WORKSHOP SUMMARY

The Magnetohydrodynamic (MHD) Workshop was conducted to bring together organizations and researchers interested in the technology efforts to share on-going research and to identify potential opportunities for advanced power applications. MHD research was initially sponsored by DOE during the 1970s – 1990s, but the work was suspended when national objectives in energy research changed. The challenges for a commercialized MHD at that time remained significant and scarce resources were needed to facilitate other technologies that were nearer term to market viability.

Through a Direct Power Extraction initiative, NETL is taking a fresh look at MHD to assess the viability via integration with newer power cycles that would increase total power plant efficiency and facilitate the design potential for near-zero emission power generation. The most likely configuration would utilize oxycombustion. Also, near term application of the technology might be accelerated by fueling the cycle with natural gas, then transitioning to coal fuels as the technology matures.

In view of the potential new uses for MHD generation, NETL hosted a workshop to present the latest findings, assess the continued research in this area, and to solicit input on the potential future needs in MHD technology research. The workshop included 64 participants from industry, government, and academia. Several alumni from the original MHD program were on hand to discuss their experiences during early development and to council current researchers on avoiding past pitfalls. The registration list is included as an Attachment to this report.

The workshop included 11 presentations to provide a broad perspective of both MHD technology research and how it might be applied as a part of future power generation applications. A poster session was held to facilitate participant's discussions of on-going research and potential teaming to achieve research goals. A total of 12 posters were displayed with each participant providing a short presentation of their research.

The workshop provided valuable input from the participants in two separate facilitated brainstorming sessions that will be useful for potential future research projects. The first session was conducted with four small groups of about 15 persons each; addressing the status of technology; research needs; and assess the drivers for pursuing MHD applications. The second session was conducted with the entire assembly to facilitate barriers and challenges for a MHD deployment. The notes from these brainstorming sessions are attached to this report. This material along with the presentations is posted on the NETL website events page (http://www.netl.doe.gov/events/conference-proceedings/2014/mhd-workshop).

TECHNOLOGY SUMMARY

The MHD assessment for power applications research is focusing on a wide array of approaches that are looking to leverage technical advancements in fields that have the potential to improve on MHD feasibility in the market place. These are summarized briefly.

MHD Power Generation System: This work is focused on characterizing the DOE work of the past generation and using mathematical modeling to identify opportunities to improve the technology for future power generation scenarios. A number of systems analysis modeling activities are in progress to help identify where focused research can most benefit a new-concept power generation facility with near-zero emissions that can best benefit from integration of MHD technology. A number of alternative schemes for application of MHD were postulated during the conference which should be included as alternative power systems designs under consideration.

MHD Propulsion: There are a number of companies, universities, and agencies that are exploring the use of MHD as a propulsion technology for the future. These concepts vary widely exploring use in high-stratospheric flight and also for space propulsion applications. The appeal of MHD is the ability to generate electrical power in addition to high velocity thrust.

MHD with Pressure Gain Combustion: Pressure gain combustion is the control of “explosive” combustion in a contained environment to harness the energy released as similar to what occurs in a piston engine. Unlike confining the explosive force to drive a piston, the pressure occurs in rapid series of bursts in the MHD generator to create a high-pressure wave that propagates through the system. This technique could be integrated into advanced cycle systems such as with combustion turbines.

Tech Transfer from Fusion Energy Program: MHD, like fusion energy, relies on extracting energy from very-high temperature environments using strong magnetic fields. The work from the fusion community to develop high magnetic flux fields, materials and components to withstand the very-high temperature environment, and control of these dynamic systems during transient conditions can all contribute to the enhancement and advancement of MHD technology moving forward.

Mathematical Simulation Tools: Nearly all the participants identified the need for better models to improve the understanding of all aspects of MHD interactions for power generation. The existing models are largely empirical based on observations from past experiments. More work is needed to understand the fluid dynamics and plasma interfaces with more accurate and faster tools for modeling systems and backed up with experimental validations for improved concept designs. This will allow for improved conceptual designs as work continues.

Seeding to Enhance MHD Performance: Historically, injection of a “seed” material (to improve the electrical field strength generated) in the MHD generator was considered essential to meeting the performance goals for the technology deployment. Using a seed material resulted in numerous technical challenges to the design of the MHD generator and the downstream subsystems. Several goals for new research is to: identify alternatives to past seeded materials; identify non-seeded approaches that contribute to improved overall power plant design configurations; and characterization of traditional seed use with natural gas fuel on balance of plant design of downstream technologies (operate effectively in a seeded environment while complying with the most stringent environmental emission limits projected for the deployment timeframe).

ATTACHMENTS:

1. **Agenda**
2. **Attendance List**
3. **Summary of Brainstorming Session 1, October 1, 2014**
4. **Summary of Brainstorming Session 2, October 2, 2014**

