American Nuclear Society
Fusion Energy Division
June 2017 Newsletter

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Letter from the FED Chair, Arnold Lumsdaine, Oak Ridge National Laboratory, Oak Ridge, TN.

My theme for this newsletter is "transitions" as we are experiencing many of these as a division.

One transition that we experience every June is a change in the membership of the Fusion Energy Division (FED) Executive Committee. We welcome new members who will be serving from 2017-2020:

- David Donavan (University of Tennessee, Knoxville)
- Arkady Serikov (Karlruhe Institute of Technology)
- Gregory Staack (Savannah River National Laboratory)

I am thankful to those who are willing to be nominated to serve in these positions, and who are able to serve actively. My heartfelt thanks to the outgoing members of the Executive Committee – Blair Bromley, Craig Taylor, and Neill Taylor, who each provided significant and valuable contributions to the Division.

A major transition that we are now experiencing is a change in editor for the ANS Fusion Science and Technology journal. It would not be possible in a newsletter to adequately describe the many tasks and countless hours that Nermin Uckan has put in as editor over the past decade, or to properly express our thanks. She has left some very large shoes to fill. The ANS Technical Journals Committee is in the process of conducting interviews, and it is hoped that a new editor will be announced in the near future. This is a journal that is uniquely tied to our Division, and so all of us in the Division should express our appreciation to Nermin for her tireless service. And we should each lend our support to the next editor when they step into that role.

We have made our first transition to a new scholarship awardee. The second recipient of the Dr. Kenneth R. Schultz scholarship is Alexander Rice of the University of Florida. Thanks to Leigh Winfrey (University of Florida), who chairs the division scholarship subcommittee.

The 2017 ANS Annual Meeting was held from June 11-15 with the theme "Innovating Nuclear Power." FED sponsored three sessions at the meeting, including two sessions on "Neutronics Challenges of Fusion Facilities" which were organized by Arkady Serikov (KIT, Germany). Also of interest at the meeting, outgoing ANS President Andy Klein announced the nine ANS Nuclear Grand Challenges, which was the main initiative of his presidency. As a part of selecting these Grand Challenges for ANS, the Fusion Energy Division developed its own list of challenges, which are described in another article below.

The FED Executive Committee does much of the "grunt work" for the Division, but it is the membership that keeps the Division alive and vibrant. In 2016, our Division membership surpassed 1000 for the first time in over a decade. Thank you for being a part of it.

ANS Nuclear Grand Challenges for Fusion, Arnold Lumsdaine, Oak Ridge National Laboratory, Oak Ridge, TN.

At the initiative of ANS President Andy Klein, the Society spent the last year to identify, accumulate, analyze, vet, select, release, and promote a set of technical Nuclear Grand Challenges that need to be addressed by 2030.

As a part of this process, 40 Grand Challenges were submitted to the ANS Fusion Energy Division. The FED Executive Committee held several videoconferences, open to all FED membership, to solicit feedback. Of the 40 submissions, seven were identified as the top Grand Challenges for Fusion. These are (in order of selection):

1. Qualification of advanced materials that can withstand extreme nuclear fusion and fission environments (high temperature, radiation damage and transmutation, helium and hydrogen surface and bulk effects, and compatibility with advanced coolants).
2. Safely and efficiently fuel, exhaust, breed, confine, extract, and separate tritium in unprecedented quantities.
3. Successfully demonstrate significant energy gain in a long pulse or steady-state burning plasma.
4. Development of an experimentally validated integrated predictive simulation capability that will reduce risk in the design and operation of fusion energy systems.
5. Development of an appropriate safety and licensing process for future nuclear fusion facilities, with related criteria, including the qualification of materials and safety-important systems.
6. Construct and operate a high flux, high-energy (10 to 15 MeV) neutron source for research in fusion, fission, transmutation, and radio-isotope production applications.
7. Demonstration of an effective plasma exhaust system that can operate under nuclear conditions and maintain performance for a lifetime that avoids frequent replacement.

You can find more information on the FED web page:
http://fed.ans.org/literature/ans-fusion-grand-challenges/.

As a Division, we were able to submit the top three challenges on this list for the ANS Grand Challenges. ANS received a total of 42 Grand Challenges from the various ANS divisions, and then selected nine of these as the ANS Grand Challenges. These were announced at the ANS National meeting on June 12:

1. Establish the scientific basis for modern low-dose radiation regulation.
2. Transform the way the nuclear technologies sector thinks about public engagement.
3. Close the nuclear fuel cycle.
4. Ensure continuous availability of radioisotopes.
5. Rejuvenate the nuclear technology infrastructure and facilities.
6. **Accelerate development and qualification of advanced materials.**
7. **Accelerate utilization of simulation and experimentation.**
8. **Expedite licensing and deployment of advanced reactor designs.**
9. Expedite nuclear education and knowledge transfer.

I have put in bold the challenges that have direct relationship to fusion. Note that challenge 6 is the top Grand Challenge offered by the fusion division (shortened and slightly re-stated), showing that this is a concern, not just for the future of fusion, but for the future of the larger nuclear community. For more information on the ANS Grand Challenges, go to the society web page: http://www.ans.org/challenges/.

What are our next steps? The ANS is going to be taking many steps to publicize these Grand Challenges, within the ANS, to decision makers and politicians, and to the larger society. FED is planning to organize sessions at future meetings around these Grand Challenges, to stimulate thinking within the fusion technology community, and to foster cross-disciplinary thinking with other divisions within ANS.

We appreciate Andy Klein having the vision to present such an initiative to the society. Thank you to all of those who participated in this effort, by submitting a Grand Challenge, by participating in one of our teleconferences, by promoting these challenges in your workplace and sphere of influence, and, especially, by being part of the community that will strive to solve these challenges by 2030.

List of Officers and Executive Committee Members, Susana Reyes, Lawrence Berkeley National Laboratory.

The FED election was held in the spring of 2017. David Donovan (Univ. Tennessee-Knoxville), Gregory C. Staack (SRNL), and Arkady Serikov (KIT, Germany) were elected to the Executive Committee. Congratulations to all!

We thank the outgoing Executive Committee members Blair Bromley (AECL), Craig Taylor (LANL), and Neill Taylor (CCFE) for their service to the Division.

