Direct Power Extraction Techno-Economic Analysis

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October 2, 2014

Objectives

- **Define basis for 3 DPE configurations with focus on DPE components for an open-cycle system**
  1. Coal-fired, with recycle if required
  2. Natural-gas fired, with recycle if required
  3. Coal- or natural gas-fired with elevated diffuser exit pressure to expansion turbine
- **Parameters defined for basis:**
  - Combustor temperature and pressure
  - DPE Channel size/dimensions
  - Magnetic field strength
  - DPE channel output with losses (friction, heat losses, and compression)
  - DPE channel exit temperature and pressure
  - Requirements for recycle and gas preheat

Sensitivity Study Modeling

- **Parameters evaluated:**
  - diffuser exit pressure
  - recycle composition/rate
  - preheat temperature on channel output
- **Approach:**
  - Perform thermodynamic modeling for given composition at range of temperatures and pressures (NASA CEA Code)
  - Calculate plasma electrical conductivities
  - Convert results from NASA CEA code and conductivity calculations to plasma property functions
  - Model system from combustor to MHD channel outlet (MHD channel code)

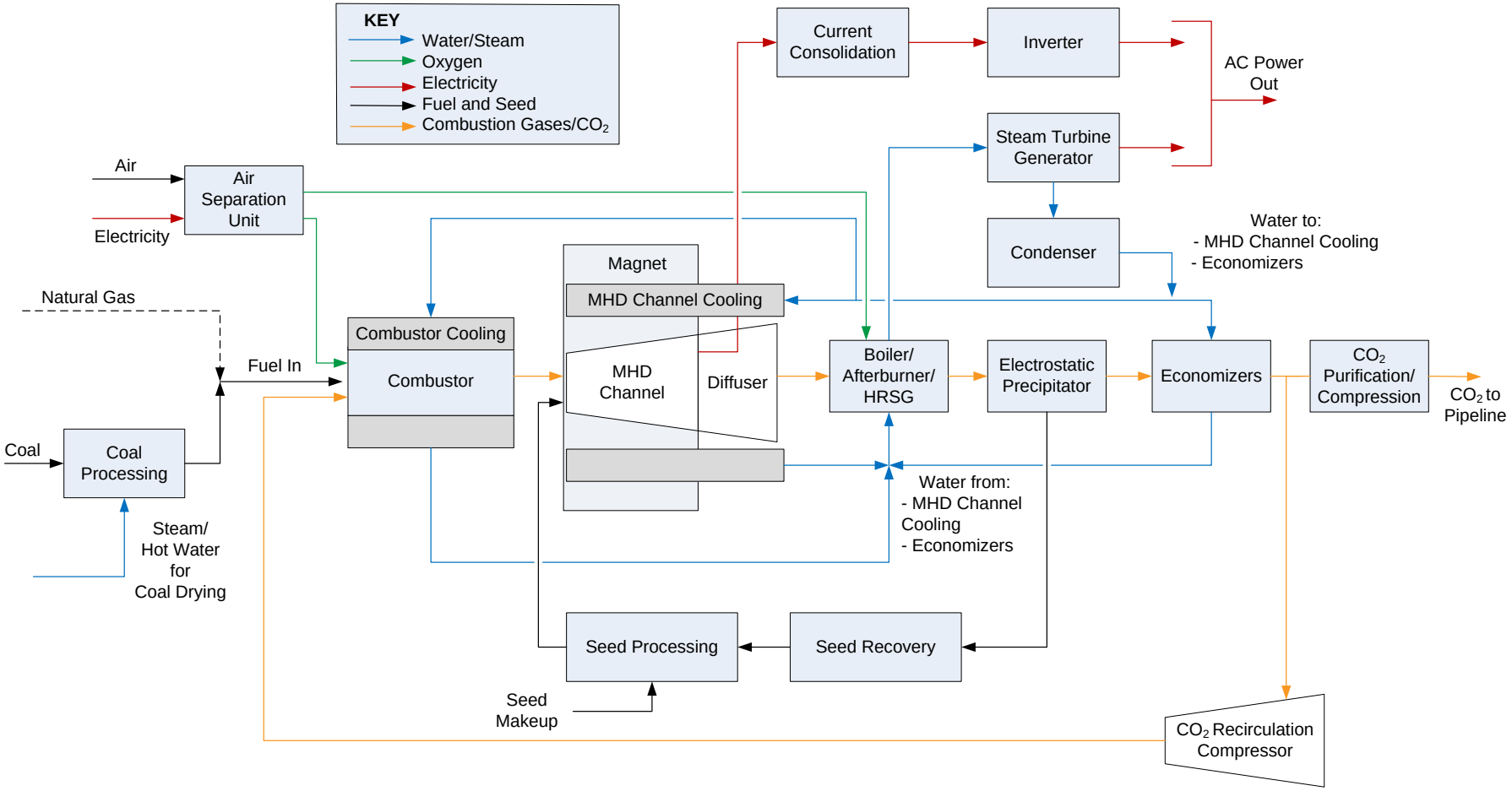
Assumptions/Selection Methodology

- **Recycle and O_2 compression**
  - Efficiency: 80%
  - Heat Capacity Ratio: 1.3
- **Heat loss in combustor and nozzle: 5%**
- **Pressures set at diffuser outlet (1, 3, 6, and 10 atm)**
