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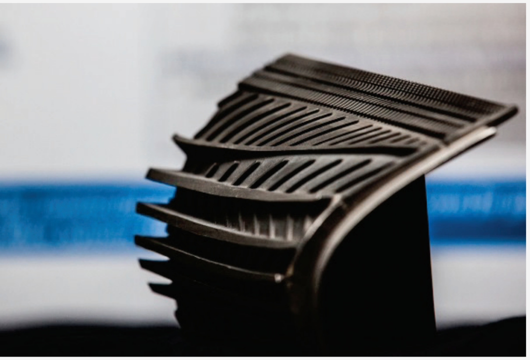
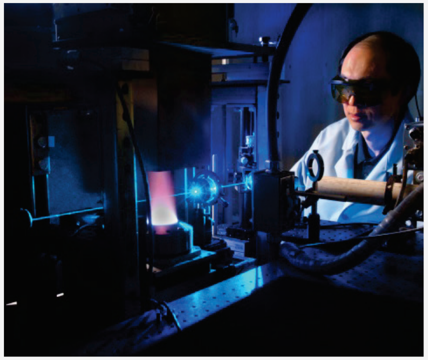
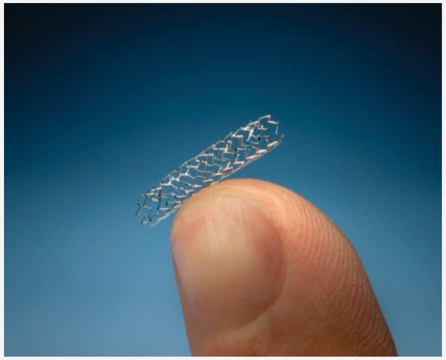
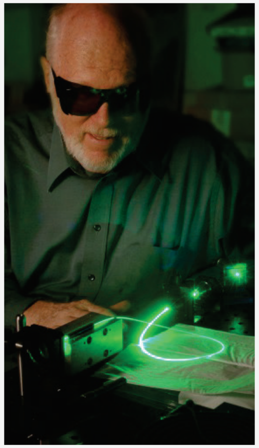







# Performance Baseline for an Oxy-Coal MHD Power Plant with Carbon Capture

**Nathan Weiland, Charles White**

First Workshop on High Efficiency, Low Emissions Coal-Fired Plant (HELE2016)

Tokyo, Japan – May 23rd, 2016

NETL-PUB-20286

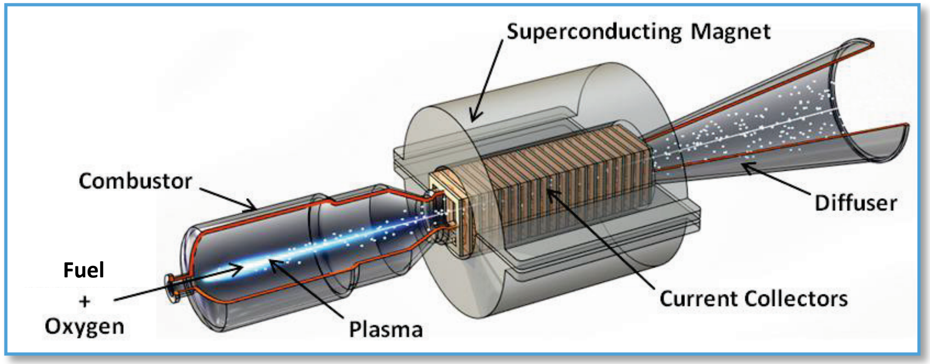
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

# "Direct Power Extraction" (DPE)
## *Making Oxy-fuel Combustion an Advantage*

- **Oxy-fuel combustion greatly simplifies carbon capture because the combustion products are $CO_2$ and $H_2O$, *<u>but</u>*, producing oxygen requires a lot of energy.**
- **If you make significant extra power *because* of the available oxygen, *<u>oxy-fuel combustion would be an advantage.</u>***
- **The high temperatures possible with pure oxygen combustion can be used to operate a magnetohydrodynamic (MHD) "topping" cycle:**
  - MHD exits to conventional steam boiler system ("bottoming cycle").
  - Provides "capture-ready" feature of oxy-fuel.
  - Could be retrofit to coal steam plants

<u>MHD generator concept</u>

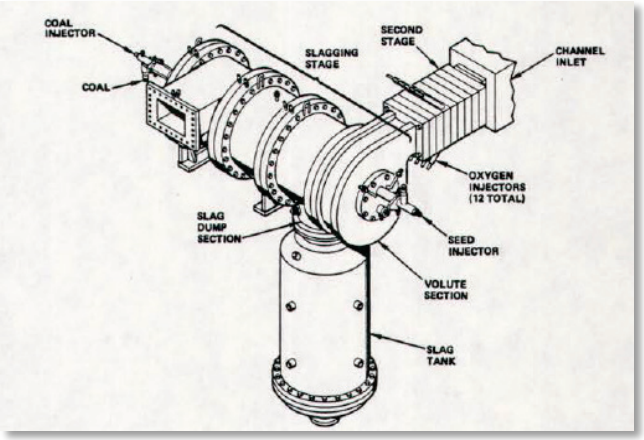
High-temperature oxy-fuel combustion (with conductivity seed) accelerates through magnetic field to produce current. Hot exhaust used in conventional steam boiler.



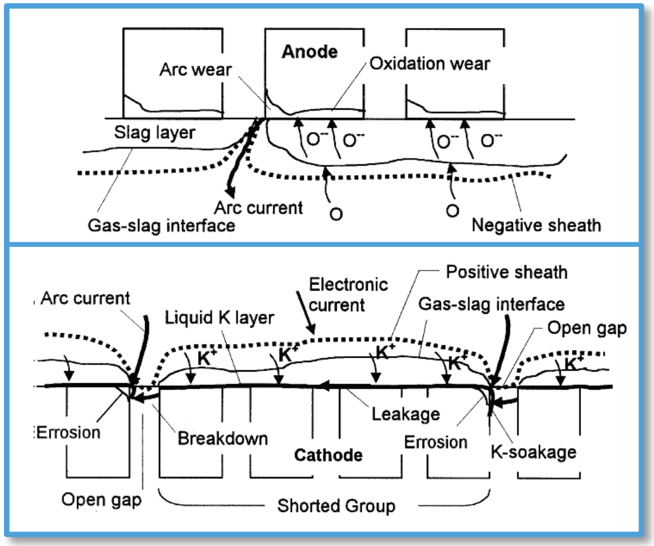
# MHD Power Generation Efforts

- **Concept proven in both U.S. and USSR in 70's and 80's:**
  - U.S. DOE: 1978-1993
  - Electricity transferred to grid
- **U.S. Direct-Fired Coal Open Cycle MHD program discontinued in 1993[1]:**
  - Slag retention problems in combustor
  - Channel operation problems, particularly with electrode damage
  - Concerns about the cost-effectiveness of seed regeneration process
  - Uncertainties in fully integrating MHD systems
  - Uncertainties in scaling up MHD systems
- ***Objective:*** **Reassess MHD power generation feasibility with recent technology advances and oxy-fuel combustion advantage for carbon capture**

