The Ultimate Heat Engine: Direct Power Extraction --- Episode 1: The Quest Begins

NETL – Research and Innovation Center
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Talk Outline

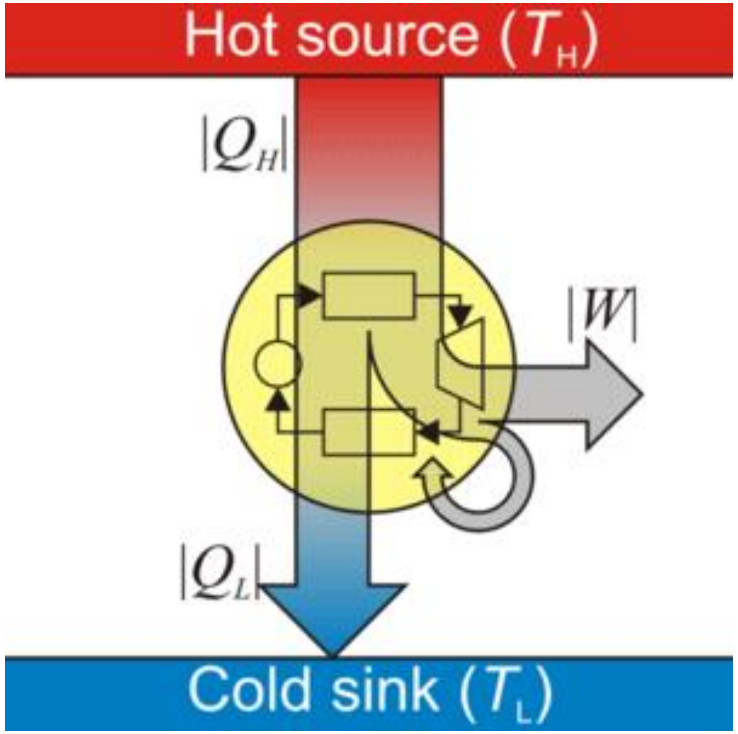
Today's Learning Menu

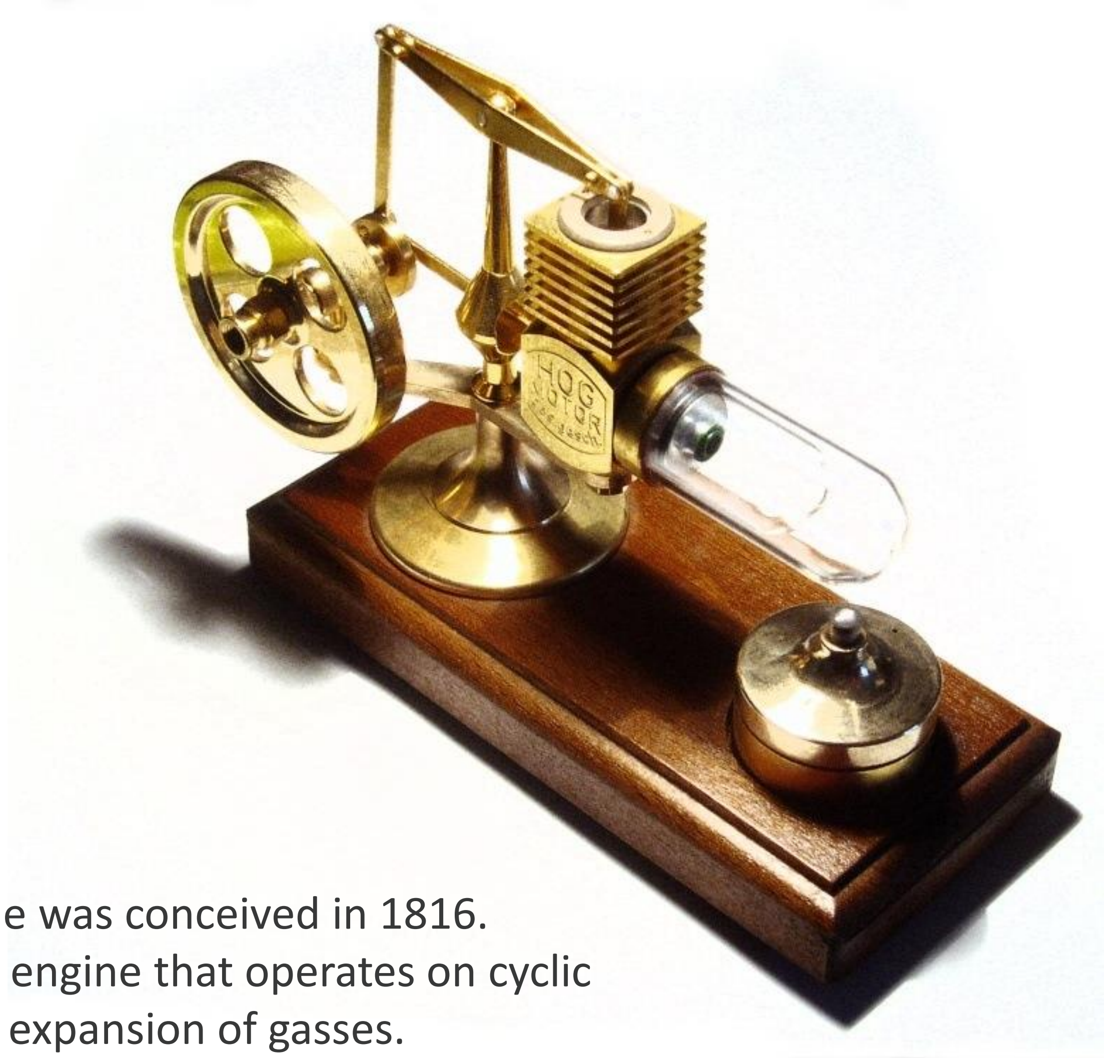
- **Introduction**
  - Definitions & Fundamentals
  - Some History
  - Overview of DPE FWP Activities at NETL
  - Old Technology vs. New Technology
- **High Expansion Seed Free MHD Power**
  - Ionization and Plasma
  - Thermodynamics
  - Gas Dynamics and MHD Power
  - Engineering Design Aspects
  - Systems and Applications
- **Conclusion**
  - Technological Projections
  - Benefits and Motivations

The Heat Engine

Is still alive

- **Heat Engine: A device for producing motive power (e.g. "Work") from heat.**





The Stirling engine was conceived in 1816.
It's a closed cycle engine that operates on cyclic compression and expansion of gasses.

Stirling Heat engine image source: Zephris at the English Language Wikipedia

Direct Power Extraction

Order a heat engine but hold the mechanical parts

- **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**

Lorentz Force

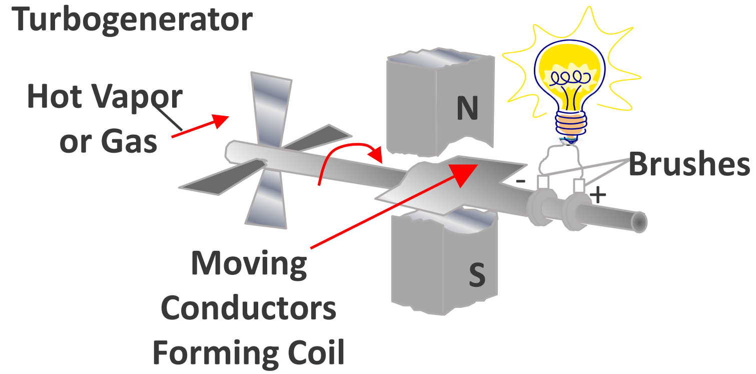
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

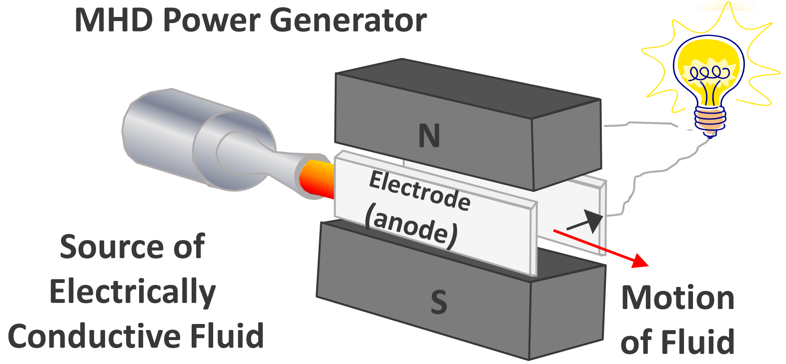
$$P_{MHD} \propto \sigma B^2 u^2$$

P_{MHD} is electric power generated
B is applied magnetic field
σ is fluid conductivity
u is fluid velocity

OCMHD: Open Cycle MHD Power Cycle
CCMHD: Closed Cycle MHD Power Cycle
LMMHD: Liquid Metal MHD Power Cycle

Today, near all of our power plants (coal, natural gas, hydroelectric, wind, concentrated solar, nuclear, bio-mass) use mechanical turbines to generate electrical power.





In the future, we may use a more efficient "electromagnetic turbine" which operates without moving parts. This is called a MHD generator.

Where this talk is headed: Concept of combustion driven MHD Power Generation which utilizes a stimulated combustion plasma and not just thermal plasma.

This talk covers OCMHD, but note CCMHD and LMMHD are also potentially viable.

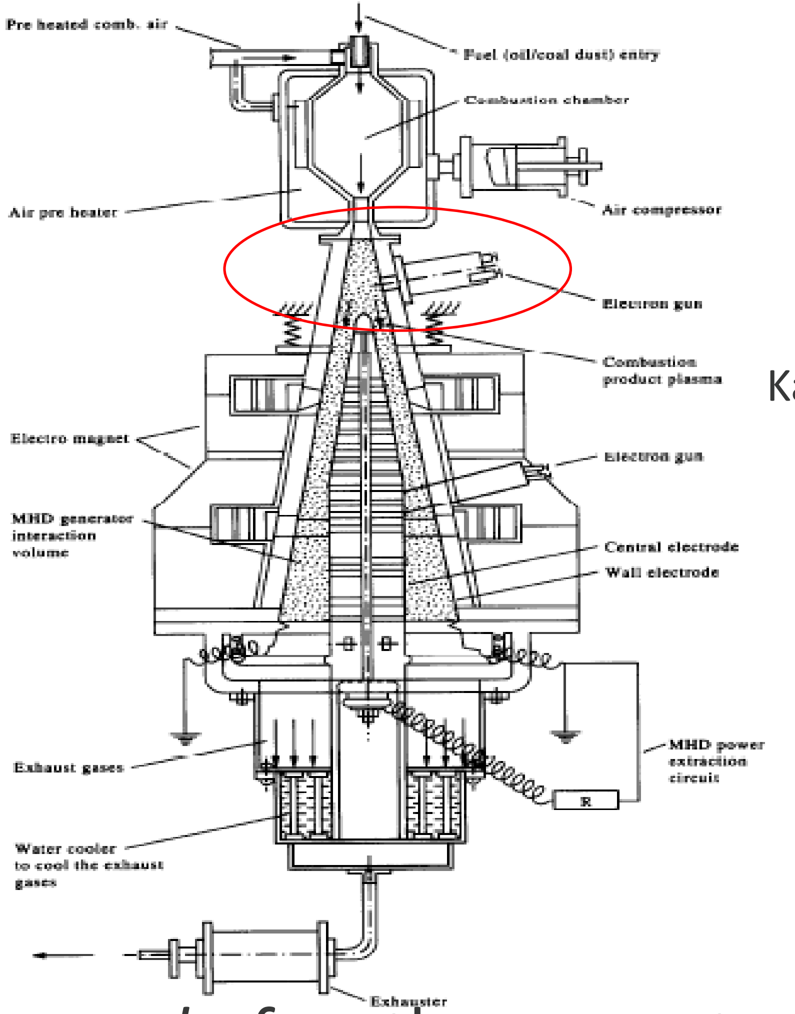
But first, a little history. Because those who fail to learn from history are doomed to repeat it.

So, let's learn something for this talk.

