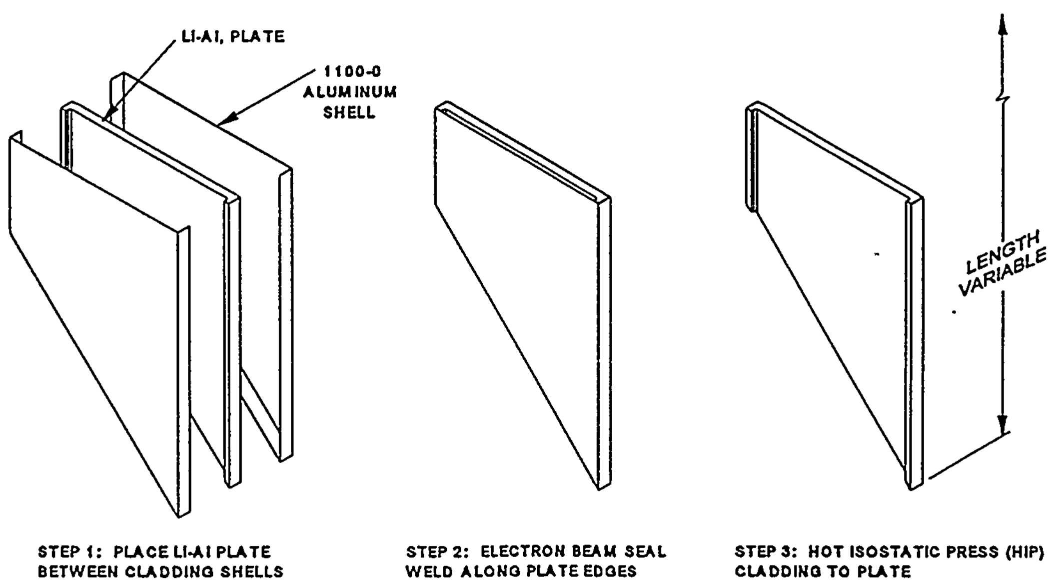

Figure 5b. Li-Al Blanket Element Construction for APT SILC Target

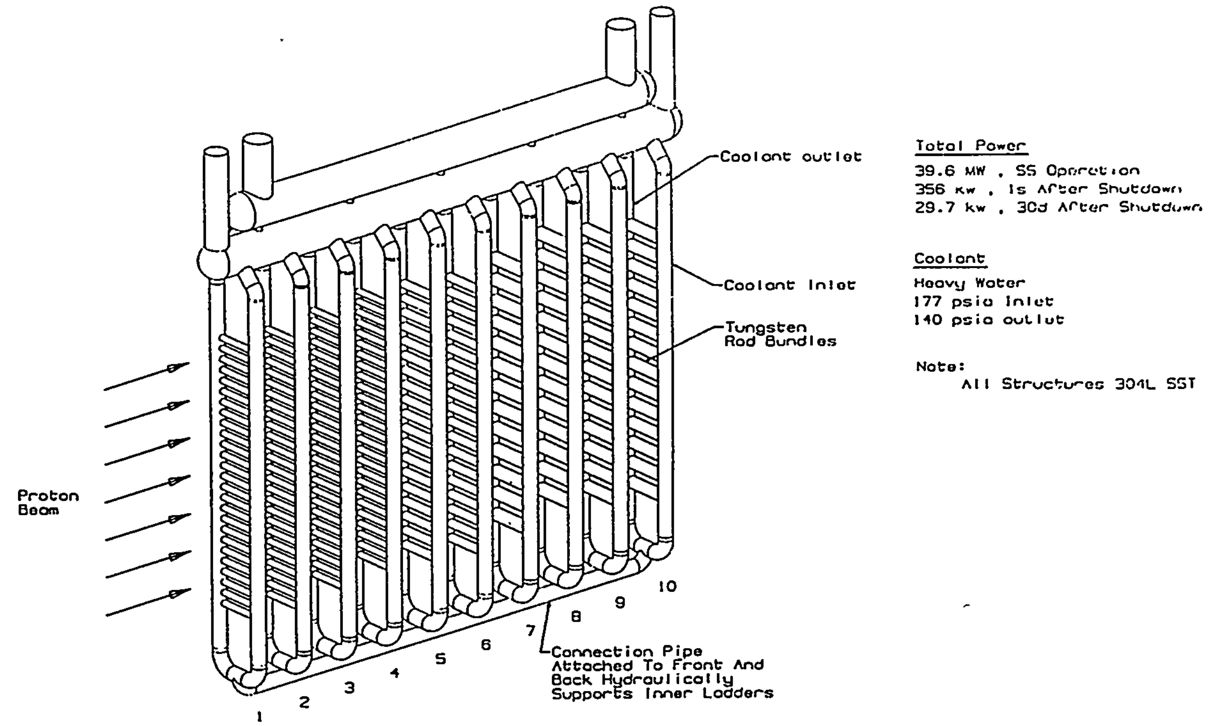