*TRW 50$MW_{th}$ oxy-coal combustor[2]*




*MHD Electrode Issues[3]*





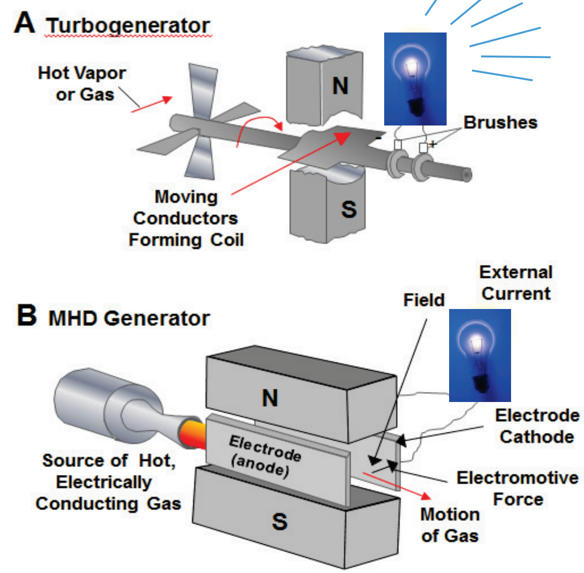

[1] U.S. General Accounting Office, Report GAO/RCED-93-174, 1993
[2] TRW, Final Technical Report No. MHD-III-89-002, 1989
[3] Kayukawa N., Progress in Energy and Combustion Science, **30**:33-60, 2004

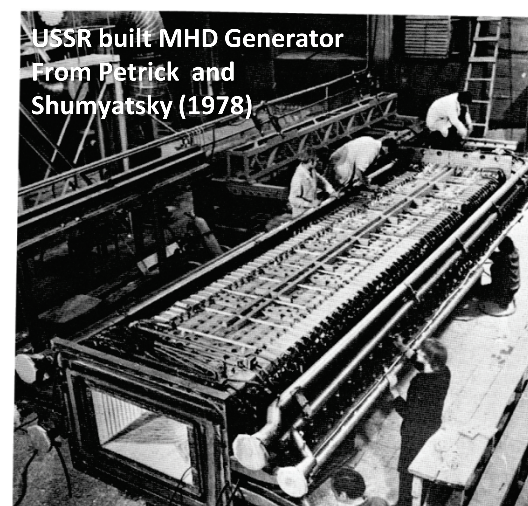
# MHD: Then and Now

| Legacy MHD program (U.S.: 1970s – 1993) | Today | Comments |
|---|---|---|
| No $CO_2$ capture | $CO_2$ Capture | High Temperature Oxy-fuel combustion for $CO_2$ capture enables MHD. |
| Large demos | Simulation & bench scale experiments | 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! Use oxy-fuel gas processing unit (GPU). |
| 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 | Advanced 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 in MHD power systems may be possible |

# Direct Power Extraction (via MHD)

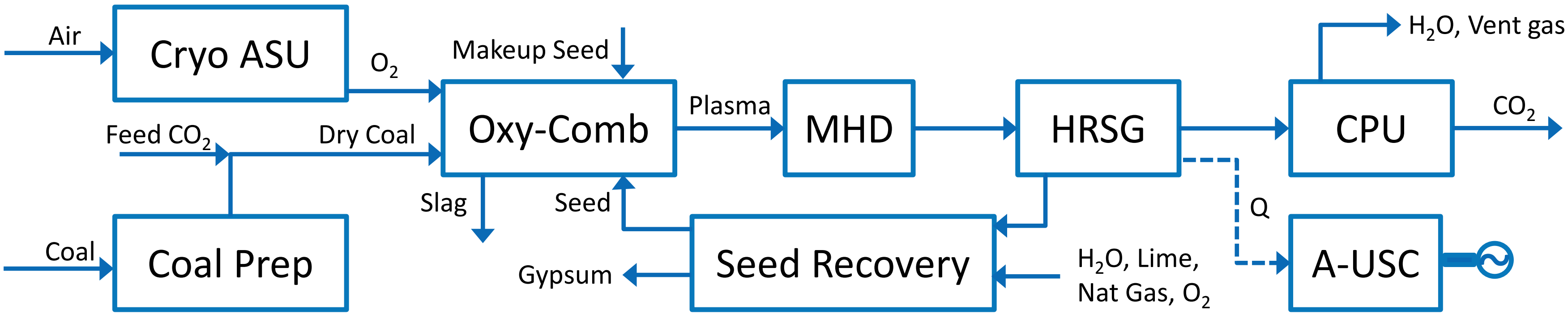
- **To generate MHD power: *Power* $\propto \sigma u^2 B^2$**
  - $\sigma$ = gas/plasma electrical conductivity
    - Generated with very high (oxy-fuel) temperature and ionizing seed materials (e.g., potassium)
  - $u$ = gas/plasma velocity
    - Accelerate plasma to near sonic velocities
  - $B$ = magnetic field
    - Use superconducting magnets for high field
- **To extract power:**
  - Need robust electrodes capable of withstanding high temperatures, thermal gradients, slagging, arcing, and high electric fields
  - Extract thermal energy in high temperature exhaust for high overall power plant efficiency





USSR built MHD Generator From Petrick and Shumyatsky (1978)

*MHD generator concept proven in 1980s w/ grid transferred power in both U.S. and USSR*

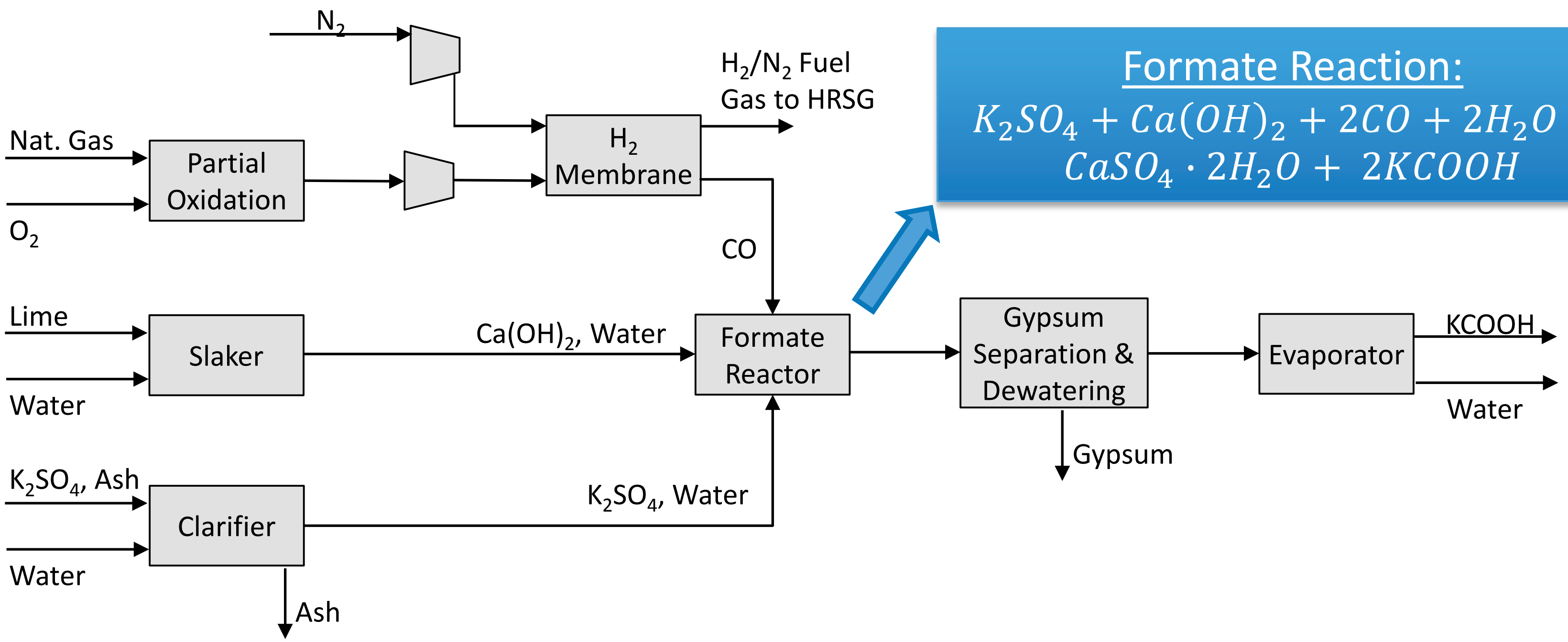
# DPE Plant Design Basis




- **Nominal plant input of 1000 $MW_{th}$ sub-bituminous (PRB) coal, dried to 5% moisture, dry-fed with 8 wt% recycled $CO_2$**
- **Cryogenic Air Separation Unit (ASU) with 95% purity oxygen (195 kW/tonne $O_2$)**
- **Oxy-coal combustion with 90% slag rejection**
- **Injection of recovered and makeup potassium seed to generate plasma**
- **MHD power extraction and conversion to AC electrical power**
- **Heat Recovery Steam Generator (HRSG) for Advanced Ultra-Supercritical (A-USC) bottoming cycle with reheat (1350 °F/1400 °F/5000 psig)**
- **$CO_2$ purification and compression unit (CPU) for pipeline-quality $CO_2$**