MHD Power Engineering Beginnings

1940s: So old school, no one working today remembers it

- **Original MHD Power idea (& patent) used an electron gun at front end of combustion driven generator**
  - This did not work!
  - Number densities of electrons needed is high
  - Non-equilibrium plasma does not persist due to frequent collisions
- **Key development: Use of an alkali metal "seed" for conductivity**
  - Low ionization potential allows for some ionization at combustion temperatures
  - K became choice for OCMHD
    - E.g. inject solution with K_2CO_3
  - Cs became choice for CCMHD



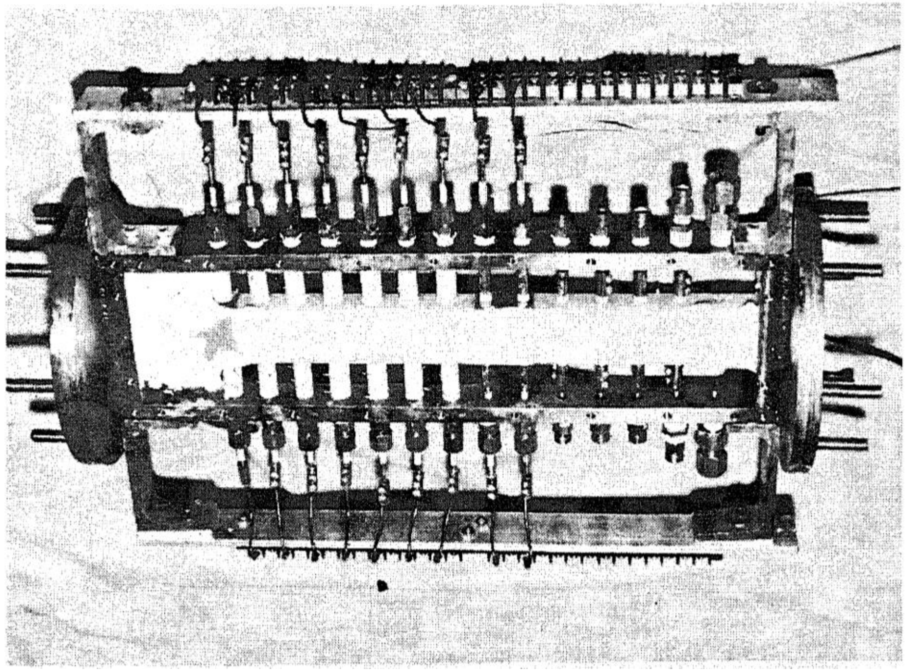
Karlovitz and Halasz U.S. patent 2,210,918, 1940. Source: USPTO

Creating a non-equilibrium combustion plasma *before* the generator doesn't work

Discovering and Solving Tech Issues

They pretty much had figured out the basics by the early 1960s

- **First alkali seeded generators did not yield expected power**
  - A “tilt” in the electric field noted
- **Key development: Hall Parameter and load factor discovery and mitigation through electrode arrangement**
  - Will mention in later slides

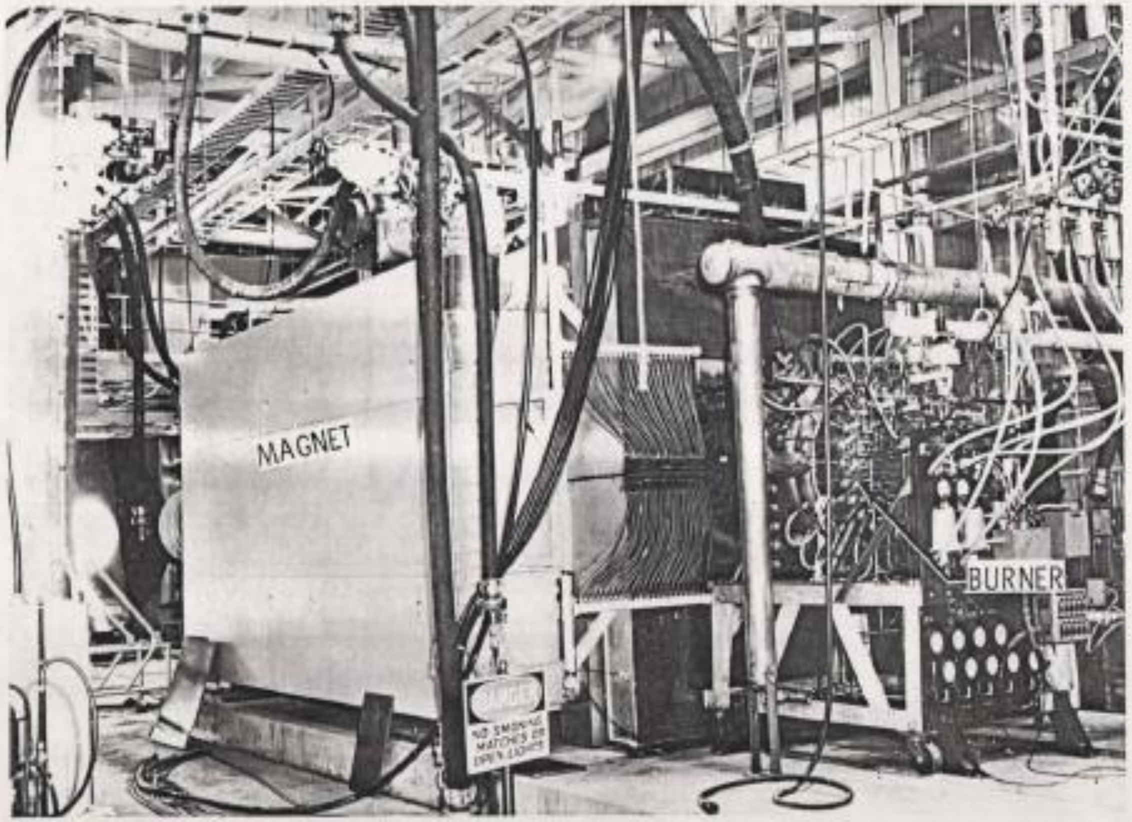


Rosa AVCO mark 1 generator (1960)
Source: U.S. ERDA report

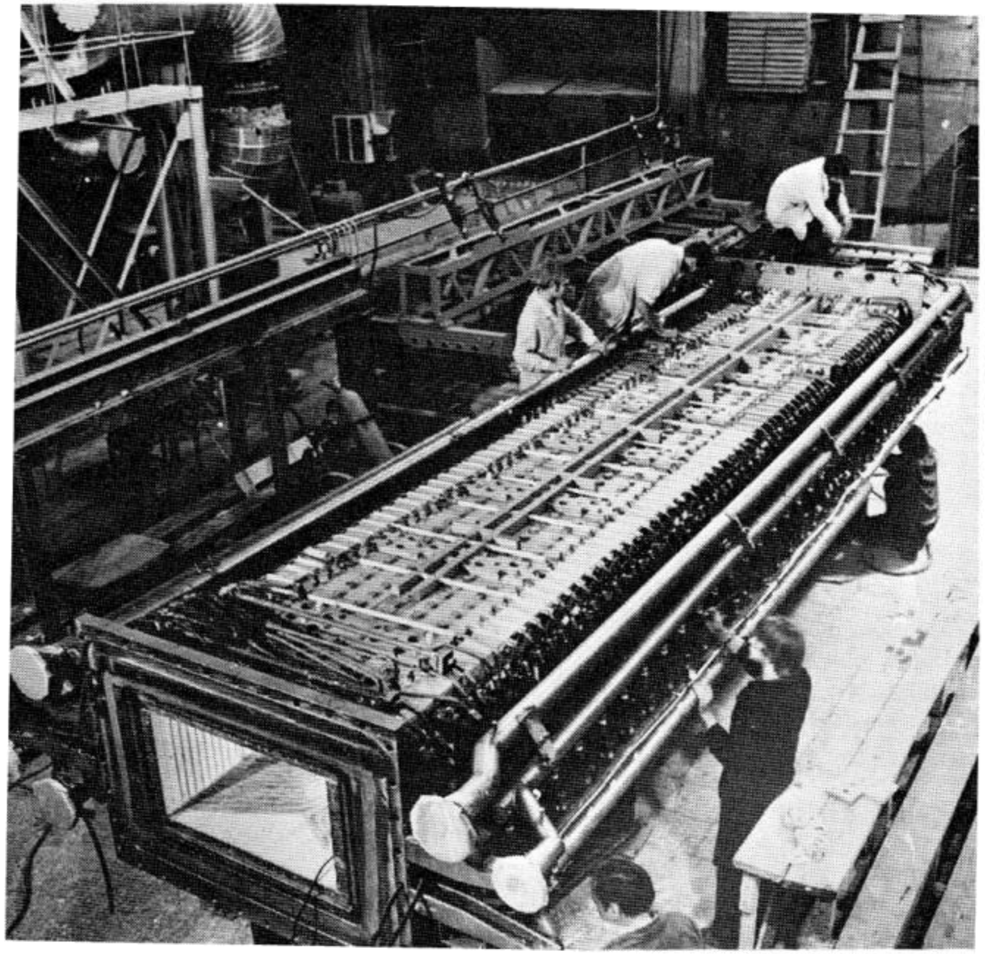
If we want a useful generator, we must pay close attention to and design for the hall parameter.

MHD Power Generation History

1970s: Going Big. Engineering and construction of MHD generators established



LORHO Facility; Magnet and Burner



Going big takes a lot of resources. Don’t go too big too soon.

MHD Power Generation History

1980s Proof of Concept Program (Direct-Fired Coal Open Cycle MHD)

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The Good + :

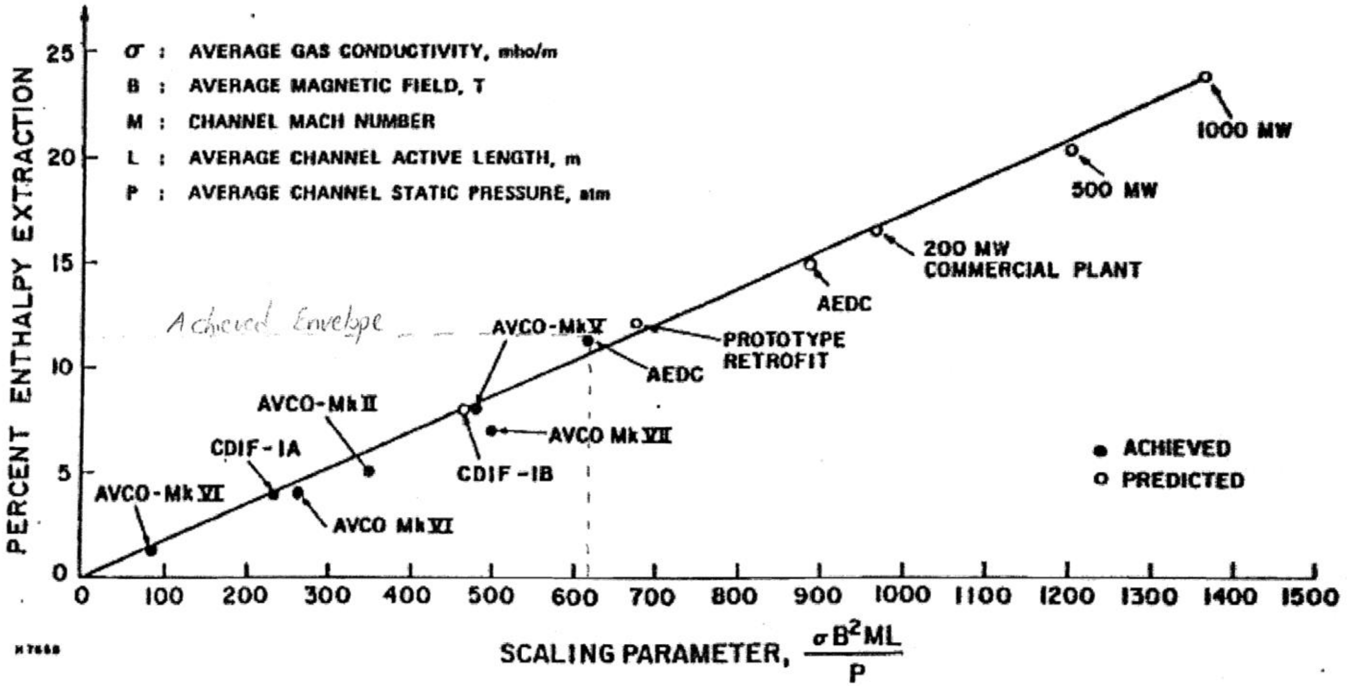
- MHD power concept proven
- MHD power generation delivered to grid

The Bad*:

- Uncertainties in fully integrating MHD systems
- Uncertainties in scaling up MHD systems
- Concerns about the cost-effectiveness of seed regeneration process

& The Ugly*:

- Slag retention problems in Combustor
- Channel Operation Problems from Arcing



- Historically, it has been assumed that MHD Power needs large size
- But this is not some fundamental law, rather systems line up b/c of consistent design characteristics
- It is possible to make this curve much more favorable

Rely on fundamentals. Crucially, we don’t need to prove MHD generates power!

