Direct Power Extraction

NETL Research & Innovation Center

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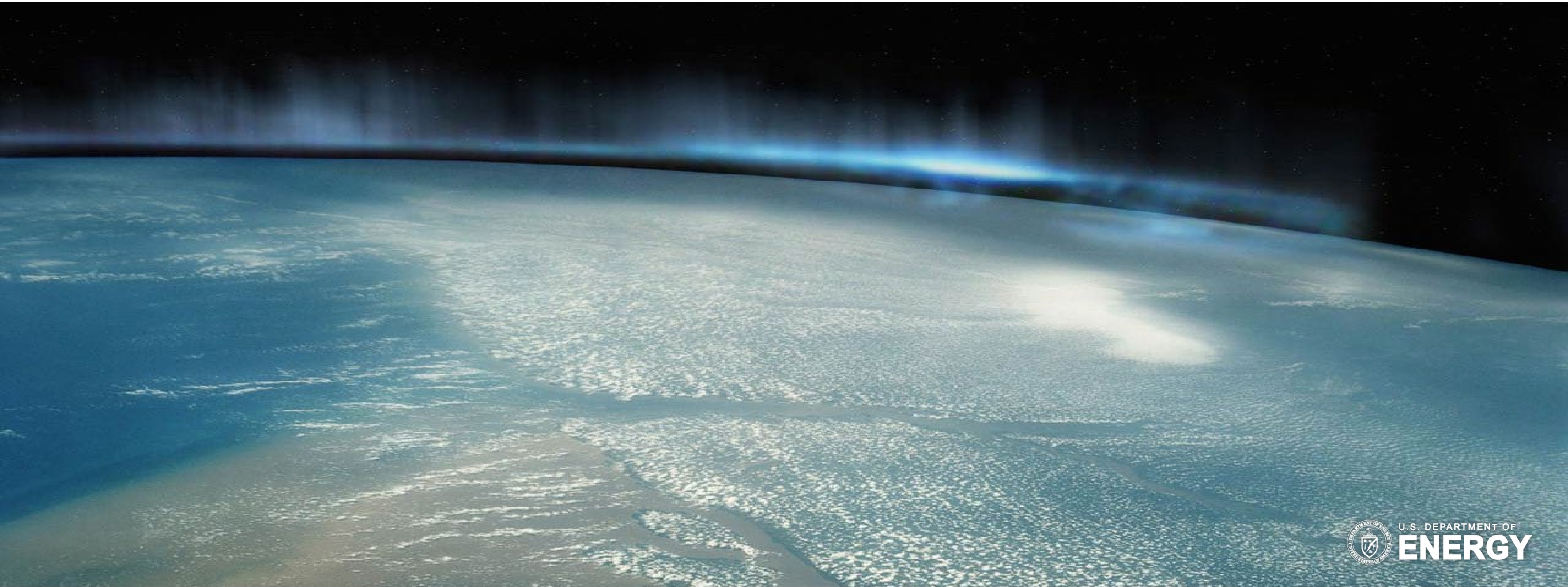
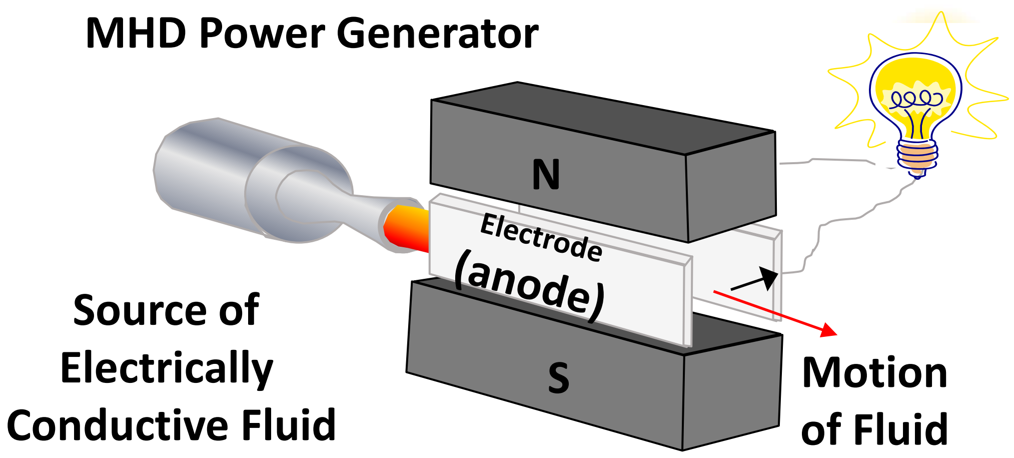
2021 Crosscutting Research & Advanced Energy Systems Project Review Meeting

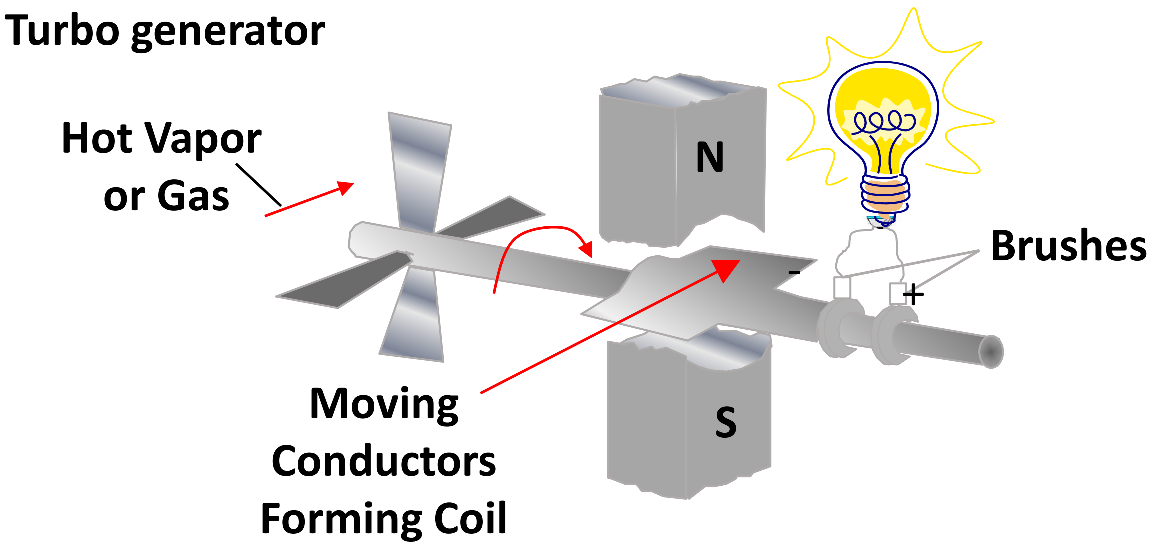


Introduction

Direct Power Extraction (DPE): The concept of directly converting thermal/kinetic power to useable electrical power.

Magnetohydrodynamics (MHD): The branch of physics which describes the interaction of an electrically conductive fluid with a magnetic field.



