IPT – Direct Power Extraction

NETL Office of Research and Development

2015 Crosscutting Technology Research Review Meeting

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Presentation Focus & Outline

Direct Power Extraction (DPE): technology which directly converts thermal/kinetic power to useable electrical power.

DPE Example: magnetohydrodynamic generator. This is our present focus, and in particular we focus on the unique challenges of this.

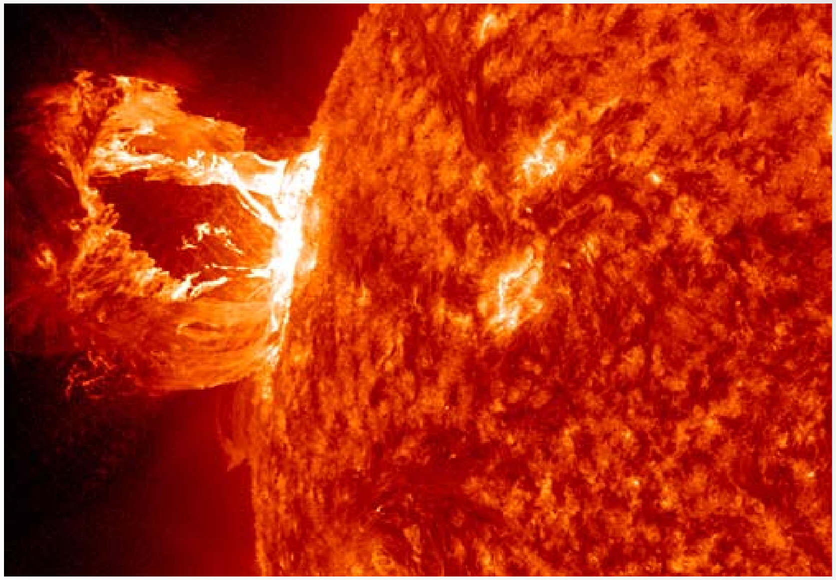
DPE Task Goal: Generate engineering data sets, simulation tools, and materials to further the prospect of using DPE

- **Introduction**
- **Analysis**
- **Computational Simulations**
- **Materials Research**
- **Experimental Plans**
- **Conclusion**

What is Magnetohydrodynamics (MHD)?

MHD describes the interactions of a magnetic field and an electrically conductive fluid

- **In Nature**
  - geomagnetic dynamo
  - solar "wind" and solar "flares"



Picture of magnetic effect in solar flare (SOURCE: universetoday.com)

- **In Engineering**
  - Materials Processing
  - Propulsion/Pumping
  - Power Generation
    - Pulsed
    - Steady
      - Compact, no moving parts
      - *High Efficiency Electrical Power Generation w/CO2 capture*

Lorentz Force Law

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B})$$

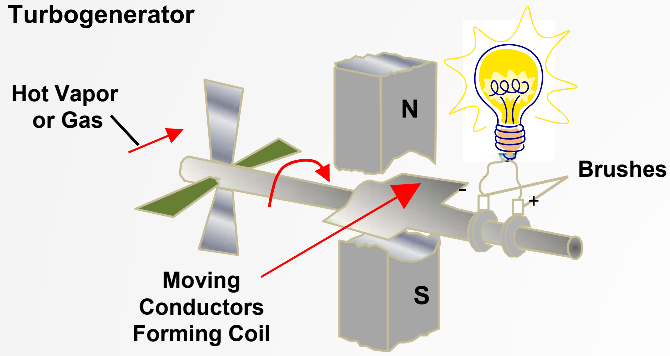
F is force vector
q is electric charge
E is electric field vector
u is velocity vector
B is magnetic field vector

MHD Generator

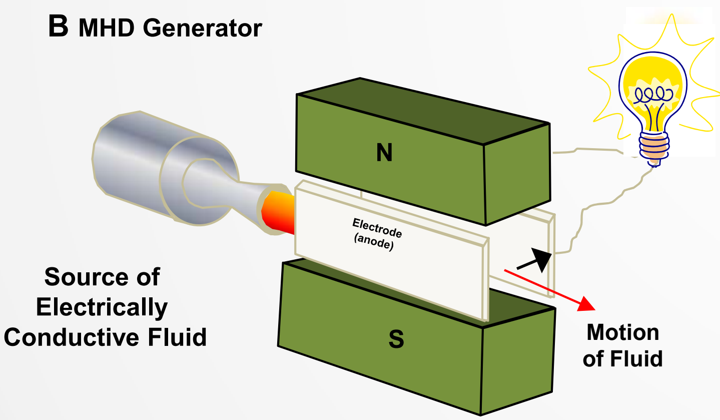
A. Turbo-generator Energy Conversion ->
chemical (fuel) to thermal/kinetic to mechanical to electric

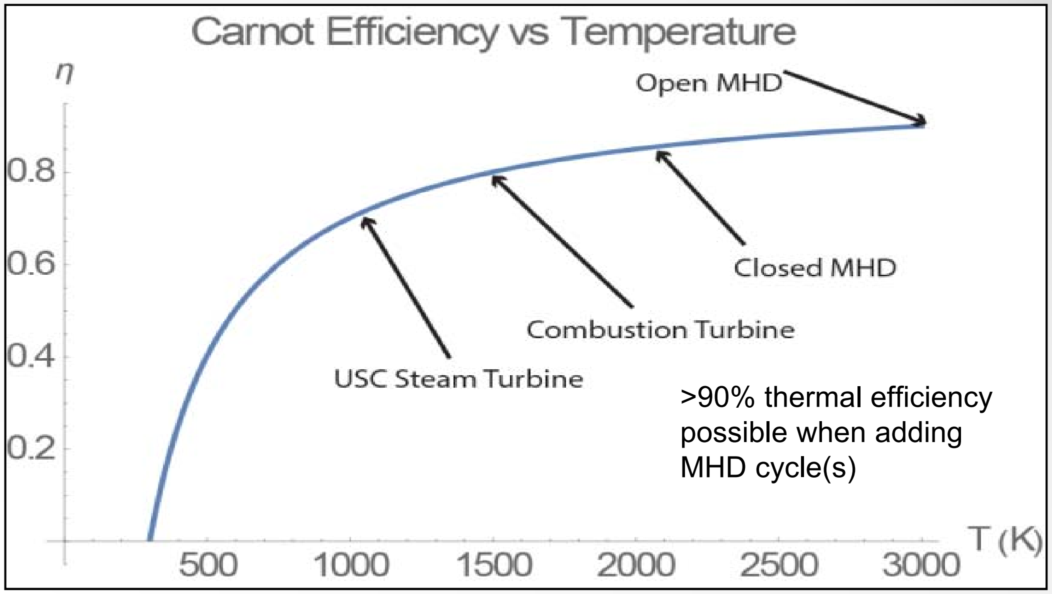
B. MHD Generator Energy Conversion ->
chemical (fuel) to thermal/kinetic to electric

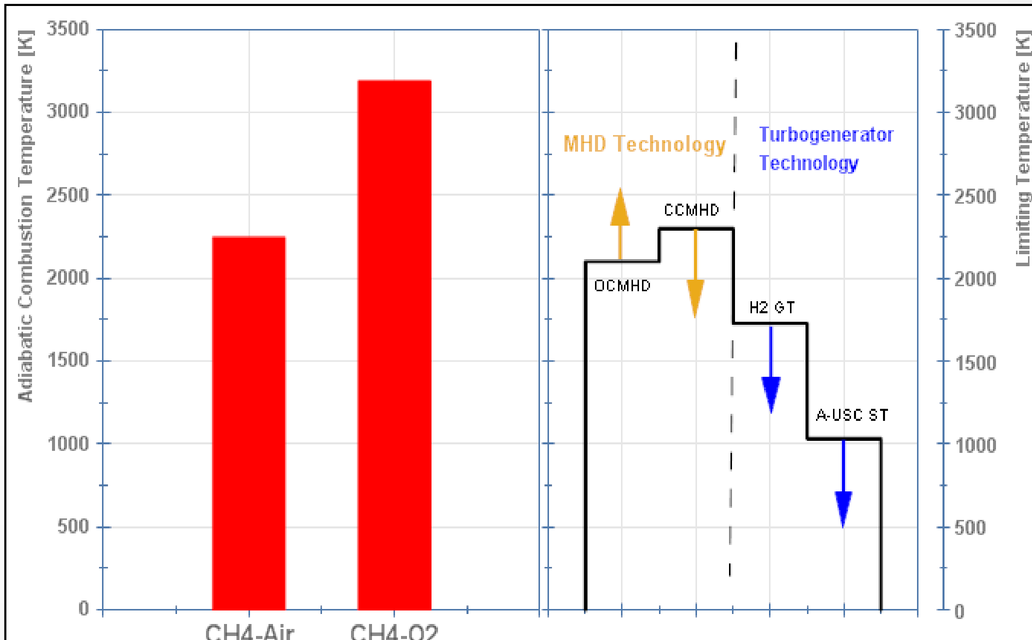
A Turbogenerator



B MHD Generator







(more) Direct Power Extraction

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

where B is applied magnetic field
σ is gas-plasma conductivity
u is gas-plasma velocity

New Motivations: USDOE FE

Exhibit 3-117 Increases in Cost of Electricity Over Non-Capture Reference Case

Study Case	First Year Cost of Electricity ($/MWh)						Increase in COE (%)[a]
	Capital	Fixed O&M	Variable O&M	Fuel	TS&M	Total (Less TS&M)	
Non-Capture Reference, Air-fired SC w/o CCS	31.68	7.97	5.03	14.22	0.00	58.90	-
Current OF Technology, O_2-fired SC w/ASU & CCS	53.72	11.81	6.47	19.08	5.83	91.07	54.6
Case 1, O_2-fired SC w/Boiler Adv. Membrane & CCS	52.35	11.53	5.99	17.32	5.60	87.19	48.0
Case 1A, O_2-fired SC w/NG Adv. Membrane & CCS	50.45	11.23	5.63	23.81	5.25	91.12	54.7
Case 3, O_2-fired USC w/ASU & CCS	54.15	11.81	6.10	17.25	5.58	89.31	51.6
Case 4, O_2-fired SC w/ASU & Co-Sequestration	48.85	10.79	4.78	17.60	5.67	82.02	39.3
Case 5, O_2-fired SC w/ASU, Wet Recycle & CCS	53.66	11.80	6.47	19.11	5.91	91.03	54.5
Case 6 O_2-fired SC w/ASU & Shock Compression	52.59	11.60	6.34	18.81	5.87	89.34	51.7
Case 7, O_2-fired SC w/ASU, Adv. Boiler & CCS	53.13	11.65	6.32	18.87	5.89	89.96	52.7
Cumulative Technology Case	**48.52**	**10.66**	**4.30**	**14.68**	**5.28**	**78.15**	**32.7**

[a]Relative to non-capture reference case

Exhibit 2-8 Cost Breakdown for Oxycombustion Power Plant

Cost Item	Percentage Contribution to COE [%]
ASU capital	29.5
ASU power	35.8
CO_2 Compressor Capital	8.6
CO_2 Compressor Power	19.1
TS&M	7.0
Total COE Increase	**100%**

Strategies for Improvement:

1. Decrease ASU cost
2. Use oxygen to enable power generation -> MHD

Note: Oxygen established benefits for rockets & melting

Source: 2012 NETL final report (DOE/NETL-2010/1405)

Analysis: Seeded Oxy-fuel Electrical Conductivity

Example Case

- **Open-Cycle MHD scenario**
- **Consider oxy-methane combustion**
  - ($CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ at $\phi = 1$)
  - Utilize potassium carbonate as seed material (K_2CO_3)…K Ionization ~ 4.3 eV
- **Thermal Equilibrium**
  - Utilize NASA's Chemical Equilibrium Analysis (CEA) code for chemistry, ionization, and gas dynamics
- **Gas Electrical Conductivity Relation (for comparative purpose):**
  - $T_e = T_g$; Electrons all at mean speed; use $Q_k = f(T_e)$; Q_{H20} from Spencer (1976)*.

$$\sigma = \frac{n_e e^2}{m_e c_e \sum_k n_k Q_k} \qquad c_e = \langle v \rangle = \sqrt{\frac{8 k_b T}{\pi m_e}}$$

-Neglects ion-electron collisions
-Scalar (no magnet effect)

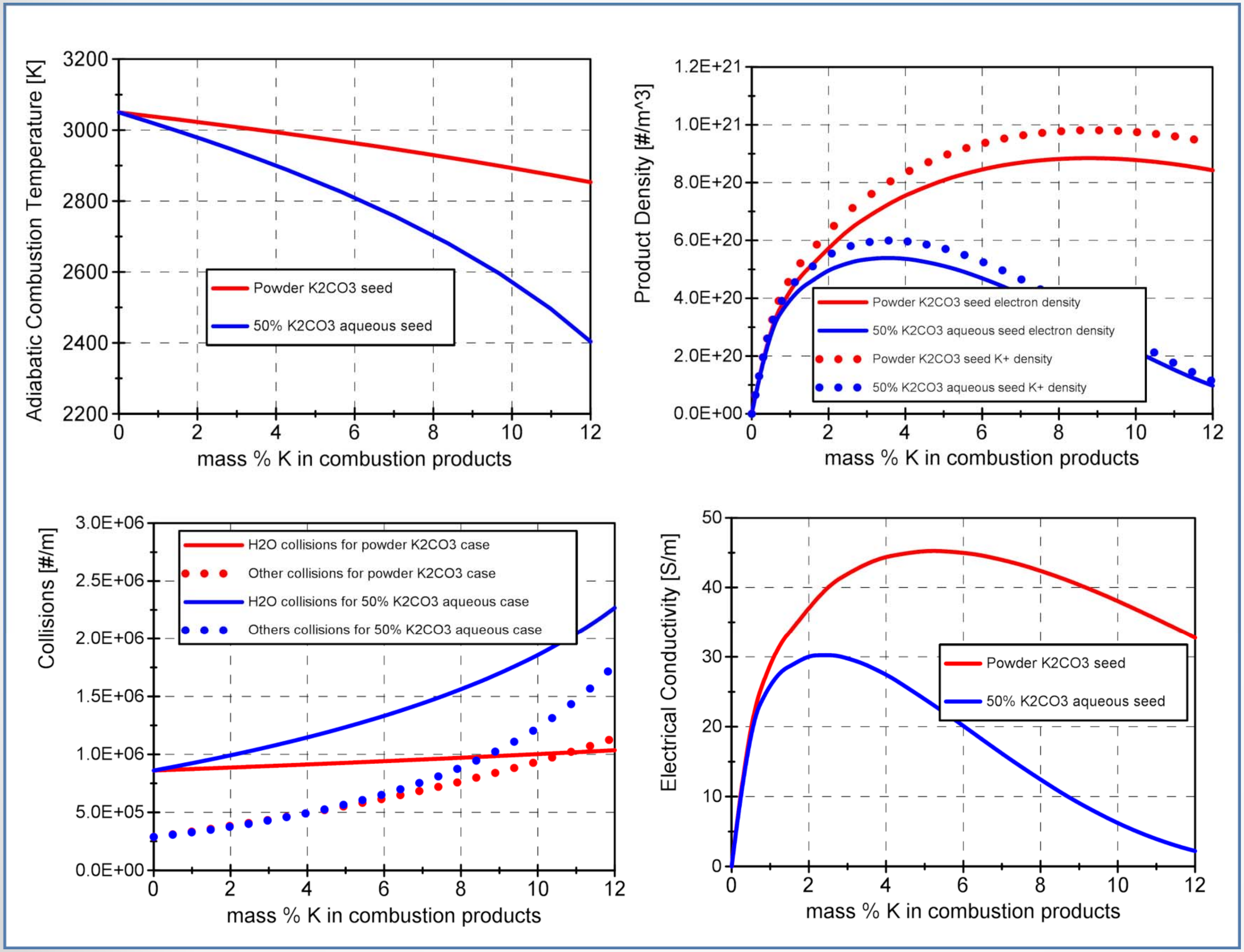
n_e= electron number density [#/m^3]
e = electron charge = 1.60 x 10^{-19} [C]
m_e = electron mass = 9.11 x 10^{-31} [kg]

c_e = random thermal electron velocity [m/s] (estimated by the Maxwell-Boltzmann mean speed, $\langle v \rangle$)
n_k = neutral species number density [#/m^3]
Q_k = neutral species momentum transfer collisional cross section [m^2]
k_b = Boltzmann constant = 1.38 x 10^{-23} [J/K]
T = electron temperature [K]

