Retrospective and Prospective Aspects of MHD Power Generation

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Outline of Talk

- **Important Aspects 101**
  - – Fundamentals
  - – Motivations
  - – Example Problem
- **Perspective**
  - – Past
  - – Future

Note: Some images have been removed due to copyrights

What is Magnetohydrodynamics (MHD)?

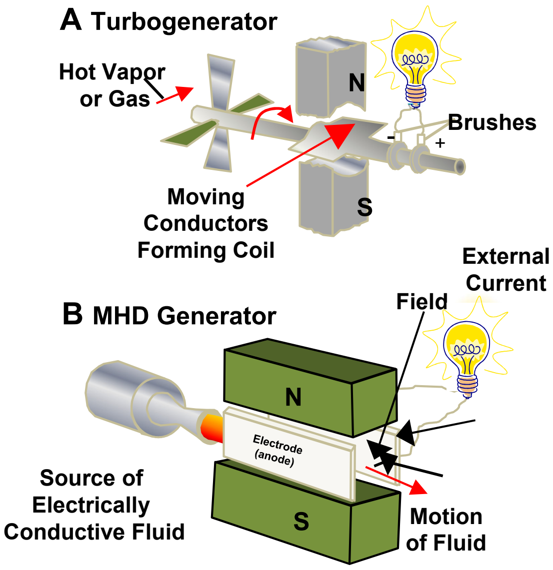
MHD describes the interactions of a magnetic field and an electrically conductive fluid

- **In Nature**
  - geomagnetic dynamo
  - solar “wind” and solar “flares”
- **In Engineering**
  - Materials Processing
  - Propulsion/Pumping
  - *Power Generation*
    - Pulsed
    - Steady
      - “Open cycle” MHD -> single pass; eg. combustion products
      - “Closed cycle” MHD -> loop; e.g. Engineered gasses
      - “Liquid metal” MHD -> loop; e.g. 2-phase gas/metal

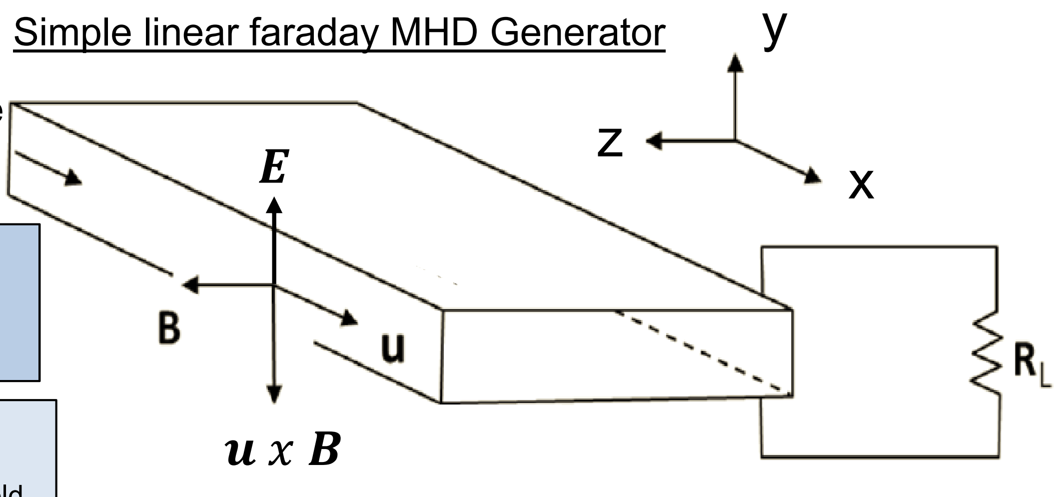
Lorentz Force

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

Engineering Aspects pt. 1



Simple linear faraday MHD Generator



MHD Ex: 1984 1000 MWe
B = 6 T
u = Mach 0.885
E = 4000V/m

B is applied magnetic field
u is the fluid velocity
E is the internal electric field

Side note: If we apply an E and K > 1, we have an accelerator instead of a MHD generator

Two important complications to extracting power:

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

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

Fluid has to “push” through generator against a **jxB** force, & produces an electric power output of:

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

Where σ is fluid electrical conductivity, j is generated electric current density & P_o is electric power density output.

2. Hall Parameter, β -> ratio between electron gyro-frequency & electron-particle collision frequency

$$\beta = \mu_e B = \omega\tau$$

Usually (gas MHD) $0.1 < \beta < 10$

β “tilts” the field and reduces current density output in above simple linear Faraday generator to:

$$j = \frac{\sigma}{1+\beta^2}(uB - E)$$

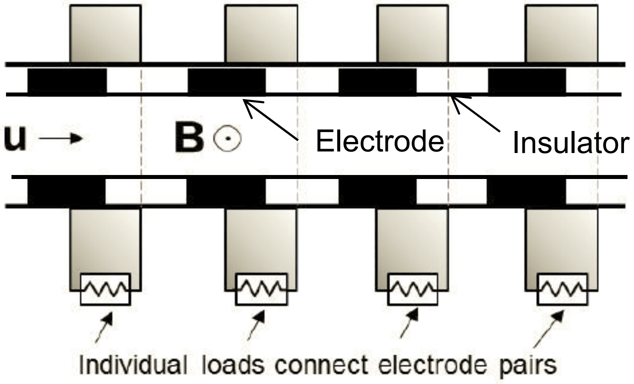
Convention: “Faraday” -> y-direction current & voltage
“Hall” -> x-direction current & voltage

