Materials and Innovations for Fusion Energy
Room 321 - Session FUS-WeM

Fusion Materials, Plasma-Facing Components, and Tritium Engineering

Moderators: Dr. Dale Hitchcock, Savannah River National Lab, **Dr. Matthew Sharpe**, The Laboratory for Laser Energetics, The University of Rochester

8:00am **FUS-WeM-1 Water Detritiation: From ML-Guided Selection to Catalyst Synthesis*, Rashad Ahmadov**, *Zachary Robinson, Mark Wittman, Matthew Sharpe,* Laboratory for Laser Energetics

Building on prior validation of a hydrogen-based surrogate unit for water detritiation, this workadvances catalyst development through integrated computational screening and targeted synthesis. The previous study established baseline performance using commercial Cu-Zn catalysts, revealing reaction rates limited by the internal mass diffusion. To identify candidates with potentially improved characteristics, Machine Learning (ML)-accelerated adsorption energy calculations (AdsorbML) were employed to screen a broader alloy design space. A promising composition was selected based on predicted surface energetics favorable for water splitting reaction adsorbates. The candidate catalyst was synthesized and characterized using XRD and XPS to confirm phase composition and surface chemistry. Temperature-programmed reduction (TPR) was performed to determine appropriate activation conditions prior to reactivity testing. The catalyst was then tested in the surrogate reactor under conditions comparable to prior experiments. Preliminary results confirm catalytic activity for hydrogen evolution with oxygen retention. This work demonstrates a computationally-guided pathway for catalyst discovery for thermochemical water detritiation, contributing toward optimized tritium recovery systems for closing the fusion fuel cycle.

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Inertial Confinement Fusion Program" under Award Number(s) DE-NA0004144.

8:15am **FUS-WeM-2 Al Intercalation Into C-Vacancy Sites in TiCx for Low-Temperature Synthesis of MAX-Phase Ti_2AlC Hydrogen Permeation Barrier Coatings*, Isabella Stepanek***, Georgia Institute of Technology*; Dale Hitchcock,* Savannah River National Lab*; Eric Vogel,* Georgia Institute of Technology

MAX-phase Ti_2AlC thin films were synthesized using PVD magnetron sputtering of a bilayer system that utilizes an Al precursor layer with a subsequent TiAlC layer, followed by vacuum annealing at 650°C for 3h up to 20h. Ex situ XRD of TiAlC only films (no Al precursor layer) reveal that annealing drives Al out of the $Ti_{0.66}Al_{0.34}C$ rocksalt phase present in the as-deposited films, generating additional C-vacancy sites to form $TiC_{0.5}$. No Ti_2AlC was synthesized from these TiAlC only films. With the utilization of an Al precursor layer deposited prior to the TiAlC layer, it was found that the as-deposited bilayer contains spatially distinct $TiC_{0.56}$ and Al phases, establishing the diffusion geometry required for Al intercalation-driven Ti_2AlC formation. This mechanism is initiated via vacuum annealing at 650°C which mobilizes Al both from the $Ti_{0.66}Al_{0.34}C$ phase in the TiAlC layer but also Al from the precursor layer. The resulting upward Al diffusion and intercalation into ordered C-vacancy planes of $TiC_{0.55}$ is identified as the primary mechanism driving low-temperature Ti_2AlC formation in Al/TiAlC films. XRD results also show the formation of Ti_3Al along with the $TiC_{0.55}$ and Ti_2AlC phases, mirroring reported two-step reaction pathways that include the formation of Ti-Al intermetallics and TiC_x that react to form Ti_2AlC. Ex situ XPS depth profiles corroborate this mechanism, showing progressive Al depletion from the precursor layer into the TiAlC layer with annealing time. Associated scans of the Al 2p orbital taken during depth profiles shows binding energy shifts evidencing changes in the Al chemical environment consistent with C-vacancy incorporation and Ti_2AlC synthesis.

These efforts towards low-temperature synthesis of MAX-phase coatings allow for their potential use on low activation structural materials used in fusion reactor blanket components. Ti_2AlC is a particularly promising candidate for this application, as aluminum-containing MAX-phases form a dense, protective Al_2O_3 scale upon oxidation that has been demonstrated to reduce hydrogen isotope permeation through structural materials.

8:30am **FUS-WeM-3 Characterizing Heavy Water Displacement in Molecular Sieve Drying Beds for Practical Trace Tritium Capture Methods*, Brandon Massett***, *Walter Shmayda,* Tritium Solutions Inc.