ATTACHMENT 1 – AGENDA

Magnetohydrodynamic Power Generation Workshop Agenda

Wednesday, October 01, 2014

7:00 am to 8:00 am	Registration – Arlington 1 and 2 Foyer

Session 1: Introduction – Salon 1	
8:00 am to 8:05 am	**1.1: Workshop Welcome** *Susan Maley*; Technology Manager for Crosscutting Research at United States Department of Energy National Energy Technology Laboratory
8:05 am to 8:20 am	**1.2: Introduction to DOE Programs and Interests** *Dr. Darren Mollot*; Director, Office of Advanced Fossil Technology Systems at United States Department of Energy
8:20 am to 9:05 am	**1.3: Emerging Technology and the Changing Nature of Power Generation** *Dr. James Black*; Lead Researcher, Thermal Sciences Division at United States Department of Energy National Energy Technology Laboratory
9:05 am to 9:20 am	Break – Salon Foyer 1
9:20 am to 10:05 am	**1.4: Retrospective and Prospective Aspects of MHD Power Generation** *Dr. Rigel Woodside*; Researcher, Thermal Sciences Division at United States Department of Energy National Energy Technology Laboratory
10:05 am to 12:00 pm	**1.5: Instructions and Breakout Session – Salon 1 and Salon 2**
12:00 pm to 1:30 pm	Lunch (on your own)

Magnetohydrodynamic Power Generation Workshop Agenda

Wednesday, October 01, 2014

Session 2: Related Research in Other Agencies and Parts of DOE – Salon 1	
1:30 pm to 2:00 pm	**2.1: The MHD-Controlled Turbojet Engine: an Alternate Powerplant for Access to Space** *Dr. Isaiah Blankson*; Senior Technologist for Hypersonics, National Aeronautic and Space Administration Glenn Research Center
2:00 pm to 2:30 pm	**2.2: Potential Exploitation of Dusty Plasma Physics to PDE Small Scale MHD** *Dr. Alan Garscadden*; Adjunct Professor/Researcher, Air Force Institute of Technology at Wright-Patterson Air Force Base
2:30 pm to 3:00 pm	**2.3: Research relevant to MHD power generation in the Naval Research Laboratory's Plasma Physics Division** *Dr. Stuart Jackson*; Research Physicist, Plasma Physics Division at the United States Naval Research Laboratory
3:00 pm to 3:15 pm	Break – Salon Foyer 1
3:15 pm to 3:45 pm	**2.4: Overview of NSF's Combustion and Fire Systems Program** *Dr. Ruey-Hung Chen*; Program Director, Combustion and Fire Systems Program at National Science Foundation
3:45 pm to 4:15 pm	**2.5: MHD: Enabling the Pursuit of Fusion Energy (and Much More)** *Dr. Sean Finnegan*; Program Manager, Department of Energy Office of Fusion Energy Sciences
4:15 pm to 4:45 pm	**2.6: MHD Power Generation Based on Pressure Gain Combustion Systems** *Greg Meholic*; Senior Project Engineer, Spacelift Systems and Concepts at The Aerospace Corporation
4:45 pm	Adjourn for Wednesday

Magnetohydrodynamic Power Generation Workshop Agenda

Thursday, October 02, 2014

Session 3: Power and Other Applications – Salon 1

8:00 am to 8:30 am	**3.1: Oxy-Fuel Combustion Components Relative to a Future MHD Concept** *Justin Strock;* Consulting Engineer – Advanced Combustion Systems, Leonardo Technologies, Inc.
8:30 am to 9:15 am	**3.2: Oxy-fuel Power Cycles and Magnetohydrodynamics** *Dr. Vic Der*; President, VKDER, Inc.
9:15 am to 9:30 am	Break – Salon 1 Foyer
9:30 am to 11:30 am	**3.3: Poster Presentations – Salon 1 followed by Salon 2** ▪ Ad Astra Rocket Company ▪ JP Aerospace ▪ Lawrence Livermore National Laboratory ▪ Massachusetts Institute of Technology Plasma Science and Fusion Center ▪ National Energy Technology Laboratory Office of Research and Development ▪ National Energy Technology Laboratory Office of Performance and Benefits ▪ Oregon State University ▪ Pennsylvania State University ▪ Princeton Plasma Physics Laboratory ▪ Princeton University & Princeton Plasma Physics Laboratory ▪ Sandia National Laboratories ▪ University of Wisconsin-Madison
11:30 am to 1:00 pm	Lunch (on your own)

Magnetohydrodynamic Power Generation Workshop Agenda

Thursday, October 02, 2014

Session 4: Facilitated Discussions – Salon 1 and Salon 2	
1:00 pm to 1:30 pm	**4.1 Instructions to Participants and Technology Goals**
1:30 pm to 2:30 pm	**4.3: Research Scenarios**
2:30 pm to 3:00 pm	**4.4: Open Discussion and Comments – Salon 1**
3:00 pm	Adjourn Workshop

Additional Poster Information

Thursday, October 02, 2014

Poster Titles and Presenters

Ad Astra Rocket Company	**Fossil Based Energy Conversion Using Radio Frequency Plasma-Catalyzed Magnetohydrodynamics** *Dr. Mark Carter*
JP Aerospace	**MHD at JP Aerospace** *John Powell*
Lawrence Livermore National Laboratory	**MHD Generators & ALE3D** *Dr. Aaron Fisher*
Massachusetts Institute of Technology Plasma Science and Fusion Center	**Large Scale Superconducting Magnet Technology for MHD Power Generation** *Dr. Joseph Minervini*
National Energy Technology Laboratory Office of Research and Development	**Magnetohydrodynamic Energy Conversion R&D** *Dr. Rigel Woodside*