*may result in bias to lower conductivity, see collision cross section slides

Seeding: Getting Conductive Flow

1 atm. combustion, $\phi = 1$; Introduce K_2CO_3 seed as powder or dissolved in water solution

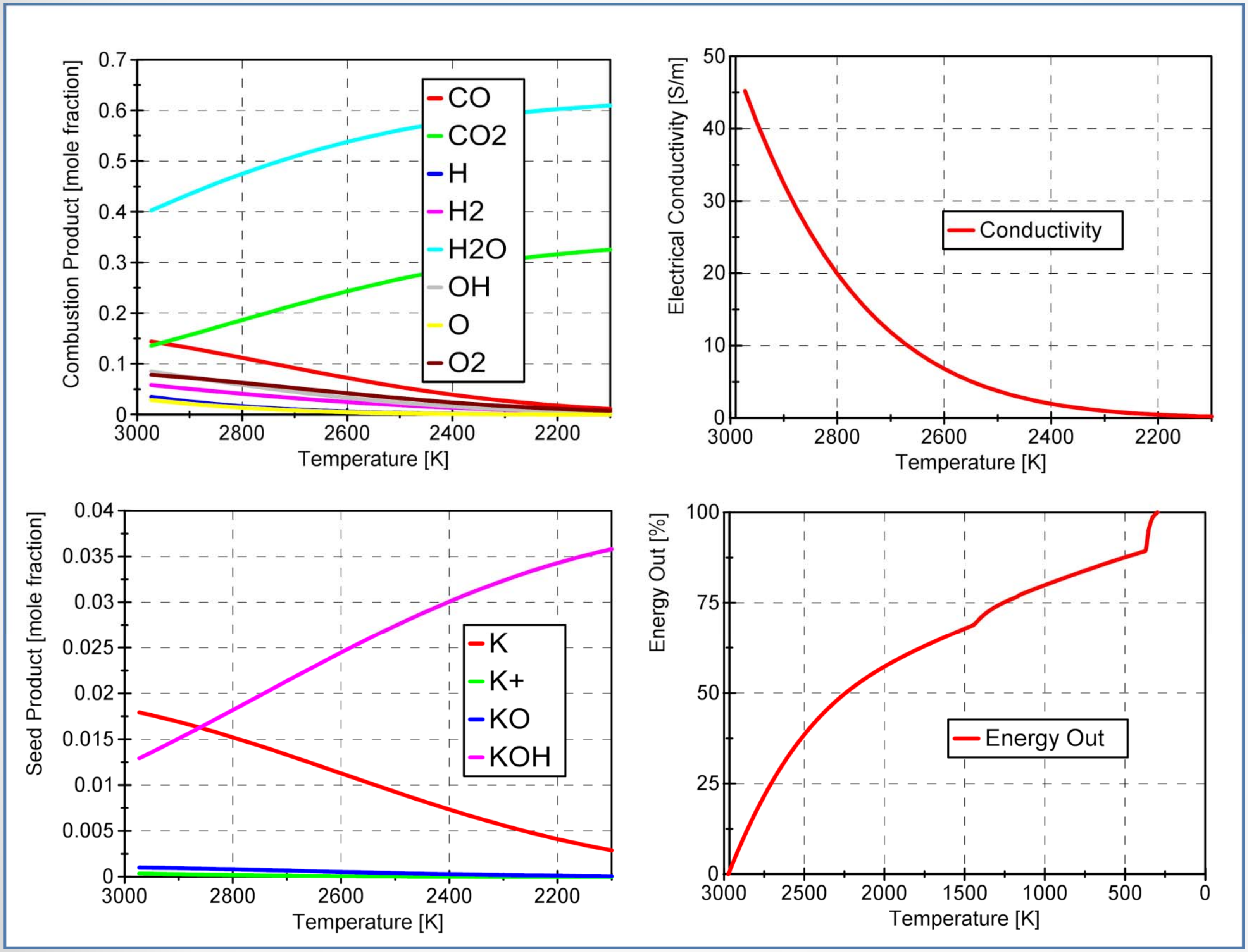


Notes:

- Cond. ~10^4 greater with seed than without
- Adding seed cools gasses
- Optimal seed amount different for powder vs aqueous
- H_2O collisions dominate
- OH radicals: ~10% reduction in e-

Combustion Product Chemistry

1 atm. combustion, ϕ = 1, 5.4 mass % K (powder K_2CO_3 added)

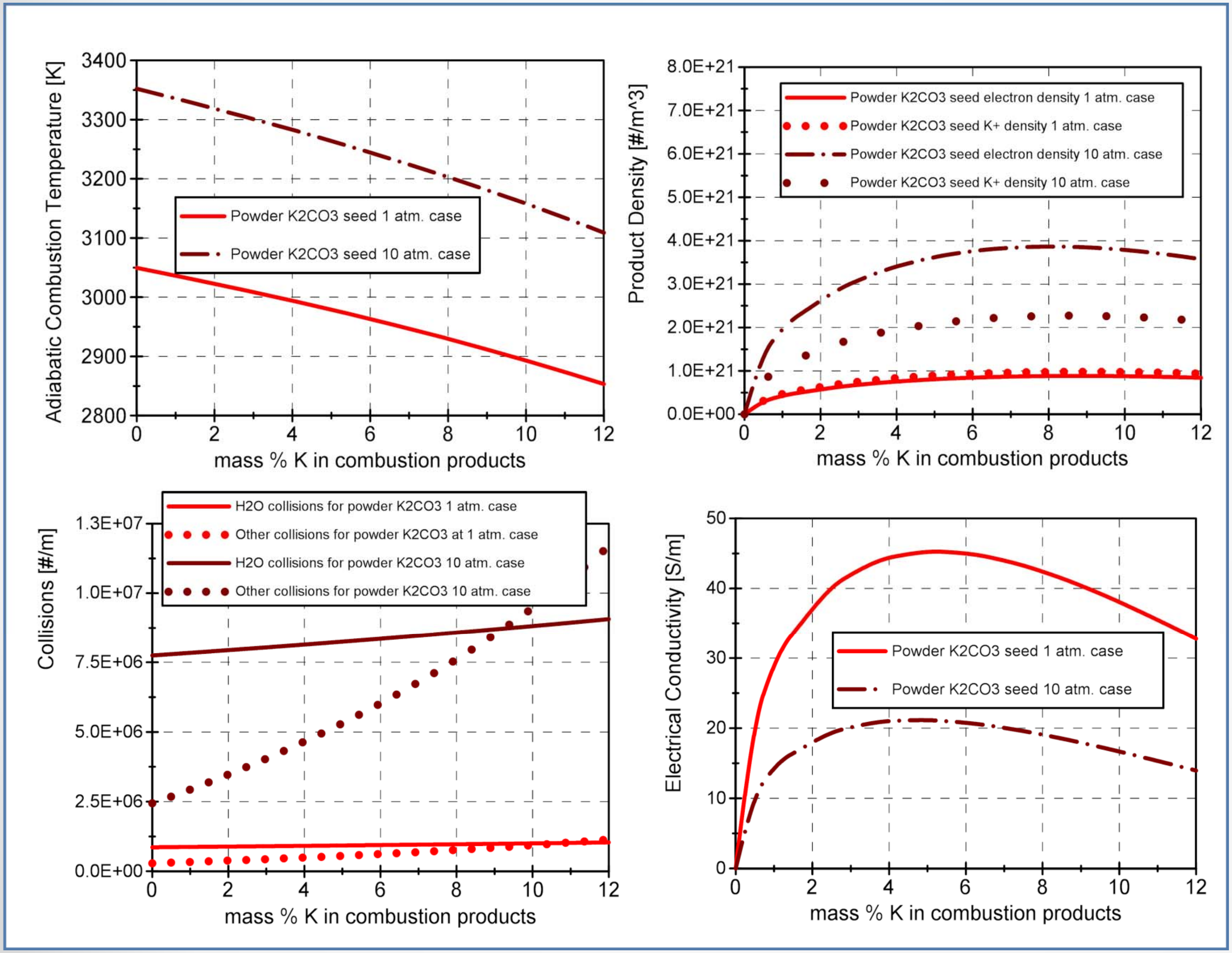


Notes:

- Dissociation important
- Very non-linear cond.
- Very little K+
- Re-association maintains T
- At 2100K cond. ~10^2 less then at ~3000K
- Higher Temp means New oxy ~3x cond. from 1980s OCMHD

Effects of Combustion Pressure

ϕ = 1, 5.4 mass % K (powder K_2CO_3 added)

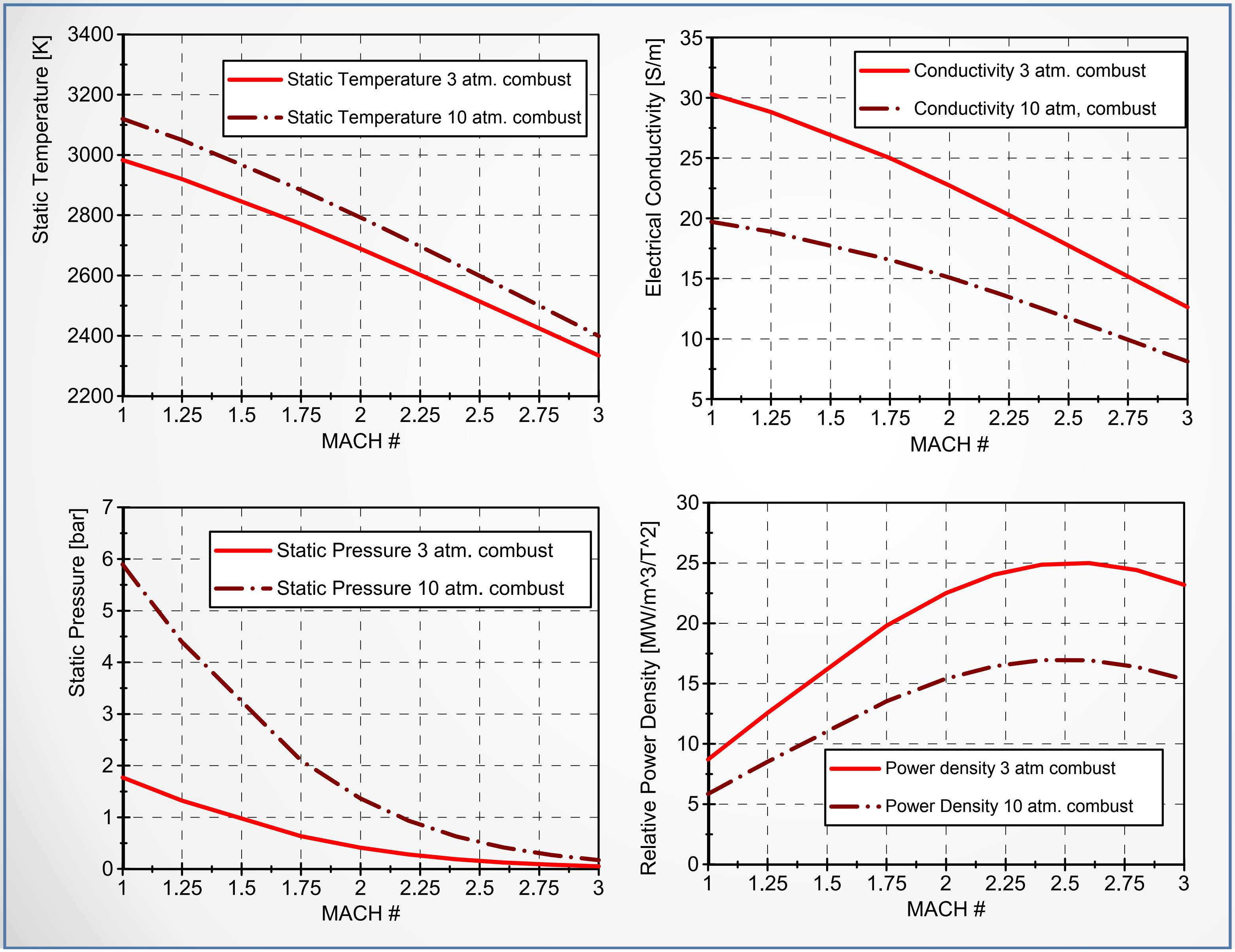


Notes:

- More Temp. & e- at higher P
- Lower cond. at higher P due to collisions
- Optimal seed amount not very sensitive to P
- OH radicals: more important at higher P

Effect of Supersonic Expansion (get velocity)

ϕ = 1, 5.4 mass % K (powder K_2CO_3 added); Relative Electric $P_{MHD} = \sigma u^2/4$



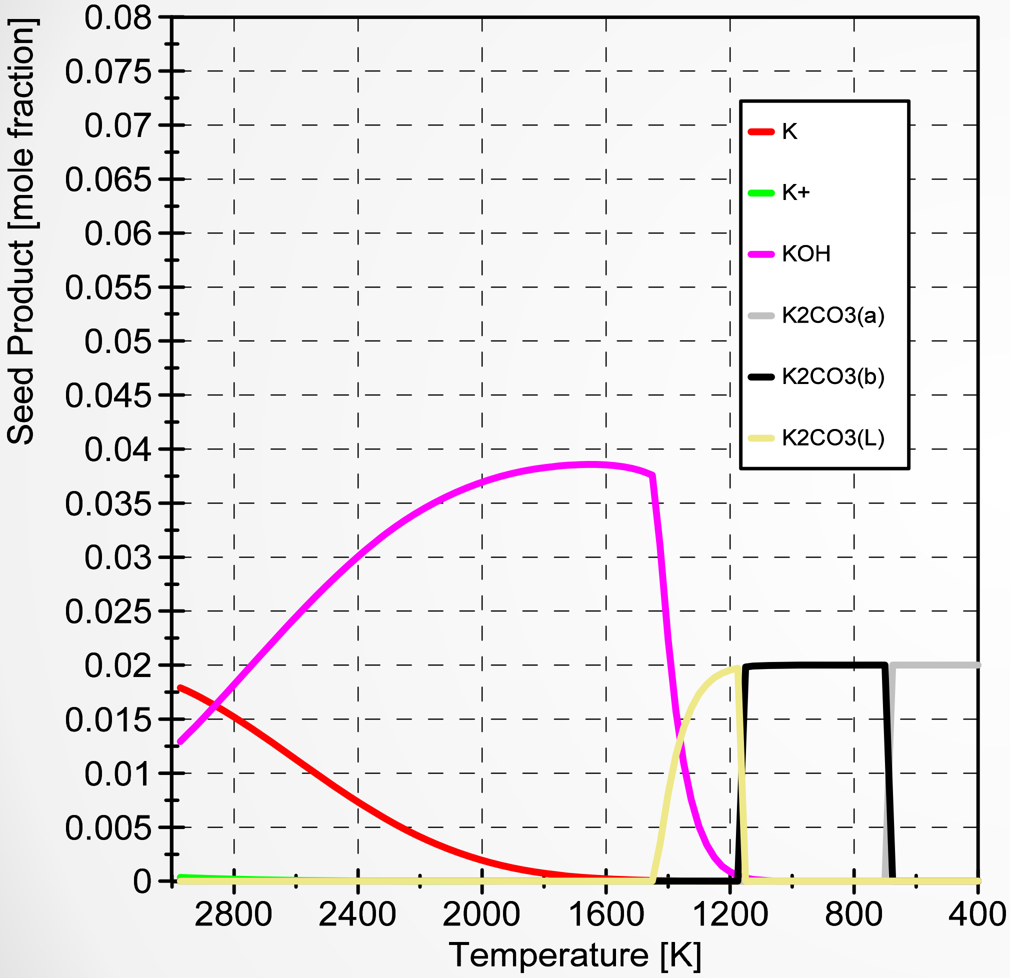
Notes:

