MTS White Paper to the Fusion Energy Sciences Advisory Committee, Subcommittee on Future Facilities

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Executive Summary:

The quest for fusion energy is critically dependent on the development of materials that can tolerate the intense and unique fusion neutron environment inside a fusion reactor. This message is stated explicitly in the Materials Facilities Initiative paper, has been appreciated worldwide for several years, and is documented in many Fusion Energy Sciences Advisory Committee (FESAC) studies and reports.[1,2] Addressing this fundamental and significant challenge and opening new frontiers in materials science requires the development of facilities that can accurately simulate fusion relevant conditions. The most direct and cost-effective route to the study of materials under neutron bombardment is to use the Materials Test Station (MTS), a spallation-driven test facility that can effectively simulate the material damage conditions of deuterium-tritium (D-T) neutrons. The exposure of materials to neutrons from the MTS would provide irradiation data at fusion-relevant damage rates. Such a facility would also have complementary value in the development and exploration of radiation-resistant materials for fission reactors.

Summary of facility research and world-leading science.

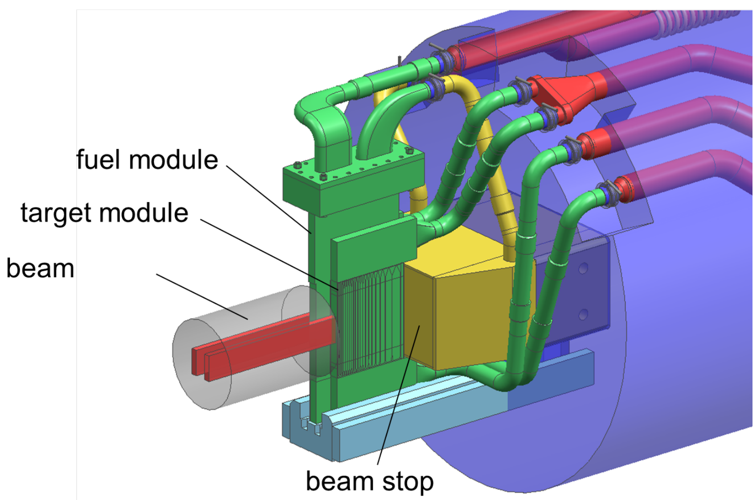
The need for facilities that provide fusion-relevant conditions is well recognized in the fusion community. Numerous reports point to the need for such facilities to advance the scientific understanding of materials.[1,2,3] These facilities would provide the United States (US) with a world-leading capability and enable breakthroughs in the understanding of materials. To our knowledge, each of the large, high-power proton accelerators in the US has pursued concepts along these lines—Project X at Fermilab, the Spallation Neutron Source at Oak Ridge National Laboratory, and the Materials Test Station (MTS) at the Los Alamos Neutron Science Center (LANSCE) at Los Alamos National Laboratory (LANL). Although the current white paper highlights MTS as an expeditious and cost-effective capability to meet this need, to greater or lesser degrees, similar capabilities could be possible at other sources of spallation-derived neutrons.

The MTS provides the prototypic environment that will be experienced by materials in fusion devices and allows for the irradiation of materials test samples for a wide variety of fusion research experiments. Materials for the structures of fusion energy systems must be capable of withstanding intense irradiation fluxes that cause every atom in the material to be dislodged from its original lattice site hundreds of times over the course of the reactor lifetime. Five general deleterious manifestations of the displacement damage exist in materials: radiation embrittlement and loss of strain hardening capacity, radiation-induced or -enhanced solute segregation to grain boundaries and other features, volumetric swelling, radiation induced creep, and high-temperature embrittlement of grain boundaries. The MTS will permit the controlled scientific investigation of each of these single physics effects, as well as offer an environment for the investigation of coupled physics phenomena.

Facility Description

The MTS,[4,5] which has been developed to sufficient maturity to have a CD-1 package pending with the Department of Energy (DOE) Office of Nuclear Energy, will be built in an existing experimental hall leveraging the billion-dollar site credit of LANSCE. The existing 1-MW proton beam at LANSCE can generate a fast neutron flux that approaches that produced by the world's most powerful research fast reactors. Neutrons in the MTS are generated via the spallation process when 800-MeV protons interact with tungsten nuclei in the spallation targets. Between the targets is the central irradiation region, and the peak neutron flux in this location is 1.6×10^{15} n $cm^{-2}s^{-1}$. At a beam power of 1 MW, the range of displacement and helium production rates in iron accessible in the MTS irradiation regions is broad, with helium-to-dpa ratios from 5 to 33 appm/dpa available.

MTS Target Assembly



Facility's impact beyond the FES mission.

The MTS provides a spallation source facility that can irradiate fuels and materials in a fast neutron spectrum with applicability to the nuclear energy mission in fission reactors. Materials research as a whole is substantially advanced through the MTS: areas of research would include the development of reduced-activation ferritic-martensitic steels, the exploration of nano-composite ferritic alloys, and the study of reinforced silicon carbide materials. Many of the materials science questions facing fusion energy are universal in scope and fundamental in nature, with potential broad applications in fields beyond fusion energy. The thermo-mechanical demands being placed on fusion materials are at the limits of today's materials science and technology, even without considering the additional demands created by radiation damage. The scientific challenges associated with developing high-strength, high-temperature materials that are micro-structurally stable are faced in many technologically demanding industries, such as aerospace, transportation, and conventional power generation. Similarly, discovery of the means to simultaneously achieve high-strength and high-ductility or fracture toughness would represent an enormous breakthrough, with broad implications for extending the lifetimes of materials that function in severe thermo-mechanical environments. Fusion materials research at a spallation source facility will advance our knowledge of reduced activation steels, which could be beneficial to the existing nuclear power industry, as well as to the primary application of fusion reactors.

