Conceptual Designs for a Spallation Neutron Target Constructed of a Helium-Cooled, Packed Bed of Tungsten Particles

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Abstract - *This paper presents the results of a preliminary investigation of a spallation target constructed of a helium-cooled, packed bed of tungsten particles. Two packed bed target designs for accelerator transmutation of waste are presented and compared: 1) A right circular cylinder, and 2) A conical target geometry. The target designs are based on requirements set by preliminary blanket designs. These requirements include: axisymmetric target geometry consistent with an axisymmetric blanket; 30 mA/1 GeV protons at the target window, uniformly distributed over a 36 cm diameter beam spot (30 μA/cm^2); spallation neutron to incident proton ratio (n/p) of 25 or better; and uniform axial distribution of spallation neutrons. Conceptual designs are presented, including scoping analysis of thermal/hydraulic performance and neutronic performance analysis (neutrons per proton and flux maps). The conical target outperforms the cylindrical target with improved n/p and improved axial distribution of neutrons.*

I. INTRODUCTION

The Accelerator Transmutation of Waste (ATW) concept involves using a high-power accelerator to produce neutrons to drive a sub-critical multiplying assembly (blanket). Nuclear waste is transmuted to shorter-lived and less dangerous isotopes following neutron exposure in the blanket. The target couples the high-intensity proton beam to the sub-critical assembly and is a crucial part of the system. The target must convert the proton beam to neutrons (via spallation reactions) with good efficiency (n/p>>1) and produce a neutron spectrum that couples well to the blanket. The target is in an intense broad-spectrum radiation field at relatively high temperature. Heat produced by the incident proton beam must be removed at a rate sufficient to maintain the integrity of the target. The target environment is stressful on the target materials.

This report contains the results of a preliminary investigation of two, helium-cooled tungsten spallation target concepts. Results are presented for each concept including scoping analysis of thermal/hydraulic performance and neutronic performance (neutrons per proton and flux maps).

The target of an ATW system must couple effectively with the transmuter or blanket side of the system for efficient use of the neutrons. Thus, the blanket optimization establishes the requirements and constraints on the target. These requirements are stipulated in this paper, but it must be understood that these are preliminary. They are, in fact, a distillation of the requirements posed by a number of different blanket design studies proceeding in parallel with each other and with this target design study. In short, it is expected that the requirements placed upon the target will change considerably over the next year or two. Consequently, the level of detail in designing and optimizing target concepts is limited. Rather, basic geometric configurations and scoping analyses are presented, which can be refined as requirements become better defined.

II. BASIC REQUIREMENTS

The ATW facility has at its foundation a target and blanket system that is driven by a proton accelerator. The subcritical blanket surrounding the target contains the nuclear waste that is

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transmuted by neutron absorption. The neutrons are generated by direct impingement of the high-energy proton beam onto the target material in a process called spallation.

The requirements for the ATW target follow from the parameters of the accelerator and the blanket. The ATW Roadmap [1] guidelines are the basis for previous ATW blanket designs summarized below:

1) Los Alamos National Lab (LANL) analysis of an LBE-cooled blanket: The target is 50 cm in diameter and 55 cm long. If the current is adjusted to maintain constant power (840 MW), it must increase from 19 mA at beginning of cycle (BOC) to 67 mA at end of cycle (EOC).
2) Argonne National Lab (ANL) analysis of LBE-cooled blanket: The target is 16 cm in diameter with a buffer region (moderator) out to 80 cm in diameter. It is assumed that this 80 cm is LBE.
3) ANL analysis of Na-cooled blanket: The target is 16 cm in diameter with a buffer region out to 80 cm diameter. It is assumed that this 80 cm is LBE.
4) LANL analysis of He-cooled blanket The General Atomics reactor design geometry is used, which allows for a hexagonal target 14.2” (40 cm) across the flats.
5) ANL analysis of He-cooled blanket: The General Atomics reactor design geometry is used, which allows for a hexagonal target 14.2” (40 cm) across the flats. The blanket is 8 m in length with axial neutron distribution as uniform as possible.

The ATW target design requirements used in this paper were based on these five blanket designs.

IIa. Accelerator

The ATW Roadmap [1] sets the following specifications for the accelerator. The accelerator portion of the facility shall be composed of two proton linear accelerators. Each provides beam to four targets that are sized at 840 MWth each. Each linac produces a 45 mA proton beam at 1 GeV, delivering 45 MW of beam power to the four-burner array. Thus, each target receives 11.25 mA. Fig. 1 shows a schematic of the beam distribution. The energy deposition fraction is assumed to be 0.5 so that at this beam power, each target receives about 5.6 MW of thermal energy.

For this preliminary ATW target design study, however, the proton beam power at end-of-cycle (EOC) for a typical burner is assumed to be 30 MW (30mA at 1GeV). The resulting beam distribution is assumed uniform with a current density of 0.03 mA/cm^2. This beam current assumption results in a beam cross sectional area of 1000 cm^2. With an energy deposition factor of 0.5, the resulting thermal energy deposited in the target is 15 MW.

