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APT Target-Blanket Fabrication Development

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APT TARGET-BLANKET FABRICATION DEVELOPMENT

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ABSTRACT

Concepts for producing tritium in an accelerator were translated into hardware for engineering studies of tritium generation, heat transfer, and effects of proton-neutron flux on materials. Small-scale target-blanket assemblies were fabricated and material samples prepared for these performance tests. Blanket assemblies utilize composite aluminum-lead modules, the two primary materials of the blanket. Several approaches are being investigated to produce large-scale assemblies, developing fabrication and assembly methods for their commercial manufacture.

Small-scale target-blanket assemblies, designed and fabricated at the Savannah River Site, were placed in Los Alamos Neutron Science Center (LANSCE) for irradiation. They were subjected to neutron flux for 9 months during 1996-97. Coincident with this test was the development of production methods for large-scale modules. Increasing module size presented challenges that required new methods to be developed for fabrication and assembly. After development, these methods were demonstrated by fabricating and assembling two production-scale modules.

I. INTRODUCTION

The U.S. Department of Energy (DOE) produced tritium for weapons by irradiating solid aluminum-lithium targets in heavy water reactors. The DOE is evaluating two other means of tritium production to maintain their weapons stockpile in the future. These are: irradiating lithium-aluminide targets in commercial power reactors, and irradiating ^{3}He gas or lithium-aluminum targets in an accelerator. This paper addresses work done to support the accelerator options.

The proposed tritium production accelerator delivers a 1700 MeV proton beam to a series of tungsten targets. Spallation occurs in the tungsten, generating a neutron-proton flux in the vicinity of the targets. Targets are surrounded by a lead and aluminum composite blanket containing an array of ^{3}He gas-filled tubes. As the flux passes through the target-blanket, additional neutrons are produced in the lead and enter the ^{3}He-filled tubes. The desired product is generated and is recovered continuously via the gas manifold.

The practical aspects of fabricating tubes and tube-bundles (called modules) were the focus of this work. Reactor fuel fabrication experience was called upon to provide practical, usable information, immediately applicable to APT plant design and operation.

II. FABRICATING ASSEMBLIES FOR LANSCE TESTS

Two different target-blanket assemblies were fabricated for testing in the LANSCE facility. These were designated Mark I and Mark II, and were prototypic of target-blanket concepts proposed for tritium production with an accelerator. Both contained aluminum-encapsulated lead and targets of ^{3}He gas or solid lithium-aluminum (also contained in aluminum tubes). Schematics of these assemblies are shown in Figure 1.

All aluminum components for the assemblies were made with 6061-T6 alloy except the external coolant piping, which was 3003 aluminum. High purity lead (99.999% pure) was used in the target-blanket assemblies and stainless steel-to-aluminum transitions were fabricated for ^{3}He gas tube closures and coolant pipe crossovers. These unusual joints met a need in this application and are discussed in the section on targets.

A. Mark I Assembly

The Mark I target-blanket assembly consists of a square aluminum housing containing eight square, lead-filled, aluminum tubes arranged around a central aluminum insert. This insert houses the a ^{3}He gas target as shown in Figure 1(a). Coolant channels between the inserts were made by welding small tabs along the outside of the tube walls, then machining them to obtain a 0.030" clearance. Separate coolant loops were provided for the target and the lead blanket inserts. A thermowell was provided in each blanket insert and positioned to give lead centerline temperatures during the test.

Mark I lead inserts were made from 1" square extruded aluminum tubes with 0.065" walls. Each tube was about 6" long with an aluminum cap and thermowell welded onto the bottom end. Molten lead was poured into the top of the insert which was kept hot to promote directional solidification and eliminate shrinkage- pipe. Lead was left 1/8" below the top of the tube to allow for thermal expansion during target-blanket operation. Since the thermal expansion of lead and aluminum are different, a gap of 0.003-0.005" can occur between them. During operation, gap size will be affected by temperature and lead creep. To evaluate the effect of gap size on heat removal, 4 of the Mark I inserts in the assembly were heated to 480°F and the lead inside the aluminum tube compressed using a punch and die jig. A constant stress of 2000 psi was maintained. Ram position measurements were made every 2 minutes until there were no changes in three consecutive readings (indicating the tube was full). This provided inserts with no gap between lead and aluminum and allowed a direct temperature comparison with as-cast inserts during irradiation. Top caps were welded onto the tubes to completely seal the lead inside the individual inserts. Each insert position was specified before module assembly. The assembled module is shown in Figure 2.

