LOS ALAMOS AQUEOUS TARGET/BLANKET SYSTEM DESIGN FOR THE ACCELERATOR TRANSMUTATION OF WASTE CONCEPT

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ABSTRACT

The Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) concept uses an accelerator driven neutron source (target) surrounded by a moderator and multiplying medium (blanket) for the transmutation of actinide and fission product waste. The reference target/blanket design is an aqueous system that uses heavy water (D_2O) for the target coolant, blanket moderator, actinide slurry carrier fluid, and fission product solution. The solid tungsten target produces neutrons efficiently and with a minimum of parasitic capture using an innovative flux-trap design. The blanket consists of regions for fission products and actinide transmutation and employs a heat-transfer loop similar to the CANDU reactor. Neutronics and thermal-hydraulic calculations indicate that each of the four ATW target/blanket modules operating at a k_eff of 0.95, combined with a 1600-MeV, 62.5-mA proton beam, can transmute the actinide waste, the technetium, and iodine waste from two light water reactors. In addition, by recovering some of the fission heat, we can produce sufficient electricity to power the accelerator.

I. INTRODUCTION

Los Alamos Accelerator Transmutation of Nuclear Waste (ATW) uses high-energy protons from a linear accelerator to produce neutrons through spallation instead of nuclear fission chain reactions. The protons are directed onto a high-atomic-number target material to produce neutrons that are then moderated in a surrounding D_2O blanket. The neutrons are slowed to thermal energy in the moderator and are absorbed in the fission product waste or they are used in the fission and transmutation of actinides. Fission products that have small neutron-absorption cross sections, such as ^{99}Tc, can be transmuted to stable isotopes in significant quantities. Fissile actinides such as ^{239}Pu can be fissioned directly, and add to the efficiency of the blanket through neutron multiplication.

The transmutation isotopes are continuously transported through the blanket region using D_2O aqueous solutions and slurries as the transport media. Dilute mixtures in the blanket region can be used, which therefore reduce the potential for criticality accidents and power excursions. The transmutation isotopes are continuously transported through the blanket region, through heat exchangers, and into separation process loops. The system is designed to make use of the fission heat and to produce electricity. Approximately 19% thermal efficiency is required to offset the power requirement of the accelerator, thereby reducing significantly the operating cost of the transmute. In this conceptual design study, we produce electricity at an overall efficiency of 20%.

Design concepts are being developed for the aqueous target/blanket system. The target design goals are to provide an efficient source of neutrons, minimize parasitic neutron capture, avoid generation of long-lived radioactive nuclides, use compatible materials that can withstand the intense proton and neutron irradiation, use passive modes of heat removal where possible, provide a safe design that minimizes potential radioactive material release during off-normal transients, and ensure ease of operation and maintenance. Design goals for the blanket of each target/blanket module are to transmute the actinide and fission-product waste from at least two 1000 MWe light water reactors (LWRS) and, through a reasonable thermal efficiency, to produce enough electricity to power the accelerator. It is desirable to exceed our design goals. For example, if we can support more than two LWRS per target/blanket module and send more power to the grid by increasing our thermal efficiency, the ATW becomes much more economically feasible. Companion papers on a system analysis, and a more efficient thermal cycle are given at this conference.

II. DESIGN FEATURES

The target/blanket design is comprised of a centrally located neutron source surrounded by a blanket that contains a moderator, fission products, and actinides. A description of the various regions, the thermal hydraulic components, and neutron physics studies is given below.

A. Neutron Spallation Target

We have considered a number of potential target materials and configurations for the spallation neutron source. These include uranium, solid lead, liquid lead, lead-bismuth, tantalum and tungsten. After comparing the relative advantages and disadvantages with respect to neutron production, parasitic capture, waste stream generation, thermal characteristics, prototypic experience, and material compatibility we have chosen tungsten as the reference design material. A tungsten target is used at the Los Alamos Neutron Scattering Center (LANSCE). This target is surface cooled with light water, and employs a void region to provide a flux trap. It is well known that tungsten is a moderate neutron absorber. To compensate for the parasitic capture, the void region between the tungsten cylinders allows for increased neutron leakage. Because tungsten is used in the LANSCE target, disposal is not a serious issue. For example, a target was recently replaced and the old target discarded at a local on-site waste depository.