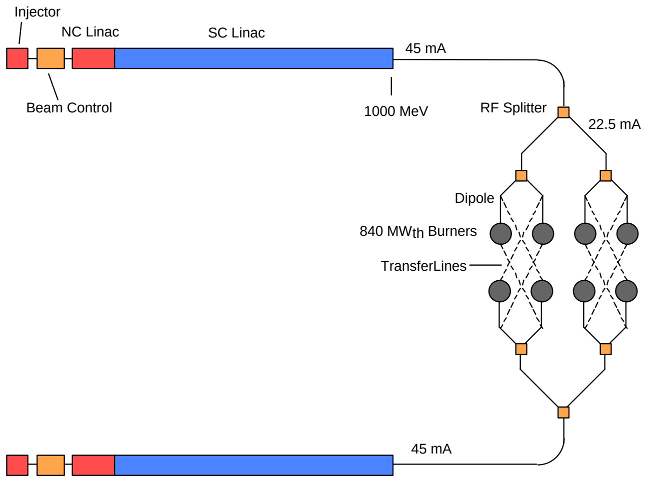


Fig. 1. The accelerator and burner architecture for the reference ATW plant (from the ATW Roadmap [1]).

IIb. Neutronics

The target design has to incorporate the proton stopping length for the materials used in the design. The neutron absorption has to be minimized so that more neutrons can penetrate through to the blanket.

It is desirable that the neutron distribution be axisymmetric and as uniform as possible over the length of the core to simplify core management issues. The neutron spectrum should be appropriate to efficiently initiate a fission chain and drive a sub-critical assembly. In order to minimize beam power requirements, the target needs to have high neutron production efficiency. One of the blanket designs mentioned previously is based on 25 neutrons per proton (n/p). The ATW Roadmap [1] specifies a neutron production efficiency of 27 n/p. For this study, therefore, the target design requirement is at least 25 n/p.

IIc. Geometry

Based on a circular cross-section beam with an area of 1000 cm^2, a target diameter of approximately 36 cm is required. The target’s length perpendicular to the beam axis is based on stopping length of tungsten and target configuration. The target geometry has to provide for good coolant flow to remove the deposited thermal energy. Also, the target should be designed to withstand thermal and mechanical stresses. The beam may be vertical or horizontal but it is assumed that the target is aligned axially with the beam. In addition, this target must be replaceable with remote handling equipment.

IId. Operational Life

The desired operational life of the target has not been determined. At present, the ATW target should be designed to have the longest possible operational life. By operational life we mean the length of time the target can work in the beam safely and effectively. In order to extend the target service life, its design should utilize reliable components and materials. All instrumentation must be able to operate in beam for the projected life of the target. Backup instrumentation, pumps, and valves may be necessary. The structural design has to withstand thermal stress and thermal cycling. The geometry has to be optimized to provide sufficient coolant flow to remove the deposited heat.

Materials should maintain their integrity for the operational life of the target. All materials must perform under the proton and neutron radiation that will be present in the target. Typically, one would place the material radiation damage limit at 40-50 dpa, never to exceed 100 dpa. Based on fission irradiation experience and estimated radiation damage rates for different target materials, one can say that the lifetime of the target structure, particularly the window and the solid target material, is limited to less than 2 years. However, the spallation process produces hydrogen and helium at much higher rates than in the fission environment (up to 100 times faster). The exact response of materials to such radiation damage has just begun to be studied.

It should be noted that the side containment structures are subject to much less proton damage compared to the window (or other frontal parts in the beam path). If target windows are separately replaceable, the target container may have a longer lifetime. Most other parts of the target outside of the active volume (pump, HX etc.) have corrosion and contamination limited lifetimes.

IIe. Safety

Spallation products have to be contained during and after operation. The target coolant also has to be contained. The target materials have to maintain their integrity for the life of the target. Adequate heat removal must be provided in the target and the auxiliary systems. If necessary, a decay heat removal system should be included in the target design. Adequate temperature measurement must be provided at critical points in the target system. Reliable monitoring of the coolant and cover gas conditions must be made, including pressure, contents, temperature, and flow speed. Backup equipment may be necessary to ensure reliable operation of the target. As mentioned earlier, remote handling of the target and its auxiliary systems is necessary.

III. HELIUM-COOLED TUNGSTEN TARGETS

A packed bed of tungsten spheres cooled by helium gas is an attractive concept for an ATW spallation target. Tungsten is a good producer of neutrons and there is extensive experience in using it as a neutron source. Small tungsten spheres will be relatively easy to cool compared with larger tungsten plates or tubes. Helium is neutronically transparent and is compatible with a wide range of materials in nuclear applications. It does not react chemically with other materials. Helium remains in a single-phase state under all operating conditions. In addition, helium has been used extensively as a coolant in nuclear reactors for over 30 years. Auxiliary technologies associated with the use of helium as a coolant such as heat exchange, filtration, and pumping are essentially “off-the-shelf.”

There are drawbacks to using a helium-cooled, packed bed of tungsten spheres for an ATW target. Tungsten has a relatively high neutron capture cross section therefore the target geometry must accommodate neutron absorption. A target geometry that accommodates neutron leakage may be difficult to cool without multiple flow paths of helium. In an accelerator-driven system, the tungsten spheres will undergo numerous thermal cycles that could lead to fracture due to fatigue. This thermal fatigue, along with other factors, may require cladding of the tungsten particles. It may be difficult to maintain the integrity of the cladding in the proton beam environment due to the buildup of tungsten spallation products within.

The helium cooling system will have to be operated under relatively high pressure. High pressure in the target will greatly increase the complexity of design and cooling of the beam entry window. This high pressure also presents the potential of catastrophic depressurization accidents. Loss of coolant in these types of accidents could lead to release of airborne radioactive contamination and ingress of oxygen into the target resulting in burning of the tungsten. The loss of coolant scenario will probably require an active decay heat removal system such as the injection of helium. Tritium and hydrogen will be generated as spallation products within the helium coolant and will have to be removed. If gas temperatures are high enough, tritium may diffuse out of the helium containment vessels into cooling water or the outside environment.

