ACCELERATOR-DRIVEN TEST FACILITY:
MODULAR TARGET AND MULTIPLIER SYSTEM CONCEPT DESIGN DESCRIPTION

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Abstract

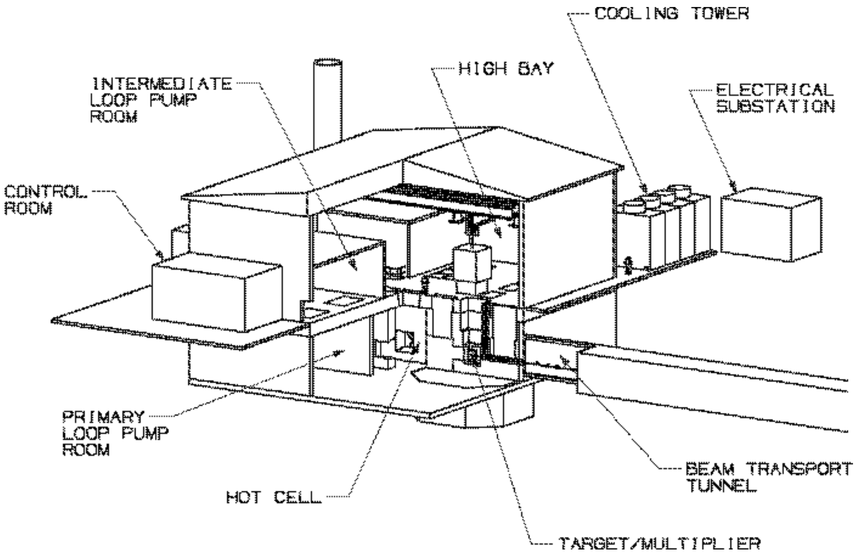
The accelerator-driven test facility (ADTF) modular design concept is a target/multiplier configuration that provides optimum flexibility in operation, and testing. The configuration proposed is based on demonstrated technologies and methods that are currently used in existing facilities. It consists of a centrally located target/multiplier experimental cell surrounded by shielding and three adjacent hot-cells. The experimental cell contains the neutron spallation source and two multiplier segments on either side. When assembled the system closely resembles a central spallation target with a surrounding multiplier in cylindrical geometry. At the completion of an irradiation cycle, target and multiplier components are moved into and out of the experimental cell horizontally from the adjoining hot-cells. All primary heat-removal equipment resides in the hot-cells providing for safe operation and maintenance. Scooping calculations show that reasonably high neutron flux levels are achievable over sufficient volume to meet the goals set for transmutation proof of performance tests. Using a safety by design strategy, a combination of active and passive safety features provide diverse and redundant beam shutdown and decay heat removal.

Facility arrangement

The concept is depicted in Figures 1-4, which show the facility isometric, plan view, primary shield isometric, and one possible arrangement for the experimental cell detail, respectively. The beam enters the experimental cell horizontally and impacts directly on the spallation neutron source, which is also inserted and removed horizontally in the opposite direction. The two multiplier segments are also inserted and removed horizontally, perpendicular to the beam-target axis (Figures 3 and 4). A steel-and-concrete shield surrounds the experimental cell, providing unrestricted access to surrounding support equipment. The inside surface of the cell is cooled to maintain the structure at a reasonable operating temperature. The hot-cells are designed such that remote operations may be performed while the beam is on. The physical interface between the target and multiplier segments allows for removal and insertion of a new target without moving the multiplier segments.

The three hot-cells adjacent and connected to the shield provide service to the target and the two multiplier segments, respectively (Figures 1 and 2). The hot-cells contain the primary heat-removal equipment, and all necessary remote handling equipment for replacement and movement of components. Piping that runs through the shield connects the heat-removal equipment to the target and multiplier segments. For the multiplier segments, the hot-cells contain sufficient space for storage of fresh and spent fuel, and space for disassembly and packaging of fuel and material test elements. Similarly for the target hot-cell, adequate space is provided for spent target materials, disposal containers, and material test coupon analysis.

Figure 1. **Target/multiplier building isometric**



Configurations of this type has been demonstrated successfully at the ISIS (UK), KENS (Japan), and IPNS (US) neutron-scattering facilities and is planned for use in the SNS (US) facility under construction at Oak Ridge, Tennessee. The layouts used in ISIS and SNS are shown in Figures 5 and 6 for comparison. These systems offer superior operational flexibility because it allows for quick replacement of the target, which is necessary to maintain overall facility availability. In the SNS facility, change-out of the liquid mercury target container is planned to take place in five days.