- **Diffuser pressure recovery factor: 1.6**
- **Conductivity at channel exit = 0.8 mhos/m**
- **Compare to limits set in design basis:**

	Range Reported in Literature	Suggest Value in Basis
Maximum Current Density (A/m^2)	7,400-12,000	8000
Electric Field Max (V/m)	1,800-8,900	2500

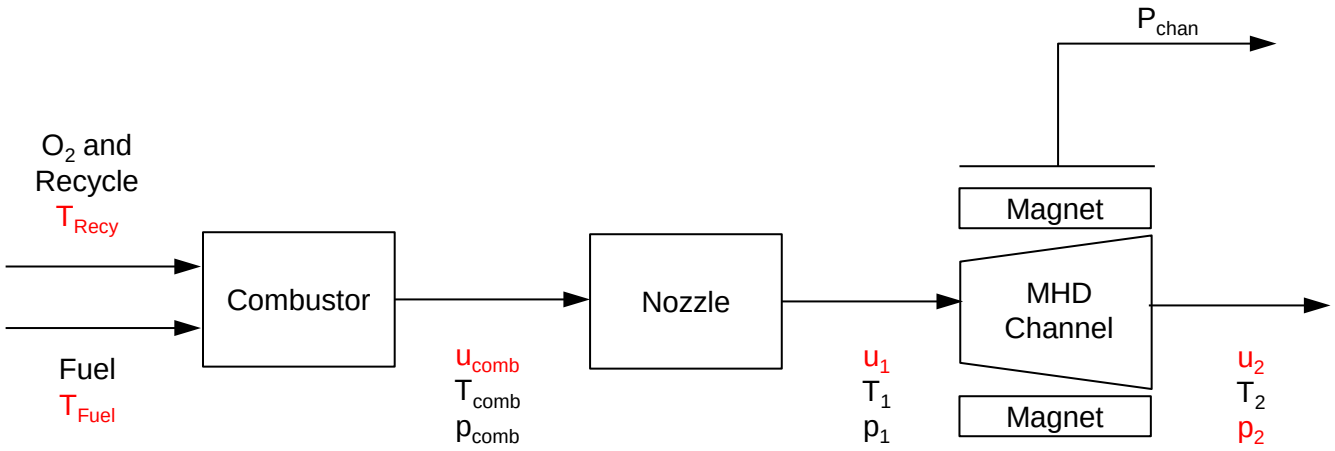
- **L/D set to 16**
- **K scanned and maximum output at each K is select to determine the most favorable configurations at each K**

Coal/Natural Gas-Fired DPE System with optional Recycle



Source: NETL

Background/Model Setup



T = Temperature (K)
u = Velocity (m/s)
p = Pressure (bar)
P = Power (MW)

T_2 : Set by Minimum conductivity and channel outlet pressure
T_{comb} and p_{comb} : Set by fuel, O_2, and recycle enthalpies

Methods/Calculations
Channel Power Output

- **From Rosa*:**

$$L(u = constant) = \frac{p_1}{(1-\eta_e)\sigma u B^2}\left(1 - \frac{p_2}{p_1}\right)$$ Rosa eq. 3.35

$$P_{unit} = E\,j = K(1-K)\sigma u^2 B^2$$ Rosa eq. 1.4

- **Channel volume (V_{chan}):**

$$V_{Chan} = \frac{A_{Ave}}{2} L_{Chan}$$

$$A_{Ave} = \frac{\dot{m}}{\rho u}$$

- **Channel power output (P_{chan}):**

$$P_{Chan} = V_{Chan} P_{Unit}$$

$$P_{Chan} = \frac{A_{Ave}}{2} p_1 \left(1 - \frac{p_2}{p_1}\right) K u$$

Note: The plasma properties, specifically σ and ρ are nonlinear with respect to position in the channel. The calculations presented here assume a certain level of linearity and the error in the resulting power production is uncertain.

