White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	June 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	S
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	Multi-phase multi-scale physics in chemical processing plasma sources
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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.**

Developing and understanding large volume plasma sources for chemical and/or material processing is important challenging endeavor. The science and technology of these multi-phase multi-scale plasmas (MMP) is not well understood despite the fact that many technological processes of interest require their use (confined plasmas, plasma-material processing devices, atmospheric pressure plasmas, laser created plasmas, *etc*.). A comprehensive understanding requires a combined approach between theory and experiment to identify plasma species, understand their production and transport, determine particles aggregation/destruction, and determine the plasma response during chemical composition or phase changes – all this over scales ranging from the atomic to meters. For example, using a mist or solid catalysts in chemically processed or post-process gas raises fundamental questions associated with droplet or cluster size and how it will effect the plasma operation. Will the particulates vaporize or act as nucleation centers for creation of larger particulates? Other examples include sludge formation in flue gas and in sulfur-containing plasmas, dust particles in gas phase switches [12], plasma operation with chemically active gases such as fluorides, hydrogen-deficient materials, damage of plasma-interface components, deposition of metal clusters materials on surfaces, laser induced breakdown in air [9] or water/liquids, plasma sustained in bubbles in water [11], *etc*. These are all important questions in which the plasma community would benefit from answers. Some fundamental knowledge of particle containing

fluids [1] or particle containing plasmas could be found in some recent books of dusty [2] or complex plasmas [3-5]. Plasma-liquid or plasma-solid interfaces (Ref. [10,14]) in MMPs are similarly challenging to model and equally difficult to investigate experimentally.

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

While any approach will likely be application driven, advancing a basic understanding of multi-scale, multi-phase plasmas can be interdisciplinary in nature and benefit from strong interactions between universities, government, and industry (Fig. 1). Indeed, combining theoretical and experimental techniques in plasma physics, chemistry, atomic physics, biology and materials science to address the range of phenomena is these plasmas can be required to understand a single system. One can also envision establishing user facilities for large scale projects involving, for example, high power electron beam- (Ref. [6, 8]) and laser-generated plasma sources, and associated diagnostics can be established for interdisciplinary teams focused on the science of a particular application. Specific theoretical and experimental approaches are outlined below.

The disparate sizes between plasma and particulates as well as the different time-scales require a combination of different numerical techniques and methods of describing MMPs leading to self-consistent description of both plasma and multi-phase multi-scale material properties. It requires an integration of statistical methods of non-equilibrium plasma description with atomic and molecular physics, Monte-Carlo, molecular dynamics and DFT methods, scattering theory, *etc*. Experimentally validate the models and building predictive capabilities is of major importance.

Use of existing methods such as x-ray absorption fine structure to probe MMPs and gives information of local atomic structure by use of intense synchrotron x-ray sources or probing materials with ultra-short laser pulses; electron probe measurements [13]; different linear (absorption and emission) and non-linear spectroscopy methods over the electromagnetic spectrum including x-rays, ultraviolet, optical, and infrared. Vibrational spectroscopy of molecules can be investigated with Fourier transform infrared, and Raman techniques.

Development of new experimental MMPs techniques and devices (spatially and time-dependent) to diagnose plasma and MMP's material properties is needed.

The database of MMP techniques will assist in identifying and narrowing the tasks to attack specific problems that contain MMPs that are of interest for better understanding.

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

This work can contribute to many technology areas important to the mission of DoE, DoD, industry, and society in general. Multi-scale, multi-phase plasmas are being explored for gas remediation [6,7] and sterilization, they are widely used in industry for large area materials processing (Fig. 6) in the semiconductors, particle-coating dusty plasmas, and glass coatings sectors. Better understanding the science of MMPs will help advance the frontiers of plasma and material sciences, astrophysics, chemistry, and biology.

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Figures (maximum 1 page)

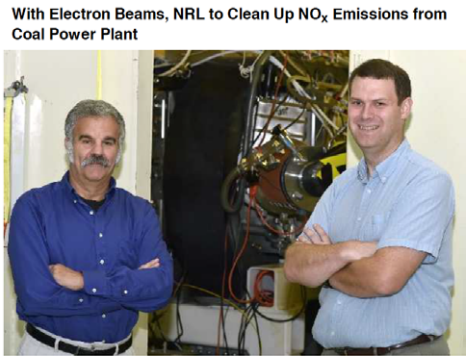

Fig. 1. Electron beam generated plasma, J. Sethian and M.F. Wolford

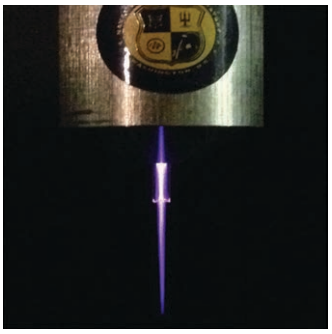

Fig. 2. NRL atmospheric pressure plasma jet (plasma interaction with solid, liquid, biological objects)