Figure 2. **Target/multiplier building plan view**

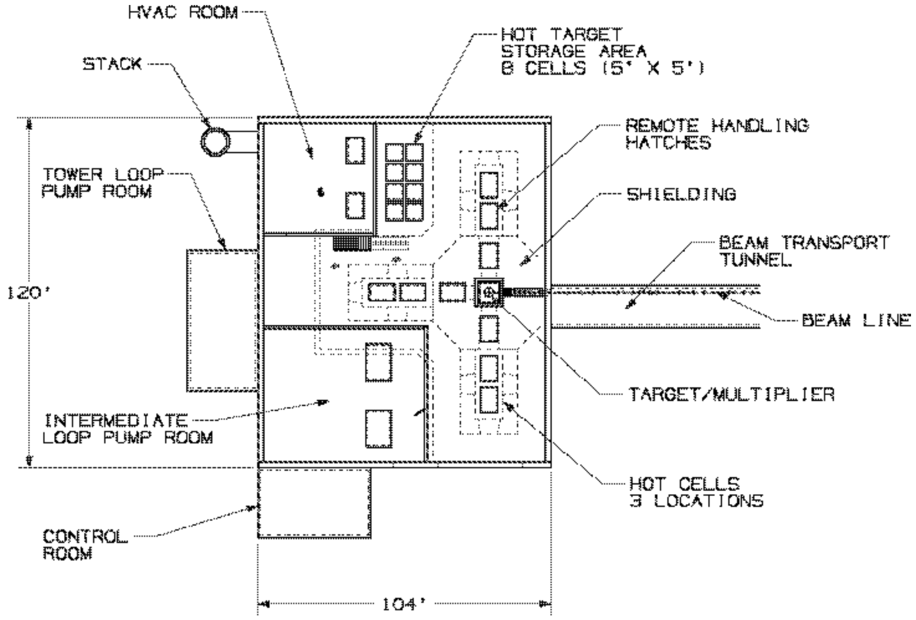


Figure 3. **Shield isometric**

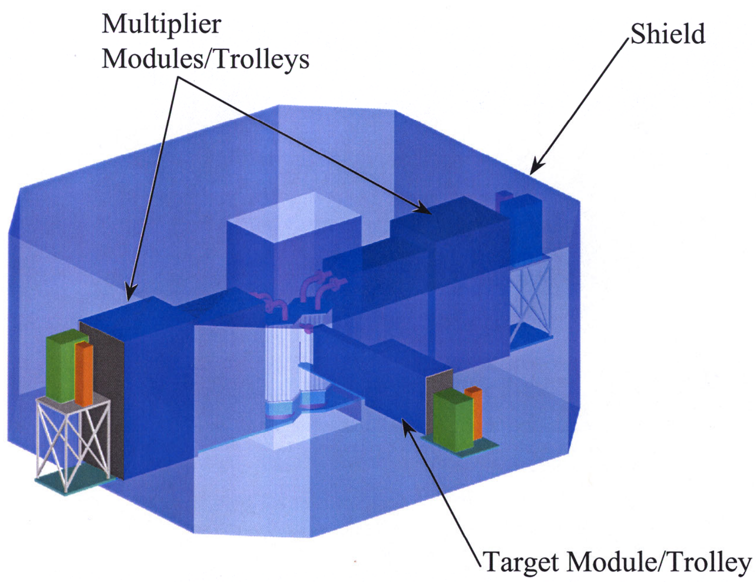


Figure 4. **Experimental cell detail**

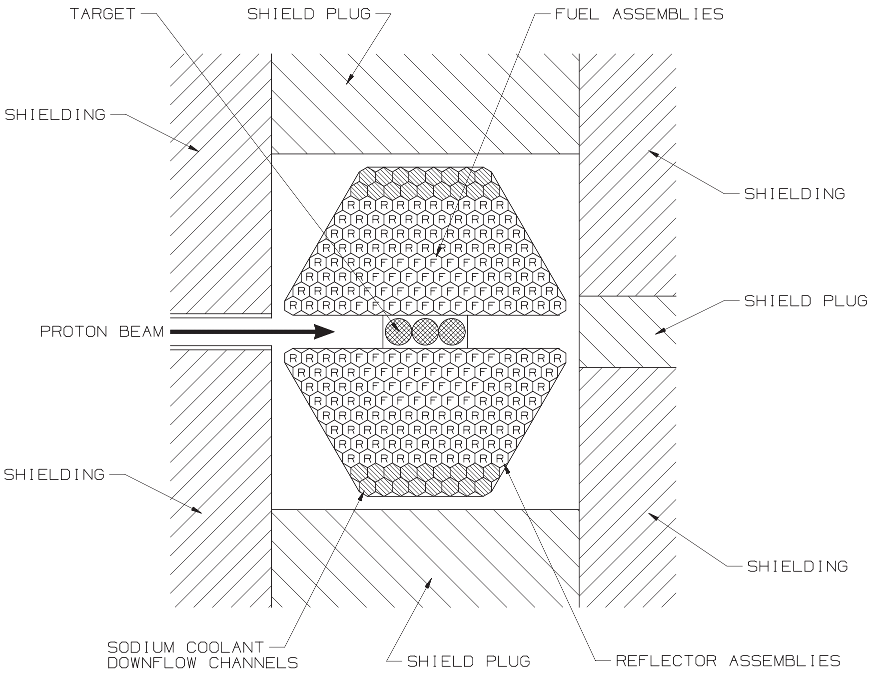
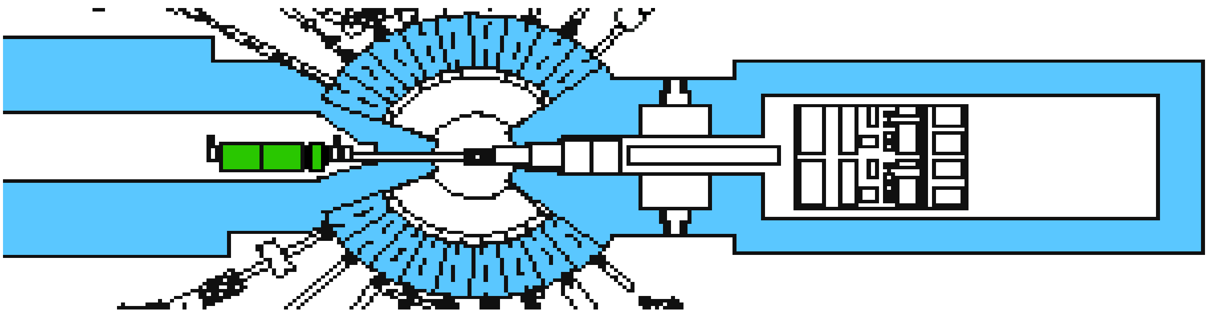


