Spallation Neutron Source for Fast Reactor Fuels Testing

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The Global Nuclear Energy Program (GNEP) has limited options for testing new fuels that incorporate the long-lived actinides from otherwise spent fuel. The proposed Materials Test Station (MTS), to be operated at the LANSCE (Loa Alamos Nuetron Scattering Center) accelerator at LANL (Los Alamos National Laboratory), is intended to fulfill that need. The MTS target is comprised of 2 stacks of 20 rectangular tungsten plates, 2.3 X 16 cm, that sandwich a flux trap region loaded with the reactor fuel rodlets. The 800 MeV proton beam, at current up to 1.25 mA, is split and rastered to create 2 rectangular beam spots measuring 1.5 X 6 cm at the front of the target. The plates are separated by 1 mm wide coolant gaps. To maintain fuel test temperatures up to 550°C, target and flux trap coolant is the lead-bismuth eutectic (LBE). This coolant can operate at high temperature and low pressure without boiling. This choice of coolant is substantiated by the extensive LBE experience in Russia, at LANL, and the recent success of the MEGAPIE target in Switzerland. This paper describes the target design, fabrication, cooling, and production of fast neutron flux at the fuel (1.4 X 10^{15} n/cm^2-s, peak).

I. INTRODUCTION

The requirements on the MTS for testing GNEP candidate fuels have placed severe constraints on the target design, resulting in unique and challenging solutions to the problems of material selection, target cooling (including decay heat removal), mechanical robustness and fabrication. One primary constraint is the high operating temperature of the target necessitated by the required fuel test temperature and the intimate contact between the target and the fuel dictated by the need to maximize neutron flux on fuel and the need for decay heat removal. This set of requirements leads to the selection of lead-bismuth eutectic coolant of a tungsten target with high solid (tungsten) volume fraction. The high flux requirement drives the design to thin-walled structures and low coolant fraction. The structural design analysis and the thermal hydraulic analysis are presented in this paper. Fabrication options are also presented. While the split target (2 target halves) are integral with the flux trap (fuel module) between the target halves, this paper describes the fuel module only in so far as is necessary to fully describe and understand the targets, their performance and their fabrication.

II.TARGET DESCRIPTION

The target/fuel module (TFM) is the heart of the MTS. The TFM was once 3 separate modules (2 targets with the fuel module in the flux trap between the targets). The requirement for decay heat cooling in a loss of coolant accident led to the decision to integrate these into one module to provide a conduction path. A view of the TFM with a horizontal cross-section is shown in Figure 1. The center of the module has 8 channels of isosceles trapezoidal cross section with rounded corners. Each trapezoid contains 5 fuel rodlets. The height of the module is driven by the height of the fuel rodlets, which is 36 cm, 12 cm of which is active fuel. The target halves are centered on the 12 cm active fuel section of the fuel, leading to the asymmetric geometry in the vertical plane. In addition, some fuel is located forward of the front of the target to create a region wherein the He-to-dpa ratio is more prototypic of a fast reactor, creating an asymmetry in the horizontal plane as well.

Each target half is comprised of a stack of 20 W plates separated by 1 mm coolant gaps. The thickness of the W plates increase with distance through the target as the beam energy and resulting volumetric heating of the W are reduced. Plate thicknesses have been set for uniform heat flux, starting at 4.0 mm at the front of the target and increasing to 22.5 mm as the beam energy degrades. Peak hest flux is nominally 550 W/cm^2 at the design current of 1.25 mA. The increased total plate power toward the rear of the target, without increased peak heat flux, is due to beam spreading. Plate thicknesses and heating information is listed in Table 1. The increased total power, with fixed coolant mass flow, results in greater heating and a slight increase in buoyancy effects. The exit temperatures for the lowest and highest total power coolant channels is 493 and 568ºC, respectively, yet the change in pressure drop due to buoyancy effects is only 143 Pa. This compares insignificantly to the overall pressure drop through the target of 58000 Pa.