** Due to β, this is for ideal segmented faraday loaded generator (next slide)

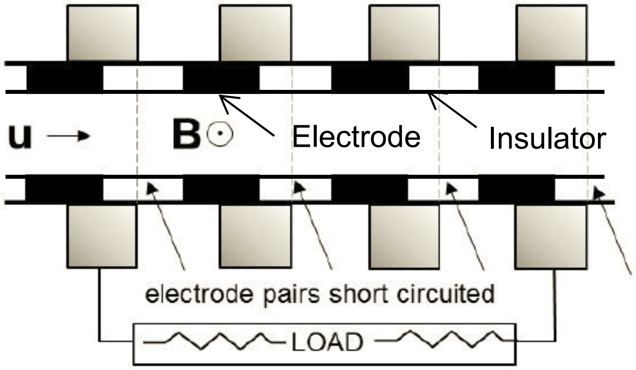
Engineering Aspects pt. 2

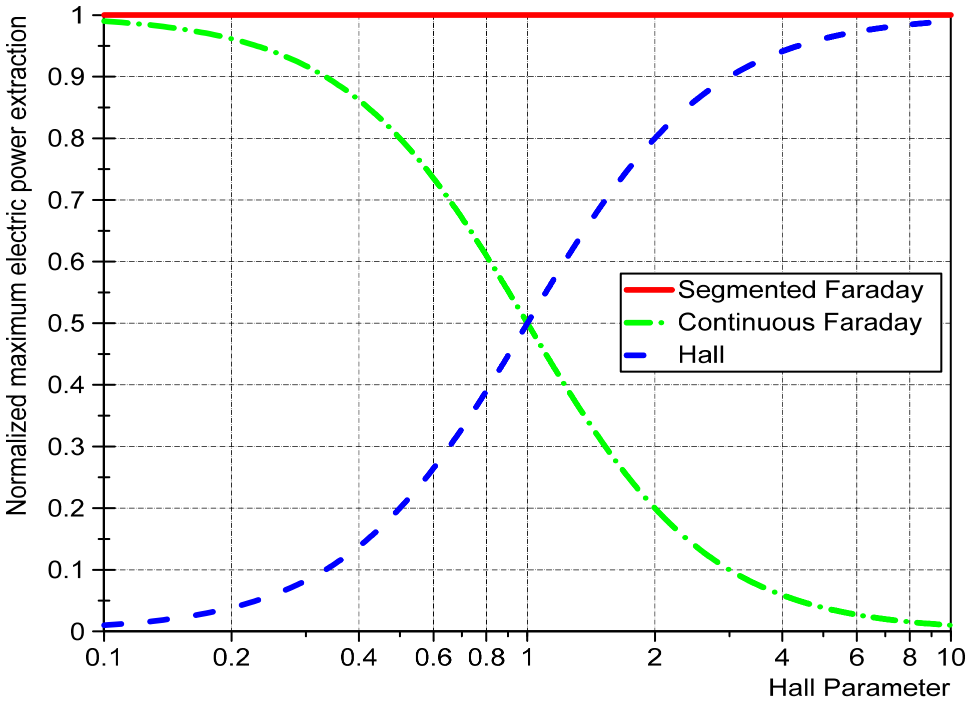
Loading Strategy

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

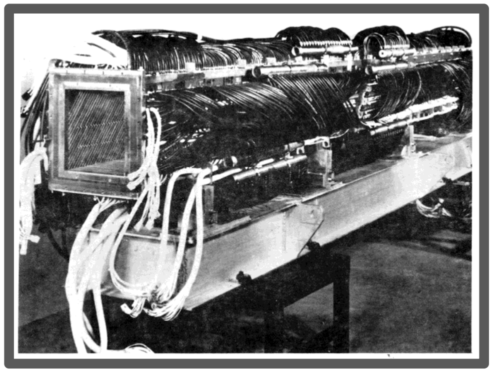




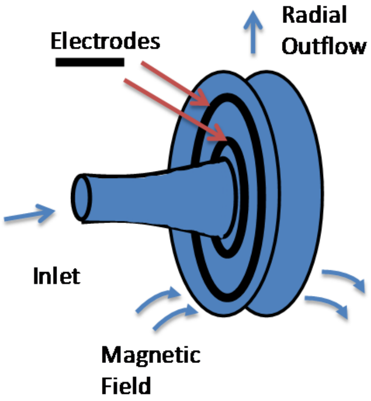
Notes:
-Segmented Faraday Ideal

-Simple continuous Faraday (schematic on last side) & Hall generator approaches ideal power output with low and high hall parameter conditions respectively

Other Variations: Flow Geometry & Loading



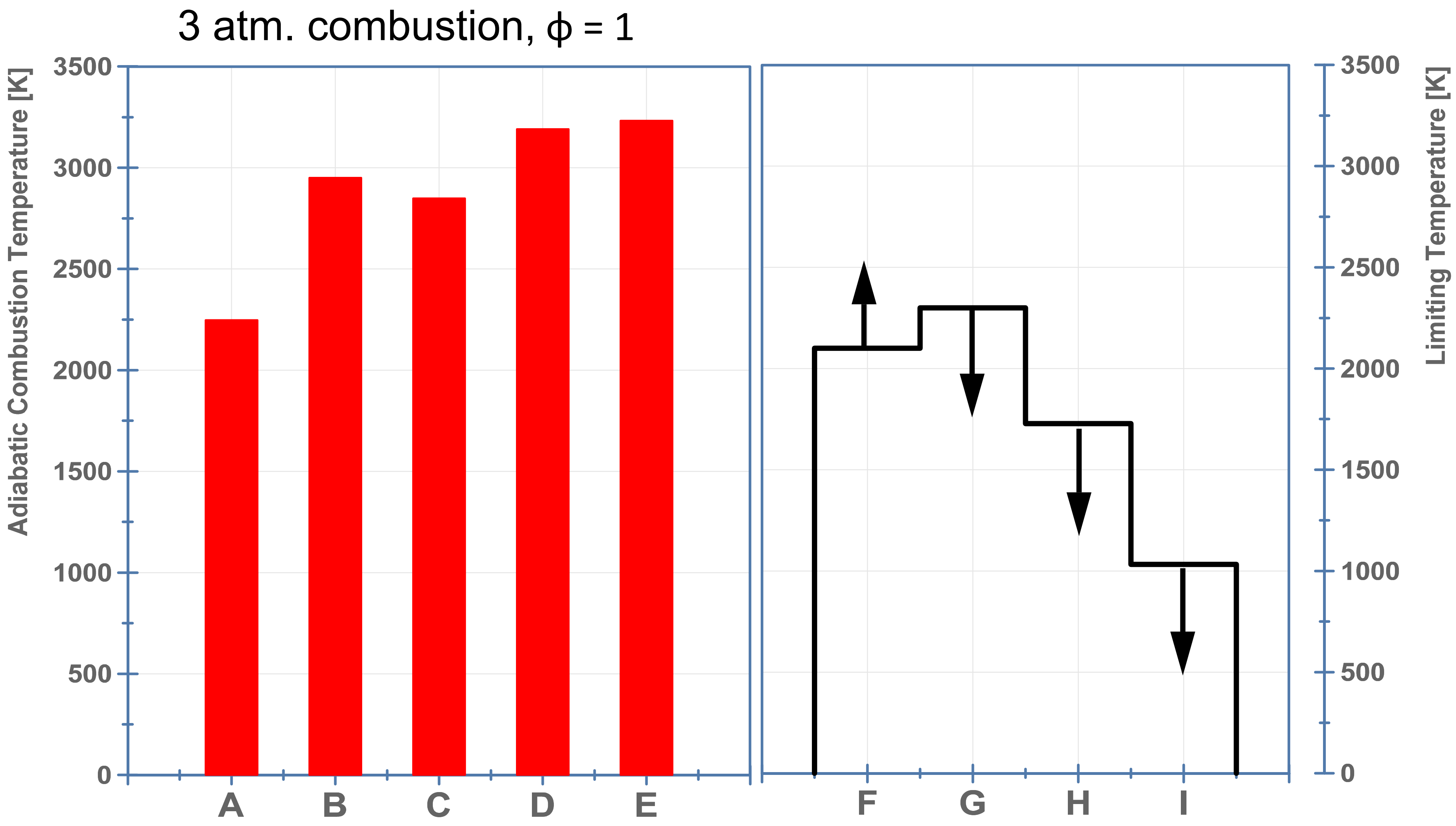
-linear Faraday w/ “diagonal” electrode pairs at angle to net electric field; thus far less load resistors possible



-disc flow geometry so faraday current closes “on itself” (Hall w/ only 2 electrodes)

Others of Interest:
-Annular Generator
-Spiral Generator

Combustion Temperatures & Limitations

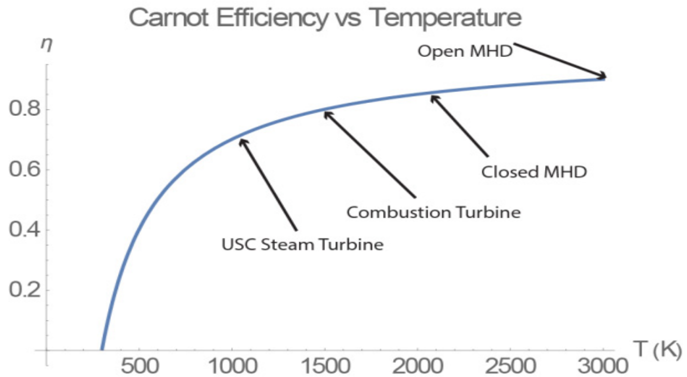


A. methane-air combust
B. methane-air combust w/ 2200 [K] air pre-heat*
C. methane-enriched air (36% O2 by vol.) combust with 922K oxidant pre-heat*
D. methane-oxygen combust
E. methane-oxygen combust w/ 922K oxidant pre-heat

