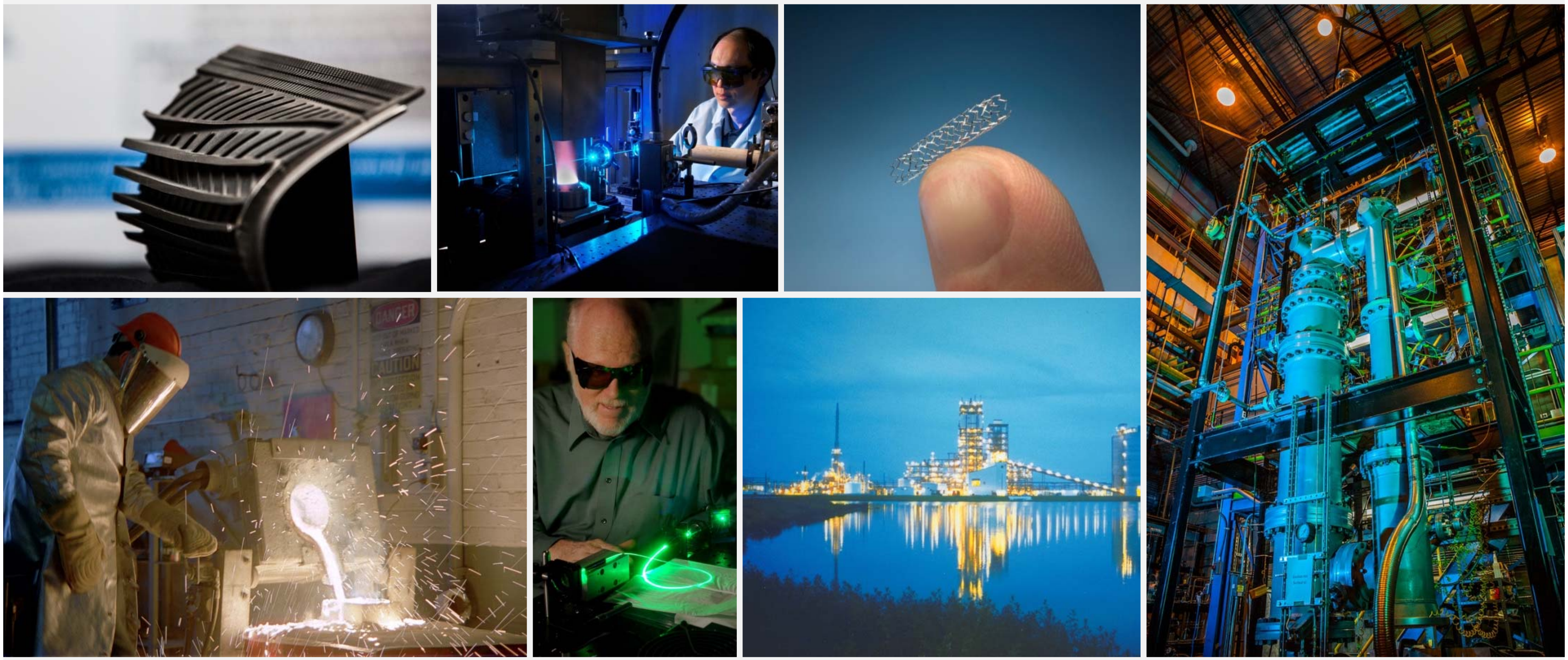
Driving Innovation ♦ Delivering Results



Systems Analyses of Direct Power Extraction (DPE) and Advanced Ultra-Supercritical (AUSC) Power Plants

Nathan Weiland, Wally Shelton

Crosscutting Research & Rare Earth Elements Portfolios Review, Pittsburgh, PA

April 18th, 2016

Presentation Outline

- **NETL's Systems Engineering & Analysis (SEA) Division**
- **Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants**
  - AUSC plants with higher thermal efficiency enabled by material developments for increased temperature and pressure operation
- **System analysis of Direct Power Extraction (DPE) power plants**
  - Supports NETL's Magnetohydrodynamics (MHD) research program
  - Leverages synergies between oxy-coal MHD and Carbon Capture and Storage (CCS)
  - Uses MHD topping cycle and AUSC steam bottoming cycle

NETL Research and Innovation Center
Core Competencies

Computational Science & Engineering

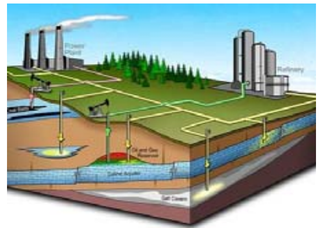
High-Performance Computing

Data Analytics

Materials Engineering & Manufacturing

Structural & Functional

Design, Synthesis & Performance



Geological & Environmental Systems

Air, Water & Geology

Understanding & Mitigation

Energy Conversion Engineering

Component & Device

Design & Validation

Systems Engineering & Analysis

Process & System

Optimization, Validation & Economics

Program Execution & Integration

Strategic Planning

Project Management

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Impact of Steam Conditions on PC Plant Efficiencies

	Temperature	Pressure (absolute)	Net Plant Efficiency (% HHV)**
Subcritical	540 - 565°C 1000 - 1050°F	16 - 22 MPa 2300 - 3200 psi	38.3 - 39.6%
Supercritical (SC)	565 - 600°C 1050 - 1112°F	22 - 27 MPa 3200 - 4000 psi	39.6 - 40.6%
Ultra-supercritical (USC)*	600 - 640°C 1112 - 1184°F	24 - 31 MPa 3500 - 4500 psi	41.3 - 42.0%
Advanced USC (AUSC) (DOE Program Goals)	700 - 760°C 1292 - 1400°F	24 - 35 MPa 3500 - 5000 psi	43.4 - 44.4%

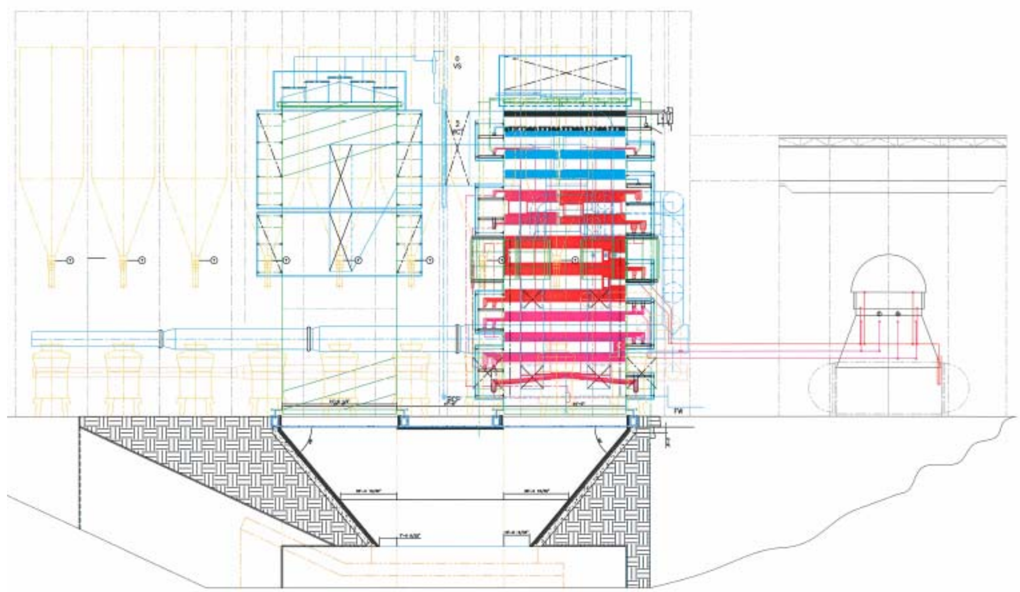
*USC represents a broad range of steam conditions; criteria on what constitutes USC are not consistent (especially internationally). Commercially available USC technology results in efficiencies similar to or slightly above the state-of-the-art SCPC plant provided here.

**Net plant efficiencies above are based on an example plant operating on Bituminous coal, at ISO conditions, with 50°F reheat, wet flue gas desulfurization, and wet cooling towers. Other design parameters and site conditions will also impact the efficiency of a specific plant.

Source: NETL, Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 3, 2015; and other internal assessments of AUSC steam conditions.