***Rosa, *Magnetohydrodynamic Energy Conversion*, Revised Printing 1987**

Methods/Calculations
Pressure Drop Across Nozzle

- **For a gas in a converging nozzle:**

$$u = \sqrt{\frac{2\gamma}{\gamma - 1}\frac{RT_{comb}}{M}\left[1 - \left(\frac{p_1}{p_{comb}}\right)^{\frac{\gamma-1}{\gamma}}\right] + u_{comb}{}^2}$$

  - In this work, T_{comb} is a function of H_{input} and p_{comb}

- **If *u* is known, it can be rearranged so that p_1 is a function of p_{comb}:**

$$p_1 = p_{comb}\left[1 - \frac{\gamma - 1}{2\gamma}\frac{M}{RT_{comb}}\left(u^2 - u_{comb}{}^2\right)\right]^{\frac{\lambda}{\gamma-1}}$$

$$p_1 = f(p_{comb})$$

- **T_1 can be found from input enthalpy, less heat losses, and p_1.**

Methods/Calculations
Pressure Drop Across MHD Channel

- **Standard expression relating temperature and pressure drops across the channel/turbine:**

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2}\right)^{\frac{\gamma}{(\gamma-1)\eta_e}}$$

- **Solving for T_1:**

$$T_1 = T_2\left(\frac{p_1}{p_2}\right)^{\frac{(\gamma-1)\eta_e}{\gamma}}$$

- **T_1 can be expressed as a function of p_{comb} with the expression from the previous page:**

$$T_1 = T_2\left(\frac{f(p_{comb})}{p_2}\right)^{\frac{(\gamma-1)\eta_e}{\gamma}}$$

- **Pressure drop from Wall friction:**

$$\Delta p = 2\gamma M^2 C_f p \frac{L}{D}$$

(C_f = Friction coefficient = 0.003)