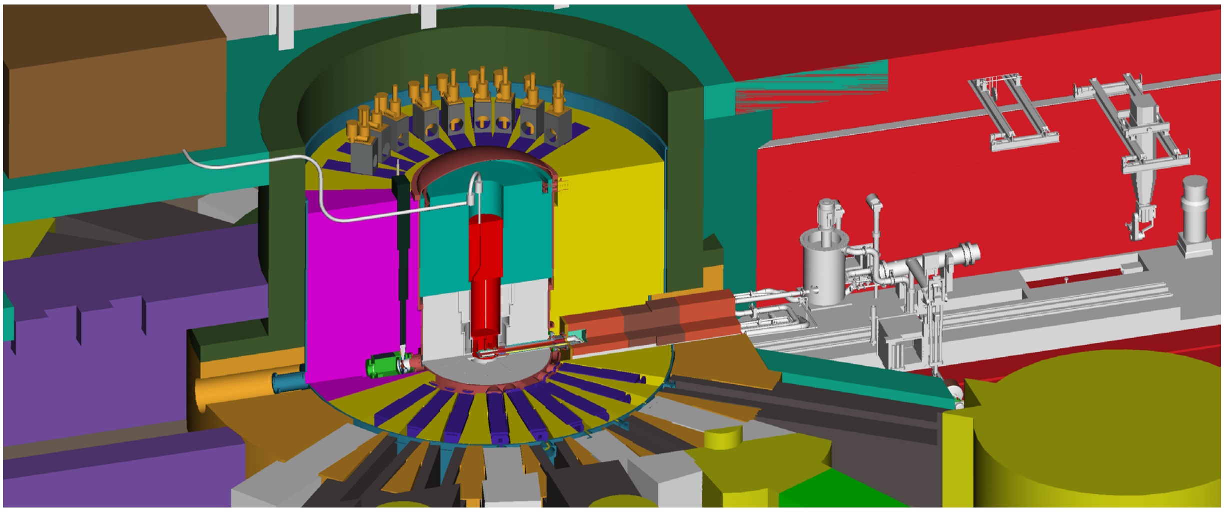
Figure 5. **The ISIS facility at the Rutherford Appleton Laboratory**



Target

The modular configuration can support the testing of either solid or liquid targets. A liquid target that provides good thermal and neutronic efficiency is the lead/bismuth eutectic (Figure 7). In this target, a row of three stainless steel pipes approximately 10 cm in diameter are positioned between the two multiplier segments. The pipes are positioned vertically, in line with the axis of the beam, and are connected at the top and bottom by inlet and outlet plena, respectively. The plena are connected to piping that runs through the removable shield and are connected to a heat exchanger and pump in the hot-cell. The lead/bismuth eutectic continually flows through the pipes, forming the neutron spallation target when impacted by the proton beam. Because the target material and coolant are the same, the amount of structural material and other low-atomic-number materials that the protons *see* are minimised. This, combined with the fact that lead/bismuth has very low neutron absorption, makes this spallation target very efficient neutronically. The amount of lead/bismuth in the beam is sufficient to completely stop and *range out* all of the protons.