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

- **Objective: Develop AUSC reference cases**
  - Enabled by DOE/Ohio Coal Development Office (OCDO) AUSC Materials Consortia
    - Steam boilers (DE-FG26-01NT41175)
    - Steam turbines (DE-FE0000234)
  - Supported by NETL Crosscutting program
  - Evaluate three steam pressures and effect of CCS
  - Conduct economic analysis based on an Inverted Tower Boiler Design (B&W)*



**Advanced Ultra-Supercritical Pulverized Coal Power Plant with and without Post-Combustion Carbon Capture*. EPRI, Palo Alto, CA: 2015.

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

Case Matrix

Case	Steam Conditions	Capacity (MW-net)	CO_2 Capture (Cansolv)	CO_2 Capture Heat Integration
1	3500 psig / 1350°F / 1400°F	550	0%	-
2	3500 psig / 1350°F / 1400°F	550	90%	No
3	4250 psig / 1350°F / 1400°F	550	0%	-
4	4250 psig / 1350°F / 1400°F	550	90%	No
5	5000 psig / 1350°F / 1400°F	550	0%	-
6	5000 psig / 1350°F / 1400°F	550	90%	No

- **Performance for all cases now reflect the steam turbine stage efficiencies extracted from steam flow diagrams provided in the A-USC Consortium literature[1] rather than those from the Bituminous Baseline Report[2]**
- **Boiler and steam piping costs reflect the conceptual B&W inverted tower boiler design**
  - Steam piping costs assume a reduced steam lead length to 150’ from 450’ for a conventional boiler

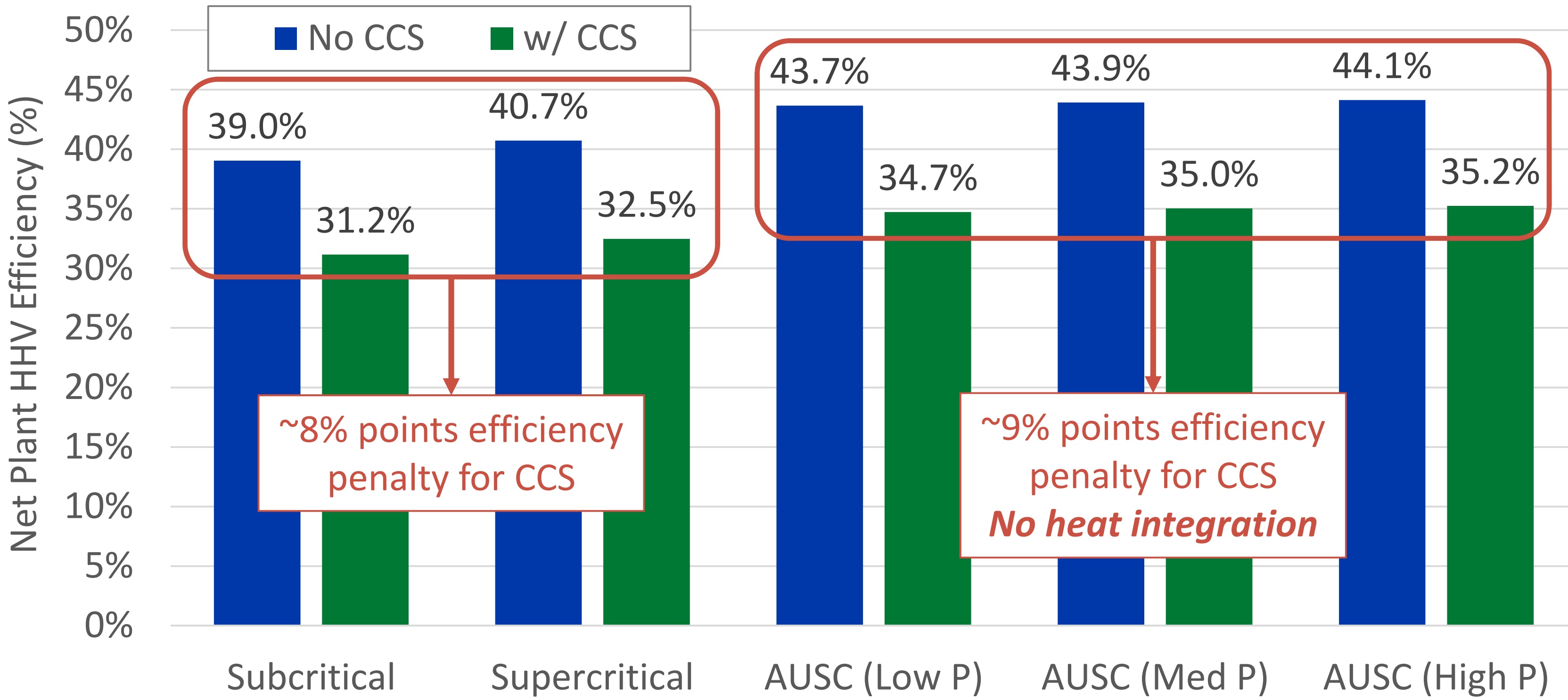
AUSC PC Plant Performance Results

	PC Subcritical		PC Supercritical		PC A-USC					
	Case B11A	Case B11B	Case B12A	Case B12B	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Nominal CO_2 Capture	0%	90%	0%	90%	0%	90%	0%	90%	0%	90%
Gross Power Output (MWe)	581	644	580	642	578	635	578	634	578	633
Auxiliary Power Requirement (MWe)	31	94	30	91	27	85	27	84	27	84
Net Power Output (MWe)	550	550	550	550	550	550	550	550	550	550
HHV Thermal Input (MW_{th})	1,409	1,765	1,351	1,694	1,260	1,583	1,253	1,569	1,247	1,559
Net Plant HHV Efficiency (%)	39.0%	31.2%	40.7%	32.5%	43.7%	34.7%	43.9%	35.0%	44.1%	35.2%
Raw Water Withdrawal, gpm	5,538	8,441	5,105	7,882	4,508	7,124	4,461	7,025	4,422	6,960
Process Water Discharge, gpm	1,137	1,920	1,059	1,813	930	1,638	919	1,615	911	1,600
Raw Water Consumption, gpm	4,401	6,521	4,045	6,069	3,578	5,486	3,541	5,410	3,511	5,360
CO_2 Emissions (lb/MWhgross)	1,683	190	1,618	183	1,515	173	1,506	172	1,500	171

- **Design basis for AUSC Study enables direct comparison to subcritical and supercritical PC plants from the Bituminous Baseline Study:**
  - National Energy Technology Laboratory. *Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3,* DOE/NETL-2015/1723. July 2015.