IIIa. Target Geometries

The simplest geometry of a packed particle bed target is cylindrical. A drawing of the cylindrical target option is shown in Fig. 2. This design configuration is compatible with an axisymmetric blanket. The target container cross-sectional area is 1000 cm^2. This area results from the assumption of a uniform beam profile at 30 $\mu A/cm^2$. The beam entry window is water-cooled. The target chamber contains a randomly packed bed of tungsten particles. These particles are assumed to have a nominal diameter of 15 mm with a sphericity of 0.7. This sphericity results in a bed void fraction of approximately 0.49.

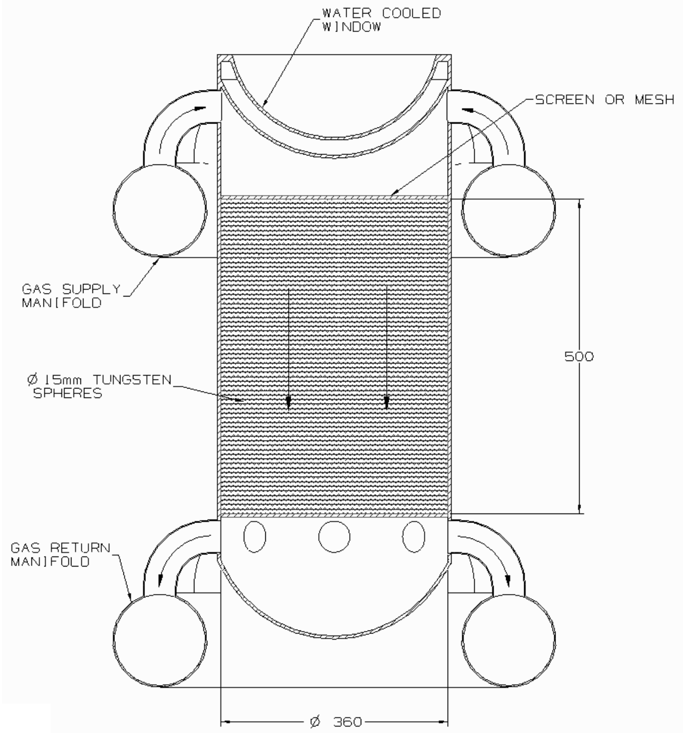


Fig.2. Drawing of Packed Bed Cylindrical Target Concept (dimensions in mm, beam entry from top).

It is not clear what level of sphericity is required in the final design. A lower sphericity leads to a reduction in packing factor and results in a higher void fraction in the packed bed. A larger void fraction will, in turn, increase the overall target dimensions. Approximately 32 cm of solid tungsten is required to stop a 1000 MeV proton beam. Based on a void fraction of 0.5, therefore, the target depth in the direction of the beam is approximately 40 to 45 cm.

The number of neutrons generated per incoming proton (n/p) is 22 for this target. This is only the first pass on a cylindrical target design and this neutron production efficiency is a good starting point. No attempt has been made to optimize the design to increase the neutron efficiency or to optimize the target-coolant thermal/hydraulics.

The flow of helium is assumed to be parallel to the beam. As particle size in a packed bed is reduced, heat transfer improves but pressure drop increases. Therefore, the thermal-hydraulic problem is one of balancing these two competing trends. Calculations were performed for a range of particle diameters from 1 to 40 mm in the vertical entry target configuration. Packed bed heat transfer and pressure drop correlations were obtained from by Kunii & Levenspiel [2]. For these thermal-hydraulic calculations, temperature-dependent helium properties were used. For tungsten, however, approximate, average, material properties were used in this preliminary analysis and design.

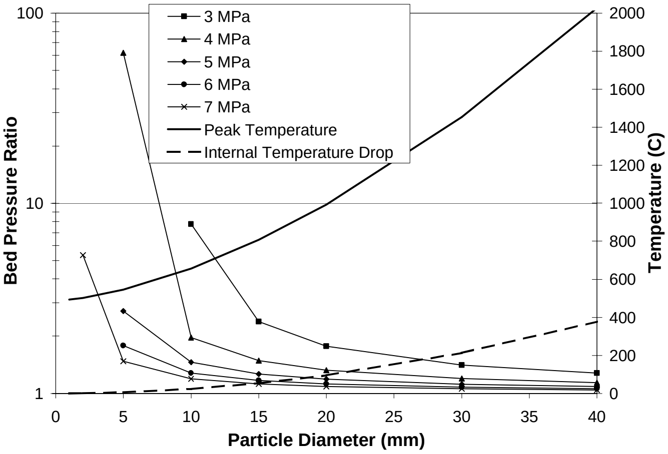


Fig. 3. Bed Pressure Drop and Particle Temperature vs. Particle Diameter.

The results of these calculations are shown in Fig. 3 versus particle diameter for varying bed inlet pressures. The ratio of inlet-to-outlet pressure for the packed bed is shown on the primary ordinate. The sharp rise in bed pressure ratio is evident as particle size is reduced. Excluding other system losses due to screens, piping, filtration, etc., this pressure ratio provides an indication of the compressor pressure ratio required to pump helium through the packed bed. Curves are shown for varying bed inlet pressure from 3 to 7 MPa. Since the mass flow rate is held constant, pressure drop through the packed bed decreases as inlet pressure is increased. This decrease in pressure drop is due to an increase in coolant density, and thus a decrease in bed superficial velocity.