Figure 6. **The Spallation neutron source target/shield and hot-cell configuration**

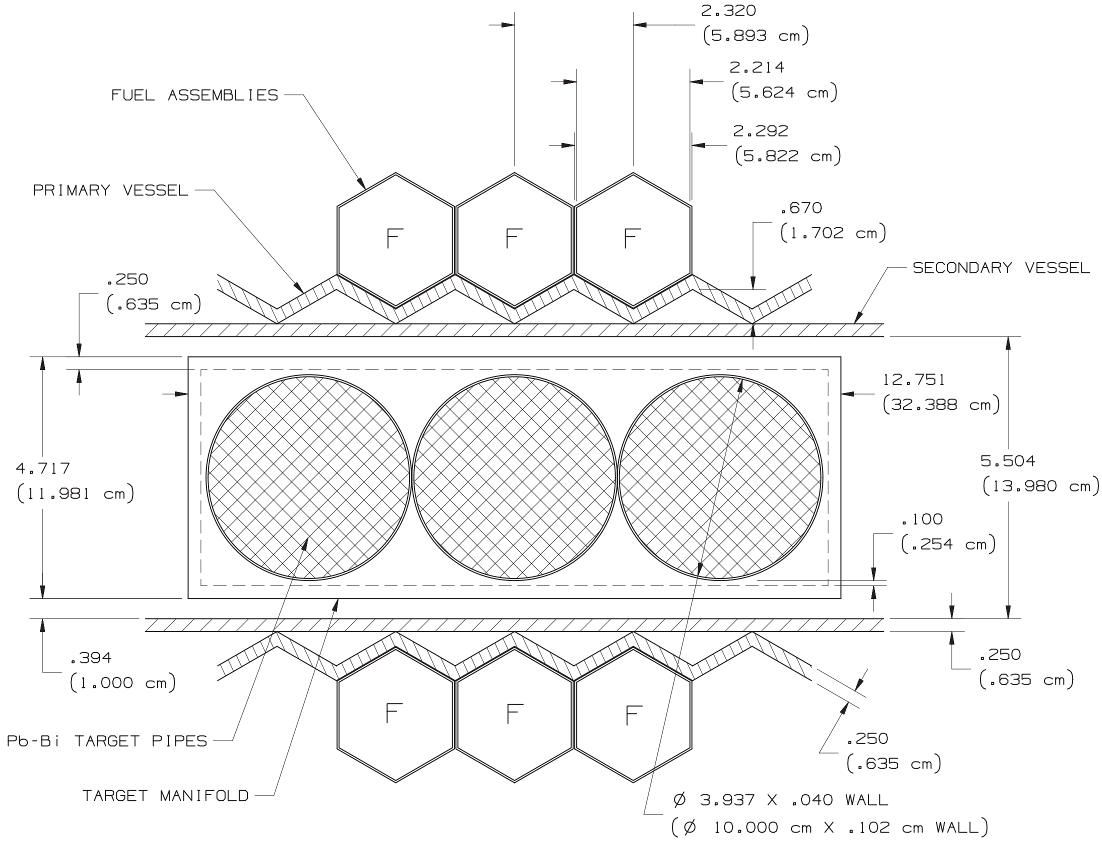


The proton beam that is delivered to the target will be at approximately 600 MeV, with up to 13 mA of current. The beam enters the experimental cell through a beam pipe in the shield and passes unobstructed to the front face of the first pipe of the target. The beam is expanded or rastered into a beam spot that is approximately 38 cm high by 6 cm wide. This beam-spot distribution and size can be changed, depending on the needs of the experimenter, as long as thermal, hydraulic, and structural limits are not exceeded in the target. Thermocouples on the front face of the target provide the necessary information for the operators to centre the beam. This is a common practice at existing spallation neutron sources. The 38×6 cm beam spot is chosen as a base case because it produces a reasonable power density in the lead/bismuth, and keeps the pipe wall at a reasonable temperature, even at 13 mA of current. If lower beam currents are used, then smaller beam spots are possible.

To provide for material coupon irradiation in the lead/bismuth environment, smaller-diameter pipes would be inserted in parallel with the three target pipes. These can be positioned in between, behind, or in front of the target pipes, depending on the needs of the experimenter.

The stainless steel pipes, which contain the lead/bismuth eutectic, are damaged by proton and neutron irradiation and must be replaced on a regular basis. Depending on the beam current and spot size that is utilised, replacement of the container may be required every 3 to 12 months, which is consistent with the expected multiplier irradiation cycle (e.g., both the Fast Flux Test Facility and Experimental Breeder Reactor (EBR-II) operated on a 100-day cycle). To change out the container, the beam is shut down and the liquid is drained into a storage vessel that resides in the adjacent hot-cell. The target insert, which includes the target, piping, heat-removal equipment, and a section of shielding, is moved horizontally back into the hot-cell on rails. Remote manipulators are used to disconnect the target container at the piping-to-plena interface and replace it with the new one. The system is then leak-checked and refilled with the same fluid as before. Some clean-up may be needed (e.g., removal of spallation products) before the lead/bismuth is recycled. The entire assembly is then reinserted into the target cell.