AUSC PC Plant Performance Results

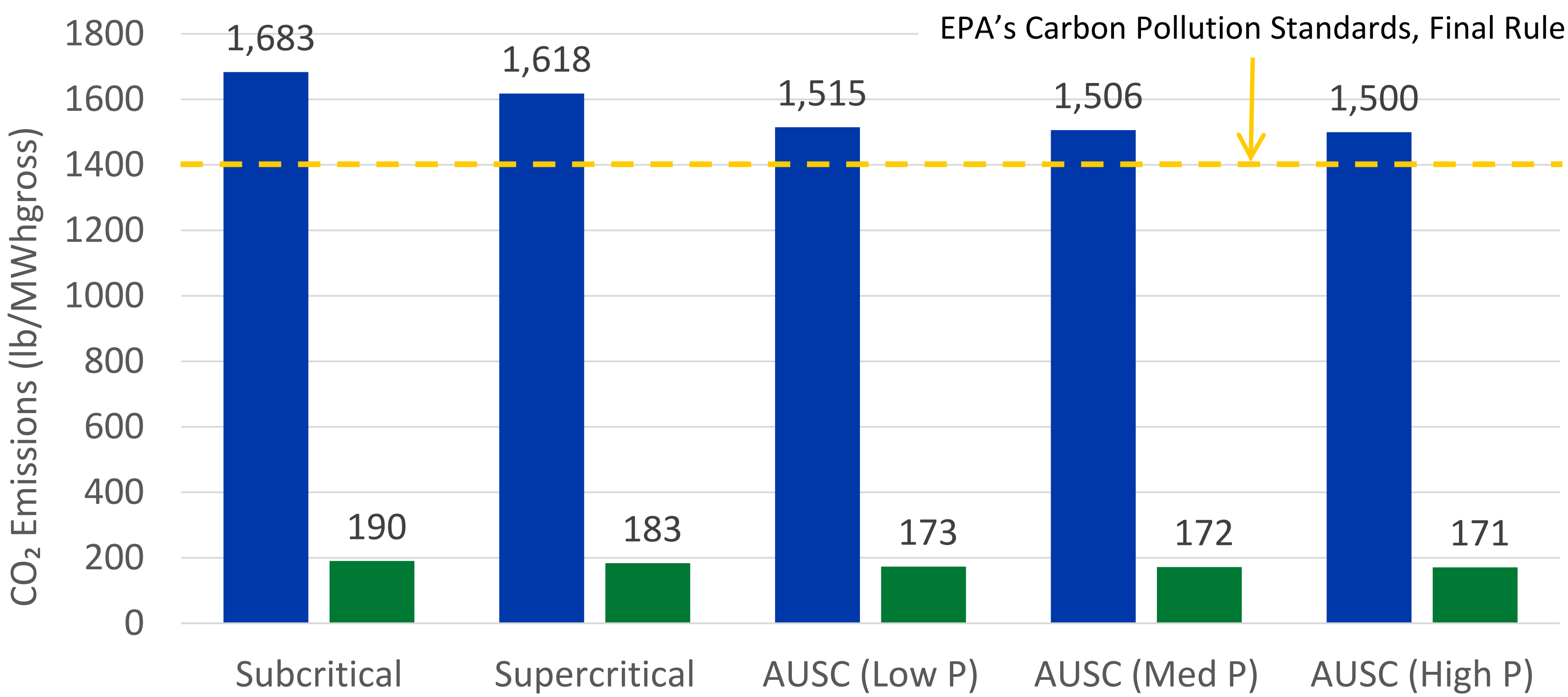
CO_2 Emissions



Case	B11A/B*	B12A/B*	1 & 2	3 & 4	5 & 6
Pressure (psig)	2400	3500	3500	4250	5000
Main Steam (°F)	1050	1100	1350	1350	1350
Reheat (°F)	1050	1100	1400	1400	1400

AUSC PC Plant Performance Results

CO_2 Emissions



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Reheat (°F)	1050	1100	1400	1400	1400

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

Conclusions

- AUSC PC plants provide 3.0-3.5% points efficiency improvement over baseline supercritical (SC) PC plants
  - Improvement of only 2.2-2.7% points efficiency for CCS cases, though thermal integration has not been considered
- Efficiency gains due to increasing main steam pressure above 3500 psig provide diminishing benefit to plant costs
- Greater confidence in AUSC steam turbine efficiency and cost has been gained due to work performed by AUSC Materials Consortium

Future Work

- Economic analysis for all six cases nearing completion
- A COE sensitivity on high-nickel-alloy components can be performed once the weight fraction of the inverted tower design boiler for these materials is estimated
- Integration of CCS systems with AUSC plant to improve efficiency

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- **System analysis of Direct Power Extraction (DPE) power plants**
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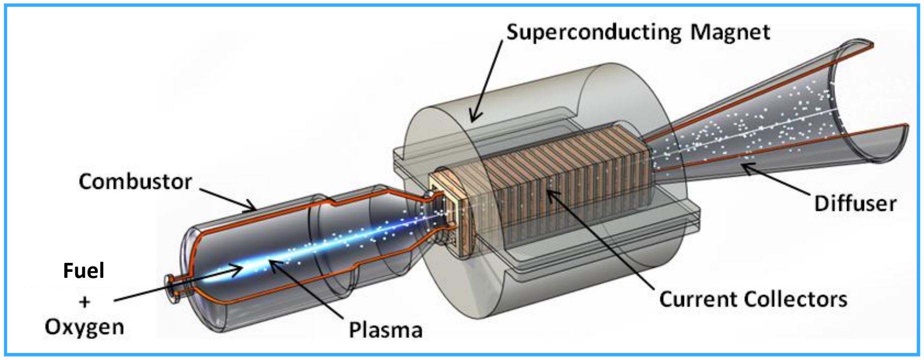
"Direct Power Extraction" (DPE)
Making Oxy-fuel Combustion an Advantage

- **Description: Extracts power using magnetohydrodynamics (MHD)**
  - Higher efficiency because it *uses* temperatures only possible with oxy-fuel.
  - Provides "capture-ready" feature of oxy-fuel; uses steam "bottoming" cycle.
  - Could be retrofit to coal steam plants

MHD generator concept

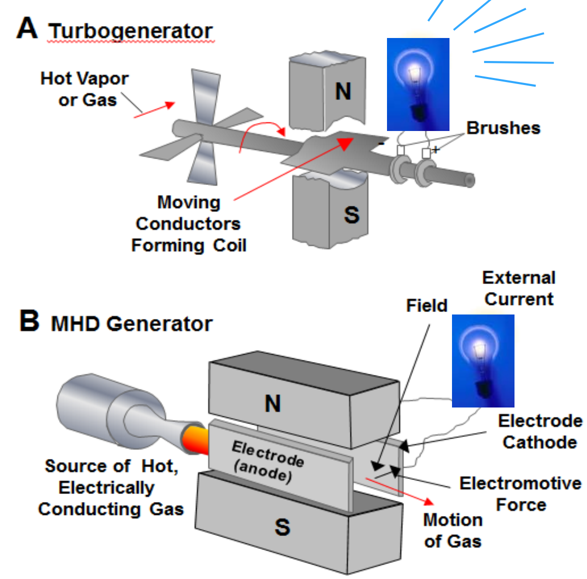
High-temperature oxy-fuel combustion (with conductivity seed) accelerates through magnetic field to produce current. Hot exhaust used in conventional steam boiler.

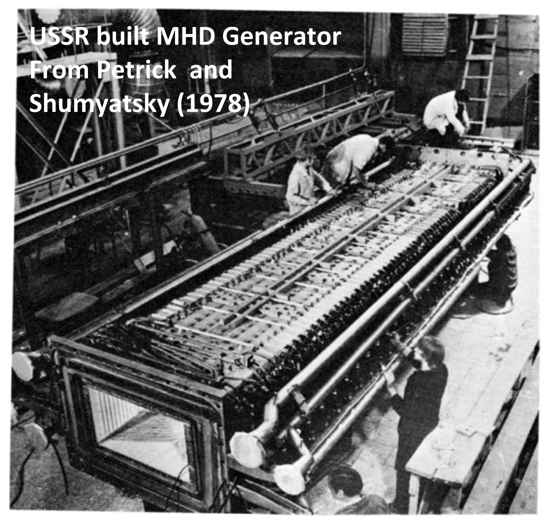


- **What is the R&D?**
  - Develop durable electrodes, current control, and optimal hydrodynamics.
  - Validate simulation tools and predict optimal generator configurations.
  - Identify and test new approaches for power extraction.
- **Benefits**
  - May allow retrofit of power plants with higher efficiency <u>and</u> carbon capture.
  - Potential spin-offs to other industries/ applications:
    - Electrically conductive ceramics, arc prevention/control (material processing)
    - Advanced propulsion and power (with DOD, NASA)

Direct Power Extraction (via MHD)

- **To generate MHD power: *Power* $\propto \sigma u^2 B^2$**
  - σ = 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



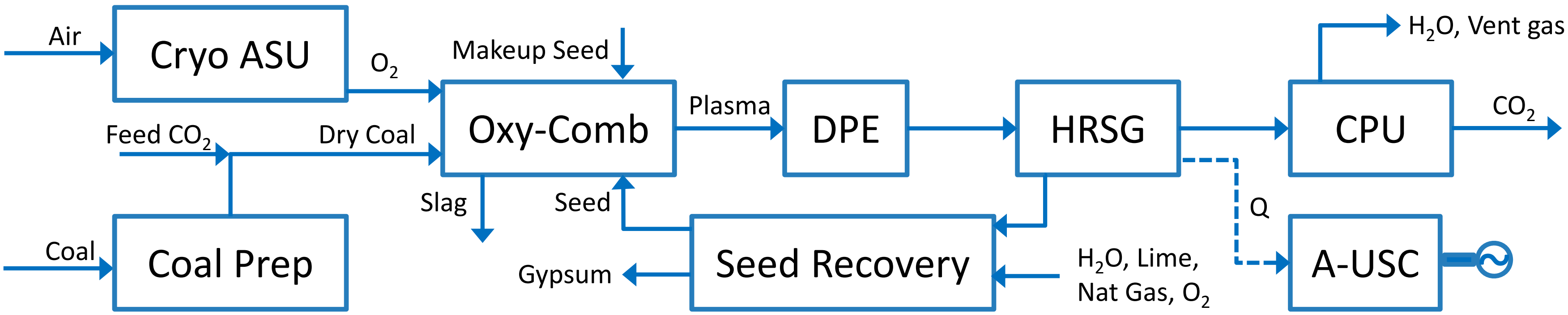


MHD generator concept proven in 1980s w/ grid transferred power in both U.S. and USSR