B. Mark II Assembly

Two Mark II modules were fabricated for testing in the LANSCE facility. One of the modules contained ^{3}He gas targets and the other contained solid aluminum-lithium targets. The Al- Li targets were made by casting or powder metallurgy. The housing was machined from solid 6061-T6 stock. Four target positions were provided as shown in Figure 1(b). Lead was cast in this housing to 1/8" below the top. A jig was necessary to hold the target housings in position during lead casting. The lead was completely encapsulated when the aluminum top cover was welded.

The Mark II modules were assembled as shown in Figure 3 with the corresponding cooling loops attached in series. Coolant is delivered by a single line, but flow can be proportioned between the targets and the lead blanket by throttling the target coolant outlet. Thermowells were built into the coolant plenums and the lead blanket so coolant temperature could be measured on-line and power input to the module calculated. The Mark II assembly weighs 44 pounds.

C. ^{3}He and Aluminum-Lithium Targets

^{3}He gas targets were made of 6061 bar stock, machined to make a tube, open on one end. Commercially manufactured aluminum-stainless steel transition joints were machined to form the cap and fill-tube for the target. These transitions are produced by inertia welding and were attached to the 6061 tube by gas tungsten arc (GTA) welding. Gas targets were proof tested to 275 psig, leak tested at 125 psig, and loaded with ^{3}He gas at 100 psig. A seal weld was applied at the stainless steel tube by a standard pinch welding procedure. This particular weld was developed for, and used in, DOE's weapons materials program and is highly reliable.

Aluminum-lithium targets contained alloy prepared by two methods. Two targets were made from material that was cast, machined into a billet, and extruded as a cylinder. Two others were machined from a hot-pressed billet of Al-Li (mechanically alloyed powder). All Al-Li target material was covered with aluminum in a swaging operation, then sealed on both ends with aluminum caps.

III. FABRICATING PRODUCTION-SCALE ASSEMBLIES

Some practical modifications were made when increasing the scale of the target-blanket modules. One was the addition of exterior ribs along the tube's length; another was decreasing material in the walls. The ribs were designed to interlock, for easy alignment during assembly, to keep coolant channels open, and to hold lead inserts in place for target tube installation and removal. Other shapes were combined with square tubes to form discrete modules containing a matrix of round neutron target tubes. The proportions of lead, aluminum, and water within the blanket were maintained within narrow boundaries. A typical cross section of one of these modules is shown in Figure 4.

Nonstandard shapes, thin walls, material/heat treatment, and small quantities of tubes did not attract many interested commercial extruders. However, one vendor did provide the necessary tubes. Measurements confirmed that the tubes were within specified tolerances (straight within 0.006" per foot, and sized per design dimensions ±0.005"). Large-scale development included tube closures (caps), the gas plenum, lead inserts, and fabrication and assembly of the module housing. It did not include qualifying welds, so best practices from previous experience were applied.

A. Tube Caps

Tube caps and welds should not restrict coolant flow and must seal the tube from liquid coolant. Caps may be inertia welded onto round tubes (inertia welding has many advantages), but other shapes would be deformed by the process. Autogenous welding (without filler) to fuse 6061 Al is not recommended for this application because it is typified by cracks and internal porosity. GTA welding with 4043 filler is the method recommended to produce good physical strength and preclude cracks. The weld surface is generally smooth and free of pits, although slight internal porosity may exist. To keep internal porosity from being exposed (minimizing corrosion sites) a cap and weld combination was sought that would require no rework (such as grinding) to bring the weld flush with the tube.

Three cap designs were fabricated and welded onto round tube sections with 0.035" wall. These designs were certainly not all inclusive but gave evidence of what approach would meet sealing requirements. One cap/weld combination was significantly easier to produce and gave the best dimensional results. It's average diameter was 0.015" larger than the tube. Features that made it easier to weld were a 0.035" rim and a groove adjacent to the rim which had the effect of balancing heat between cap and tube during welding. Samples were welded on four inch lengths of tubing, held in a motorized welding turntable.

The preferred design was translated into the various tube shapes, machined, cleaned, and welded onto the production-scale tubes. Increasing the tube length from 6 inches to 10 feet, and from round to square (and approximately square) kept the tube from being vertical during welding, and made the use of a turntable difficult. As in the Mark I module, one cap was welded on before filling the tube, and one afterward. A gap of 3/8" was left between the lead slugs and the end of the tube. This was space for the second cap (1/8" thick) and thermal expansion. Lead was not melted during the final cap welding since the cap does not touch the lead, the weld is small, and the tube material carried away heat.