Figure 7. **Lead/bismuth target detail**



Corrosion is an issue in a lead/bismuth target. An effective way of reducing the corrosion rate is to maintain a protective oxide layer on the pipe surface. For a short-lived target, it may be sufficient to control the initial oxygen content in the system. If necessary, an active oxygen control system can be easily implemented. In an active system, oxygen levels are continuously monitored. When needed, small amounts of oxygen are added to the lead/bismuth. Excess oxygen can be reduced by small additions of hydrogen.

If the use of a lead/bismuth target with a sodium-cooled multiplier is not desirable, an alternative target configuration would be a solid tungsten target with either sodium or helium coolant. This may be necessary for safety reasons because of a potentially exothermic chemical reaction between sodium and lead/bismuth when they are mixed together. Conceptually such a target would be similar to that shown in Figure 7, where tungsten tubes would be nested inside the vertical target pipes. Sodium or helium would flow upwards through the gaps between the tungsten tubes to provide cooling. A tremendous amount of fabrication experience was gained in the APT programme for the solid tungsten option, and would be directly applicable to this application.

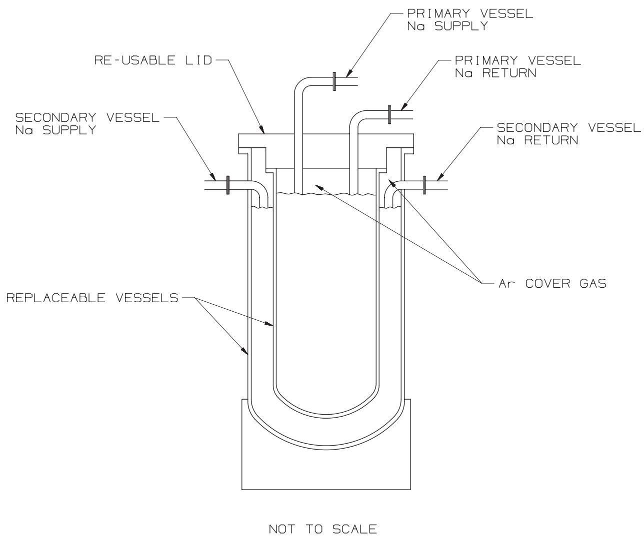
To replace a solid target, the cooling fluid would remain flowing on the tungsten until decay heat was sufficiently low that the fluid could be safely drained (or, in the case of helium, removed). Then the target would be disconnected, removed, and replaced with the new one. To maintain adequate availability and provide flexibility in operation, adequate space exists in the hot-cell such that a spare target assembly can be readied for operation while the other assembly is in use. From a waste-generation standpoint, the liquid target offers a substantial advantage over the solid target because only the target container (stainless steel) needs to be replaced on a regular basis. Once radioactive, however, the lead/bismuth becomes a mixed waste and must be handled appropriately at the end of facility life.

Multiplier

In the modular configuration the multiplier is separated into two segments that are brought in from the side (Figure 3). The segments can be identical or different, depending on the needs of the experimenter. Each segment has an attendant hot-cell similar to the target that allows for safe replacement of components. For the pre-conceptual design a fast-spectrum, sodium-cooled multiplier is being investigated as the base case, and as an option, a helium-cooled thermal-spectrum system that would be implemented using the same experimental cell but different multiplier components. This demonstrates the flexibility of the configuration for testing a wide range of nuclear systems and, therefore, supports both the transmutation and advanced nuclear technology missions. For instance, this concept provides an ideal setting if LBE is pursued as a nuclear coolant for ATW or advanced fast-reactor applications. For the current discussion, only the base-case fast-spectrum system is presented in detail.

For the fast-spectrum system, the fuel and reflector bundles are contained in a small vessel cooled with liquid sodium. As shown in Figure 8, this small primary vessel sits within an enclosed guard vessel that is also sodium-cooled but on a separate circuit. Note that this figure is not drawn to scale, and is used only to depict the principal concept. The heat-removal system for the primary vessel is configured to provide natural circulation decay-heat removal in the event of loss of forced flow. In addition, the flow of sodium in the guard vessel is sufficient to remove the decay heat, providing a redundant heat-removal mechanism. Diverse, redundant beam shutdown ensures that whenever cooling is degraded to the multiplier segments or the target, the beam is shut down with very high confidence through fail-safe connections to the accelerator injector.

Figure 8. **Multiplier vessel component**



Although not shown in Figure 3, the fuel or assemblies can easily be replaced with fuel test assemblies and material irradiation tests. Experimenters would position these assemblies and fuels to optimise the irradiation environment they seek. In the event that an experimenter desires a thermal flux over a small volume (for testing long-lived fission product targets), a reflector position could be replaced with an assembly containing yttrium hydride moderator to locally thermalise the neutron spectrum.

Depending on the flux level achieved, the small vessel components used in the multiplier will need to be replaced on a 1-3 year interval. In the conceptual design state, strategies to extend the vessel's lifetime will be pursued. For instance, designing an axisymmetric vessel capable of being rotated periodically will be considered. This will be performed in a manner similar to the target replacement. An inert atmosphere in the hot-cell will allow the safe removal of fuel elements out of the vessel and into storage or removal to a disassembly and packaging area. When fuel needs to be replaced or shuffled after an irradiation cycle or experiment bundles need to be removed, the vessel is moved into the hot-cell, and the operations are performed in the inert environment.