National Energy Technology Laboratory Office of Performance and Benefits	**Direct Power Extraction Techno-Economic Analysis** *Dr. Robert Stevens*
Oregon State University	**Estimating Current Densities in Equilibrium Magnetohydrodynamic Generator Channels** *Dr. Duncan McGregor*
Pennsylvania State University	**Processing of Metals, Ceramics and Composites by Field Assisted Sintering Technology (FAST) for MHD Power** *Dr. Jogender Singh*
Princeton Plasma Physics Laboratory	**Liquid Electrodes for Harsh Environments and Kinetic Theory for Plasma Discharge Control** *Dr. Michael Jaworski*
Princeton University & Princeton Plasma Physics Laboratory	**New Capabilities for MHD Power Generation Enabled by Nanosecond High-Voltage Pulses and Electron Beam Methods** *Dr. Mikhail Shneider* (Princeton University)
Sandia National Laboratories	**Understanding the Complexities of Enhanced Oxygen, High Temperature Pulverized Coal Char Combustion** *Dr. Ethan Hecht*
University of Wisconsin-Madison	**Overview of MHD Computation for Magnetic Confinement Fusion** *Dr. Carl Sovinec*

ATTACHMENTS 2 – ATTENDANCE LIST

Name	Organization
Mark Carter	Ad Astra Rocket Company
Kenneth Sprouse	Aerojet-Rocketdyne of DE Inc.
Uma Bruegman	Aerospace
Mitat A. Birkan	AFOSR
Alan Garscadden	Air Force Institute of Technology
James Grossnickle	Boeing
Philip Johnson	Boeing
Dejan Nikic	Boeing
William Owens	Consultant
Miodrag Cekic	Intellectual Property Strategists LLC
John Powell	JP Aerospace
Perry Bissell	Leonardo Technologies, Inc.
Joseph Pierre	Leonardo Technologies, Inc.
David Stopek	Leonardo Technologies, Inc.
Justin Strock	Leonardo Technologies, Inc.
Christopher Munson	Leonardo Technologies, Inc.
Aaron Fisher	LLNL
Xianzhu Tang	Los Alamos National Laboratory
John Lineberry	Lytec
Joseph Minervini	Massachusetts Institute of Technology
Ronald J. Litchford	NASA
Isaiah Blankson	NASA Glenn Research Center
Gerald Hill	NASA Glenn Research Center
Ruey-Hung (Ray) Chen	National Science Foundation
Ramagopal Ananth	Naval Research Laboratory
Stuart Jackson	Naval Research Laboratory
Steven Tuttle	Naval Research Laboratory
David Cann	Oregon State University
Nathan Gibson	Oregon State University
Duncan McGregor	Oregon State University
Jogender Singh	Penn State University
Michael Jaworski	Princeton Plasma Physics Laboratory
Igor D. Kaganovich	Princeton Plasma Physics Laboratory
Mikhail Shneider	Princeton University
Ethan Hecht	Sandia National Labs
Christopher Shaddix	Sandia National Labs
Dale Cunningham	Sextant Technical Services
Greg Meholic	The Aerospace Corporation
Don LaRiviere	The Boeing Company

Name	**Organization**
Daniel Haworth	The Pennsylvania State University
Curt Bolton	U.S. Department of Energy/FES
Jim Black	U.S. Department of Energy/NETL
Patcharin Burke	U.S. Department of Energy/NETL
Regis Conrad	U.S. Department of Energy/FE
Sean Finnegan	U.S. Department of Energy/NETL
Jason Hissam	U.S. Department of Energy/NETL
Robie Lewis	U.S. Department of Energy/NETL
Susan Maley	U.S. Department of Energy/NETL
Darren Mollot	U.S. Department of Energy/FE
Patricia Rawls	U.S. Department of Energy/NETL
George Richards	U.S. Department of Energy/NETL
Bhima Sastri	U.S. Department of Energy/FE
Ann Satsangi	U.S. Department of Energy/FES
Robert Stevens	U.S. Department of Energy/NETL
Nathan Weiland	U.S. Department of Energy/NETL
Rigel Woodside	U.S. Department of Energy/NETL
Robert Wright	U.S. Department of Energy/FE
Lance Smith	United Technologies Research Center
Sergei Krasheninnikov	University of California, San Diego
Carl Sovinec	University of Wisconsin-Madison
Victor Der	VKDER, Inc.
Clinton Bedick	West Virginia University

ATTACHMENTS 3 – SUMMARY OF BRAINSTORMING SESSION 1

Consolidated Brainstorming Notes - Groups 1 – 4; Session 1; October 1, 2014

INSTRUCTIONS

Instructions for the Brainstorming Session were provided to the participants prior to the session. These included general questions to be considered for each of the ten topic areas listed below. Results are grouped according to this outline, but were discussed in the order deemed most important by each group at their session.

- **For the whole concept of MHD power development, please comment:**
  - How do recent & future changes in power generation requirements make it more or less valuable to develop MHD power?
- **For the topical area:**
  - How do recent and expected changes in technology make it technically harder or easier to develop MHD?
  - What technical advance (i.e., a possible development, but not known today) would make this topic technically easier or more beneficial for MHD power development?
  - If possible, describe the importance of a technical advance as essential versus beneficial to MHD power development?

(A) Oxy-fuel via ASU: no preheat – smaller volume flow & CO_2/H_2O working fluid.

(B) Numeric models: to optimize combustor & generator

(C) Current collectors: advanced materials, advanced manufacturing

(D) Current management: arc control via digital electronics

(E) Magnetic technology: lower cost, smaller, higher temperature

(F) Seed recovery: capture with oxyfuel gas processing unit

(G) Generator configuration: tube, versus radial, or other

(H) Cycle configuration: closed versus open, with gasification, others?