FED Officers:

Arnold Lumsdaine (ORNL) Chair (16-18)
Keith Rule (PPPL) Vice Chair/Chair-elect (16-18)
Kelsey Tresemer (PPPL) Secretary/Treasurer (16-18)

Executive Committee:

Nicole Allen (PPPL) (16-19)
David Donovan (Univ. Tennessee-Knoxville) (17-20)
Lauren Garrison (ORNL) (16-19)
Ahmad Ibrahim (ORNL) (15-18)
Takeo Muroga (NIFS) (15-18)
Arkady Serikov (KIT, Germany) (17-20)
Gregory C. Staack (SRNL) (17-20)
Chase Taylor (INL) (15-18)
Leigh Winfrey (U. Florida) (16-19)

Past Chair:

Susana Reyes (LLNL) (16-18)

FED Standing Committee Chairs:

Nominating: Susana Reyes (LBNL) – Chair
Honors and Awards: Nermin Uckan (ORNL) – Chair
Program Committee: Keith Rule (PPPL) – Chair

FED Representatives on National Committees:

ANS Publications: Nermin Uckan (ORNL)
ANS Public Policy: Susana Reyes (LBNL)
ANS Program Committee: Keith Rule (PPPL)

Editors:

Newsletter: Laila El-Guebaly (UW)
Fusion Science and Technology Journal: Nermin Uckan (ORNL).

Treasurer's Report, Kelsey Tresemer, Sandia National Laboratories, Livermore, CA.

This last year was very successful for the Fusion Energy Division. After two Class 1 sponsored conferences (revenue: $11,792.59 for TOFE 2016 and $3,505.87 for the Tritium Meeting), a slight uptick in division dues, and a successful launch of the new Dr. Kenneth R. Schultz Scholarship (for which we have allocated $50k with ANS and will award a $2500 scholarship each year), we closed 2016 with a balance of $24,879.18.

For 2017, the first quarter financial statement shows we are ahead of budget for membership dues ($506 vs. expected $432). The only other allocated expense thus far is $500 to support the 2017 Student Conference. Other budgeted expenses include $500 to support the ANS NEED program and a residual $300 in Student Support. Finally, there was an additional $70 spent on miscellaneous FED needs this quarter.

Fusion Award Recipients, Laila El-Guebaly, Fusion Technology Institute, University of Wisconsin-Madison, Madison, WI.

Fusion awards have been established to formally recognize outstanding contributions to fusion development made by members of the fusion community. The following awards (listed in alphabetical order) were available to the newsletter editor at the time of publishing this newsletter. We encourage all members of the fusion community to submit information on future honorees to the editor (laila.elguebaly@wisc.edu) to be included in future issues. The ANS-FED officers and executive committee members congratulate the honored recipients of the 2015-2017 fusion awards on this well-deserved recognition and our kudos to all of them.

IEEE Award

The IEEE Nuclear and Plasma Science Society has awarded the IEEE NPSS 2017 Fusion Technology Award to Dr. **David Humphreys**, from General Atomics. This award has been bestowed on him in recognition of his outstanding contributions and leadership in advancing the field of real-time control of magnetically confined plasmas, backed by an impressive record of publications and citations. The award has been presented during the 2017 Symposium on Fusion Engineering (SOFE) in Shanghai, China, June 4-8, 2017.

Nuclear Fusion Awards

A presentation for the winners of the 2015 and 2016 Nuclear Fusion Award was held on 17 October 2016 at the 26th IAEA Fusion Energy Conference in St Petersburg, Russia:

- The recipient of the 2015 *Nuclear Fusion* Award was **R.J. Goldston** for the paper "Heuristic drift-based model of the power scrape-off width in low-gas-puff H-mode tokamaks" (*Nucl. Fusion* 52 103009).
- The recipient of the 2016 *Nuclear Fusion* Award is **S. Bresinsek**, for the paper "Fuel retention studies with the ITER-Like Wall in JET" (*Nucl. Fusion* 53 083023).

Sherwood Student Poster Awards

At the May 1-3, 2017 Sherwood Conference in Annapolis, six students received Poster Awards:

- **Tyler Cote**, University of Wisconsin, "Ballooning stability of tokamak pedestals in the presence of strong applied 3D magnetic perturbations."
- **Benjamin Faber**, University of Wisconsin, "Examining the zero-magnetic-shear approximation for low-shear stellarators."
- **Adrian Fraser**, University of Wisconsin, "Coupling of Damped and Growing Modes in Shear Flow Turbulence."
- **James Juno**, University of Maryland, "Continuum Vlasov Simulations of Magnetized Shocks."
- **Elizabeth Paul**, University of Maryland, "Rotation and Neoclassical Ripple Transport in ITER."
- **Caoxing Zhu**, PPPL, "Flexible optimized coil designing method using space curves."

SOFT Awards

At the 29th 2016 Symposium on Fusion Technology (SOFT), held on September 5-9, 2016 in Prague, Czech Republic:

- Three prizes were awarded to recognize new physics or technology linked to fusion research that has potential for further exploitation:
    - The first Innovation Prize was awarded to a team of researchers of the Karlsruhe Institute of Technology (KIT) in Germany (**W. Fietz, R. Heller, K.-P. Weiss and M. Wolf**) and the Swiss Plasma Center (SPC). Scientists of the Institute for Technical Physics of KIT have developed a novel superconducting conductor concept for fusion magnets. It could also be used as a basic element in future high-current cables of fusion power plants, industrial facilities, or DC power grids.

- The second prize was awarded to a team from Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA) and Commissariat à l'énergie atomique et aux énergies alternatives (CEA) [**Silvano Tosti**, ENEA; **Karine Liger**, CEA; **Nicolas Ghirelli**, ITER; **Fabio Borgognoni**, ENEA; **Fabrizio Marini**, ENEA; **Alessia Santucci**, ENEA; **Pierre Trabuc**, CEA; **Xavier Lefebvre**, CEA]. The group has worked on membrane technologies and developed high-performance membranes to separate out tritium from fusion reaction-rejected mixtures. The capabilities of membranes, made of palladium-silver alloy, have already stretched beyond fusion research, for example, to separate hydrogen from olive mill waste water.
- The third prize was awarded to **Jonathan Naish** from the Technology Department of the Culham Centre for Fusion Energy (CCFE) for development of new software called VORTEX. The VORTEX (Virtual Operator RadiaTion EXposure) software prototype combines virtual reality environments with the high-fidelity 3D data output of radiation transport calculations, such as gamma radiation dose and nuclear heating. The software has the potential to be used in a variety of nuclear environments, including those outside of the fusion arena.

- KIT PhD student **Simone Pupeschi** was awarded with the "PhD Poster Prize" for his work: "Effective thermal conductivity of advanced ceramic breeder pebbles".

News from Fusion Science and Technology (FS&T) Journal, Nermin A. Uckan, FS&T Editor, Oak Ridge National Laboratory, Oak Ridge, TN.