The secondary ordinate in Fig. 3 shows the peak temperature within a particle (solid line) and the temperature difference within a particle from the centerline to the surface (dashed line). Peak particle temperature increases with particle size. This temperature increase is due to a reduction in heat transfer coefficient with increased particle size and an increase in heat transfer path length. Particle heat transfer (and thus particle temperature) is independent of packed bed inlet pressure. This pressure independence occurs because particle Reynolds number is not a function of inlet pressure.

To select a design point from Fig. 3, detailed particle stresses should be calculated. These stress calculations will depend on how the tungsten particles are formed (pressed and sintered, machined, etc.). Particle cladding material and thickness will also impact the stress calculations, if cladding is required. In addition, it would be prudent to keep the tungsten material temperature below 1000ºC. This temperature restriction will help prevent oxidation should any oxygen contaminant be present in the helium coolant. Keeping the tungsten below 1000ºC will also ensure that the tungsten temperature will be below containment metal melting and softening temperatures.

Tentatively, the 15-mm-diameter particle, which has a peak temperature of 808ºC, is selected as a reasonable, preliminary design point. Next, a bed inlet pressure must be selected which balances beam exit window considerations with compressor pressure ratio. An inlet pressure of 4 MPa generates a bed pressure ratio of 1.5 (a bed pressure drop of 12.9 atm). After adding losses to the coolant system, the resulting compressor pressure ratio required will probably be within practical limits. This bed pressure ratio along with other system losses (piping, filtration, etc.) will most likely result in an acceptable compressor pressure ratio. The resulting design point information for the cylindrical target is shown in Table 1.

Table 1. Cylindrical Target Thermal/Hydraulic Results

Target thermal deposition (MW)	15
Target cross-sectional area (cm^2)	1000
Total target length (cm)	45
Particle diameter (mm)	15
Packed bed void fraction	0.49
Helium flow rate (kg/s)	10
Helium inlet temperature (ºC)	200
Helium outlet temperature (ºC)	489
Helium inlet pressure (MPa, psi)	4.0, 580
Helium outlet pressure (MPa, psi)	2.7, 390
Helium inlet density (kg/m^3)	4.0
Helium inlet superficial velocity (m/s)	24.8
Helium inlet speed of sound (m/s)	1295
Helium specific heat (J/kg·K)	5193
Peak volumetric heating (W/m^3)	$6.52x10^8$
Peak heat flux (MW/m^2)	1.6
Heat transfer coefficient (W/m^2·ºC)	6135
Peak film ΔT (particle to fluid) (ºC)	265
Peak particle ΔT (center to wall) (ºC)	53
Peak particle temperature (ºC)	808

Selected operating temperatures are somewhat arbitrary. It is assumed that the thermal power extracted from the target is waste heat rejected to the environment, not to be used in the power conversion system. The inlet temperature of 200ºC was selected, therefore, to enable the rejection of this heat to the environment. It is possible to raise the helium temperature for better power plant effectiveness or to couple with blanket coolant temperatures. Helium inlet temperatures as high as 500ºC may be reasonable. The helium outlet temperature was chosen as a trade-off between temperature and flow rate requirements to remove 15 MW. There is considerable latitude to modify this product of helium temperature rise and flow rate, in either direction, in more detailed design studies.

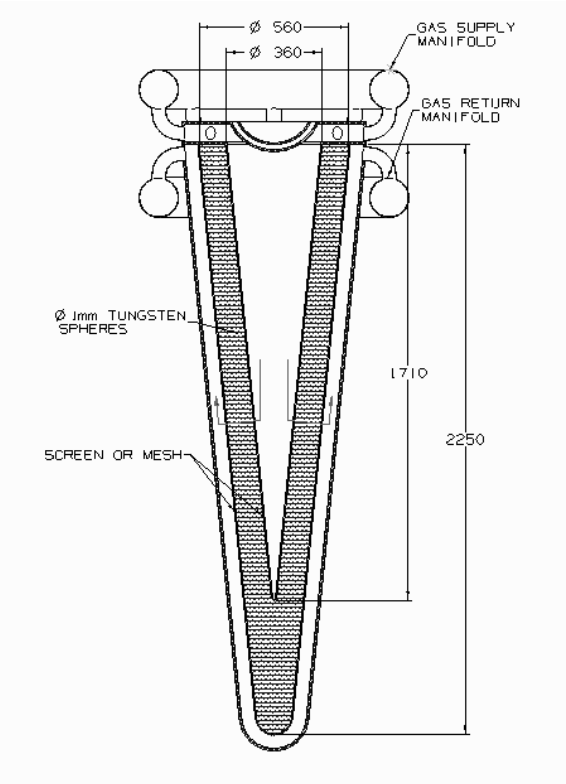


Fig. 4. Drawing of Concentric Cone Target Concept (dimensions in mm, beam entry from top).

An alternate target geometry that promises better neutron production and neutron distribution is a concentric cone arrangement. A drawing of the concentric cone target option is shown in Fig. 4. This configuration is compatible with an axisymmetric blanket. The concentric cone configuration provides several benefits over the cylindrical concept. First, the target length is increased thus providing a longer axis of neutron production. Secondly, the maximum target thickness between the inner and outer cones is approximately 10 cm, which allows more neutrons to escape the target. Finally, the helium flow path is reduced to approximately 10 cm in most locations, and the flow path cross-sectional area is greatly increased, both of which results in lower target pressure drop.