- Expansion cools gasses
- Expansion reduces pressure
- Pressure is sub-atm. in channel at peak MHD power density
- Lower cond. but more power density
- Lower P still better but gap between Ps closes

Seed Recovery

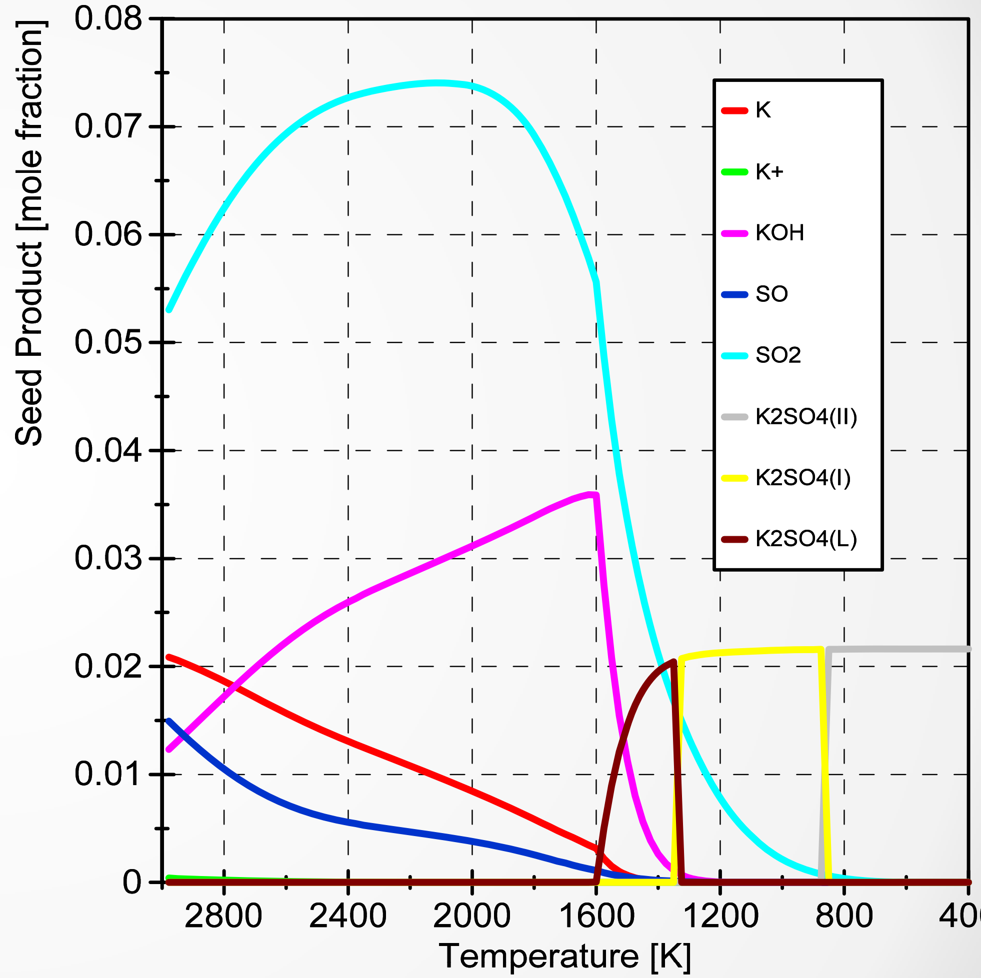
1 atm. combustion, ϕ = 1, 5.4 mass % K (powder K_2CO_3 added)

No sulfur in system:



K_2CO_3 in -> K_2CO_3 out

With sulfur in system (example):

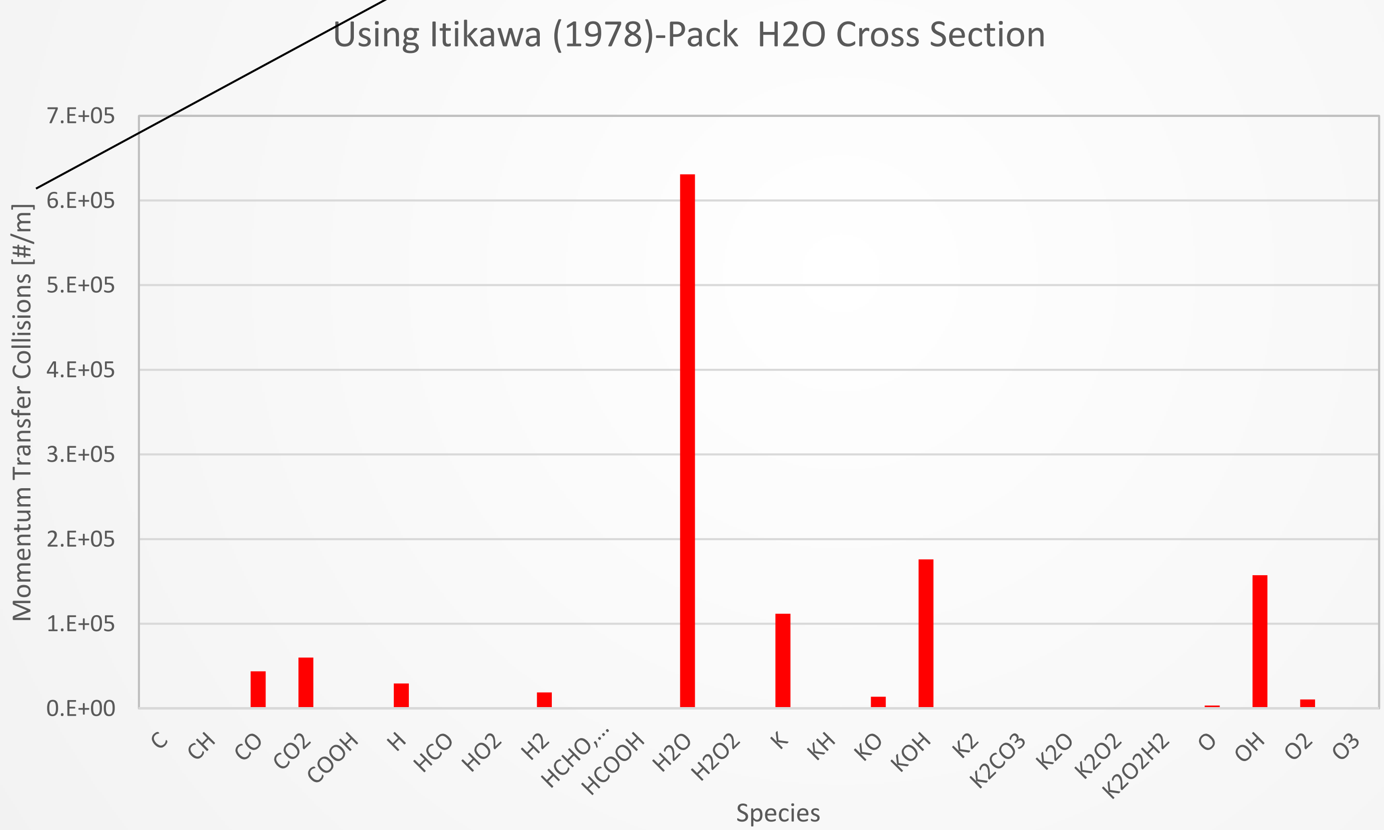


K_2CO_3 in -> K_2SO_4 out (sulfur scrubbing)

Side Note: Seed aerosols/particles form at T_s where gas turbines operate (an issue for turbine integration)

Analysis: Collisional Cross Sections

- **Summarize electron-molecule collisional cross section data sets**
  - » $\sigma = \frac{n_e e^2}{m_e c_e}\left[\frac{1}{\sum_k n_k Q_k + 3.9 n_i \left(\frac{e^2}{8\pi\epsilon_0 k_B T}\right)^2 \ln\Lambda}\right]$
  - » $P \propto \sigma u^2 B^2$

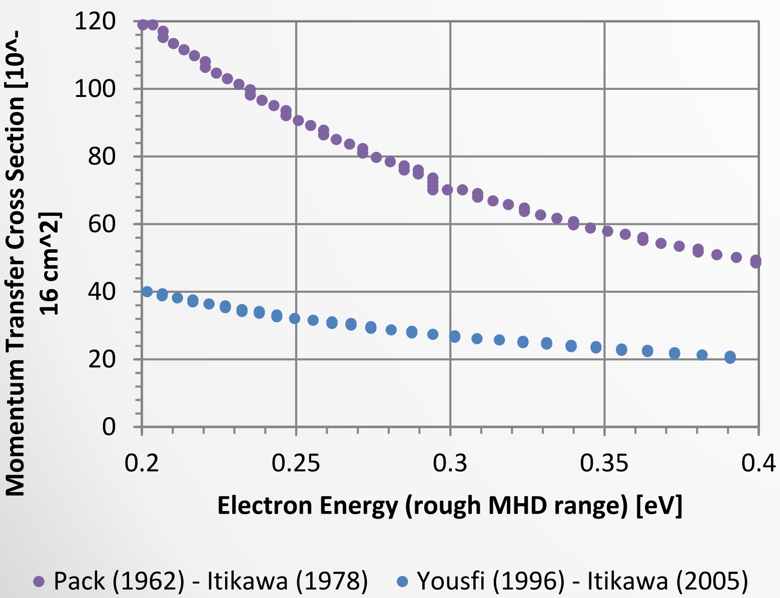


Example of electron collisions with powder seeded methane-oxygen combustion products

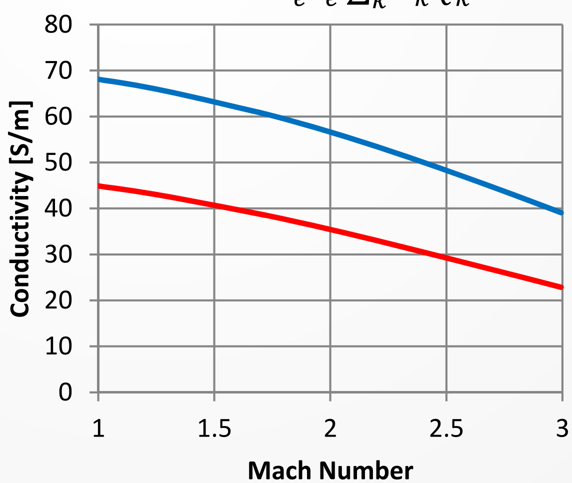
H_2O is most important species for oxy-fuel MHD systems.

Analysis: H2O- "Root" Sources

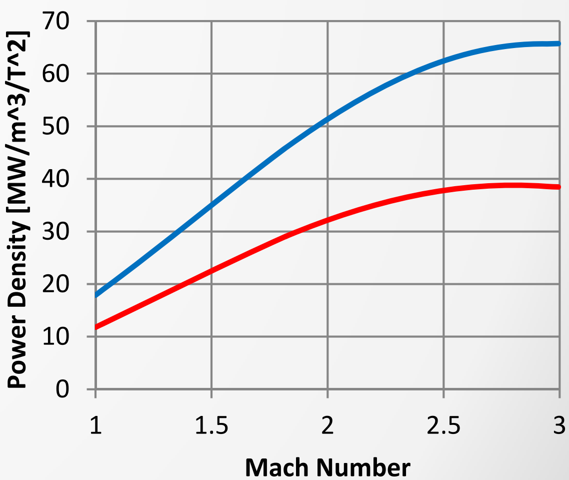
- **Two "root" H_2O data sources, "Pack" and "Yousfi" which multiple references derive values from**
- **Pack and Yousfi vary by a roughly calculated 60 to 70 % in the MHD range of interest**
  - Results in differences for conductivity and power calculations
  - Example case below: kerosene + pure oxygen combustion expanding flue gas w/3 atm. combustion pressure



$$\sigma = \frac{n_e e^2}{m_e c_e \sum_k n_k Q_k}$$



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



Red: uses Itikawa (1978) with Pack (1962) data
Blue: uses Itikawa (2005) with Yousfi (1996) data

Analysis: new conditions of Oxy-MHD

This data is at 1 atm. pressure and is for comparative purposes.

Fuel: CH_4, Oxidant case:

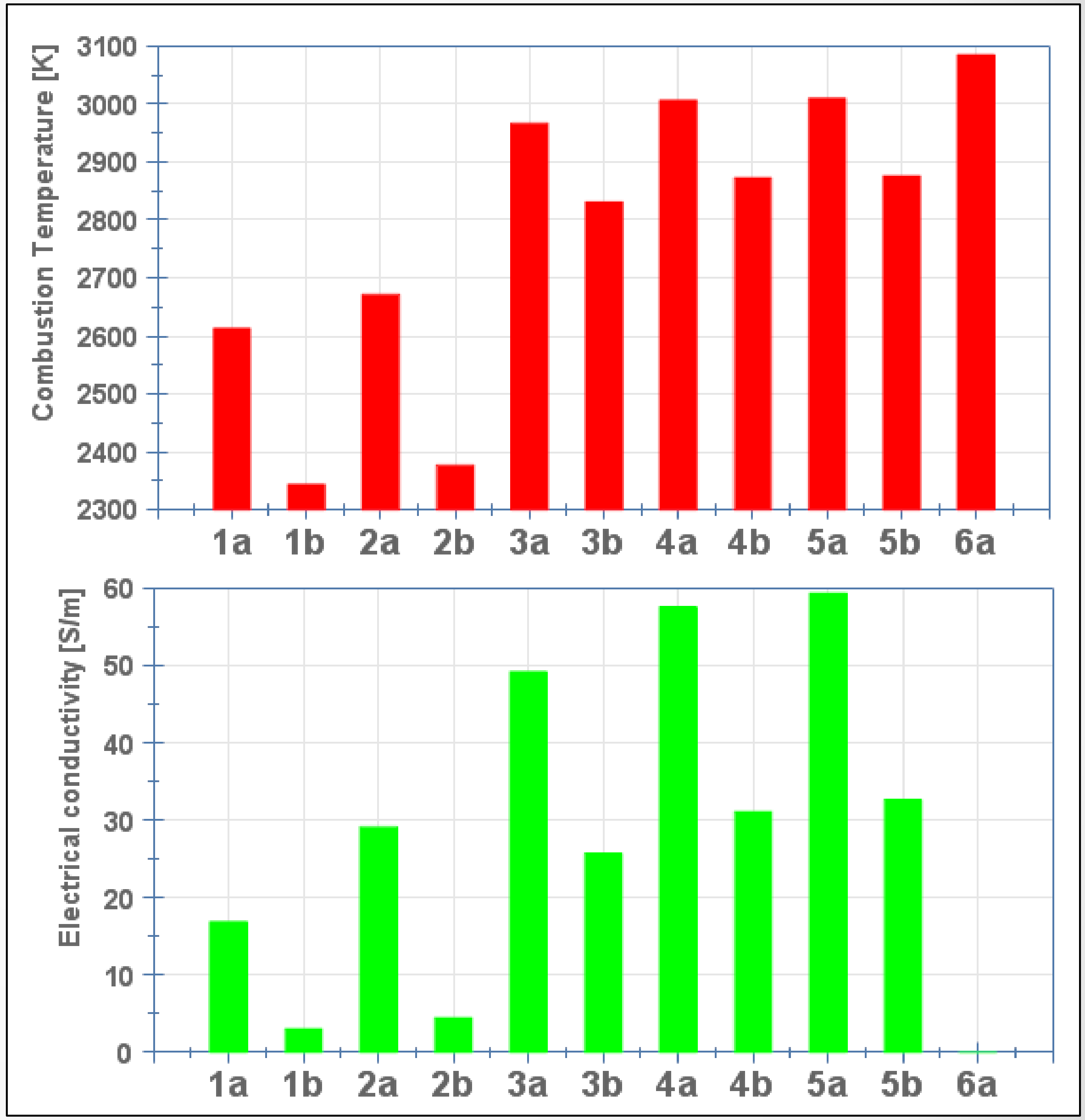
1a: 36% O_2 enriched at 922K
1b: 36% O_2 enriched air at 922K
2a: air at 2200K
2b: air at 2200K
3a: 100% O_2 no pre-heat
3b: 100% O_2 no pre-heat
4a: 100% O_2 at 922K
4b: 100% O_2 at 922K
5a: 100% O_2 at 922K
5b: 100% O_2 at 922K
6a: 100% O_2 at 922K

Stoichiometry for cases:

1,2,5,6: 0.9 stoic. (fuel rich)
3: 1.0 stoic.