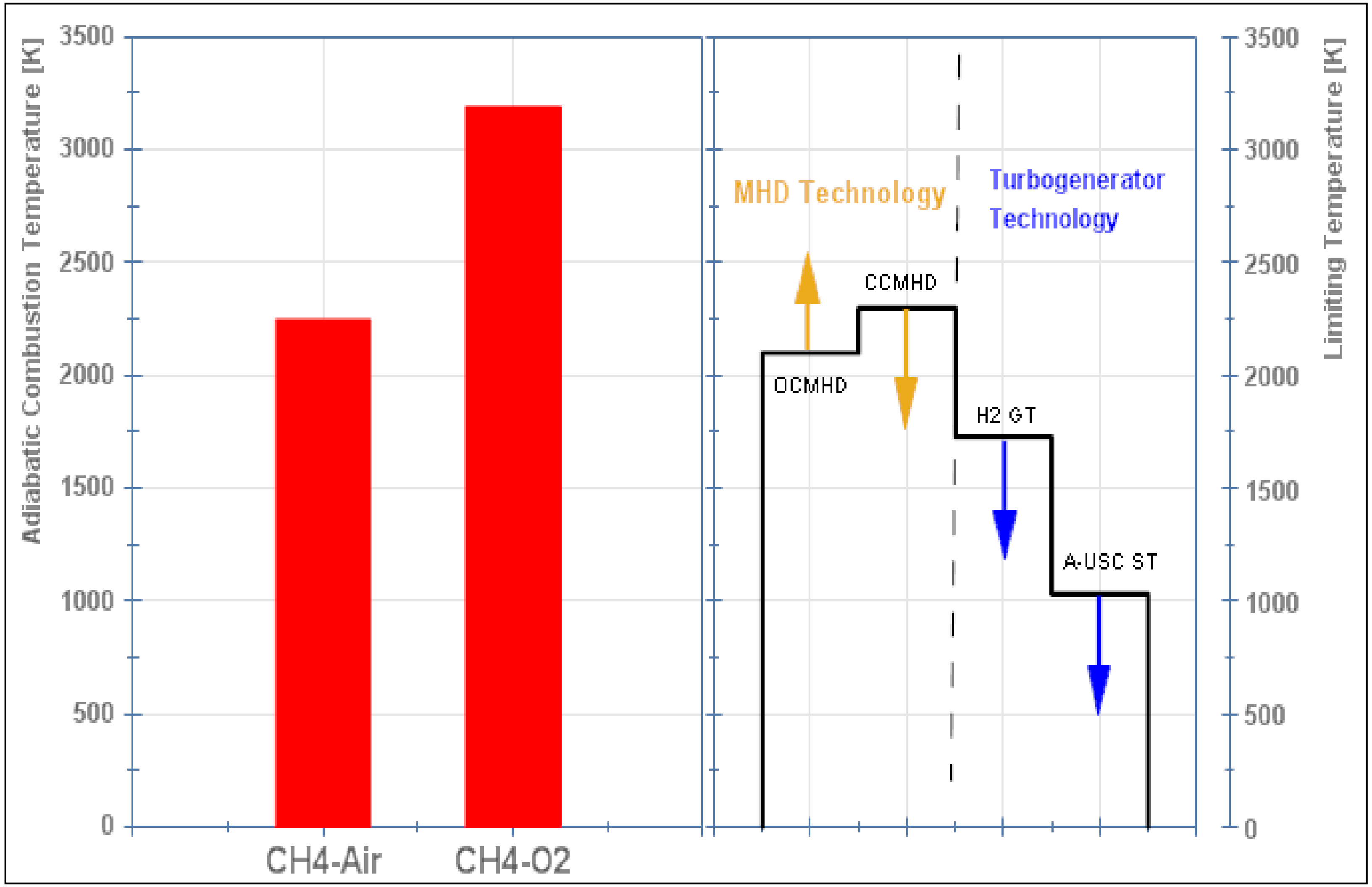


Like a turbo generator, an MHD power generator harnesses the Lorentz force to generate electrical power. Thus, An MHD Generator could be described as a “electromagnetic turbine”.

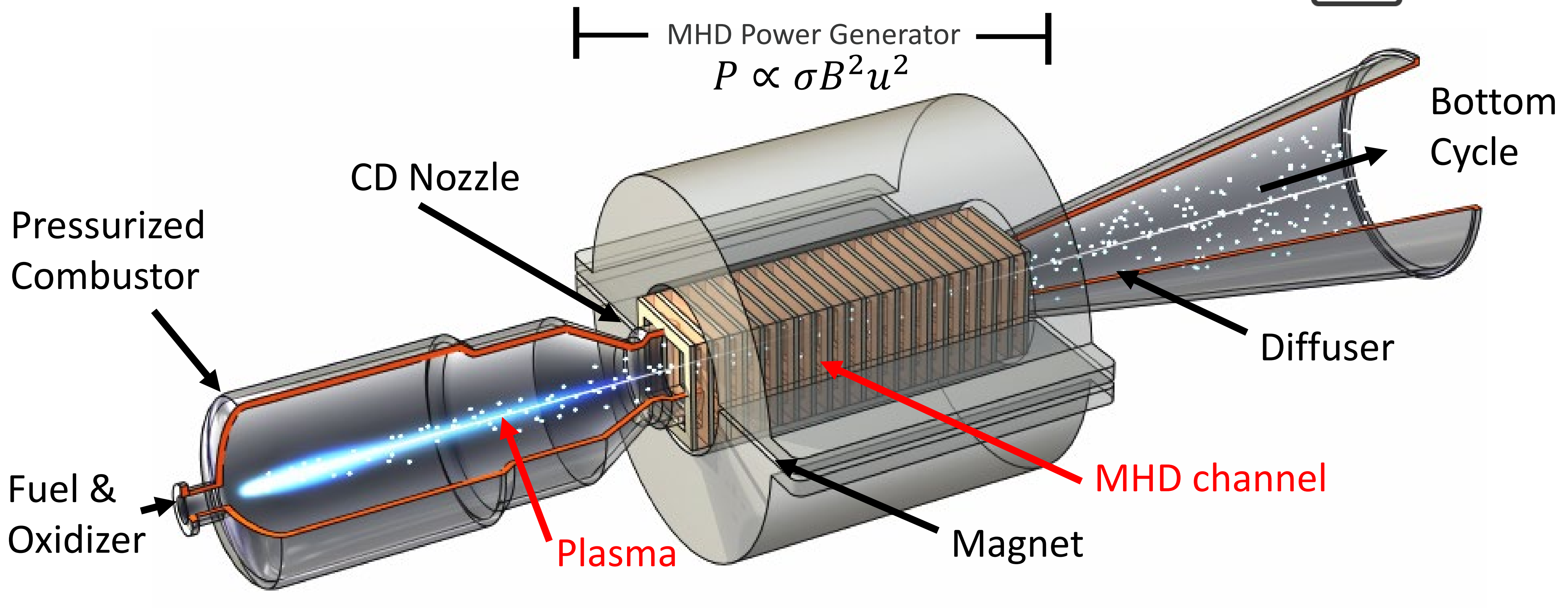
Motivation for Direct Power Extraction

Good Fundamentals

- **Increased power generation efficiency**
  - Can use high temps for higher Carnot efficiency
  - Use as topping cycle
  - Synergy with CO_2 capture
  - Coal plant retrofit possible
  - New combined cycles
- **Fuel Flexible**
  - Thermal power input
- **DC Power Output**
  - Future grid transmission?
- **Dynamic Load Response**
  - Good for grid performance and reliability



Open Cycle MHD Topping Unit



MHD channels are the least developed component for the technology

FWP Topics Presented

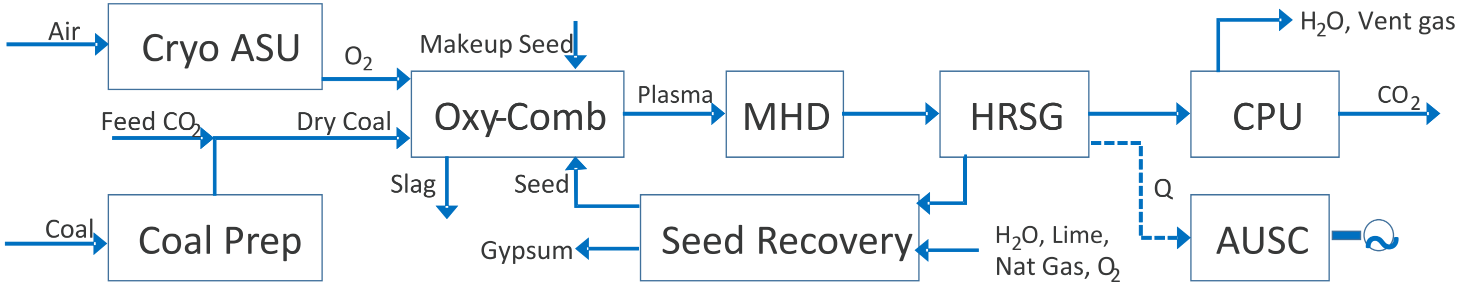
- **Systems techno-economics analysis**
- **Oxy-fuel plasma generation & conductivity**
- **MHD generator performance**
- **Channel materials development and testing**

DPE Scoping Study

Goal: Identity the most promising systems for further development

- **Baseline:** Oxy-combustion, MHD, AUSC system
  - Widely available performance data from historical systems studies (1970s-1990s)
  - Direct-fired (OCMHD) MHD proven power generation performance at demo scale
- Both Coal and Natural Gas MHD systems evaluated
  - Focus on systems with CCUS
  - 22 systems qualitatively assessed
  - 9 systems quantified efficiency; 3 systems quantified COE