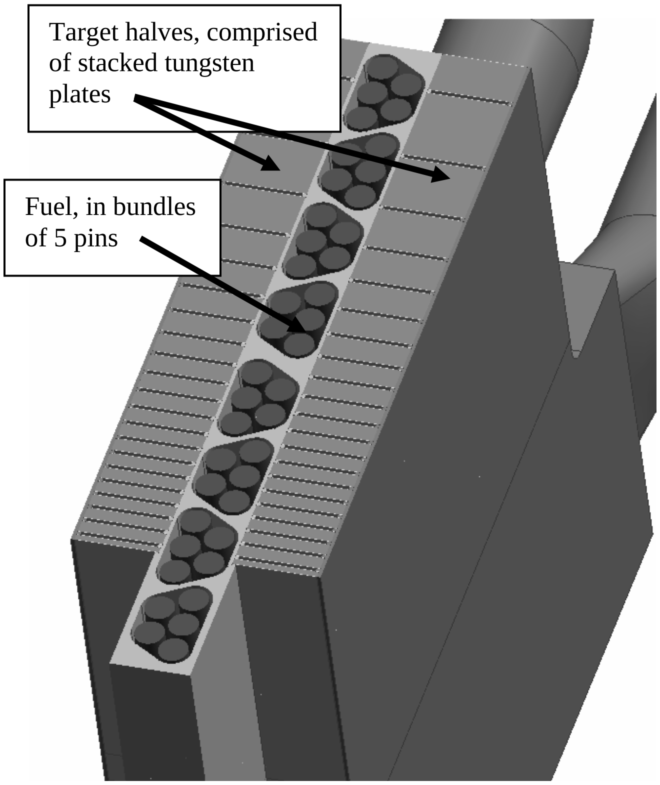

Fig. 1. Cross-section view of the fuel module along with the integral target halves.

The target front and rear faces are Ta. The W and Ta plates are clad in HT-9 steel, 0.127 mm (0.005 in) thick. Although there is no corrosion reaction between LBE and tungsten, and there are no volatile radioactive vapors possible (as in the case of an overheated water-cooled tungsten target), the clad serves to maintain the structural integrity of the W in the event that the brittle material cracks under thermal or mechanical loads. The cladding will contain the W and minimize the chance of partial flow channel blockage.

The targets have coolant manifolds top and bottom, with parallel flow through the plate coolant channels from bottom to top (see Figure 2). The module housing will be fabricated from HT-9 steel, chosen for its strength at 550°C and its compatibility with the LBE coolant. Alloy HT9 steel is a ferritic/martensitic Cr-Mo stainless steel. The ferritic/martensitic stainless steels are generally defined as those containing at least 10 wt.% chromium and have microstructures of α-iron (ferrite) plus carbides. Alloying elements in addition to Cr and Mo are W (up to 3 wt.%), V (<0.5 wt.%), and Nb (<0.5 wt.%). Alloy HT9 is classed as a 12C-MoVW type.

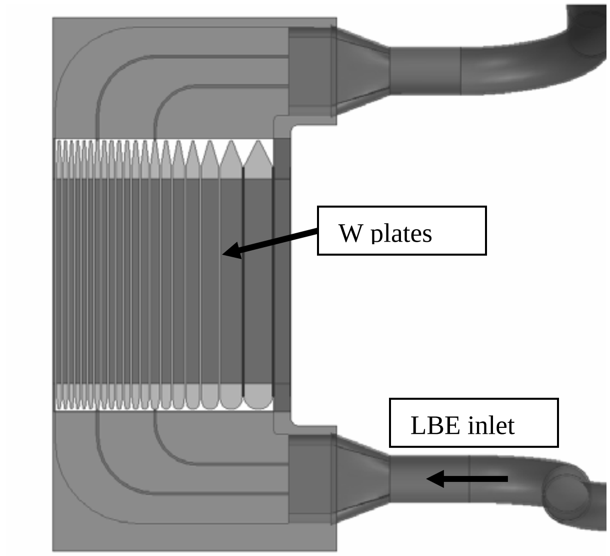

Fig. 2. Cross-sectional view of a target half.

TABLE I. Table of target plate thicknesses, with total power and maximum heat flux.