MHD: Then and Now

Legacy MHD program (U.S.: 1960s – 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

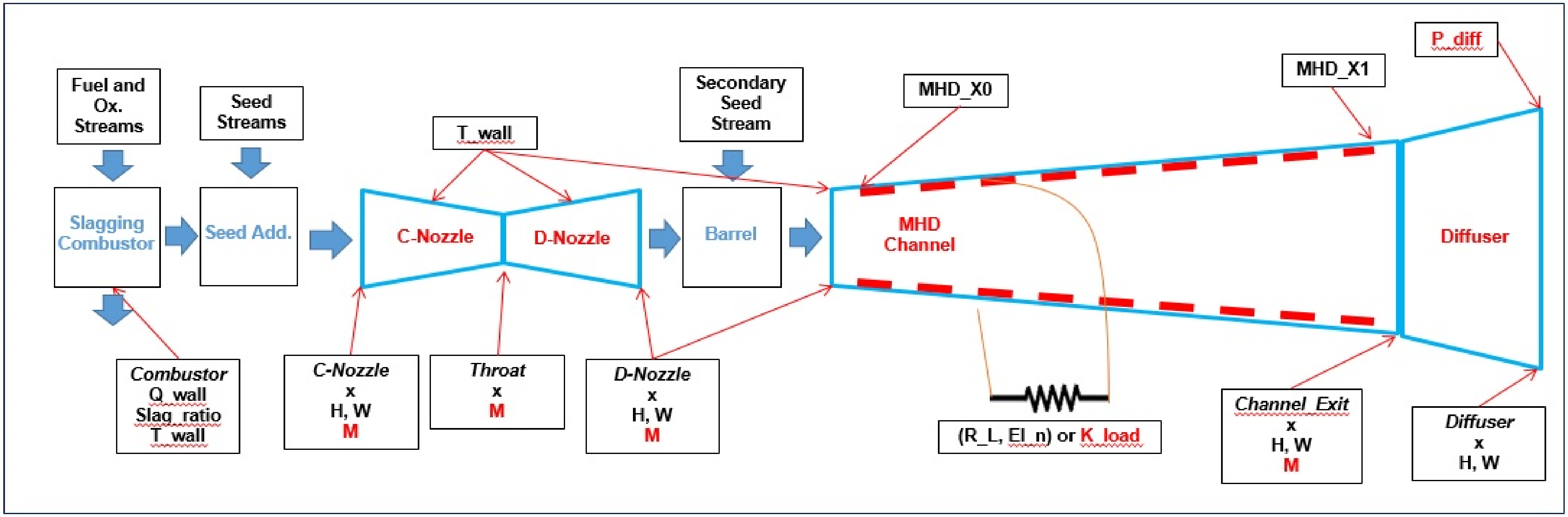
DPE Plant Design Basis



- **Nominal plant input of 1000 MW_{th} PRB coal, dried to 5% moisture, dry-fed with 8 wt% recycled CO_2**
- **Coal combustion in 95% purity oxygen from ASU, with 90% slag rejection**
- **Potassium formate seed injection to generate required plasma, with Econoseed™ seed recovery process**
  - ~1.3 wt% potassium loading to recover coal sulfur as gypsum
  - Requires natural gas partial oxidation to generate CO for reaction
- **Advanced Ultra-Supercritical (A-USC) steam bottoming cycle with reheat (1350 °F/1400 °F/5000 psig)**
- **CO_2 purification and compression unit for pipeline-quality CO_2 capture**

1-D Model for Channel Design

- **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**

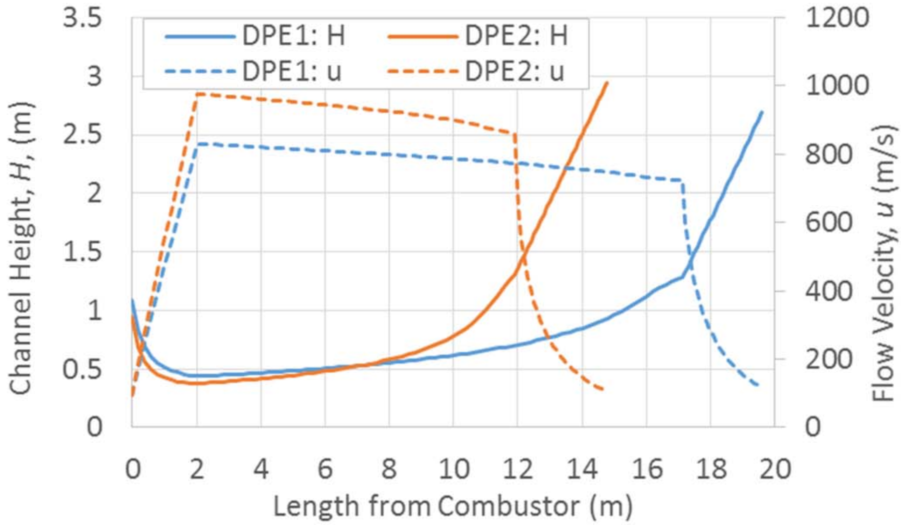
Channel Design Results

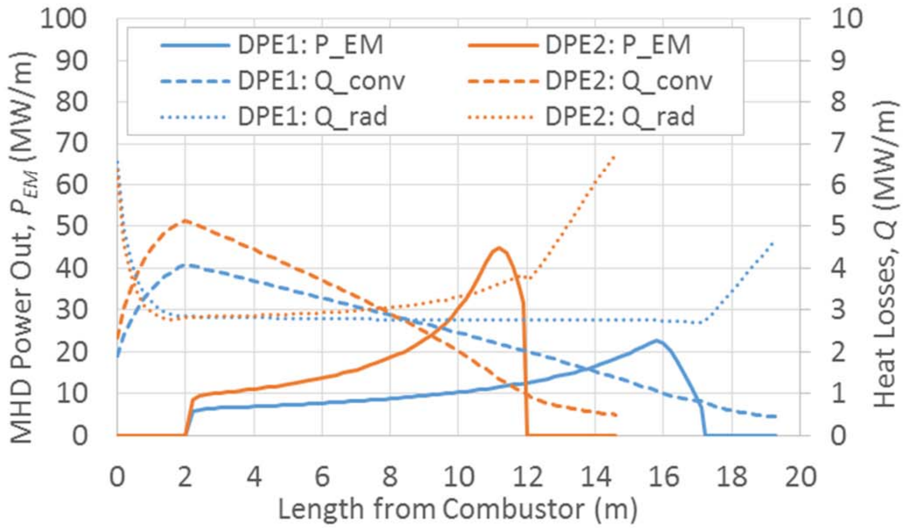
- **Stoichiometric combustion for DPE-2:**
  - Increases mass flow
  - Increases channel inlet temperature
- **Higher power density and Mach number for DPE-2 allows for:**
  - Higher power extraction with increased pressure
  - Reduced channel length and lower heat losses

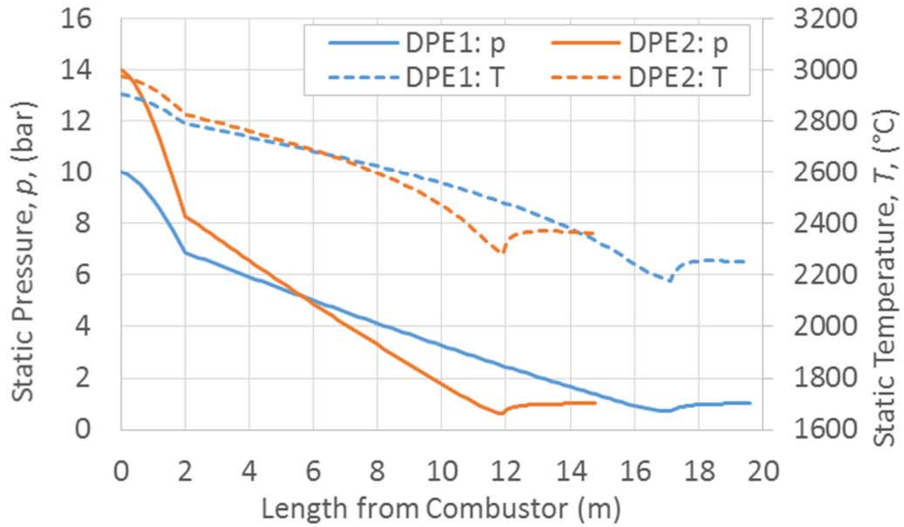
Parameter	units	DPE-1	DPE-2
Stoichiometry		0.9	1.0
Combustor Pressure	bar	10	14
Mass Flow	kg/s	121.8	129.7
Mach Number		0.8	0.95
Combustor Exit Temperature	°C	2904	2976
Channel & Diffuser Length	m	19.6	14.4
Diffuser Exit Temperature	°C	2247	2366
Convective Heat Loss	MW	46	42
Radiative Heat Loss	MW	59	51
MHD DC Power output	**MW**	**171**	**197**
Electric Field, *E_x*	V/m	2324	3842
Current Density, *J_y*	A/cm^2	0.79	1.50