F. Open cycle MHD
G. Closed cycle MHD
H. H-class H2 Gas Turbine
I. A-USC Steam Turbine

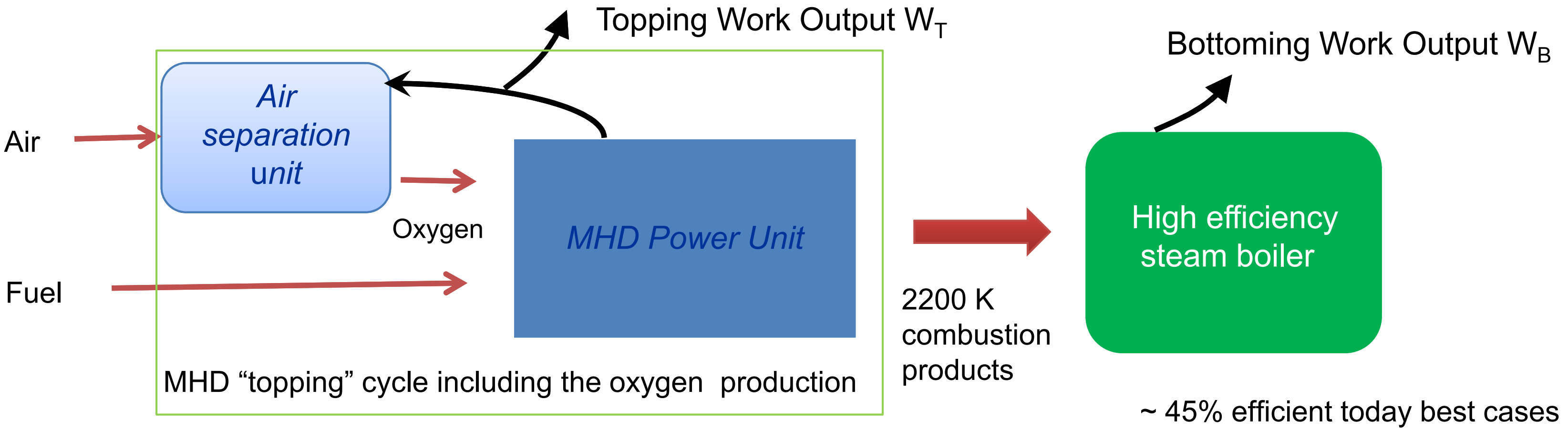
* Representative of “legacy” Open cycle MHD conditions envisioned

Advantages of MHD Power Generation



MHD Power Advantages

1. **Improved C.C. Thermal Efficiency**
2. **Pulsed Power & High Power Density**
3. **No moving parts**



Topping Work Output W_T

Bottoming Work Output W_B

Air

Air separation unit

Oxygen

Fuel

MHD Power Unit

MHD “topping” cycle including the oxygen production

2200 K combustion products

High efficiency steam boiler

~ 45% efficient today best cases

Enthalpy into the “top” = mass flow of fuel x HHV = Q
Work from the top : $W_T = \eta_T \; Q$

Enthalpy into the “bottom” = $Q - W_T = Q\,(1 - \eta_T)$
Work from the bottom: $W_B = \eta_B$ (Enthalpy into the bottom) = $Q\,(\eta_B - \eta_T\,\eta_B)$

Combined cycle efficiency: $(W_T + W_B)/Q = \eta_T + \eta_B - \eta_T\,\eta_B$

Example

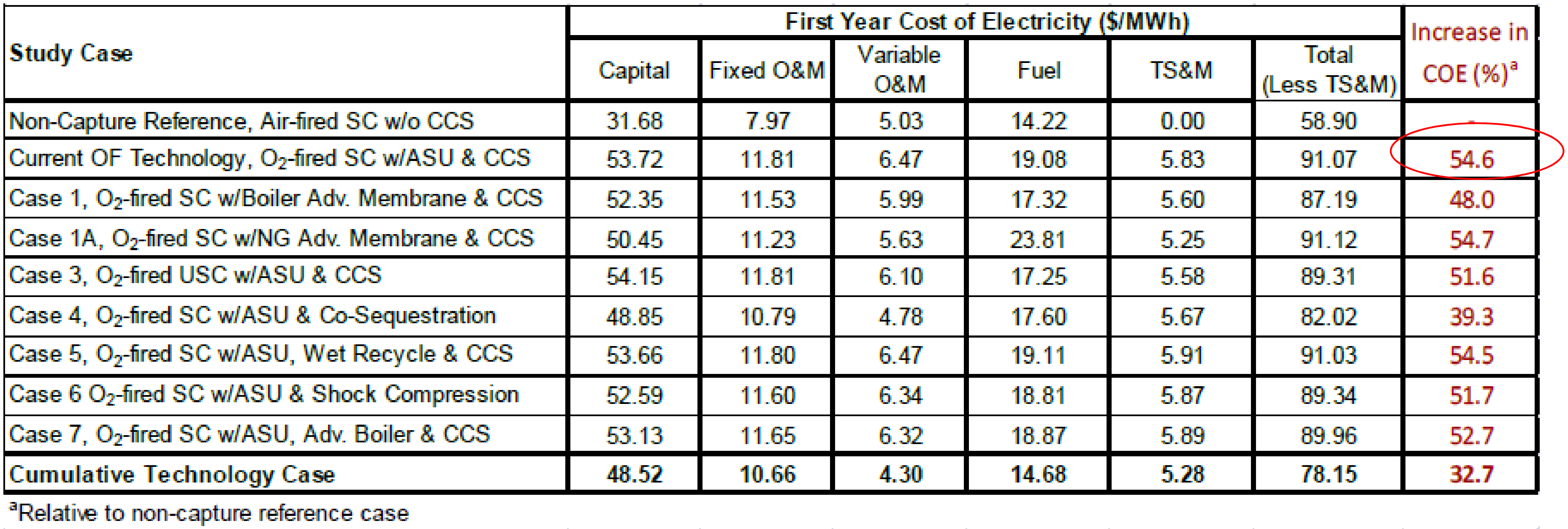
$\eta_T = 0.15$ (15%)

$\eta_B = 0.45$ (45%)

Combined Efficiency:
.15+.45 – (.15)(.45)
= 0.53 (53%)

New Motivations: USDOE FE

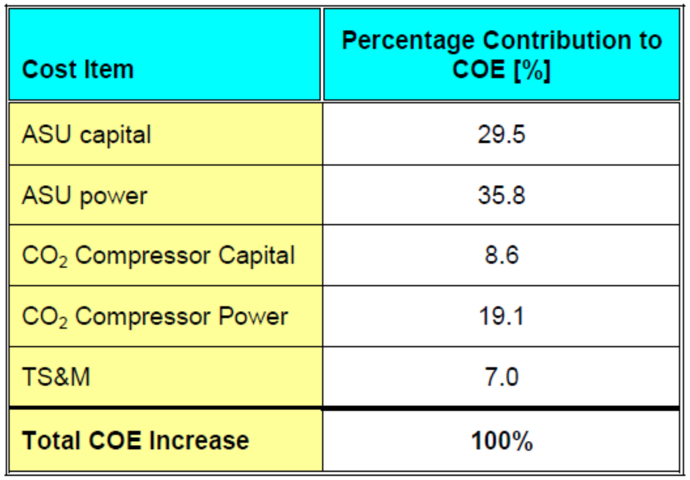
Exhibit 3-117 Increases in Cost of Electricity Over Non-Capture Reference Case



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

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

Example Problem: Conductivity/Gas Dynamics

- **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).