Tritium plays a crucial role in nuclear fusion power plant designs, and adsorption beds are essential tools for managing tritiated water vapor. A series of tests was performed to investigate whether a saturated adsorption bed preferentially adsorbs heavy water vapor. The design of passive tritium control systems could potentially rely on adsorption beds preferentially trapping heavier isotopologues of water. This work investigates the displacement phenomenon, as well as the effects of carrier gas superficial velocity and heavy water concentration on bed performance. Significant displacement was observed when a humid stream containing heavy water was diverted through a bed pre-saturated with light water, as indicated by changes in the partial pressures of D2O and H2O. Following the capture of heavy water in the bed, the subsequent rise in D2O partial pressure depended on both the superficial gas velocity and the heavy water humidity in the gas stream. Higher superficial velocities and humidities led to faster and steeper mass transfer profiles within the adsorption bed. These heavy water breakthrough curves were fit and compared with theoretical models for adsorption beds operating under standard conditions.

8:45am **FUS-WeM-4 Characterizing the Behavior of Hydrogen Isotopes and Impurity Species on Vanadium Surfaces by Direct Recoil Spectroscopy*, Feng-Jen Chang***, *Antonio Cruz, Mary Alice Cusentino, Robert Kolasinski,* Sandia National Laboratories

Due to their high permeability for hydrogen isotopes (HI), vanadium (V) membranes are being considered for separation of HI from the plasma exhaust of future fusion reactors. Surface effects, particularly the presence of impurities, have a large influence on the performance of such membranes. However, it is often difficult for conventional surface analysis tools to directly observe how HI interacts with other surface species. Ion scattering spectroscopy (ISS) and direct recoil spectroscopy (DRS) offer the advantage of being able to directly detect adsorbed HI by analyzing the energies of scattered and recoiled particles from ion scattering on the surface.

In this study, we use a 2 keV Ne^+ ion beam to probe the surface composition of a polycrystalline V sample while dosing with hydrogen (H) or deuterium (D) with increasing pressure [Fig. S1(a)]. Gas species and surface temperatures (T_s) are varied for comparison, and a gas doser heated to 1100 °C is available for dissociating H_2/D_2 molecules into H/D atoms. DRS peaks of H/D are clearly identified in the ion energy spectra [Fig. S1(b)]. Pressure dependences of the peak intensities can be well fitted by a simple site-blocking model with Langmuir isotherm [Fig. S1(c)], which assumes that adsorbates only interact with each other by competing for empty adsorption sites. Such fittings reveal the change of the adsorption-desorption balance of HI with different surface conditions. The ratio between the adsorption rate coefficient and desorption rate coefficient, $K = k_{ad} / k_{de}$, decreases with increasing T_s, indicating that desorption is stronger at higher T_s [Fig. S1(d)]. K is also higher with atomic H/D dosing than with H_2/D_2 dosing, since atomic species have higher chemical energy to overcome the adsorption energy barrier, and thus result in higher adsorption rates.

In addition, preliminary studies of oxygen (O) adsorption by DRS while dosing the V surface with O_2 have been performed. The DRS O peak intensity growth with increasing O_2 pressure is similar to that measured by X-ray photoelectron spectroscopy (XPS) [Fig. S1 (e)], which validates the DRS results. The ongoing work includes sequentially dosing O_2 and HI to validate the site-blocking model. Finally, investigation of the effect of permeation barrier coatings, such as SiC, W or Al_2O_3, on V and V-alloys with both DRS measurements and density functional theory (DFT) modelling is also underway, and preliminary results from this work will be included in this presentation.

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9:00am **FUS-WeM-5 Theoretical and Experimental Study of Hydrogen Super-Permeation in Iron*, Masashi Shimada***, *Thomas F. Fuerst,* Idaho National Laboratory **INVITED**

Metal foil pumps (MFPs) exploit plasma–driven hydrogen super–permeation to selectively separate and compress hydrogen isotopes (D/T) from helium and impurity species in the fusion exhaust stream, forming a key enabling technology for Direct Internal Recycling (DIR)–based fuel–cycle

architectures. Despite their promise, the technical readiness level of MFPs remains insufficient for integration into next–generation fusion systems. Advancing the understanding of hydrogen super–permeation in metallic membranes is therefore essential for developing high–performance pumping components capable of operating under reactor–relevant plasma conditions.