The beam cross-sectional area is 1000 cm^2. This area results from the assumption of a uniform beam profile at 30 $\mu A/cm^2$. The beam entry window is assumed to be water-cooled. The target chamber contains a randomly packed bed of tungsten particles with a nominal diameter of 1 mm and a sphericity of 0.7. A sufficient beam stopping distance is achieved everywhere in the beam path due to the high slope in the cone walls. Two different beam stopping distances were examined. A beam stopping distance of 50 cm resulted in the generation of 22 neutrons per proton. The target with a beam stopping distance of 100 cm generated 26 neutrons per proton and is therefore shown in this study. The packed bed volume for the concentric cone target is twice the volume for the cylindrical concept. No attempt has been made to optimize the design to increase the neutron efficiency or to optimize the target-coolant thermal/hydraulics. The length of the target can be changed by modifying the cone angle. Currently, the cone angle is 5.7 degrees.

The flow of helium enters on the inside of the cone and exits on the outside. Calculations were performed for a range of particle diameters from 1 to 40 mm in the concentric cone target configuration. The results of the particle temperature calculations for the concentric cone target are shown in Fig. 5 compared with those for the cylindrical target. The particle temperatures for the concentric cone target are substantially increased over those of the cylindrical target. This increase occurs even though the power density per particle for the concentric cone target has been cut in half as a result of the doubling of the packed bed volume. The increase in temperature for the concentric cone target is due to the large increase in flow path area through the target, which results in significantly reduced coolant velocity.

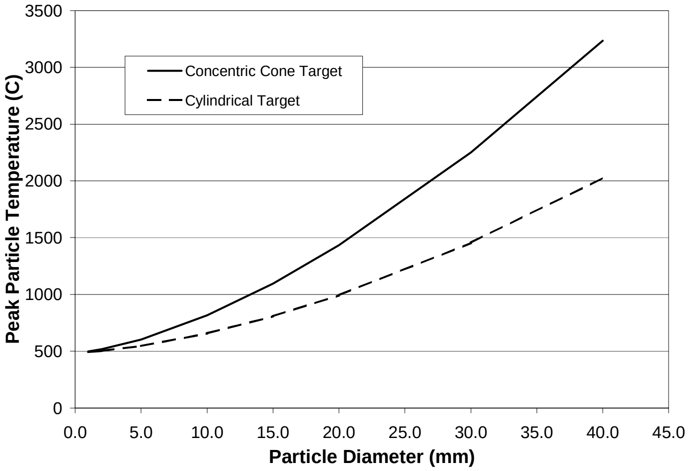


Fig. 5. Peak Particle Temperature vs. Particle Diameter.

Due to the reduced flow path length through the packed bed and increased flow area, a significantly lower helium inlet pressure can be selected compared with the cylindrical target concept. A much smaller particle size can be selected, therefore, without paying a large penalty in pressure drop. A tungsten particle size of 1 mm was chosen which results in a peak particle temperature of 498ºC. Tentatively, an inlet pressure of 1 MPa is chosen for this configuration which generates a bed pressure ratio of 1.2 (a bed pressure drop of 1.3 atm). One problem that arises with this hydraulic scheme is cooling of the tip of the cone. The flow path, and therefore the flow resistance at the tip, is considerably greater than through the sides of the cone. Perhaps a separate flow could be channeled to the tip to alleviate this problem. The resulting design point information for the concentric cone target is shown in Table 2.

Table 2. Concentric Cone Target Thermal/Hydraulic Results

Target thermal deposition (MW)	15
Target cross-sectional area (cm^2)	1000
Total target length (cm)	225
Particle diameter (mm)	1
Packed bed void fraction	0.49
Helium flow rate (kg/s)	10
Helium inlet temperature (ºC)	200
Helium outlet temperature (ºC)	489
Helium inlet pressure (MPa, psi)	1.0, 145
Helium outlet pressure (MPa, psi)	0.87, 126
Helium inlet density (kg/m^3)	1.0
Helium inlet superficial velocity (m/s)	10.1
Helium inlet speed of sound (m/s)	1283
Helium specific heat (J/kg·K)	5193
Peak volumetric heating (W/m^3)	3.26x10^8
Peak heat flux (MW/m^2)	0.054
Heat transfer coefficient (W/m^2·ºC)	5869
Peak film ΔT (particle to fluid) (ºC)	9.3
Peak particle ΔT (center to wall) (ºC)	0.1
Peak particle temperature (ºC)	498

Other geometries may be compatible with the packed bed target approach. For example, an APT-like concept could be studied with a series of cylinders arranged on “ladders” in a high-aspect-ratio rastered beam. The cylinders could be filled with tungsten spheres. Helium could be delivered to the cylinders by a manifold arrangement similar to the cooling water manifolds of the APT concept. While this approach is more complex than either the cylindrical or conical targets and is non-axisymmetric, it appears feasible. Further study would be required to determine if the merits of such an elaborate target are sufficient to warrant the engineering complexity.

IIIb. Spherical Tungsten Particles

It appears possible to obtain tungsten in spherical particle form. Tungsten spheres have been manufactured using a CVD process in a fluidized bed to diameters of hundreds of microns. It is not clear whether this type of operation could generate larger particles on the order of 1 cm in diameter. In another manufacturing process, small tungsten granules are pressed into a rough spherical shape and then sintered to increase their density. These particles are then polished, say in a tumble-deburring operation, to increase their sphericity. The resulting spheres may possibly achieve a density 96% of standard tungsten. In another potential manufacturing process, particles are cut to approximate diameter from a tungsten rod. These particles are then machined to obtain a measure of sphericity.