Seeding for cases:

"a": powder K_2CO_3 at 5.4% potassium mass input
"b": 50/50 aqueous solution of K_2CO_3 at 1% potassium mass input
"6a": No seeding



Note: this analysis uses 1978 Itikawa-Pack collisional H20 data set

Analysis: Summary

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

where B is applied magnetic field
σ is gas-plasma conductivity
u is gas-plasma velocity

- Seeded oxy-fuel much higher conductivity then legacy open cycle MHD systems
- Powder seeding offers notable advantage to oxy-fuel MHD over aqueous solution seeding
- Oxy-fuel MHD peak power densities at Mach 2.5 to 3
- Pressure needed to drive flow, but MHD power density decreases with increasing pressure
- Uncertainty in H_2O electron-molecule cross section most significant
- Note: Costs and engineering constraints/considerations often dictate final design specifications
  - E.g. max hall parameter and critical current densities

Simulation: NETL's 1D MHD code

Goal: Develop efficient open source code for general analysis and design of MHD generators

Programming language:
- Python, Numerical libraries use C, C++ and Fortran

Key libraries:
- Cantera – thermodynamics, transport and reactions
- Assimulo – interface for SUNDIALS
- SUNDIALS – DAE integration package from Sandia

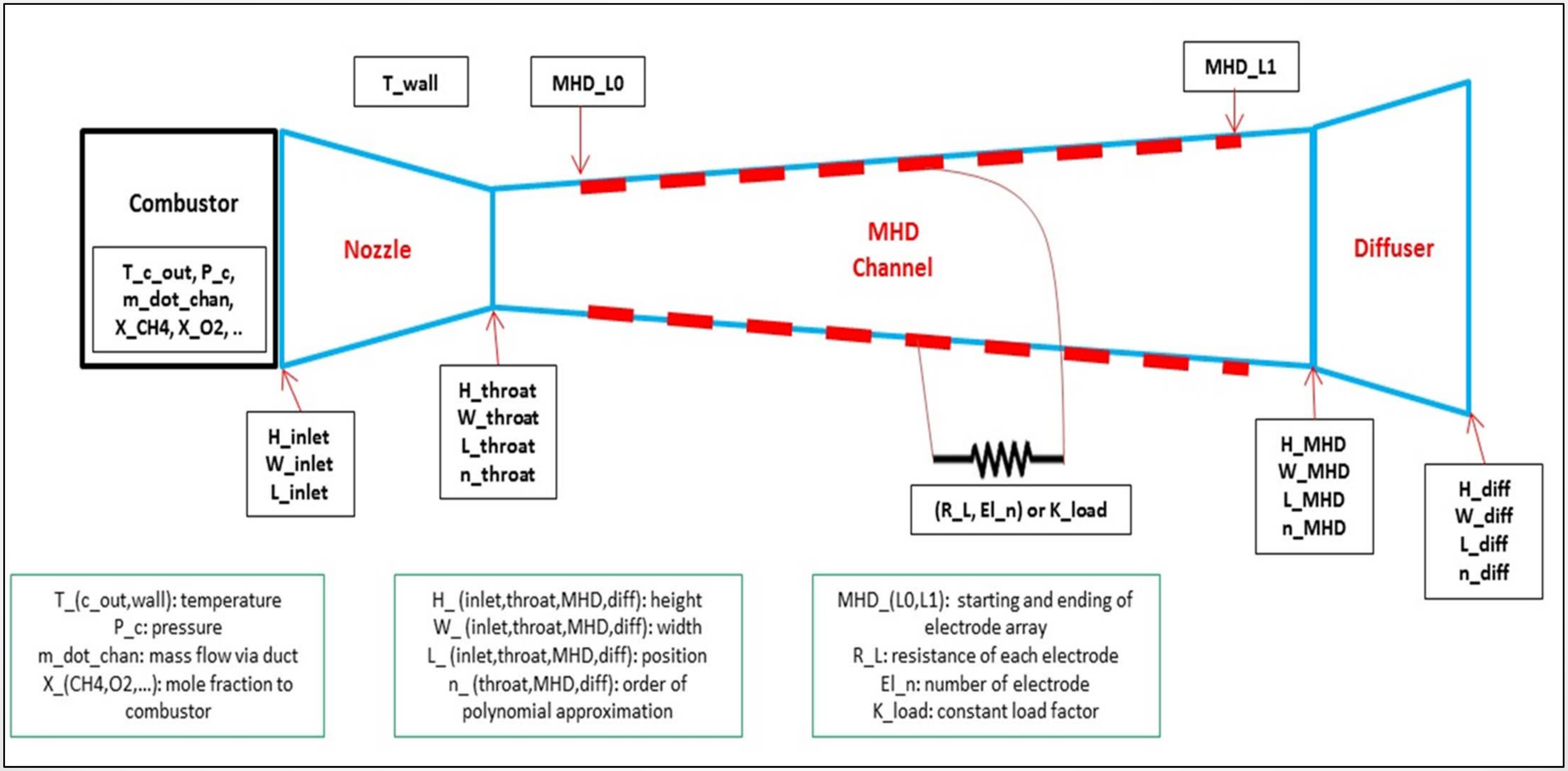


Diagram showing 1D code design variables for MHD Power train simulation

Input excel spreadsheet example

(1) Global parameters

	A	B	C	D	E
1	<Comments>				
2	<File Options>				
3	Output Directory	in_out			
4	Output File	DPE1_out.xls			
5	CrossSectionFile	SpencerPhelps_CrossSection_SEAM1976.csv			
6	GasTransport	drm19_withKOH.cti			
7	GasTransportName	gas			
8	GasThermo	coal.cti			
9	GasThermoName	gas_small_ash			
10	AshThermo	ash.xml			
11	CoalThermo	coal.cti			
12	<ThermoTable>				
13	T_min	2000			
14	T_max	4000			
15	n_T	20			
16	logT	FALSE			
17	P_min	5.00E+02			
18	P_max	5.00E+06			
19	n_P	20			
20	logP	TRUE			
21	LoadThermo	100			
22	Recalulate Thermo	TRUE			
23	filename	thermo_table.npy			
24	<Study Options>				
25	Number	1			
26	<Solver Options>				
27	Chemical Equilibrium	TRUE			
28	Pressure Iteration	FALSE			
29	Fixed Geometry	FALSE			
30	maxCPU	45			

(2) Stream composition

	A	B	C	D
1	<Fuel Coal>			
2	Fuel stream (PRB Coal)			
3	HHV	kJ/kg	25454	
4	FA_mol	kmol/kmol	1	
5	FA_mass	kg/kg	1	
6	Cp	kJ/kg-K	1000	
7	Material	Mass Frac	Mole Fract	MW
8	C	0.6416	0.4834	12.0110
9	H	0.0434	0.3892	1.0079
10	O	0.1411	0.0798	15.9994
11	N	0.0091	0.0059	14.0067
12	Cl	0.0001	0.0000	35.4527
13	S	0.0093	0.0026	32.0660
14	Water	0.0501	0.0251	18.0153
15	SiO2(a-qz)	0.0516	0.0078	60.0843
16	AL2O3(a)	0.0227	0.0020	101.9613
17	CaO(cr)	0.0224	0.0036	56.0774
18	Fe2O3(cr)	0.0087	0.0005	159.6922
19	MgO(cr)	0.0000	0.0000	40.3044
20	TiO2(cr)	0.0000	0.0000	79.8788
21	**Total**	**1.0000**	**1.0000**	**9.0494**
22	**Combust**	**0.8446**	**0.9610**	**-1**
23	**Moisture**	**0.0501**	**0.0251**	**-1**
24	**Ash**	**0.1054**	**0.0139**	**-1**
25	<Oxidizer>			
26	Oxidizer Stream			
27	Material	Mass Frac	Mole Fract	MW
28	O2	0.9474	0.9574	31.9988
29	N2	0.0000	0.0000	28.0135
30	Ar	0.0526	0.0426	39.9480
31	**Total**	**1.0000**	**1.0000**	**32.3373**

(3) Conditions for simulation running

	A	B	C	D	E	F	G	H	I	J	K	L
1	Section	Fuel Coal				Fuel Gas			Oxidizer			
2	Name	Thermal Input	Flow	Flow	Temp	Flow	Flow	Temp	Stoich.	Flow	Flow	Temp
3	Label	Q_fuel	m_dot_F	N_dot_F	T_F	m_dot_G	N_dot_G	T_O	phi	m_dot_O	N_dot_O	T_O
4	Key	Q	mdot	Ndot	T	mdot	Ndot	T	phi	mdot	Ndot	T
5	Units	MWth	kg/s	kmol/s	K	kg/s	kmol/s	K	none	kg/s	kmol/s	K
6	1	1000	39.287	4.341	377	0.000	0.000	300	0.9	71.369	2.207	300
7	2	1000	39.287	4.341	377	0.000	0.000	300	0.9	71.369	2.207	600
8	3	1000	39.287	4.341	377	0.000	0.000	300	0.9	71.369	2.207	800
9	4	1000	39.287	4.341	377	0.000	0.000	300	0.9	71.369	2.207	1089
10	**<End>**											
11	Comments										Update later to include fuel gas	

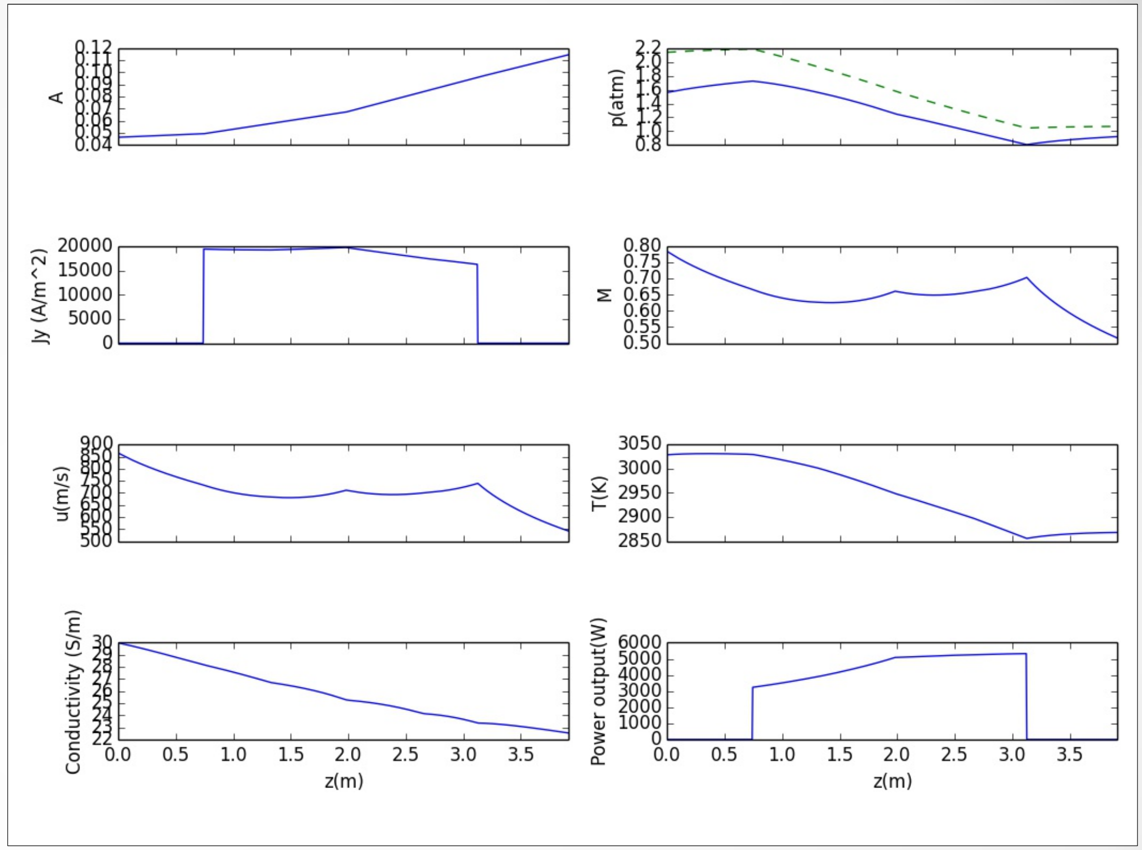
	A	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	Section	Coal Transport				Exhaust Recycle				Seed Input				
2	Name	wt fract	Flow	Flow	Temp	wt fract	Flow	Flow	Temp	K needed	K min	Flow	Flow	Temp
3	Label	Y_transport	m_dot_T	N_dot_T	T_T	Y_R	m_dot_R	N_dot_R	T_R	K_S_rat	K_min	m_dot_S	N_dot_S	T_S
4	Key	gas_to_coa	mdot	Ndot	T	wt	mdot	Ndot	T	seed_to_coa	K_min	mdot	Ndot	T
5	Units	kg/kg	kg/s	kmol/s	K	kg/kg	kg/s	kmol/s	K	kmol/kmol	kg K/kg	kg/s	kmol/s	K
6	1	0.08	3.143	0.073	300	0	0.000	0.000	300	2.8	0.01	0.084	0.003	372
7	2	0.08	3.143	0.073	300	0	0.000	0.000	600	2.8	0.01	0.084	0.003	372
8	3	0.08	3.143	0.073	300	0	0.000	0.000	800	2.8	0.01	0.084	0.003	372
9	4	0.08	3.143	0.073	300	0	0.000	0.000	1089	2.8	0.01	0.084	0.003	372
10	**<End>**													
11	Comments									potassium needed to remove all sulfur from the coal	placeholder for minimum seed mass fraction		Update later for const wt% K seeding	