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

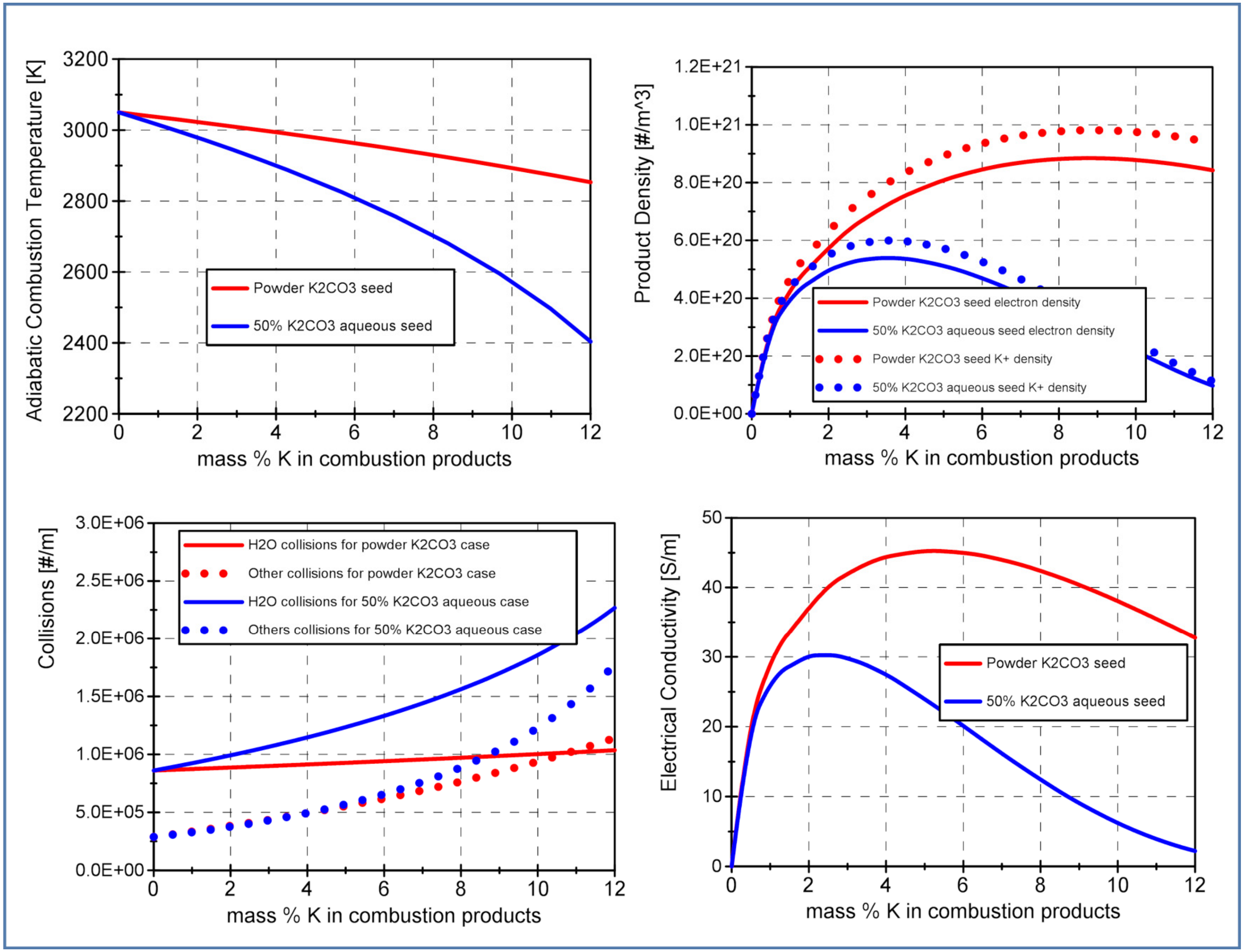
-Neglects ion-electron collisions
-Scalar (no magnet effect)

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]

Seeding: Getting Conductive Flow

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

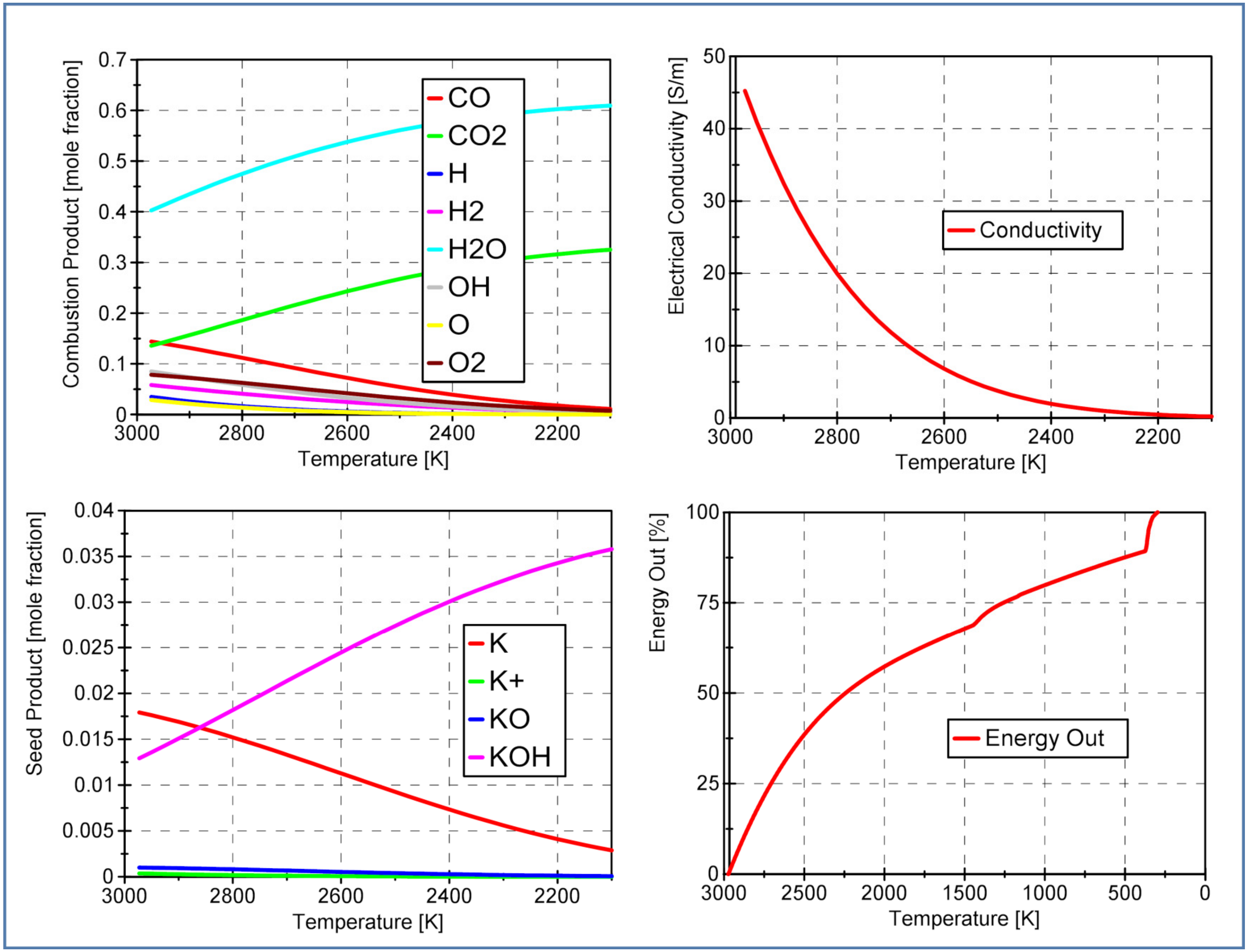


Notes:

- 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, $\phi = 1$, 5.4 mass % K (powder K_2CO_3 added)