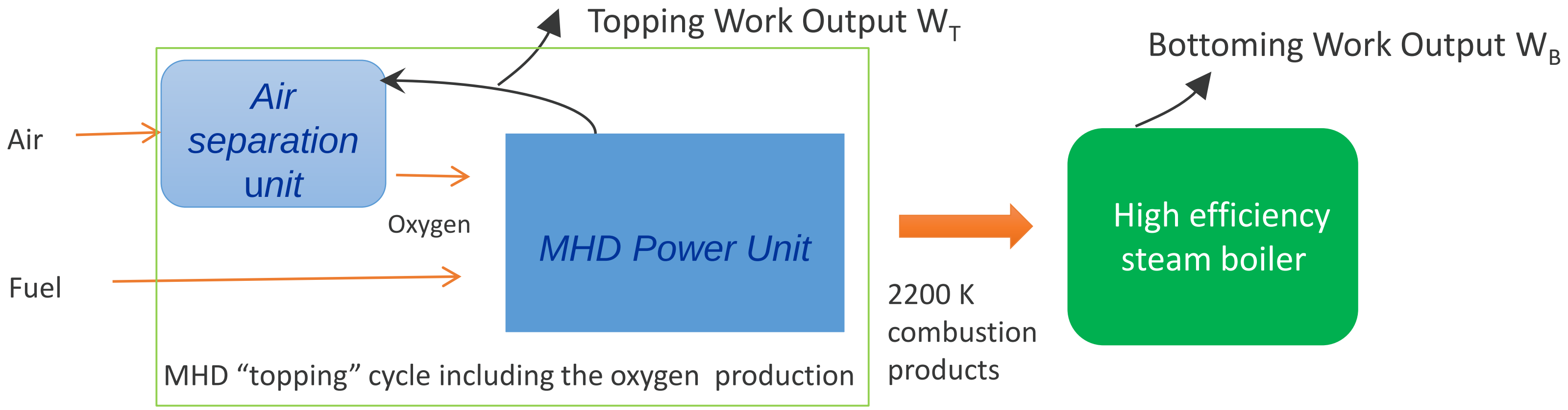
NETL Revisits MHD Power Idea

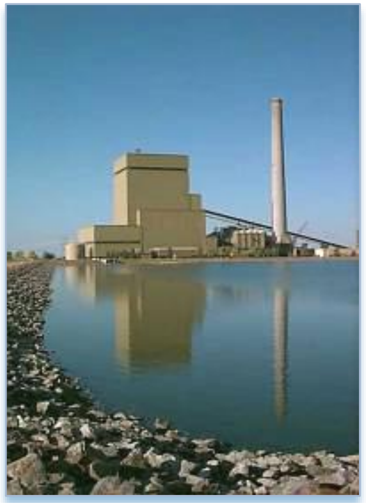
Have the cake and eat it too

- Oxy-fuel w/CCS SOTA in 2012: 54.6% COE increase
- Oxy-fuel w/CCS for Cumulative technology case in 2012: 32.7% COE increase
- For SOTA case, 65% of COE increase due to oxygen production

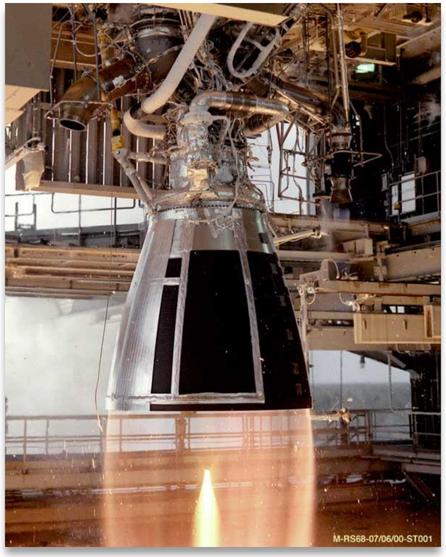
Strategies for Improvement:

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





Oxy-fuel already provides advantages in propulsion (rocket engines)



Oxy-fuel already provides an advantage for process industries that benefit from high temperatures (e.g., glass making, steel).

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

NETL's Direct Power Extraction FWP

An on-going 5-year plan funded by FE cross cutting research (2015-2019)

Goal: Determine if MHD Power Generation is a technically feasible option for future coal-power generation and develop a technology road map to get there

Objective: Produce engineering data sets, simulation tools and materials and perform a robust performance assessment for the technology

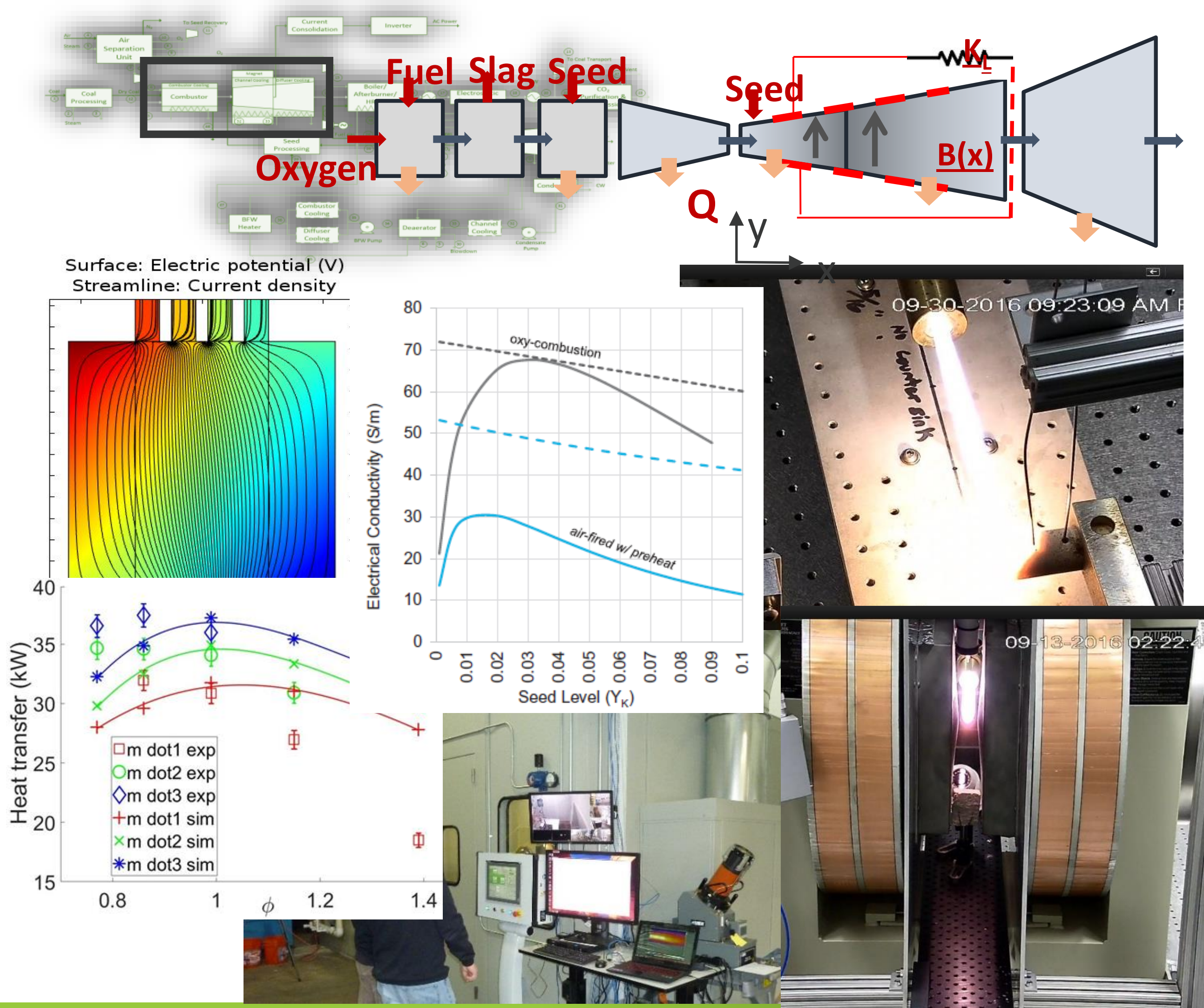
Approach: Apply systems level modeling to screen the various technology options; Develop, utilize, and validate simulations to predict the performance of components in those systems

NETL's Direct Power Extraction FWP

R&D in NETL Research and Innovation Center

NATIONAL ENERGY TECHNOLOGY LABORATORY

- Analysis
  - Scoping analysis
  - Techno-economic studies
- Component simulation
  - Developed and validated a 1D+ MHD generator engineering code
  - Developed and validated 3D simulation tools for critical design details
- Experimentation to validate predictions
  - Component heat transfer/balance
  - Electrical conductivity of seeded oxy-fuel
- Materials
  - Electrodes: high temperature & electrically conductive
    - Novel materials system development
    - Durability testing
- Advanced concept exploration
  - Photoionization
  - **Adding pulsed non-equilibrium study in EY2018**



Old Technology & New Technology

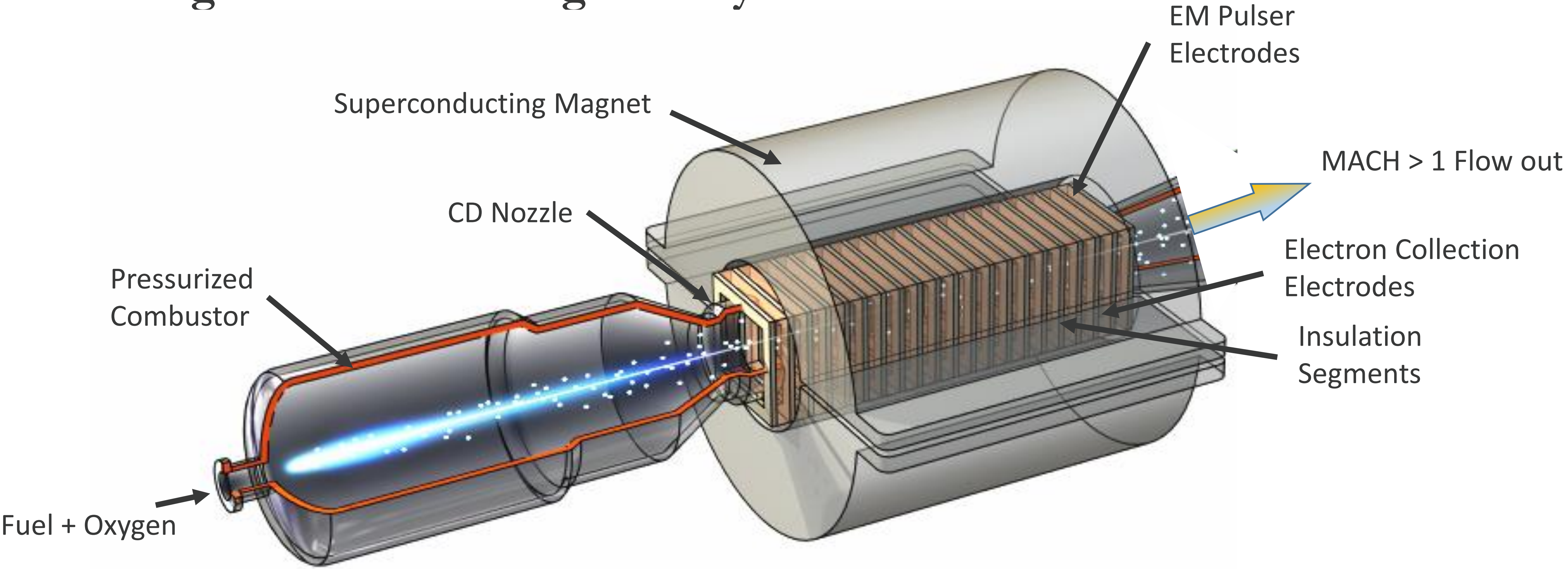
Sure, we'll take the fortuitous technology improvements for MHD Power

Legacy MHD program (U.S.: 1970s – 1993)	Today's Approach	Comments
Large demonstrations	Simulation & lab/bench scale validation	Validated models for different generator concepts & conditions, not demos
Inefficient oxygen production	Efficient oxygen production	ASU power requirements have dropped ~40% since 1990
SOx and NOx control	Capture GPU	No emissions possible! Use oxy-fuel gas processing unit (GPU)
CO_2 capture not considered	CO_2 Capture considered	High Temperature Oxy-fuel combustion for CO_2 capture synergistic with MHD
Low temperature superconducting magnets	High temperature superconducting magnets	Liquid helium cooled magnets are no longer the only superconductor option
Magnets < 6 Tesla	Magnets > 6 Tesla	Stronger magnets exist today, with large scale deploy (LHC & CERN)
Analog electronics	Digitally controlled electronics	New MHD generator measurement & control possibilities
Conventional manufacturing	Advanced manufacturing	New channel construction approaches
Seeded flows	"Excited" plasma	"clean gas" or new ionization approaches for "cold plasma" in MHD power systems possible

Sketch for high expansion seed free MHD

It's about time we got here

- **Linear Segmented Faraday Generator Shown but not only option**
- **Drawing not to scale and geometry details TBD**



Ionization & Plasma

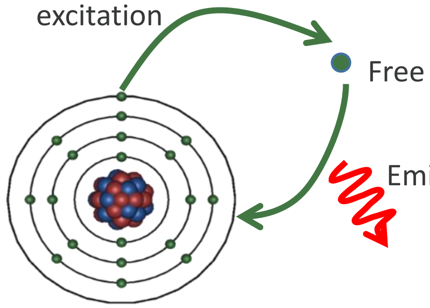
Let's electrify gasses

1. **Thermal Ionization**
2. Surface Ionization (e.g. dusty plasma)
3. Photoionization (e.g. UV)
4. Ionization by electron collisions
5. **Ionization by high-frequency electric fields**
6. Ionization by high energy radiation (e.g. x-rays and gamma rays)
7. Chemical ionization
8. Cumulative ionization

$$P_{MHD} \propto \sigma u^2 B^2$$

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

Alkali elements have low enough ionization potentials to yield thermal ionization (at combustion Temps (3000 C > T > 2100 C)
This is the "seed"