This work presents an integrated experimental and theoretical investigation of deuterium super–permeation in high–purity α–Fe. Plasma–driven permeation experiments conducted in the Tritium Plasma Experiment (TPE) at Idaho National Laboratory demonstrated that a 99.99% α–Fe foil can achieve a maximum pumping throughput of 3.0 L s^{-1} cm^{-2} and a pumping speed of 3.0 m^3 s^{-1} m^{-2} at 523 K under a D_2 pressure of 0.013 Pa. The permeation behavior was found to be strongly governed by the surface sticking coefficient, α, and by the incident D^+ ion energy. Comparison with the Pick–Sonnenberg model showed excellent agreement when using a previously measured $\alpha \approx 1.6 \times 10^{-9}$, with peak pumping performance occurring near an incident ion energy of 10 eV [1]. In contrast, incident energies above 50 eV caused a sharp decline in pumping performance, consistent with sputtering–induced removal of the native oxide monolayer—an effect also reported in prior studies of Nb and Fe.

A complementary theoretical study applied the Pick–Sonnenberg formulation to evaluate hydrogen permeation in candidate group–V membrane materials, focusing on vanadium with an experimentally measured effective permeability influenced by surface oxide and subsurface carbide layers [1]. Modeling showed that even with the reduced permeability, an uncoated 1 mm–thick V membrane can achieve approximately 10% hydrogen permeation at 973 K when operating with $\alpha \approx 10^{-3}$ and ion fluxes near 10^{20} m^{-2} s^{-1}. These findings highlight the potential for high–temperature operation to enable attractive pumping performance without the Pd coatings typically required for group–V metals.

Collectively, these results deepen the mechanistic understanding of hydrogen super–permeation in metallic membranes and provide a physics–grounded basis for optimizing high–flux MFP systems within advanced fusion fuel–cycle concepts.

Reference:

[1]M.A. Pick and K. Sonnenberg, *J. Nucl. Mater.* **131** (1985) 208-220

9:30am **FUS-WeM-7 Development of Tungsten Alloys to Mitigate Impacts of Neutron Irradition on Tritium Inventory***, **Yuji Hatano**, Qicong Chen, Yuga Kimura, Naoko Oono, Katsuya Suzuki,* Tohoku University, Japan*; Tatsuya Kuwabara,* Aichi Institute of Technology, Japan*; Koji Inoue,* Tohoku University, Japan*; Jing Wang,* Hefei University of Technology, China **INVITED**

While Tungsten (W) is a leading candidate for a plasma-facing material in fusion reactors, neutron-induced displacement damage creates vacancy-type defects that significantly increase tritium retention [1,2]. To mitigate this, we developed W alloys using undersized solute elements like chromium (Cr) and rhenium (Re). These elements promote the annihilation of vacancy-type defects during irradiation at temperatures ≥773 K and reduce the resulting trap density [3-8]. Furthermore, recent findings show these alloying elements enhance defect recovery during post-irradiation annealing at approximately 1473 K, offering a potential pathway for in-vessel trap removal during scheduled maintenance. This presentation explores the mechanisms driving these enhanced annihilation and recovery processes.

[1]Y. Hatano et al., Nucl. Fusion, 53 (2013) 073006.

[2]Y. Hatano et al., J. Nucl. Mater., 438 (2013) S114.

[3]Y. Hatano et al., Nucl. Mater. Energy, 9 (2016) 93.

[4]J. Wang et al., J. Nucl. Mater., 545 (2021) 152749.

[5]J. Wang et al., J. Nucl. Mater., 559 (2022) 153449.

[6]J. Wang et al., Mater. Design, 229 (2023) 111899.

[7]J. Wang et al., Mater. Design, 259 (2025) 114783.

[8]Y. Nobuta et al., J. Nucl. Mater., 566 (2022) 153774.