In ATW, tungsten target intercepts the proton beam and produces the main source of neutrons. The proton beam impinges on the target with a 25-cm square shape and has a flat power profile. The beam first passes through an entrance window which is a double wall inconel structure cooled with D_2O. A lead region surrounding the tungsten produces additional neutrons from scattered protons and (n,xn) reactions. Most of the heat in the target is deposited in the tungsten. The tungsten is in the form of small diameter (0.3 175 cm) rods that are spaced with wire wrap and placed in inconel hexagonal channels (Fig. 1). Each channel contains a bundle of 91 tungsten rods. The assembled target is made of multiple rows of the tungsten rod bundles separated by approximately a 10-cm space containing low-pressure helium. Each channel receives about 3.96 kgfs of D20 with an average coolant velocity of 6.07 m/s, which flows parallel to the rods. The average power density in the tungsten is 3.02 MW/l, which produces a peak rod temperature of 189°C and a maximum fluid temperature of 177°C (an approximately 77° C film-temperature drop). The pressure of the coolant is 1.33 MPa at the outlet of the rod bundle, which provides 15°C of subcooling. The rod bundles contain by volume 51% tungsten, 7.7% inconel structure, and 42.3% D20 coolant. The total length of the tungsten region provides an equivalent thickness of 30.4 cm of tungsten.

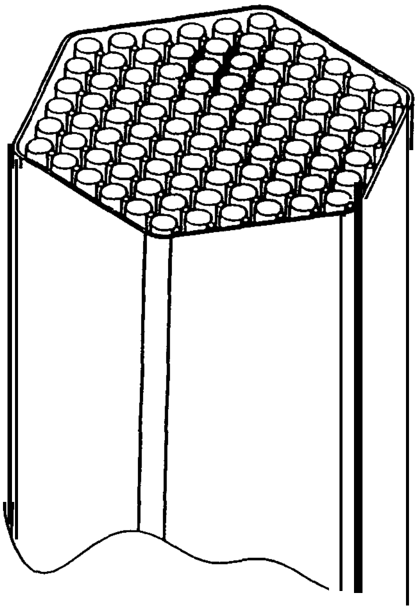


Fig. 1.
Tungsten neutron source design.

B. Blanket

The blanket consists of regions for fission products and actinide transmutation and employs a heat-transfer loop similar to the CANDU reactor design. The blanket is housed inalow-pressure moderator tank that contains the structure to support the target, zircaloy tubes that contain the technetium fission-product solution, and -250 double-walled tubes that contain the actinides (Fig. 2). Each actinide tube is 10 cm in diameter, is constructed from zircaloy, and contains about 23.51 of slurry. The average power density is 0.26 MW/l with 26.9 kgJs flow rate through each tube at an average velocity of 3.7 m/s. The sensible heat gain causes the slurry temperature to increase from 197 to 249°C.

As a basis for the overall blanket-system configuration and balance of the plant, the D_2O-CANDU reactor system is used. The CANDU system operates at a baseline primary-system pressure of 13.1 MPa, with the secondary side of the primary heat exchanger at 13.2 MPa. The system has a thermal-to-electric conversion efficiency of -3 1%. For ATW, an advanced system would operate at a similar pressure of 13.5 MPa, and have a thermal efficiency of about 30%. However, to reduce the structural material for the base case, we have reduced the slurry system pressure to 4.6 MPa. This change has favorable neutronic consequences because of the reduction in parasitic capture in the tube's zircaloy. The lower pressure (and corresponding temperature drop) makes the slurry-based system more reliable. With this system, we obtain a thermal efficiency of about 2070.

We made several modifications to the CANDU configuration for ATW. To eliminate the possibility of the release of slurry material to the steam generator, we added an intermediate heat-transport loop that uses light water as a working fluid. The intermediate system operates at 4.7 MPa, which is slightly higher than the slurry pressure. This heat is then transferred to the steam generator, which operates at 1.1 MPa. These low-pressure conditions are similar to the conditions at the N-Reactor (Hanford, Washington). Although the base-case design operates at a low thermal efficiency, it is sufficient to power the accelerator.

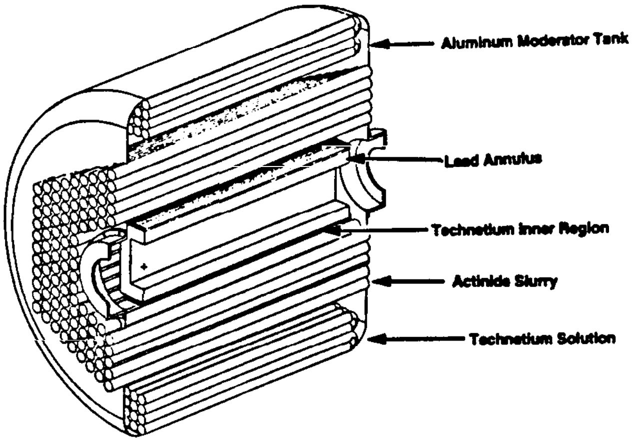


Fig. **2.**
ATW blanket design.