# Seed Recovery Process

- **Potassium recovery required for economic MHD plant operation**
  - Precipitates out as $K_2SO_4$ in the HRSG, captured with ash in the ESP
- **Based on the Formate seed recovery process from the University of Tennessee Space Institute[4]**
  - ~1.3 wt% potassium loading to recover coal sulfur as gypsum
  - Requires natural gas partial oxidation to generate CO for reaction



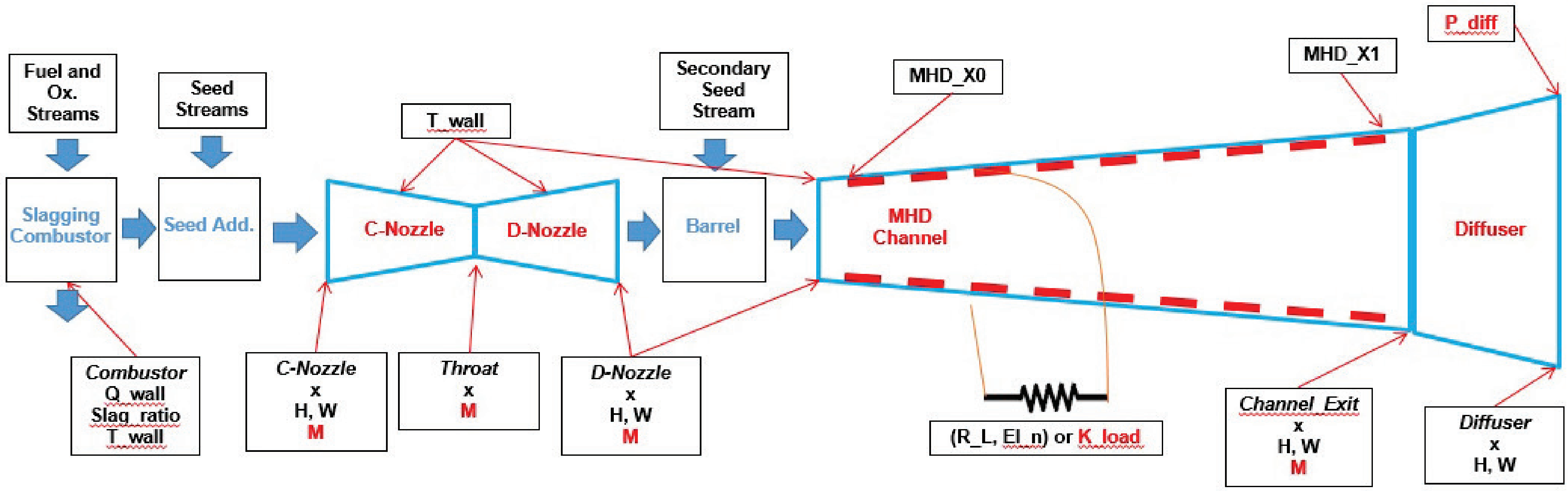

<u>Formate Reaction:</u>

$$K_2SO_4 + Ca(OH)_2 + 2CO + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + 2KCOOH$$

[4] Sheth, A., J. Holt, D. Rasnake, L. Crawford, R. Solomon, G. Wilson, and H. Herrigel, MHD Seed Recovery and Regeneration Based on the Formate Process – Phase I Final Report, DE-AC22-87PC79671, October 1988.

# 1-D Model for Channel Design

- **NETL 1-D MHD channel model tailored to meet channel and overall plant design needs**
  - Includes block calculations for combustion, slag rejection, & seed addition
- **Forward-integrated 1-D calculations include:**
  - Nozzle, MHD channel, diffuser for specified area or Mach number
  - Profiles of: heat loss, power extraction, temperature, pressure, etc.



# DPE Channel Design Assumptions

- **Assume 6 Tesla superconducting NbTi magnet, channel wall temperature of ~1650 °C, and diffuser exhaust at atmospheric pressure**
- **Evaluate plants for two channel designs:**
  - DPE-1 (current state-of-the-art): Mach 0.8 flow, fuel-rich combustion, modern channel electrical parameters
  - DPE-2 (advanced channel design): Mach 0.95, stoichiometric combustion, advanced electrical design for higher power density
- **Channel Processes Modeled:**
  - Convective and radiative heat losses to the channel walls
  - Boundary layer viscous losses
  - Electrode voltage drops due to loss of plasma electrical conductivity in the thermal wall boundary layer
  - Tapered magnetic field to meet electrical channel constraints
- **Channel designs optimized using a second law thermodynamic work potential function**

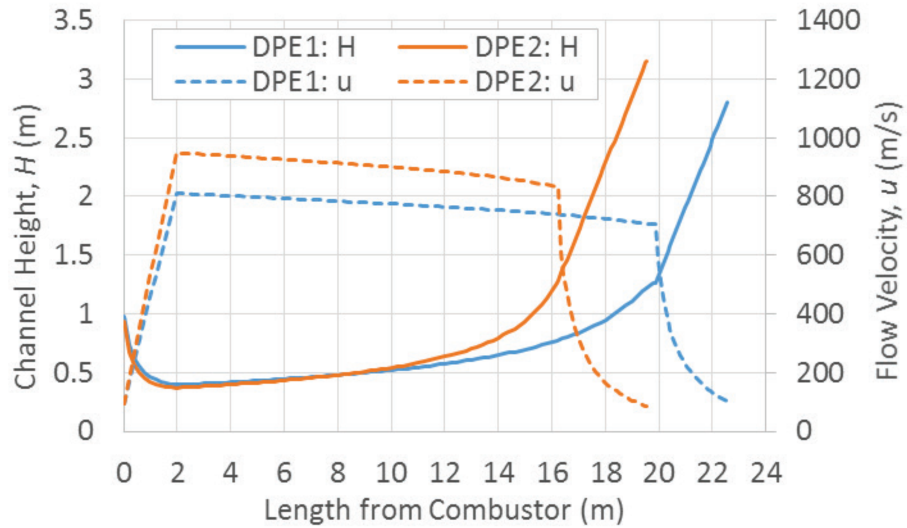
# Channel Design Results

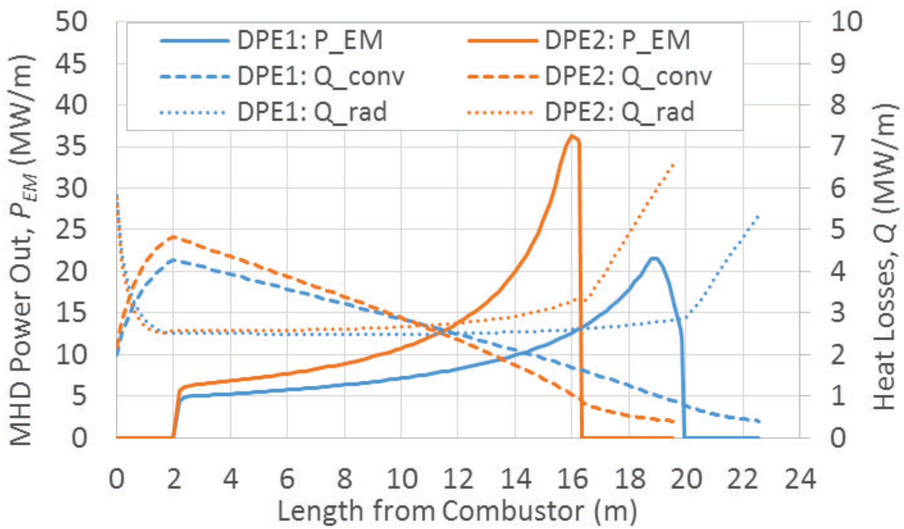
- **Stoichiometric combustion for DPE-2:**
  - Increases mass flow
  - Increases channel inlet temperature
- **Higher power density and Mach number for DPE-2 allows for:**
  - Higher power extraction with increased pressure
  - Reduced channel length and lower heat losses