Heat removal

Because the primary coolants for both the target and multipliers will become highly radioactive, the heat exchangers and pumps are located in their respective hot-cells. Secondary coolants are pumped into the hot-cells to provide the necessary heat-removal capability. The heat from the secondary loop is dissipated to the environment through dump heat exchangers. The facility will not use the heat to run a steam cycle and produce electricity. The secondary system is modular such that increased heat-removal capability can be added in future facility upgrades. To support a helium-cooled primary system, the secondary system must have sufficient heat-removal capability with a compatible working fluid. Adequate space in the facility is provided to add this additional heat-removal equipment as well.

Although the accelerator will be designed to provide high reliability, a number of beam trips of both short and long duration are expected during the irradiation cycle. The structures and components that make up the primary heat-removal systems for both the target and the multipliers will be designed for the ensuing temperature transients in order to reduce transient stresses to allowable levels. Components that reach end-of-life due to fatigue will be engineered for easy replacement.

The inner lining of the target cell, which will be made of steel, is designed to last the life of the facility. Because of the intense radiation from the target and multipliers, the liner will need to be cooled to maintain a reasonable operating temperature, which is dictated by structural limits. The total heat load is expected to be in the kW range. The preferred heat removal will be performed with a passive system either using natural circulation or heat pipes.

On the secondary side, we are considering helium as the working fluid. This design will avoid the potential of sodium leaks and fire outside the hot-cell. In addition, because helium is compatible with all conceivable primary coolants, it provides additional flexibility for future multiplier test options (including water).

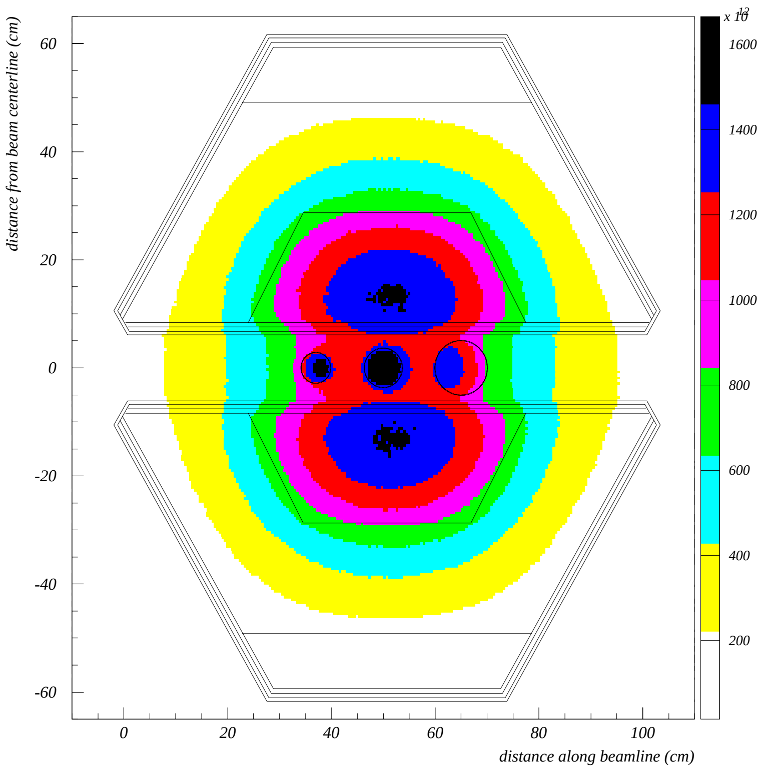
Beam transport

The proton beam is transported from the end of the accelerator to the target/multiplier building using the standard bending magnet and beam tube technology employed for the APT design. Vacuum pumps maintain the hard vacuum necessary for low-loss beam transport. Elevation of the beam is identical to that of the centroid of the target such that no vertical axis beam bending is required. Before entering the shielded experimental cell, a series of beam expansion and/or raster magnets are used to send the beam on a trajectory that provides the desired beam-spot distribution at the front face of the target. Assuming a raster system is acceptable (as was the case for APT), a beam distribution can be provided that is uniform with variations less than 10% over the desired area. Impact of a rastered beam on the neutronic fluctuations and cyclic thermal stresses will be assessed in deciding on the beam expansion strategy. For the beam to transport to the front face of the target with little or no loss, a relatively hard vacuum is required. To provide this vacuum level in the experimental cell without using a beam entrance window, vacuum pumping will be provided along the beamline, through the expansion chamber, and to the experimental cell. Vacuum seals for the target and multiplier inserts in the low-radiation zone on the outside of the shield provide the necessary pressure boundary. Redundant, fast-acting valves in the beamline outside the shield and upstream of the expansion magnets provide protection for the accelerator beamline in the event of the leak into the experimental cell. Any leak into the experimental cell, either from a seal failure or a container failure, automatically shuts down the accelerator, even if the active systems fail because the beam cannot be accelerated without sufficient vacuum. This provides a passive beam-shutdown mechanism in the event of either target container or multiplier guard vessel fails.