11:00am **FUS-WeM-13 Liquid Metals as Plasma-Facing Components in Fusion Devices: Can They Solve the Power Handling Challenge?** *, **Martin Nieto-Perez**, Calixto Alvarado,* Pennsylvania State University*; Daniel Andruczyk,* University of Illinois at Urbana-Champaign*; Lane Carasik,* Virginia Commonwealth University*; Ama Dahanayakle,* Pennsylvania State University*; Bruce Koel,* Princeton University*; Mike Kotschenreuther,* Exofusion*; Rajesh Maingi,* Princeton Plasma Physics Laboratory*; David Ruzic,* University of Illinois at Urbana-Champaign*; Sergei Smolentsev,* Oak Ridge National Laboratory*; Vlad Soukhanovskii,* Lawrence Livermore National Laboratory*; Xing Wang,* Pennsylvania State University*; Kevin Woller,* Massachusetts Institute of Technology

One of the most daunting challenges on the road to commercial fusion machines is the development of materials and components capable of withstanding the enormous power loads associated with particle leakage from magnetically confined plasmas; in addition to being resilient enough to withstand very high heat loads, these components need to facilitate the recovery of any valuable tritium fuel that reaches them. To satisfy these requirements, plasma-facing component systems based on liquid metals are considered a viable option, but remain at a lower technology readiness level (TRL) than their solid counterparts. To advance the maturity of these technologies, a DOE-funded initiative, Liquid Metals: Advancing the technical Readiness of plasma-facing Materials Operational Response (LM-ARMOR), has been established, spanning multiple federal laboratories and academic institutions. The overarching aim uses a combination of dedicated experiments and targeted calculations to explore and develop different PFC systems based on liquid metals. This collaboration aims to derisk LM technologies by addressing specific scientific and technological gaps that must be overcome to develop next-step integrated fusion test facilities and fusion reactors. The four overarching topics are material compatibility assessments, MHD flows, development of novel liquid metal alloys, and integrated testing. In this talk, efforts to develop the capillary pore system and to study novel metal alloys will be highlighted, emphasizing the need for experimental measurements of critical properties, including wetting, hydraulic permeability, sputtering, and surface segregation.

11:15am **FUS-WeM-14 Atomic Layer Deposition Affecting Gas Retention in Fusion Targets***, **Mark Bonino**,* University of Rochester

Glow discharge polymer (GDP) is the primary material used as an ablator for spherical, direct-drive laser experiments at the University of Rochester's Laboratory for Laser Energetics. GDP capsules are millimeter-scale hollow spheres with gas permeation time constants of ~1 min for hydrogen isotopes—the gases used for fusion reactions. Gas permeation time constants, however, must be significantly longer (tens of hours) to meet the specified fuel pressure at the time of the laser shot. Most experiments require fuel pressures of 15 atm±10%. Sputter-deposited aluminum has been demonstrated to increase the gas permeation time constant, using layers of around 100 nm. However, sputtered aluminum films often exhibit a broad distribution of time constants, rendering many samples unusable. An alternative to sputter deposition is atomic layer deposition (ALD), where layers of Al_2O_3 are applied using a vapor-phase deposition process to produce a contiguous gas-permeation layer. ALD is an alternative method to increase hydrogen gas retention and is investigated in this study.

The presented work will report gas-permeation time constants on spherical and cylindrical plastic shells from a decay curve measured using a residual gas analyzer. In our time-constant measurement system, the targets are pumped out to high vacuum (10^{-6} Torr) and filled to pressures up to 1000 Torr. Preliminary observations show time constants ranging from 1000s to 2000s, with a dependence on pressure. Changes in the permeation rate as a function of cycling will be investigated. Characterization (using x-ray photoelectron spectroscopy, a scanning electron microscope, and an atomic force microscope) will be performed to observe microscopic changes on the sample surfaces that impact gas retention.

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Presentation Type: Oral presentation

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11:30am **FUS-WeM-15 Measurement of Residual Impurities after a Cryogenic DT Inertial Confinement Fusion (ICF) Implosion***, **Errol Alden**, Zak Robinson, Matt Sharpe,* University of Rochester

In order to gauge the impurities entering the tritium fuel cycle (FC) in an ICF target chamber, we focus on residual target material left after a shot in the forms of ablation coating and gaseous species. The ablation coating, or material left on surface of chamber, was measured by placing sapphire wafers 26 cm away from the target. The gaseous species are measured via Residual Gas Analyzer (RGA) directly mounted on the ICF target chamber. The RGA provides mass information for the major gas species residual in the chamber. After being exposed to an ICF target implosion, the wafers will be separated into two testing groups: one to measure tritium activity and the other to measure surface changes. Tritium surface activity will be measured through etching, while surface changes will be measured by X-ray photoelectron spectroscopy and X-ray reflectivity. The goal is to understand the depth that tritium reaches, surface changes on the wafer, contaminants left on surface, and contaminants left in gas.