IIIc. Cladding

It is not clear at present whether cladding will be required for the tungsten particles when used with the helium coolant. The use of cladding will depend on several factors including, corrosion, erosion, and thermal-induced stresses. The presence of impurities in the helium, such as oxygen and water could cause corrosion of the tungsten. If corrosion of the particles is a possibility, then the rate of corrosion will have to be investigated relative to the expected operating life of the particles. It may be possible to dope the coolant with hydrogen to control the oxygen levels.

Thermal-induced stresses may affect mechanical stability of tungsten and thus require cladding. If the tungsten begins to break apart due to thermal fatigue, then radioactive solid particulates will be released in the coolant gas stream. Both steady state and transient (thermal cycling) stresses should be investigated.

Because of the small size and large numbers of particles to be clad, various cladding processes should be investigated to determine the most effective and least costly solution. Options include fluidized bed coating and barrel plating. Another option besides coating the particles with metals such as nickel, inconel, or stainless steel is to coat them with tungsten disilicide. This coating will protect the tungsten from oxidation and can be exposed to higher temperatures than metal coatings.

It would be desirable to avoid cladding if possible. The performance of cladding in a proton beam is unknown. Separation of the clad from the tungsten due to thermal cycling and possible trapping of gaseous spallation products within the clad are issues that must be understood. In addition, some cladding processes generate toxic waste streams that must be considered as well.

IIId. Coolant

Helium is neutronically transparent and is compatible with a wide range of materials in nuclear applications. It does not activate appreciably and does not react chemically with other materials. Helium remains in a single-phase state under all operating conditions. In addition, helium has been used extensively as a coolant in nuclear reactors for over 30 years. Auxiliary technologies associated with the use of helium as a coolant such as heat exchange, filtration, and pumping are essentially “off-the-shelf.”

It is assumed that the target coolant is not used to generate power. Therefore, the helium is assumed to enter the target at 200ºC. The flow rate is assumed to be 10 kg/s, which results in an exit temperature of 490ºC.

There are several reasons why the target coolant is not used to generate power.

1) The thermal energy deposited in the target represents only about 2% of the total thermal power output expected from the target/blanket assembly. Excluding this target energy from power generation has a small impact on system power production.
2) Using gas for power generation would require a high target exit pressure [GA’s Gas Turbine – Modular Helium Reactor (GT-MHR) design assumes a pressure of 7 MPa]. This requirement for high pressure within the target is incompatible with the desire for low pressure on the target side of the beam exit window.
3) The target cooling gas will contain spallation products. While the individual spallation products can be predicted, practical experience with them is small compared with the fission products that will appear in the blanket coolant stream. At this early stage, therefore, it is prudent to keep the two streams separated.
4) Assuming a separate target-cooling loop allows the flexibility to use other coolants, if desired, for blanket heat removal.

Due to viscosity-induced thermal instabilities, target designers must be careful to provide relatively high coolant velocities within the packed bed. Since the viscosity of helium increases with temperature, local hot spots within the bed will lead to reduced coolant flow rates within the area of the hot spot, thus further increasing local temperatures. Since the stability limits are known, an appropriate target design should be able to avoid these instabilities. In contrast, velocities should not be made too high or erosion may become a problem.

It is assumed that a compressor will be required to pump the helium through the target-cooling loop. Because of the potential for beam fluctuations, it is recommended to drive the compressor with an electric motor. Compared with sodium as a coolant, for example, helium typically requires more pumping power. For the concentric cone target investigated, the pumping power required is approximately 400 kW (excluding all other losses).

A detailed inventory and rate of generation of spallation products must be produced to determine which helium cleanup option is most feasible. This inventory should consider impurities or doping substances that may be introduced into the coolant flow to prevent corrosion. The primary spallation products generated using helium as a coolant will be spallation product ejecta from recoiled nuclei, spallation product noble gasses that diffuse out of the tungsten, and spallation product hydrogen and tritium. These isotopes of hydrogen could be removed by passing a slipstream of the cooling flow through palladium membranes. The palladium membranes will generate a high pressure drop, therefore the entire cooling flow would not be passed through them. In addition, the temperature of the helium gas may have to be reduced before it can be passed through the palladium membranes. Another option for removing these isotopes would be to run the cooling flow in batches. When the quantity of spallation products reaches a designated level, the batches could be switched and a cleanup performed.

Depending on the coolant temperature, tritium could have a high diffusion coefficient and may be difficult to contain.

Preliminary calculations suggest, however, that tritium production in the helium will be approximately 25-40 Curies per year. This is not a significant hazard. Releases from tritium processing facilities are often 1 Curie per day.

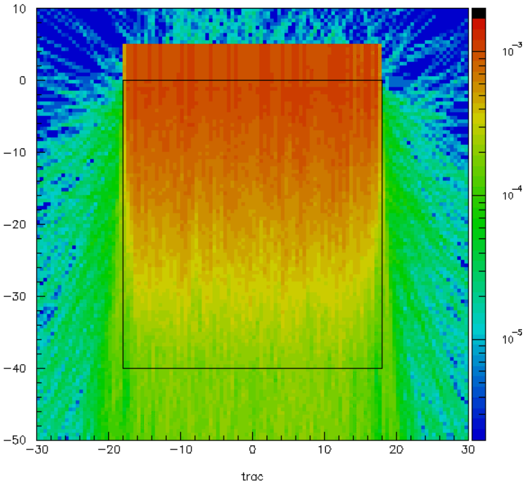
IIIe. Beam Entry Window

High pressures in the target associated with using helium gas as a coolant will greatly increase the complexity of design and cooling of the beam entry window. The thickness of the windows will have to be relatively high to withstand these pressures. Increased window thickness will lead to significantly higher heat depositions from the proton beam. Use of helium alone would probably be insufficient to cool these windows. The beam entry windows for these gas-cooled configurations, therefore, would probably be water-cooled inconel. The specific cooling methodology depends upon target geometry, window cooling requirements, window and target replacement scheme, etc. Stainless steel may be an acceptable alternate window material, but the tensile strength is much lower.