Figure 6. Tungsten Neutron Source Assembly

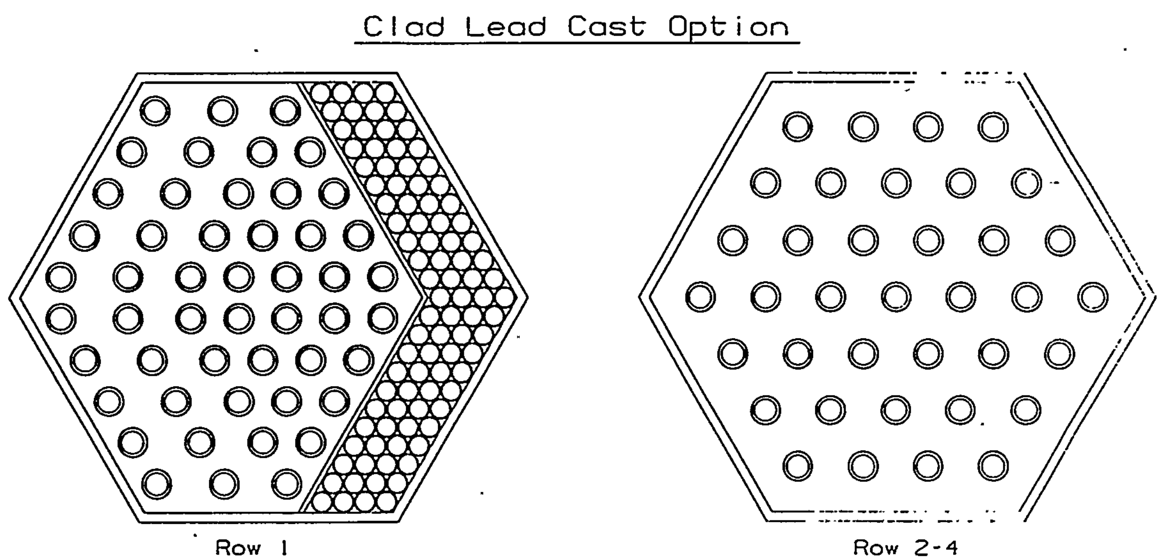

Figure 7. Blanket Module Detail

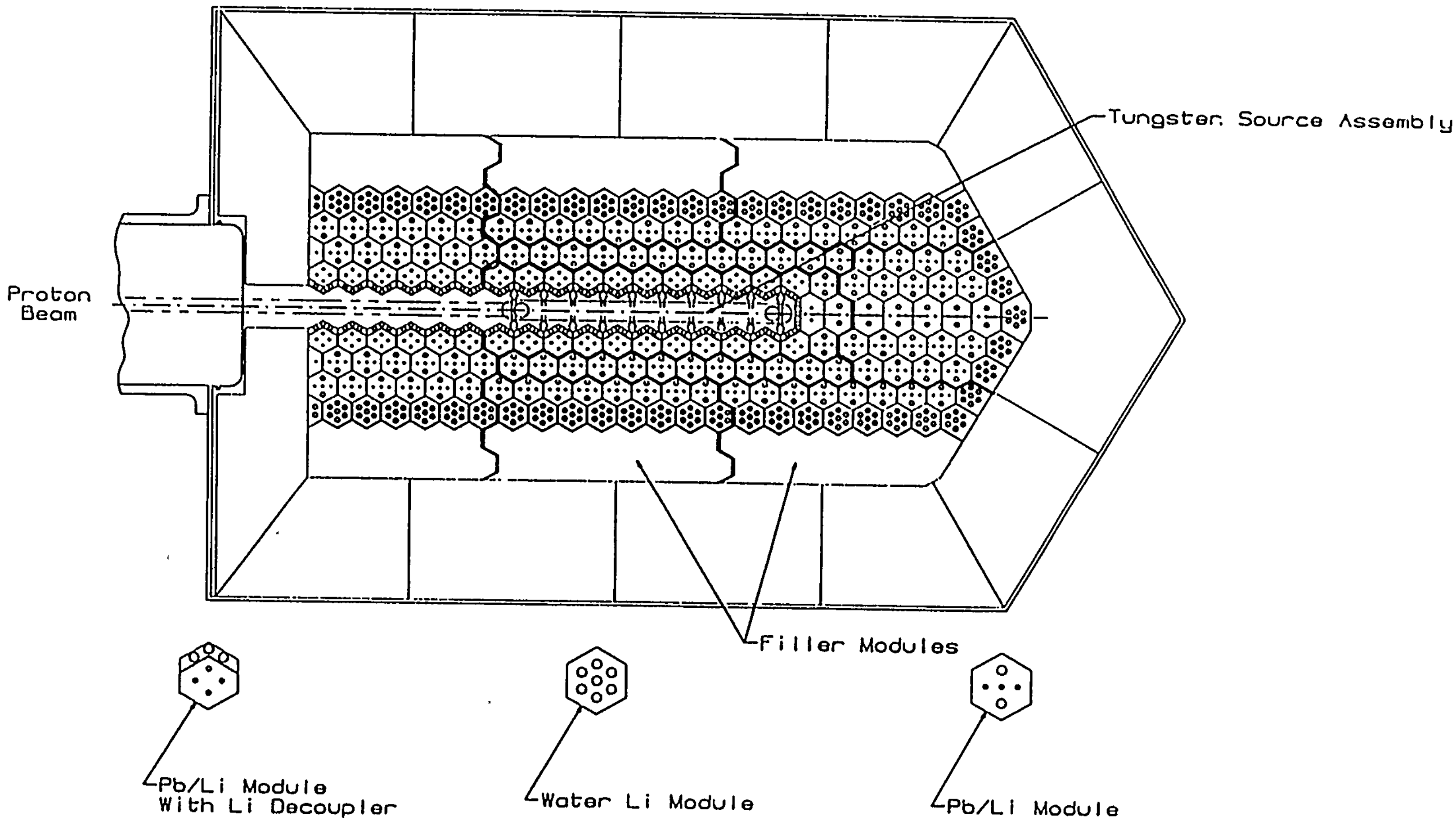