Context for the facility with respect to research gaps, needs, and opportunities.

A major overarching gap identified in Fusion Energy Sciences (FES) planning documents[2] is a lack of knowledge of the potential behavior of a host of functional and structural materials in the fusion energy environment. The presence of intense gamma-ray and high-energy neutron fluxes, along with high heat fluxes, tritium, high temperature coolants, and in many cases high mechanical stresses, creates a uniquely hostile operating environment. There presently exists no appropriate fusion-relevant test bed to develop and qualify suitable materials for these fusion environments.

This gap results in a daunting scientific challenge to the successful development of a viable fusion power system: namely, acquiring a firm scientific understanding and devising mitigation strategies for the deleterious microstructural evolution and property changes that occur to materials in the fusion environment. Although considerable progress has been made in exploring the resistance of structural materials to neutron irradiation in fission reactors (to damage levels on the order of ~30 dpa), the current knowledge base for reduced-activation structural materials exposed to fusion-relevant irradiation conditions is almost nonexistent.

Context of the facility relative to the world effort in fusion and plasma science research.

The helium-to-dpa ratio for iron at the peak flux position in the MTS is similar to that experienced by the first wall of a typical D-T fusion reactor.[4] Because the helium-to-dpa ratio varies with the irradiation position within the MTS, a broad range of ratios is available to experimenters. The MTS offers fusion materials researchers the ability to acquire radiation damage at a rate that is about half of that which will be available in the International Fusion Materials Irradiation Facility (IFMIF), with irradiation volumes on par with the IFMIF. The IFMIF generates neutrons with energies up to 55 MeV[6], whereas the MTS energy spectrum extends to 800 MeV. Both generate helium-to-dpa ratios near 10 in iron. Displacement rates for similar volumes in the MTS fuel module (400 cm^3) and IFMIF high-flux test module (HFTM) (500 cm^3) are both about 25 dpa per full power year, which is more than twice that expected on the International Thermonuclear Experimental Reactor's (ITER's) first wall. A spallation neutron source would be subject to occasional beam trips from the incident proton beam. However, the sensitivity of sample irradiation temperature to beam trips has been examined and is believed to be manageable. Because LANSCE's proton source and MTS target area are already available, MTS operations could be realized in about 3–4 years, whereas the IFMIF would appear to be more than a decade away from realization.

The proton beam used for the MTS will be pulsed at a frequency of 100 Hz, compared with the continuous neutron flux expected in the leading design for a fusion reactor. At this frequency, the irradiation temperature is constant to better than 1°C. Mean distances between displacement cascades produced during one pulse under such frequencies are so large that they act independently of each other and would not be expected to affect irradiation creep. Modeling has shown that low pulse frequencies (<10 Hz) lead to reduced void growth at high irradiation temperatures. Very little effect on void growth would be expected at 100 Hz.[5]

Estimate of the construction cost, annual operation cost, and schedule.

The existing CD-1 package pending with the DOE Office of Nuclear Energy provides the basis for the following estimates. The total project cost for the MTS is ~$100M; this amount leverages the ~$1B LANSCE site credit, as well as an existing and ready experimental hall. The estimated annual operation cost is $15M. The project schedule is estimated at 4 years: a 2-year preliminary and final design phase followed by a two-year construction and commissioning phase.

Assessment of the readiness of the facility concept.

The MTS, with a CD-1 package in hand, is ready to initiate preliminary design in accordance with DOE Order 413.3. In conjunction with the CD-1 documentation, the MTS has a clear definition of the mission, technical requirements for the project, and an appropriately scaled risk mitigation plan to address remaining scientific and engineering challenges.

Conclusion:

New materials must be discovered to make fusion a technically viable and economically attractive future energy source. The most efficient approach to materials discovery is a science-based effort that closely couples development of physics-based, predictive models of materials behavior with key experiments to validate the models. The MTS, a neutron spallation source at LANL using the existing high-power, 800-MeV proton beam at LANSCE, can efficiently provide the test bed for this materials discovery in a cost-effective manner with relatively low risk.

References:

1. Fusion Energy Sciences Advisory Committee Reports, *Scientific Challenges, Opportunities, and Priorities for the US Fusion Energy Sciences Program* (April 2005).
2. Fusion Energy Sciences Advisory Committee Reports, *Priorities, Gaps, and Opportunities: Towards A Long-Range Strategic Plan for Magnetic Fusion Energy* (October 2007).
3. Fusion Energy Sciences Advisory Committee Reports, *Research Needs for Magnetic Fusion Energy* (2010).
4. Eric J. Pitcher, *Fusion Materials Irradiations at MaRIE'S Fission Fusion Facility,* in 26th Symposium on Fusion Technology 27, September 1–October 2010, Porto, Portugal.
5. Eric Pitcher et al., *Progress on the Materials Test Station,* International Conference on the Physics of Reactors, "Nuclear Power: A Sustainable Resource", Casino-Kursaal Conference Center, Interlaken, Switzerland, September 14–19, 2008.
6. Anton Möslang , *IFMIF: the Intense Neutron Source to Qualify Materials for Fusion Reactors, C. R. Physique* 9 (2008), 457–468.