Oxy-combustion, MHD, AUSC system (baseline)



Qualitative Reviews		Criteria													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
DPEC	Brief System Description	Enhanced Efficiency Potential	CO_2 Control	Flexible Operation	Deploy-ability	Scalability & Modularity	Pollutants/ Byproducts	Water Usage	DPE Technology Status	System Technology Status	O&M Complexity	System Availability	MHD Legacy Issues	Crosscutting or Enabling Platform	Synergy w/ NETL Programs
DPEC-1	Oxy-combustion, MHD, AUSC	N	SA	N	D	D	N	N	A	SA	A	D	D	A	A
DPEC-2	CO_2 MHD System	A	SA	N	D	A	A	N	N	N	A	D	N	A	A
DPEC-3	Natural Gas DPE System	D	SA	N	D	D	A	N	A	SA	D	D	A	A	A
DPEC-5	Top Gasification MHD-Steam	A	N	D	D	D	A	A	A	A	D	N	A	SA	SA
DPEC-11	Noble Gas Closed Cycle MHD	SA	A	SA	D	N	A	N	A	A	N	N	N	SA	A
DPEC-14	SOFC/ MHD Combined Cycle	SA	SA	D	D	N	SA	N	D	N	D	D	N	SA	SA
DPEC-19	Dry Methane Reforming (DMR)	N		A	D	D	A	N	A	SA	D	D	A	A	A
DPEC-21	Coal Plant Retrofit DPE	N		A	N	A	N	N	SD	A	A	A	SA	A	SA
DPEC-22	Closed Cycle Non-capture Coal	A		SA	N	A	N	A	D	A	N	N	A	SA	A

SA = Significantly agree; A = Agree; N = Neutral; D = Disagree; SD = significantly disagree

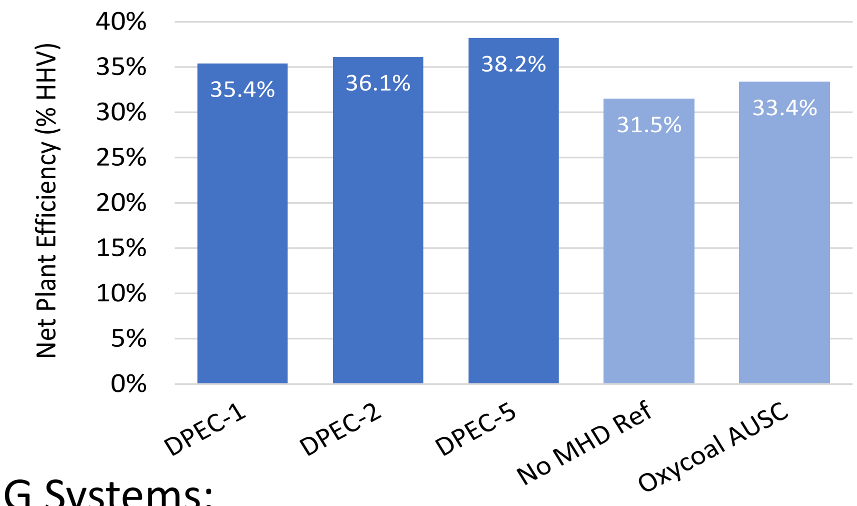
Scoping Study Quantitative Results

Selected Systems

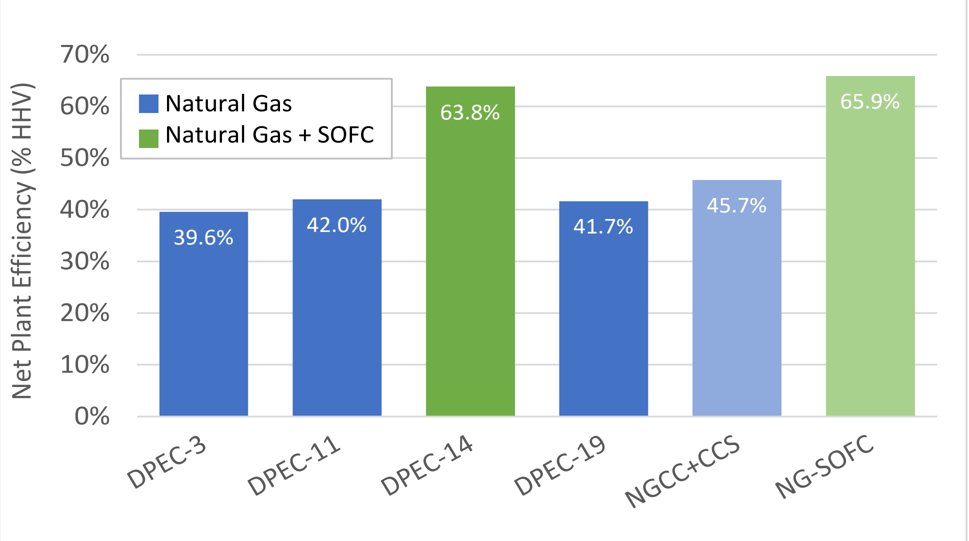
- Coal: better then reference CCUS cases
  - DPEC-5 (top gasification) highest efficiency
  - DPEC-1 (baseline) and variants have lowest COE
  - Capital costs dominate COE
- NG: similar performance to reference CCUS cases
  - MHD generator power extraction on par w/ gas turbine, so little value in replacing gas turbine with MHD (e.g. in NGCC)

Component	DPEC-1 $/MWh	DPEC-2 $/MWh	DPEC-5 $/MWh
Capital	68.78	69.00	90.68
Fixed O&M	17.00	17.04	21.28
Variable O&M	12.65	12.54	11.63
Fuel	22.30	21.86	19.07
Total w/out T&S	**120.72**	**120.45**	**142.65**
CO_2 T&S	8.83	8.65	8.36
Total w/ T&S	**129.55**	**129.10**	**151.02**

Coal Systems (w CCUS):



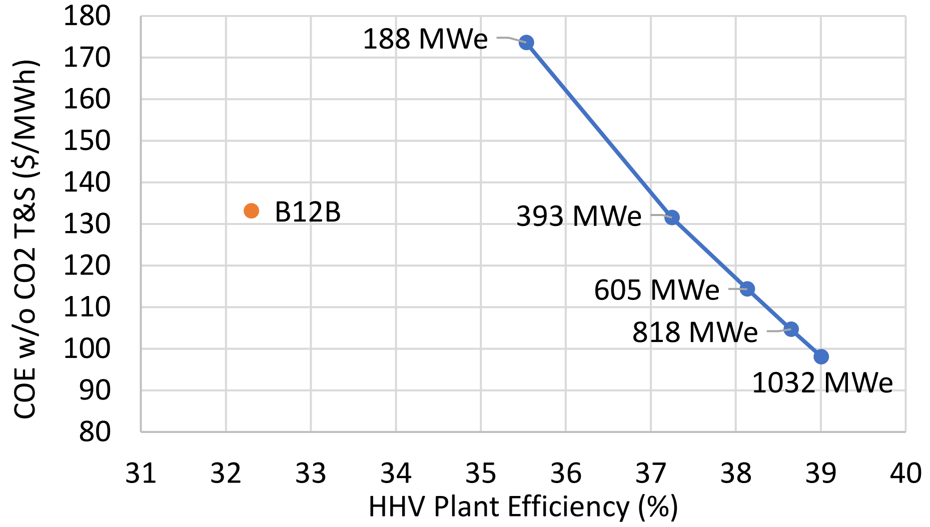
NG Systems:

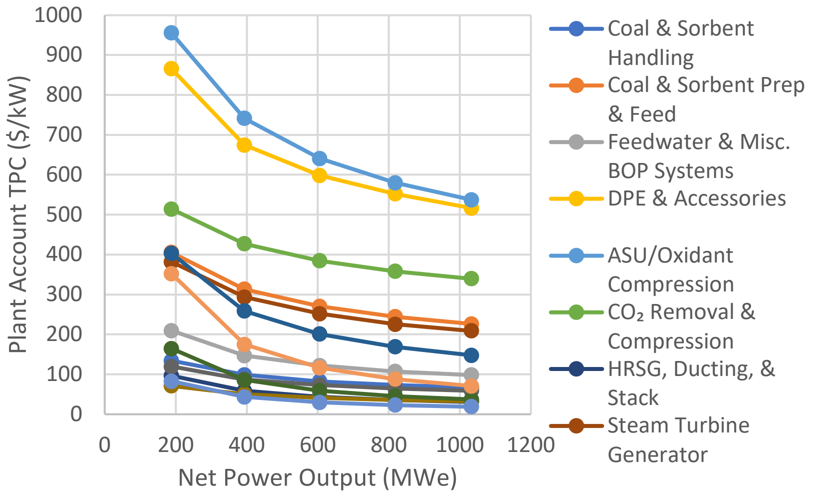


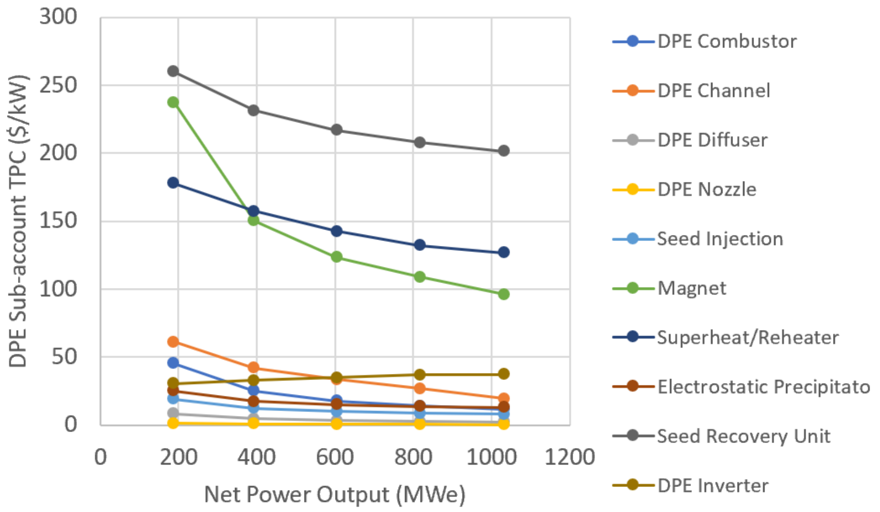
TEA Sensitivity of Baseline Case

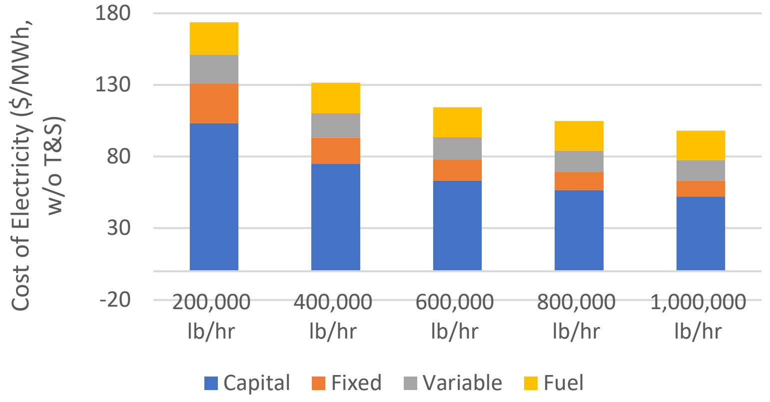
High Sensitivity to Plant Scale

- **COE very sensitive to plant scale**
  - Larger MHD Generator is more efficient (eg due to less wall heat losses)
  - Larger plant costs less from economies of scale
    - Magnet cost is significant driver
  - Seed regeneration large capital cost in “DPE & Accessories”
- **At 550 MWe, ~10% COE reduction relative to B12B (coal w/CCS)**
- **At 1032 MWe ~30% COE reduction relative to B12B (coal w/CCS)**
  - Meets crosscutting program goal







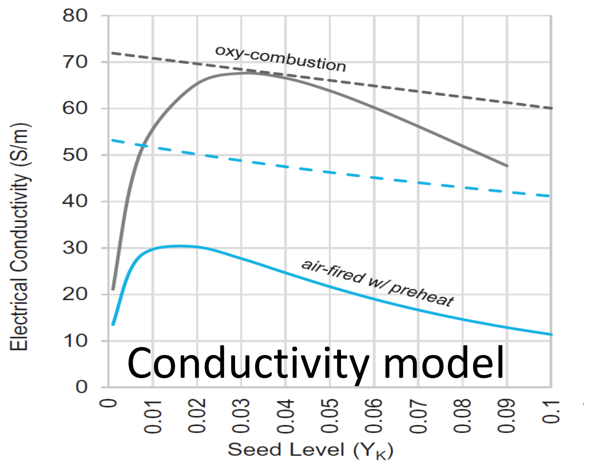


Oxy-fuel Combustion Plasma Conductivity

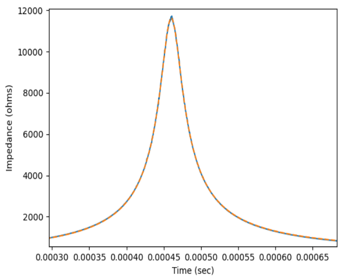
Model & Experimental Validation

$$P \propto \sigma B^2 u^2$$

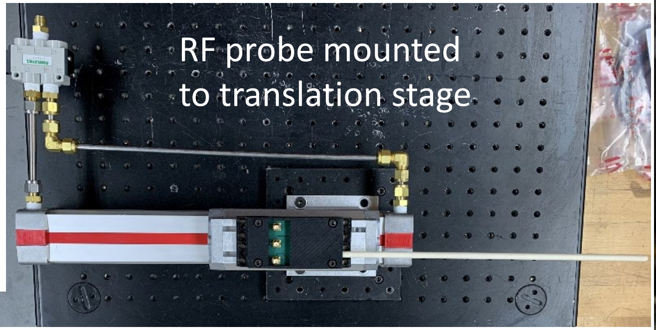
- **Analytical models for plasma conductivity (σ)**
  - electron-neutral MTCS data key for accurate predictions
  - Model includes ion-electron interaction
- **Experimental Validation**
  - Uses Hencken burner
  - K_2CO_3 seeded oxy-methane combustion
  - Parametric studies using full diagnostic suite: electrical conductivity, ion concentration, K concentration, H2O concentration, temperature
- **Combustion Plasma Diagnostics**
  - Langmuir probe
  - K-absorption spectrometry
  - H_2O TDLAS for temperature
  - Improved RF-probe for direct electrical conductivity under development
    - Companion probe & plasma models using COMSOL
    - Custom design achieved
    - Testing underway



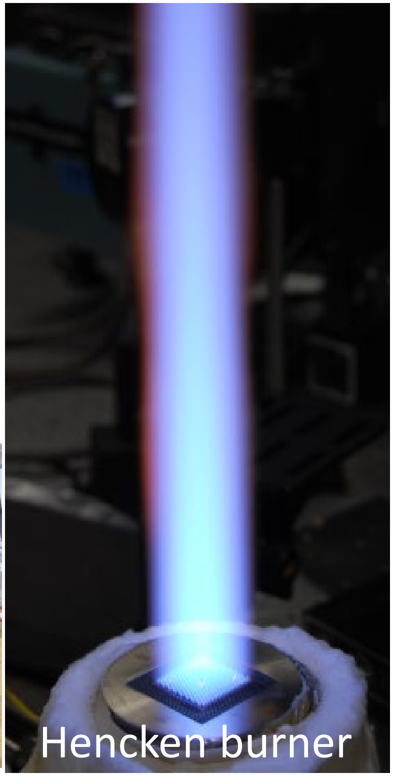
Conductivity model



RF probe impedance curve & fit

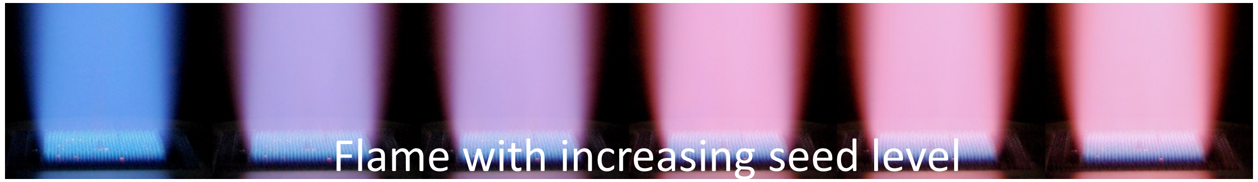


RF probe mounted to translation stage



Hencken burner

No Seed | 0.5 mL/min | 1 mL/min | 2 mL/min | 5 mL/min | 10 mL/min



Flame with increasing seed level

C. R. Bedick, L. Kolczynski, and C. R. Woodside, “Combustion plasma electrical conductivity model development for oxy-fuel MHD applications,” Combust. Flame, vol. 181, pp. 225–238, 2017

Irudayraj, M., Bedick, C., “Determination of Electrical Conductivity in Potassium Seeded Oxy-Fuel Flame using RF Coil Approach”, AIAA 2020 SciTech Forum, Orlando, FL, 6-10 January 2020.