Figure 8. Target/Blanket with the LiAl Blanket

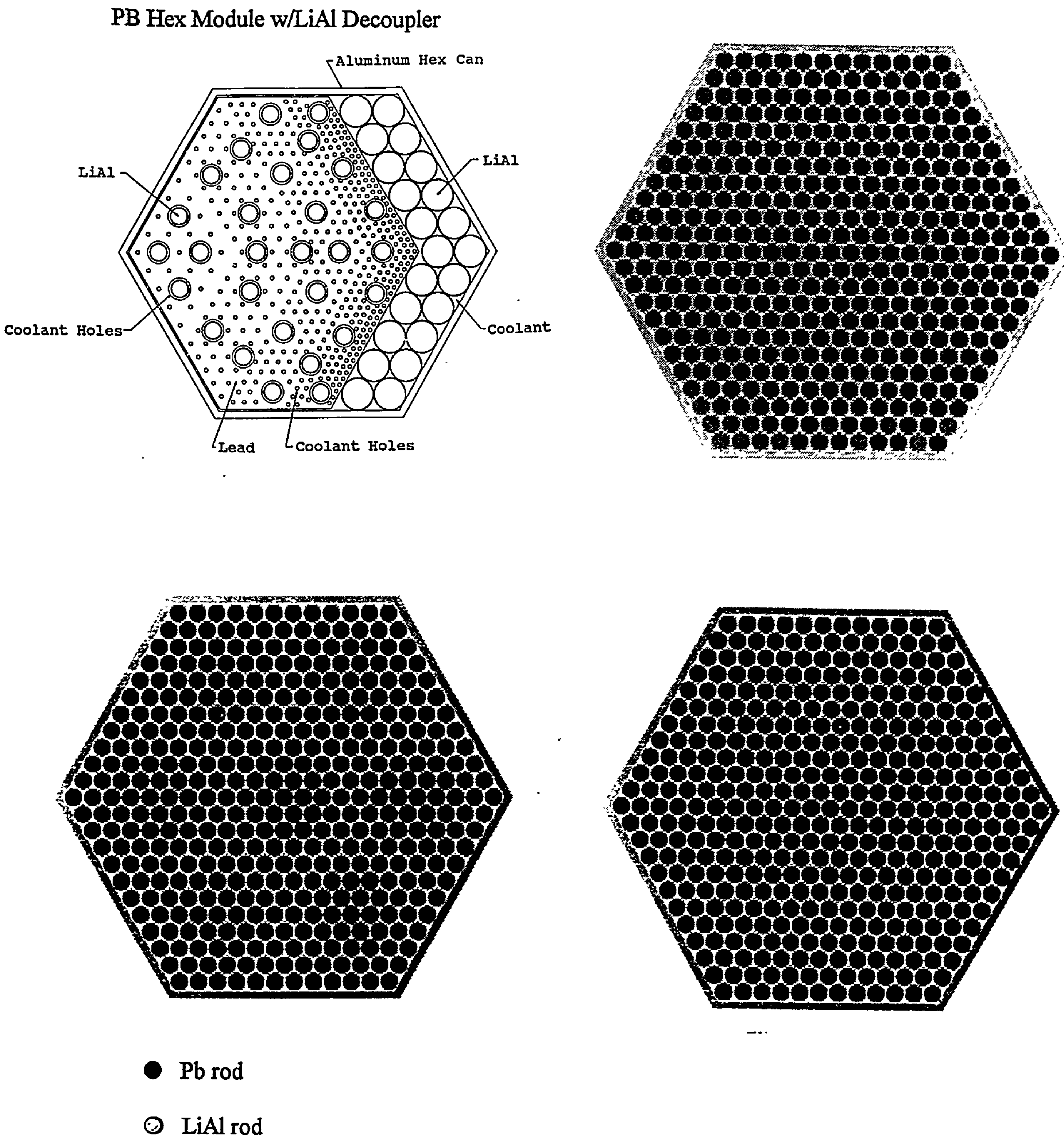

Figure 9. Options for Blanket Modules with LiAl for APT Hybrid Target