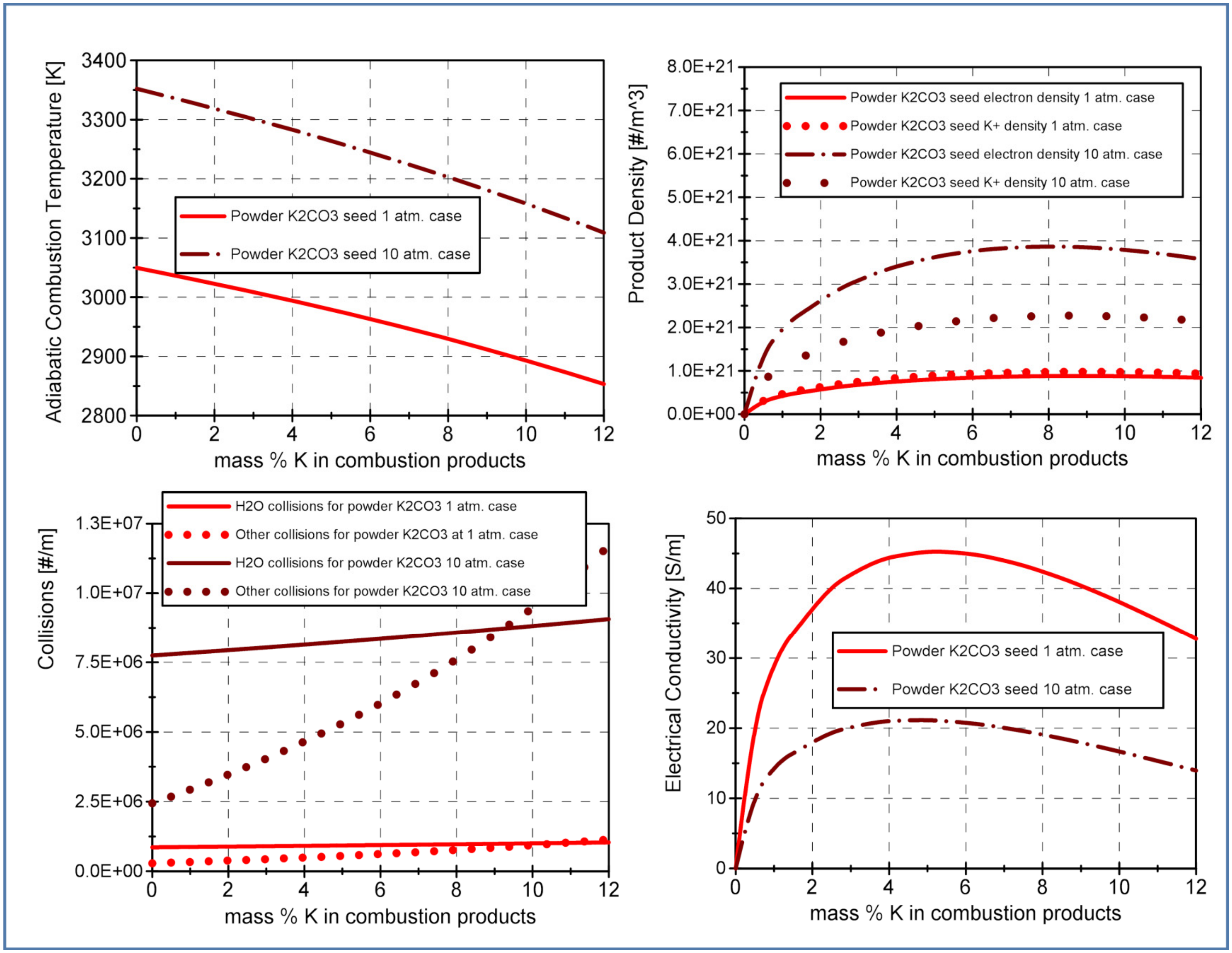


Notes:

- 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)

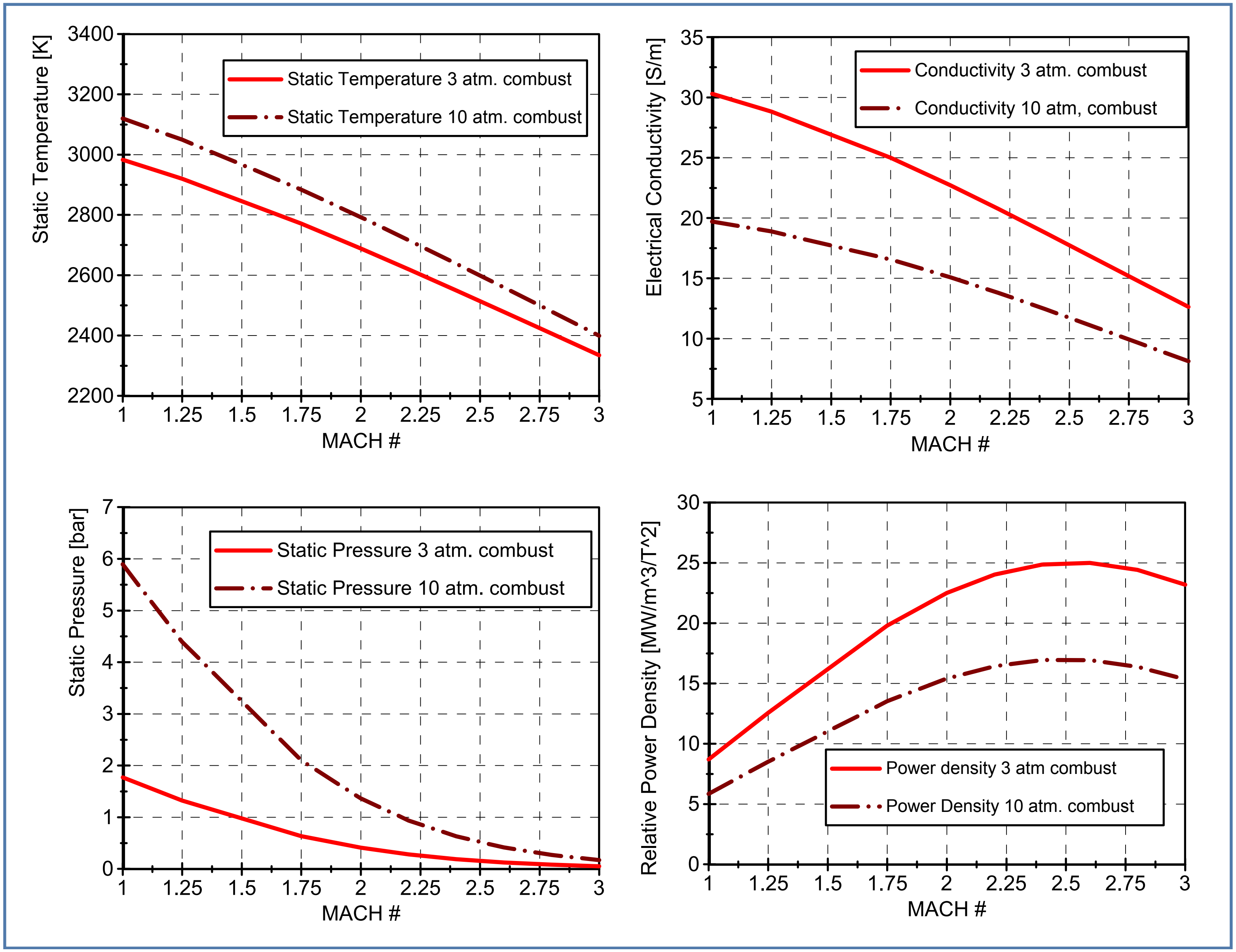


<u>Notes:</u>

- 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)