The following is a summary of paper statistics and editorial activities for *Fusion Science and Technology* (FS&T). During the past 12 months (May 1, 2016, to April 30, 2017), FS&T received a total of 203 manuscripts. *Papers rejected/withdrawn from pre-selection of the conferences and special issues are not included in paper counts and regional breakdowns in the ANS/FS&T database.*

Of the 203 manuscripts, 87 were from North America, 23 from Europe (including Russia), 82 from Asia, and 11 from others, with the following breakdown: 94 have been accepted, 65 have been rejected/withdrawn, and 44 are under review/revision.

<u>The following dedicated issues were published during the period 5/1/16 to 4/30/17:</u>

- Target Fabrication 2015 special issue – FS&T Aug./Sept. 2016
- APS Special Issue on Plasma Material Interactions – FS&T Jan. 2017
- Selected papers from Tritium 2016 Part 1 – FS&T (Apr. 2017).

<u>The following issues are scheduled/planned for remainder of 2017 and beyond</u>

- Selected papers from Tritium 2016 Part 2 – FS&T (May 2017)
- Selected papers from TOFE2016 – FS&T (Oct. & Nov. 2017)
- Target Fabrication 2017 special issue (planned) – FS&T (2018 first half).

Starting with 2017, all three ANS Journals (Fusion Science and Technology, Nuclear Science and Engineering, and Nuclear Technology) are now being published by Taylor & Francis for ANS. I have been serving as the Editor of the FS&T journal since 2001. It was a great privilege to serve for a professional society and the fusion community as a whole during the past 16 years. With the change to a commercial publisher, I have decided to step down from the editorship, allowing others to serve as editor under this new arrangement. Potential candidates will be interviewed during the 2017 ANS Annual Meeting, June 11-15, San Francisco, CA. I look forward to working with the new designated editor(s) for a smooth transition.

ONGOING FUSION RESEARCH

New Developments in the Design and Manufacturing of a He-Cooled Divertor for European DEMO, B.-E. Ghidersa, J. Reiser, S. Antusch, Y. Chen, Karlsruhe Institute of Technology, Germany.

Particle exhaust in modern tokamaks and stellarators is associated with high loads on the divertor regions and requires substantial power exhaust capabilities, way superior to that of the first wall components. This makes the development of the divertor targets one of most challenging tasks in the designing of ITER and future power plants, including DEMO. As part of the sustained efforts in providing solutions that could be integrated into a fusion power plant like DEMO, Karlsruhe Institute of Technology (KIT) has developed a helium-cooled divertor: the HElium cooled Modular divertor with Jet cooling (HEMJ). While it has been demonstrated experimentally that this divertor concept could remove up to 10 MW/m^2 of surface heat flux [1], using tungsten both as armor and as structural material, the licensing of such a concept requires the development of new design rules for brittle materials, rules that are not currently available in the pressure vessels codes and standards. Until such design rules are available, as an alternative, KIT has started the development of new W-based structural materials that would allow the operation at low coolant temperatures, while remaining ductile under fusion-specific neutron flux. The present aim is to extend the divertor operating window by decreasing the lower temperature limit below 500°C while still having a ductile behavior of the structural material. One of the possible solutions to achieve these goals is the development of tungsten laminates. However, since it is difficult to apply such materials to the HEMJ concept, a new helium-cooled divertor has been proposed [2]. This concept combines the jet-impingement cooling with an ITER-like target arrangement where the armor is made of tungsten slabs installed on a helium-cooled tungsten laminate pipe. For the armor, the preferred solution is the one of fine grain tungsten obtained by powder injection molding [3]. This article gives a brief overview of the current activities concerning the development of these novel materials with focus on W-Cu laminates developed at KIT, as well as new progresses achieved in developing improved armor materials via tungsten powder injection molding (W-PIM). In addition, the thermal-hydraulic performances of a new helium-cooled divertor concept will be discussed.

Structural material development

One major drawback of using monolithic coarse-grained tungsten as structural material is its high tendency to brittle – low energy fracture at low temperatures. Recently published studies confirm a rise in fracture toughness, K_{IQ}, and a clearly decrease of the brittle-to-ductile transition temperature (BDTT) through cold rolling [4,5]. In our search for ductile materials for divertor applications, we make use of these facts by taking severely cold-rolled ultrafine-grained tungsten sheets to build tungsten laminated composites. The idea of the laminated composites is to produce a bulk material that retains the ductility and toughness of the heavily cold-rolled tungsten sheets. Tungsten laminates allow the assembly of three-dimensional shapes and geometries such as caps and pipes. Figure 1A shows several W-Cu laminated pipes produced at KIT: four pipes with a length of 500 mm and, one pipe with a length of 1000 mm. All pipes have an outer diameter of 16 mm and a wall thickness of 0.9mm. These pipes can be directly used for the manufacturing of high heat flux components as it can be seen in Figure 1B where the manufacturing of a divertor mock-up has been demonstrated. Thus, the armor is made of tungsten blocks installed on a W-laminate pipe that contains the coolant, in this case helium at 10 MPa. The cooling of the loaded surface is done through impingement jets that are generated through a cartridge inside the pipe that acts also as inlet manifold.

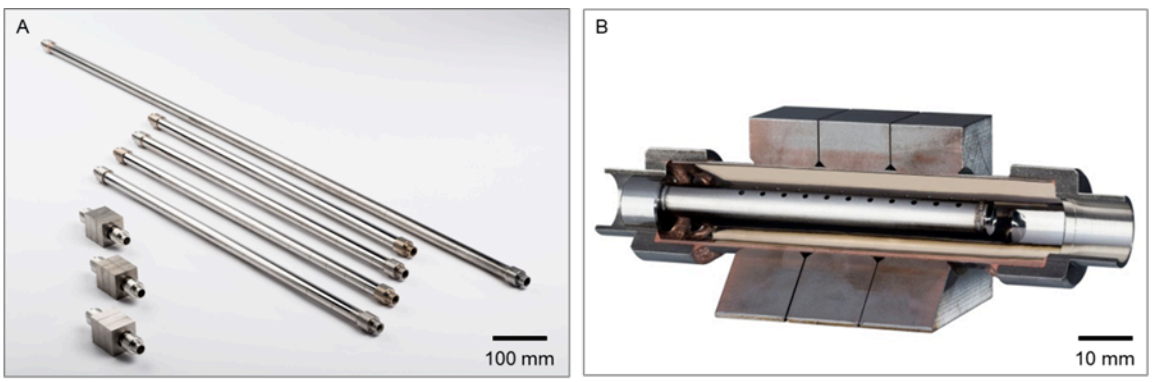

Figure 1. A: W-Cu laminated pipes with a length of 1000 mm can be produced.
B: Manufacturing mockup for a high-temperature helium cooled divertor.