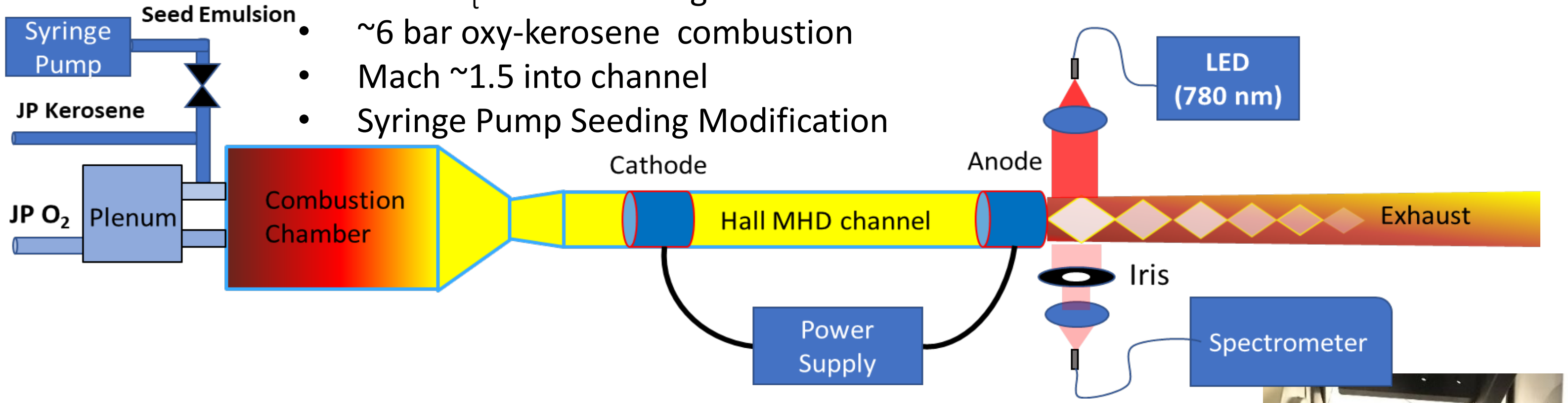
Generator Performance

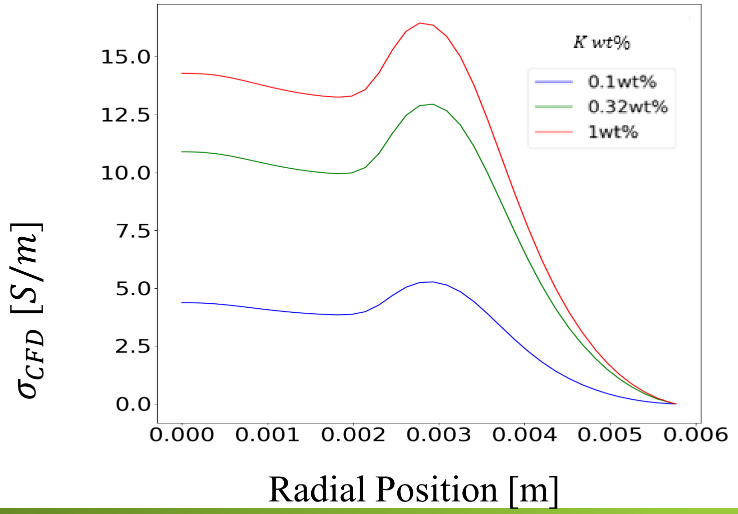
Electric Current Extraction and Boundary Layer Losses

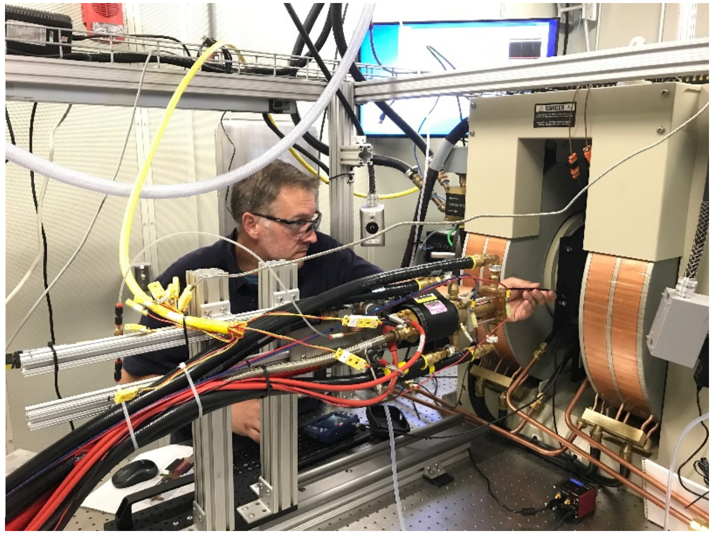
- **Hall channel designed and built for MHD channel plasma resistance & impedance measurements**
  - For model design & validation
- **Generator Resistance**
  - Complex function of position-dependent temperature, pressure, species concentrations etc. modeled using CFD

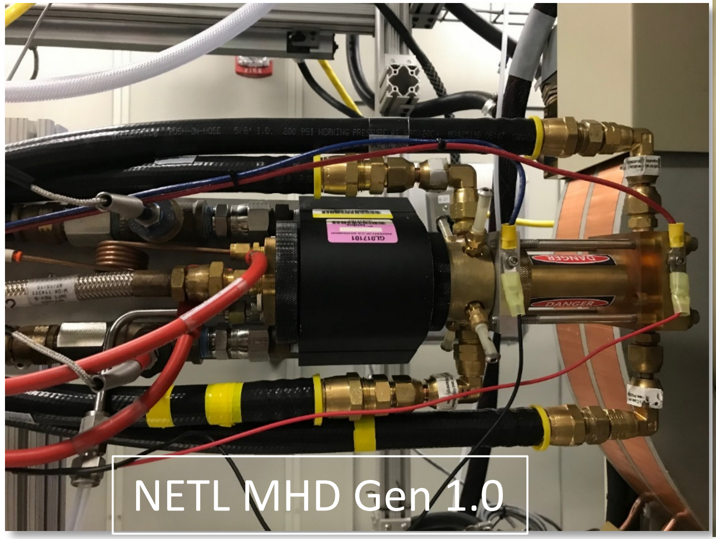
Praxiar JP-8200 High-Velocity Oxy-fuel (HVOF) system:

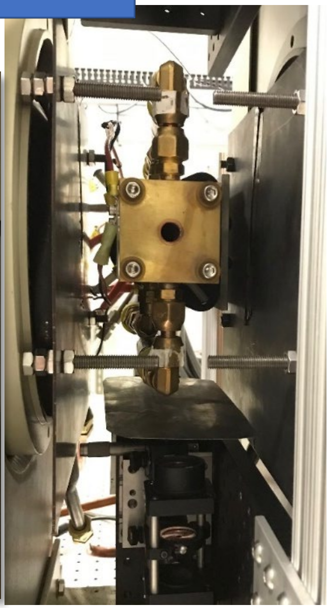
- 160 kW_t Nominal rating
- ~6 bar oxy-kerosene combustion
- Mach ~1.5 into channel
- Syringe Pump Seeding Modification











Ignition!

Combustion

Over 50 sensors continuously logged with National Instruments PXI system

>100 dB sound inside booth!