Channel Design Results

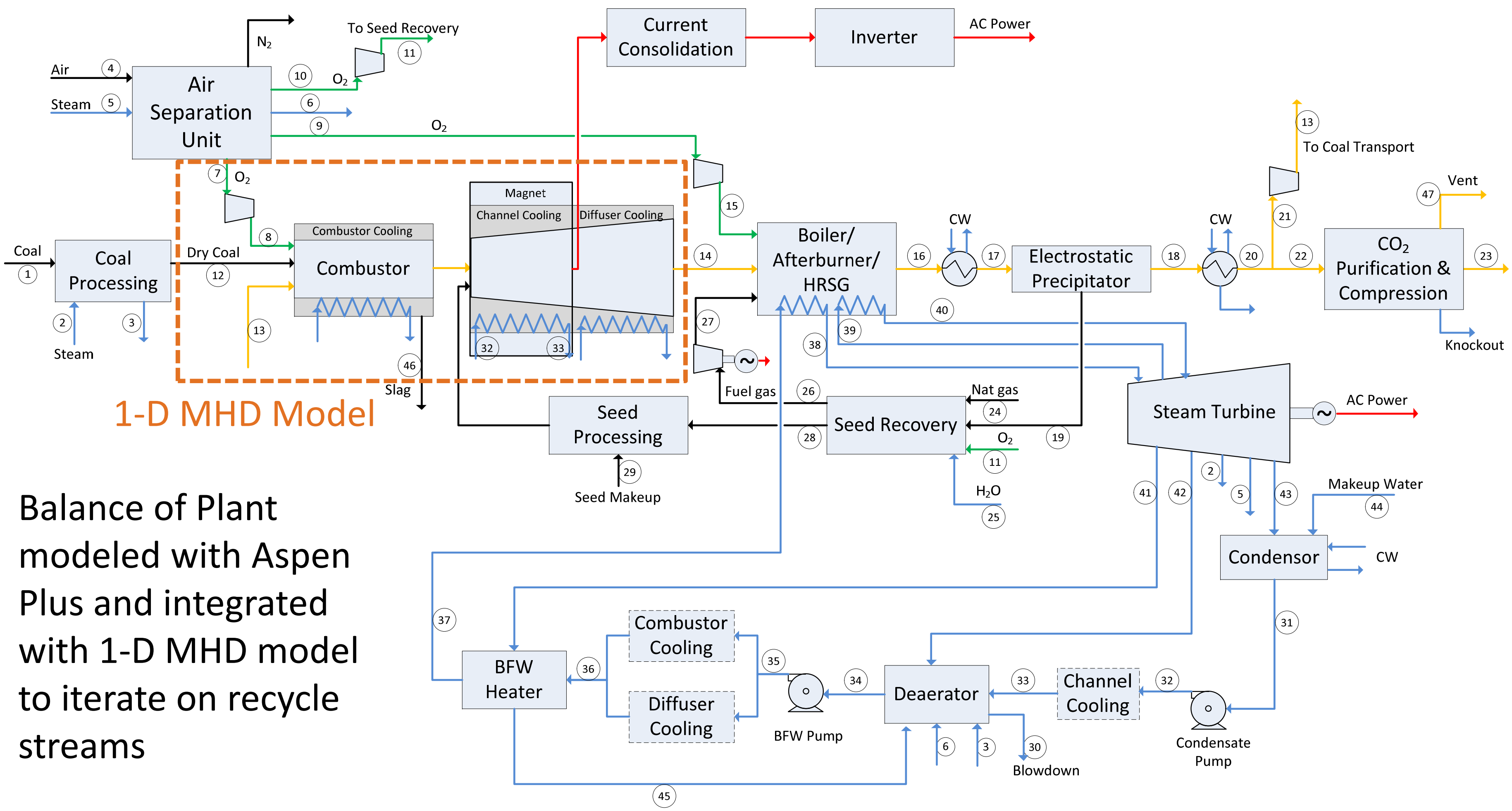
- **MHD profiles include:**
  - Nozzle (first 2 meters)
  - Constant Mach number MHD channel
  - Diffuser (last 2-3 meters)
- **Heat losses partially recovered in bottoming cycle**







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

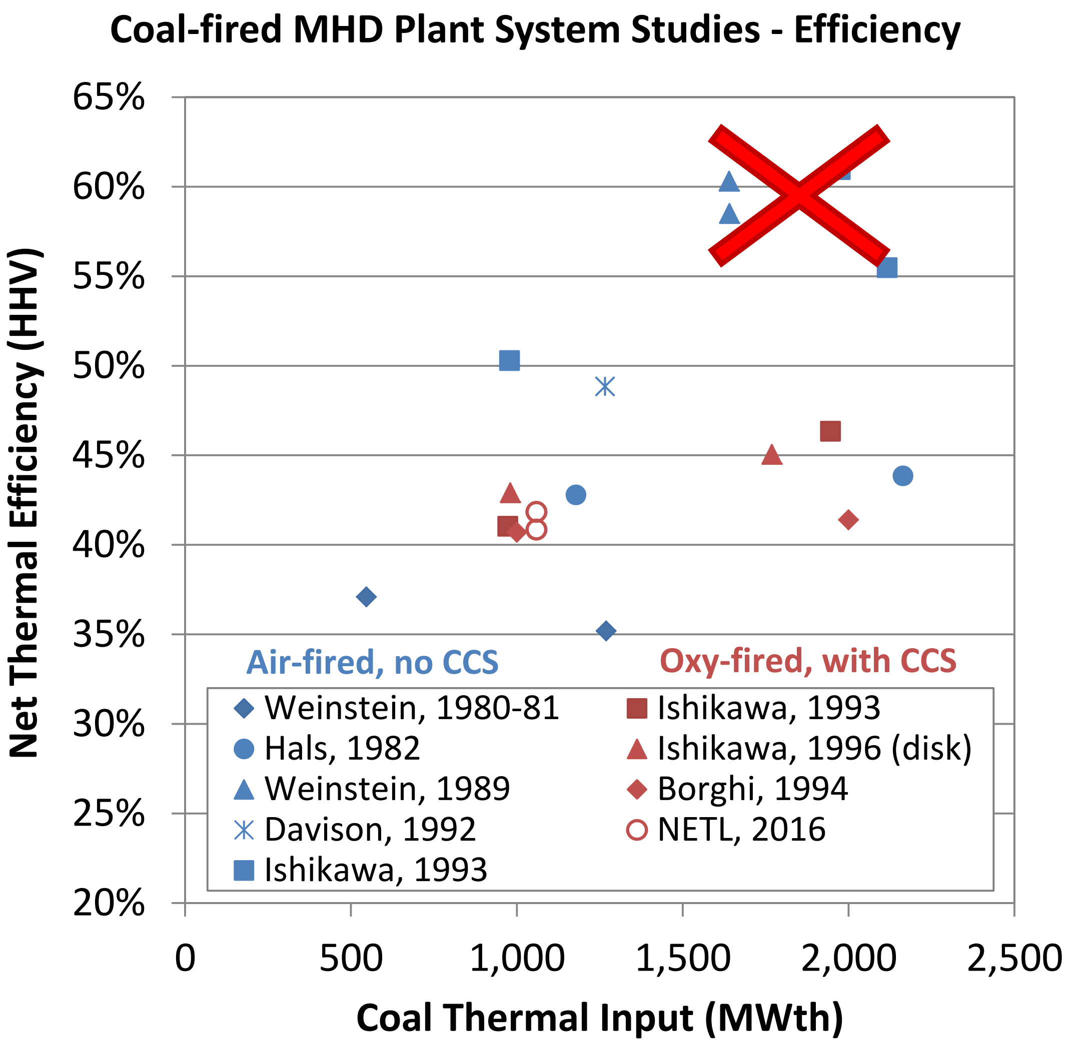
Final Plant Performance Results

- **DPE-2 includes**
  - Higher channel output
  - Lower steam cycle output
  - Higher combustor compression power
- **Thermal efficiencies consistent with other oxy-coal MHD studies**
- **NETL analysis considers more auxiliary systems than other oxy-fired DPE studies to date**