Divertor armor material development

KIT research on armor material is mainly focused on the development of new tungsten grade materials via Powder Injection Molding (PIM), as well as on the manufacturing of small or full divertor armor parts (medium size mono-blocks). With its high near-net-shape precision, the method offers particularly the advantage of reduced costs compared to conventional machining [6]. The combination of an inorganic metal or ceramic powder with a small quantity of a polymer, a so-called feedstock, can be molded. The average particle size distribution of the used tungsten powder is in the range of 1.0 to 2.0 μm Fisher Sub-Sieve Size (FSSS). Depending on the size and shape of the parts, for simple geometries, only 20 seconds are needed to produce a green part [7]. After shaping the green part (consisting of powder and binder), the polymeric binder must be extracted and the powder sintered at 2400 °C to the near-theoretical density. Isotropic materials, equiaxed grain orientation, good thermal shock resistance, shape complexity and high final density (>98% theoretical density) are typical properties of powder injection molded

tungsten [8]. Such manufactured pure tungsten parts have an achieved grain size in the range of 50 to 100 μm. This process is very effective and easy to up- and down-scale the size and shape of parts, from a micro gearwheel 3 millimeters in diameter and a weight of 0.050 grams, up to a 1.4 kilo plate with the dimensions 60 x 60 x 20 mm, as shown in Figure 2 [9].
One of the possibilities for manufacturing fusion relevant parts via W-PIM has been already demonstrated by the latest produced series of Langmuir samples for diagnostics for the French tokamak WEST (Tungsten (W) Environment in Steady-state Tokamak) [10]. WEST is intended to become one of EUROfusion's test benches for tungsten components under ITER-like conditions. Figure 2 (left) shows two of 70 produced probes, each 25 mm long, 17 mm tall and 2 mm thick. The feedback from using these Langmuir probes in WEST will provide a valuable input for the ITER design process [11].

Figure 2. Range of dimensions for the produced W-PIM parts (left side) [9]; W-PIM Langmuir probes for WEST (right side) [10].

Fracture mechanics and high heat flux tests already performed on W-PIM manufactured samples indicate better transition temperatures and higher crack resistance than that for tungsten materials produced by common manufacturing routes. These results indicate that tungsten produced by PIM is a viable option for armor applications [11]. Furthermore, the W-PIM process enables the further development and assessment of new custom-made tungsten materials, as well as allowing further scientific investigations on prototype materials for use in general R&D, and for developing industrial products for a wide range of applications.

Divertor concept and thermal-hydraulic performance evaluation

To evaluate the heat transfer performances, Computational Fluid Dynamics (CFD) simulations were done with Ansys-CFX V15 using the k-ω-SST turbulence model. The geometry used for the investigations was the same as the one for the manufacturing mock-up shown in Figure 1. The only difference was that, to reduce the computational time, only one tungsten slab was considered. For this mock-up, besides the 16 mm laminate pipe, the distribution manifold was done out of a 6mm steel pipe and the jet holes are 1 mm in diameter. The tungsten blocks had 32x13 mm plasma facing sides. The thickness of the tungsten block towards the plasma facing side is 8 mm. A helium flow rate of 20 g/s and an inlet pressure of 10 MPa have been considered, while the inlet temperature was adjusted to meet the lower operating limit of tungsten laminate pipe, namely 500°C. This temperature was chosen by extrapolating the results of the first irradiation campaign performed for the W-laminates [12] assuming that, during the divertor lifetime, the pipes material will be subject to 3 dpa.

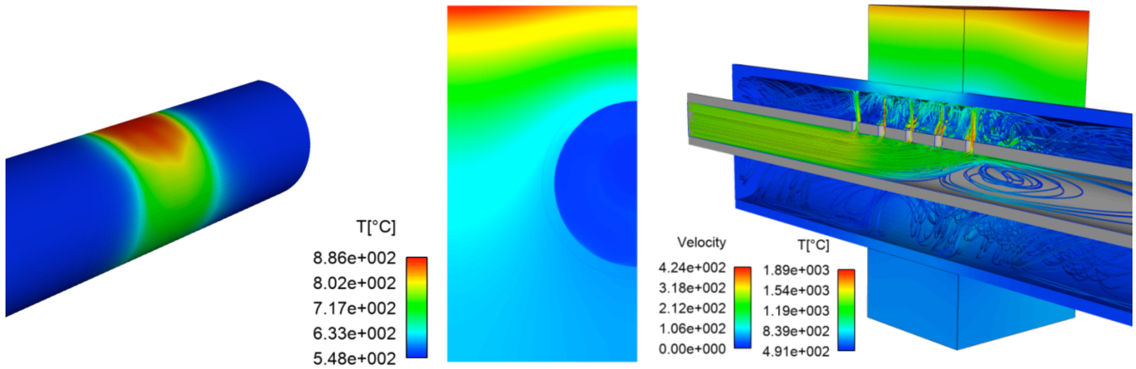

Figure 3. Pipe-multi jet concept: temperature field for 10 MW/m² heat flux.

The results show that, for the W-Cu laminate pipe the proposed concept could operate at fluxes up to 10 MW/m² and the pipe wall temperature approaches 900°C at the outer surface which is within the operating window defined for these materials (see Figure 3). Further simulations are currently focusing on optimizing the cooling pattern in order to reduce the required flow rates. Thus, parametric studies concerning the holes pattern as well as the distance between the inner manifold to the pipe heated surface are currently under way. In addition, the integration of such a cooling concept into a DEMO divertor target with a length of about 650 mm is also investigated.

Acknowledgments
This work has been partially carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Development of Liquid Metal Divertors for Fusion, R. Majeski, E. Kolemen, M. Hvasta, T. Kozub, J. Winkelman, Princeton Plasma Physics Laboratory, Princeton, NJ.

Introduction

Liquid metal-based plasma-facing components (PFCs) can potentially solve a host of issues vexing solid high-Z PFCs, including erosion, dust formation, power handling limits, and damage from disruptions as well as fast electron populations formed during disruptions. The two liquid metals currently considered for PFC applications are liquid lithium and tin; liquid lithium is the only low-Z material which may be deployed in a fusion reactor. Low-Z PFCs have long been known to provide superior core plasma performance. Lithium coatings, in particular, have produced the highest performing tokamak discharges in devices ranging from the National Spherical Torus Experiment (NSTX) [1] to the Tokamak Fusion Test Reactor (TFTR) [2] at the Princeton Plasma Physics Laboratory (PPPL).