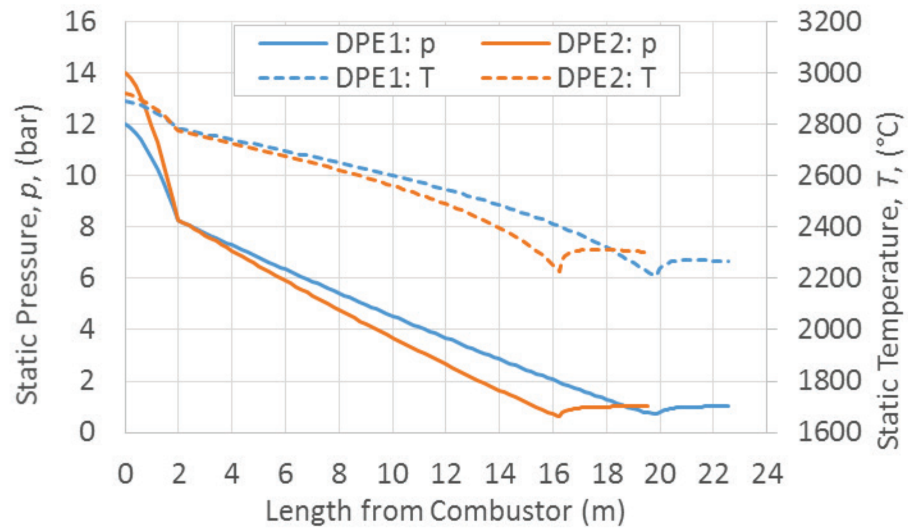
| Parameter | units | DPE-1 | DPE-2 |
|---|---|---|---|
| Stoichiometry | | 0.9 | 1.0 |
| Combustor Pressure | bar | 12 | 14 |
| Mass Flow | kg/s | 121.4 | 129.3 |
| Mach Number | | 0.8 | 0.95 |
| Combustor Exit Temperature | °C | 2891 | 2919 |
| Channel & Diffuser Length | m | 22.6 | 19.5 |
| Diffuser Exit Temperature | °C | 2265 | 2302 |
| Convective Heat Loss | MW | 56 | 53 |
| Radiative Heat Loss | MW | 63 | 61 |
| **MHD DC Power output** | **MW** | **168** | **184** |
| Electric Field, $E_x$ | V/m | 2496 | 3909 |
| Current Density, $J_y$ | $A/cm^2$ | 0.80 | 1.00 |

# Channel Design Results

- **MHD profiles include:**
  - Nozzle (first 2 meters)
  - Constant Mach number MHD channel
  - Diffuser (last 2-3 meters)
- **Heat losses partially recovered in bottoming cycle**

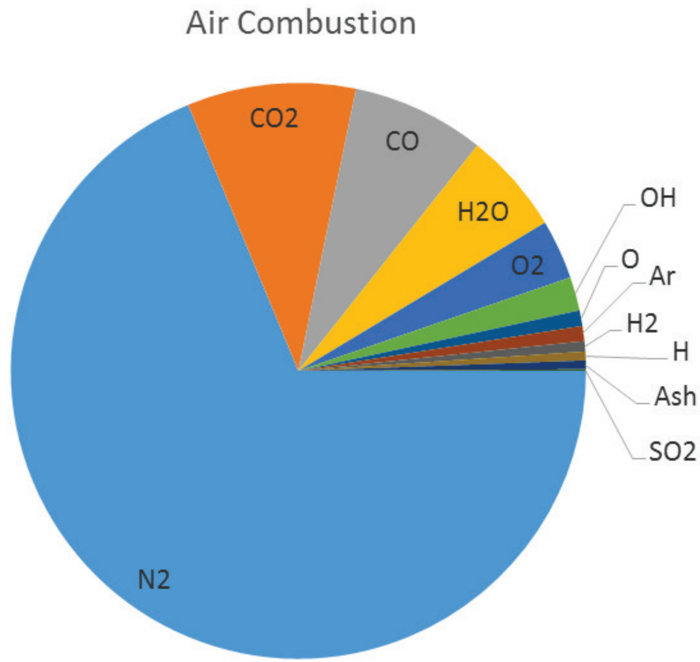


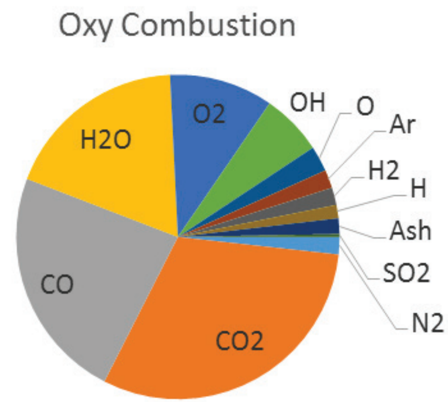



# Air-fired vs. Oxy-fired MHD

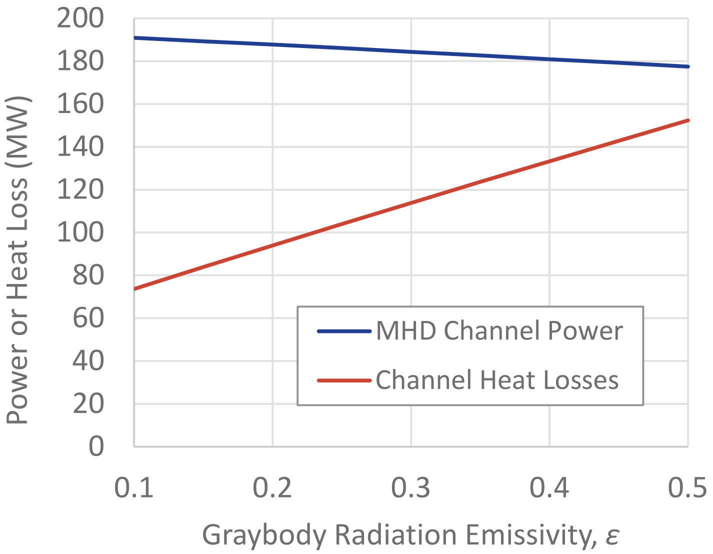
- **Absence of nitrogen from air is significant**
  - For a given fuel input, channel mass flow and cross-sectional area are reduced
    - Larger impact of heat losses to the channel walls due to higher surface area to volume ratio.
    - Reduced channel cross-sectional area reduces costs of channel and superconducting magnet
  - Fuel derived material is a larger fraction of channel mass flow
    - Ash and sulfur mass fractions increase
    - Potassium seed requirements more driven by sulfur recovery than plasma conductivity needs
  - Final oxy-combustion temperatures reduced
    - Higher heat capacity of $CO_2$ and $H_2O$ relative to $N_2$
    - Increased impact of $CO_2$ dissociation to CO & $O_2$
    - Air combustion dependent on air preheating to achieve thermal plasma temperatures