B. ^{3}He Gas Plenum

Prototype target-blanket gas plenums were machined and evaluated for ease of fabrication, alignment, and gas tightness. Cap-weld samples were used to complete the assemblies, gauging fabricability and the effect of welding on shape and alignment. The plenums were measured with a coordinate measuring machine before and after welding.

Plenum material was 6061-T6 aluminum, GTA welded with 4043 aluminum filler. Plenums and tubes were cleaned before welding by treating in heated caustic solution, water rinsing, immersing in nitric acid, water rinsing, and oven drying. Some welds proved difficult due to deep countersinks and pin alignments. Hand work was sometimes required to fit pieces together, but the results were acceptable. Flatness was not degraded and tubes were parallel, varying from perpendicular (to the lower plenum surface) by little more than 1 minute of angle (0.040" in 10 feet). Finished plenums were bubble tested at 100 psi under water; no leaks were found.

Incremental changes were made to gas plenum configuration, eliminating some welds and balancing heat distribution during welding. A typical plenum is shown in Figure 5. One plenum concept, not fabricated yet, may require only machine welds. It would eliminate crevice corrosion sites, reduce the number of welds, and add strength. Aluminum to stainless steel transition joints were not installed on these plenums since they have already been proven in operation.

C. Lead Insert Fabrication

Mark I and Mark II modules were filled by casting molten lead into heated containers. Scaling this operation to production-sized tubes added obstacles due to the volume of lead, length of the tubes, their wall thickness, and material properties. Hydrostatic pressure could be a substantial factor in the success or failure of this method, especially when combined with temperature's effects on aluminum tensile strength. Time-temperature-strength information on 6061-T6 indicates that more than 50% of the tensile strength is lost after one hour at 260°C (lead melts at 327.5°C). This is the result of overaging the alloy. A computer model of tube stress from internal hydrostatic pressure indicated no margin of safety in the proposed casting operation.

Two basic approaches to filling target-blanket tubes with lead were cold methods and hot methods. Cold methods include lead shot, wool, or slugs and hot methods include varieties of casting. The aluminum tubes used for fill development were 1" square with 2 ribs per side. All were 10' long except induction-cast tubes which were 3' long. Square geometry is representative of various target-blanket tube shapes although not identical.

Among the cold filling methods, lead shot was discounted because of its low filling capacity (52% of available volume with uniform shot). Another material available was lead wool, which was compacted into a small cubic form producing a finished product which closely approached lead's theoretical density. On a larger scale this could not be duplicated without deforming the aluminum tube. Tubes could be constrained as the small sample was, but the time and effort required to load lead wool and compact it make the method impractical.

Filling tubes with lead slugs was plausible and volume fractions would easily exceed both lead shot and wool. The uncertainty with this method was the clearance needed to push slugs through a tube. Aluminum tube tolerances (±0.005") defined the practical limits of this method, forcing the largest slug to be 0.005" undersize. Lead slugs, sized in 0.005" increments, helped determine clearances and lengths that work. With this restriction, successively smaller slugs filled 98%, 97.2%, and 96.2% of the aluminum tube volume.

Tubes were laid on a horizontal work surface and filled. Once inserted, slugs were pressed into place with a long rod. A tube can be filled easily in 10 minutes if all the necessary supplies are available. The largest slugs could stick inside a tube if it were dirty, dented, or bent. Go/no-go gauges for each tube shape were made to assure satisfactory dimensions before pressing slugs. Pressing short slugs into more than a few tubes becomes tedious, but can be automated with reasonable expense and effort.

Although casting was the fabrication method used for Mark I lead inserts and the Mark II assembly, it presents additional challenges with increased length and decreased wall thickness. Hydrostatic pressure generated by a 10' column of molten lead is equal to a 114' column of water. Bending stress on tube corners under this pressure was estimated at 16,000 psi (which is within the capabilities of the 6061-T6 at room temperature) but elevated temperature has a permanent weakening effect on the material, decreasing its tensile strength. Although the effect is small with brief exposures and low temperatures, it can be significant at the melting point of lead. Aluminum also loses strength (even in an annealed state) with increasing temperature. This combination of temperature factors and the internal pressure caused uncertainty about casting without taking measures to prevent distortion. Casting methods included pouring, melting slugs in-situ, and zone-melting. Tube orientation was varied and some tubes were constrained. Best efforts produced tubes that were within 0.001" of their original dimensions and 98 to 99% full of lead.