Note very little K thermally ionizes at combust T (~1-3% of it)

Ionization Energy of Dry Air Constituents (ev)

H	13.53
N	14.48
O	13.55
C	11.26

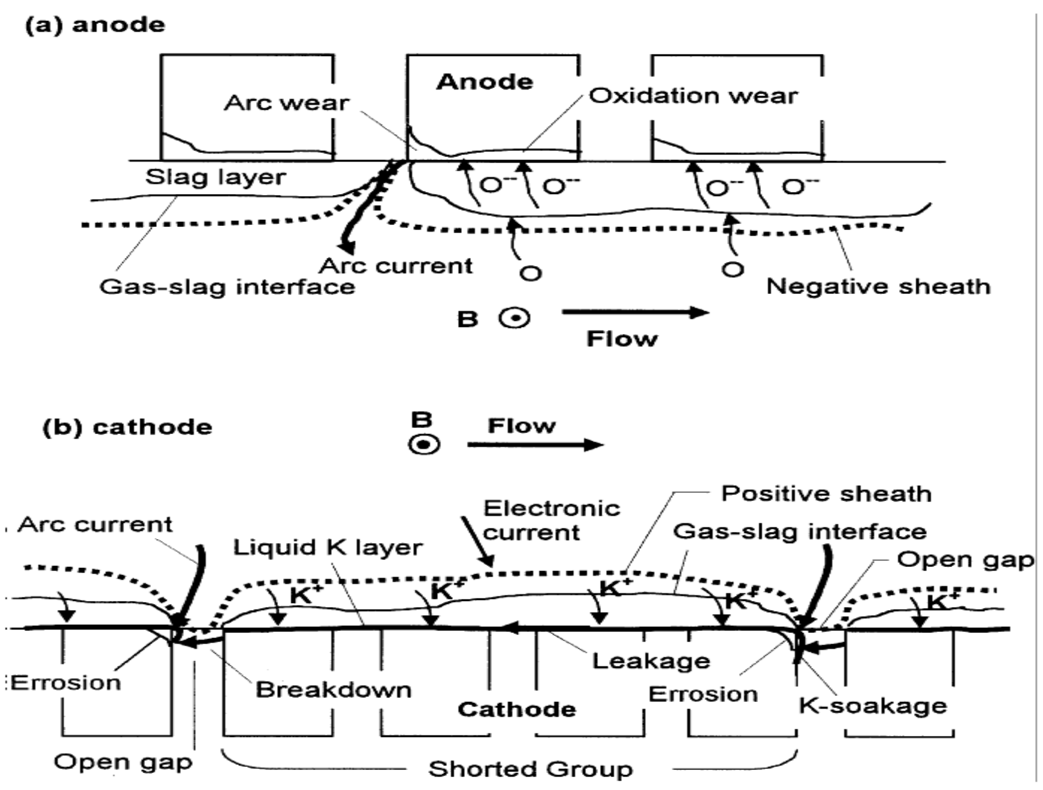
Ionization Energy of Selected Elements (ev)

Cs	3.89
Rb	4.18
K	4.34
Na	5.14
Li	5.39
Ba	5.21
Ra	5.28
Ce	5.60
La	5.61
Sr	5.69
In	5.79
Th	5.81
Al	5.89
Ch	6.76
Ni	6.88
Mo	7.10
Mn	7.43
Mg	7.64

The Problems with Traditional Seeding

Putting ~2% by weight potassium into system has some issues.

- **Large chemical plant needed to regenerate and recycle seed**
  - Equipment cost and complexity
- **Electrochemical corrosion of system components in bottom cycle and gas clean-up**
- **Seed penetration and then spalling of electrodes after a shut-down**
- **Diffusing potassium through slag causes current leakage**
- **Seed aerosols/particles form at Temp where gas turbines operate (major problem preventing gas turbine cycle integration)**



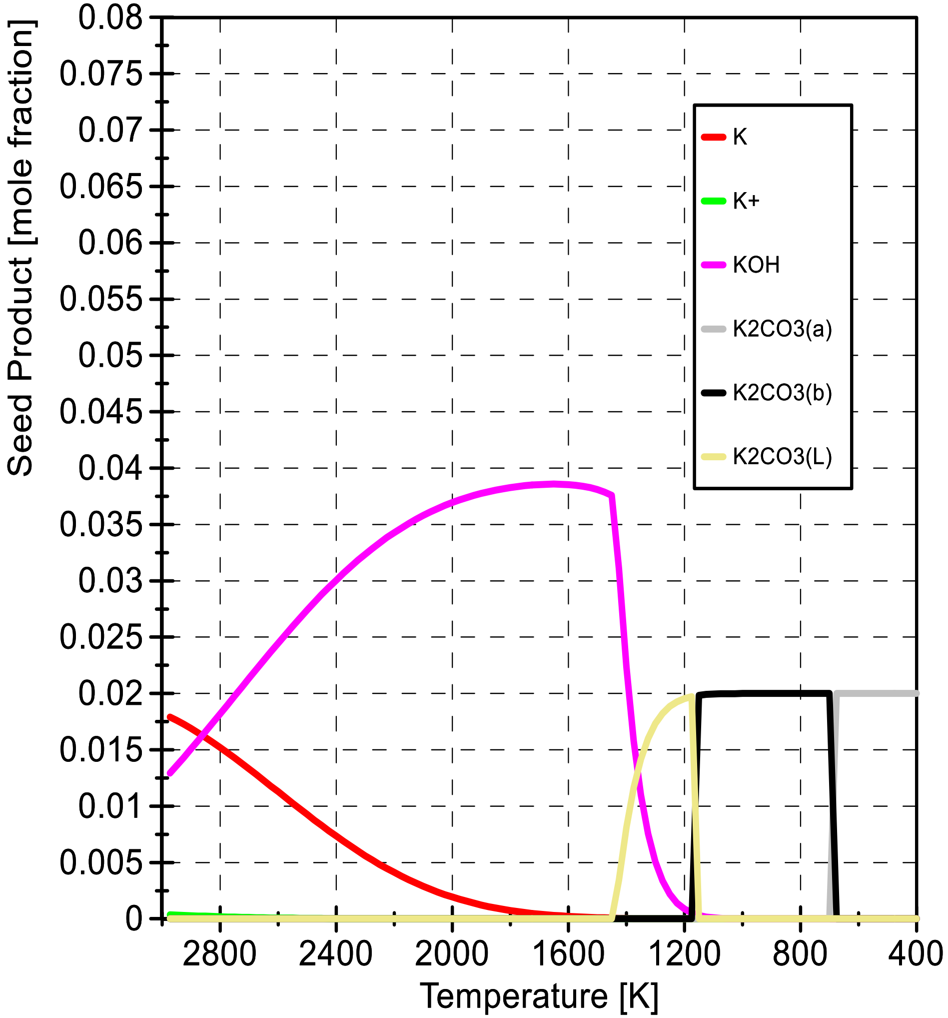
Plot Source : Kayukawa 2004

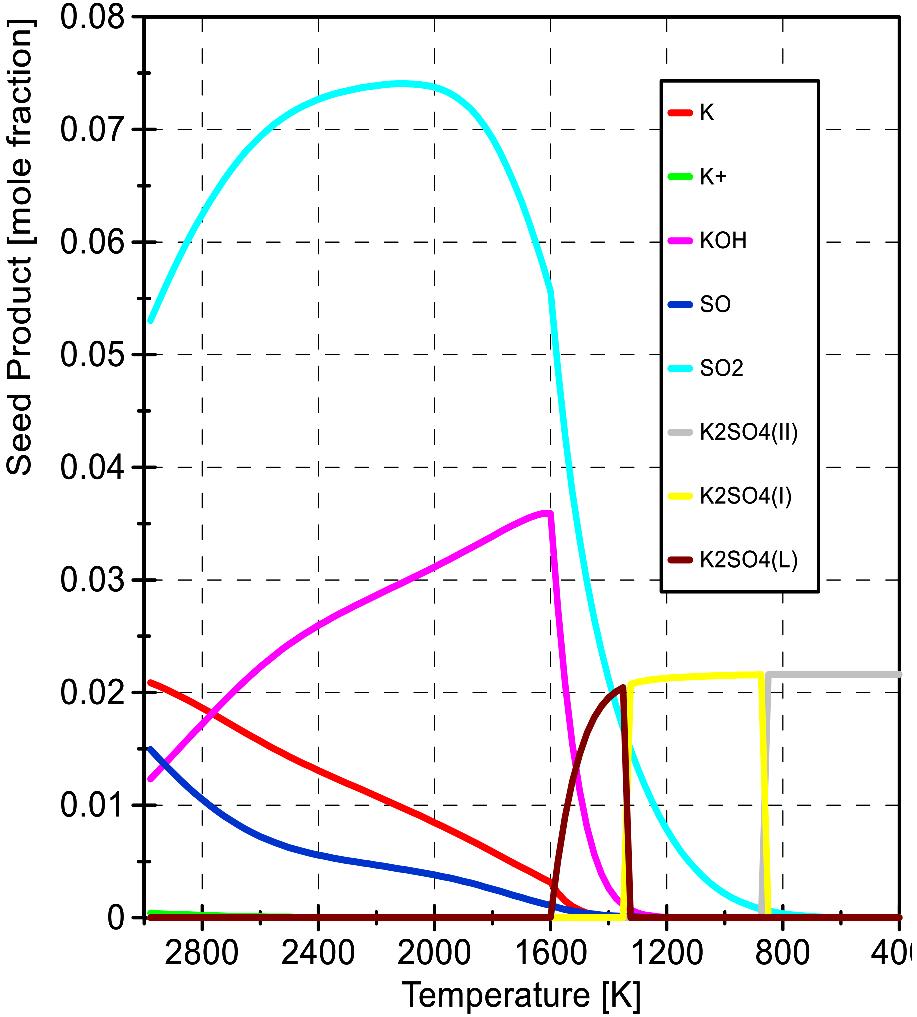
Note: Most of the above issues also addressed (in other ways) in main line FWP effort

More On Seed

To be fair, It's not all bad news

- **No sulfur in gas**
  - K_2CO_3 in -> K_2CO_3 out
- **Sulfur in gas**
  - K_2CO_3 in -> K_2SO_4 out (provides sulfur scrubbing)
- **Historically, MHD seed amount used considered sulfur**
  - amounts needed to scrub sulfur similar to that needed for plasma generation

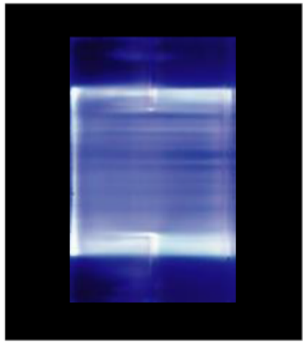


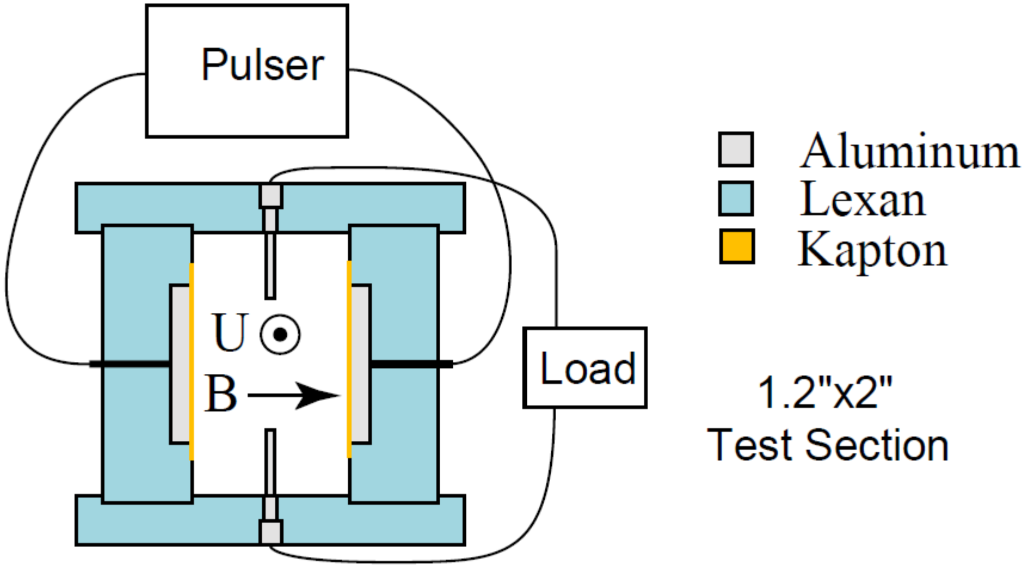


Ionization & Conductivity

Via stimulated plasma from within generator

- **Experimentally demonstrated by Dick Miles et. al. at Princeton using air**

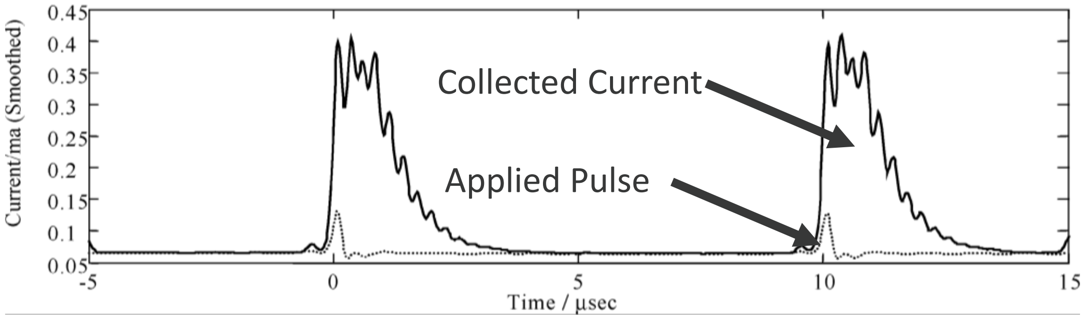




Mach 3 in-draft tunnel
- 1.2" x 2"
- 600 m/sec, 30 standard Torr, 100 Kelvin

High voltage, short pulse duration, high repetition rate pulser
- ~30 kV, 2.5 ns, 100 kHz

6.5 Tesla Magnet
- A superconducting Helmholtz coil
- 3" cube x 3 bores



Although an E-beam may be more efficient at ionization, this approach is simple allowing for relatively easy integration within MHD generator

Note it is thought that these tests ionized the oxygen in the air (after dissociation)

Ionization & Conductivity

Via stimulated plasma from within generator

.