Adding Seed for Plasma

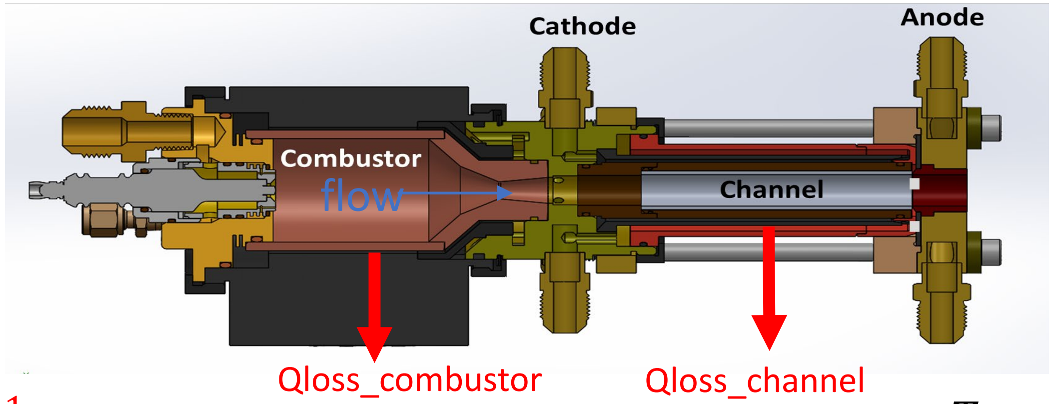
For Plasma Conductivity

- Potassium Carbonate emulsion added with syringe pump
- Note the ‘residual seed’ from adsorbed K2CO3 on walls

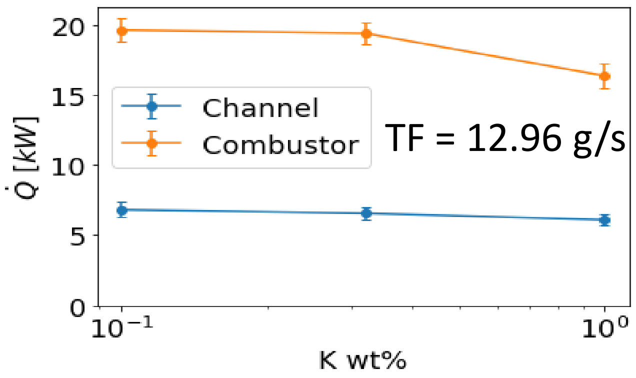
Models of Generator Resistance

Analytical model w/ Cantera

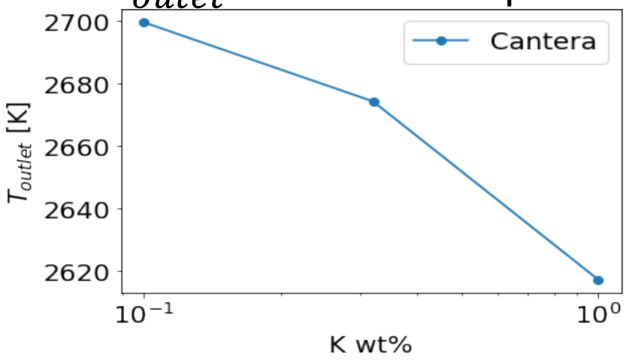
1. Determine Thermodynamic State of gas by considering:
   - A. Ideal combustion calc at measured pressure in combustion chamber
   - B. Conversion of static enthalpy to kinetic energy (reduces T,P) $\Delta H_{K.E.} = \frac{1}{2}\dot{m}v_{exit}$
   - C. Reduce total enthalpy using measured combustor & channel wall heat transfer losses



$\dot{Q}$ = Wall Heat Transfer



T_{outlet} = Outlet Temperature



2. Calculate generator resistance using plasma conductivity model & Thermodynamic State

Model resistance with simple cylindrical model

$$R = \frac{4}{\sigma}\frac{L}{\pi D^2}$$

$L = 10\ cm$

$D = 1\ cm$

This model expected to underestimate generator resistance as it does not consider a cold boundary layer

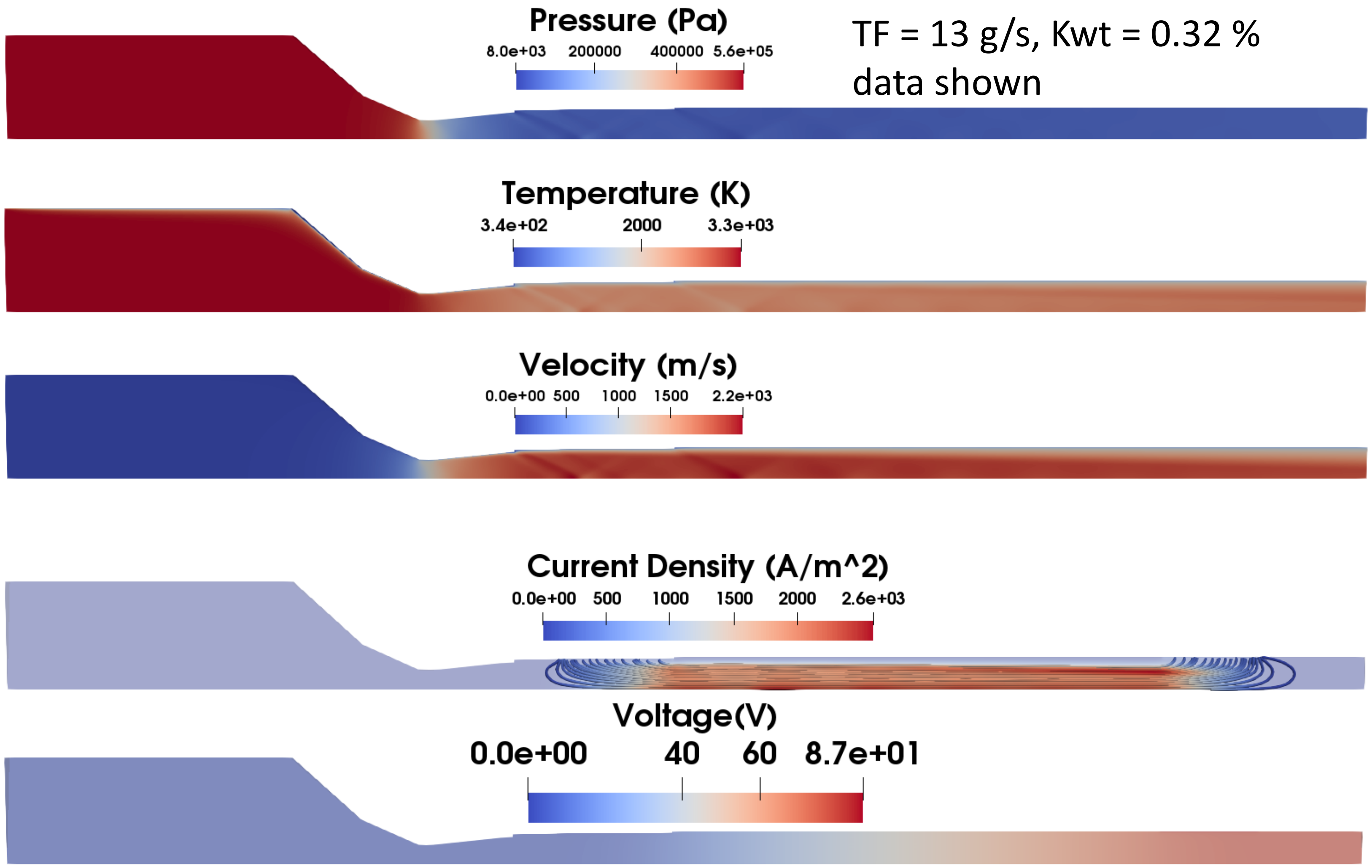
Models of Generator Resistance

CFD model w/ OpenFOAM

1. Solve fluid flow & thermo properties:
   - uniform mixture of combustion product of fuel, oxygen and seed, injected at combustor back plate section.
   - 2D axi-symmetric geometry
     - Convective wall heat transfer & boundary layer formation
   - finite rate chemistry for tracing the evolution of species (considers non-equilibrium chemistry)