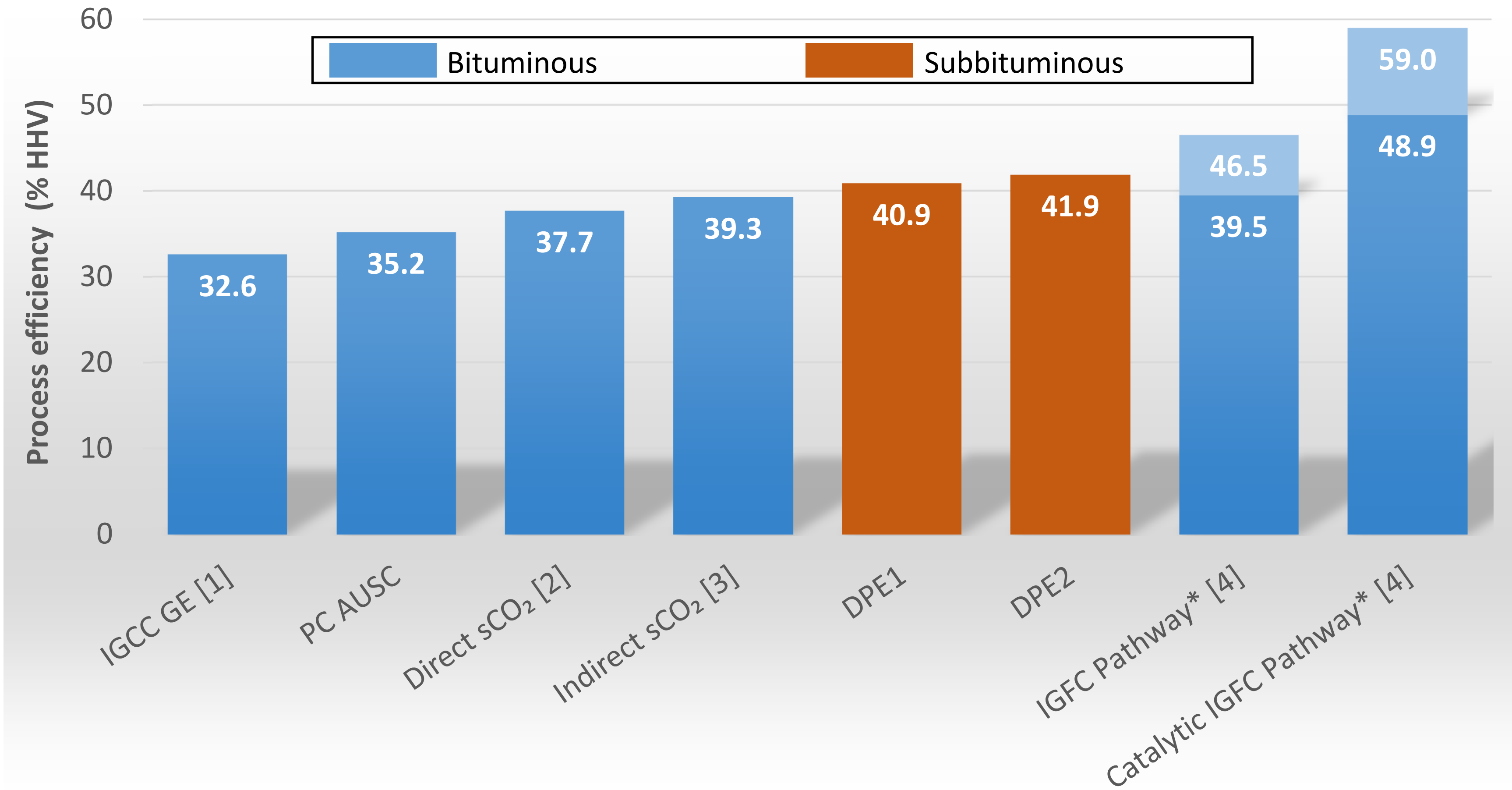
Parameter	Units	DPE-1	DPE-2
Gross Power Output	MW	586	601
MHD Channel	MW	166	***191***
Steam Turbine	MW	420	***410***
Auxiliary Power	MW	154	158
ASU Compressors	MW	64	64
CPU Compressors	MW	42	42
Oxygen Compressors	MW	18	***22***
Other Auxiliaries	MW	30	30
Net Power Output	MW	433	443
Thermal Input (HHV)	MW	1059	1059
Net Thermal Efficiency (HHV)	**%**	**40.9**	**41.9**
Steam Cycle Efficiency (HHV)	%	47.1	47.1
CO_2 Capture Rate	%	96.2	96.2
CO_2 Purity	%	99.99	99.99

Comparison of Air- vs. Oxy-fired Systems

- **Compared to legacy MHD studies with *partial* oxygen use**
- **Air-fired efficiencies range from 35% to 60% for *aggressive* MHD assumption cases**
  - Cases >55% efficiency are aspirational
- **Most oxy-fired system studies predict 40-46% thermal efficiency**
  - Includes CO_2 capture
  - Reduced MHD power due to CO_2 higher heat capacity and tendency to dissociate, recovered in bottoming cycle



Advanced Coal-fired Power Plants with CCS
Efficiency Comparison (% HHV)



* Lower value denotes baseline case, upper value denotes endpoint of cumulative technology development pathway

Advanced Coal-fired Power Plants with CCS

Efficiency Comparison References

1) **National Energy Technology Laboratory. *Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Bituminous Coal (IGCC) to Electricity Revision 2b – Year Dollar Update,* DOE/NETL-2015/1727. July 2015.**
2) **Weiland, N., Shelton, W. W., White, C., and D. Gray. *Performance Baseline For Direct-fired sCO_2 Cycles.* The 5th International Symposium - Supercritical CO2 Power Cycles. San Antonio, Texas. March 2016.**
3) **Shelton, W. W., Weiland, N., White, C., Plunkett, J., and D. Gray. *Oxy-coal-fired Circulating Fluid Bed Combustion with a Commercial Utility-size Supercritical CO_2 Power Cycle.* The 5th International Symposium - Supercritical CO2 Power Cycles. San Antonio, Texas. March 2016.**
4) **National Energy Technology Laboratory. *Techno-Economic Analysis of Integrated Gasification Fuel Cell Systems.* DOE/NETL-341/112613. November 2014.**

Conclusions and Future Work

- **Developed the *first* pure oxygen-fired coal MHD system performance analysis with CCS**
  - Net plant thermal efficiency of ~42% (with CCS) is *very* competitive
- **Currently 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 longer channels for higher DPE power output
  - 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

Questions

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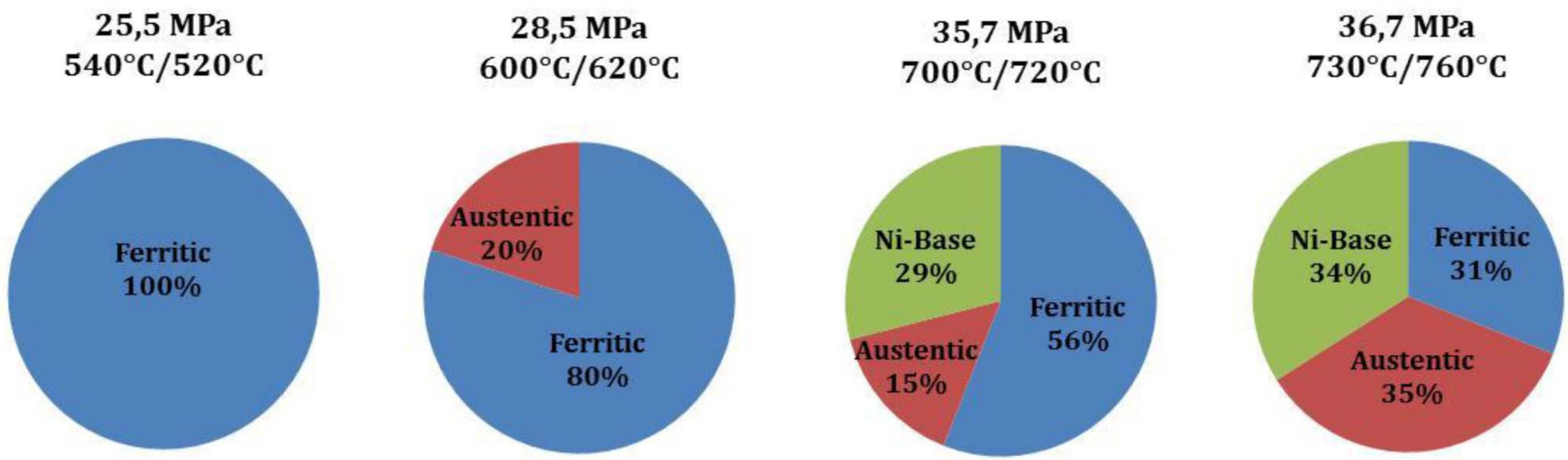
Back-up Slides