Idea enabled by progress in solid state electronics

MV-level pulse generation with rise time of less than 1 ns
Efficiency of about 80% with 1 ns pulse width
Peak power of 1 GW in a volume of 1 liter

- Some initial estimates suggest ~10% of MHD power out needed for pulser.
- But how will it do at various pressures in an combustion environment?
  - Which gas species will we ionize (excess oxygen?)
- Note this would also would be useful for CCMHD
  - Since a mechanical gas compressor is used which is not seed compatible

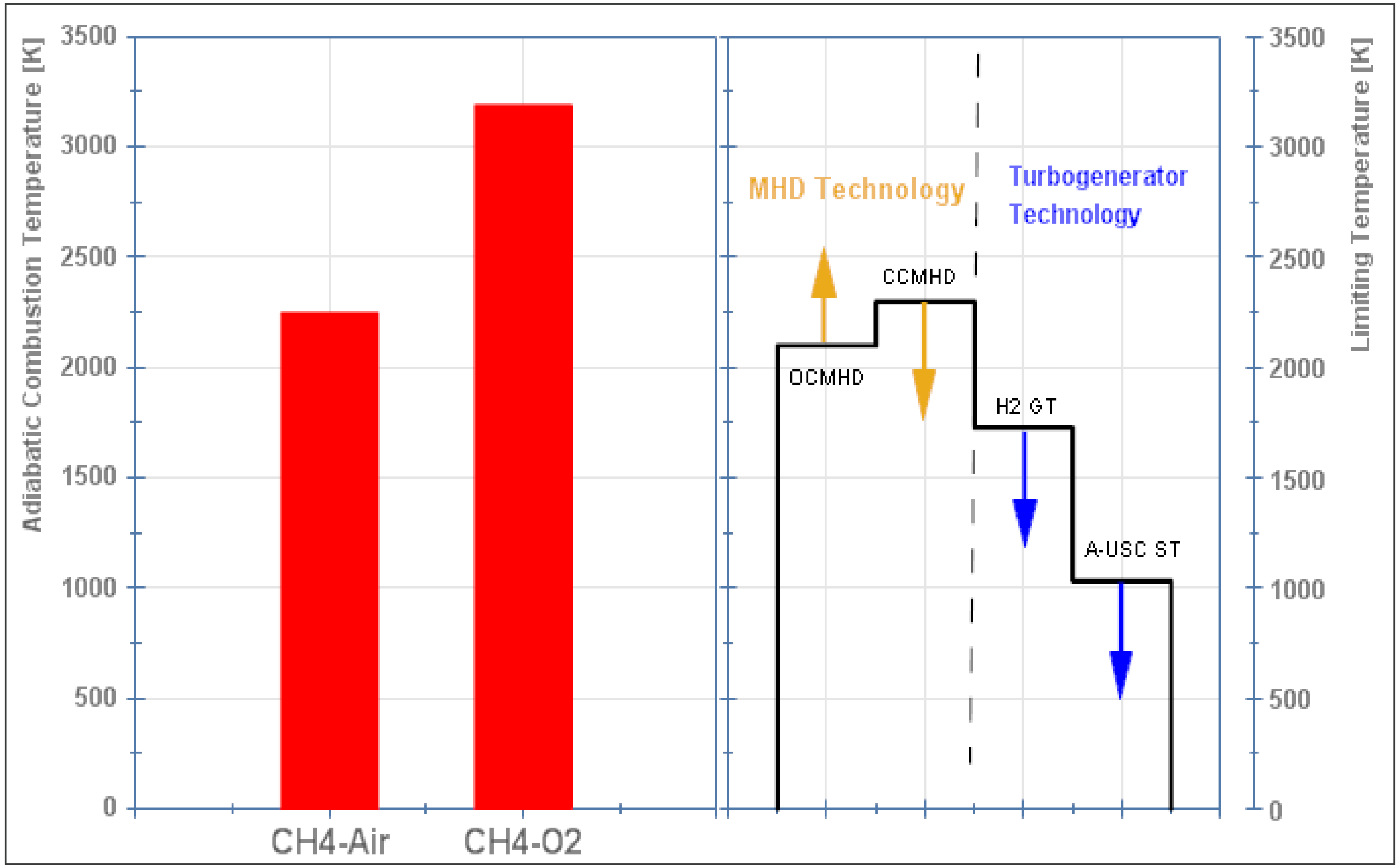
Heat Conversion Thermodynamics

The entropy of the universe is increasing

- Conversion of heat into work or electrical power limited by the 2nd law of thermodynamics
- Usually, it is stated that efficiency is limited as:

Carnot limit

$$n_{th} \leq 1 - \frac{T_C}{T_H}$$

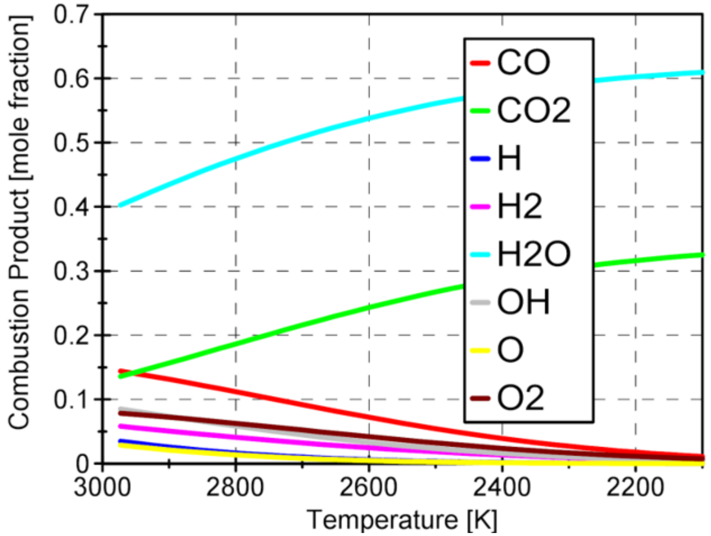


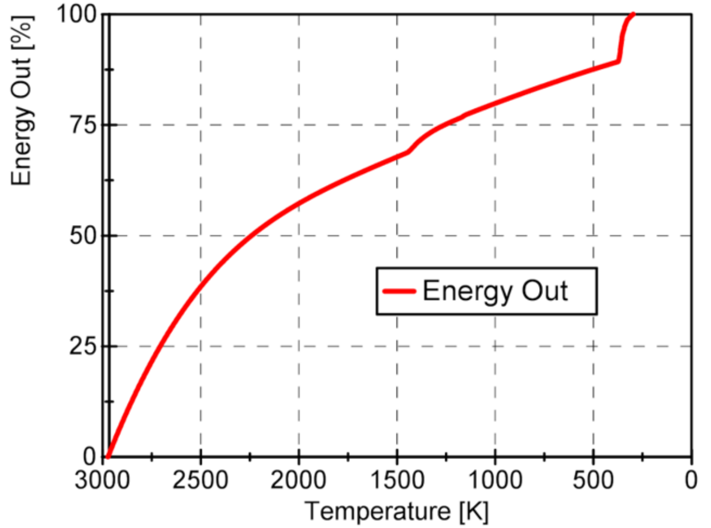
Thus, an energy conversion system employing a OCMHD has the highest theoretical efficiency. So let's figure out how this could lead to the ultimate heat engine.

Thermodynamics with Chemistry

An interesting aspect

- **At oxy-combustion temperatures (e.g. 3000K) CO_2 and H_2O combustion products undergo disassociation, limiting temperature increase**
  - These reactions are reversible with T
  - Changing moles leads to non-linear energy extraction curve
- **Since number of moles change, the Carnot limit for high temperature combustion systems may be greater then implied simply by temperature differences**
  - perhaps ~95% instead of 90%
  - Fuel and pressure dependent
- **But Carnot not achieved with real energy systems**
  - Particularly for a Brayton cycle
- **But we can conjecture efficiency improvements for OCMHD based on Carnot increase**
  - Maybe ~10 to 15% net cycle efficiency improvement over turbines if both run as Brayton cycle





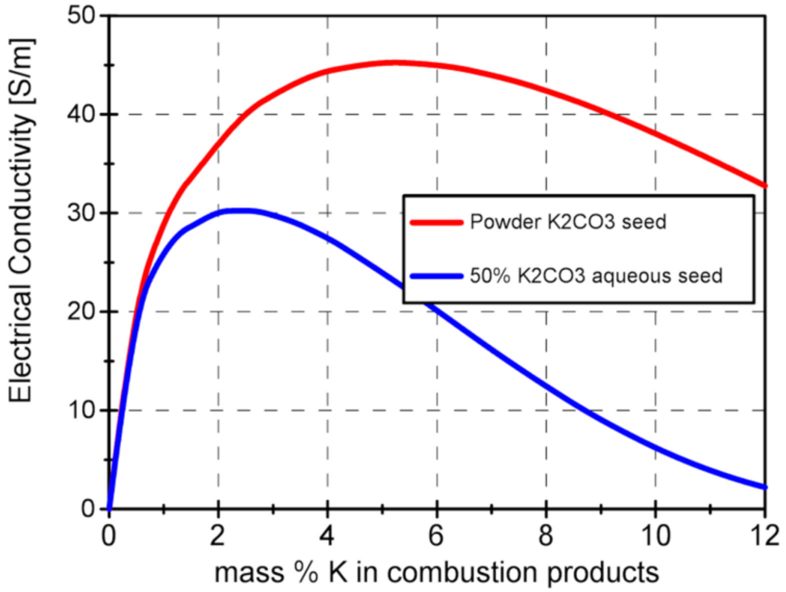
Ionization & Conductivity

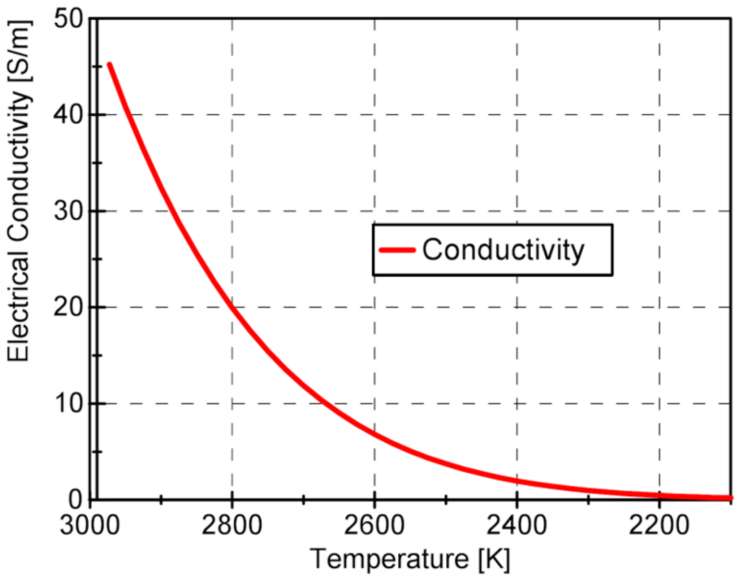
Via thermal excitation and what to expect for pulser produced plasma