Plate No.	Thickness (mm)	Power (kW)	Flux (W/cm^2)
1	4.0	10.8	571
2	3.8	10.5	558
3	3.8	10.4	548
4	3.9	10.6	541
5	4.0	10.6	542
6	4.2	10.9	545
7	4.3	10.7	543
8	4.5	10.8	537
9	4.8	10.9	531
10	5.1	11.1	546
11	5.4	11.1	542
12	5.9	11.4	548
13	6.5	11.7	551
14	7.2	12.0	556
15	8.1	12.3	560
16	9.4	12.9	572
17	11.0	13.2	573
18	13.6	13.8	566
19	17.6	14.5	566
20	22.5	14.0	493

III. TARGET THERMAL-HYDRAULICS

The target plates are cooled with liquid LBE flowing upward in the 1 mm gaps between plates at 1.75 m/s. Because of the very low vapor pressure at the operating temperatures, there is no concern for 2-phase phenomena. The flow velocity is a compromise between minimizing the coolant temperature rise in the target and minimizing corrosion, erosion and pressure drop. While Russian lead-cooled reactors have operated at 1.8 m/s for extended periods of time (Ref 1), there is experimental evidence that this velocity and higher can cause significant erosion at the entrance regions (Ref 2). Erosion tests are planned for the conditions and geometry of the MTS target.

At this velocity, pressure drop through the target, based on entrance form loss, channel flow and exit form loss, is 72 kPa. The loss coefficients used for entrance and exit are 0.25 and 1, respectively (Ref 3). Friction factor (0.025) was calculated by:

$$f = 1.02\,(\mathrm{Log}(Re_d))^{-2.5} \qquad (1)$$

also from Ref 3, with Reynolds Number, Re (24300), based on the hydraulic diameter of the rectangular channel.

Heat transfer coefficient is calculated using the following correlation (Ref.4):

$$Nu = 5 + 0.025Pe^{0.8} \qquad (2)$$

Where Nu is the Nusselt number an dPe is the Peclet number. Thermal and hydraulic target conditions for the target are listed in Table 2.

TABLE 2. Target module operating conditions for a channel velocity of 1.75 m/s (each half).

Total Power (kW)	208
Target plate length (cm)	16
Peak heat flux (W/cm^2)	572
Flow Area (cm^2)	4.4
Velocity (m/s)	1.75
Vol. flow rate (l/s)	0.77
Re	24300
Nu	7.6
h (W/m^2-ºC)	58800
LBE temp rise (ºC)	225
Wall-LBE ΔT (ºC)	119
Pressure drop (kPa)*	193

* Total circuit pressure drop through heat exchanger, pumps, etc.

IV. TARGET FRONT FACE ANALYSIS

The target design is driven in part on the need for a front face design that meets ASME BPVC allowable stress criteria. This is the dominate stress-related design concern. The target module is shown in cross-section view in Fig 2. The target front face will be a contoured tantalum plate clad in the HT-9 foil. Fig 3 shows the results of a thermal analysis of the target front face with the first tungsten target plate (peak temperature 650 ºC). The contour on the front face provides for a more uniform temperature distribution. Tungsten is not suitable for the front face material because it is too brittle to serve as a containment boundary for the coolant. The high coefficient of thermal expansion (CTE) of HT-9 precludes it use as a front face due to the large expansion mismatch with tungsten.

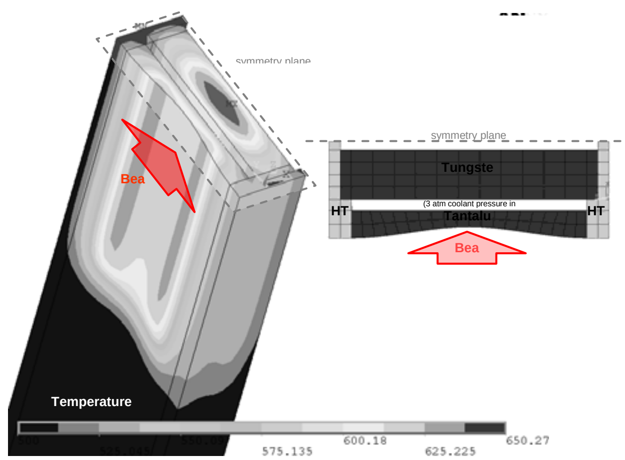

Fig. 3. Temperature contours in tantalum front face at beam-on conditions.

A multi-step FEA analysis was performed on the target front face to assess fabrication and operation stresses in the tantalum. The results of this analysis are shown in Figure 4. The first step is a cool-down to room temperature following a post-fabrication heat treat at 760ºC, which results in a slight plastic deformation in the tantalum. The second and third steps are beam-on operation (Fig 2 temperatures) and beam-off station keeping (400°C). The operating stresses are within the elastic regime. The results from this analysis are within the ASME Boiler and Pressure Vessel Code allowable design stresses for tantalum.