(I) Non-equilibrium plasma generation: no seed

(J) Other ____________________

DISCUSSION

Question: Present & Future Changes in Power Generation Requirements effect on MHD

General Issues:

- Efficiency
    - Potential efficiency increase needs to be revisited and the higher efficiency of MHD cycles must be reviewed as a future technology with the prospect of new and incipient regulations which also directly or indirectly demand higher efficiency (via improved emissions on unit basis, etc.)
    - The improvement in technologies for materials, magnets and combustion kinetic advancements are significant. The potential impacts from these needs to be assessed to determine the impact on a new power plant system(s) with MHD.
- Carbon Capture
    - Carbon capture is a driver for the technology. Oxygen based combustion for MHD looks attractive from anticipated carbon capture and sequestration requirements providing significant benefit. Fossil developments with MHD should benefit future nuclear cycle development.
- Load Following:
    - It is not clear at this time how MHD systems will function under typical power plant needs for load following. Issues such as turndown and the use of DC to AC conversion technologies may all impact this question. Based on what is known today, the MHD system probably could be turned down, but would not like to be cycled on/off.
    - If MHD is the most environmentally efficient technology, would it be a must run unit on the Grid in terms of dispatch? Could MHD contribute to spinning reserve on the power grid?
    - For a single channel, what are the impacts of on/off operation as a form of cycling? If multiple MHD generators are installed on a single boiler, how would that improve cycling?
    - Variation in daily/seasonal electric demands on the electrical grid suggests a need for a diversification of power sources across the grid, perhaps favoring smaller generators.
    - Magnet cooling requirements are a constant, parasitic loss
    - Thermal cycling problems are exacerbated in high temperature MHD
    - The use of seed fraction fluctuations could also impact turndown issues.
    - Can computer simulations of various turndown concepts be used to evaluate this issue? They would need to understand the impacts on the mechanical design of the MHD system.
    - The current need is to address combustion dynamics of oxy combustion with natural gas.
- Fuel price is a big driver
    - When legacy MHD program was terminated, fuel prices were low for coal. Was natural gas in the mix for consideration? Is there any natural gas data from old trials? Would a

new MHD system need to be designed as fuel flexible? Able to run on coal, natural gas, biomass and/or other fuels?
  - The complexity and cost of the MHD power plant needs to be reasonable.
  - MHD may be a good option especially with renewable/biomass-based plants; regulations driving increased use of renewables therefore create increased potential for MHD
  - The disadvantage of the technology continues to be the seed regeneration and the interaction with ash (if coal is the fuel). Use of biomass fuel might be self-seeding because of the high concentration of alkali metals in the ash. If MHD can be operated effectively with high-sulfur coal as the fuel there may be new advantages that have not been explored. If waste fuel streams are to be used their waste should be completely oxidized, thus thermally destroying any fuel contaminants.
- Technology Development
  - Recent advances in new materials; plasma science; power generation; and in high strength magnets frame the need to assess their impact on MHD technology.
  - DC power generation with advances in DC/AC systems improve the potential for deployment of the technology.
- General Aspects
  - It is difficult to explain MHD and how it might be included in a new power system to politicians others with a non-technical background. We need supporting materials that better confer the concepts so that the program can be understood and supported.
  - There were some general questions about the impact of early designs for retrofitting MHD vs. new plant designs. It appears that retrofit can pose a variety of challenges. There were questions of where MHD testing/demonstration might be conducted. Retrofitting issues will likely need to be addressed by industry. In general, some technology elements will need to be addressed by longer-term, government support. Trade-offs in retrofit design is a plant-specific consideration.
  - Direct conversion of power plays into general thrust of lowering the overall cost of power plants. Overall complexity and balance of plant capital and operating demands for these facilities will need to be understood.
  - MHD has potential to blend disciplines that normally do not interact or collaborate at the research stage. This research may produce synergies in technology advancement and efficiency/performance gains from interdisciplinary interaction.

Specific MHD Cycles discussion

- Open Cycle
  - This will pose a variety of difficulties and would not address the removal of CO_2 which needs to be integrated into the technology. It is possible that the facility could not be permitted if it did not meet new source performance standards for power plants. To be permitted it would need to have very high efficiency as well as control any seed emissions. In general waste heat would not be captured in an open cycle, unless it was via some type of recuperator.
  - Coal slag and potassium are corrosive and erosive and can damaging to channel if used as part of a demonstration. Design needs to consider what is in the flue gas, if

