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The materials test station: A fast-spectrum irradiation facility

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ABSTRACT

The United States Department of Energy is developing technologies needed to reduce the quantity of high-level nuclear waste bound for deep geologic disposal. Central to this mission is the development of high burn-up fuel with significant inclusion of plutonium and minor actinides. Different fuel forms (e.g., nitrides, oxides, and metal matrix) and composition are under study. The success of these cannot be judged until they have been irradiated and tested in a prototypic fast neutron spectrum environment. In 2005, the US Congress authorized funding for the design of the materials test station (MTS) to perform candidate fuels and materials irradiations in a neutron spectrum similar to a fast reactor spectrum. The MTS will use a 1-MW proton beam to generate neutrons through spallation reactions. The peak neutron flux in the irradiation region will exceed 1.2×10^{19} n m^{-2} s^{-1} and the fast neutron fluence will reach 2×10^{26} n m^{-2} per year of operation. Site preparation and test station fabrication are expected to take four years.

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1. Introduction

In February 2006, the United States Department of Energy (DOE) announced plans for its global nuclear energy partnership [1], which seeks to reduce the risks of nuclear proliferation while simultaneously expanding the use of nuclear power worldwide. Central to achieving these goals is the development of a closed nuclear fuel cycle wherein spent fuel from nuclear reactors is recycled, resulting in more effective utilization of the world's limited uranium resources and a significant reduction in the amount of high-level radioactive waste.

Recycling spent fuel involves transmuting minor actinides (Np, Am and Cm) in fast-spectrum nuclear reactors. While such reactors have existed for over half a century, they have not traditionally been designed to transmute minor actinides (MA's). This function requires the development of new fuel forms containing significant quantities of minor actinides that can survive high fast-spectrum neutron fluence ($>10^{27}$ n m^{-2}). Qualification of new fuel forms will require testing in prototypic spectra. Unfortunately, only a few fast-spectrum irradiation facilities exist around the world. There are no fast reactors currently operating in the USA, and the earliest a new reactor could reasonably be expected to begin operation would be towards the end of the next decade.

Recognizing the need to establish a domestic fast-spectrum irradiation capability, in 2005 the US Congress appropriated funds to design the materials test station (MTS), to be located at the Los Alamos Neutron Science Center (LANSCE) [2] within Los Alamos National Laboratory (LANL). The primary purpose of this facility will be to irradiate candidate MA-bearing fuels and cladding being developed under the global nuclear energy partnership. The MTS will differ from all other fast-spectrum irradiation facilities in that it is not a nuclear reactor. Rather, the primary source of neutrons is spallation reactions resulting from the interaction of 800-MeV protons with tungsten nuclei.

For nearly three decades, the LANSCE accelerator reliably delivered 1 mA of 800-MeV protons (H^+) to pion production targets in support of fundamental nuclear physics experiments. While the LANSCE accelerator has continued to deliver 800-MeV H^- beam to other targets, the 1-mA proton beam has not been utilized since 2000. The DOE is planning to refurbish the LANSCE accelerator so that it can continue to reliably deliver beam for another two decades or more. This refurbishment consists primarily of replacing antiquated power supplies that deliver radiofrequency power to the accelerator structure. Once refurbished, the LANSCE accelerator will be capable of delivering 1.25 mA of 800-MeV protons, or 1 MW of proton beam power, to the MTS, with no reduction in beam delivery to all other existing facilities at LANSCE.

2. Target design

The basic configuration of the MTS target system, depicted in Fig. 1, consists of two spallation target regions separated by a fuel irradiation region. The spallation targets are tall, narrow blocks of tungsten cooled by liquid lead–bismuth eutectic (Pb–Bi). The fuel irradiation region is 20 mm wide and can hold up to 40 fuel pins, each with an active fuel pellet stack height of 120 mm. The pulsed

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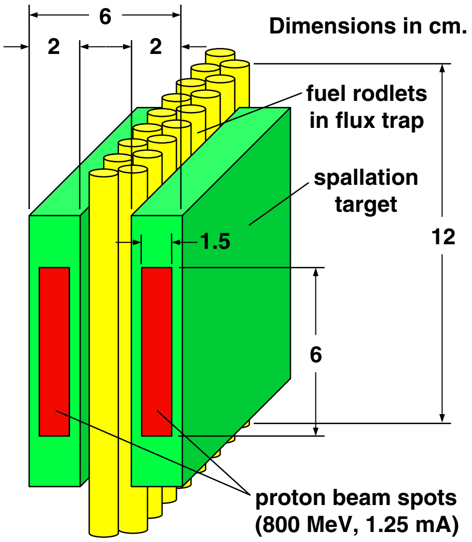

Fig. 1. Basic configuration of the MTS target assembly.