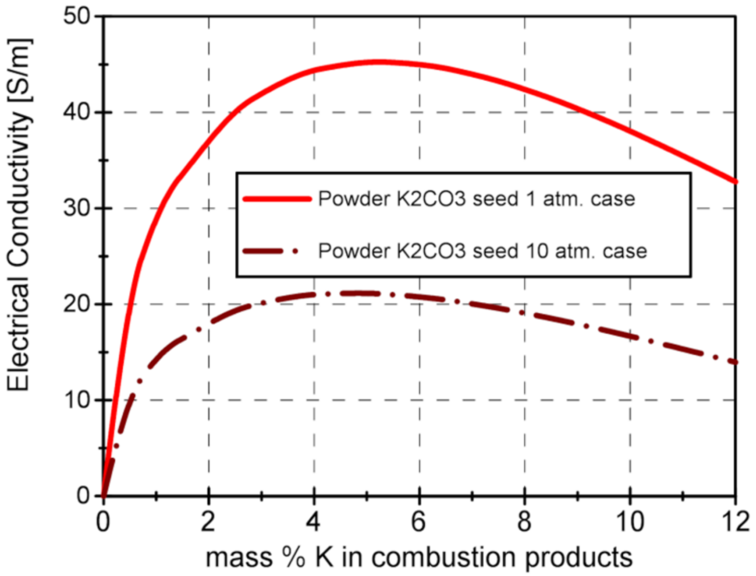
- **Conductivity a function of electron number density and electron mobility**
- **Mobility mainly a function of MTCS of electrons with neutral gas species and total pressure**
  - Combustion products have large MTCS compared to monatomic gasses, this limits conductivity and leads to a thermal plasma (difficult to maintain non-thermal plasma)

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

- **Seeded oxy-combustion conductivity plots shown**
  - Pulsed ionization means left two plots (below) no longer valid
  - But conductivity should still go down with pressure (e.g. like below right plot)



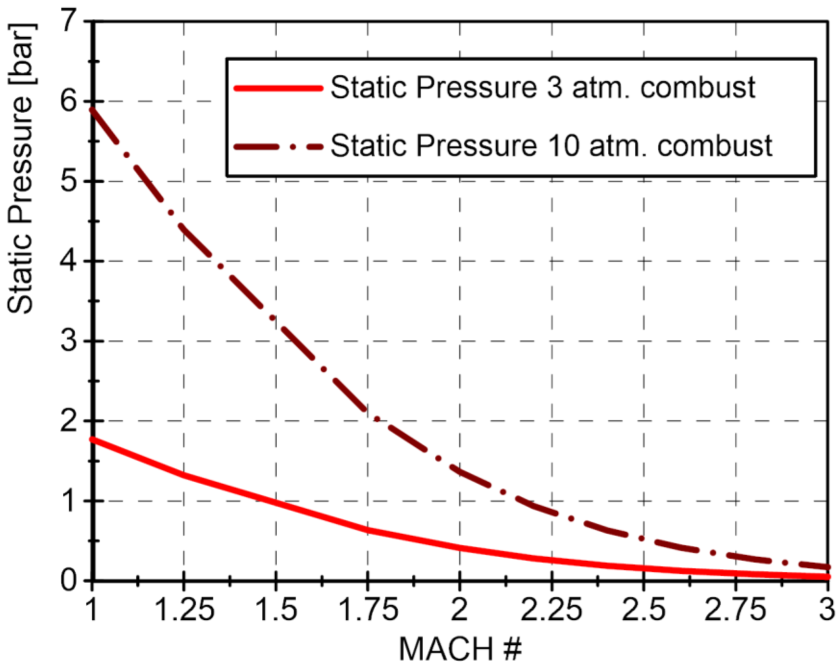


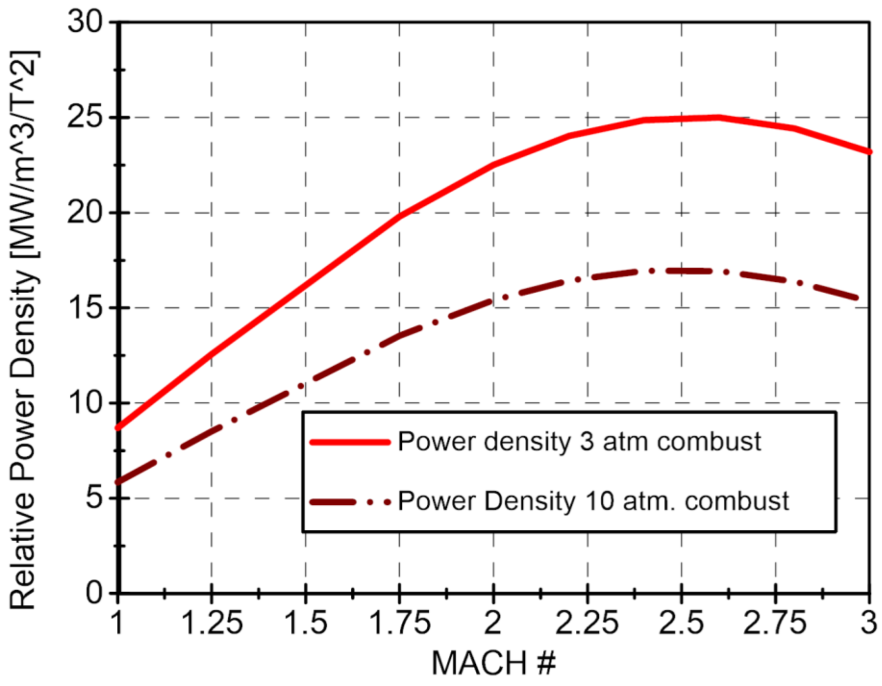


Gas Dynamics

Now we have both dynamic and static temperatures

- **Seeded oxy-combustion conductivity plots shown**
  - Plot on left is still valid for stimulated plasma, but not plot on right
  - Instead, power densities should exponentially increase with MACH # (not plateau)





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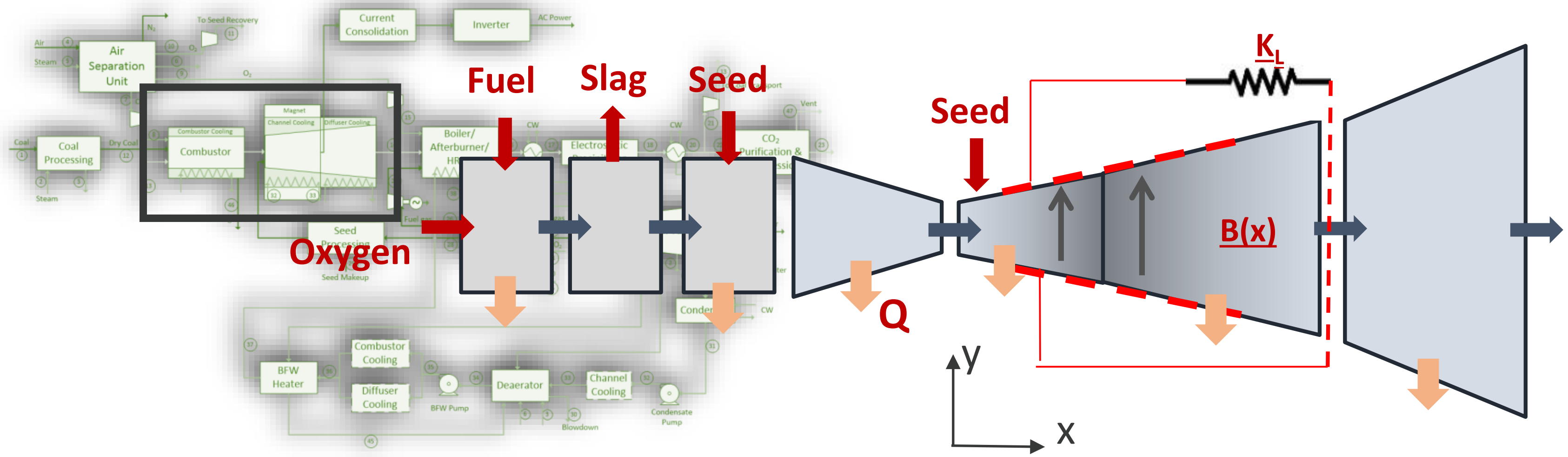
MHD Power Generation

Stand by for some math talk



- **Numerical solution needed for an MHD generator**
- **NETL code based on open source tools**
  - Assimulo: DAE solver
  - Cantera: thermochemical database with kinetics
- **Power extraction means Lorentz force against flow**
  - need a counter force (e.g. from pressure gradient in channel)

Conservation Equations

Mass	$\frac{d}{dx}(\rho u A) = 0$
Species	$\rho u \frac{dY_k}{dx} = R_k W_k$
Momentum	$\rho u \frac{du}{dx} + \frac{dP}{dx} = F_{EM} - F_{friction}$
Energy	$\rho u \left(u \frac{du}{dx} + \frac{dh}{dx} \right) = P_{EM} - Q_{wall}$
Lorenz	$F_{EM} = J_y B_z$
EM power	$P_{EM} = J_y E_y + J_x E_x$

Generalized Ohm's Law

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

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

Electrode configuration

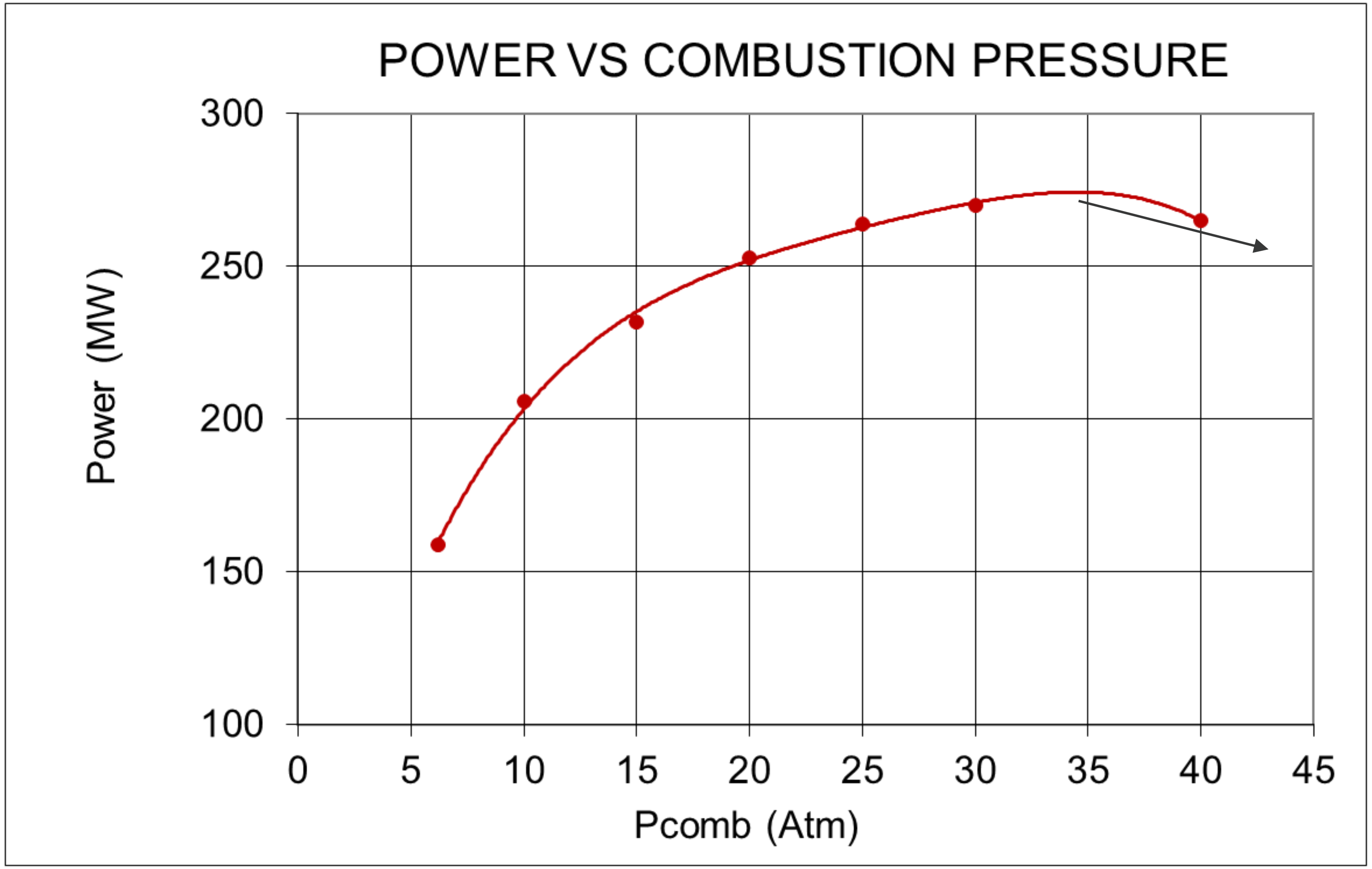
$$J_x = 0, \quad E_y = K_L u B_z \quad \Rightarrow \quad E_x = -\beta_H u B_z (1-K), \quad J_y = -\sigma u B_z (1-K)$$

MHD Power Generation Code Results

For what we know works (seeded flows, thermal equilibrium)