A large base of experience was gained in the development of homogeneous nuclear reactors in the 1950s at Oak Ridge National Laboratory (ORNL). During this time both U03 and ThO_2 slurries were studied. The U03 slurries were at concentrations of several hundred g/L at 250°C; the ThO_2 slurries were concentrationsof5G1500 g/L up to 300°C. During fission, it was found that particles of less than 10 microns in diameter eject daughters from the particle. Information regarding the material effects, particle size, equipment development, particle preparation, and chemistry is available. Based on several long-duration loop tests at ORNL, zircaloy shows good resistance to erosion up to 500 g/L and 300°C for flow velocities up to 5.0-6.0 m/s. For ATW, we require a 75 g/L slurry, and flow velocities of 3.7 m/s. Based on the ORNL experience, zircaloy is a good choice for containing the slurry.

C. Beam Entry Window

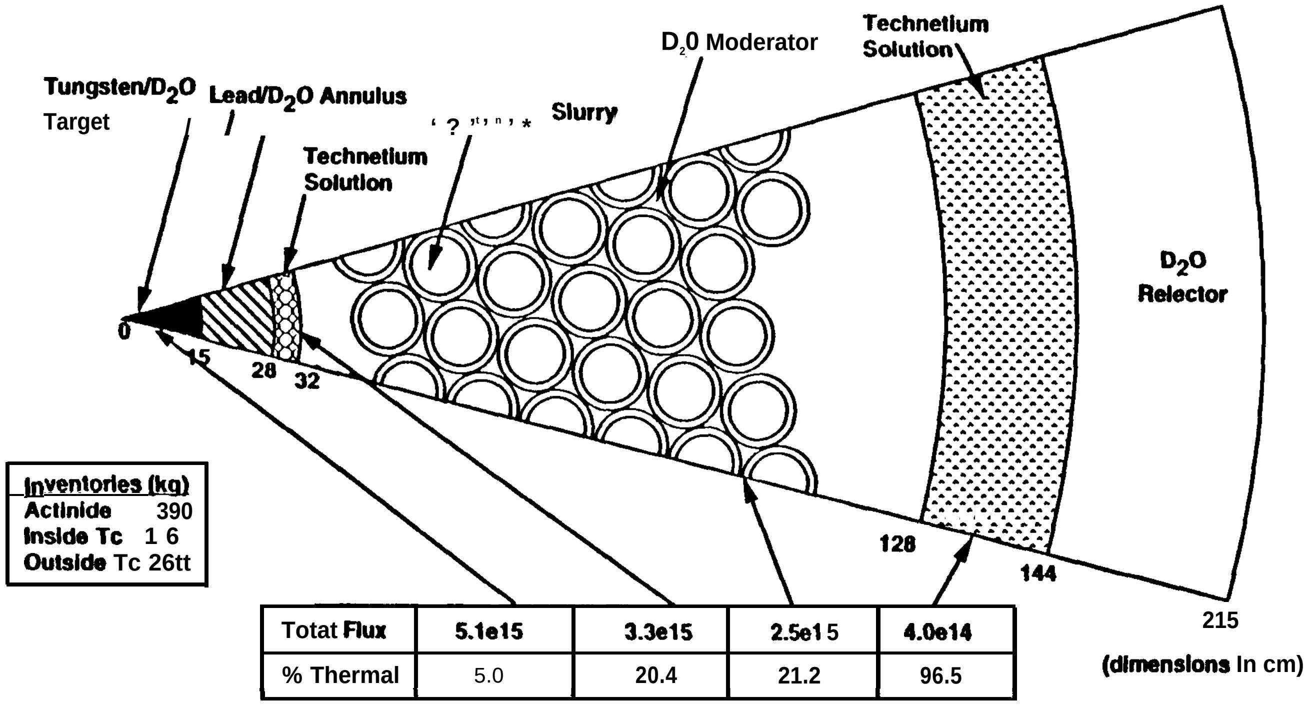
At high-energy accelerator facilities, a metal interface is used to maintain a vacuum in the accelerator and to protect the equipment in the experimental area. In accelerator-facility jargon, this metallic interface is referred to as a window. Results of research at the Los Alamos Meson Physics Facility (LAMPF) have provided considerable data about window survivability. The LAMPF accelerator produces an 800-MeV, 1-mA beam. The double-walled flat window used on the current beam stop at LAMPF has been exposed for 17,500 h at 20-30 μA/cm² for a total proton fluence of 1.3 x 10^{22} p/cm². This window is made of Inconel 718.

For a comparison with ATW, the 1600-MeV, 62.5-mA proton beam provides an average flux of about 70 μA/cm², and in one full-power year provides 1.4x 10^{22} p/cm² of proton fluence. This fluence is similar to that of the LAMPF beam stop window, which is still in service. Although the energy level for the ATW accelerator is twice that of LAMPF, the damage to the window is expected to be roughly the same. Thus, it may be reasonable to assume that a window in ATW would require replacement no sooner than every 6 months. Lifetime tests will be conducted to determine the performance of the final window design for ATW. Based on the experience at LAMPF, we have chosen Inconel 718 as the material for the beam entrance window and the tungsten rod bundle channels. These are the primary structures that are exposed to the proton beam.