Running 1D simulation and output

(1) Running 1D simulation

```
Composition of gas is consistent with pre-tabulated gas_table.npy


Starting Channel Simulation With
        T = 3028.75 (K)
        p = 1.55962 (atm)
        M = 0.784351
        rho = 0.157333 (kg/m^3)
        u = 864.891 (m/s)
        sigma = 29.8632 (S/m)


Final Run Statistics: ---

 Number of Steps                          : 310
 Number of Function Evaluations           : 614
 Number of Jacobian Evaluations           : 169
 Number of F-Eval During Jac-Eval         : 1014
 Number of Root Evaluations               : 311
 Number of Error Test Failures            : 64
 Number of Newton Iterations              : 614
 Number of Newton Convergence Failures    : 0
 Number of State-Events                   : 0

Solver options:

 Solver                 : IDA (BDF)
 Maxord                 : 5
 Suppress Alg           : False
 Tolerances (absolute)  : [  1.00000000e-06   1.00000000e-06   1.00000000e-06   1.00000000e-06
   1.00000000e-06   1.00000000e-06]
 Tolerances (relative)  : 1e-06

Simulation interval    : 0.0 - 3.915 seconds.
Elapsed simulation time: 10.82 seconds.
The success = True
Heat flux =  -5520.652272 kW
Electric power output =  -2241.35380986 kW
Total power output =  -7762.00608186 kW
Joule heating =  2240.75929043 kW
1st energy balance =  3.7071263067 kW
There is no transonic point.
mass flow: inlet =  6.31390e+00, outlet =  6.31434e+00
Power difference =  -7765.71320817 kW
```

(2) Brief simulation result



(3) Output excel spreadsheet containing all numerical data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1		x	A	rho	u	p	T	theta	h	M	c	gamma	c_p	sigma
2	units	m	m^2	kg/m^3	m/s	Pa	K	m	J/kg	none	m/s	none	J/kg-K	S/m
3	0	0	0.645059	1.837938	98.97297	1800000	3330.55	0	-1877046	0.090909	1088.703	1.210255	1694.807	19.95832
4	1	0.1	0.484843	1.832029	132.0803	1792960	3329.057	0	-1883257	0.121364	1088.302	1.21021	1694.786	19.94533
5	2	0.2	0.389327	1.824377	165.1497	1783944	3327.212	0	-1890801	0.151818	1087.812	1.210155	1694.759	19.93193
6	3	0.3	0.326295	1.814991	198.1734	1772977	3325.02	0	-1899641	0.182273	1087.236	1.210093	1694.726	19.91755
7	4	0.4	0.281464	1.80389	231.1442	1760096	3322.49	0	-1909744	0.212727	1086.575	1.210022	1694.685	19.90137
8	5	0.5	0.247639	1.791096	264.0553	1745344	3319.627	0	-1921080	0.243182	1085.835	1.209944	1694.638	19.88233
9	6	0.6	0.222384	1.776638	296.9001	1728772	3316.438	0	-1933622	0.273636	1085.017	1.209858	1694.582	19.85923

Simulation: 1D MHD code equations

Numerical methods: Governing equations solved as an initial value problem given the inlet conditions. The equations are a DAE (differential algebraic equation) system.

$$\frac{d}{dx}(\rho u A) = 0$$

$$\rho u \frac{dY_k}{dx} = R_k W_k$$

$$\rho u \frac{du}{dx} + \frac{dP}{dx} = J_y B_z - F_{friction}$$

$$\rho u \left(u \frac{du}{dx} + \frac{dh}{dx} \right) = (J_y E_y + J_x E_x) - Q_{wall}$$

$$\frac{d\theta}{dx} + \frac{\theta}{u}\frac{du}{dx}\left(2 + \frac{\delta^*}{\theta} - M^2 \right) = \frac{1}{2} C_f$$

$$J_y = \frac{\sigma}{1+(\omega\tau)^2}\left[\left(E_y - uB_z \right) + \omega\tau E_x \right]$$

$$J_x = \frac{\sigma}{1+(\omega\tau)^2}\left[E_x - \omega\tau \left(E_y - uB_z \right) \right]$$

- 5 main equations (**mass**, **momentum**, **energy**, **chemical reaction**, **boundary layer**) for the flow state.
- 2 equations (generalized Ohm's law) for the EM field.
- Need two additional equations.
  - Electrode Configuration
  - External Load

Segmented Faraday linear :

$$J_x = 0 \quad \Rightarrow \quad \begin{cases} E_x = \omega\tau (E_y - uB_z) \\ J_y = \sigma (E_y - uB_z) \end{cases}$$

Fixed Load Resistance : R_L

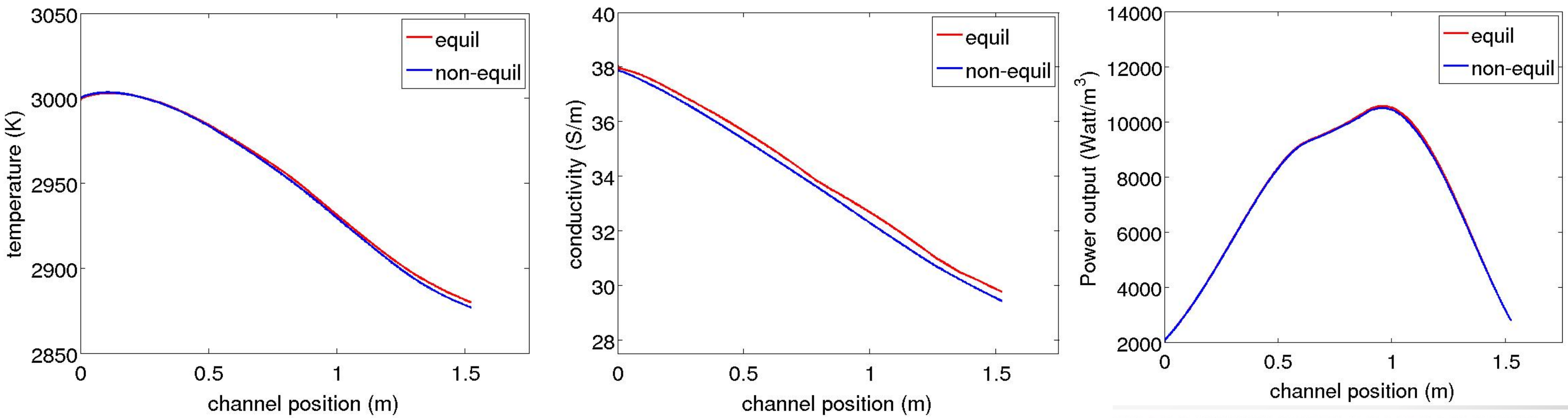
$$K \equiv \frac{E_y}{uB_z} \quad \Rightarrow \quad K = \frac{\sigma}{\sigma + \sigma_L} = \frac{R_L}{R + R_L}$$

$$E_y = KuB_z$$

Simulation: Reaction/Composition Models

Species concentration are in flux due to recombinations. Non-equilibrium considered.

- **Thermophysical model is for hydrocarbon products seeded with potassium.**
  - DRM19 - methane oxidation mechanism reduced from GRI30 Mech
  - Interaction of K w/ combustion products
  - K ionization products and reaction equations
  - *"Coal" model (equilibrium only) includes condensed and non-condensed ash-species*
- **Equilibrium Model:**
  - composition is in local thermodynamic equilibrium but still changes as the temperature and pressure change in the channel.
  - composition and thermophysical properties are pre-tabulated functions of temperature & pressure
  - code runs faster due to reduced number of equations (4 vs. 4 + N_species)
  - reaction rates are not required to perform simulations
- **Non-Equilibrium Model:**
  - Explicitly track balance between the rates of convection, production and destruction of individual species.
  - Better estimates of unburnt fuel and electron attachment may not that critical for energy performance estimates



Simulation: 1D MHD code equations

Numerical methods: Governing equations solved as an initial value problem given the inlet conditions. The equations are a DAE (differential algebraic equation) system.

$$\frac{d}{dx}(\rho u A) = 0$$

$$\rho u \frac{dY_k}{dx} = R_k W_k$$

$$\rho u \frac{du}{dx} + \frac{dP}{dx} = J_y B_z - F_{friction}$$

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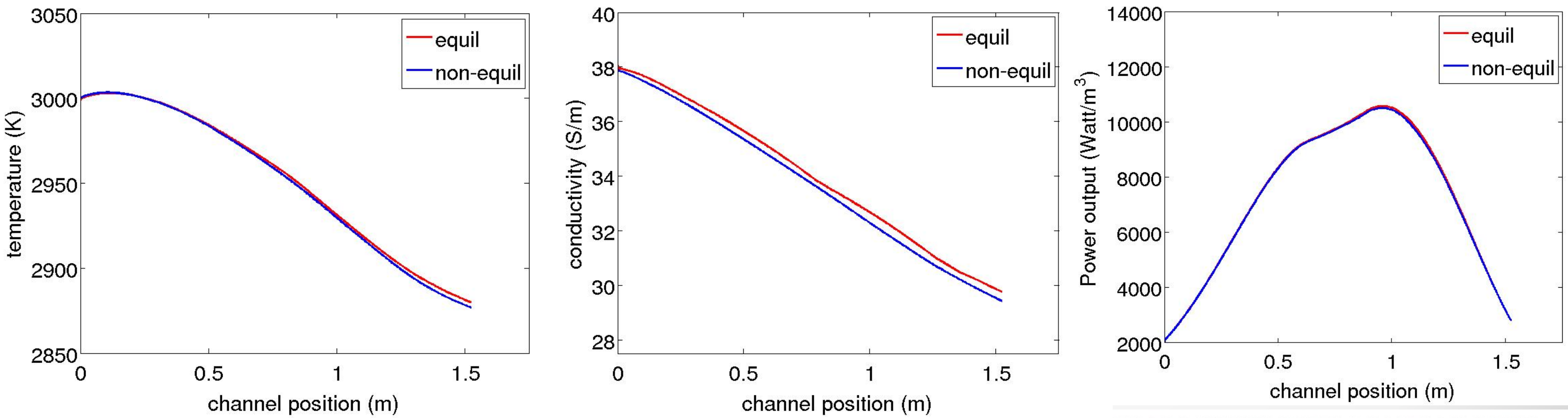
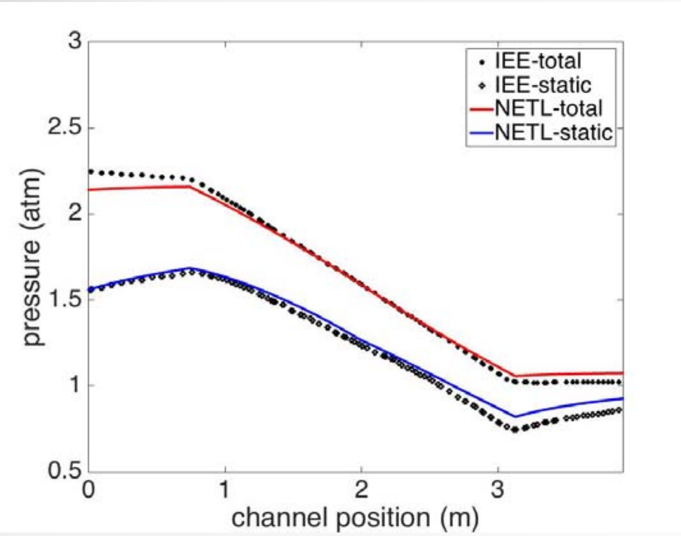
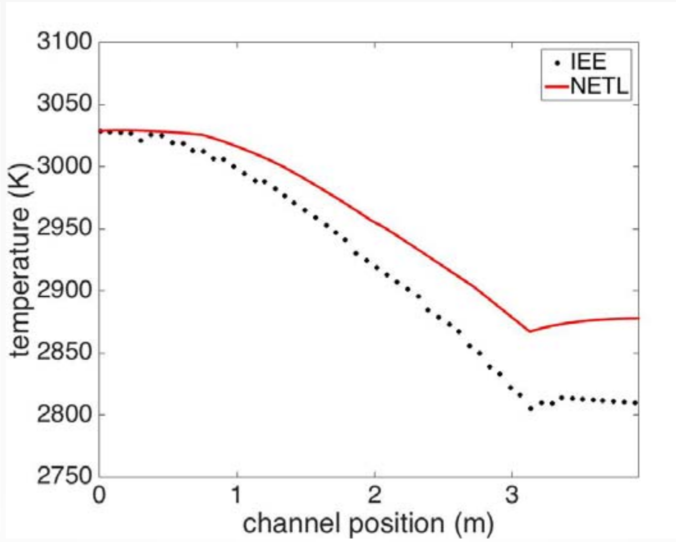
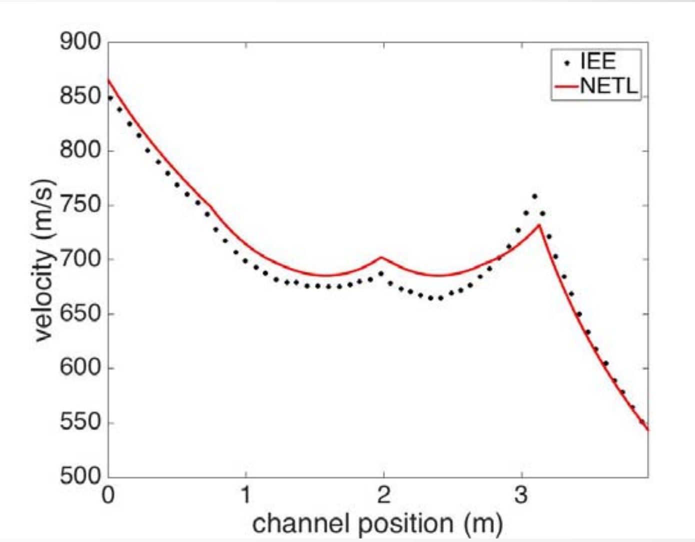


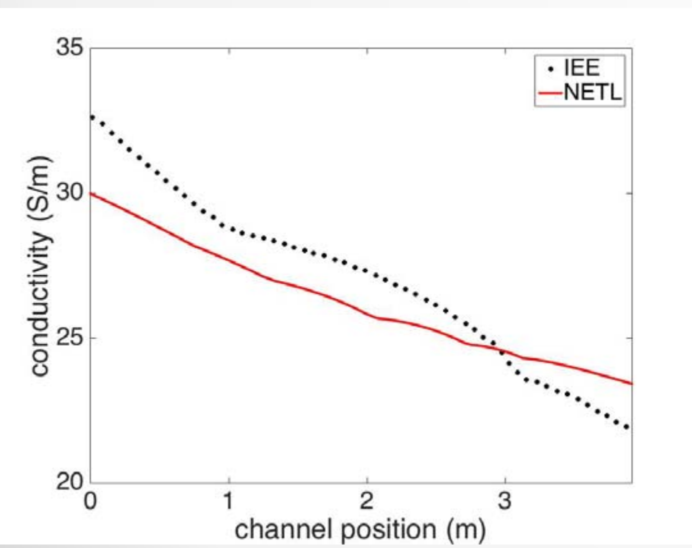
Simulation: 1D code verification

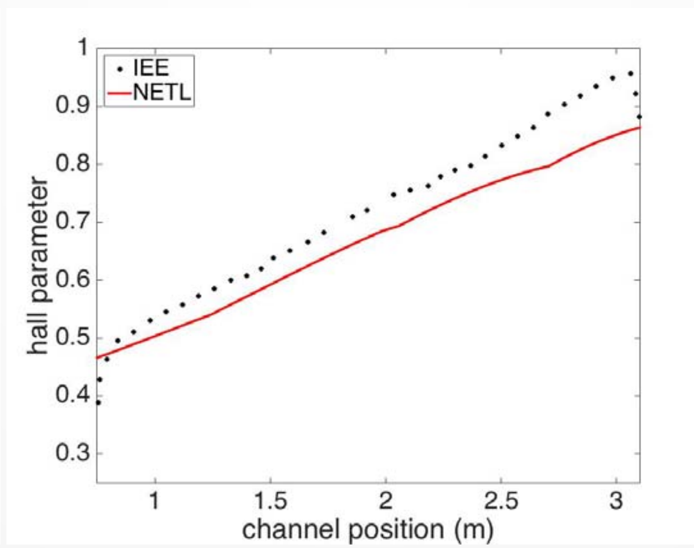
IEE Mark-II: theoretical simulation work by UTSI & IEE in 1987