K_2CO_3 seeded Oxy-methane, 1 GWt plant size

- **Each data point is different system (sweeping combustion pressure)**
- **Follows standard fixed Mach design for MHD gen (M = 1.2 shown)**
  - Wall heat losses and oxygen compression cost considered
  - Practical electrical design parameters for E_x and J_y considered – this is basically why selected Mach # slower then ideal here



Historically, reported OCMHD enthalpy extraction topped out at 35%. Yields C.C. eff (with steam) ~60% HHV Coal

MHD Power Generation Results

What we might expect to happen with high-expansion seed free MHD

- **Lower Electrical Conductivity (e.g. ~1 S/m instead of ~20 S/m)**
  - But much higher velocities can more then make up for it.
- **Can we avoid or manage large hall parameters at high expansion?**
- **Can we relax constant M assumption without electrical problems?**
  - Since we are aiming to control conductivity, this is more viable
- **Likely to underperform system (last slide) due to energy required for ionization**
  - Considering that current limitation is O_2 pumping and wall heat losses & not ionization

Engineering Considerations

Those pesky details. An OCMHD generator is a "low impedance" power supply

Load Factor (K) -> relation of load electrical resistance (R_L), to the resistance in the generator (R_g)

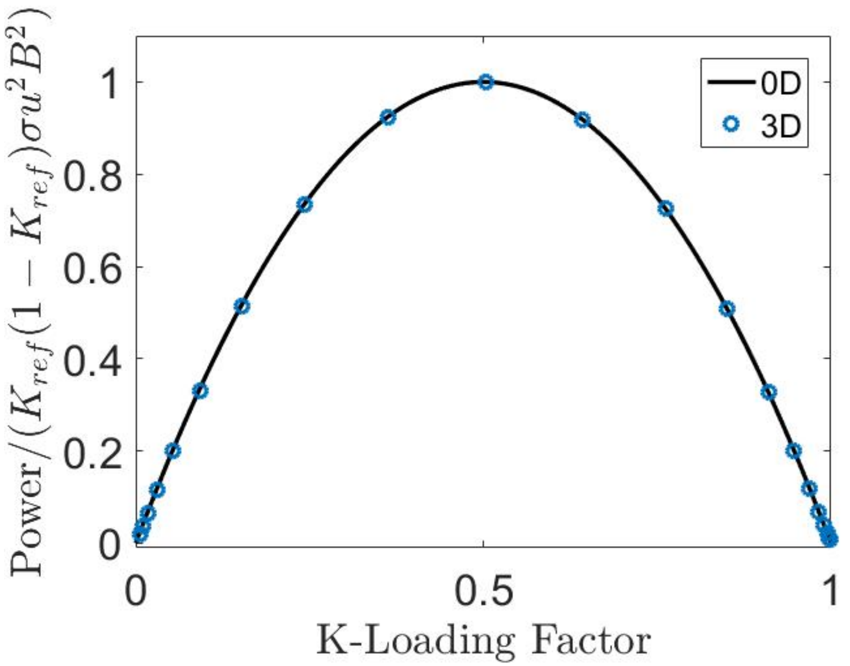
$$K \equiv \frac{R_L}{(R_L + R_g)}$$

And then:

$$P_o = K(1-K)\sigma u^2 B^2 \quad **$$

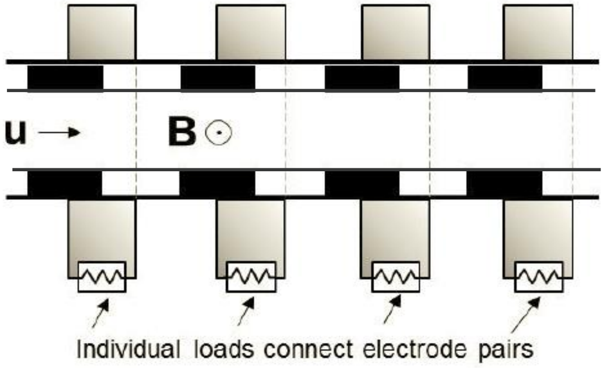
Where σ is fluid electrical conductivity, u is fluid velocity, B is applied magnetic field & P_o is electric power density output.

**: For ideal segmented faraday generator

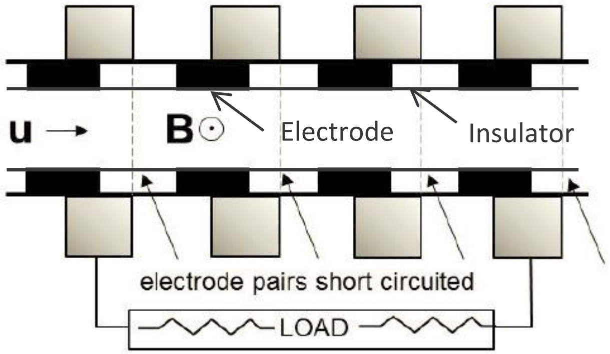


Note that when considering fluid and electrical design parameters, it can often make sense to make K > 0.5

Segmented Faraday Generator. The ideal segmented Faraday generator has an infinite number of pairs & thus no Hall current.



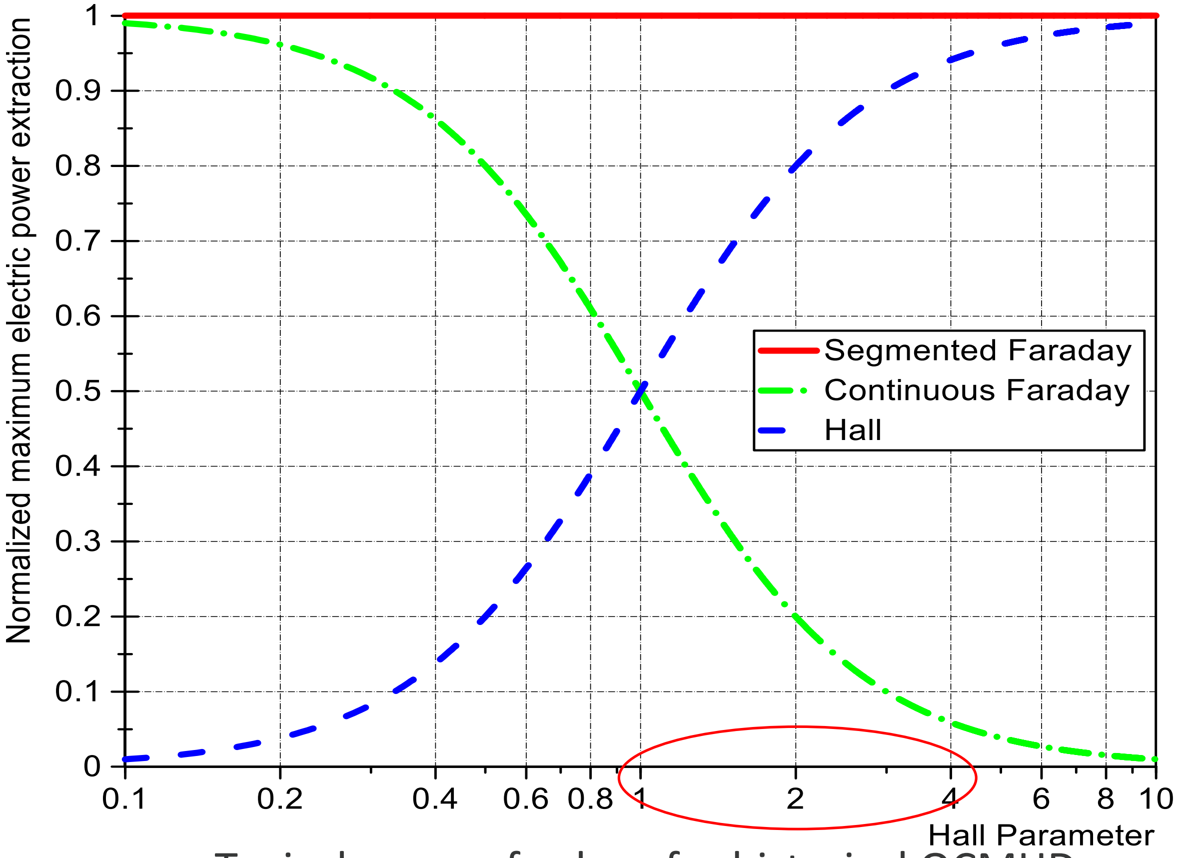
Hall Generator. This loading minimizes Faraday voltage & maximizes Hall current for extraction



Engineering Considerations

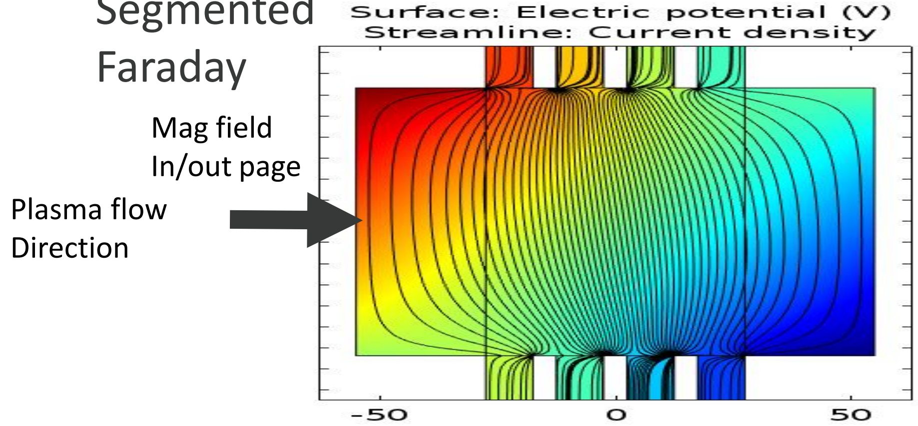
Those pesky details. System must be designed to consider this!

Hall Parameter, β = electron mobility * applied mag field

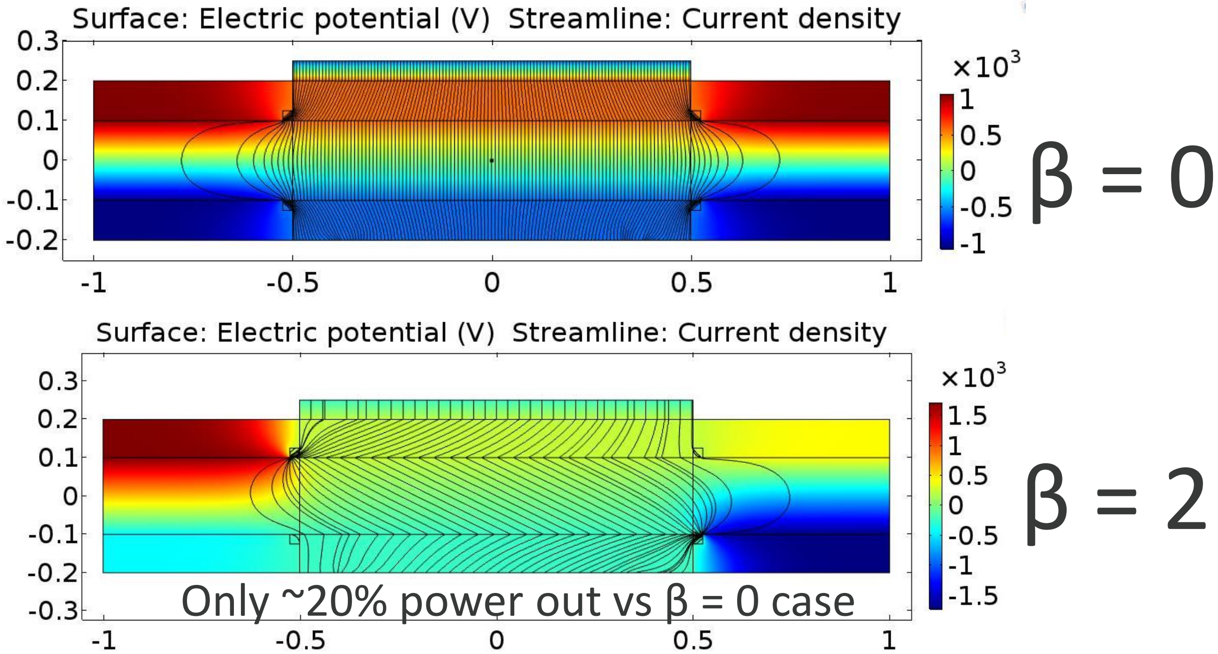


Typical range of values for historical OCMHD

Segmented Faraday



Continuous Faraday



More Considerations

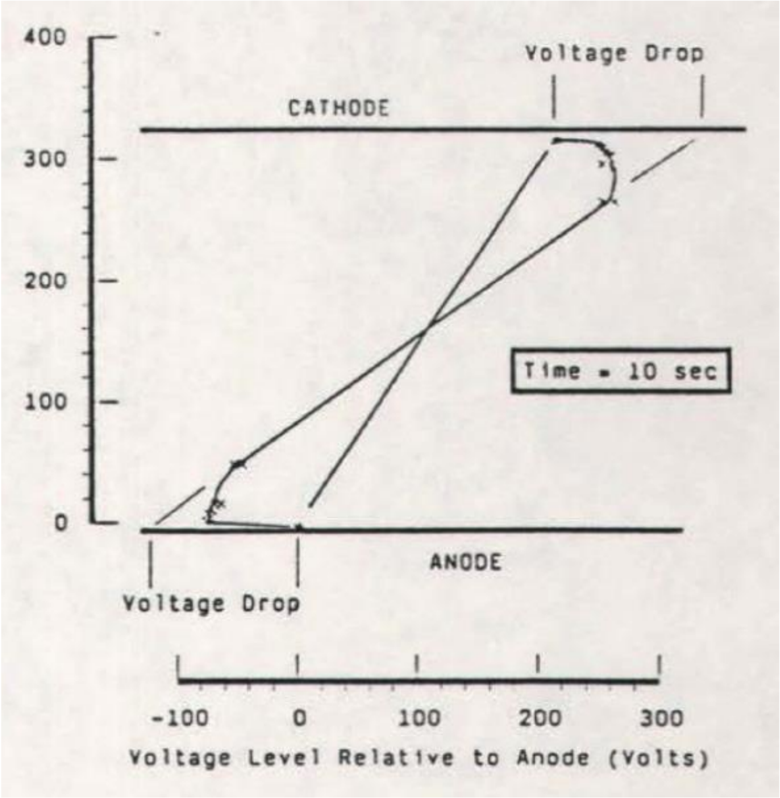
Those pesky details for segmented Faraday channel