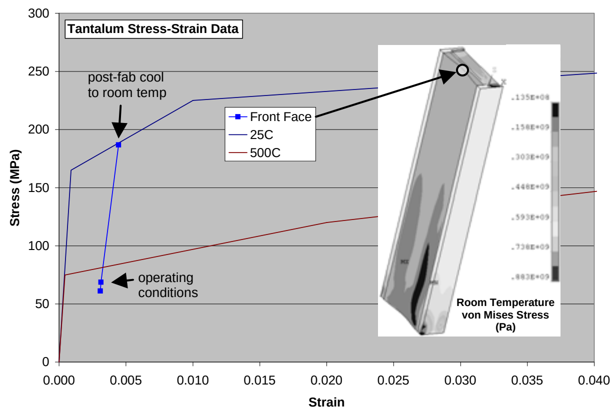

Fig. 4. Tantalum stress-strain data.

V. TARGET-FUEL MODULE FABRICATION

The target and fuel combined module will be fabricated in a series of diffusion bond steps. In the first step, the W plates and 2 Ta plates (front and back target faces) are clad on the front and back faces with HT-9 in a hot isostatic press (HIP) operation. The module is then built up from the back forward in a number of slices of varying thickness in the vertical plane. The backmost slice is an HT-9 plate that ultimately forms the back wall and the inlet and outlet piping for the targets, up to a flange seal. Then, moving forward, the stack of slices alternates between slices the thickness of the W or Ta plates and plates 1 mm thick with the coolant channels machined in. The target plates are set in pockets in the slices designed to hold them. The inlet and outlet manifolds of the targets are also machined into each slice. Pilot holes for eventual electron discharge machining (EDM) of the fuel channels are incorporated into the slices at the appropriate locations. The slices are stacked and diffusion boned in a uniaxial press furnace at a predetermined pressure and temperature. In Fig 5 is a cross-sectioned stack of slices showing the details of the plates and channels. After the diffusion bonding steps, the fuel channels and manifolds are machined into the part.

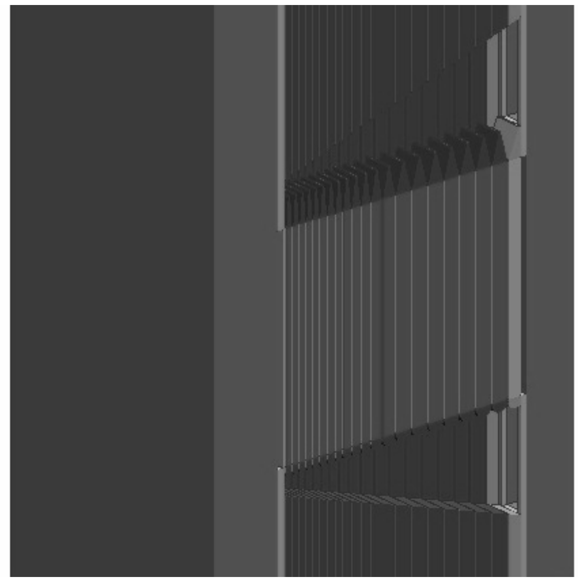

Fig. 5. A section view of the stack of slices, showing the W target plates, cooling channels and integrated manifolds.

An alternative fabrication technique, also a series of diffusion bond steps, builds the combined module in the other vertical plane, perpendicular to the beam. This process begins with a block of HT-9 machined to the dimensions of the fuel module but with the target plate end caps as raised features 2 sides, as shown in Fig 6. Each tongued target plate is slid into its mating grooved end caps, a cover plate with 1 mm raised ribs to maintain the coolant gaps is placed over the target plates, and the part is diffusion bonded in a uniaxial press. See Fig 7. Inlet and outlet manifolds are integrated into the diffusion bonding step. Some final machining and welding is required to complete the part.