Although high power handling divertor solutions which involve vapor shielding (in lithium) have been recently proposed [3], here we discuss single-phase solutions to the formation of high power handling PFCs employing liquid metal. In order to limit the surface temperature of the liquid metal to levels which do not produce significant evaporation, fast flow of the liquid metal is required. Some experimental work involving free-surface fast flow of liquid metals in strong magnetic fields has been performed; this includes work done on the Magnetic TORus (MTOR) facility [4] at the University of California-Los Angeles (UCLA), work on liquid metal jets [5] at Sandia, and more recently work on the Liquid Metal Experiment (LMX) [6] at PPPL. Recently, the University of Illinois-Urbana Champaign (UIUC) has also been investigating an intermediate flow-rate regime using self-induction of flows via the thermoelectric magnetohydrodynamic (TEMHD) effect [7], but this approach would likely require separate cooling of the supporting structure, and is not considered here. Larger scale free surface flows of liquid metals in geometries suitable for implementation as a tokamak divertor target or wall have not yet been experimentally investigated. So far, experiments have also used external liquid metal pumping systems. Implementation of such a system for a fusion reactor would require large inventories of the liquid metal, flowing at high rates through the tokamak vacuum boundary into an external pumping system, an obvious safety concern. One of the major obstacles to the consideration of liquid metals as PFCs is the lack of integrated designs. This task is currently under consideration in the U.S. by a design team. Here, we describe a design for a fast flow divertor system, which could be implemented in a tokamak or test stand.

A fast-flow liquid metal divertor target

The required flow velocity is determined by the surface heating of the liquid metal, and the resulting evaporative flux, which is an impurity source for the plasma. For lithium, which has a melting point of 180.5°C, a surface temperature limit for the lithium of 400°C is often assumed, so that the total thermal excursion of the surface under plasma heating in the divertor should not exceed 200°C. Lithium will not radiate significantly in the plasma core, but it does dilute the plasma and reduce the fusion power. For tin, which has a melting point of 232°C, a maximum temperature in the range of 600 - 700°C can be assumed, so that the total thermal excursion of the surface can be 400°C. Tin is high Z (50); radiation losses limit the allowable concentration of tin in the plasma to a concentration of a few $\times 10^{-4}$. If we assume a maximum power deposition of 20 MW/m^2 at the divertor target, over a radial footprint of a few tens of centimeters, then limiting the surface temperature of lithium to 400°C will require a flow rate of ~ 10 m/sec. Because of the higher surface temperature limit of tin, a flow rate of 10 m/sec will allow up to 60 MW/m^2 divertor power density (for the same radial footprint). Thus flow rates in the range of 10 m/sec are desirable, and previous work during the ALPS (Advanced Liquid Plasma facing Surfaces) program typically focused on this range of velocities for fast flowing liquid metal divertors [5].

A moving conductor in a strong magnetic field is subject to MHD drag. It can be shown that MHD drag vanishes for axisymmetric flow in a toroidal magnetic field, in the absence of surface-normal field components [8]. Initial liquid metal divertor studies in the new PPPL test stand (FLIT – the Flowing LIquid metal Torus) will therefore focus on axisymmetric geometry in a toroidal magnetic field; a CAD view of the design is shown in Figure 1. The prototype will provide a model horizontal liquid metal divertor surface for flow studies. Two-dimensional curvature in the liquid metal surface (which preserves axisymmetry) will be introduced in subsequent test articles, to model vertical inner divertor leg targets as well as inclined outer leg targets. Perturbations to exact axisymmetry will be introduced, and alternative flow geometries, such as flow along the magnetic field, which require entirely new test articles, will be investigated.

The toroidal field coil set is designed to provide 1 Tesla operation; the coil set has a major radius of 60 cm and a coil window of 76 cm (radial) × 106 cm (vertical). Additional coils can simulate poloidal field components, and even time-varying fields due to MHD instabilities in the plasma. The liquid metal to be used initially will be galinstan, a eutectic of gallium, indium, and tin that is liquid at room temperature. The liquid metal will be recirculated within the chamber by electromagnetic (J×B) pumps; more detail on the pumping system is provided in Figure 2. Six electromagnetic pumps will recirculate the galinstan, to provide free-surface flow speeds from a few m/sec, to up to 10 m/sec. In a fusion system, a sampling loop would exit the vacuum chamber and toroidal field coils for deuterium and tritium removal [9]. A reservoir ("b") would be necessary, but in a fusion system the reservoir would be equipped with a heat exchanger to remove the plasma heat. If lithium is the liquid metal used as a PFC, the presence of a reservoir volume will not negatively impact the tritium breeding ratio, since tritium will be bred in the reservoir and removed via the extraction process in the sampling loop. The integration of such LM divertors with the main heat transfer and tritium recovery systems of fusion power plants needs further investigation.

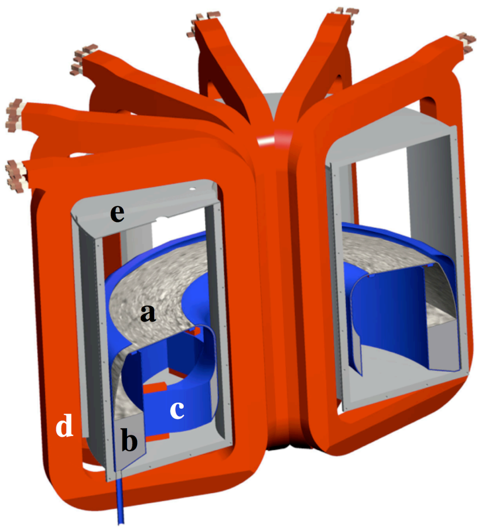

Figure 1. Elevation of one half of FLIT. Six of the twelve toroidal field coils ("d") are shown. The free surface flowing liquid metal forming the "divertor target" is indicated by "a", the low-field side catch basin for the liquid metal is indicated by "b". Six pump ducts ("c") return the liquid metal to the high field side nozzle. The test article is enclosed in an argon-filled chamber ("e"). FLIT will not operate with plasma; the "divertor target" is located at the midplane of the coilset for convenience, and to minimize the effects of toroidal field ripple.

Summary

The successful development of liquid metal PFCs for fusion will require experimental testing in adequate toroidal facilities, with a sufficiently high magnetic field to provide adequate MHD effects. Test stand facilities such as described here can be used to validate numerical codes which model free surface liquid metal flows in magnetic fields. Test stands will help determine the practicality of using liquid metal PFCs in fusion reactors.