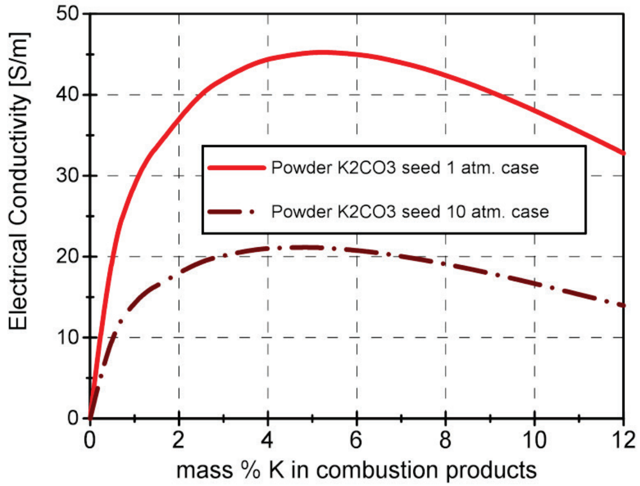


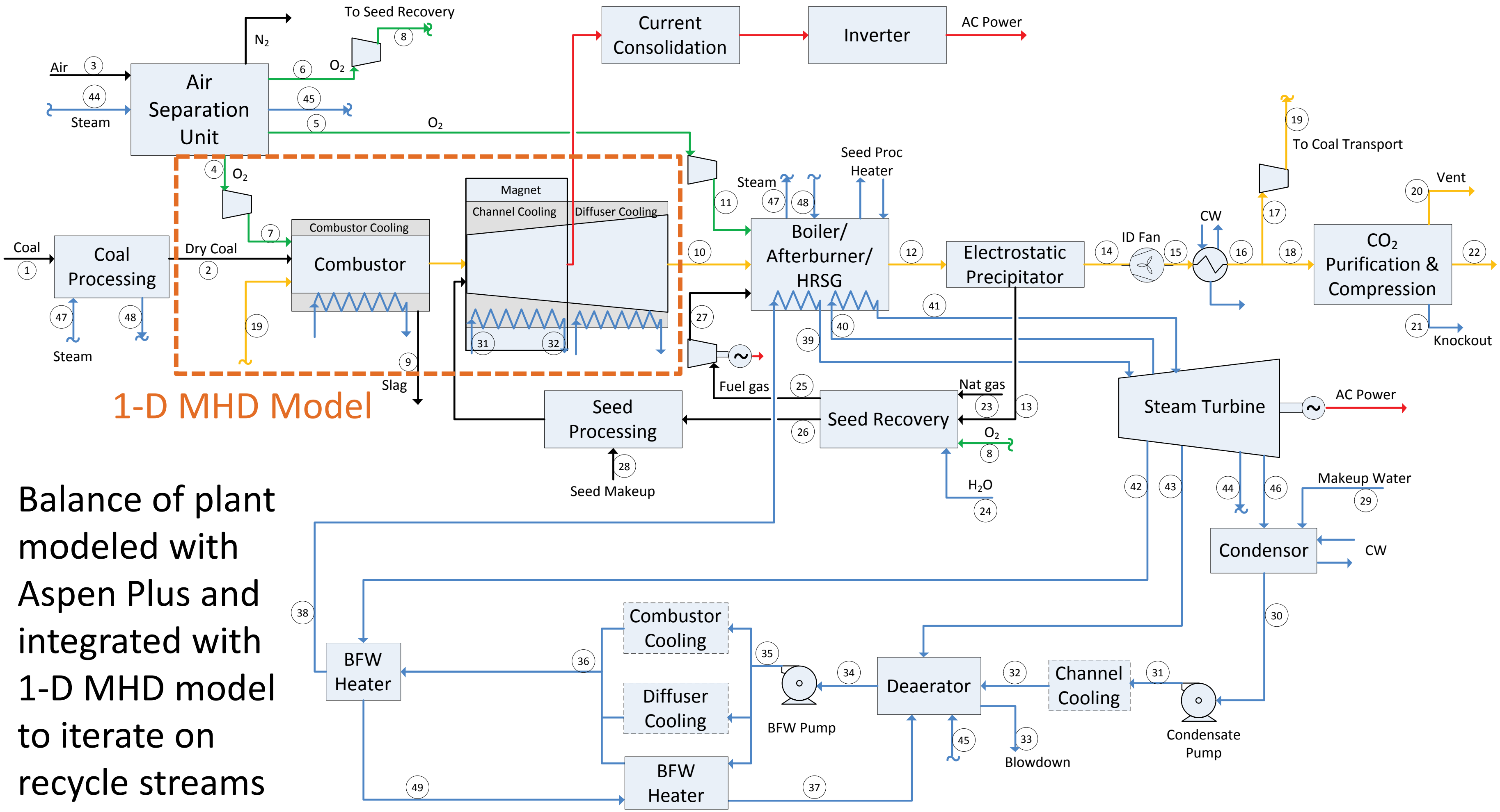
# Sensitivity to Channel Assumptions

- **Due to change in primary channel fluid from $N_2$ to $CO_2$, many modeling assumptions require validation for the oxy-coal combustion case**
  - Overall radiative heat transfer emissivity
  - Boundary layer development and electrode voltage drops
  - Plasma electrical conductivity
- **Experiments and/or CFD modeling efforts are underway at NETL to refine these assumptions**



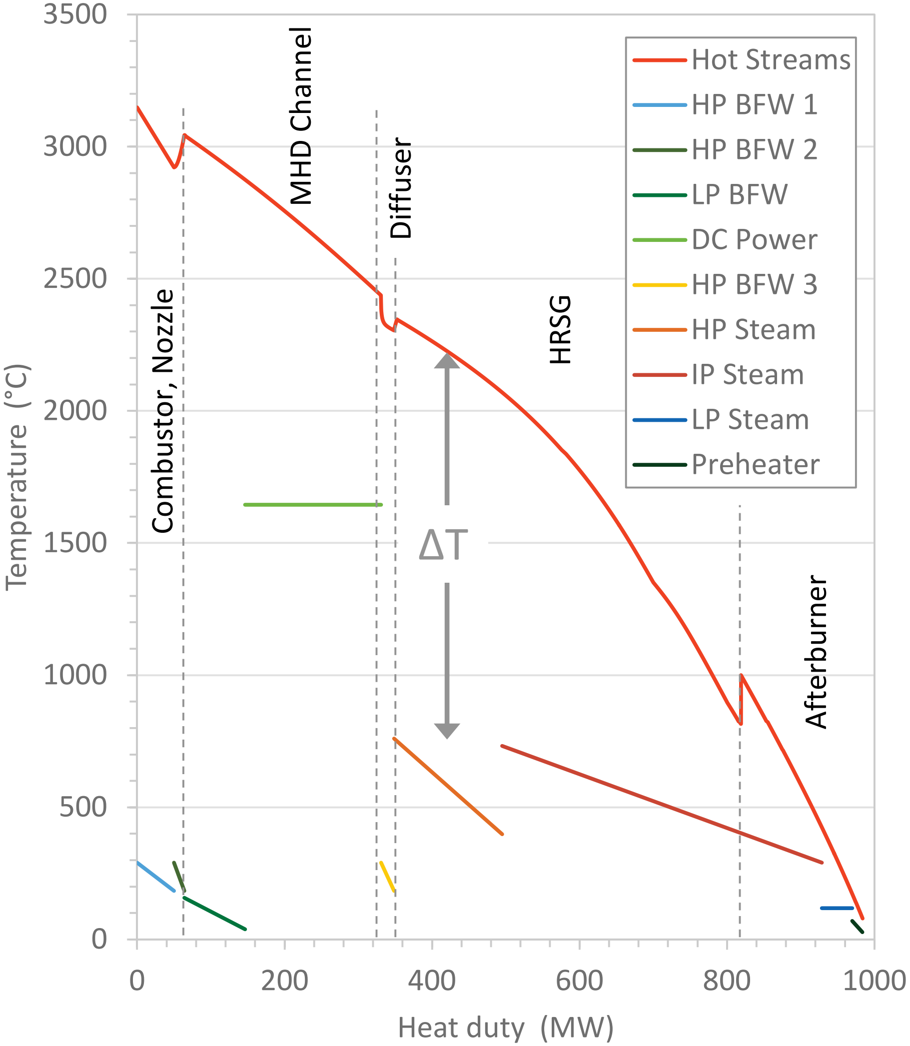
# DPE Power Plant - Process Flow Diagram