Irradiation environment

Initial scooping calculations have been performed on the fast-spectrum sodium-cooled multiplier system. For this analysis a total inventory of 339 kg of heavy metal was assumed in a core made up of 60 EBR-II type fuel assemblies. The fuel was assumed to be the standard EBR-II uranium/zirconium alloy metal with an enrichment of 67%. The resulting static k_{eff} of the system is 0.85. With the target operating at a power of 2.3 MW (beam current of 8.35 mA), the resulting power level in the two multipliers is approximately 20 MW, total. As shown in Figure 9, at this power level, the calculated peak neutron flux in the fuel is 2×10^{15} n/cm^2/s, and the average neutron flux over the fuel volume is 1×10^{15} n/cm^2/s. It is a significant advantage for the modular configuration that the spallation neutron-source distribution can be tailored to be uniform in the axial direction by control over the beam spot. This provides a uniform axial power distribution in the adjacent fuel over its full height, and therefore makes efficient use of the fuel.

Figure 9. **Flux distribution in the target/multiplier**



Fuel

For the two options being considered (fast-spectrum or thermal-spectrum), the fuel is vastly different. For the base-case fast-spectrum system EBR-II fuel is assumed, and for the thermal-system, unused Fort Saint Vrain fuel is assumed. Only the EBR-II fuel is discussed here.

The EBR-II fuel was made at the Argonne National Laboratory-West (ANL-West) outside Idaho Falls, Idaho. Approximately 32 subassemblies' worth of fuel slugs is in storage. The equipment used to fabricate the fuel and put it into the assemblies is in storage and can be reconstituted at a reasonable cost (few USD M). The facility used to fabricate the fuel is still in operation, performing other fuel-related tasks. Plans are to keep it operating for the future. To operate the ADTF, approximately 60 subassemblies will be required for a full load. However, it is expected that operation will start with a smaller amount of fuel and low multiplication constants, and then gradually work up to higher power. Thus, 30 subassemblies may be sufficient for initial operation. Nevertheless, the fuel fabrication line at ANL-West should be set up starting approximately 3 years before beginning ADTF operation in order to provide the necessary fuel.

Because this fuel is fully qualified and demonstrated for a fast reactor operation, we assume we will use this exact fuel design for our *driver* fuel. The specifications and dimensions assumed are shown in Table 1. These dimensions are consistent with the sketches shown in Figures 4 and 7. As shown in the table, the uranium enrichment used in EBR-II was 67%. For our purposes, this is considered to be a maximum value. Lower enrichments are possible by blending in more natural uranium. This can be accommodated at the fuel fabrication facility. It is expected that varying the enrichment in the multiplier will be used to flatten the power distribution in the radial direction.

The environment in the current design is similar to but not identical to the EBR-II. In addition to the typical fast reactor spectrum, there is also some fraction of high-energy particles (scattered protons and spallation neutrons), especially in the row closest to the spallation target. Because of accelerator trips, the fuel and structures will experience a higher thermal cycling rate than in a critical reactor environment. Therefore in the early phase of operation, it is expected that the fuel-operating parameters (e.g., temperature, power density, maximum burn-up) will be limited to values more conservative than the limits used in the EBR-II.

Table 1. **EBR-II fuel and assembly specifications**

Feature/Dimension	Value
Fuel slug diameter	0.173 inch
Fuel slug length	13.5 inches
Fuel alloy	U10Zr
Uranium enrichment	67%
Clad diameter	0.230 inch
Clad thickness	0.015 inch
Slug to clad bond material	sodium
Number of fuel rods per assembly	61
Pin to pin spacer	wire wrap 0.042 inch diameter
Pin arrangement	triangular pitch
Assembly duct	hexagonal
Duct flat to flat distance inside	2.214 inches
Duct thickness	0.039 inch
Hex assembly pitch	2.320 inches

Safety features

The design strategy for the modular concept embraces the safety-by-design principal. During all phases of the design, safety features will be designed into the system initially rather than as an afterthought. For the modular design, the goal is to provide an overall level of safety that meets or exceeds that of advanced nuclear systems. Several features are used to meet that goal and are summarised below.

Beam shutdown

For sub-critical systems, the beam acts as the power switch for the multiplier. With the beam off, the multiplier power quickly reaches decay-heat levels with a time transient behaviour similar to that of a critical reactor. In reactor terms, it can be thought of as an instantaneous control rod because it takes only microseconds to shut off once the trip signal is received.