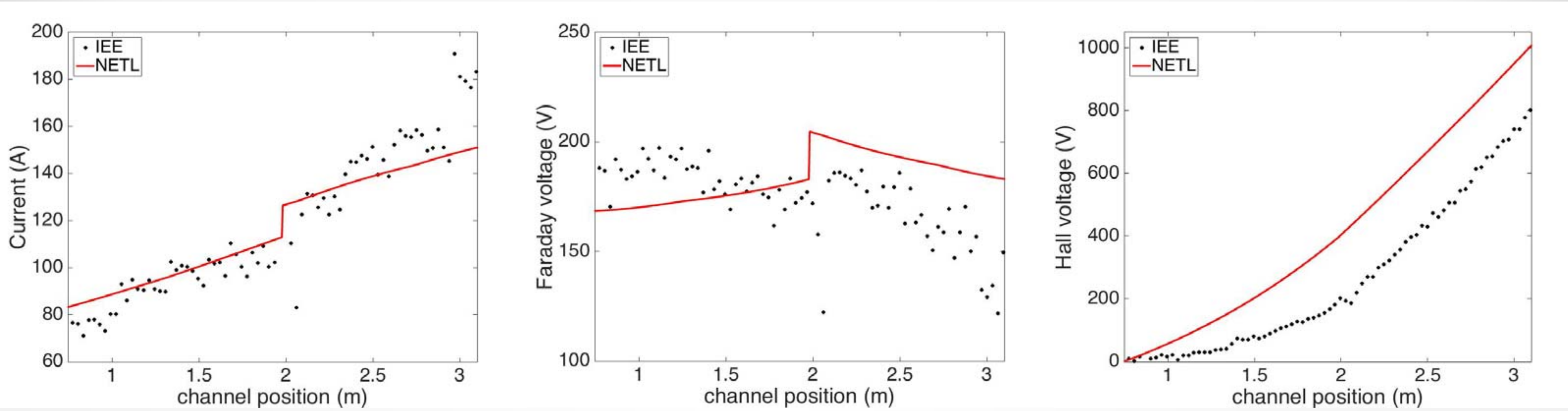
On-going MHD channel simulation work:

- Incorporating boundary voltage layer drop into model
- Running coal case for OPPB systems study
- Consider other channel geometries
- Supersonic channel case validation

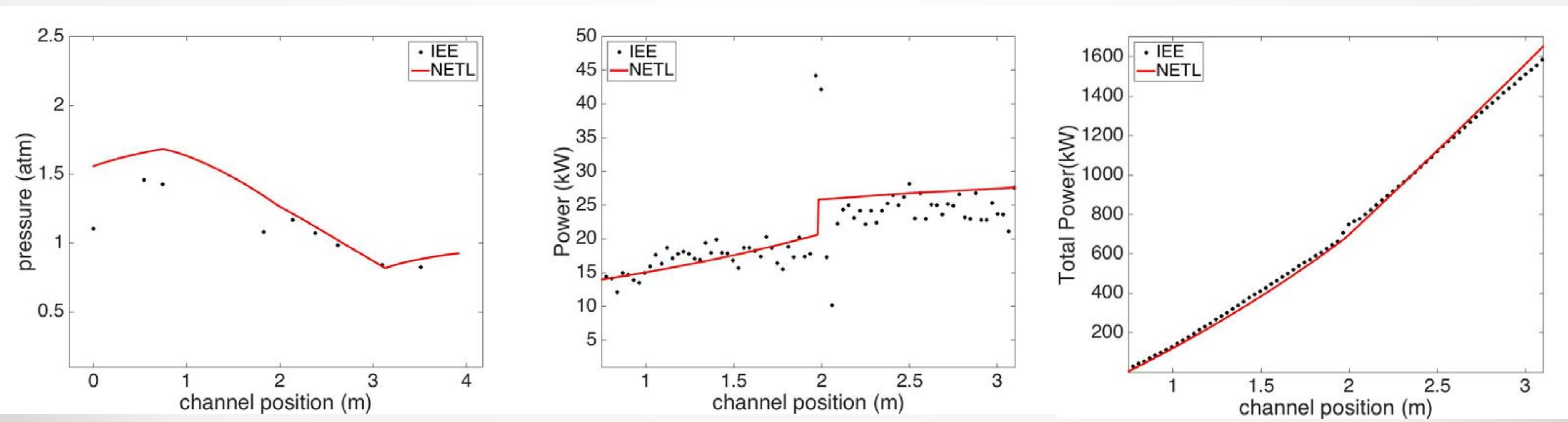
* Ref: Lineberry et al., AIAA-87-1214, 1987, U.S. – China Cooperative MHD Experiments at IEE Academia Sinica

Simulation: 1D code validation

IEE Mark-II: subsonic MHD channel testing from late 1980s*



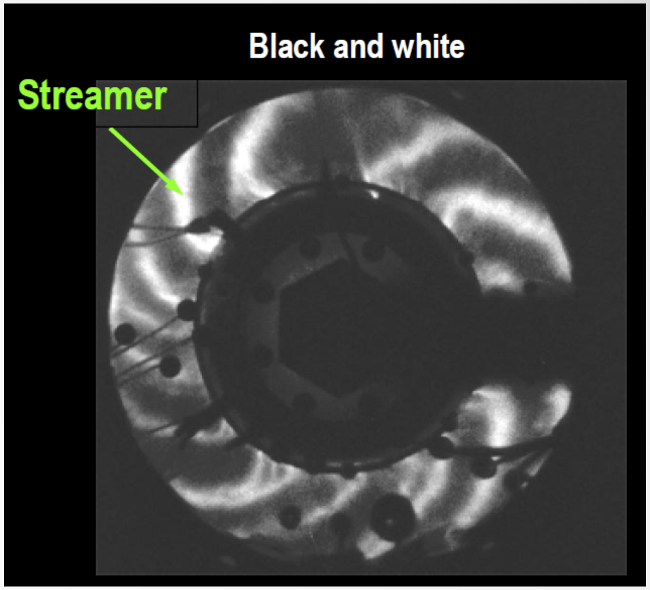
Simulation results are consistent with experimental data obtained.



* Ref: Lineberry et al., AIAA-87-1214, 1987, U.S. – China Cooperative MHD Experiments at IEE Academia Sinica

Simulation: Toward detecting arcs

We are interested in detecting arcs (or streamers) by measuring the magnetic fields they induce. We therefore wish to model these magnetic fields which may be observable outside the channel.



Tokyo Tech disc generator*
showing arcs ("streamers") in channel

Forward Model and Computation

- Assume magnetostatic equations applicable
- Utilize NETL1D MHD code for fluid & state conditions
- Assumes Induced field << applied field (B_0)

$$\nabla \cdot \epsilon \mathbf{E} = \rho_c \qquad \text{(Gauss' Law)}$$

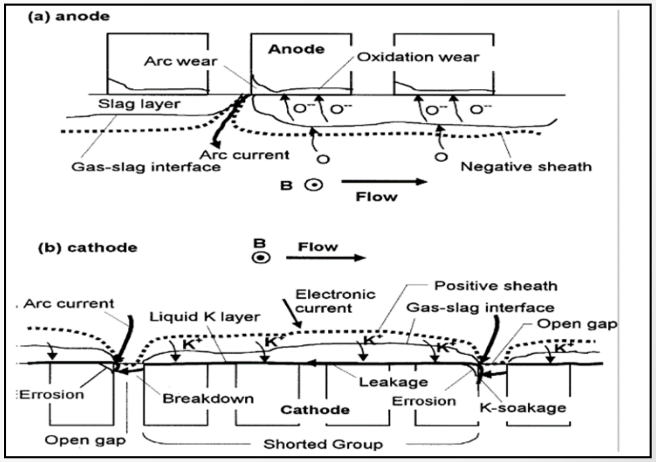
$$\nabla \times \mathbf{E} = 0 \qquad \text{(Faraday's Law)}$$

$$\nabla \cdot \mathbf{b} = 0 \qquad \text{(Gauss' Law for Magnetism)}$$

$$\nabla \times \mu^{-1} \mathbf{b} = \mathbf{J} \qquad \text{(Ampere's Law)}$$

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}_0) + \nu \mathbf{J} \times \mathbf{B}_0 \qquad \text{(Generalized Ohm's Law)}$$

$\mathbf{B}_0$	applied magnetic flux density	$\mathbf{E}$	electric field
$\mathbf{b}$	induced magnetic flux density	$\mathbf{J}$	current density
$\mathbf{u}$	fluid velocity	ρ_c	charge density
ϵ	electrical permitivity	μ	magnetic permeability
ν	electron mobility	σ	electrical conductivity



Arcing is known to be a major
problem for MHD channel materials**

*Source: Okuno Presentation (2007)

**Source: kayukawa (2003).

Simulation: 3D MHD Currents

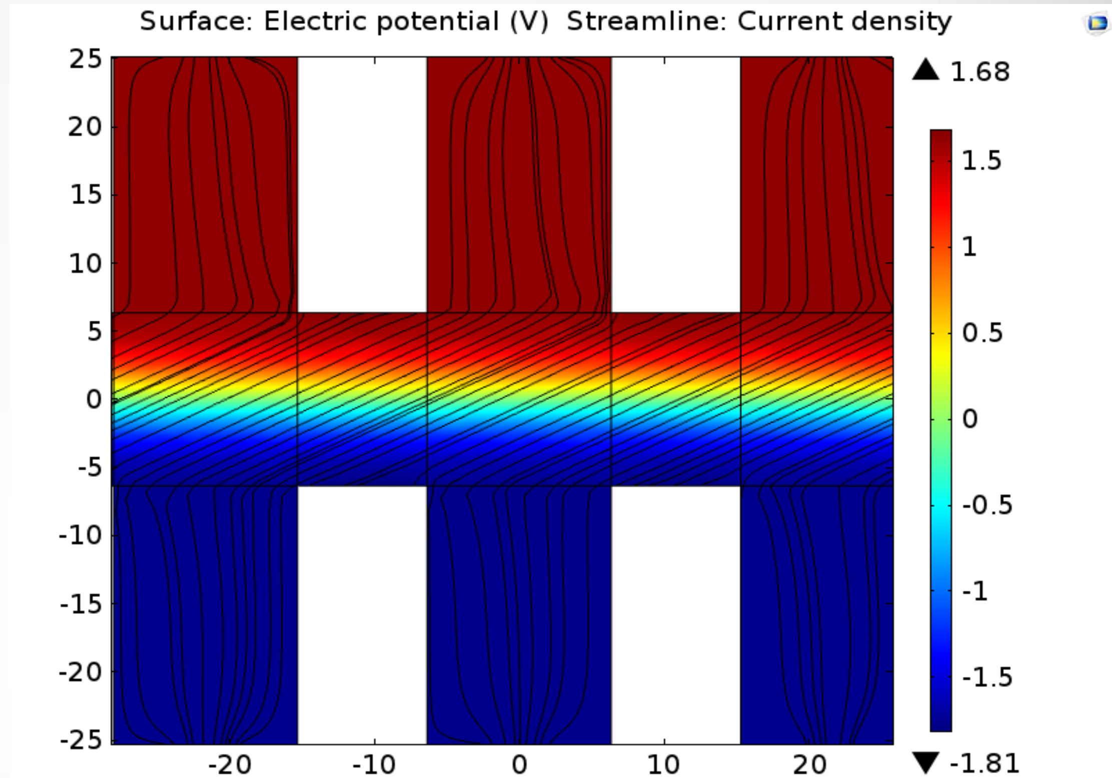
Magnetostatic MHD current

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}_0) + \mathbf{J} \times \beta$$
$$\nabla \cdot \mathbf{J} = 0$$
$$\mathbf{E} - \nabla V = 0$$

Equivalent to

$$\underline{\sigma} = \frac{\sigma}{1+\beta^2} \begin{pmatrix} 1 & \beta & 0 \\ -\beta & 1 & 0 \\ 0 & 0 & 1+\beta^2 \end{pmatrix}$$

$$\nabla \cdot \underline{\sigma}\mathbf{E} = -\nabla \cdot \underline{\sigma}\mathbf{u} \times \mathbf{B}_0$$
$$\mathbf{E} - \nabla V = 0$$



This can be solved for using standard PDE based FEM (eg Comsol).

β	$= \nu \mathbf{B}_0$	$\beta = \lvert\beta\rvert$	Hall parameter
$\underline{\sigma}$	effective conductivity	V	Voltage

The interesting aspect of MHD currents is they are not necessarily perpendicular to electric field gradient

Future work: Inverse problem theory and application based on forward simulation

Channel Materials Selection & Design

MHD Electrode Requirements

1. Good electrical conductivity
2. Adequate thermal conductivity
2. Resistance to electrochemical corrosion (seed/slag)
3. Resistance to erosion by high velocity particle laden flow
4. Resistance to thermal shock
5. Compatibility with other system materials
6. Resistance to/minimization of arc attack

Candidate Hot Electrodes Fabricated

1) **$La_{0.95}Mg_{0.05}CrO_3$**
identified as promising from 1970s USSR-USA work

2) **88% ZrO_2 – 12% Y_2O_3**
baseline from 1970s USSR-USA joint work

3) **89% ZrO_2 – 10% Sc_2O_3 – 1% Y_2O_3**
well characterized for fuel cells

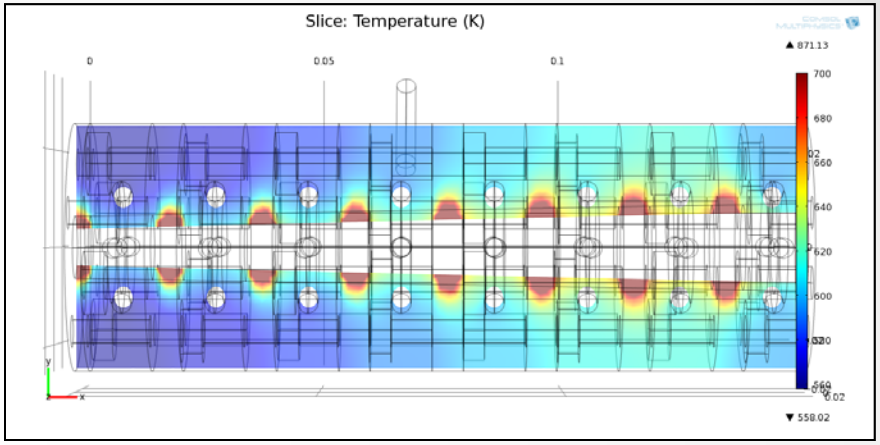
4) **82% HfO_2 – 10% CeO_2 – 8% Y_2O_3**
identified as promising from 1970s USSR-USA work

5) **83% HfO_2 – 17% In_2O_3**
PNNL selection from late 1980s but untested

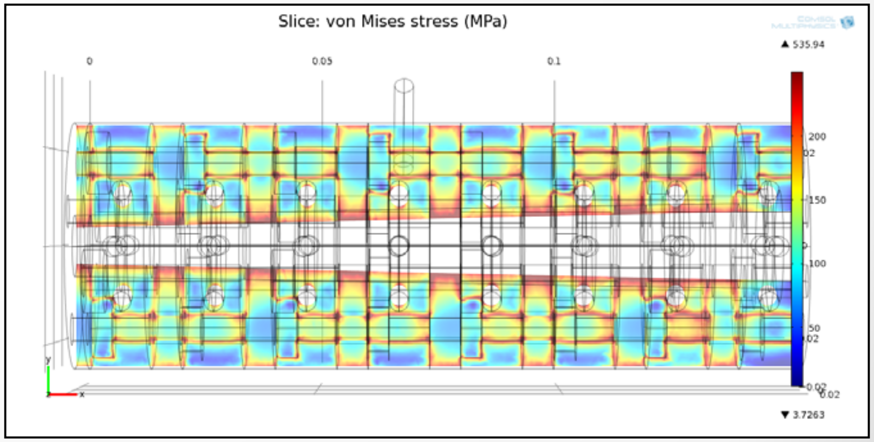
- Oxide powders generated using co-precipitation
- Samples fabricated via both “spark plasma sintering” (SPS) and pressureless sintering.