Balance of plant modeled with Aspen Plus and integrated with 1-D MHD model to iterate on recycle streams

# Temperature/Heat Duty Analysis

- **Very large temperature differences lead to inefficiency (exergy destruction)**
  - Cooling water losses (and costs) dictate shorter MHD channels
  - Higher electrode temperatures would improve MHD efficiency
- **Large ΔT in HRSG and afterburner limited by AUSC steam conditions**
  - High quality thermal energy better utilized in legacy MHD program via high temperature air preheating
    - Preheating oxygen presents a safety concern
  - Potential for improvement:
    - Closed (disk) MHD "middle" cycle
    - Coal gasification

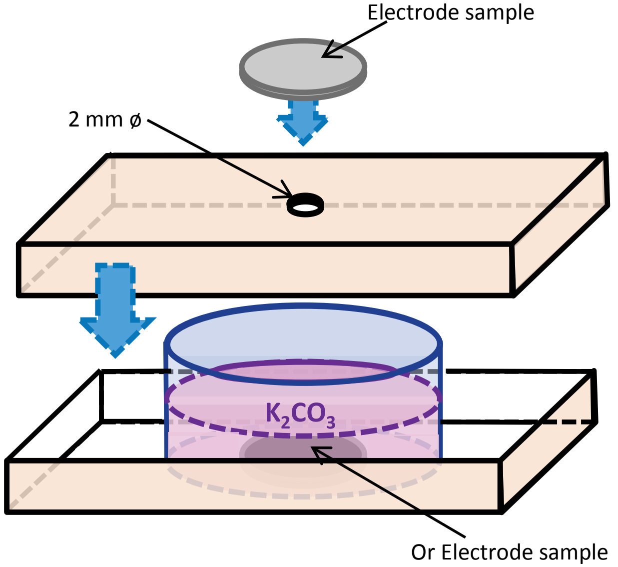


# Conclusions and Future Work

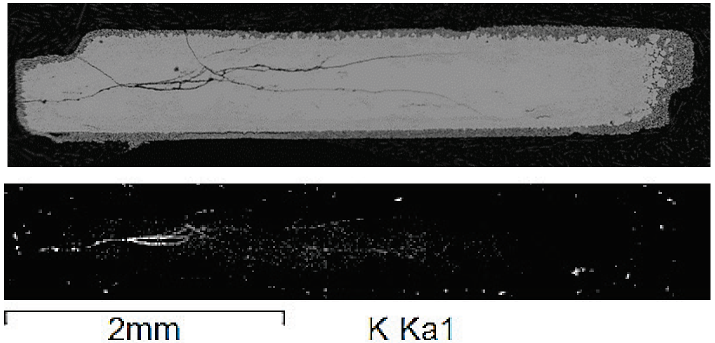
- **Developing the *first* pure oxygen-fired coal MHD system performance analysis with CCS**
  - Net plant thermal efficiency expected to be competitive with competing oxy-coal technologies
- **Currently completing balance of plant design and estimating capital costs to determine COE, completing a baseline systems study**
  - Large magnet cost in legacy systems is reduced ~75% for oxy-coal DPE
  - Obtain channel and combustor costs by updating legacy cost scaling algorithms to present day dollars
  - Seed recovery process cost estimated with Aspen Plus Economic Analyzer
- **Several future analyses being considered to extend this work**
  - Investigate effects/dependency on channel wall temperature
  - Optimization of seed recovery process to improve cost & performance
  - Look at alternate fuels (e.g., petcoke), supersonic channels, non-equilibrium plasma effects, triple cycles, and other improvements

# NETL R&D – High Temperature Materials

- **R&D Focuses on MHD Electrodes**
  - Good electrical conductivity & adequate thermal conductivity
  - Resistance to electrochemical corrosion (seed/slag)
  - Resistance to erosion by high velocity particle laden flow (seed/slag)
  - Resistance to thermal shock
  - Compatibility with other materials in system
  - Resistance to/minimization of arc attack/erosion
- **Internal NETL Activity**
  - Electrode exposure characterizations ->
- **University Funded R&D on "Hot" Electrodes**
  - Carbon nanotubes in ceramic matrix: Univ. Nebraska
  - Nanostructured SiC based materials: Univ. of Washington
  - Boride based materials: Univ. of Idaho
  - Combustion synthesis of Boride based materials: UTEP
  - Carbide and Boride Ceramics: FIU



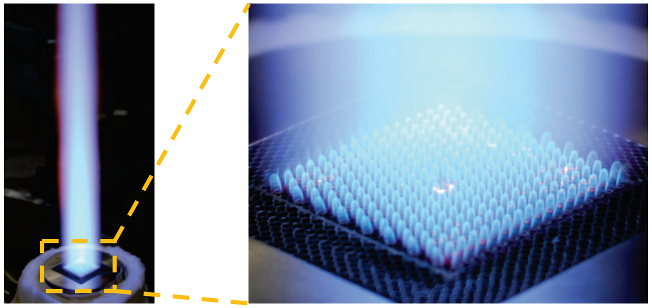

**82%$HfO_2$-10%$CeO_2$-8%$Y_2O_3$ – exposed to $K_2CO_3$ liquid**

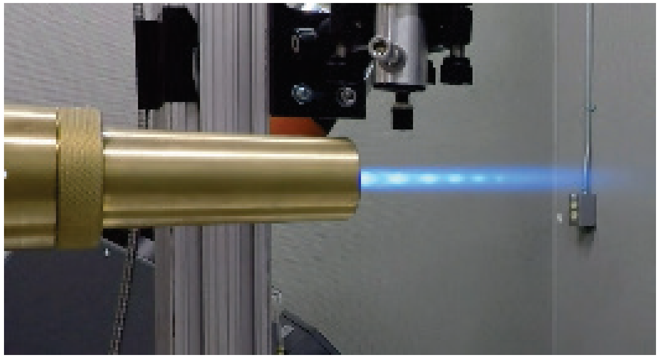


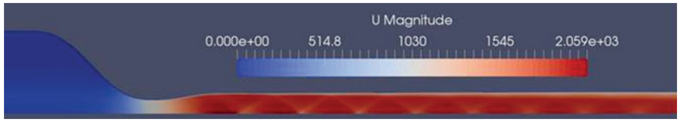

**Sample Cracking Visible with K present**

# NETL R&D – Experimentation & Simulation

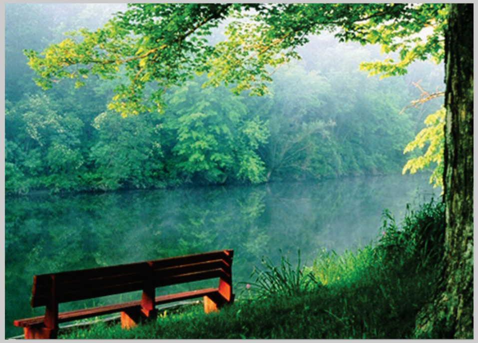
- **Experimentation in NETL's FC lab**
  - Custom oxy-fuel Hencken burner
  - Potassium carbonate solution seeding
  - Double Langmuir probe for conductivity measure
- **Experimentation in NETL's MHD lab**
  - Operation of liquid fueled high velocity oxy-combustor (supersonic) w/ seed injection
  - Goal is bench scale MHD channel testing
  - Studying non-equilibrium plasma generation in the channel wall boundary layer
  - 2-D and 3-D channel simulations to validate
- **Experimentation at UTEP**
  - Developing and testing a high velocity oxy-methane combustor