2. Calculate resistance using conductivity model & electrostatic model
   - Electrostatics decoupled from flow

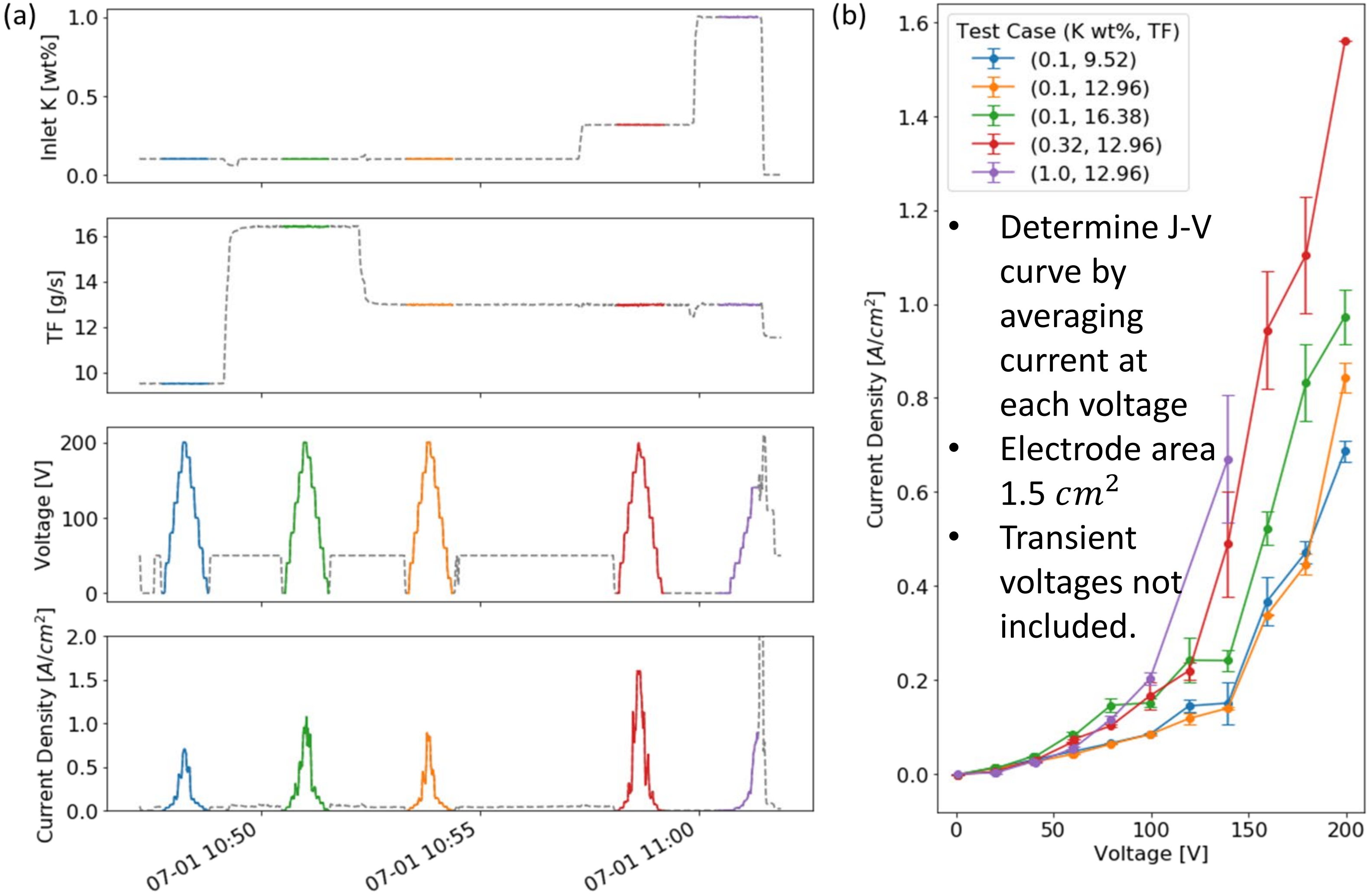
TF = 13 g/s, Kwt = 0.32 % data shown



This model considers a cold boundary layer, but does not consider arc transfer of current to electrode

Experimental Results

Generator Resistance Testing (Apply power to generator)

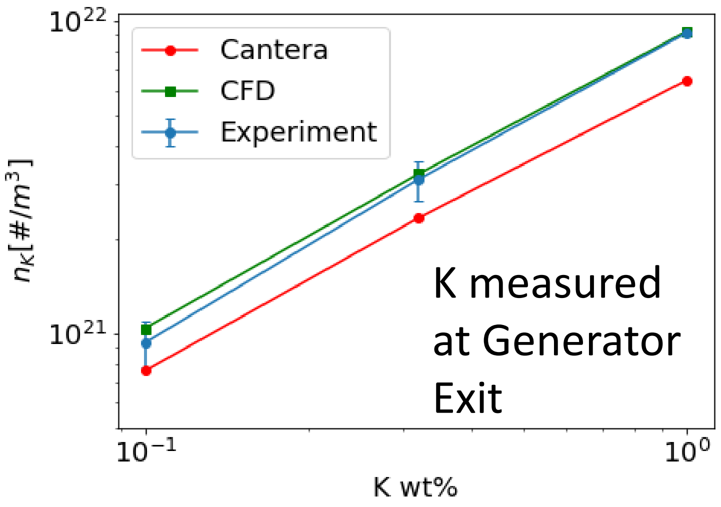


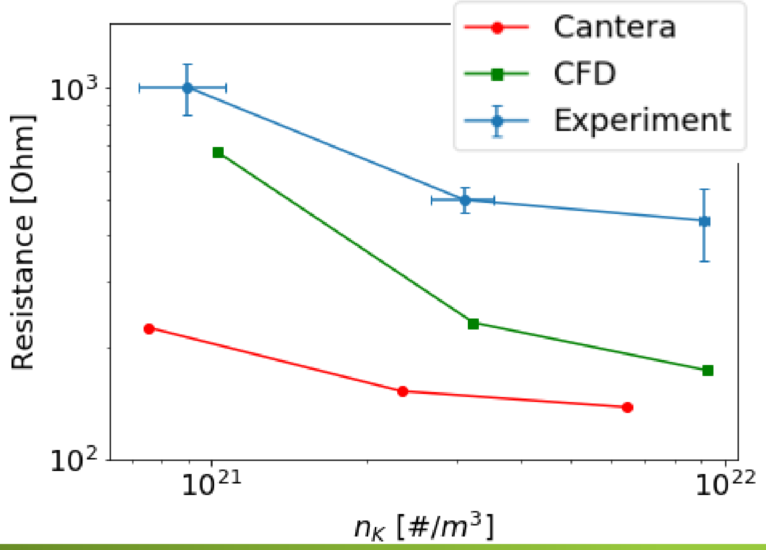
Notes:

- Historical limit (long duration operation) for copper electrodes thought to be ~1 A/cm^2
- ~200V experimental limit due to observed interchannel arcing
- Higher seed yields lower resistance, as expected
- minimal resistance trend with mass flow
- Resistance change observed above ~100V
    - Arc regime change?
- Resistance (for model comparisons in next slide) calculated in lower voltage range to avoid Joule heating effects

Measured and Modeled Generator resistance

Results & Conclusions





- Modeling results consistent with measurement, $n_{K,expt}$
  - Expected result if:
    - Successful vaporization and ionization of potassium from all injected seed
    - Modeled thermodynamics reflective of experimental conditions

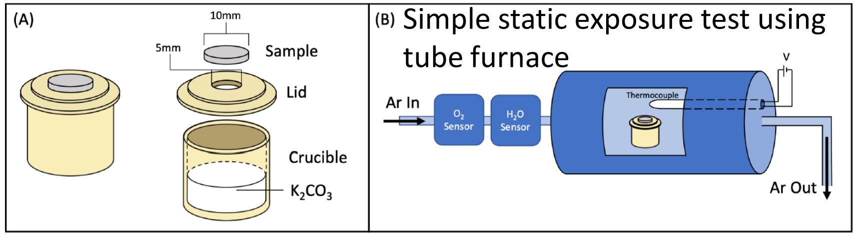
- R_{expt} is significantly higher than the resistance predicted in a simple cylindrical resistor model using fluid conductivity calculated in Cantera-based chemical equilibrium calculations.
  - As expected, since no boundary layer consideration