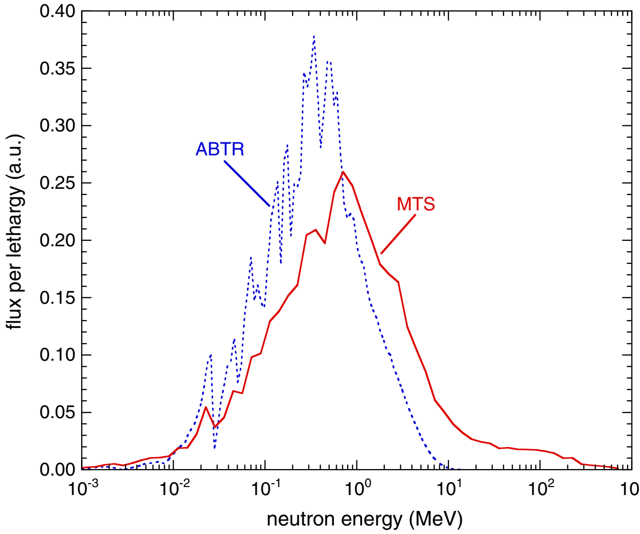

Fig. 3. Neutron energy spectrum at the peak flux position in the irradiation zone of the MTS compared to that of a fast reactor (ABTR).

nature of the proton beam allows alternate beam pulses to be directed onto first one, then the other, spallation target in a straightforward and direct manner.

The reason for using two spallation target sections and alternating the beam pulses between them is to achieve nearly uniform time-averaged neutron flux in the fuel irradiation region, which is located between the two spallation targets. Fig. 2 shows the spatial distribution of the neutron flux from a horizontal cut at target mid-plane. It shows the flux gradient across the 20-mm gap between spallation targets to be quite low. The peak flux occurs directly in the spallation targets where most of the neutrons are created. The peak flux in the fuel irradiation region is 1.6×10^{19} n m^{-2} s^{-1}.

The neutron spectrum at the peak flux position in the irradiation region is compared to the spectrum of a fast reactor in Fig. 3. The fast reactor chosen for comparison is the proposed advanced burner test reactor (ABTR) [3], which is currently undergoing pre-conceptual design. The MTS spectrum is quite similar to that of a fast reactor, with the addition of a high-energy tail above 10 MeV that reaches up to the incident 800-MeV beam energy. The only significant impact of this high-energy tail is high hydrogen and helium production in metals. Compared to an equivalent flux level in a typical fast reactor, the peak flux position has about 60 times greater helium production rate in iron. For the ferritic/martensitic steels that are currently under consideration as fuel clad material for fast reactors, high concentrations (>600 appm) of helium can lead to embrittlement. The impact of higher-than-prototypic fast reactor helium production in candidate clad materials irradiated in the MTS must be given careful consideration with respect to assessing clad performance.

Calculations indicate that He production in oxide fuels irradiated in MTS is about twice that produced in a typical fast reactor. Yet, when considering overall gas production that includes the heavier nobles produced by fission (Xe and Ar), calculations predict that gas production in fuel irradiated in MTS is not appreciably greater (~10%) than that produced in fast reactors.

The spallation targets consist of tall (180 mm), narrow (21 mm) tungsten plates stacked along the direction of proton beam propa-