Fabricated sample goal: Establish baseline characterizations for hot electrodes using known materials

NETL Thermo-mechanical FEM Analysis of 1MWt round copper electrode MHD Channel



FEM Highlights problems due to CTE mismatches and mechanical fastening



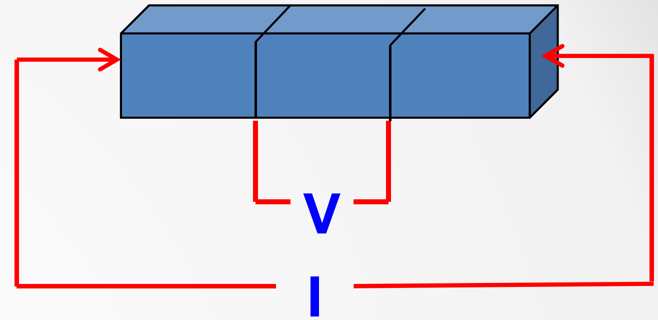
Stress concentrations in ceramic insulators can cause failure

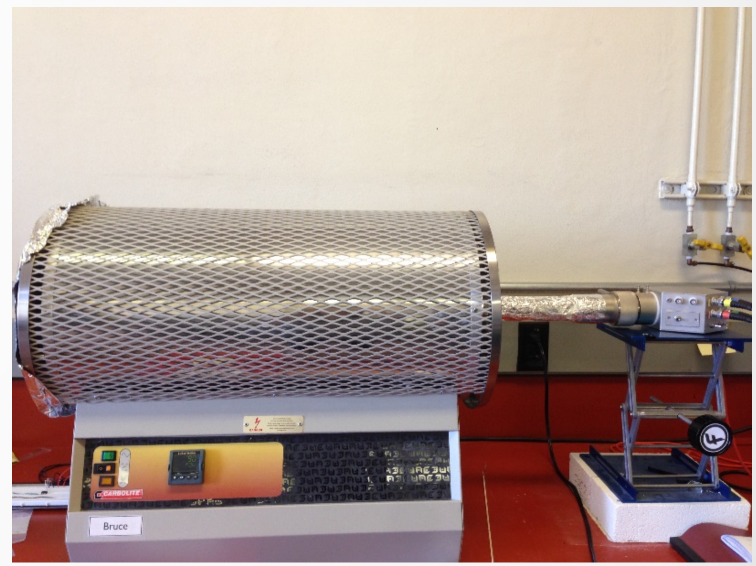
Electrical resistivity measurements

- Measurements taken with 4-wire approach
  - DC resistivity
  - AC resistivity (impedance spectroscopy)
    - 1Hz- 5 MHz

- **4 pressureless sintered compositions tested converged to resistivity values on order of 20 to 40 Ω-cm at 900°C**
  - Comparable to existing literature values (with T extrapolation)
- **All samples exhibited contact resistance due to Pt electrodes**
  - Will be a consideration in the design of MHD systems
  - In addition, non-Ohmic behavior was seen in some samples
  - Could be due to work function mismatch or electrode/ceramic reactions
- **All samples showed grain/grain boundary mechanisms**
  - Electrically heterogeneous – oxygen non-stoichiometry

- On-going work:
  - Compare to SPS samples (preliminary results show some differences)
  - Increase testing temperature
    - Note resistivity very sensitive to T

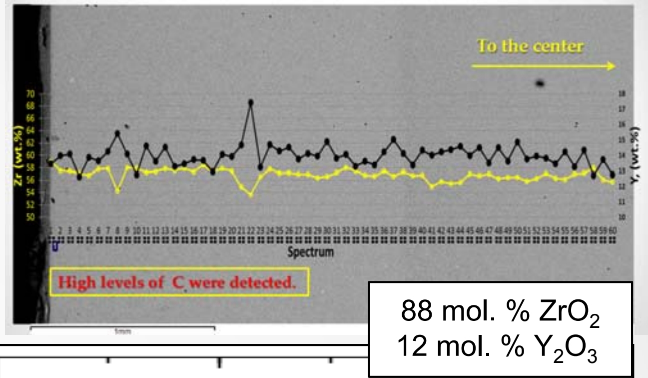


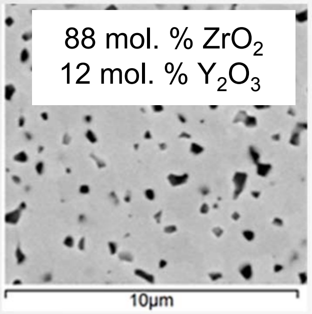


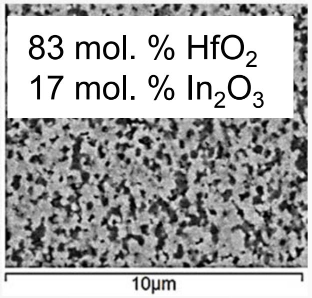
- **High temperature cell NorECs Probostat in Carbolite tube furnace**

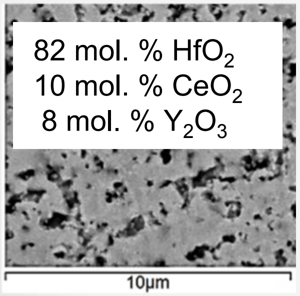
Microstructure & Phase Analysis of SPS Samples

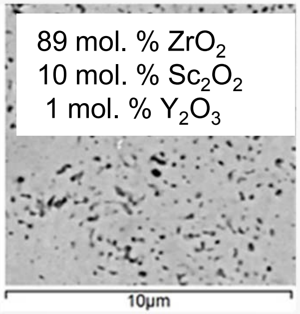
- **SEM imaging of microstructure**
  - SEM-EDS for surface chemistry profiling
- **XRF for bulk chem. and XRD for phase identification**
- **Optical Microscopy for surface analysis**

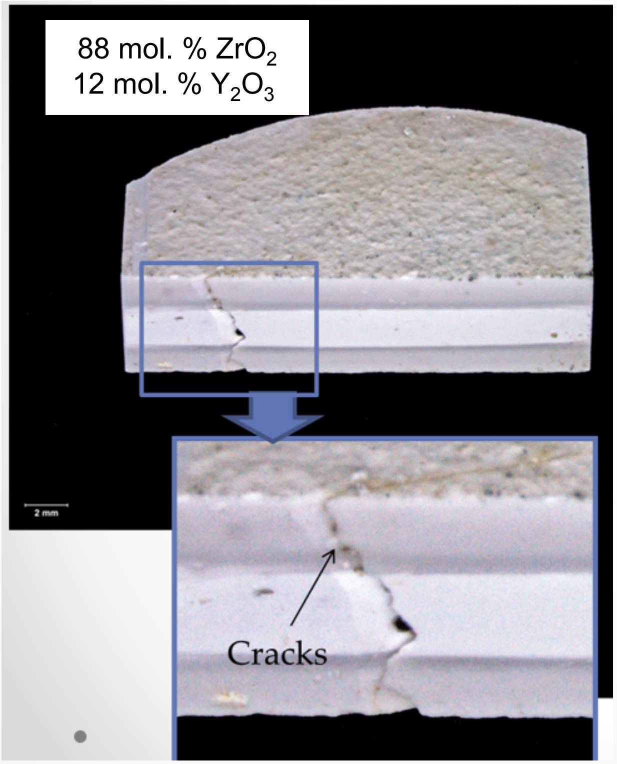


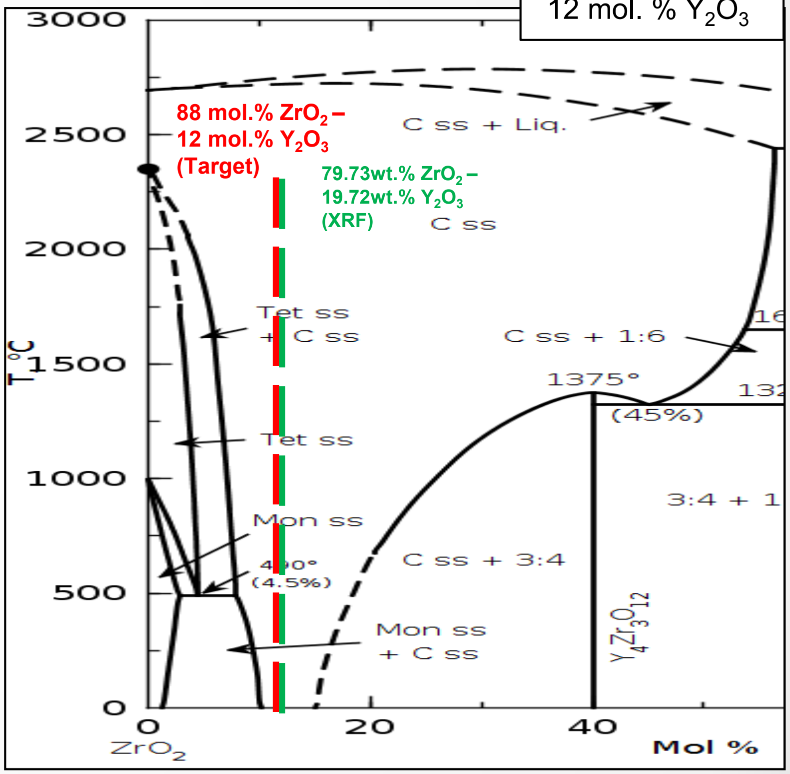








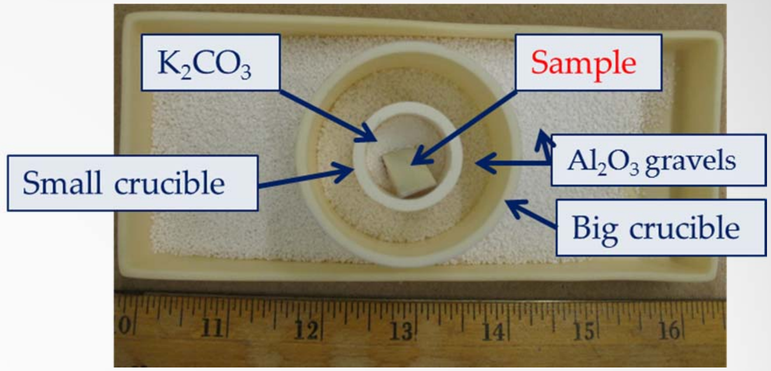




- SPS samples had numerous cracks -> processing far from optimized
- Carbon contamination likely from SPS system (coloration above) -> could be causing issues
- Microstructure suggests high porosity which varies through cross section -> may be related to carbon
- 12%YSZ single phase -> multiple phases in others due to powder prep. and/or sintering issues

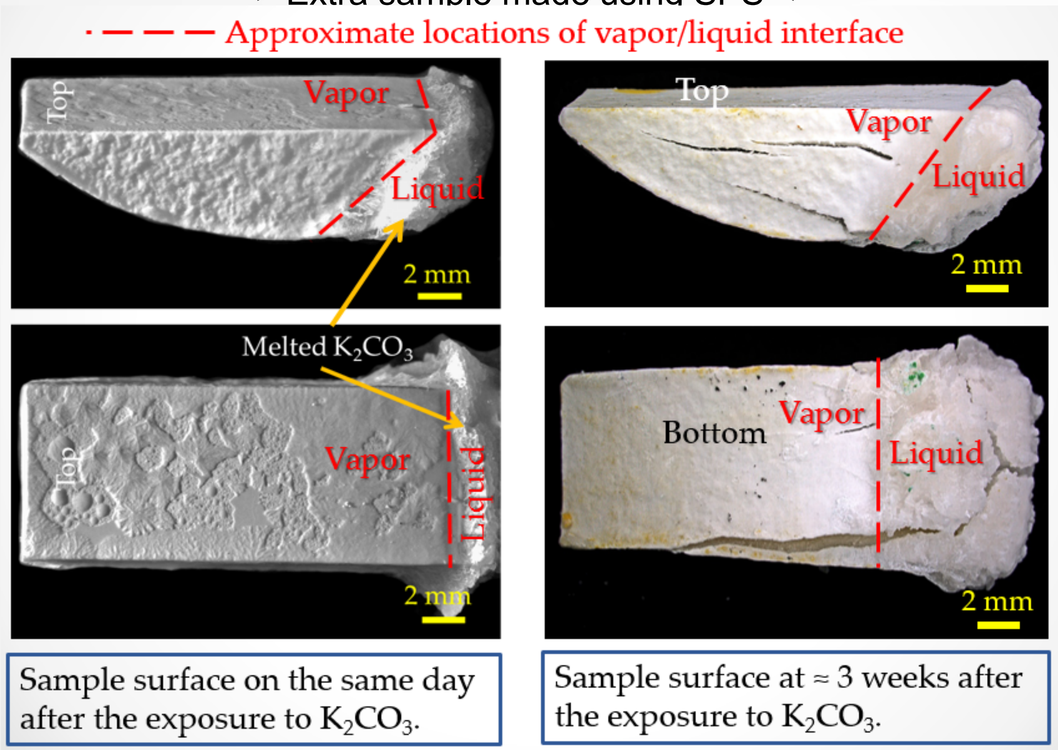
Seed Material Interaction with Samples

- **Expose samples to K_2CO_3**
  - Based on ASTM test C987
  - 24 hrs at 1500°C in air (semi-closed w. lid)



Exposure of 92% ZrO_2 – 8% Y_2O_3

-> Extra sample made using SPS <-



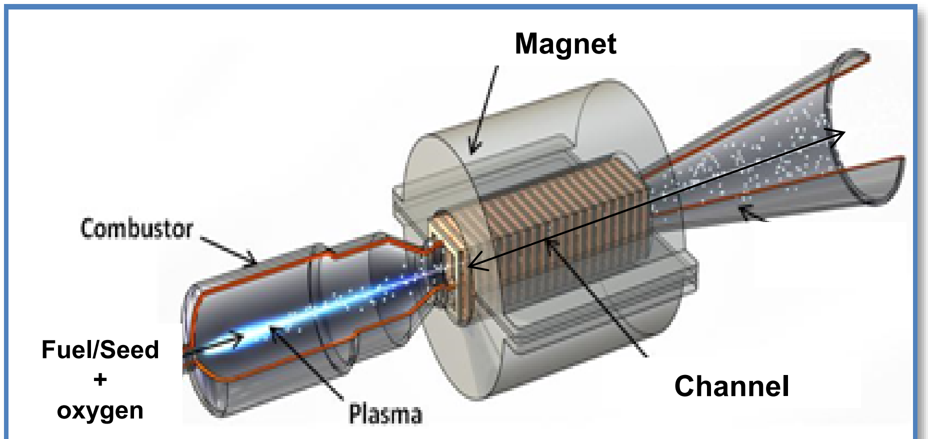
Optical (above) and SEM of cross sections indicate potassium penetration and interaction leading to a degradation of material