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



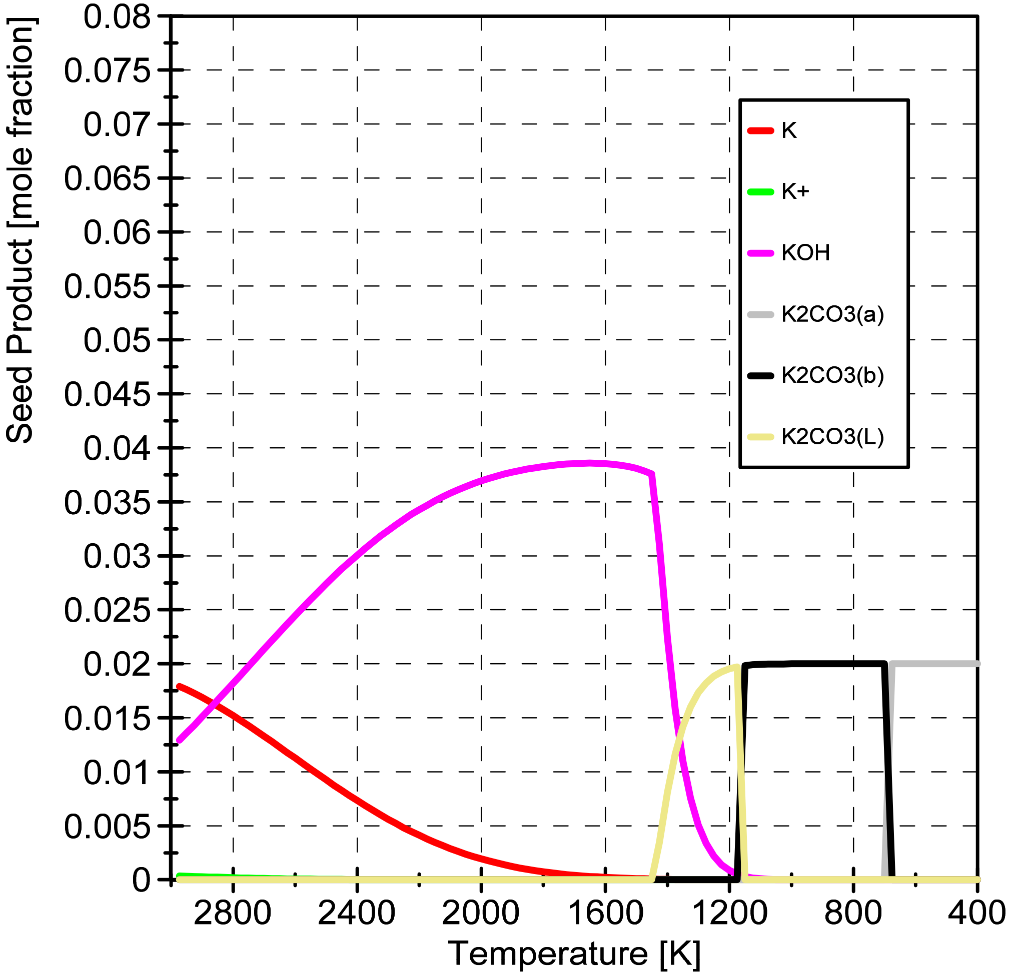
Notes:

- 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

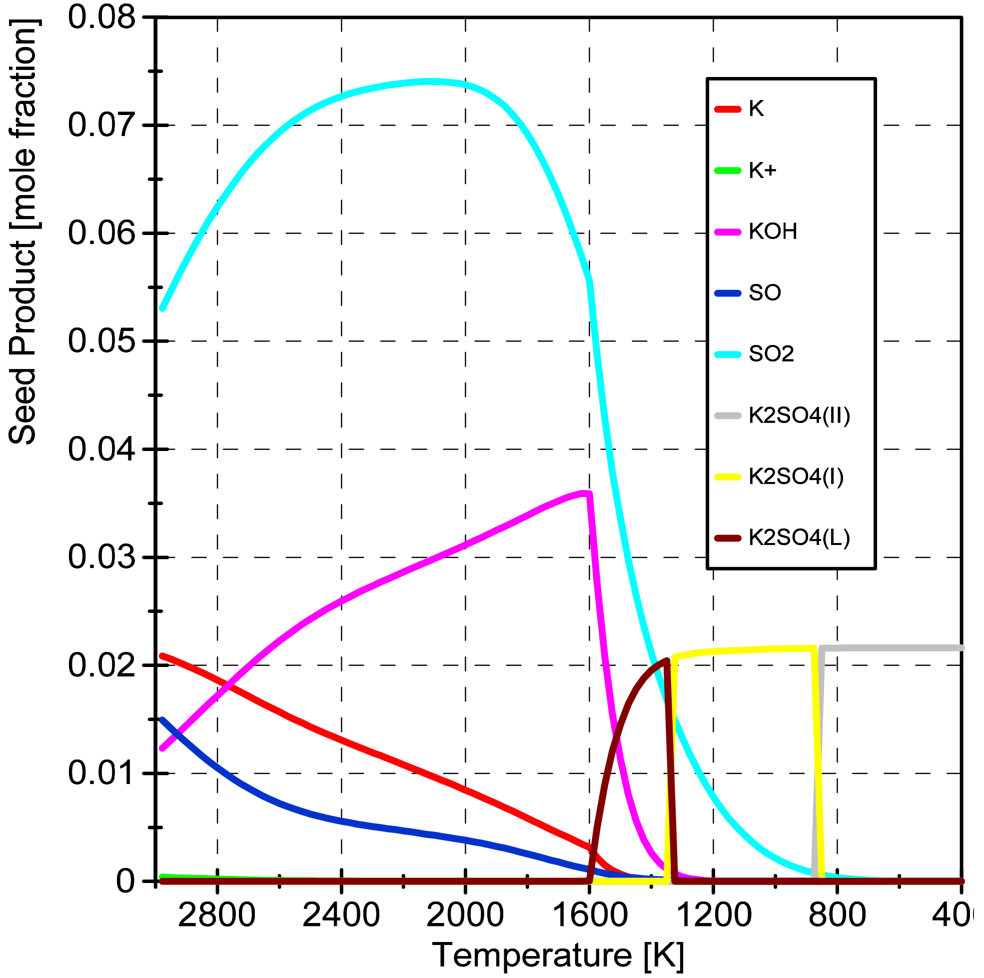
1 atm. combustion, $\phi = 1$, 5.4 mass % K (powder K_2CO_3 added)

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)

MHD Power 101 Summary

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

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

- **The terms are not quite independent**
  - We noted relation of conductivity and velocity
    - Lower pressure better for MHD
    - Supersonic gives highest power density (molecular gasses)
  - Higher B means higher Hall parameter
    - **u**x**B** effects materials issues (higher current density -> arcing)
  - B is expensive, cost driver for electric power gen.
    - Electromagnet, <u>superconductor</u>, permanent magnet
    - Weight likely means different motivation for land vs air