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11:45am **FUS-WeM-16 FORGED-PFC High Heat Flux Facility Vacuum Vessel Design Status***, **Jared Tippens**, Ezekial Unterberg,* Oak Ridge National Laboratory

Oak Ridge National Laboratory has partnered with Type One Energy and The University of Tennessee Knoxville to build a world-class High Heat Flux Experimental facility focused on testing and qualifying fusion energy plasma-facing components (PFCs). This facility will utilize two converging high-power electron beams (~1.6 MW total) to heat test articles at fusion-relevant PFC power densities. Heat will be removed from the test articles via a dedicated helium loop with flowrates up to 1 kg/sec at a pressure of 8 MPa. Large components measuring over 1 m x 1 m x 0.5 m can be tested in this facility, enabling sub-component PFCs to be evaluated under representative operating conditions for thermomechanical stress testing and qualification. There are currently no dedicated testing facilities in the Western Hemisphere with these capabilities. Therefore, the FORGED-PFC facility will fill this needed capability and operate as a community resource to accelerate domestic fusion research and deployment of fusion energy systems.

For effective high heat flux testing at this scale, experiments must take place in a vacuum environment at pressures on the order of $1x10^{-4}$ mbar and lower. The two electron beams will be mounted to a relatively large vacuum vessel (~ 10 m^3) that will also house the test articles during experiments. Robust thermal management of the vacuum vessel is required to dissipate up to 1.6 MW of heat from the inner walls, necessitating a jacketed design. In addition, numerous ports are required for diagnostics to enable reactor relevant measurements and support predictive modeling validation. To achieve target pressures and minimize downtime between experiments, a multi-stage roughing pump system is required in tandem with cryopumps. To optimize the layout of the electron beams and diagnostics relative to the test articles, a custom D-shaped vacuum vessel is envisioned for this application.

An overview of the FORGED-PFC project and its current status will be provided, along with design details of this high-performance vacuum vessel and associated pumping system.

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12:00pm **FUS-WeM-17 Materials and Deposition Technologies Underlying Target Fabrication for Inertial Confinement Fusion***, **Salmaan Baxamusa**, Sean Hayes, Liam Sohngen, Juergen Biener,* Lawrence Livermore National Laboratory*; Christoph Wild, Tobias Fehrenbach,* Diamond Materials GMBH, Germany*; Casey Kong, Mark Ratledge, Anthony Allen,* General Atomics*; Corie Horwood, Parminderdeep Singh, Alec Schwartz,* Lawrence Livermore National Laboratory*; Loosineh Aghaian,* General Atomics*; Bernard Kozioziemski, Laura Kegelmeyer, Gabrielle Hamza,* Lawrence Livermore National Laboratory*; Nancy Spafford,* Lawrence Livermore National Lab

The demonstration of laser-based inertial confinement fusion (ICF) ignition on the National Ignition Facility (NIF) in 2022 was a triumph of integrated physics and decadal science. This experiment, and the subsequent experiments building up to energy gains >4, are to date the only experimental demonstrations of fusion exceeding the Lawson criterion in the laboratory. Yet underlying this physics result was a complex blend of materials science and vacuum deposition needed to create and field an igniting target. This presentation will cover two aspects of the igniting physics package where vacuum deposition plays a key role: the hollow, spherical fuel capsule that implodes and the cylindrical hohlraum that provides x-ray drive for the implosion.

The capsule used in ignition experiments is CVD-deposited nanocrystalline diamond deposited. This talk will describe improvements to fabrication including machine-learning based diagnostics, Monte Carlo modeling, integrated experiments, and infrared reflectometry to improve coating thickness uniformity to > 99.8% on non-planar, non-stationary substrates.X-ray computed tomography was used to confirm that improvements to coating uniformity did not create additional internal defects.Finally, by controlling the composition along the growth axis we created capsules that stabilized the implosion and resulted in a record gain of >4. We will briefly mention materials science challenges of other capsule materials including boron carbide and glow discharge polymer.

The cylindrical hohlraum that contains the imploding capsule is a high-atomic number material (gold and uranium) that converts incoming laser light into a spherical bath of x-rays that drives the capsule implosion.Despite decades of study, the complex oxidation pathways of uranium are incompletely understood.We observed catastrophic oxide spalling on depleted uranium hohlraums that requires both an oxidant during processing and an environmental trigger. An experimental study confirmed that removing one or the other effectively increased the shelf-life of these components from ~weeks to ~months or years, eliminating a major cause of late-stage target failures for NIF.

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