Aluminum tube samples from each casting method were tested for tensile strength. Samples that had been heated, regardless of method, lost an average of two-thirds of their original tensile strength. No samples were taken from grossly deformed sections of the tubes, so average strength loss may be somewhat greater.

The significant loss of strength was considered unacceptable. Although refinement in method could reduce the time aluminum tubes are exposed to elevated temperatures, tensile properties would still be degraded to some extent. Some undesirable characteristics of casting operations are: they are slow, they generally require additional safety precautions (especially with molten lead), they require special cooling regimes (to minimize strength loss in the aluminum tubes), and a void is left at the top surface (ideally) which requires an additional operation to fill.

Pressing extruded slugs into aluminum tubes was preferred over all other methods because material properties were not altered in any way, the volume filled rivaled the best method (within 1%), extraordinary worker protection was not necessary, and it is simpler. Pressing requires less energy and is faster. A tube can usually be filled with slugs in 10 minutes. The practical method used to keep from sticking slugs in tubes was a go/no-go gauge pushed the length of the tube before the first slug is inserted. Because of the repetitive nature of pushing slugs into a tube, automating the process is necessary.

IV. ASSEMBLING LARGE SCALE MODULES

Module assembly began with a "dry run" using empty low-flux target-tubes plus housing parts. Two sides of the housing were fabricated horizontally in V-blocks before tubes were loaded. The housing was made of 1/4" aluminum sheets welded together along adjacent sides. Empty target tubes were "cradled" in the housing and loaded from the sides rather than the end. Some effort was required to engage the interlocking ribs while loading tubes. Spacers were used in place of the ^{3}He tubes to complete the module. With all tubes in place, the remaining module pieces were clamped in place and welded to the V formed by the first two sides. With the housing together, tube mobility was nil. Tubes in intimate contact will tend to distribute heat evenly. This assembly method eliminated clearance and alignment requirements that were part of earlier target-blanket concepts which lowered bundles into module shells. Figure 6 shows a completed (empty) target-blanket module.

The same method was demonstrated on a high-flux and low-flux module with finished lead inserts. Inserts were stacked in the housings, one-by-one, from the side. Horizontal loading is preferred because tubes won't tip, lean, or bow when placed in the housing, they aren't required to slide on one-another (galling is common with aluminum), and a high bay shop (≥30') isn't necessary. Overhead handling equipment could be used to move lead inserts and finished modules, but is not needed. The inserts (≤50 lb.) were placed manually by one or two workers. Heavier parts require other methods.

Interlocking ribs on the lead inserts fit together nicely and were kept in place by the weight of the lead. A lift plate was welded into the bottom of the housing and lifting rods attached. A strongback frame, crate, or pallet is necessary for handling and transporting modules. These devices keep modules from flexing during handling and shipping.

V. CONCLUSIONS:

Irradiating Al-Li or ^{3}He in an accelerator to produce tritium was practically demonstrated using small assemblies prototypic of the APT target-blanket concept. These in-beam modules also exposed material and weld samples for analysis. The results of these analyses should supply a basis for many material and fabrication choices for the APT and other projects.

The modular target-blanket concept used in the Mark I assembly was scaled up to production-size units. Fabrication techniques adapted from the small assembly, or developed specifically for the large modules, were used to produce two production-scale modules . Modular design allows container size to be changed without changing tooling and allows components to be produced at one point, easily handled, and shipped to another where they can be assembled into larger units appropriate to the handling equipment available.

Ease of fabrication and the effects of fabrication methods on material properties were documented and support the recommendation of cold filling methods for target-blanket lead inserts. Tube caps, plenum connections, and module housings must be welded to give the gas and liquid tightness and strength desired. Component designs which allow machine (friction) welds can improve weld consistency and reliability.

Providing finished production-scale target-blanket modules requires piece-by-piece assembly. Containers must be built around the lead inserts for a solid structure with no play. Module assembly requires some care to prevent galling and maintain proper alignment for the ^{3}He tube array, which will be inserted later. This fabrication and assembly experience can be applied to APT target-blanket preparation as the design evolves toward final configuration.