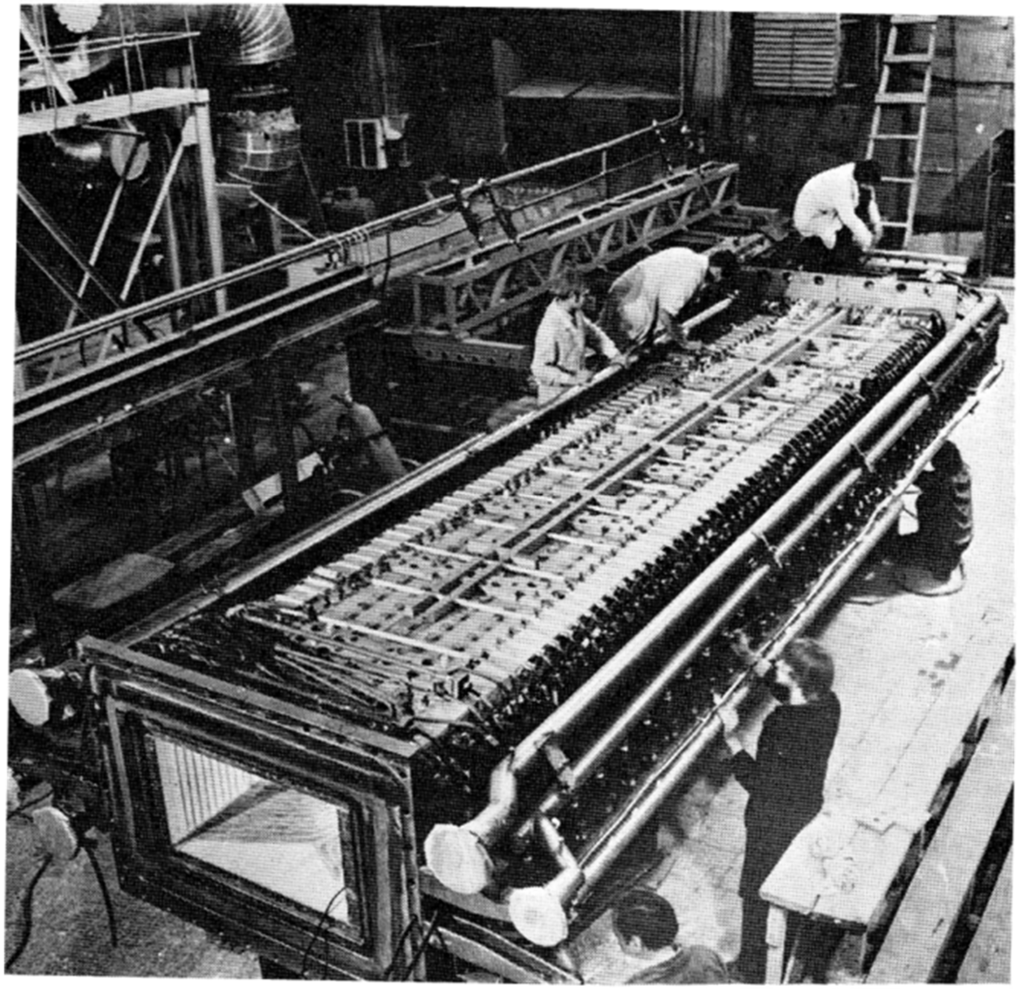
Past and Future Perspectives

1940-1960: MHD Power Tech. Discovery

- **Karlovitz and Halasz**
  - U.S. patent 2,210,918, 1940.
  - Non-seeded annular hall generator
    - Did not work very well
  - Alkali seed use began
- **Rosa AVCO mark 1 generator (1960)**
  - successful

1960s-1970s: Technology Establishment

- **International Research begins**
  - Soviets build U-02 test facility
  - U-25 US-USSR collaboration 1973-1979
- **U.S. Patent 3,294,989 describes a Liquid Metal MHD concept**
- **Rosa book written (1968)**
- **Aerospace and nuclear interests as well.**
- **Pulsed Power Interest**



AVCO Mark 6 U-25 channel R
(Source: Petrick/Shumyatski book,1978)

1970s ERDA/DOE: Demos & Studies

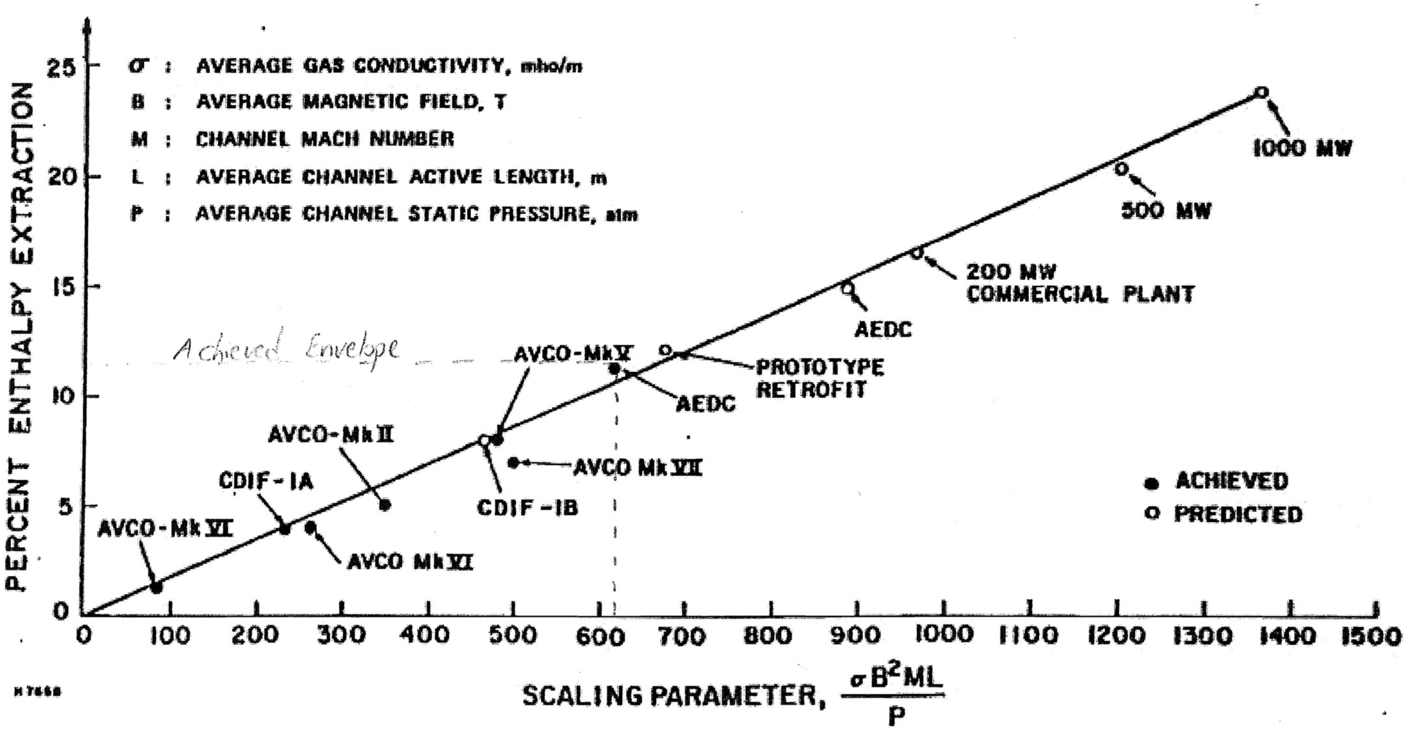
- **AEDC HPDE (record open cycle enthalpy extraction experiment)**
  - Magnet exploded during test
- **CCMHD vs OCMHD vs LMMHD**
- **Decisions ~1980 set stage for USDOE work thereafter.**
  - Systems studies shows open cycle MHD to be most promising

Key analysis assumptions made in the late 1970s have turned out wrong.