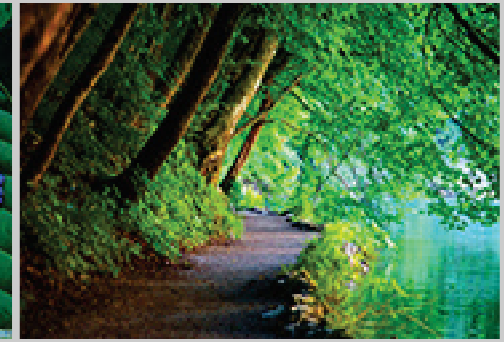






# It’s All About a Clean, Affordable Energy Future



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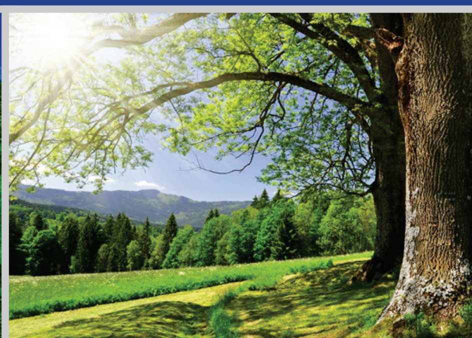
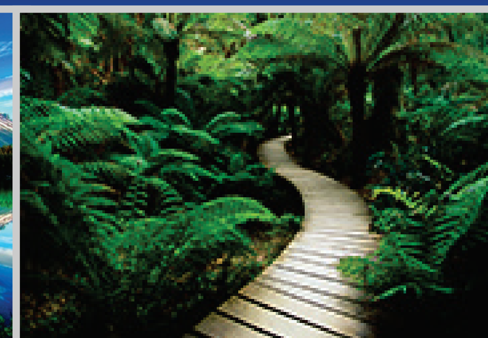




# 1-D Channel Code Methodology

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

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

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

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

$$\text{Momentum}: \rho u \frac{du}{dx} + \frac{dP}{dx} = F_{EM} - F_{friction}$$

$$\text{Energy}: \rho u \left( u \frac{du}{dx} + \frac{dh}{dx} \right) = P_{EM} - Q_{wall} - Q_{rad}$$

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

$$\text{Lorentz}: F_{EM} = J_y B_z$$

$$\text{Power}: P_{EM} = J_y E_y + J_x E_x$$

- 5 main equations (**mass**, **momentum**, **energy**, **chemical reaction**, **boundary layer**) for the flow state.
- 2 equations (generalized Ohm’s law) for the EM field.
- Additional equations for Channel to account for:
  - Electrode Configuration
  - External Load

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

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

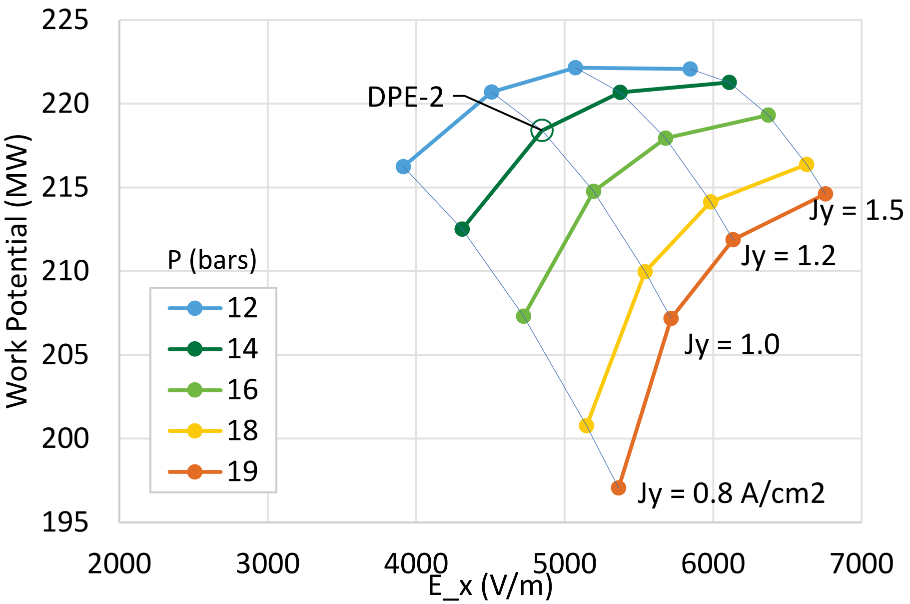
$$E_x = \frac{1}{\sigma}(J_x + \omega\tau J_y)$$

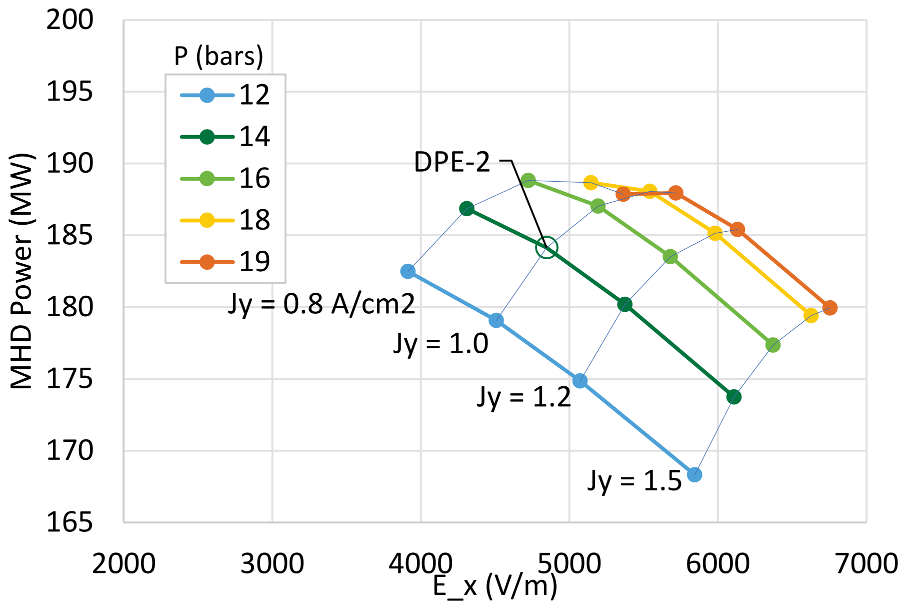
$$E_y = \frac{1}{\sigma}(-\omega\tau J_x + J_y + \sigma u B)$$

The code calculates the variable power outputs along channel length.