potassium is there, how will it be controlled? If an unseeded plasma generation is used, will its efficiency be sufficient for an open cycle demo to meet new source performance standards (NSPS)?
   - If the MHD unit is sufficiently small, the permitting issues may not be a concern as long as it is not operated with seeding.
- MHD Coupled to Waste Heat Boiler
   - A discussion covered what would govern a retrofit boiler vs. a new design boiler. A retro-fit would be limited to the pressures/temperatures of the existing power cycle. Multiple MHD generators would likely be needed to provide gas dispersion across the entire furnace (if it was reused) and for reliability regardless of the scale capability of the MHD system. If alkali seed is required, collection of the condensed seed will need to be a critical consideration in that the boiler emission controls may not be capable of recovering the seed material to environmental limits. Note that for FutureGen 2.0, only the steam cycle and some auxiliary equipment was salvaged while the boiler was replaced. The alkali can form a hard fouling deposit as it condenses which will require cleaning and downstream collection systems. The boiler will need to be examined to determine how the flue gas from the MHD system correlates to the heat transfer of the existing boiler.
   - One issue is the size of the MHD system has to be large enough to avoid boundary layer impacts. It may not be compatible.
   - Note that atmospheric oxycombustion systems require CO_2 recycle to help balance the radiative and convection heat transfer within the existing design.
   - Boilers in service today are old 40-50 years of operation, in another 15 years they will be that much older.
   - How can burners be integrated, likely will need multiple MHD generators for reliability.
   - If the MHD generator is too small, boundary layer effects can occur. Boundary layers will influence the size of the MHD channel. As plasma enters channel; boundary layer grows, boundary layer effects accumulate so that a small MHD system ceases to function.
   - Steam turbine and downstream equipment aren't optimized for MHD; multiple problems. This is especially true for retro-fit applications.
   - Flow velocities and distribution; heat transfer in the waste heat boiler need to be studied carefully and modeled with the MHD generator size taken into account. Flows under turndown conditions need to be analyzed to understand the overall dynamics of the design.
   - Oxy-fuel flue gas flow-rates are lower; recycling of CO_2 in the furnace/boiler is typically used to improve heat distribution (as in FutureGen 2.0). This recycle gas can be used to reduce incoming plasma temperatures and increase gas flow in the boiler.
   - The host company will likely dictate many of the design considerations, technology developers and government researchers will have less input unless they put up more than the typical 50% cost share.
- Advanced cycles
   - Other cycles considered were as a topping cycle ahead of a combustion turbine. This concept is very much in line with some of the development ongoing in development of pressure gain combustion related to MHD. There is active work looking at coupling jet engines with MHD for near space travel. For adaption to a natural gas combined-cycle it

might be possible to recycle CO_2 to cool the plasma into the combustors. However, sub-stoichiometric combustion does not seem practicable for now.
  - The use of pressure gain combustion may result in higher efficiencies due to the imparting of compression without the need for a compressor. The MHD generator could be located in the lower pressure section of the channel prior to the compression wave thus yielding the best of both worlds.
  - Mixing and steady state and unsteady state needs to be studied.
  - The Impact of high pressure design needs to be considered for the electrical output of the entire system, although less may be achieved in the MHD generator, more may be extracted from the natural gas combined-cycle system.
  - Some organizations are studying the use of these concepts for lightweight thrust for high-altitude propulsion on aircraft; emissions are good for thrust.
  - Can combined heat and power systems be considered for future MHD systems? It is likely that any industrial processes could benefit; but the size of the MHD channel would have to be considered. Total gross efficiency can be 75% if turbine is used as bottoming cycle. Note that small systems may not be suitable for CO_2 capture.
  - Natural gas combined-cycle – sub stoichiometric burning use CO_2 as a seed substitute? Heat transfer problems with energy consumption of CO to CO_2.

(A) Oxy-fuel via ASU: no preheat – smaller volume flow & CO_2/H_2O working fluid.

No Discussion

(B) Numeric models: to optimize combustor & generator

- Validation Importance
  - Hardware advances (parallel processing) and software development (programming for taking advantages of massive parallel processing, new algorithms) have shown dramatic improvements over the last two decades in computational speed and efficiency and when taken together are significant. However, first-principles based simulations are still intractable, therefore experimentation is still essential. Experimental input still will go hand-in-hand with modeling and simulation.
  - Matching measurable data to models is important for accurate validation. The use of external measurements to extrapolate to internal, non-measurable parameters substitutes for hard verified data. But, for reliable models work to develop better sensors for this environment will be important.
  - Weakly ionized gases data cause problems; better measurement techniques are needed to verify the models
  - Decent validation data for models is needed, but it is not widely available. Wider access to data will assist in model development by the wider community. It is very hard to understand the physics of experiments without a model. Significant progress in models is being made, but combined with MHD, it not clear that we have reliable models at this time.

  - Linking MHD model predictions to rest of plant is important for understanding the complete system performance.
  - We need canonical experiments that combine all the features so we can validate step-wise. Examples of high performance computational capabilities were mentioned.
  - Need to combine different communities that work on MHD simulations – they don't talk very much among themselves extensively? Researchers need to "de-silo" their communities and the funding areas. Good discussion of how to tackle the organization across groups – there is no evident collection of people addressing MHD, but discrete applications. More workshops like this are a useful tool in this direction.
  - Do test rigs exist for validation data? Might be some TRL 1-3 rigs, but no TRL 4-6 rigs.
- Specific Technical Issues for Modeling
  - Computational fluid dynamics expertise and capabilities in other fields need to be leveraged in the MHD area. Plasma dynamics, fluid dynamics, and combustion kinetics, all need to be synergistically brought together to properly deal with MHD systems. Programs, efforts to anchor these are needed. Need a good understanding of MHD models (that can be applied confidently) to develop design models for application of mechanical design tools/models. Specific parameters and areas where more work is needed include:
    - Magnetic geometry improvement to take advantage of intrinsic MHD phenomena needs to be explored in modeling.
    - Divergence of the magnetic B field goes to zero; this condition must be met; closed solver
    - Mach 2 (Mach 2.5) models of the plasma itself
    - Coefficients are questionable
    - Model the kinetic effects, taking into account kinetics vs. boundary effects? Two separate issues but should be combined. Look more intensely at kinetics (weak ionization).
    - Electron distribution function will have a huge impact on the equilibrium
    - Could have large deviation from Maxwellian plasma sheath conditions
    - Hall thrusters – changing materials to higher degree of electron transmission, drastically change the behavior of the hall thrusters
    - Important to model arcing, but very difficult problem. Match experiments with modeling – still lots of discrepancies between experiments and models. Need validation.
    - Plasma and plasma-material modeling is needed. Most energy in creating the plasma.
    - May be able to make some headway on slag
    - Boundary conditions determined by the fluid; good (trustworthy) computational models can lead to avoiding empirical measurements and experiments
    - Polarization and excitation need to be investigated further
  - Fusion research and aerospace research groups do not interact frequently; combining their particular strengths can improve the knowledge base anticipated for MHD modeling. Efforts to merge those efforts and strengths (or bringing together the