1. NG prices would rule out substantial use of that fuel in the future
2. High sulfur coal would continue to dominate

1980-1993 USDOE: Near Commercialization

- **Large demos**
  - Industry cost share
- **Enhanced air was near term—aggressive air cooling later**
- **Performance to date:**



1980s-2000s: Japanese Closed Cycle Work

- Closed Loop Experimental Facility:
- Good summary and images here:

http://vips.es.titech.ac.jp/pdf/090325-meeting/Okuno.pdf

Issues Summary (past U.S. Program)

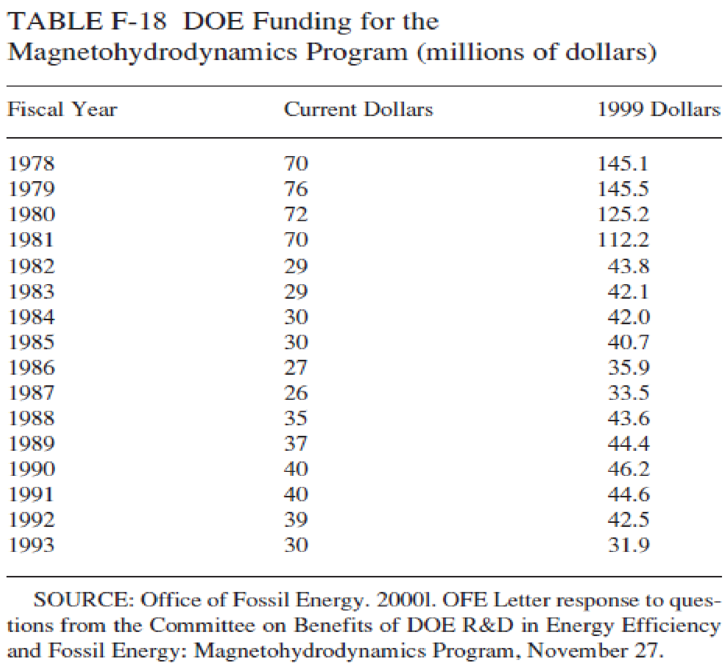


TABLE F-18 DOE Funding for the Magnetohydrodynamics Program (millions of dollars)

Fiscal Year	Current Dollars	1999 Dollars
1978	70	145.1
1979	76	145.5
1980	72	125.2
1981	70	112.2
1982	29	43.8
1983	29	42.1
1984	30	42.0
1985	30	40.7
1986	27	35.9
1987	26	33.5
1988	35	43.6
1989	37	44.4
1990	40	46.2
1991	40	44.6
1992	39	42.5
1993	30	31.9

SOURCE: Office of Fossil Energy. 2000l. OFE Letter response to questions from the Committee on Benefits of DOE R&D in Energy Efficiency and Fossil Energy: Magnetohydrodynamics Program, November 27.

The Good: +Concept proven (Power generation)
+Enabled other advances

The bad* (Direct-Fired Coal Open Cycle MHD):
1) Slag retention problems in Combustor
2) Channel Operation Problems
3) Concerns about the cost-effectiveness of seed regeneration process
4) Uncertainties in fully integrating MHD systems
5) Uncertainties in scaling up mhd systems

*1993 U.S. G.A.O. Report + NRC report (2001)

Then and Now

Legacy MHD program	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

Prospects: Electrical & MHD

- **Fast Switches**
  - Generator control (digital)
- **Improved DC Power conversion & conditioning**
- **Or DC Power on Grid**
  - Attractive with renewables
- **Need for carbon capture**
  - EPA emissions limit (proposed)
  - Natural gas (eventually)
- **Distributed Power Generation**
  - smaller systems are more likely

Prospects: Smaller MHD Devices

- **More oxygen = less flow rate**
  - ~4x less volume.
- **Bad: Material Exposures**
  - smaller and higher temps means more heat loss issues
    - More reason for high temp materials for low heat losses
  - Current density issues (more potential arcing)
- **Good: Less materials (cheaper)**
  - Magnet costs scales with bore volume
  - Smaller (less expensive) generator with same power

Prospects: Air Separation Technology

For 100% pure O2 production, theory limit*:

$$W_{\min} = -RT[\ln(x_{O2}) + \frac{(1-x_{O2})}{x_{O2}}\ln(1-x_{O2})] = -8.314\times 298.15\times 2.447$$
$$= 6.067(kJ/molO_2) = 47.82\ (kWh/tonO_2)$$

- **Consider best cryogenic currently at 3x to 4x limit (~6x in 1980s)**
- **Consider Thermo Limits**
  - Oxy-fuel MHD more attractive with ASU costs going down.
  - Enhanced-air MHD for partial capture?
    - Slip stream Cryogenic CO_2 or Chemical Scrubbing

- **ASU technologies**
  - Absorption
  - Cryogenic (most widely adopted large scale today)
  - Membranes (different types)

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

Prospects: Magnets part 1/2

- **Materials- > Lots of possibilities**
  - LTS: NbTi; Nb_3Sn
  - HTS: YBCO, FeAs

- **Fabrication into windings (the bigger challenge)**
  - Ceramics tend to be brittle
  - New fab, techniques.

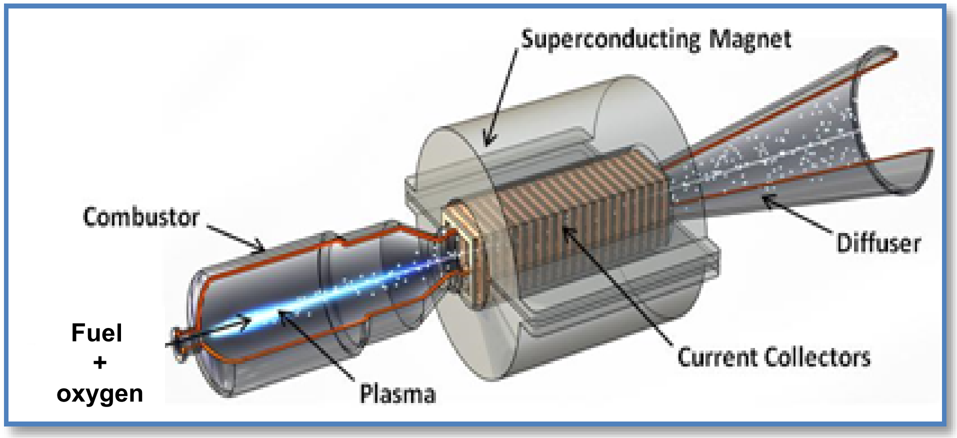
Prospects: Magnets part 2/2

- **Side note: SMES (Superconducting Magnetic Energy Storage)**
  - Eg: torrodial (an advantage is low stray fields)
- **Cooling**
  - Cryocooler advances: designed operating temperature with HTS

Prospects: Materials & Manufacturing

- **Field Assisted Processing**
- **3D printing**
- **Automation**

Handle higher current densities



MHD materials needs

- **Combustion Injectors & Igniters**
- **Combustion wall material (and TBC)**
- **Convergent/divergent Nozzle**
  - Copper traditionally used
    - High heat losses small scale
- **Superconductors for magnet**
  - Economics & issues in windings
- **MHD Channel Insulators**
- **MHD Channel Structural elements**
- **MHD Channel Electrodes**
  - Traditionally cladded copper
  - Durability Identified as major problem in legacy work

Uniqueness of MHD Power Generation (w/ gas)

Things that have been less studied/developed in last ~25 years

- **Partially Ionized Plasma Characteristics**
  - Ionization strategies and time scales
  - Electron-molecular collisional cross sections between 0.2 eV < 1 eV
  - Boundary layer behavior in B field
    - electron transfer
    - velocity and turbulence
    - Temperatures and heat transfer
- **T,E, P, B materials exposure in MHD Generator**
  - Note hot flow might be 3000K, cold magnet 4K
- **MHD combined cycle system performance & techno-economics**
- **Generator Loading and Control Schemes for Power Optimization**

Path Forward: Many Routes for MHD

- **Applicable Energy Sources for MHD: Coal, NG, diesel, biofuels, concentrated solar, wave/water/wind, nuclear**

- **Some Major Tech. Considerations (performance and cost):**

  1. Conductivity (thermal, excited)
  2. Current Extraction (Hall, Faraday)
  3. Material Exposure (clean, slagging, wall cooling)
  4. Operation (steady, pulsed)
  5. Flow Geometry (linear, rotating, disc, spiral)
  6. Magnet Type & Strength (LTS, HTS, permanent)
  7. Velocity (subsonic, supersonic)
  8. Emission Controls (GPU type)
  9. Cycle (Open, Closed, Metal / Combined)
  10. Chemical Energy Conversion (combustion, detonation)

“Those who fail to learn from history are doomed to repeat it”

Questions?

- **Presentation Acknowledgments: Geo Richards, Tom Ochs, Lauren Kolczynski, John Lineberry, Bill Owens**