- **Ratio of electrode/insulator thickness impacts efficiency**
  - Usually, optimal is around 2/1 ratio
- **Need high channel width/electrode width ratio to achieve expected efficiency**
  - > ~75/1
  - So in a small MHD channel the electrode width could be less than a mm wide!
  - This necessitates thinking of a small channel as a single piece, not something bolted together
    - Thermal stresses can be enormous in these systems
    - Functionally graded additive manufacturing could do this
- **How do we manage pulsing power out for this concept?**
  - Offset multiple pulsers to ensure continuous power generation?

MHD Power Generation

To make it small, we need it all.

- **Minimize wall boundary layer voltage drop**
  - Increase velocities near wall
  - Increase wall temperatures
  - Laser schemes (photoionization) may be possible to control
- **Minimize wall heat losses**
  - Higher temperature electrodes
  - Cooler gas operation
- **Minimize wall friction**
  - Contoured walls
  - Smooth surfaces



0.32m x 0.145m Segmented Faraday Generator. Sub-sonic oxy-fuel, hot ceramic electrodes ~32.5MWt

Plot Source: John Lineberry

Small MHD Power?

I'll just drive it over to you guys. This has been done before in Russia!

~10 MW output geophysical MHD rig

Picture source: Active Geophysical Monitoring by Kasahara et. al.

Summary of Concept

So far

- **We can conjecture performance of a OCMHD seedless high expansion MHD generator to be on par with a gas turbine**
  - Since power limitation does not appear to be elec. conductivity
  - more power generation
  - but power offset by need to supply the pulser
  - we are planning to do detailed analysis and to quantity this
- **This means we may still need a combined cycle to reach "ultimate" status**
  - Dual cycle: OCMHD-LMMHD
  - Dual cycle: CCMHD-LMMHD
  - Dual cycle: OCMHD-CCMHD
  - Triple cycle: OCMHD-CCMHD-LMMHD

Some notes for LMMHD

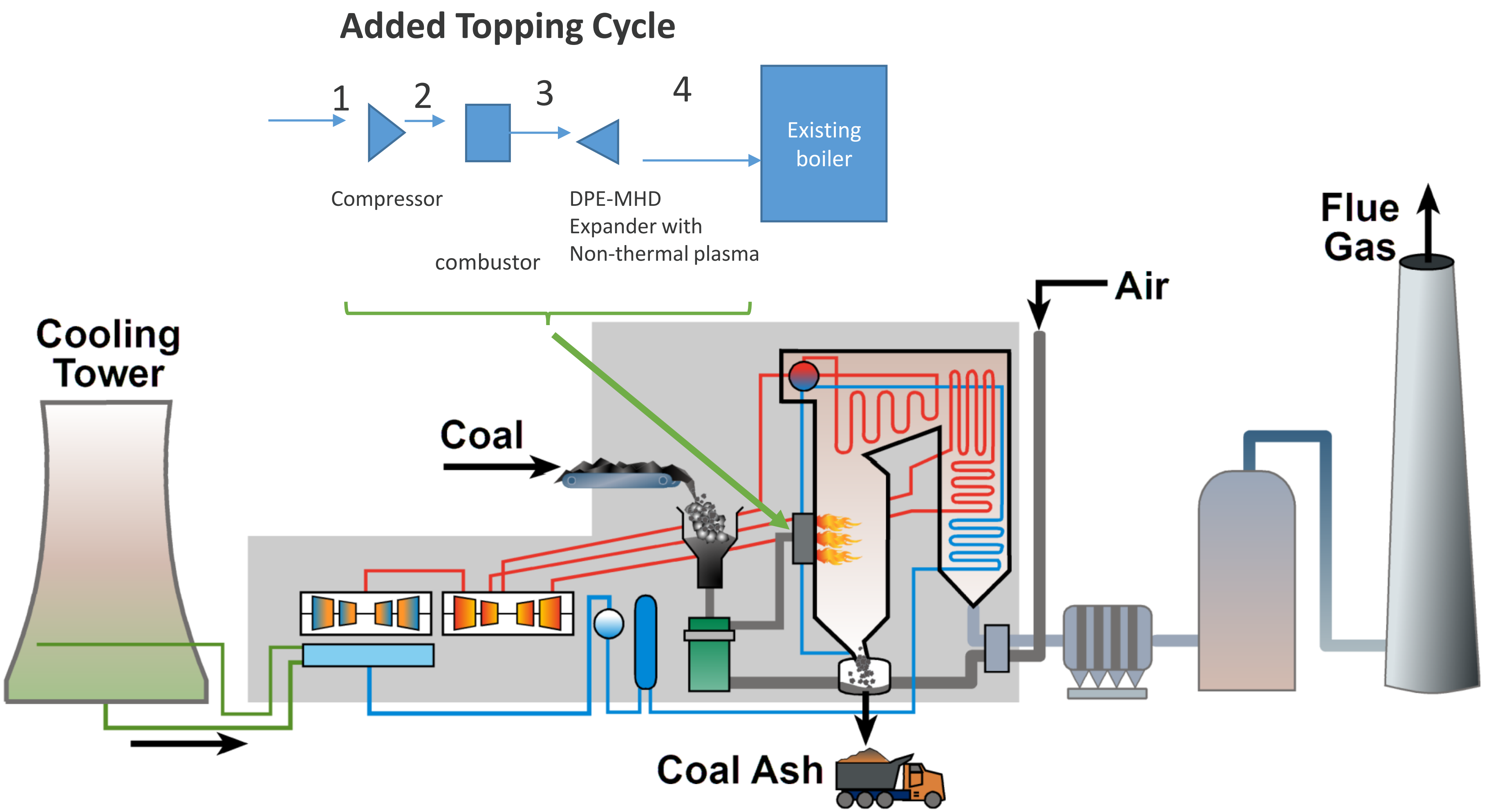
If we need the combined cycle to become "ultimate"

- **LMMHD as bottom cycle has a good size match to OCMHD**
  - In contrast to steam boiler
- **2 main LMMHD routes**
  - 2 phase system (gas: expansion, metal: conductivity)
  - Thermoacoustic generator with liquid metal (LM) "piston"
- **Combining MHD cycles enables potential shared use of a magnet**
  - Reducing a major system cost
- **Use the LM to cool the OCMHD walls**
  - Instead of cooling with bottoming cycle water

A nearer term concept with this?

Retrofit An existing coal plant with "MHD burner" augmentation.

- **Simple, continuous faraday slagging MHD generator**
  - Low ~1T field
    - Keep Hall low
  - Pulser conductivity to avoid seed
- **Add 1-2% efficiency to plant**
  - So balance of plant mostly unchanged
- **Simple slag coated cladded copper electrodes**
  - Boiler integrated cooling
- **Must work at single burner size**
  - E.g. < 60 MWt



Steps for analysis from here

The To Do List – Quantified Results will be in "episode 2".

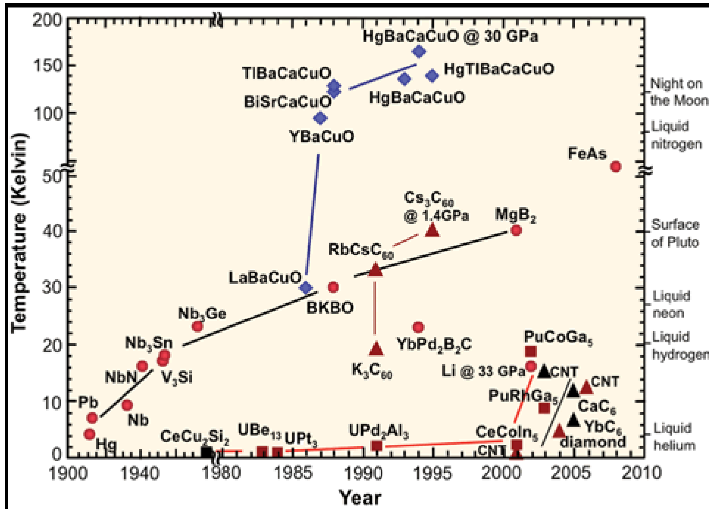
- **Establish MHD Power Gen performance curves using our code**
  - What load factor values make sense to use?
  - Can we mange electrical parameters through generator?
  - How does wall heat transfer impact optimization?
  - Can we "extract" more with a velocity drop and not just pressure drop?
  - What is ideal combustion pressure to use?
- **What are realistic maximum and minimum pressures to use?**
- **What generator geometry and electrode loading scheme to use?**
  - Can this be built?
- **Establish conductivity f(T,P,t) for pulser with an efficiency metric**
  - Likely most difficult part – and needs experimental validation
- **Explore possible variations to the idea**
  - Detonation driven
  - Use of LOX instead of GOX
- **Perform basic combined cycle assessment of the all MHD combined cycle system**

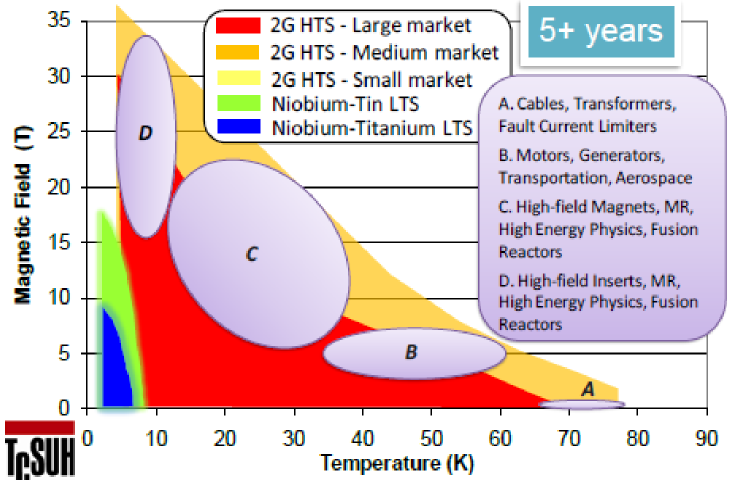
Key Supporting Technologies

I'm from the future, so I know this stuff ;)

- **Magnets**
  - New superconducting materials & higher operating Temp.
  - New manufacturing techniques for windings/tapes
  - "Holy Grail": superconducting at room temperature
- **Oxygen production**
  - Cryogenic O_2 ~2x better then 1980s.
  - Membranes for 3x better improvement, toward approaching limit of ~48 kWh/ton O_2*
- **Power electronics**
  - More efficient, faster pulsed power supplies
  - Dynamic digitally controlled electrode loading systems
- **Additive manufacturing**
  - "one piece" MHD channel with integrated thermal management
    - Functionally graded structures
  - Progress in rocketry builds translates to MHD tech.

Source: wikipedia





bottom right from Selvamanickam (2011).

*2012 NETL final report (DOE/NETL-2010/1405)

Technology Benefits and Motivations

Not just because it's a super cool (HOT) concept.

- **Increased power generation efficiency**
  - Topping on existing cycles
  - New combined cycles
  - Synergy with CO_2 capture
- **Fuel Flexible**
  - Thermal power input
- **Compact Generation**
  - Small footprint & potentially portable
  - Modular: swap channels in/out of magnet (magnet is $$$ part)
- **Performs well in CCS/CCUS scenario**
  - An Oxy-MHD cycle more then makes up for CCS and ASU efficiency costs
- **DC Power Output**
  - Future grid transmission?
- **Dynamic Load Response**
  - Good for grid performance and reliability
- **No water use**
  - If all MHD cycle
- **Cost?**
  - Could be low (but TBD)

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Please contact me if you have useful ideas/capability and wish to collaborate as the concept is further developed.

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