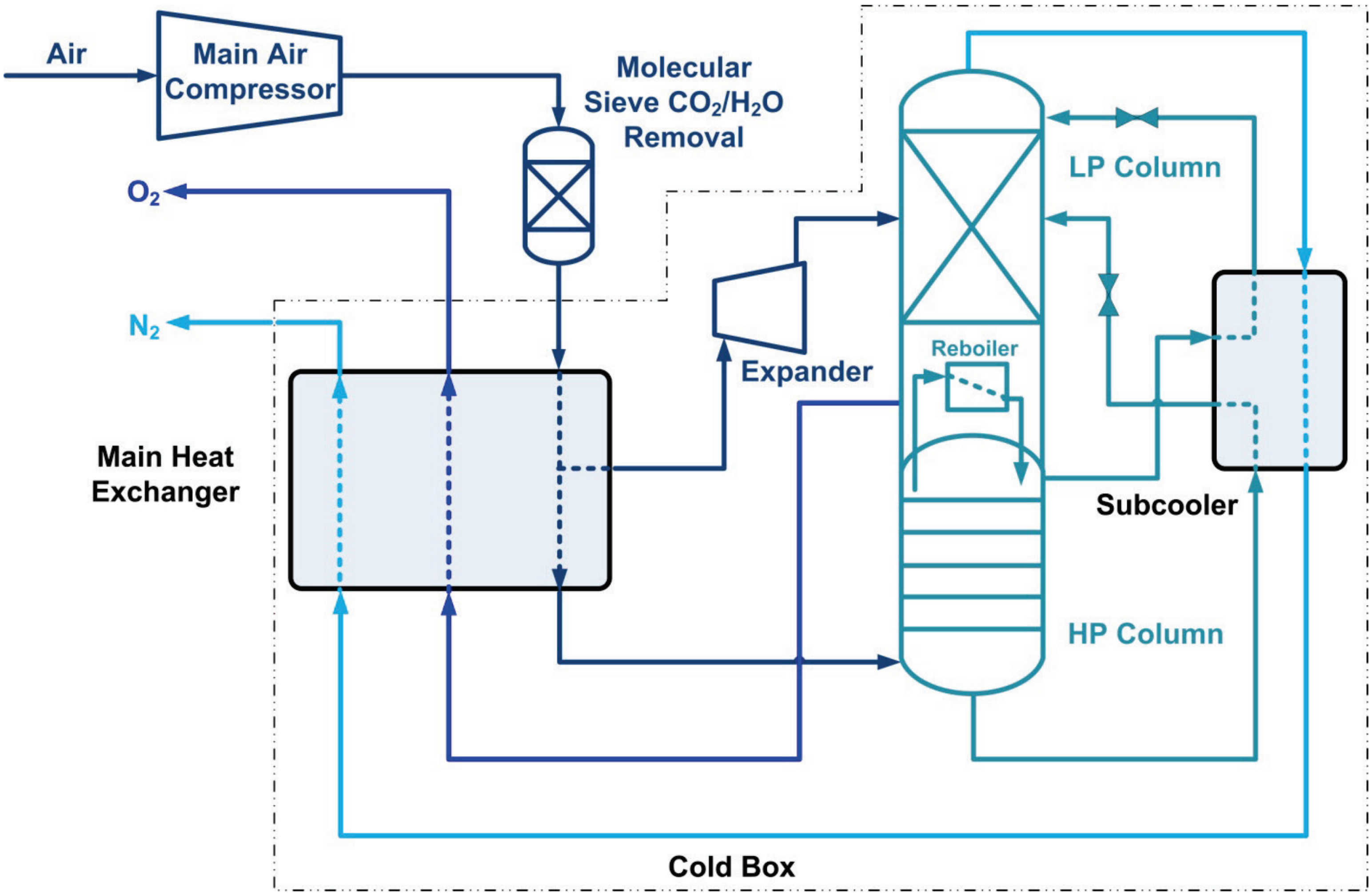
# DPE Channel Design

- **Channel designs optimized using second law work potential function**
- **Design procedure:**
  - Vary pressure and electrode spacing at desired values of current density, $J_y$
  - Maximize work function at reasonable values for axial electric field, $E_x$
  - Limit channel length based on boiler feedwater heating duty of steam cycle
  - Taper magnetic field to meet exact $E_x$ specification



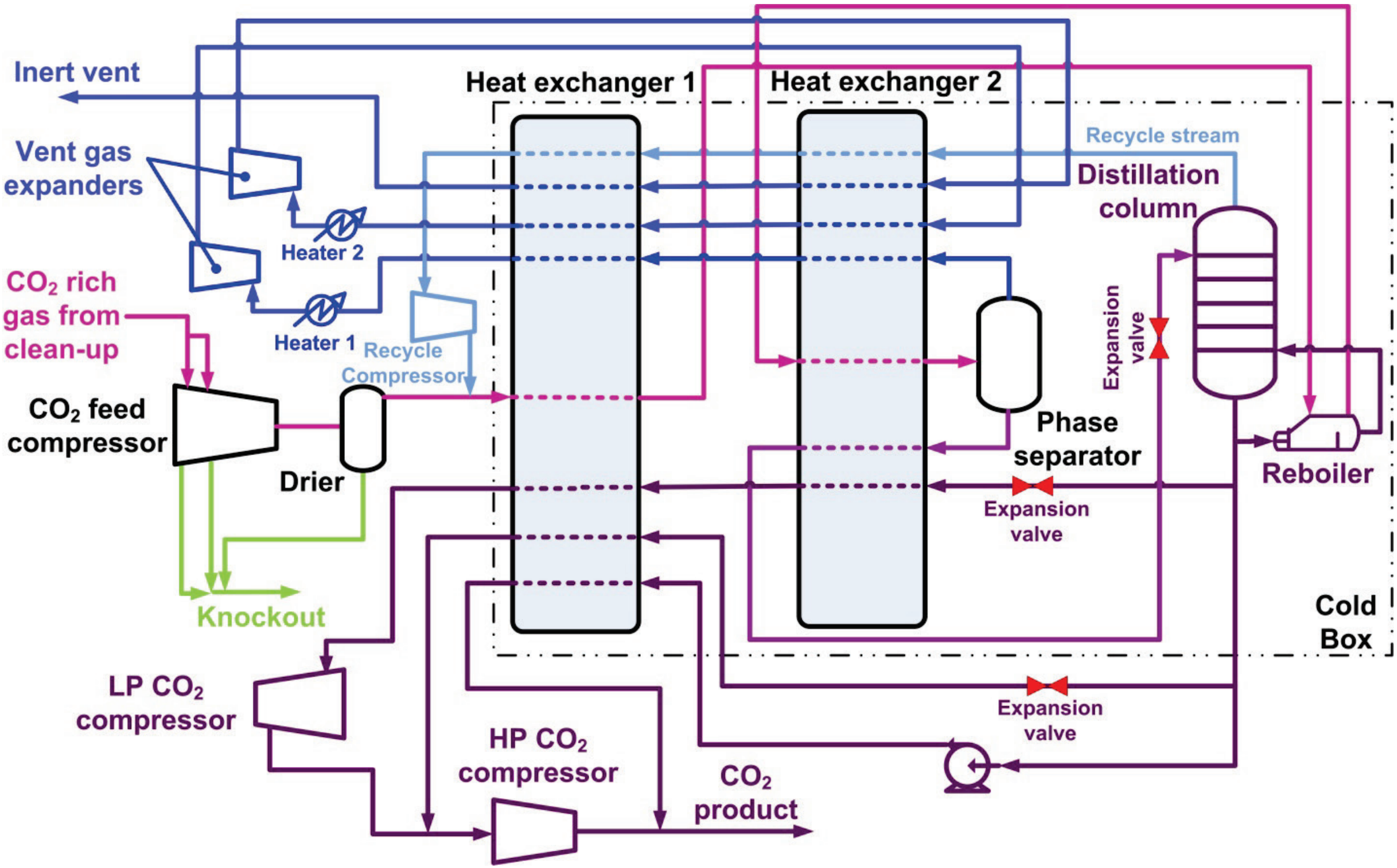
# ASU Sub-Model Block Flow Diagram



# ASU Sub-Model

- **Granular model developed to attain target specific power**
  - Specific power = 195 kW/tonne $O_2$
- **Oxygen product purity is 95 mole percent $O_2$**
  - 2.8 mole percent Ar
  - 2.2 mole percent $N_2$
- **Aspen System Model used "Black box" ASU Representation**
  - Split fractions tuned to give same output as granular ASU model
  - MAC outlet pressure adjusted to yield target specific power

# CPU Sub-Model Block Flow Diagram



# CPU Sub-Model

- **Granular CPU model not embedded into DPE system model**
  - No integration of CPU with other portions of DPE process
  - This sped up convergence significantly
  - Granular model run once after system model converged

- **$CO_2$ purity 99.99 mole percent**
  - $O_2$ concentration in $CO_2$ product 10 ppmv
  - Ar concentration in $CO_2$ product 62 ppmv
  - $NO_x$ concentration in $CO_2$ product 10 ppbv
  - $SO_x$ concentration in $CO_2$ product 4 ppbv
  - $N_2$ concentration in $CO_2$ product < 1 ppbv

- **$CO_2$ recovery 96.3 percent**