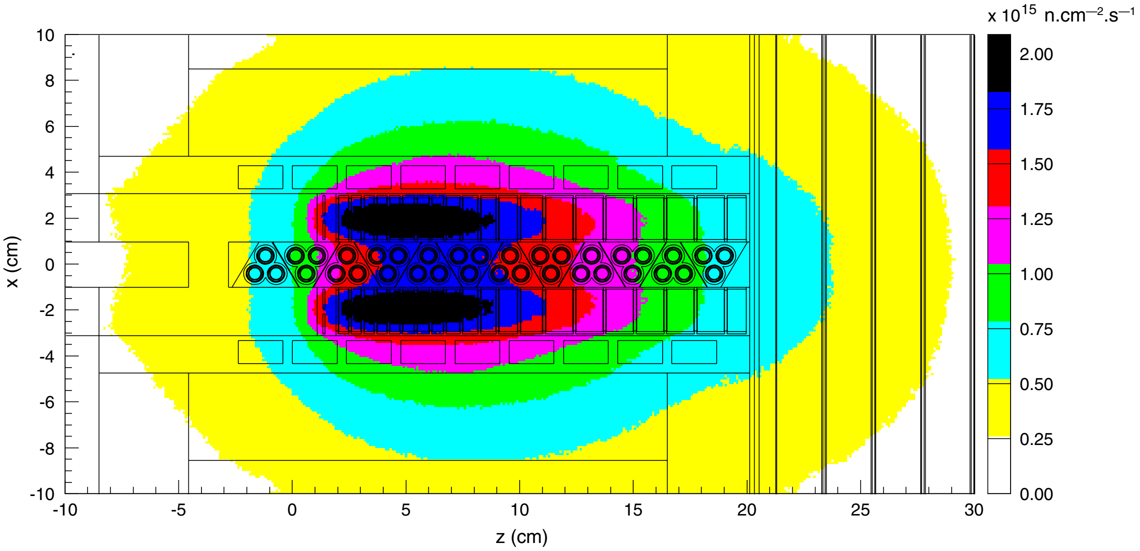

Fig. 2. Spatial distribution of the neutron flux at target mid-plane.

gation. The plates start out thin (4.4 mm) at the front end of the target, and grow progressively thicker (up to 20 mm) toward the back. Between the plates are 1-mm-thick cooling channels. The plate thicknesses are adjusted in this manner so that the heat flux at the cooling surfaces is limited to 6 MW/m², which does not challenge the thermal-hydraulic capability of the Pb–Bi coolant.

A critical parameter for obtaining meaningful irradiation data is the temperature at which the irradiations are performed. In order to achieve conditions similar to that of a fast reactor, the fuel clad temperature must be controlled within a specified tolerance, and irradiation temperatures up to 550 °C must be attainable in the MTS. These requirements are very difficult to achieve using water as the fuel coolant. After considering a number of coolant options, Pb–Bi has been selected as the coolant for the test fuel pins. This coolant does not react exothermically with water or air (as is the case with sodium), has a high heat transfer coefficient, and is liquid over a large temperature range. It has the disadvantages of not being a liquid at room temperature (requiring trace heating on loop piping and components), requiring active oxygen control to reduce corrosion, and producing ^{210}Po as an activation product. Polonium-210 is an alpha emitter with a 138-d half-life, and limiting its release during off-normal events will require special attention to the design of safety systems. The high heat transfer coefficient of Pb–Bi yields a relatively low film drop (~30 °C) that is predictable to within 30%. Thus by measuring the inlet and outlet temperatures of the Pb–Bi, the fuel clad temperature at any point along the fuel pin height should be known to within 10 °C. The fuel clad temperature can be controlled by adjusting the Pb–Bi inlet temperature, which can be done in a straightforward manner.

3. Facility design

The beam spot on each spallation target is nominally 15 mm wide by 60 mm tall. A nearly uniform current density over the beam spot is achieved by rastering a small beamlet (approximately 3 mm wide by 8 mm high, FWHM) over the beam spot dimensions. This results in a peak current density on target of 70 μA/cm². Over a calender year, the MTS is expected to operate 4400 h at a beam current of 1.25 mA. Thus the annual proton dose on the target front face will be 6.9×10^{25} protons/m². For reference, a tungsten target at the ISIS facility at the Rutherford Appleton Laboratory in the United Kingdom was replaced after receiving a dose of 3.2×10^{25} protons/m² due to the failure of thermocouples used to monitor plate temperatures. At the time of replacement, the target was performing satisfactorily [4]. Thus the anticipated minimum life of the target is expected to be 6 months, but the expectation is that, with operating experience, it will not require more than annual replacement. The leading candidate material for the fuel module housing and spallation target housing is T91 alloy, a ferritic/martensitic steel that has demonstrated good ductility retention to high dose in fast reactor environments. T91 alloy was used as the Pb–Bi container material in the recently completed MEGAPIE experiment [5]. In this application, the T91 alloy received a proton dose of up to 1.1×10^{25} protons/m². Post-irradiation examination of this material is anticipated before 2010.