  - parameter regimes explored in these arenas) would be very valuable in making the advances that would be needed in MHD modeling.
  - Systems modeling is needed to develop overall concept designs.
- General Comments
  - Can modeling in other fields (e.g. plasma welding modeling, propulsion modeling, etc.) be applied with benefit to MHD? Possibly an effort to survey modeling in other fields would be worthwhile to identify possible applicability or utility for MHD modeling purposes. Need a better literature review on past models and data.
  - Accurate diagnostics are critical to validation of design predictions
  - Time scales of plasma generation (nanoseconds)
  - Open cycle traditionally assumed equilibrium, this is true but not on boundaries where the assumption breaks down, i.e. in the past non-equilibrium regions were ignored. This is a good problem (non-equilibrium at boundary layers, etc.)—a significant modeling effort in the area (transients/kinetics/excitation) is in order.
  - Lots of good older work was done without modeling. Fewer assumptions can now be made in the engineering by using modeling. Simulation based computational design on systems level.
  - Computational materials are also a means for narrowing down materials that will work in these harsh conditions. Material modeling is also much better. Can model surface – electrical interactions
  - Advances in fusion that may be applied to MHD: high performance computing and the ability to minimize the number of prototypes

(C) Current collectors: advanced materials, advanced manufacturing

- Materials: research needed on electrical materials. Material issues for addressing the impact of slag on electrode life continue to be a challenge. But for clean flow (natural gas) this may diminish somewhat. Suggests that early demonstrations start with natural gas. Voltage drop at the electrode is a killer. The electrode could be the most important problem. Nano-surface design could help alleviate this. Electrode interactions are also of interest. It was noted that the slag had electrical and durability challenges.
- We have advances in turbine and fuel cell – but a question: why do we think these apply to slag flow? Today's thermal barrier coatings are not relevant? What advanced materials will survive in slag?
- Many sharp points would serve to help focus the field.

(D) Current management: arc control via digital electronics

- Pulse plasma generation allows AC, and electrode-less pickup may eliminate problems associated with the electrodes. Previous problems in this area may have new solutions from innovative combinations of MHD configurations.
- Materials and plasma: need to consider both.
- Arcing problems remain a significant operational issue
- Need for electron-neutral collision cross sections; there are databases for this information in Japan and France.

- There is work being done with liquid electrodes for fusion technology that may help resolve these issues
- Significant issues remain surrounding power cleanliness and power conditioning/cleanup. This issue represents a new challenge that needs exploring. However, available technology in power control from other technologies exists that could be applicable in the area.

(E) Magnetic technology: lower cost, smaller, higher temperature

- But, there are no big magnets commonly available for MHD, at commercial scale, and this limits the size of validation test facilities. There is no easy way to build such magnet. The validation facilities need to have adequate surface to volume size. Although large magnets have been fabricated for fusion testing, these are very unique and have been fabricated in a Argonne National Laboratory.
- Superconducting magnet development (particularly as has resulted from recent large scale magnet applications such as European Center for Nuclear Research (CERN), fusion) is applicable to MHD power generation and need to be considered for new progress in MHD area. Superconducting magnets lose superstructure and tolerance at high Tesla
    - High fields by pulsing and capturing the magnetic field
    - 6 Tesla superconducting magnet at Argonne
- Thermal management for these magnets is critical. The ability to rapidly quench the temperature of operating magnets when problems arise will help with component life. Water cooled-magnet MHD was being done in 1980s timeframe; informs potential future retrofit activities. On the other hand, regulatory and political issues may be show-stoppers for certain scenarios (e.g. Sierra Club-driven legal agreement to shut down a plant that may have been an ideal choice for MHD retrofit demo).
- Advances in fusion that may be applied to MHD: magnetic technology. National magnet lab in Florida, accelerator technology uses magnets, as does fusion energy sciences
- Cryogenic refrigeration is also advanced. Larger scale of cryogenic systems works to advantage efficiency-wise (therefore larger scale magnets go hand-in-hand but larger magnet coils are more difficult to engineer). In any case optimization/trade-offs of magnet system components are in order. One research cautioned: Don’t use liquid nitrogen, direct cooling; systems engineering – important!! Liquid nitrogen has a gravity effect; directly cooled the superconductor.
- Ability to build very large, high field magnets, manufacturing capabilities is much more advanced. That needs to be assessed for MHD. Questions: availability magnet materials (not an issue for Nb/Ti materials). Problem might be with high-temperature superconductor magnet materials.
- Magnet structure around certain geometries is an engineering challenge (generator configuration plays into this problem).
- There may be a scale issue; how do you make a robust structure? Build like a shuttle tile; close fit to avoid eddy currents
- Other components may fail faster than the magnetic field, which leads to shut-down and start-up of the magnets
- Computer codes are progressing for 3D magnets

- Fusion energy – Super large superconducting systems (ITER project); major radius of 7m, small radius of 2.5m
- Channel itself and the generation of the plasma is the greatest concern
- Chinese were investigating nano magnets, need to perform a literature search for developments
- Can medical magnet advancements be used?