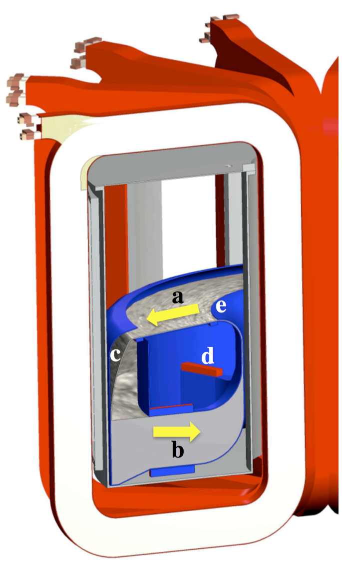

Figure 2. Detail of the recirculation system envisioned for the first test divertor in FLIT. The flow direction is indicated by the yellow arrows; the "divertor surface" is again indicated by "a". Liquid metal flows over a "waterfall" indicated by "c" into the catch basin/reservoir. Six rectangular ducts ("b") return the liquid metal to the flow-forming nozzle on the high field side ("e"). One of the electrodes which inject current through a neighboring liquid metal duct to provide the J×B pumping force is indicated by "d". All six ducts are joined to form an axisymmetric flow channel before the liquid metal is ejected through the nozzle "e".

Acknowledgments
This work was supported by USDoE contract DE-AC02-09CH11466. We acknowledge very helpful discussions with R. Maingi and M. Zarnstorff.

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ANNOUNCEMENTS

Invitation and Guidance for Community Input for FESAC Transformative Enabling Capabilities (TEC) Subcommittee

Executive Summary
The Fusion Energy Sciences Advisory Committee (FESAC) Transformative Enabling Capabilities (TEC) subcommittee welcomes the submission of white papers and talk requests (see below) that describe concepts and technologies that can bring fusion power closer to reality. For full impact, all talk requests should be accompanied by white papers. While we recommend that all white papers be accompanied by talk requests, white papers will be considered in the absence of a companion talk. Every effort will be made to honor all talk requests responsive to the charge, subject to practical time constraints.

Background
The FESAC was recently charged "to identify the most promising transformative enabling capabilities for the U.S. to pursue that could promote efficient advance toward fusion energy, building on burning plasma science and technology."

The charge lists sample focus areas including ”liquid metals, additive manufacturing, high critical-temperature superconductors, exascale computing, materials by design, machine learning and artificial intelligence, and novel measurements.” Note that these are only examples. The committee will be accepting community input on any ”promising transformative enabling capabilities” that promote efficient advance toward fusion energy associated with the subject mater being investigate by the TEC subcommittees listed below as designated by their titles. The full charge can be found at: https://science.energy.gov/~/media/fes/fesac/pdf/2017/Charge_Letter_FESAC_Feb_2017.pdf.

Note that this activity is an assessment of (multiple) technical capabilities, and not an evaluation of confinement devices. According to the charge “Identification of R&D that may have general impact that both includes and extends beyond” tokamak and stellarator concepts “is welcome. However an assessment of various types of confinement devices is not to be performed.”

The TEC subcommittee (R. Maingi, Chair, and A. Lumsdaine, Vice-Chair) has been broken up into three sub-panels corresponding to different areas of technology application:

- Plasma Diagnostics, Actuators, and Control (lead: A. White)
- Plasma Materials Interaction (lead: J.P. Allain)
- Reactor and Balance of Plant (lead: C. Greenfield).

Community Input Meetings

In order to facilitate broad input, three meetings where the community can present to the FESAC subcommittee are planned:

- **May 30-June 1, 2017** (Washington DC area): Community input meeting for Plasma Diagnostics, Actuators, and Control sub-panel, and also for Reactor and Balance of Plant sub-panel; workshop starts at 9 AM on 5/30 and ends by 6 PM on 6/1.
- **June 20-22, 2017** (Chicago or Washington DC area): Community input meeting for Plasma-Materials Interaction sub-panel; workshop starts at 1 PM on 6/20 and ends by 6 PM on 6/22.
- **July 19-21, 2017** (PPPL, Princeton NJ): Final workshop for all three sub-panels; additional community input time, if necessary; workshop starts at 1 PM on 7/19 and ends by 6 PM on 7/22.

Details on the locations for these workshops will be posted on the TEC website. All presenters are strongly encouraged to attend one of the first two workshops.

White paper and talk request submission details and guidelines

White papers should be submitted to the FESAC TEC home page at the following website: FESAC TEC Panel Public Info Home Page with cc to the Chair (Rajesh Maingi, rmaingi@pppl.gov) and the Vice-Chair (Arnold Lumsdaine, lumsdainea@ornl.gov) by May 16 for the May 30 meeting, and by June 6 for the June 20 meeting. The full talk and white paper guidance is given here: FESAC TEC White Paper Invitation.

Talk requests with prospective titles should be submitted to rmaingi@pppl.gov and lumsdainea@ornl.gov at the earliest convenience, but no later than May 16 for the May 30 meeting, and by June 6 for the June 20 meeting. It is assumed that all talk requests will be followed up with white paper submissions. Any talk requests not accommodated in the first two meetings will be considered for the third meeting, July 19-21. Final talks should be submitted to the same BPO website above, using the proper radio button link, with cc to the Chair (Rajesh Maingi, rmaingi@pppl.gov) and the Vice-Chair (Arnold Lumsdaine, lumsdainea@ornl.gov).

Please use the naming convention <author>_FESAC_TEC2017_<paper or talk>.pdf. White papers are limited to 4 pages, and should include the components listed below. We will attempt to accommodate all requests for presentations that are responsive to our charge, subject to our time constraints. Our intention is to plan for a 15-minute talk with 15 minutes of Q/A from the FESAC subcommittee, but these may be shortened in order to provide additional presentation slots. If there are more requests than we can accommodate, even with shorter time slots, they will be accepted on a first-come, first-served basis. Please use the white paper template, linked to the FESAC TEC home page above, as a guideline, noting that not all questions will be relevant for all proposed technologies.

1. Description of the technology
2. Application of the technology for fusion energy, e.g. in a fusion power plant
3. Expected performance of the technology – what is the critical variable (or variables) that determines or controls the output of the technology?
4. Design variables – what are the parameters that can be controlled in order to optimize the performance of the technology?
5. Risks and uncertainties with the technology development and performance
6. Current maturity of the technology, using e.g. Technical Readiness Levels (TRL – see Appendix 2 for DoE TRL guidelines)
7. Required development for the technology.

Initially, white papers will only be reviewed by the subcommittee and not publically available. White papers will later be posted on the web site, if permission is granted by the primary authors. Please address questions to Rajesh Maingi (rmaingi@pppl.gov) or Arnie Lumsdaine (lumsdainea@ornl.gov).