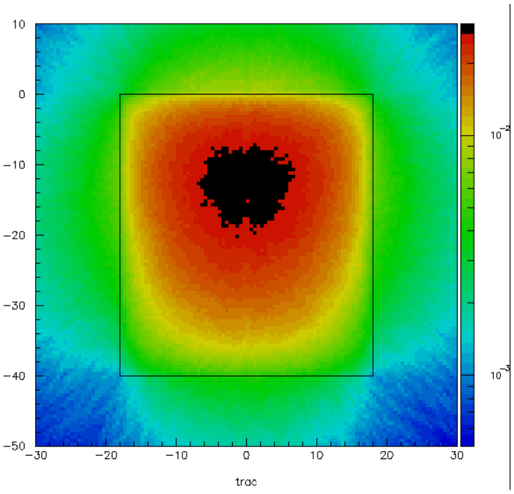
IV. NEUTRONICS

An analysis was performed on the cylindrical target to investigate the proton and neutron fluxes. (The target that was analyzed neutronically was 40 cm in length rather than 45 cm.) This target has a neutron yield of 22 neutrons/proton. Figure 6 shows side views of the proton (Fig. 6a) and neutron (Fig. 6b) flux within the cylindrical target. Figure 6a shows that the target length should be increased to provide total beam stopping length. There appears to be a fair amount of proton leakage from the sides as well. By modifying of the target geometry, it may be possible to take advantage of these protons to increase the total neutron yield. Figure6b shows that a target diameter of 36 cm has a high of neutron capture in its center. Target geometry refinement would be required to increase the neutron production.

A neutronics analysis was also performed on the concentric cone target. This geometry spreads out the neutron production along the length from a circular beam of uniform density. The neutron production was 26.0 n/p in this geometry. The average flux leaving the exterior cylinder was 4.926×10^{-4} n/cm^2 per proton. For a 30-mA source beam, this works out to 9.22×10^{13} n/cm^2/s. The spectra are given in Fig. 7. The peak of the distribution is around 0.6 MeV. Figure 8 shows images of the proton and neutron flux distribution for this target.



6a. Proton Flux



6b. Neutron Flux

Fig. 6. Proton and Neutron Flux for the Cylindrical Target.

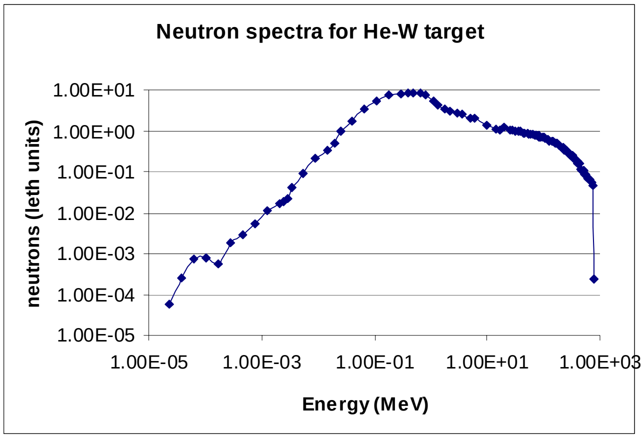
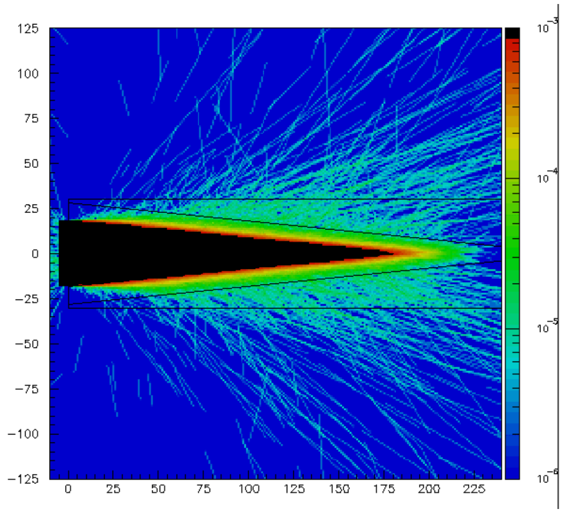
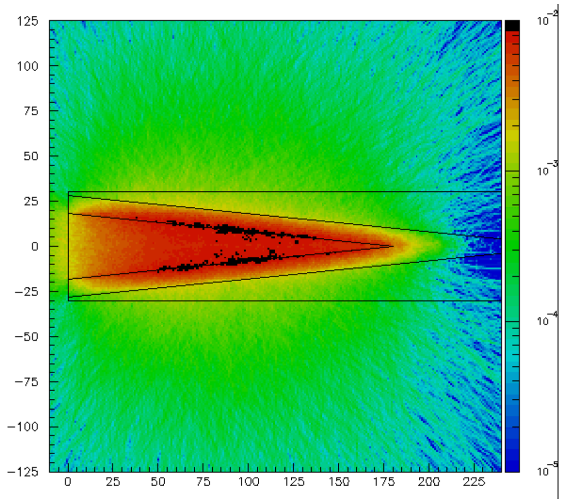


Fig. 7. Neutron Spectra (Lethargy Units) for Cylindrical Target.



