White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/19/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	P
• Turbulence and transport	
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	

Title:	High-density, high-impurity fraction plasma physics
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

It is common practice to attempt to simplify our physics problems as much as possible to understand the physics of interest. While extremely powerful, many physical systems of interest are now exhibiting strong coupling between multiple physical phenomena. These plasmas are found in a wide range of situations ranging from gas-metal arc welding to magnetohydrodynamic power generation electrode systems as well as to vapor-shielded fusion divertor targets. At high-density, collisional effects begin dominating the plasma state as one approaches local thermodynamic equilibrium (LTE). Even in LTE plasmas, the presence of multiple species can strongly impact the radiation and transport properties of these plasmas. The introduction of multiple species can be effected by design (i.e. gas mixture) or as a consequence of the plasma interactions with nearby structures. The rate of introduction is, however, dependent on material properties and material composition which can be altered by the plasma particles impinging the surface, a problem exacerbated in high-density plasmas where particle fluxes can be very large. Large influxes of particles can have a strong influence on the sheath and pre-sheath regions of the plasma and the transport of impurities are altered by the resulting changes in electrical field, flow and impurity fractions. The combined impact of material introduction, cooling and transport can even have an impact on the plasma kinetics. When plasma properties (i.e. temperature and density) vary on length scales approaching the mean-free-path of electrons in the plasma, then the assumptions underpinning the

fluid description of the plasma begin to break down. A fully self-consistent description of all of these effects is lacking, yet these multi-physical couplings are increasingly present.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Approach:

At present, there seems to be a dearth of research in the US on plasmas in these conditions. For example, a search for the keyword "arc" in the 2014 APS-DPP program revealed one poster presentation on self-organized plasma and material processes in a carbon arc. For research on vapor-shielded fusion divertor targets, transient targets have been examined in plasma-gun experiments, very few steady-state studies have been conducted though this is a recent topic of interest for the NSTX-U program on liquid lithium plasma facing components. In the general topic of plasma-modified surfaces, in particular liquid surfaces, the US OFES previously had a materials research program but this was discontinued. Finally, while the US DOE had previous funded research on MHD power generation, this program was discontinued in the mid-90s, though there have been recent workshops to examine a potential restart. In the case of welding arcs and novel fusion divertors, the surface of interest is a liquid metal of various types (e.g. lithium, iron or others). In the case of MHD power generation, molten-salt, liquid electrodes have been recently proposed and would provide a self-seeding surface to the generator. Facilities conducting this research should have some flexibility in the materials of study.

It would appear that a coordinated approach including both theory and experiments could continue on several fronts that were previously investigated. For an experimental approach, there are many methods of producing plasma of interest in this regime. The study of welding arcs is achieved with standard equipment and often does not require vacuum vessels. High-power linear plasma devices for simulating divertor plasmas and MHD generators require significant magnetic fields to be relevant as well as to produce significant plasma densities (c.f. the MDPX facility). In combination with easily ablated materials, this unique plasma regime can be addressed with some modification to existing systems. A larger investment is likely required for diagnostic sets to investigate the physics associated with these systems. Due to the densities and heat fluxes involved, these diagnostics are often optical (both passive and active) but also include particle probe measurements. Novel diagnostics would be needed to probe the material surface during plasma bombardment and would have to be developed. Investigation of kinetic effects has previously relied on Langmuir probes, but robust and accepted interpretation schemes are often lacking.

On the theory side, there has been some success modeling welding arcs to date. Very few experimentally validated simulations exist of vapor shielding simulations in a fusion context. MHD generators are actively studied abroad (e.g. Japan has an active program) but an evaluation US capabilities would require investigation. Materials simulations have been maturing across a number of fields and researchers can now apply molecular dynamics simulations with the use of ab-initio potentials or potentials derived from density-functional theories. Kinetic electron transport has been simulated in magnetic fusion scrape-off layers though there are few observations of the expected results (most with Langmuir probes). Inertial fusion experiments have also developed theories for kinetic electron transport but diagnostic schemes are even more challenging in this context.

In short, there are a handful of experimental and theoretical models used in disparate areas. A coordinated effort could be made to unify the appropriate expertise and explore this parameter regime.

Resources: As mentioned, there is a dearth of experimental facilities examining this topic. The NSTX-U Materials and PFCs program has a research thrust to examine continuously vapor-shielded targets using high-temperature liquid lithium as a plasma-facing material (nominal divertor densities should reach 10^{20}-$10^{21}m^{-3}$). Cascaded arcs in a high-field environment can be used to achieve significant plasma densities and study these phenomena in a more controlled environment (e.g. the Magnum-PSI experimental device in the Netherlands can routinely achieve similar densities as the NSTX-U divertor, a similar device could be created in the US using high-field facilities such as MDPX). Welding arcs operated in atmosphere require relatively modest facilities and can instead concentrate on diagnostic implementations. Finally, high-field facilities in the US could again be leveraged for MHD power generation studies with appropriate adjustments. Molten salt electrodes have been proposed as a novel technology for use in MHD generators but understanding the physics associated with their use is a brand new field of investigation.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

This white paper has been written with three major areas of impact: welding arcs, novel liquid metal fusion divertors and MHD power generation systems. Welding arcs are ubiquitous in society. The magnitude of their use suggests improvements in efficiency can have a major impact on the energy required for such activities. A major open issue in welding arcs is the production of metal fume which is also a safety and health hazard for operators and renewed examination of these systems could potentially improve the understanding and mitigation of such fumes. Fusion energy offers a very attractive alternative to fossil fuels and nuclear fission base-load power generation. At present however, the choice of material for a fusion device is unknown. The present front-runner solid material is tungsten but the use of tungsten carries a severe penalty in terms of machine size and component lifetime. Liquid metals, in particular liquid lithium, have been proposed as a viable alternative material. The use of liquid lithium as a high-temperature PFC, however, remains to be demonstrated and understood in a fusion device. Operation of a fusion divertor at high-density and high-impurity fraction would be a significant departure from typical conditions found in a conventional, tungsten-target divertor scheme. Demonstration could represent a major “game-changing” moment for fusion energy. Finally, until fusion energy is demonstrated to be economical, this country and the world will continue to burn fossil fuels. Improvements in efficiency of these fossil fuel systems will lead to a reduced carbon-intensity factor for each fuel used. New power generation facilities utilizing MHD power generation can provide this boost in efficiency while also leveraging carbon-capture and sequestration technologies (e.g. oxy-fuel combustion would greatly benefit from MHD power generation systems). Research on this field would reduce the “carbon footprint” associated with fossil fuel use as well as more efficiently utilize the natural resources available to us.

References (Maximum 1 page)

Figures (maximum 1 page)