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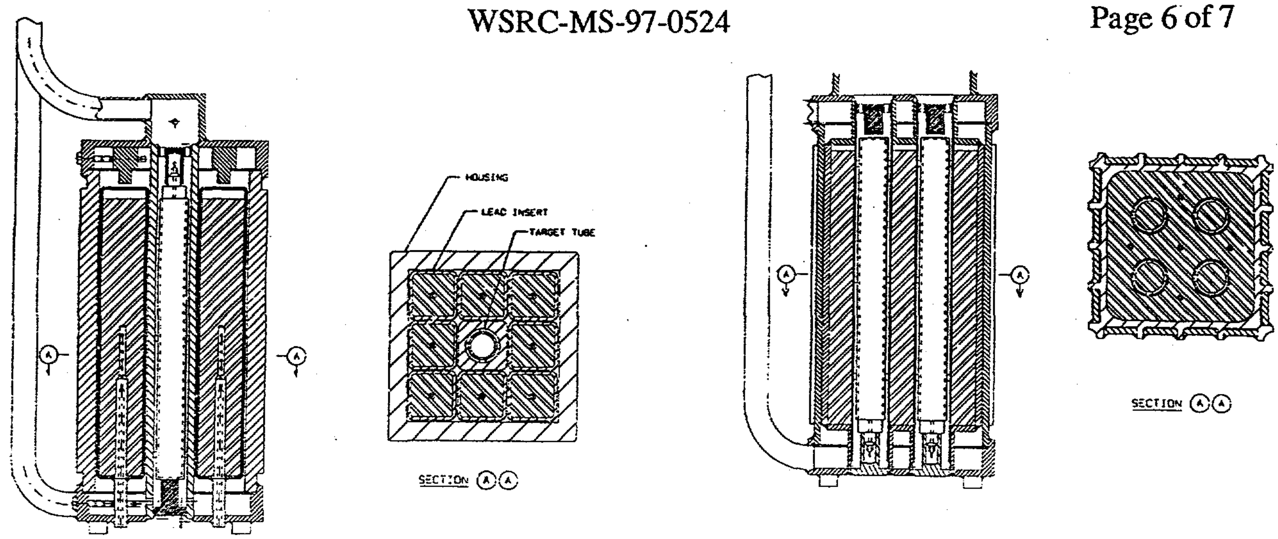