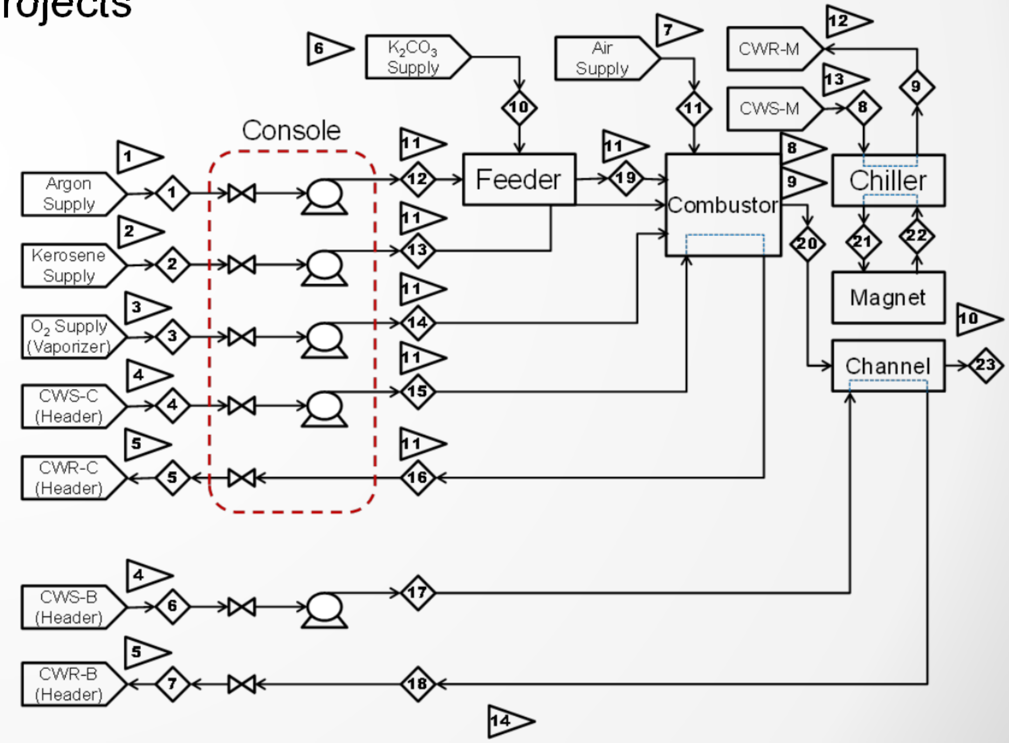
Future work:
Utilize Yonejkura "hot stage" Confocal scanning laser microscope (Olympus)

NETL MHD Laboratory

Under construction: 7/10/2015 scheduled completion date

- **Lab goal: Build "Test bed" for simulation validation and MHD materials performance and durability studies**
  - System flexibility is important
  - leverage existing commercial equipment/knowledge to extent possible
  - Incremental Design/R&D approach
  - Low "TRL" level: not doing demonstration projects





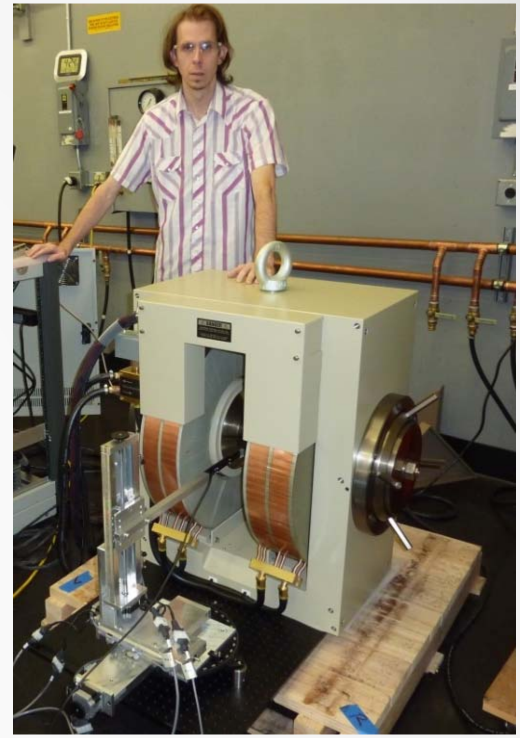
Initial Conditions:

Fuel: K-1 kerosene
Oxidant: 100% oxygen
Seed: K2CO3 powder w/ argon

Nominal 1 MWt sized system is target

MHD Laboratory Equipment

- **Major Test Hardware**
  - TAFA 8200 console, powder feeder, and HVOF combustor
    - Up to 10 bar combustion
    - Nominal Mach 1.8 output
    - Up to 0.5 MWt through console
  - GMW custom electromagnet
    - Adjustable 2 Tesla field at ~50mm gap
    - Adjustable pole caps with optical access
  - Up to 12,000 cfm bag house and blower
  - 150 GPM at 70F delta chiller
  - 248nm Excimer laser
  - Up to 10,000 cfm liquid oxygen vaporizer
  - 20'L x 12'W sound insulated test chamber



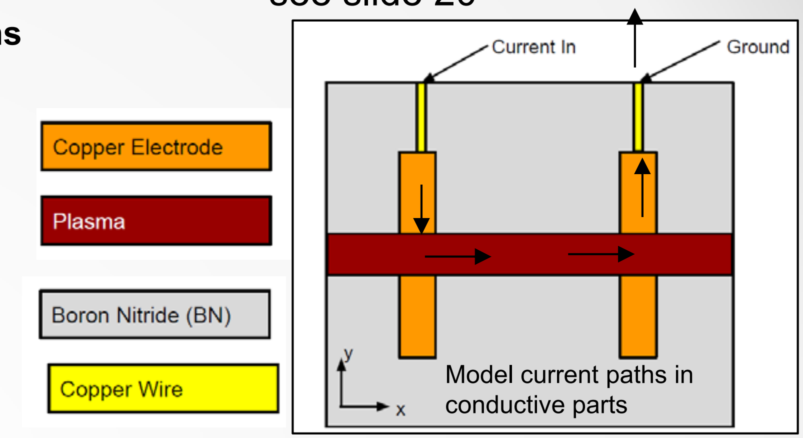
Lab electromagnet

High efficiency HVOF combustor

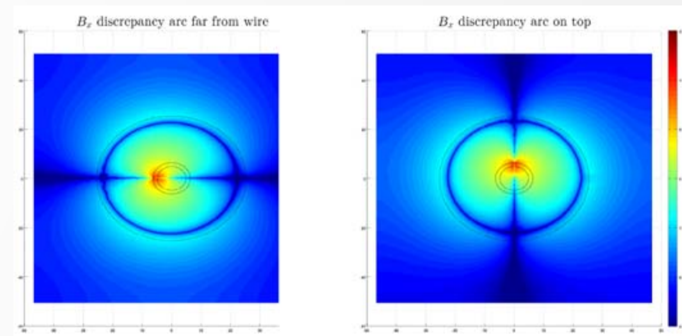
Planned Experiment: Back-powered channel

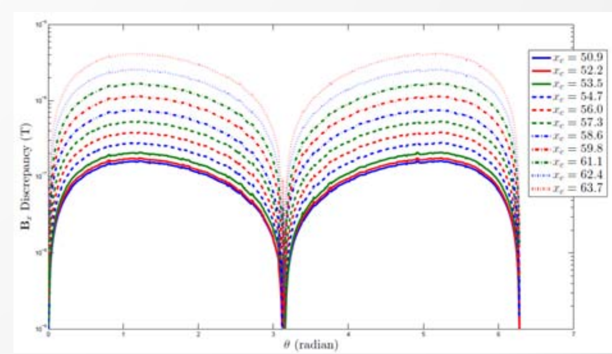
- **HVOF powered circular hall channel -> power supply controls current into channel**
  - No magnetic field in this test
- **Establish effective plasma conductivity using various insulator lengths**
- **Establish spatial and temporal arc characteristics in channel**

FEM electromagnetic model -> see slide 20



Arcs location causes spatially varying mag fields.





Commercial sensors measure these induced fields nT to μT

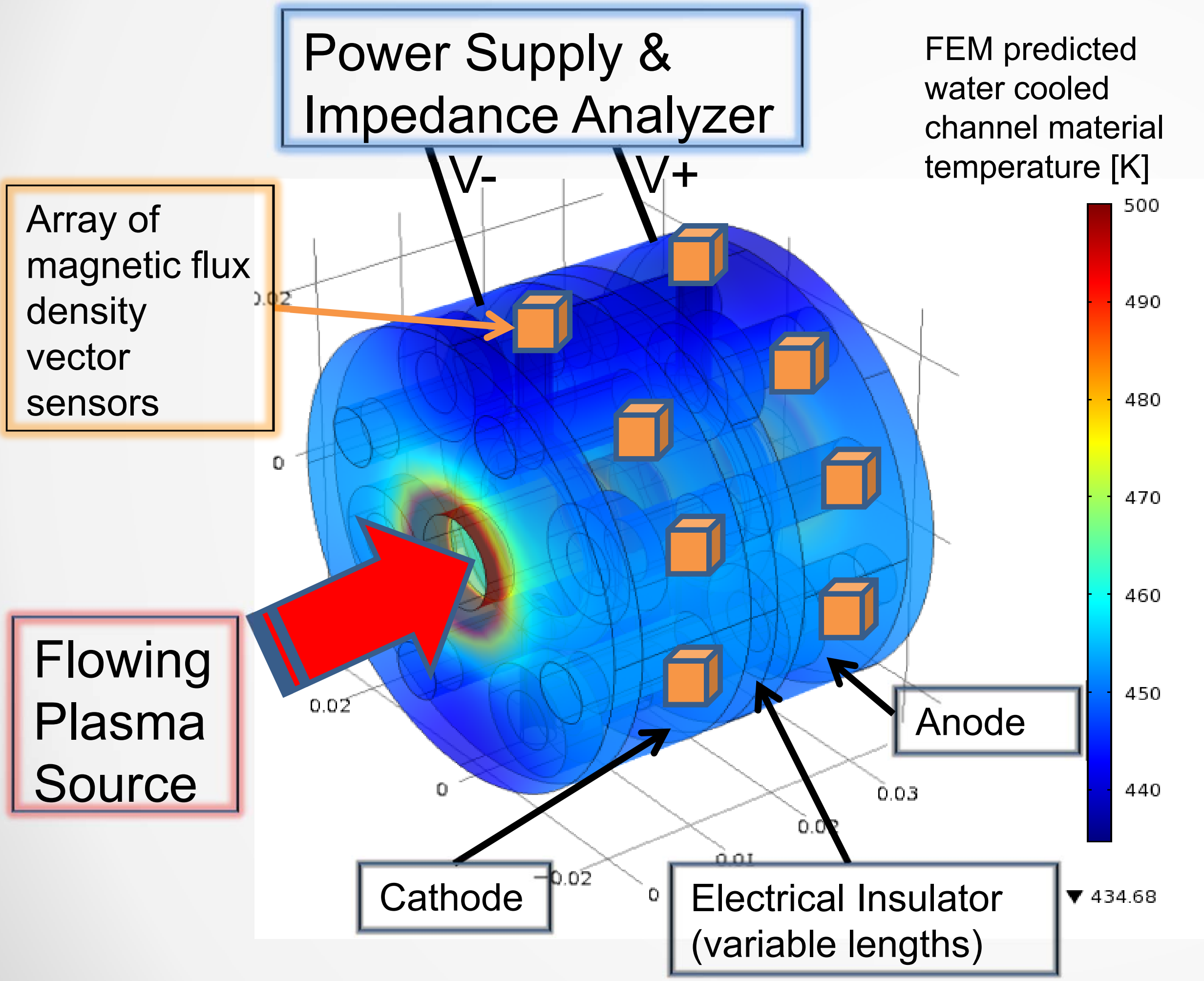
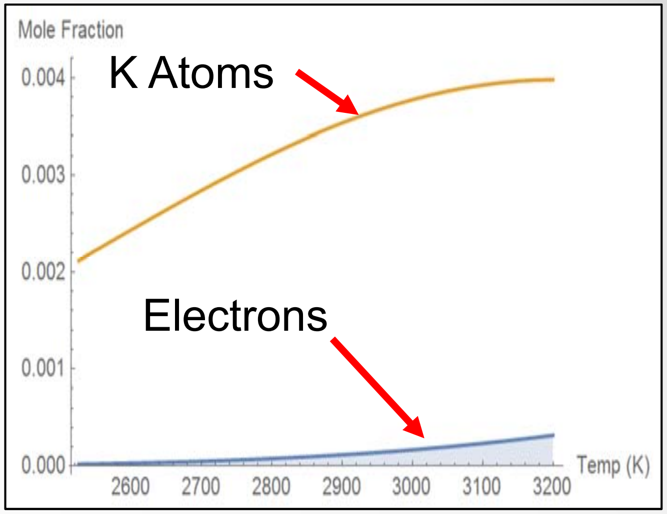


Figure showing concept of experiment

Experimental: Photoionization

What we know:

- **Combustion driven MHD plasma is a partially ionized system which rapidly reaches thermal equilibrium**
  - Very little seed introduced actually ionizes (~1% of it)
  - Ionization rapidly drops as temp decreases-> limits low temp. of cycle (MHD open cycle low temp: ~ 2200 to 2500K)
  - However, local non-equilibrium likely persists near wall due to large gradient and arcing
- **Ionization potential of K is 4.34 eV**
  - So "photoionization" of potassium using UV photons < 285nm
- **Good spatial and temporal control of directed energy with lasers**

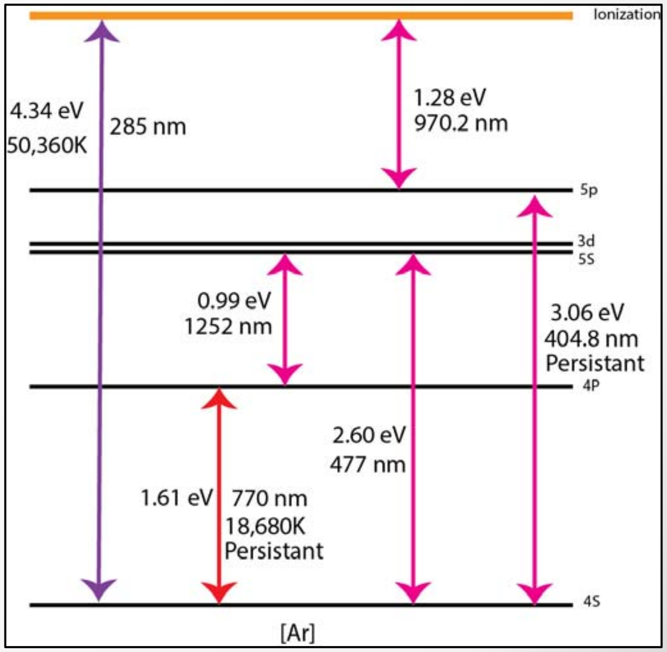


What we would like it to do:

1. **Apply directed laser sheet across electrode surfaces**
   To control and mitigate arcing issues
2. **Apply laser beam to enhance ionize within a MHD channel**
   Decrease seed use
   Extend low temperature

Initial Experiment:

- **Flash potassium seeded HVOF combustion products with Excimer laser (248nm)**
  - Measure absorption
  - Measure relaxation time scales



Electron transitions for K

Group Publications (last 9 months)

- Kim, Hyoungkeun et.al.; "Numerical modeling and simulation of magnetohydrodynamic generators", 2014 APS meeting.
- McGregor, Duncan et. al.; "Towards Estimating Current Densities in Magnetohydrodynamic Generators", 2014 CCP Proceedings.
- Ochs, Thomas et al.; "Improvements in Exergetic Efficiency in High-Temperature Oxyfuel Combined Cycle Systems", Paper and Presentation at 2014 PCC conference.
- Woodside, Rigel; "Retrospective and Prospective Aspects of MHD Power Generation", Presentation at MHD workshop, 10/01/2014.
- Woodside, Rigel et.al.; "MHD Energy Conversion R&D", Poster and Presentation of NETL MHD R&D at MHD Workshop, 10/02/2014.

Questions?