Classification Survey and Thermodynamics Studies for Pulverized Coal (PC) Plants

Classification of advanced power plant steam conditions is driven by the boiler and turbine materials utilized*



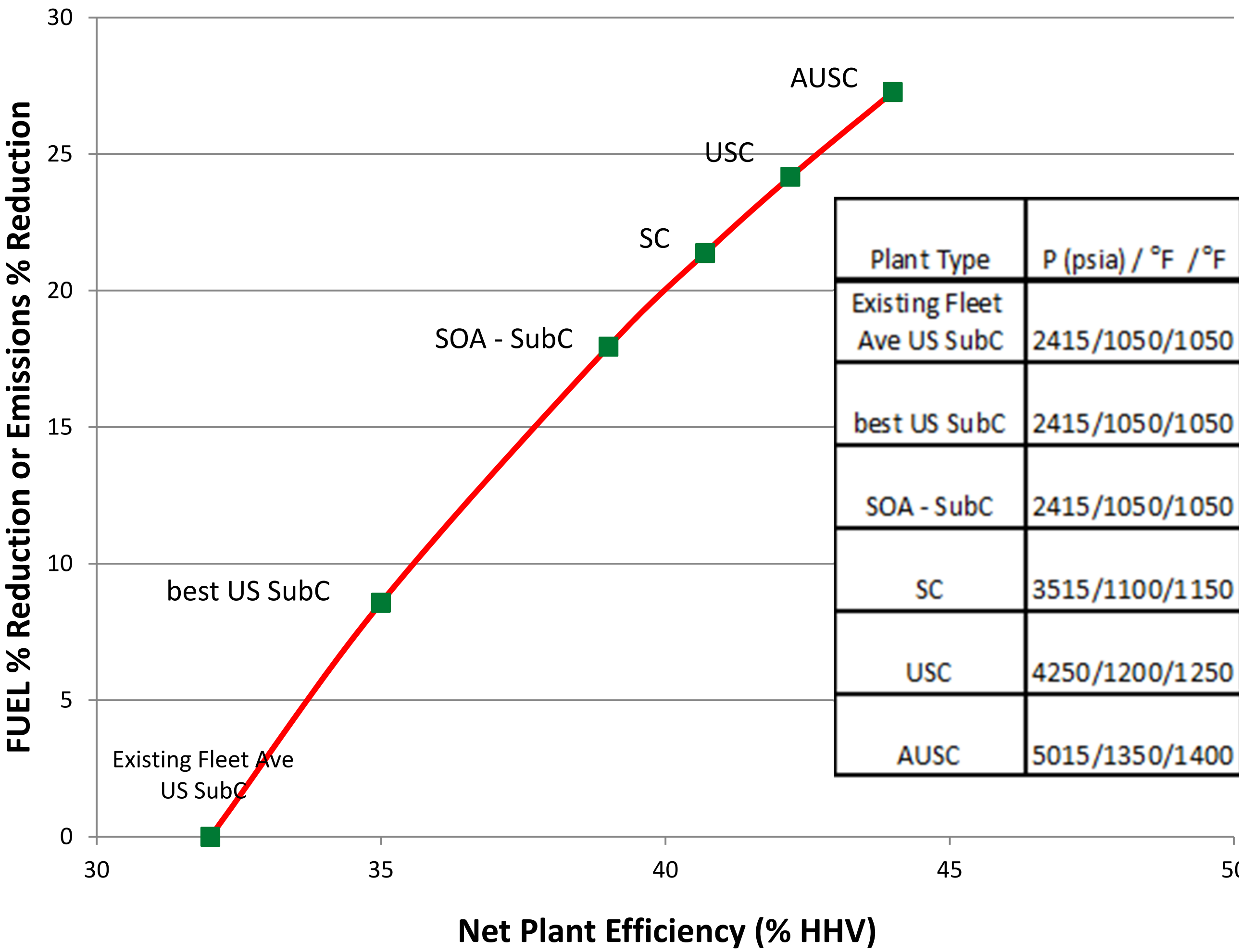
Subcritical (SubC)
Supercritical (SC)

Ultra-supercritical
(USC)

Advanced Ultra-supercritical
(AUSC)

* Rogalev, N., *et al.*, "A Survey of State-of-the-Art Development of Coal-Fired Steam Turbine Power Plant Based on Advanced Ultrasupercritical Steam Technology," *Contemporary Engineering Sciences*, **7(34)**:1807 - 1825, 2014.

Coal Flowrate and Emissions Reductions for Advanced PC Plants



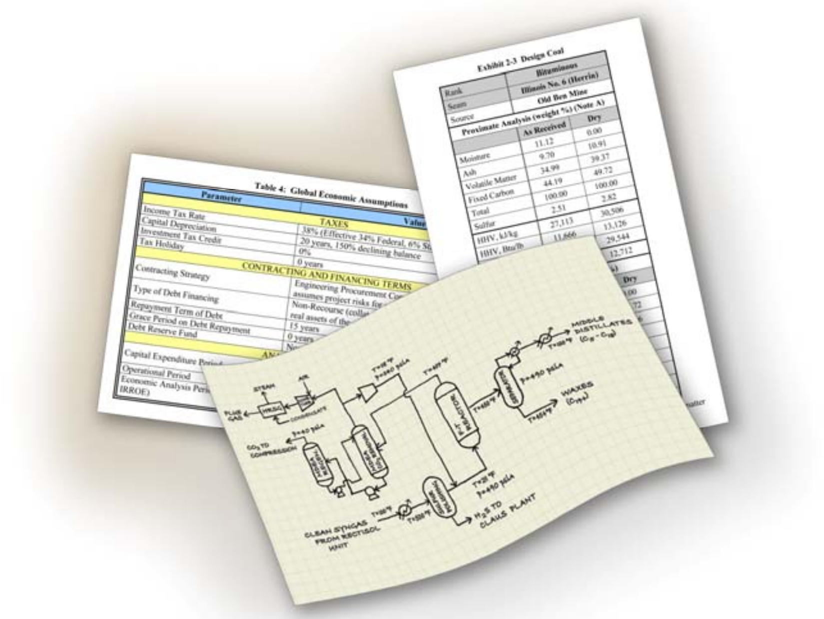
Plant Type	P (psia) / °F / °F	Efficiency %HHV	Basis
Existing Fleet Ave US SubC	2415/1050/1050	32	Power Magazine (2014)
best US SubC	2415/1050/1050	35	Power Magazine (2014)
SOA - SubC	2415/1050/1050	39	OPPB Bituminous Baseline (2014)
SC	3515/1100/1150	40.7	OPPB Bituminous Baseline (2014)
USC	4250/1200/1250	42.2	OPPB Baseline Study (planned)
AUSC	5015/1350/1400	44	OPPB Baseline Study (planned)