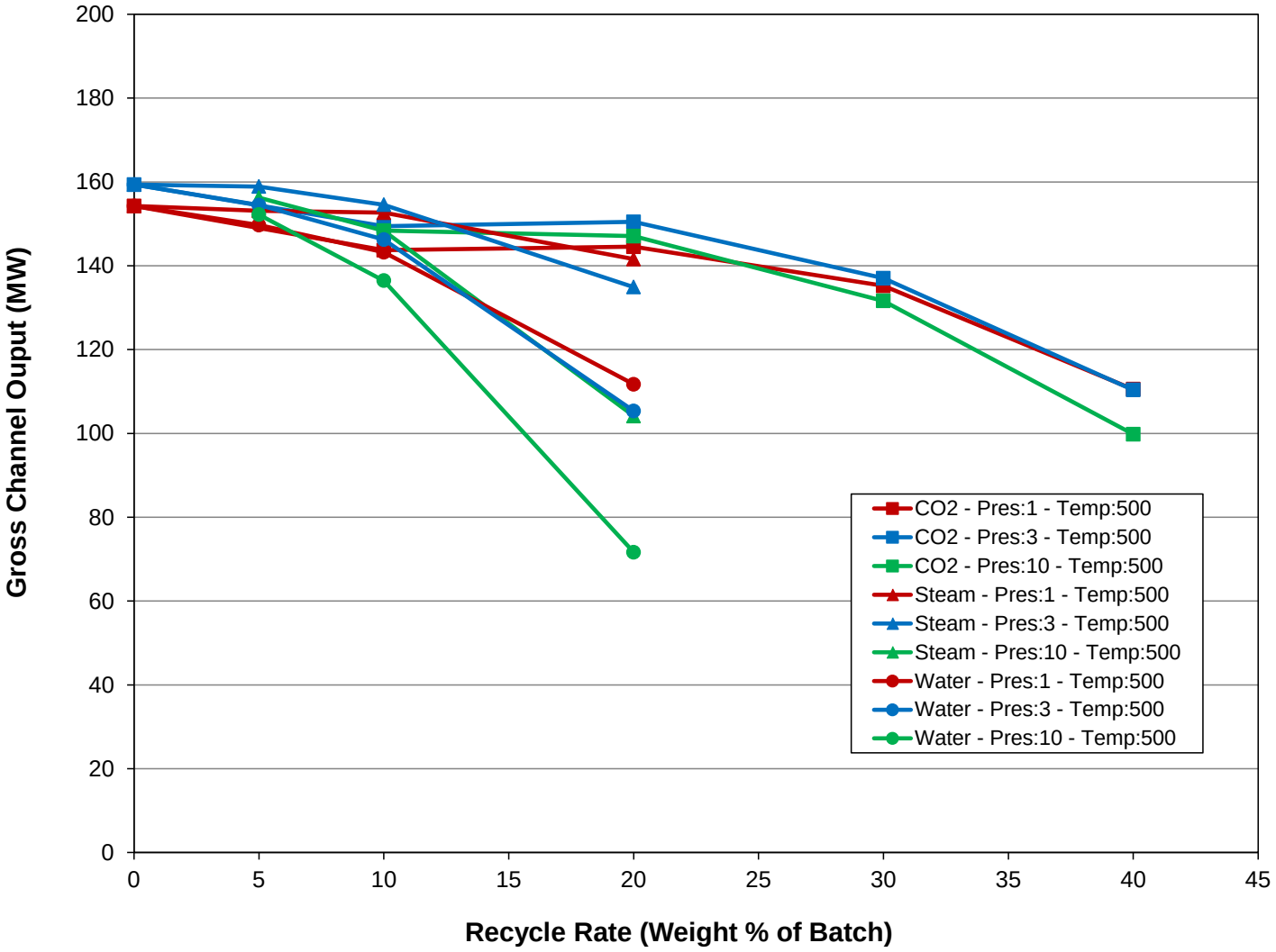
Screening Example
PRB Coal with K=0.5

		PRB with CO_2											
	Case	CO_2 - Pres:1 - Temp:81	CO_2 - Pres:1 - Temp:500	CO_2 - Pres:1 - Temp:1000	CO_2 - Pres:1 - Temp:1500	CO_2 - Pres:3 - Temp:81	CO_2 - Pres:3 - Temp:500	CO_2 - Pres:3 - Temp:1000	CO_2 - Pres:3 - Temp:1500	CO_2 - Pres:6 - Temp:81	CO_2 - Pres:1 - Temp:500	CO_2 - Pres:1 - Temp:1000	CO_2 - Pres:1 - Temp:1500
	Diffuser Pressure (atm)	1				3				6			
	Recycle Temp (°C)	27	260	538	816	27	260	538	816	27	260	538	816
Current Density (A/m^2)	0	5,132	5,298	5,509	5,729	10,839	11,191	11,717	12,302	16,882	17,543	18,383	19,264
	5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
	10	4,138	4,307	4,557	4,808	8,710	9,100	9,607	10,147	13,344	13,900	14,722	15,632
	20	3,211	3,397	3,638	3,895	6,784	7,177	7,685	8,205	10,418	11,051	11,839	12,641
	30	2,280	2,467	2,713	3,009	4,802	5,242	5,795	6,380	7,253	7,931	8,830	9,803
	40	1,380	1,595	1,850	2,123	2,772	3,197	3,792	4,459	4,070	4,705	5,692	6,799
Average E (V/m)	0	976	979	986	994	2,562	2,583	2,594	2,597	4,520	4,520	4,532	4,554
	5	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
	10	934	946	956	957	2,422	2,434	2,455	2,485	4,257	4,328	4,393	4,432
	20	856	864	876	892	2,198	2,262	2,329	2,347	3,949	3,966	4,013	4,094
	30	747	779	814	821	1,977	1,991	2,025	2,084	3,393	3,447	3,560	3,729
	40	628	654	669	698	1,604	1,655	1,739	1,863	2,704	2,872	3,096	3,273
Power Output (MW)	0	234.0	243.6	255.9	268.8	X	X	X	X	X	X	X	X
	5	X	X	X	X	X	X	X	X	X	X	X	X
	10	206.2	217.3	231.9	247.5	X	X	X	X	X	X	X	X
	20	169.9	183.3	200.9	219.6	168.6	181.4	198.4	X	X	X	X	X
	30	122.4	138.5	159.8	182.9	123.6	139.1	159.9	182.0	X	X	X	X
	40	57.8	77.9	104.7	133.5	64.1	83.1	108.4	135.4	X	X	X	X