There are several ways to shut down the beam, including turning off power to the accelerating cavities or the injector or losing vacuum in the beam tube. The easiest way is to turn off the beam at the injector. Several low-power switches must be simultaneously closed and the components operating correctly in order for the injector to provide the initial proton beam to the first accelerating structure. We will use these basic features to provide diverse and redundant beam shutdown. This system is fail-safe and will be implemented as a safety-class feature into the facility. For example, to protect against a loss-of-flow incident in the multiplier, a simple permanent magnet flow meter may be used in the primary sodium loop. The electric current created by the flowing sodium in the magnetic field acts as a flow switch and is connected directly to the injector. The current must be *on* for the injector to operate. The resulting fail-safe mechanism protects against any type of accident that causes flow to be reduced or to cease in the primary heat-removal system. Similar signals can be used in the guard vessel, target, and secondary coolant systems.

Another inherent safety feature of the modular configuration is derived from the fact that the experimental cell environment is connected directly to the accelerator vacuum. Active systems will shut the beam down in the event of loss of vacuum in the experimental cell or the beam pipe itself. Multiple, fast-acting valves in the beam transport line just upstream of the experimental cell shield will quickly close to protect the accelerator. In the extremely unlikely event that automatic shutdown does not occur, beam shutdown will occur naturally because it cannot be accelerated without sufficient vacuum. This provides a passive beam shutdown mechanism in the event the multiplier guard vessel, the target, or the vacuum seals leak.

Power and reactivity

To prevent over-power events, physical constraints are used in the injector to prevent the accelerator current from exceeding a preset value for the run cycle. The multiplier segments are designed so the multiplier is in its most reactive position during operation. Physical constraints on the vessels prevent the segments from moving closer together. Thus, the fuel cannot reach criticality unless reconfigured due to melting and pooling of the fuel.

Decay-heat removal during postulated accidents

To preclude the possibility of accidental melt-driven criticality for all credible accidents, the fuel-assembly geometry is maintained by providing diverse and redundant decay-heat removal. The heat-removal system for the primary vessel is configured to provide natural circulation decay-heat removal in the event of loss of forced flow. In addition, the flow of sodium in the guard vessel is sufficient to remove the decay heat, providing a redundant heat-removal mechanism for both loss-of-flow and loss-of-coolant events in the primary system. A more detailed assessment of the decay-heat removal strategies for a variety of design basis accident initiators continues. Event trees are being developed to identify all the necessary mitigation systems and components.

Containment

The experimental cell and its shield form the containment boundary for the target/multiplier. Because a good vacuum level is required to operate the multiplier, the integrity of this system is being checked continuously during operation. The hot-cells offer excellent containment of upsets in the cooling loops. Because they operate in an inert argon atmosphere, coolant leaks can occur without the possibility of sodium fire. We are considering the use of helium in the secondary loop, as discussed previously. Thus, no liquid metal will exist outside the hot-cell.

Summary

The modular configuration for the ADTF offers a flexible system that can provide the test and irradiation environments necessary to demonstrate transmutation technologies and advanced nuclear systems. Horizontal beam insertion provides for a simple, straightforward beam transport system from the accelerator to the target/multiplier. Horizontal target and multiplier insertion configuration is a demonstrated technology based on existing and planned facilities such as the Spallation Neutron Source. A prototypic materials-irradiation environment is achieved for both the target and the multiplier regions with a flexible system for removal and retrieval. The base-case fast-spectrum design employs a driver-fuel design whose performance is predictable based on a previously established database. Upgrade to higher power levels (e.g., 100 MW) can be implemented using more fuel and an expandable heat-removal system.

Analyses show that using this design configuration, one can produce neutrons with a spectrum prototypical of the current base-case ATW system, which is envisioned to employ a sodium-cooled multiplier and a lead-bismuth target. The environment is achieved with a lead/bismuth target and sodium-cooled multiplier with a k_{eff} between 0.8 and 0.97. Calculations show a fast-spectrum flux level greater than 1×10^{15} n/cm^2-s is achievable using metal fuel. The total multiplier power level is approximately 20 MW at this flux level. Because the beam is delivered to the target and multiplier horizontally, neutron source distribution can be tailored to provide a uniform flux over the length of the fuel.

The target/multiplier and beam shutdown systems are designed with the maximum reliance on passive safety features. Natural circulation of coolants for both the target and multiplier segments and diverse cooling mechanisms provide adequate protection in the event of accidents. In the event of a leak or break in either the target or multiplier pressure boundary inside the experimental cell, the loss of vacuum will passively shut down the beam.

Additional assessments in support of the pre-conceptual design continue. The on-going studies include neutronic and thermal-hydraulic sensitivity studies for different design options. Also, an initial assessment for the damage rates and the relevant structural design criteria is being developed. Decay heat removal strategies for a variety of design basis accidents and operational transients also are being assessed. In addition, different operational options are being identified for further considerations during the conceptual design phase. At the pre-conceptual design stage, some of the assessments will be qualitative in nature, especially for the support systems. These assessments will be used to guide the more quantitative design studies planned for the conceptual design phase.