III. PHYSICS ANALYSIS

We have performed ID and 3D physics calculations to investigate the performance of an aqueous ATW blanket to burn actinides and long-lived fission products from the LWR fuel cycle. The calculations were performed with equilibrium actinide isotopic concentrations that were derived from iterative neutron transport and point depletion analyses. Also it was necessary to prepare several actinide and high-temperature D_2O cross sections. The calculations indicate that a blanket, combined with a 1600-MeV, 62.5-mA beam, may be able to transmute wastes from slightly more than two LWRS. The results of our simulations including the geometry, inventories, and flux levels are depicted in Fig. 3.

Each LWR produces about 33 kg of technetium, 7 kg of iodine, and 300 kg of actinide mixture (neptunium, americium, and plutonium) per year. There are several ways to add the technetium and actinides depending on the parameters that are being optimized. These parameters include beam current, and actinide and technetium



Totat Flux	5.1e15	3.3e15	2.5e1 5	4.0e14
% Thermal	5.0	20.4	21.2	96.5

Fig. 3. ATW blanket physics calculations.

inventories. Based on the results of various sensitivity studies performed in one dimension, we decided to add technetium in thin-walled zircaloy tubes in two parts of the blanket: 1) in a relatively thin buffer region between the target and actinide tubes, and 2) toward the outside of the radial reflector. The inner buffer region allows the burning of some technetium in a region of high neutron flux, thereby reducing the total technetium inventory. It also increases the neutron efficiency by capturing neutrons in technetium that would otherwise be reflected back and lost in the target materials. Finally, varying the thickness of the inner buffer region affords a convenient way of balancing the required actinide and technetium burns. After optimizing the physics design with ID calculations, 3D MCNP calculations were performed to obtain final physics parameters. The system operates at a k_eff of 0.946. For each accelerator produced neutron (from the tungsten source), 11.8 neutrons are produced from fission in the actinide slurry, 0.309 neutrons are captured in the inner Tc region, 0.746 neutrons are captured in the outer Tc region, and 0.502 neutrons leak out of the system.

Iv. SAFETY

The ATW is a complicated design that contains a variety of loops and coolant systems. Separate coolant systems are provided for the tungsten neutron source, the beam entrance window, the moderator (which also contains the lead multiplier), the technetium fission products, and the actinides. The majority of the heat generation is produced in the tungsten rod bundles and the actinide slurry.

Through the process of spallation, the tungsten rod bundles become radioactive. The resultant decay heat is 0.5% of full power (a factor of ten less than a fission reactor). This, coupled with the fact that the tungsten is a very high-temperature material (3300°C melting point), provides for inherent safety. In fact, system transient analyses show that with a two-loop coolant system, the rod temperatures will remain below 200°C even during a large-break loss-of-coolant accident. In addition, if the coolant is completely lost for some reason, radiation heat transfer alone will keep the tungsten below the melting point of the material during decay heat.

A more potential safety concern is the actinide slurry. A safety advantage is that the system operates in a subcritical mode and the slurry is dilute. The main disadvantage is that the slurry's primary containment is the primary loop piping. To provide containment of radioactive material in the event of a pipe leak or break, the primary loop, pump, and heat exchanger must reside inside a containment vessel. To address the safety concern, we are investigating the possibility of using an in-vessel heat exchanger. In this design option, the actinides would remain in the blanket, and fission heat would be transfered to a separate non-radioactive coolant. This would reduce significantly the overall actinide volume, and facilitate containment.

V. CONCLUSION

Design concepts are being developed for the aqueous target/blanket system of the ATW. Our base-case design employs a solid tungsten and lead target that is D20 cooled. This innovative target produces neutrons efficiently and with a minimum of parasitic capture. The blanket consists of regions for fission products and actinide transmutation, and employs a heat-transfer loop similar to the CANDU reactor design. The neutronics and thermal-mechanical design have been investigated in some detail for the base-case design. The design goals are to optimize the neutron utilization, minimize material inventories, make use of existing technologies to the extent possible, and place a high priority on the overall environmental and safety considerations. Our neutronics and thermal-hydraulic calculations indicate that each of the four ATW target/blanket modules operating at a k_eff of 0.95, combined with a 1600-MeV, 62.5-mA proton beam, can transmute the actinide waste and the technetium and iodine waste from two LWRS. In addition, by recovering some of the fission heat, we can produce sufficient electricity to power the accelerator and return a small amount to the grid. We are currently investigating the use of in-core cooling of the slurry to reduce the actinide inventory and increase safety characteristics.