A Strategic Plan for U.S. Burning Plasma Research

Statement of Task:

A committee of the National Academies of Sciences (NAS), Engineering, and Medicine will be formed to study the state and potential of magnetic confinement-based fusion research in the United States and provide guidance on a long-term strategy for the field. The study will focus on research that supports understanding the magnetically confined burning plasma state but will take a broad view beyond plasma confinement science, and as such consider capabilities such as simulation and materials. Specifically, the committee will prepare an interim report that will:

1. Describe and assess the current status of U.S. research that supports burning plasma science, including current and planned participation in international activities, and describe international research activities broadly.
2. Assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

The committee will also prepare a final report, building on the interim report, which will:

1. Consider the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source, including the scientific and technical developments since the 2004 NAS study on burning plasma research.
2. In two separate scenarios in which, after 2018, (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER: provide guidance on a long-term strategic plan (covering the next several decades) for a national program of burning plasma science and technology research which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing economical fusion energy in the long term.

In doing the above, the committee will consider the priorities for the next ten years developed by the community and FES that were recently reported to Congress. The committee will also consider the current level of participation by U.S. scientists in international activities as well as what role international collaboration should play over the next 20 years. The committee will also consider the health of the domestic fusion research sectors (universities, national laboratories, and industry). Elements of any strategic plan for U.S. burning plasma research should ensure that the United States maintains a leadership role in this field. The committee may assume that economical fusion energy within the next several decades is a U.S. strategic interest. The committee may take into account how unanticipated events or innovations may necessitate mid-course re-directions. The committee will use the prior work of the Academies as well as that of FESAC and the domestic and foreign communities in its deliberations. The committee is not to compare fusion as an energy source against other current or potential energy sources. The committee will consider the budget implications of its guidance but will not make recommendations about the budget for burning plasma research itself. The committee will only consider magnetically confined burning plasma research as within its purview. The committee may make recommendations or offer comments on organizational structure and program balance, with accompanying supporting discussion of the evidentiary bases, as appropriate.

Committee Members

The remaining committee members will be announced on the National Academies Current Projects System and reproduced here upon appointment.

Michael Mauel, Columbia University

Melvyn Shochet, University of Chicago.

The main web site for the review is:
http://sites.nationalacademies.org/BPA/BPA_177107.

Community Workshops on Strategic Directions for U.S. Magnetic Fusion Research

Workshop 1: July 24-28, 2017 in Madison, WI
Workshop 2: Tentatively December 11-15, 2017 in Austin, TX

I. Overview

This document is an announcement for two magnetic fusion community workshops to enable community presentation and discussion focused on the recent charge to the National Academies of Sciences (NAS), Engineering, and Medicine (http://sites.nationalacademies.org/BPA/BPA_177107). The NAS Committee has been charged to prepare an interim report and a final report focused on the importance of burning plasmas in the future of U.S. fusion energy development, along with consideration of the scientific and engineering challenges and opportunities on the path toward fusion energy, and possible scenarios to achieve that goal. Specifically, the committee will prepare an interim report that will:

- I1. Describe and assess the current status of U.S. research that supports burning plasma science, including current and planned participation in international activities, and describe international research activities broadly.
- I2. Assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines.

The committee will also prepare a final report, building on the interim report, which will:

- F1. Consider the scientific and engineering challenges and opportunities associated with advancing magnetic confinement fusion as an energy source, including the scientific and technical developments since the 2004 NAS study on burning plasma research.
- F2. In two separate scenarios in which, after 2018, (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER: provide guidance on a long-term strategic plan (covering the next several decades) for a national program of burning plasma science and technology research which includes supporting capabilities and which may include participation in international activities, given the U.S. strategic interest in realizing economical fusion energy in the long term.

It is anticipated that the U.S. Burning Plasma Organization, the Virtual Laboratory for Technology, and the broader fusion research community within the U.S. combined with previous recent community reports will assist the NAS study in providing information for charge question I1 and for identifying developments since 2004 in charge question F1. The primary purpose of the fusion community workshops is to **foster community discussion** on NAS strategic charge questions I2 and F2 and **identify key opportunities** relevant to charge question F1.

The fusion community workshops have two overarching goals:

1. Provide an open forum to hear community views on strategic charge questions I2 and F2 and opportunities in charge F1, and to provide community feedback on these views.
2. Identify key elements of a long-term U.S. fusion strategic plan (both with and without the U.S as a partner in ITER) including both domestic and international research, and identify points of community consensus on the most critical key elements of that plan.

II. Factors for Assessing Proposed Strategic Elements

Specifically noted in the NAS charge is the assumption that economical fusion energy within the next several decades is a U.S. strategic interest. Further, the NAS committee has been asked to consider several factors in preparing their reports, and therefore the U.S. fusion community workshops should consider these factors in proposing key strategic plan elements:

1. Elements of a strategic plan for U.S. burning plasma research that ensure the U.S. maintains a leadership role in this field.
2. The current level of participation by U.S. scientists in international activities as well as what role international collaboration should play over the next 20 years.
3. The health of domestic fusion research sectors: universities, national labs, and industry
4. How unanticipated events or innovations may necessitate mid-course re-directions

The workshop program committee has also highlighted the importance of identifying scientific and engineering opportunities associated with advancing magnetic confinement fusion as an energy source and therefore includes an additional 5th factor for consideration and assessment:

5. Key scientific and engineering opportunities for advancing magnetic confinement fusion as an energy source.

Lastly, in addition to addressing the NAS charge questions and considerations above, it is also recognized that there is significant U.S. fusion community interest in maintaining a strategic vision for fusion that adapts to advances in the field. Thus, the community workshops will also consider ideas on how to foster effective and timely community-based strategic planning for the U.S. fusion program that enhances cooperation with DOE and builds on key strategic elements.

III. Workshop Deliverables

Workshop 1: Building on charge question I2, this workshop will "assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines". Key examples of present U.S. burning plasma research importance will be identified, and relative weaknesses and potential growth areas for the U.S. program will also be considered. In response to charge question F1, this workshop will also address broader opportunities for advancing magnetic confinement fusion as an energy source. This workshop will also begin to address charge question F2, but emphasis will be placed on charges I2 and F1.

Brief presentations by the community are requested which:

(a) Assess the importance of U.S. burning plasma research to the development of fusion energy as well as to plasma science and other science and engineering disciplines,

(b) Propose key strategic elements for the U.S. fusion program, and

(c) Begin to consider these elements in the context of the whether the US is / is not a partner in ITER. Presentations are requested to explicitly discuss how the proposed strategic elements address the 5 factors listed above.

Major deliverables for Workshop 1 include:

1. An open forum to hear community views on strategic elements, and provide community feedback on these views.
2. A preliminary discussion and documentation led by the workshop program committee of the degree to which community-proposed elements address the 5 factors listed above.
3. Identification of potential points of consensus and also areas in which future discussions would be needed in resolving future directions.