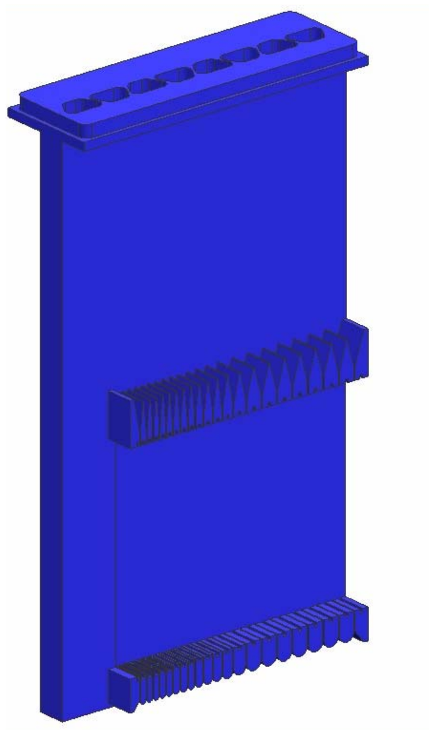

Fig. 6. Fuel module block with target plate end cap features.

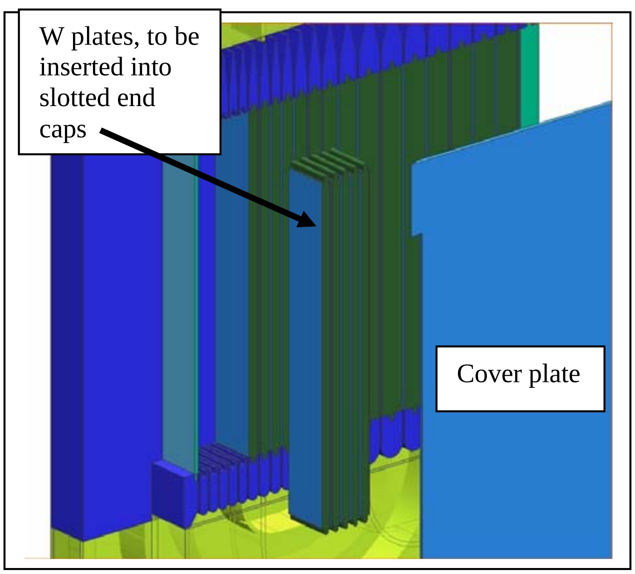

Fig. 7. Tongued target plates being slid into their mating grooved end caps, with cover plate to from outer wall after diffusion bonding.

A series of tests are planned in order to establish the best diffusion bonding parameters. The first such test will determine suitable bonding pressure, temperature and coatings for bonding HT-9 to W, HT-9 to Ta, and HT-9 to HT-9. This test will be conducted by Refrac Systems, a company based in Phoenix, AZ. Table 3 lists the parameters to be used for 3 separate bonding tests.

The stack of materials to be bonded in each of the 3 heats listed in Table 4 is shown in Figure 7. Material cleaning, coating and diffusion bonding will take place at Refrac. All parts that have been EDM'd with a brass wire will be etched with a sulfuric acid solution to remove any copper or zinc. For most metal pieces, coating will be done on only 1 surface of each metal piece indicated in Figure 7. One piece of HT-9 will have Ni-P coating on top and Ni coating on bottom.

TABLE 3. Time, Temperature, Pressure specifications for experiments DB-1, DB-2, DB-3

Experiment	Temperature (C)	Pressure (MPa)	Time (hrs)
DB-1	1060	5.5 (800 psi)	1
DB-2	1060	34.5 (5,000 psi)	1
DB-3	800	34.5 (5,000 psi)	24

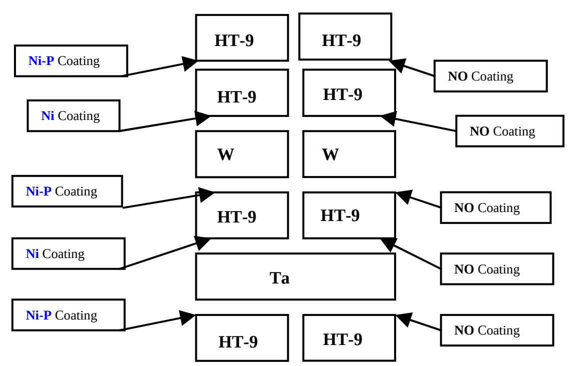

Fig. 8. Diffusion Bonding Stack for DB-1, DB-2, DB-3. Front View.

VI. CONCLUSIONS

The target described above meets the requirements for fuels irradiations for the GNEP program. The current status is that of conceptual design. Many details remain to be resolved, including erosion and corrosion rates, swelling effects, fabrication methodology and accident and off-normal events. The high temperature, high power conditions have resulted in a unique target design that contributes new ideas to the global community seeking ever high power densities in spallation neutron targets.

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