(F) Seed recovery: capture with oxy-fuel gas processing unit

- Slagging is a large problem in coal fired combustors and with removal after combustion solutions may include allowing slag to blow through the channel without collection. Gas fired system with potassium carbonate is a new challenge that wasn't investigated during past research. Application of a downward flowing channel to prevent slag formation on walls might help. In coal combustion: dust particles (fly ash) may either cause erosion in the high speed channel, or may tend to collect electrons which reduces the overall conductivity
- Seed regeneration is also needed especially with NG based MHD in that the properties of the seed exiting the MHD system will be different from that experienced with coal combustion.
- Liquid electrodes may allow the seed to float to the top for easy capture

(G) Generator configuration: tube, versus radial, or other

- We can make very sophisticated geometry and test a lot of these concepts very quickly, today (compared to decades ago). This allows many variants to be tested. Advanced manufacturing allows easy manufacture of test articles. This does not affect the final overall configuration as much; this is still needed to develop a low-maintenance design. Suggestion that the configuration will depend on the Hall parameter; it is likely to end up as a diagonal channel. A lot of data exists on radial flow, but these designs did not work well in practice except for high Hall parameters.
- Requirements-driven design is important as opposed to pre-supposing certain engineering solutions, geometries, etc. Significant compromises are required in technical parameters to find ideal MHD operating points. Costs should not be of excessive concern at earlier development stages however (which might stymie development in worthwhile though initial boundary layer problems – boundary layer control, among problems to be pursued in new research.
- When does NETL need to decide these issues?
    - Configuration
    - Fuel - coal versus natural gas, or both
    - End user needs
    - New build versus retrofit

(H) Cycle configuration: closed versus open, with gasification, others?

- System design of the MHD would be dependent on total plant scale; at a very large scale, the MHD generator may be prefer to use tubular design as it favors larger gas flows. At a smaller scale, radial may be better in certain applications; one configuration may be better than the other depending on overall plant size and individual MHD size.
- Studies need to consider optimization between the MHD scale, the cycle configuration, and pressure of operation of the MHD and cycle.

- Magnet type/construction may be very different depending on the configuration of the MHD.
- Cryogenic magnets use helium; not nitrogen, but could be investigated; might be different properties of the fluid at the magnet operation temperature
- Studies should consider:
  - Non-equilibrium plasmas in rotating detonation engines
  - High pressure combustion to drive turbines
  - Can you integrate gasification in the coal case? Use gasification, shift to H_2, remove CO_2, then plasma MHD with air-blown combustion in an integrated gasification combined-cycle of H_2 fuel to reduce size of the air separation unit. Reduces some capital and operation and maintenance needs a separate study.
- Low velocities behind detonation, may not work well in MHD? Detonation is not very efficient, thermodynamically?

(I) Non-equilibrium plasma generation: no seed

- Non-equilibrium plasma generation would benefit a lot of applications: nuclear, high-atmospheric and space applications. Research is needed in low eV plasma and in partially ionized. Very recent technology break-through in micro-switches suggests that this is possible. However, very hard to do this in combustion gases, due to cross section, but might work fine in closed systems. The key is noble gases but per discussion, even minor amounts of diluted gases will destroy conductivity of non-equilibrium. The technology to generate the plasma does not exist, either, so this is a big area. Closed cycle might be possible with natural gas as the fuel.
- Open cycle, followed by separate closed cycle might solve above problems with gas turbine integration. Open cycle needs to withstand material challenging corrosive conditions, using silicon carbide, etc. Open cycle is best for combined cycle with a gas turbine, but seed going to aerosol/solids in worst possible place (i.e. turbine blades)
- Specific areas for focused research include:
  - Boundary layer problems – boundary layer control, among problems to be pursued in new research.
  - Minimizing plasma-wall interactions remains important concern.
  - In the plasma, higher conductivity is better, but balancing the cost of seeding is an issue.
  - In-situ irradiation of flow to generate non-equilibrium plasma? (lasers, microwaves, RF, etc.)
  - Pulsed ionization/non-equilibrium plasmas for pulsed MHD systems. In non-steady state: can a one-use pulse system work well? Lower cost, short life system (expendable). Any future for this?
  - Carbon composite fiber conductivities: 4000 S/m, 20 eV – fully ionized plasma. In closed loop, yttrium for seeding? Can a combination of plasma and potassium be added to increase potassium ionization? Can the potassium be added pre-ionized?
  - Can fully ionized plasma be injected?
  - Fire a laser down the channel to ionize?
  - Higher temperature and higher pressure to run the core higher

  - Too high of pressure, high quenching. At high pressures, the technology hasn't been developed
  - Plasma generation optimized for location right before MHD generator essentially. Issues with pressure persist (pressure drops, etc.)
  - Electron beams most efficient generate ionized flow – 100kV minimum, generates x-rays which mess with instrumentation – tried before but not utilized
  - Pulsed microwaves – titanium/aluminum foil would deteriorate in days
- Question of where MHD testing/demo might be accomplished; retrofitting issues need to be addressed by industry however. Some technology elements need to be addressed by longer-term, government support. Trade-offs in retrofit requires plant-by-plant considerations.
- Significant compromises are required in technical parameters to find ideal MHD operating points. Costs should not be of excessive concern at earlier development stages however (which might stymie development in worthwhile though initially high-cost directions).
- Pulse plasma generation allows AC, and electrode-less pickup may eliminate problems associated with the electrodes. Previous problems in this area may have new solutions from innovative combinations of MHD configurations.
- MHD has unusual opportunity to tailor exhaust gases to meet technical needs (conductivity), though seedless plasma remains the "holy grail" of the technology
- Legacy program: ran tests on conducting ceramics (withstand high temperatures but are conductive), but they won't work with the seed
- Protective layer, hot layer – only possible in a cold background
- Big questions arise about power cleanliness and power conditioning/cleanup which represent new challenges that need exploring. However, available technology in power control exists that should be applicable in the area.