Workshop 2: Building on the generation and discussion of key strategic elements and possible points of consensus from Workshop 1, Workshop 2 will primarily consider proposed key strategic elements in the context of the two scenarios of charge question F2: (1) the United States is a partner in ITER, and (2) the United States is not a partner in ITER. In addition, the organization and effectiveness of these community workshops will be assessed by the community, and ideas for how to foster more frequent, community-based strategic planning that partners effectively with DOE will be explicitly solicited and discussed.

Major deliverables for Workshop 2 include:

1. An open forum to hear community views on strategic elements, and provide community feedback on these views.
2. Discussion and documentation led by the workshop program committee of proposed strategic elements for scenarios in which the US is / is not a partner in ITER
3. A community assessment of the workshop process and ideas for future workshops
4. A document summarizing the workshop process and high-level outcome.

IV. Community Input

Meeting Timing: The first and second NAS meetings incorporating public input are tentatively scheduled to be in May/June and August/September timeframes, respectively - exact dates TBA. The timing of the first fusion community workshop (July) was chosen to provide input to the second NAS meeting. The timing of the second community workshop (December) was chosen to provide time to assess and incorporate the NAS interim report (due October 31, 2017) in the second workshop discussions and to provide input to a later third and/or fourth NAS meeting.

Input Format: Community input will be solicited in the form of 2 page whitepapers briefly summarizing a proposed strategic element and how this element is impacted by the 5 factors noted in Section II. A whitepaper template and submission instructions will be made available in the near-term on the workshop website.

Whitepapers will be due 11:59 PM Eastern June 26, 2017.
Community input will also be sought in the form of brief presentations at the workshop(s). It is expected the whitepapers will be used by the Program Committee to select and/or consolidate strategic elements or topics for oral presentation.

Website: The workshop website is: https://sites.google.com/site/usmfrstrategicdirections and also here: www.usmfrsd.org.

If you have any questions, please contact the meeting co-chairs: David Maurer, Jon Menard, and Mickey Wade: maurer@physics.auburn.edu, jmenard@pppl.gov, wade@fusion.gat.com

V. Workshop Agenda

Workshop agenda(s) will be formulated based on community interest, whitepaper content, and program committee input.

VI. Travel Funding and Registration

These workshops are community-led and not directly sponsored by FES. However, FES has indicated that workshop participants funded by grants, cooperative agreements, and national labs have the discretion to use available funding to travel to the workshops provided that the workshop is related to ongoing work and no contract deliverables are jeopardized by the travel. Workshop attendance should be treated as analogous to attending an annual APS-DPP meeting. It is expected a registration fee will be charged to pay for meeting space and logistical support.

VII. Program Committee Program Committee Membership for U.S. Fusion Community Workshops

Name	**Affiliation**	**E-mail Address**
Workshop Co-chairs		
David Maurer	Auburn University	maurer@physics.auburn.edu
Jonathan Menard	Princeton Plasma Physics Laboratory	jmenard@pppl.gov
Mickey Wade	General Atomics	wade@fusion.gat.com
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Francois Waelbroeck	University of Texas - Austin	flw@mail.utexas.edu
Steven Zinkle	University of Tennessee - Knoxville	szinkle@utk.edu

You can begin to participate in the Madison workshop NOW with these actions:

- Submit a 2 page whitepaper (Deadline: 11:59 PM Eastern June 26, 2017)
- Register for the workshop (Deadline: July 5, 2017)
- Reserve a hotel room (Room blocks expire beginning June 12, 2017)
- Join the informational e-mail list to receive updates on the workshop.

If you have any questions, please contact the meeting co-chairs:
David Maurer, Jon Menard, and Mickey Wade
maurer@physics.auburn.edu, jmenard@pppl.gov, wade@fusion.gat.com

CALENDAR OF UPCOMING CONFERENCES ON FUSION TECHNOLOGY*

2017:

1st IAEA Workshop on Challenges for coolants in fast neutron spectrum systems
July 5-7, 2017, Vienna, Austria
https://nucleus.iaea.org/sites/fusionportal/Pages/List-of-Workshops-on-Coolants.aspx

2nd Asia-Pacific Symposium on Tritium Science (APSOT-2)
September 5-8, 2017, Livermore Valley, CA, USA
https://connect.sandia.g ov/sites/apsot2

10th International Conference on Inertial Fusion Sciences and Applications (IFSA)
September 11-15, 2017, Saint Malo, France
http://web.luli.polytechnique.fr/ifsa2017/

19th International Spherical Torus Workshop (ISTW2017)
September 19-22, 2017, Seoul, S. Korea
yhwang@snu.ac.kr

5th International Symposium on Liquid metals (previously: Lithium) Applications for Fusion (ISLA)
September 25-27, 2017, Moscow, Russia
http://isla2017.mephi.ru

13th International Symposium on Fusion Nuclear Technology (ISFNT)
September 25 – 29, 2017, Kyoto, Japan
http://www.isfnt-13.org

59th American Physical Society - Division of Plasma Physics (APS-DPP) meeting
October 23-27, 2017, Milwaukee, WI, USA
http://www.aps.org/meetings/meeting.cfm?name=DPP17

ANS Winter Meeting
October 29-November 2, 2017, Washington, DC, USA
http://www.ans.org/

18th International Conference on Fusion Reactor Materials (ICFRM)
November 5-10, 2017, Aomori, Japan
www.icfrm-18.com

38th FPA Annual Meeting and Symposium: Pathways and Progress Toward Fusion Power
December 6-7, 2017, Washington, DC, USA
http://fusionpower.org

2018:

ANS Annual meeting
June 17-21, 2018, Philadelphia, PA, USA
http://www.ans.org/

30th Symposium on Fusion Technology (SOFT)
September 17-21, 2018, Sicily, Italy

27th IAEA Fusion Energy Conference (FEC)
October 2018, India

60th American Physical Society - Division of Plasma Physics (APS-DPP) meeting
November 5-9, 2018, Portland, OR, USA
http://www.apsdpp.org/meetings/upcoming_meetings.php

ANS 23rd Topical Meeting on the Technology of Fusion Energy (TOFE)
November 11 -15, 2018, Orlando, Florida, USA
winfrey@mse.ufl.edu

ANS Winter meeting
November 11 -15, 2018, Orlando, Florida, USA
http://www.ans.org/

* Calendar of other meetings (of interest to researchers in atomic, molecular and plasma-material interaction processes and data relevant to plasma physics and fusion energy research) are posted at: https://www-amdis.iaea.org/w/index.php/Calendar_of_Meetings.