Gray shading = values meet the current density or electric field criteria

X = Not viable configuration

Trends
PRB-Fired Channel



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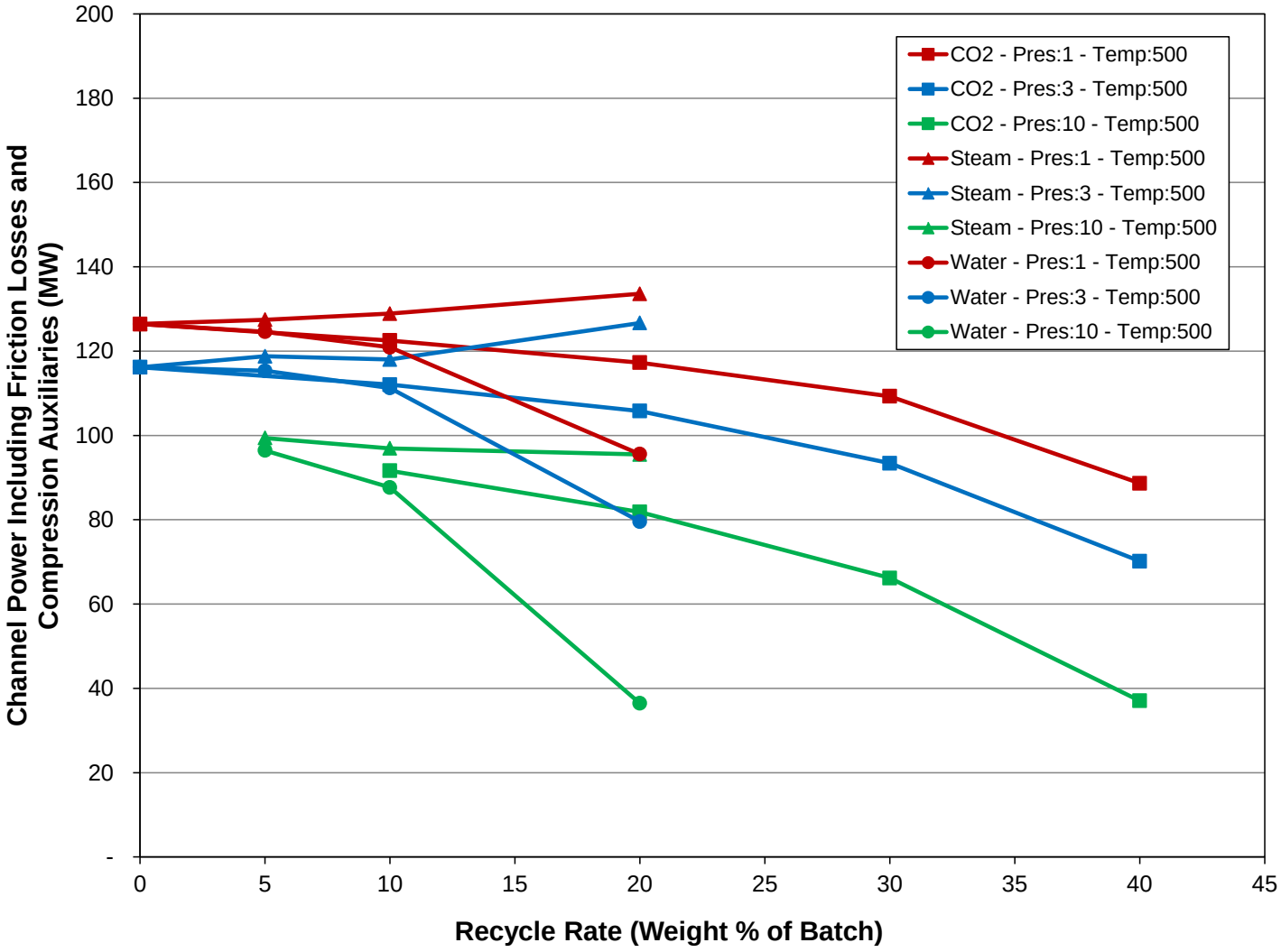
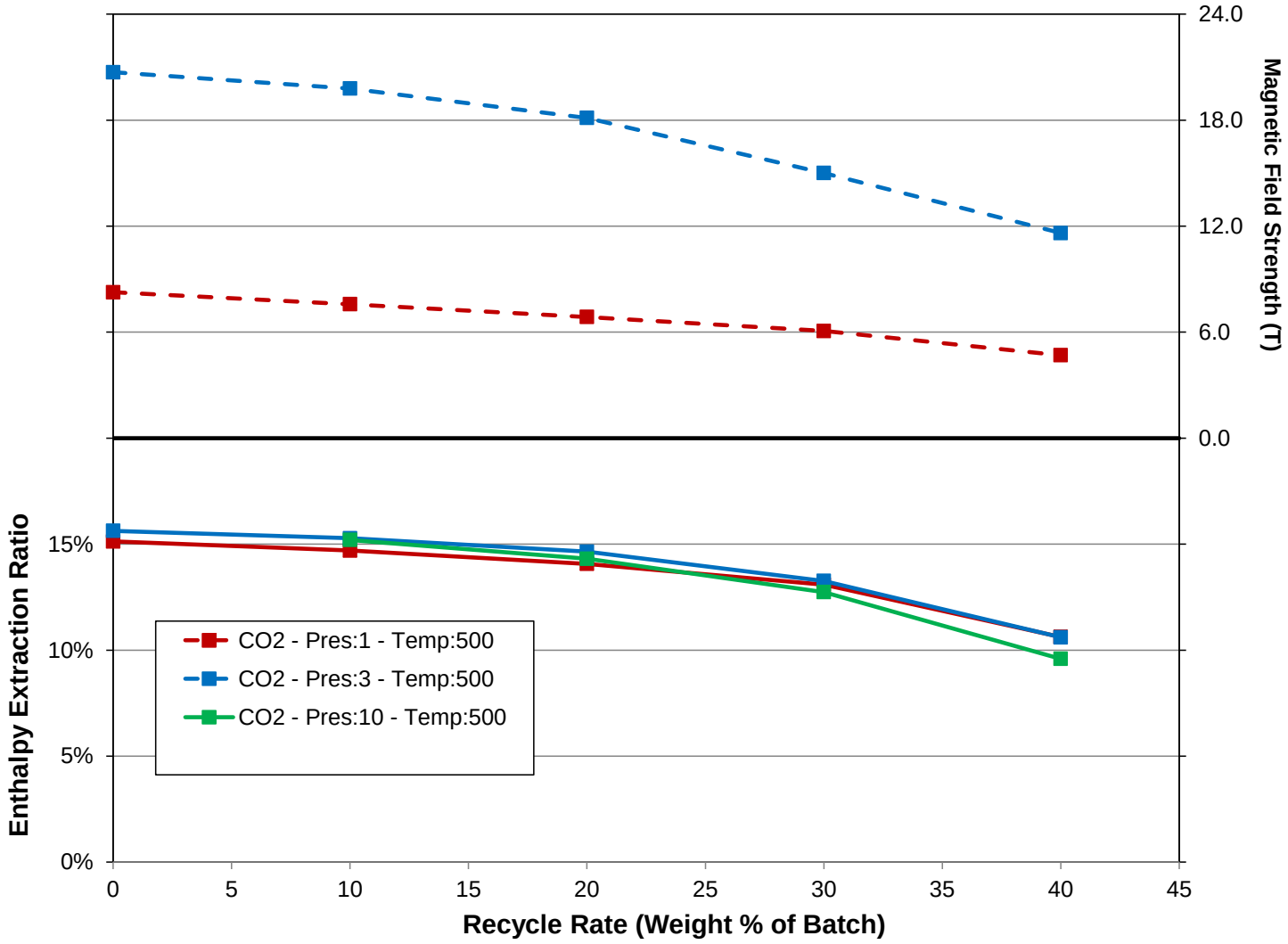
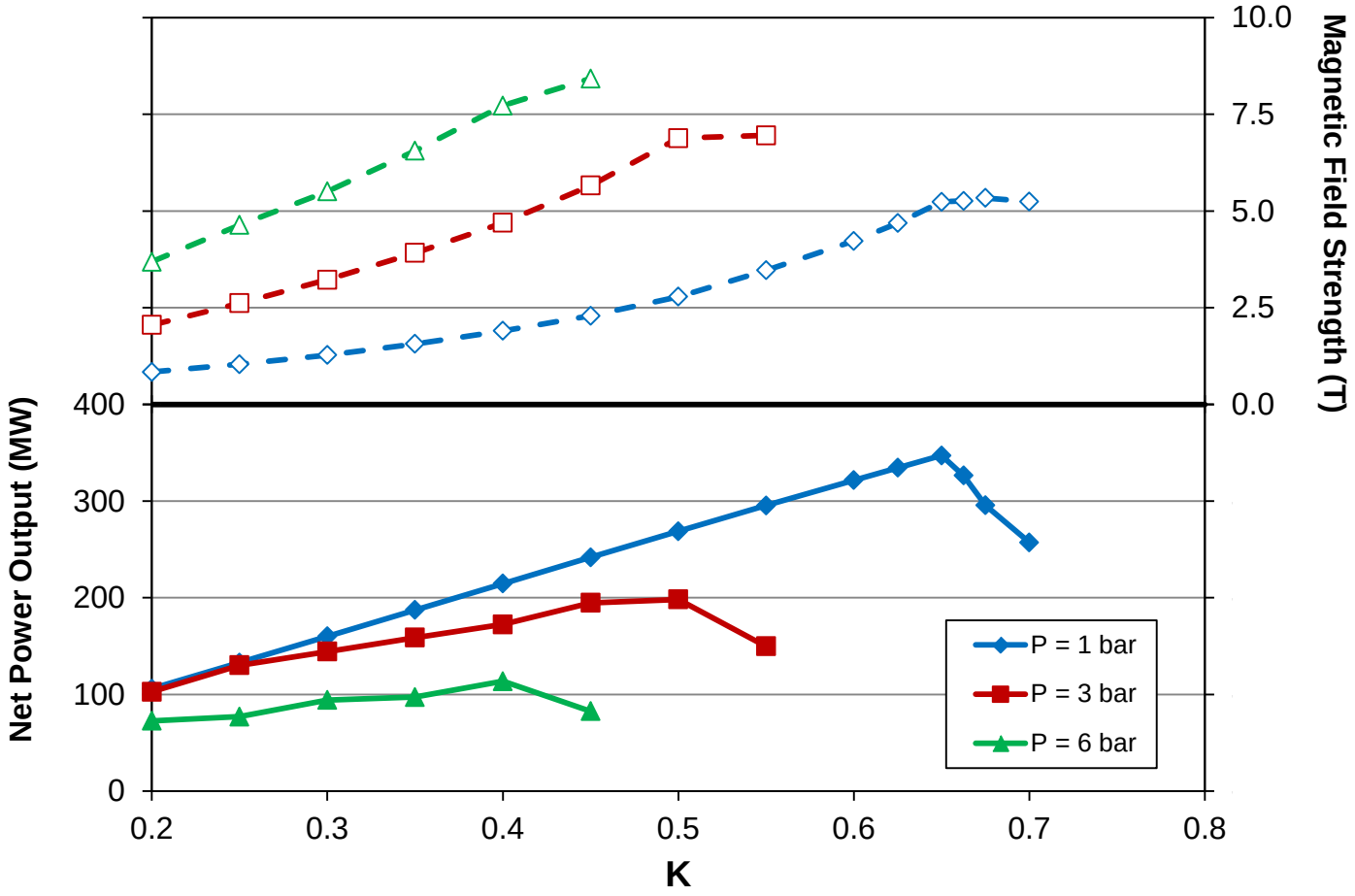


Trends –PRB
Enthalpy Extraction Ratio and Magnetic Field



Power Output and Magnetic Field vs K
PRB Coal-fired Channel with CO_2 Recycle



Source: NETL

Results-Parameters for PRB Coal Configurations

Diffuser Exit Pressure (bar)	1	3	6
K	0.65	0.50	0.40
Net Power Out (MW)	347.1	198.4	113.8
B(T)	5.24	6.88	7.72
Percent Recycle	0%	20%	20%
Oxidant/Recycle Preheat Temperature (°C)	815.6	537.8	815.6
Combustor Temperature (K)	3395	3200	3096
Combustor Pressure (bar)	8.16	10.33	12.43
Channel Inlet Temperature (K)	3223	3010	2874
Channel Inlet Pressure (bar)	5.97	7.63	9.24
Channel Exit Temperature (K)	2085	2132	2179
Channel Dimensions			
Length (m)	15.0	10.9	9.0
Entrance Height (m)	0.51	0.49	0.46
Exit Height (m)	1.36	0.87	0.66