(I) **Other Discussion**

- Data Issues:
  - Question: why did the last program end? Could not justify capital in light of (at that time) regulations. But, these have changed today (CO_2). Also comment that the materials have changed a lot. Also, the old MHD program included a DOD contribution, yet was run by NETL – so there was immediate data sharing.
  - Discussion to available data and how it can be used
  - There is a whole set of literature that is not organized- how do researchers find it?
  - Corporate knowledge needs to be addressed, need to save design details that are not well documented in reports
  - Proprietary data exists, but can't be accessed.
  - How will all of this information be vetted? There are some things being discussed that, in some opinions, are not issues solely in MHD and they could be beneficial to other applications.
  - Data from aerospace applications may be useful for other applications
- For rocket power, the technology is lighter than batteries at the present time (might change in the future).

- Flight application inlet flow control + power out.
  - What would this look like in a system? Nice to look at components, but the overall system and configuration is important.
  - More modern automatic control methods that exist now that could be developed.

ATTACHMENTS 4 - SUMMARY OF BRAINSTORMING SESSION 2

Breakout PM Session Notes - MHD Workshop
October 2, 2014

Scenario Discussion:

- Staged approach focused on future scale-up seems prudent
- Multiple smaller units for reliability rather than one big MHD generator more prudent
- Rather than focusing on a 10:1 scale-up factor, using scale-up steps of 3:1 poses less risk
- Should we consider smaller to allow for distributed generation applications? Provide combined heat and power / cogeneration opportunities. Would this approach lend itself to a near-zero emission power plant?
- Would development of modular MHD components yield more rapid deployment?
- How will MHD integrate into the grid?
- System studies should be used to address many of the questions just posed to optimize the design for best deployment
- Assuming the technology works, how big a plant should we focus on for development? Perhaps focusing on gas though it appears to be available for power generation now, might it not be more expensive when we deploy the technology in 15 – 20 years? Perhaps a continued coal focus would be beneficial.
- Suggest gas fuel to keep development simpler
- Coal might be simpler since the solids help with electron mobility (use existing metals in the ash)
- Targeting coal as a primary fuel for MHD may be better for long term energy security and a means to export the technology to the developing nations.
- A 2050 timeline may be too far in the future for a deployment goal
- There was a discussion of the New Source Performance Standards for CO_2 as it would impact future goals and siting of the facility. Will the current limit of 1100 lb/MWg remain beyond 2030? Will this rule be tightened to push toward a national goal of an 80% reduction by in GHG emissions by 2050.
- For power generation, it is likely that the technology needs to succeed at a demonstration scale of 100MW to be taken seriously by the energy and financial communities.
- It may be difficult to attract foreign investment into this technology

Scenarios:

- Rather than a stretch goal of 65%, we should consider establishing intermediate goals with incremental improvement along a development timeline
- We need to identify gaps in the technology where R&D will be most beneficial
- Recognize that current technology near-zero emission power plants will likely have an efficiency of only 30 – 35%. A 50% improvement in efficiency (which is significant) would be a plant with an overall efficiency of 45 – 50%. Although 65% is an admirable goal, it would represent an improvement of over 100% to current technology.

- Systems analysis needs to be conducted on the entire power plant system to identify sensitivity of component improvements to the overall plant. This will identify trade-offs between operations with seed to maximize MHD output but might eliminate other options that would take advantage of advanced cycle concepts.
- Is there a MHD system that can be constructed today using current state-of-the-art to demonstrate the technology, and where individual components can be evaluated and developed on the MHD generator?
- Do we develop all component areas or focus on select components to improve the technology.
- There has been of the discussion over the past day that shows the need for research to focus on fundamentals and science to develop alternative approaches vs. legacy designs.
- Remember that any system is only as strong as its weakest part. If we are too aggressive in pushing the envelope of development, we might never succeed because we are fixing too many broken links.
- Has there been an investigation to determine which components are closest to commercial readiness?
- There should be a team formed to teach technology to collectively awaken the development community
- Industry will want to know the return-on-investment for work to be authorized on MHD development
- Is industry actively looking at MHD as an option for power generation in the future?
- Do we want to face a situation of technology-push or can we develop a technology-pull with MHD bases systems.
- Are there collaboration opportunities for NETL to work with other Government agencies that have been funding MHD for other purposes?
- Will solid state electronics be able to transform the direct current at the scale of the MHD systems to be adequately integrated into the grid? Perhaps multiple smaller systems would be easier to integrate in the near term.
- How do we recover past knowledge from the legacy MHD program before it becomes unattainable? We have some “veterans” of the past campaigns that have extensive knowledge that may not be clearly recovered in the files. This knowledge would be beneficial to avoid repeating the past mistakes.
- DOE found over 100 boxes of files in a store room and is progressively scanning that material onto computer drives.