1a. Mark I Module

1b. Mark II Module

Figure 1. Schematic of Mark I and Mark II Modules

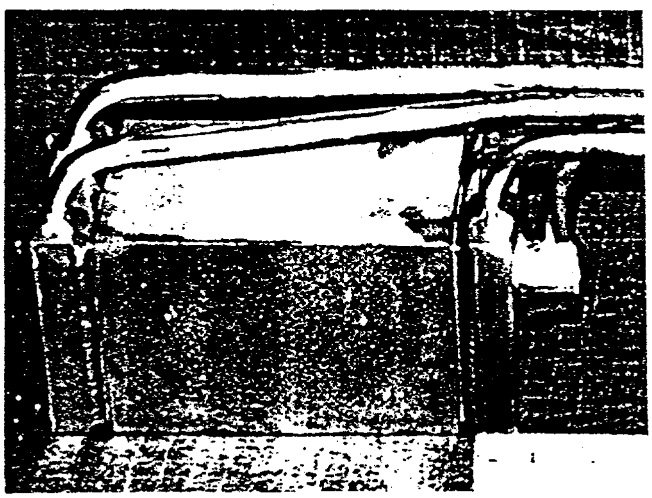

Figure 2. Mark I Target-Blanket Assembly

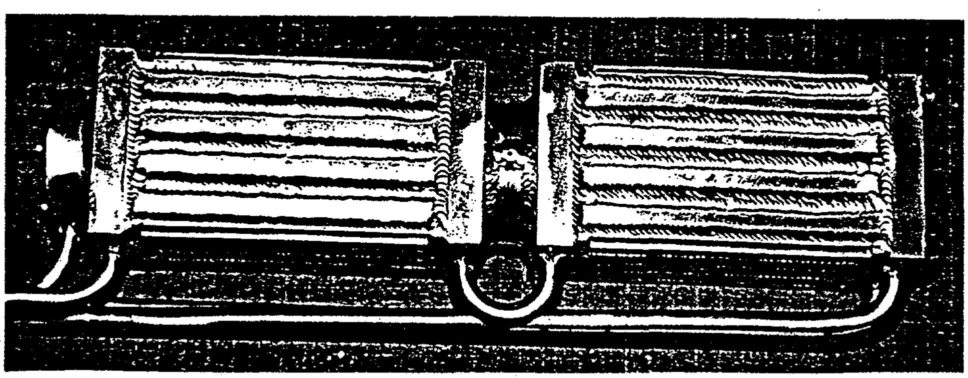

Figure 3. Mark II Target-Blanket Assembly

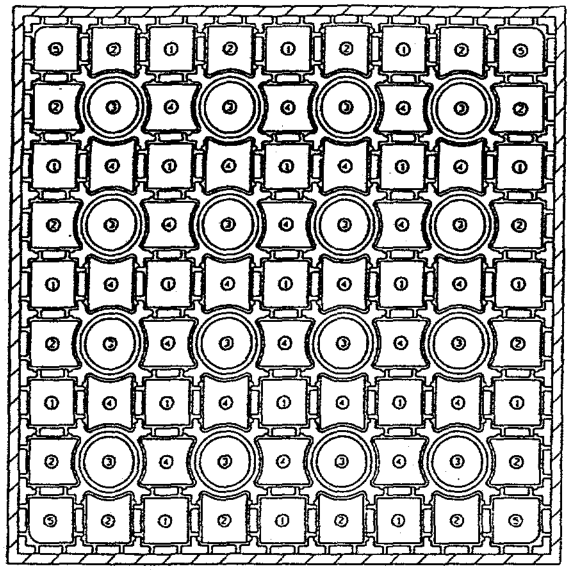

Figure 4. Cross-Section of a Production-Scale Target-Blanket Module

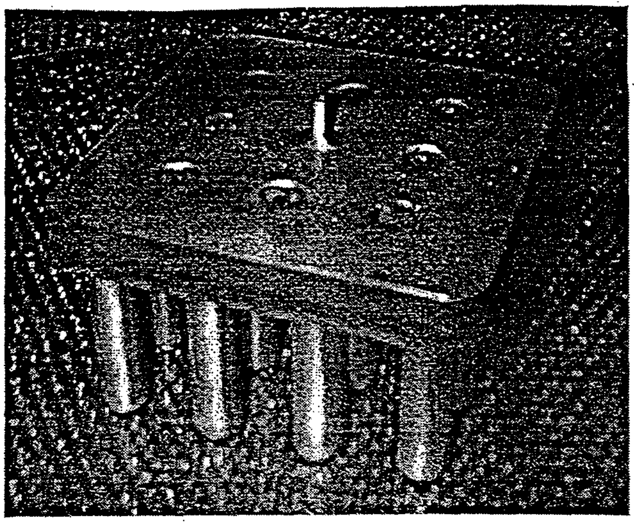

Figure 5. He3 Gas Plenum

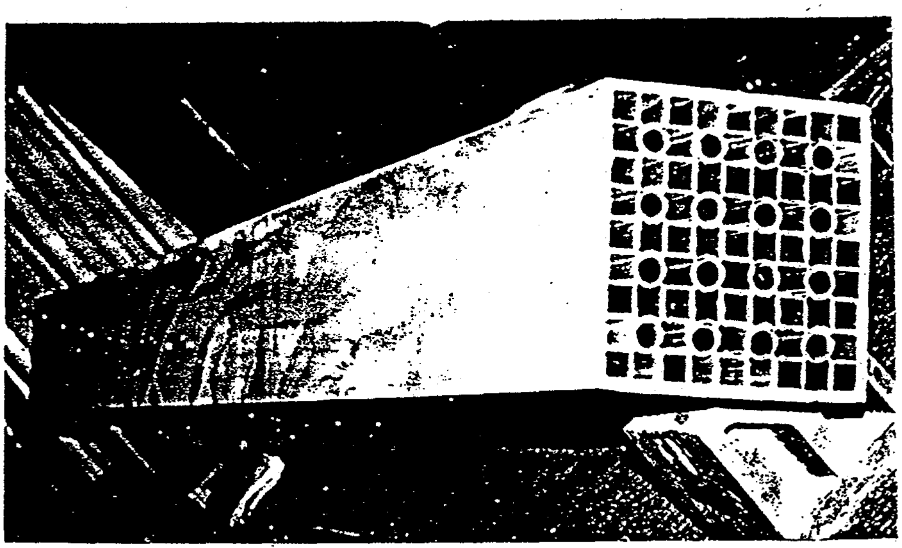

Figure 6. Production-Scale Target-Blanket Module