A beam transport system, shown in Fig. 4, has been designed that meets the beam-on-target requirements. The horizontal and vertical beam envelopes for the final 72 m of transport are shown in Fig. 5. The raster magnet section, consisting of a total of 10 magnets, produces a crossover in beam deflection 7.5 m upstream of the target front face. A 2-m thick backstreaming shield wall is located at this crossover position, with only a 50-mm diameter beam pipe penetrating the wall. This reduces activation of all beam line

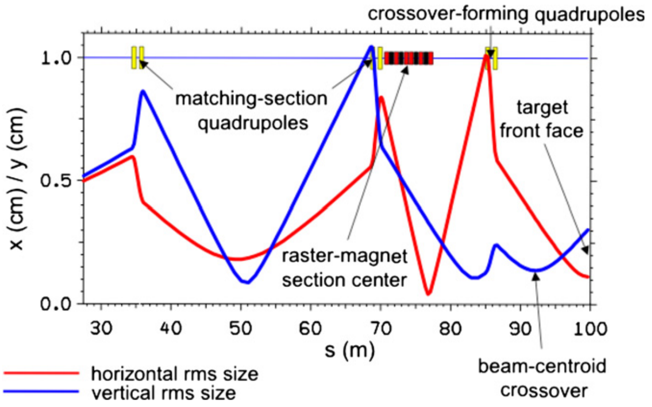

Fig. 5. Beam envelope through the final 72 m of the beam transport section.

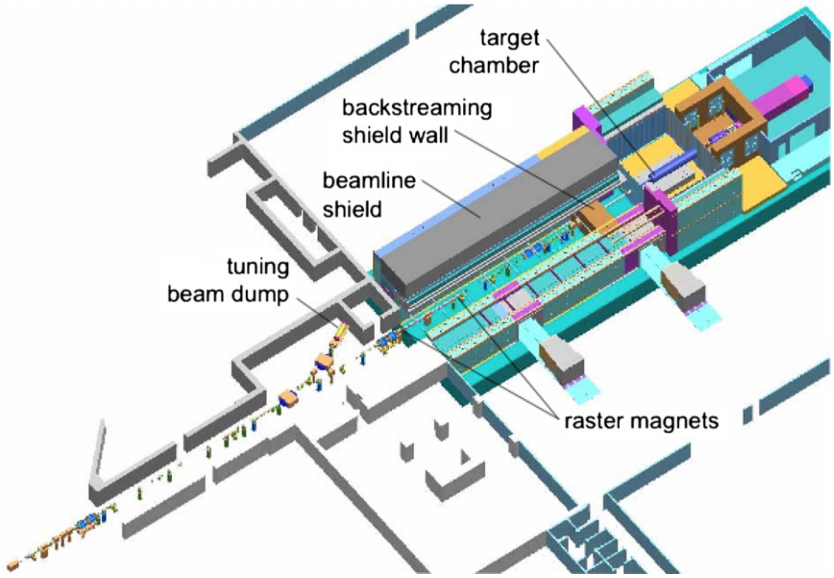

Fig. 4. Physical layout of the beam transport system.

components by neutrons emitted at back angles from the target such that hands-on maintenance will be possible upstream of this wall.

Located laterally outboard of the spallation targets are additional irradiation positions where materials samples may be placed. The neutron flux gradient in the lateral direction is rather high, about 3% per mm, yet this is acceptable if the samples are sufficiently thin in one dimension (no more than 250 μm), as is typically the case with modern test specimens. The peak flux in this region is about 20% less than in the flux trap.

The highly activated target assembly will be serviced in a hot cell located downstream of the target operating position. The target assembly is being designed to be remotely serviceable. Spent activated components will be loaded into transfer casks and transported to appropriate facilities for disposal. Reasonably rapid retrieval of irradiated fuel pins is accomplished through the use of a gasketed cover plate on top of the fuel module. Once removed from the fuel module and loaded into transfer casks, the irradiated pins can be shipped to hot cells at LANL or other laboratories for post-irradiation examination.

4. Cost and schedule

Use of the existing LANSCE accelerator and the Area A experimental hall results in significant cost savings over a green field site for the MTS. A bottoms-up cost estimate completed within the last year yielded a total project cost for the MTS of $73 M, including 25% contingency. This estimate includes the cost of preparing Area A for siting the MTS, which is approximately $13 M. Other major cost components are the accelerator beam transport ($12 M), hot cell and external shielding ($11 M), target assembly services ($8 M), and target assembly fabrication ($7 M). Annual operating costs for the MTS are estimated to be between $9 M and $12 M.

The MTS project schedule is subject to timely approvals of DOE critical decisions. If this process proceeds smoothly, the period from the initiation of conceptual design to completion of MTS installation in the Area A facility can be as short as 4.5 years.

5. Summary

The MTS will provide a critical domestic irradiation capability to the DOE, allowing fast-spectrum irradiations of new MA-bearing fuels to commence well before a new fast reactor can be expected to start operation in the USA. The neutron spectrum in the fuel irradiation region is similar to that of a fast reactor, and fast flux levels in the irradiation region are about one-third that of the peak fast flux in the Phénix reactor, which currently produces the most intense fast flux in the world.

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