8a. Proton Flux



8a. Neutron Flux

Fig. 8. Proton and Neutron Flux for the Concentric Cone Target.

V. TARGET MATERIALS

At low to intermediate temperatures (less than 550ºC – 600ºC), HT-9 type F/M steels and nickel alloys can be used for windows and other parts in the active portion of the target. For higher temperatures (greater than 600ºC), perhaps only nickel alloys are suitable due to the loss of strength in F/M steels and helium induced embrittlement. The helium has to be extremely pure, free of gaseous impurity and suspended particles to prevent corrosion and erosion.

A potential area of concern is the need for high pressure containment (typically ~ 7 MPa). This constraint, with the likelihood of radiation induced embrittlement in the window, and thermal gradient induced stress (enhanced by the thickened window for pressure containment), may become a very challenging obstacle.

VI. SAFETY ISSUES

There are several safety issues involved with using a helium-cooled tungsten target, including depressurization, loss of coolant, and containment of spallation products. Using high-pressure helium as a coolant presents the possibility of a depressurization accident. In such an accident, there is the potential for release of radioactive contamination, which may require double-walled containment.

In the event of a catastrophic loss of coolant, natural convection of the target would probably not suffice to remove decay heat. It is possible that decay heat could conduct through the bed to the target container surface and be removed by natural convection. If conduction is not sufficient, an active decay heat removal cooling system must be added, such as the injection of helium into the target.

If a breach in the cooling system occurs which allows the introduction of oxygen to the high-temperature tungsten, an exothermic reaction can occur. This may be an issue that forces the tungsten to be clad. There is a possibility of helium injection into the target to prevent the ingress of oxygen. Additionally, in loss-of-flow (LOF) or loss-of-heat-sink (LOHS) accidents, a gas-cooled target, compared with liquid metal or liquid-metal-cooled targets, has a much lower grace time until particle melting occurs.

Tritium production will occur in the target and measures must be taken to remove this spallation product from the cooling gas. Tritium might be removed by passing a slipstream of the cooling gas through palladium membranes. There is a possibility that tritium will diffuse through the heat exchanger into the cooling water. If tritium concentrations are too high in the cooling water, some type of tritium trap will need to be employed.

VII. TECHNOLOGY DEVELOPMENT ISSUES

Some details of the data needs and development issues depend upon the configuration of the target. Thus, the first step in a helium-cooled tungsten target development would be a detailed design to optimize neutronics and geometry consistent with a viable blanket configuration. A study of heat transfer and hydraulic issues would then proceed.

Extensive computational and analytical calculations should be performed on potential, in-beam, packed-bed target configurations to determine a likely candidate. Variations in particle size, sphericity, packing factor, and target shape can be modeled. Once an in-beam candidate has been selected and adequate flow distribution has been verified, it should be evaluated in an out-of-beam, experimental gas flow facility to verify pressure drop and heat transfer characteristics. The effects of erosion on clad and unclad tungsten particles can be assessed in this facility as well.

Once target requirements are fully specified and detailed designs are underway, the requirements of external systems become known. No significant complications are expected in the development of these systems. Nonetheless, a considerable engineering and design effort will be required, along with performance testing, in some cases. Heat exchangers, compressors, filtering systems, and instrumentation systems have all been developed for helium-cooled reactors. The detail is in the scaling to ATW target requirements and completing fabrication.

If cladding of the tungsten spheres is required, studies should be performed to determine the cladding design and the best cladding method. Prototype particles should be produced for both out-of-beam testing (e.g. thermal/hydraulic and cyclic thermal loading) and in-beam testing. Of particular importance is the performance of the clad/tungsten interface with repeated thermal cycling, and in-beam performance under prototypic conditions. The necessity of cladding is not yet established, but the presence of cladding can minimize the release of spallation products from the tungsten to the coolant. An analytical and experimental program will be required to develop the cladding technique and to produce samples for testing.

Ultimately, an integral test demonstrating the performance of a stopping length target in a high-energy proton beam is needed. This target would be designed on the basis of the testing and development described above. An integral test also evaluates all external components: compressors, heat exchangers, instrumentation, etc.

VIII. CONCLUSIONS

This paper presents the results of a preliminary investigation of a spallation target constructed of a helium-cooled, packed bed of tungsten particles. Two packed bed target designs for accelerator transmutation of waste are presented and compared. These targets were designed to prototypic ATW plant requirements. The concentric cone target concept proved to be superior to the cylindrical concept for the following reasons:

1) The concentric cone nature of the conical target provided a reduced-length flow path and an increased coolant flow area. This reduced length and increased area resulted in lower target pressure drop and lower overall operating pressure. Particle temperatures for the conical target, however, were higher due to the reduced coolant flow velocity resulting from this geometry.
2) The thinner conical target had lower neutron capture characteristics. Therefore, the neutron efficiency of the conical target (n/p=26) was higher than the cylindrical target (n/p=22).
3) The increased length of the conical target compared with the cylindrical target provided improved axial distribution of neutrons.

REFERENCES

1. A Roadmap for Developing Acceleration Transmutation of Waste (ATW) Technology: A Report to Congress, October 1999.

2. D. KUNII and O. LEVENSPIEL, *Fluidization Engineering*, Robert E. Krieger Publishing Company, Inc., Florida, (1984).