- CFD simulations predict resistances closer to R_{expt}, which we attribute in part to modeling the cold boundary layer near the electrodes.
  - But result is outside of error bars, so model improvements needed

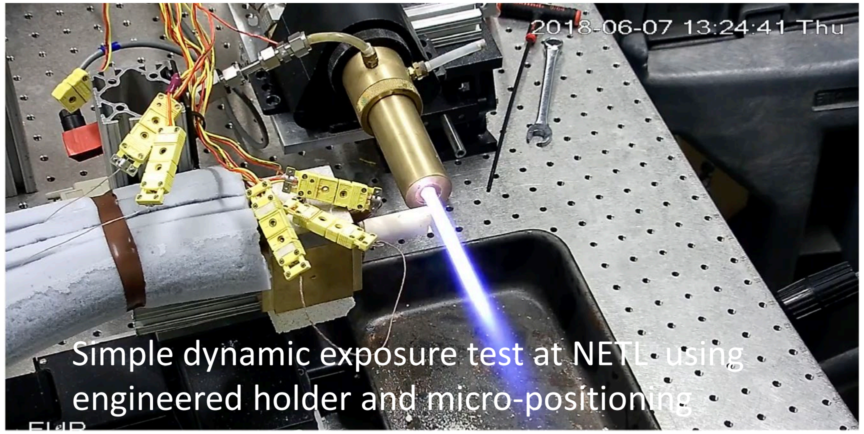
MHD Channel Materials

Direct-Fired Oxy-fuel System

- **Pursuing super hot wall channels (T>1800C)**
  - Advantage: less wall heat losses (important with oxy-fuel)
  - Advantage: reduces cold boundary layer and in turn voltage drops
  - Hot surface avoids seed & slag deposits on surfaces
    - Important as this caused major problems in legacy studies
- **MHD electrode properties**
  - Elec. Conductivity > 10 S/m (but depends on channel size)
  - Corrosion resistance
  - Electrical arc resistance
  - Resistance to thermal shock & cracking
  - Compatible with suitable electrical insulator
  - Low emissivity & low thermal conductivity to min. heat losses
  - Resistance to erosion from high-speed flows

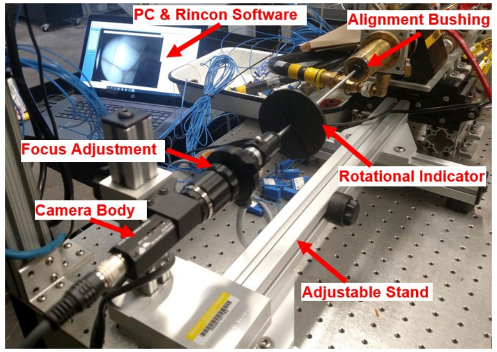


Simple static exposure test using tube furnace



Simple dynamic exposure test at NETL using engineered holder and micro-positioning

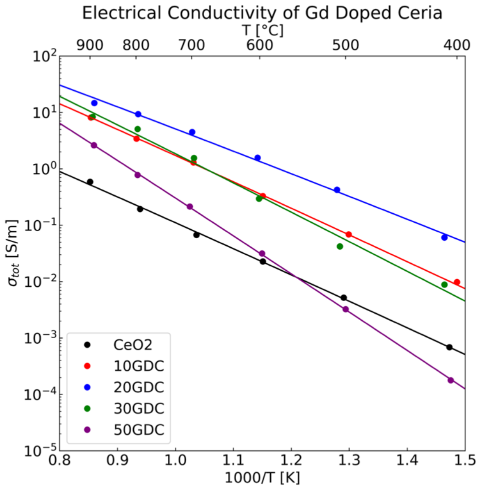
Borescopic channel inspection for ceramic channel inserts in NETL MHD lab

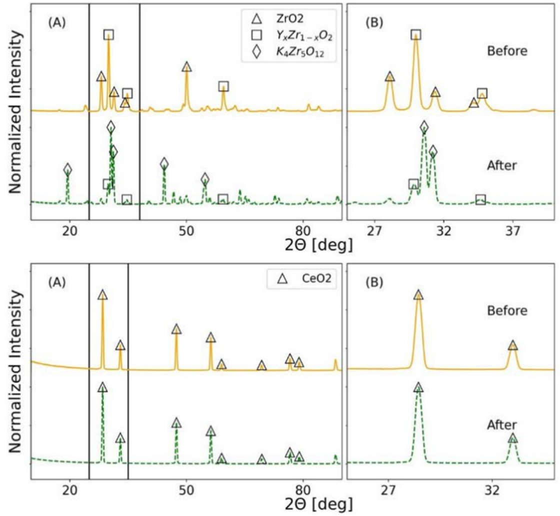


GDC Electrodes & MgO insualtors

For super hot MHD channel

- **GDC electrode & MgO selected following literature review**
  - MgO known MHD channel insulator
  - GDC previously not considered for electrode use
- **Electrical property measurements showed compositions rich in CeO_2 have high conductivity values ~100 S/m for T>1600 K**
- **Controlled-atmosphere potassium-exposure tests were performed on various refractory oxides**
  - ZrO_2, HfO_2, and Al_2O_3 based materials were found to be unstable in the presence of potassium
  - MgO and CeO_2 based materials were not found to react indicating potassium corrosion resistance
- **GDC & MgO have similar thermal expansion**
  - Graded GDC & MgO disc has been successfully fabricated





Ex-Situ XRD evaluation of materials

Bowen, M.S., Johnson, M., McQuade, R., C. Rigel Woodside *et al.* Electrical properties of gadolinia-doped ceria for electrodes for magnetohydrodynamic energy systems. *SN Appl. Sci.* **2,** 1529 (2020)

Michael S. Bowen, Kyei-Sing Kwong, Peter Hsieh, David P. Cann, C. Rigel Woodside; *"High Temperature Corrosion Stability of Ceramic Materials for Magentohydrodynamic Generators"*; 2021 ASTM International Journal on Materials Performance and Characterization

EY2021 & Future Work

New & planned activities for DPE (Selected)

- **Systems Analysis**
  - Improve system integration
  - Investigate reducing cost of seed recycle process
  - Investigate viability of DPE powdered hydrogen production
- **Planned MHD Generator Improvements**
  - Increase continuous seeding time from minutes to hours
    - Needed for ceramic channel material testing
  - Increase channel temperature toward MHD Gen 2.x
    - Approach prototypical temperatures
    - Prevent precipitation of seed material ← improve material balance
  - Added & new diagnostics in 2021
    - Impedance spectroscopy
      - Separate boundary layer and bulk conductivity contributions
    - Absorption emission spectroscopy at entrance and exit of generator
      - Atomic potassium density mass balance
    - Developing and testing Microwave scattering system:
      - Directly measure free electron density in plasma
- **MHD Channel Materials**
  - Perform dynamic exposure testing with HVOF
  - Fabricate ceramic MHD channel using additive manufacturing

Assembling MHD Gen 1
In NETL's MHD Lab

Conclusions

Selected

- **TEA of Oxy-MHD system w/ CCUS shows concept viability for coal**
  - Natural gas power gen systems not as promising
  - Plant can hit target COE reduction of 30% over SOTA (w CCUS) at larger scales
  - System & component improvements may enable smaller systems viability
  - COE dominated by capital costs
    - Seed recycle major cost
- **NETL 1.0 Generator design and test successful**
  - Current through a conductive plasma & typical current densities achieved
  - Interchannel arcing issue to consider in greater detail in design
  - CFD model used did not accurately predict generator resistances
    - Likely need specialized arcing or another boundary layer model
  - Potassium spectrometry works well as diagnostic
- **Candidate MHD channel materials selected (GDC and MgO) and show promise**
  - Moving forward with ceramic channel manufacturing

Acknowledgements

Rigel Woodside*, Nathan Weiland, Chuck White, Clint Bedick*, Lee Aspitarte*, Danylo Oryshchyn*, Peter Hsieh*, David Huckaby, Hyoungkeun Kim, Michael Bowen, David Cann, Paul Thomsen, Jon Fulton; NETL management, ES&H, Engineering, IT, Multi-media, & Site Operations Staff

***Principal Investigators in NETL EY2021 DPE FWP**

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