Advanced Ultra-Supercritical (AUSC) Pulverized Coal Reference Plants

Design Basis

General Evaluation Basis

Quality Guidelines for Energy System Studies

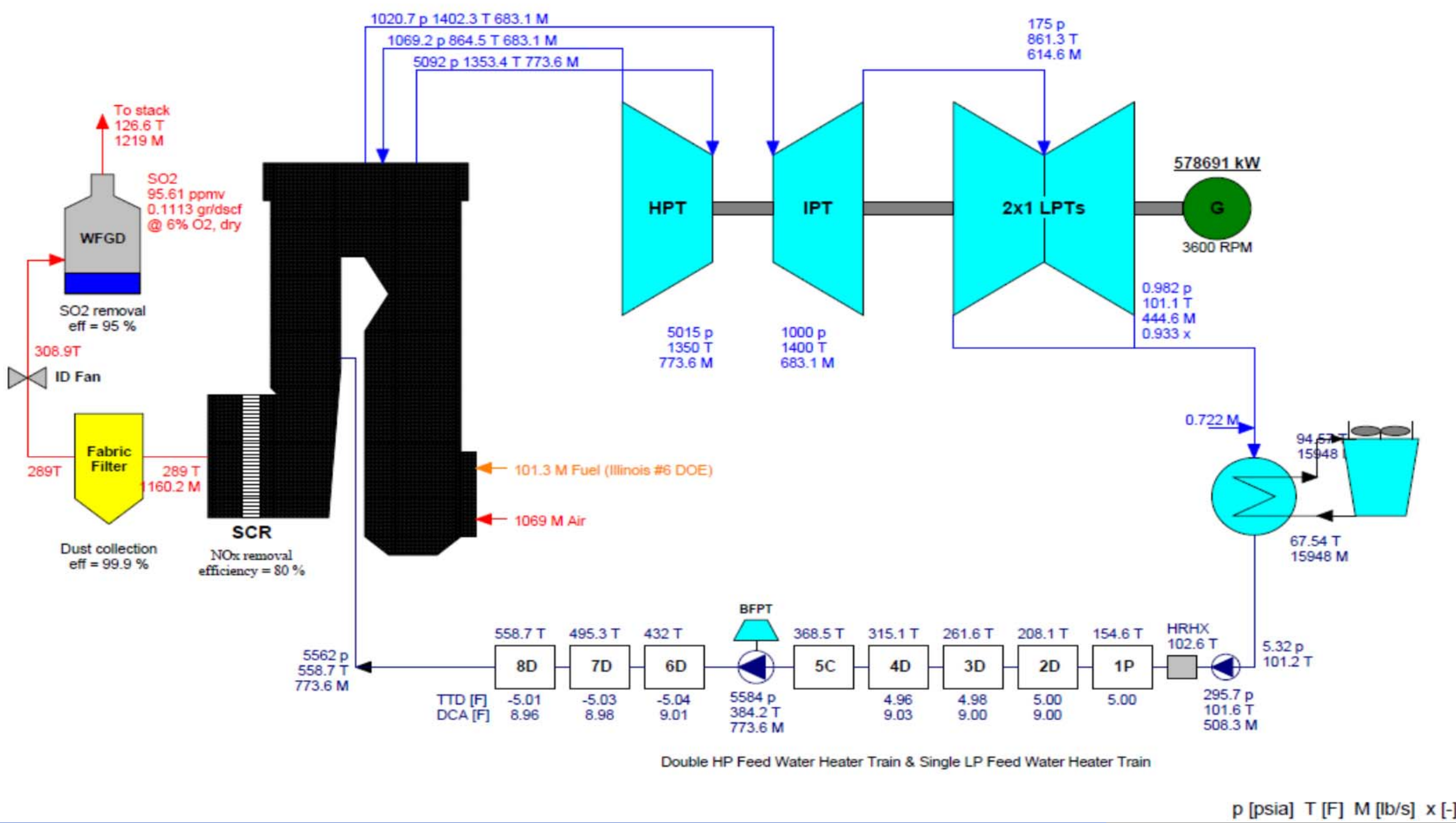


- **Performance and Economic simulation will conform with the following QGESS Guidelines:**
  - CO_2 T&S
  - CO_2 Purity
  - Cost Estimation Methodology
  - Capital Cost Scaling Methodology
    - With modifications for A-USC components
  - Energy Balance
  - Feedstock Specifications
  - Fuel Prices
  - Process Modeling Design Parameters
  - Techno-Economic Analysis

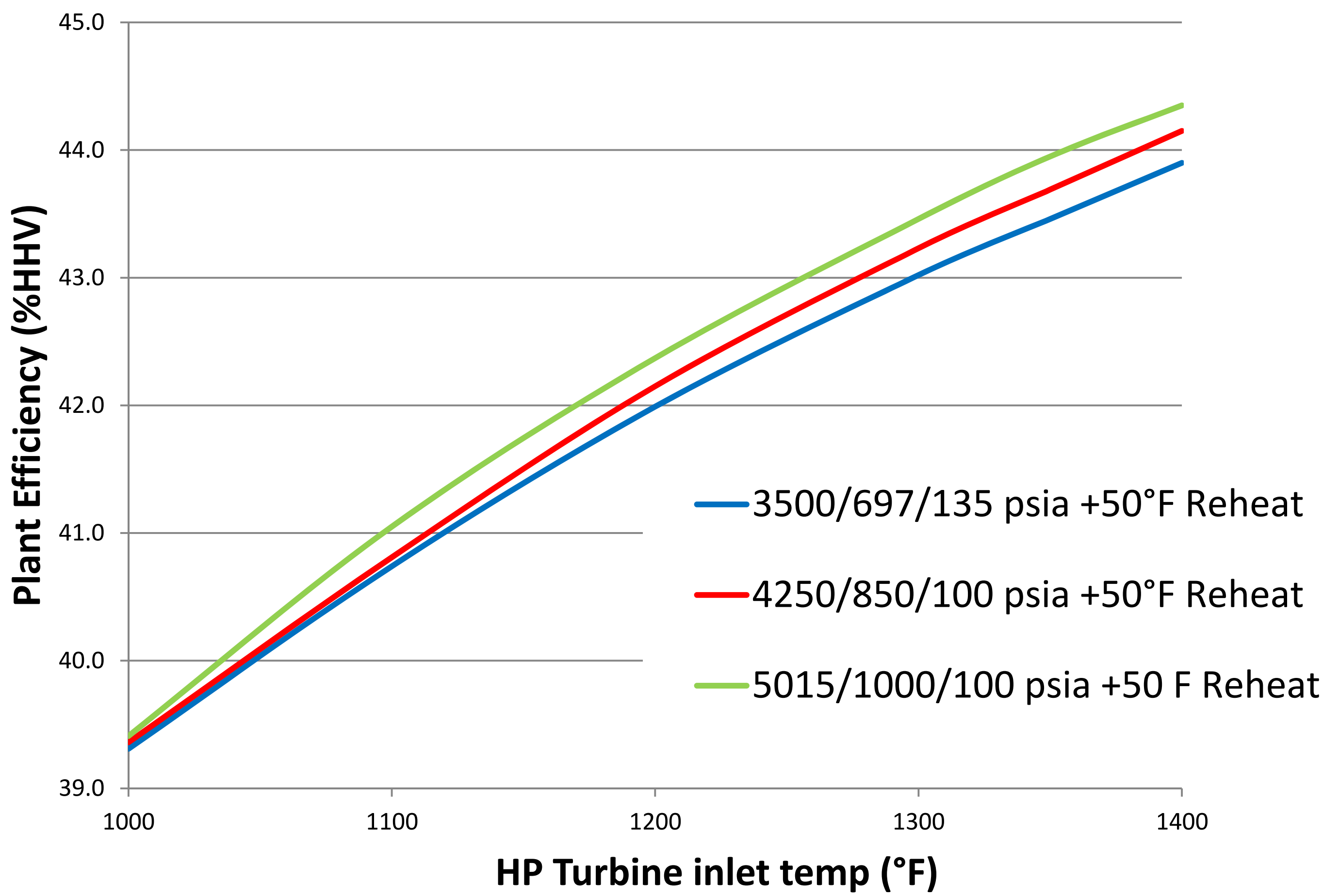
Thermodynamic Modeling
(Thermoflow: Steam-PRO /PEACE / Thermoflex)

Plant gross power	578691	kW
Plant net power	550021	kW
Number of units	1	
Plant net HR (HHV)	7738	BTU/kWh
Plant net HR (LHV)	7380	BTU/kWh
Plant net eff (HHV)	44.1	%
Plant net eff (LHV)	46.24	%
Aux. & losses	28670	kW
Fuel heat input (HHV)	1182192	BTU/s
Fuel heat input (LHV)	1127565	BTU/s
Fuel flow	4378	ton/day

Ambient
14.7 p
59 T
60% RH
51.48 T wet bulb



Thermodynamic Modeling
Plant Efficiency % HHV



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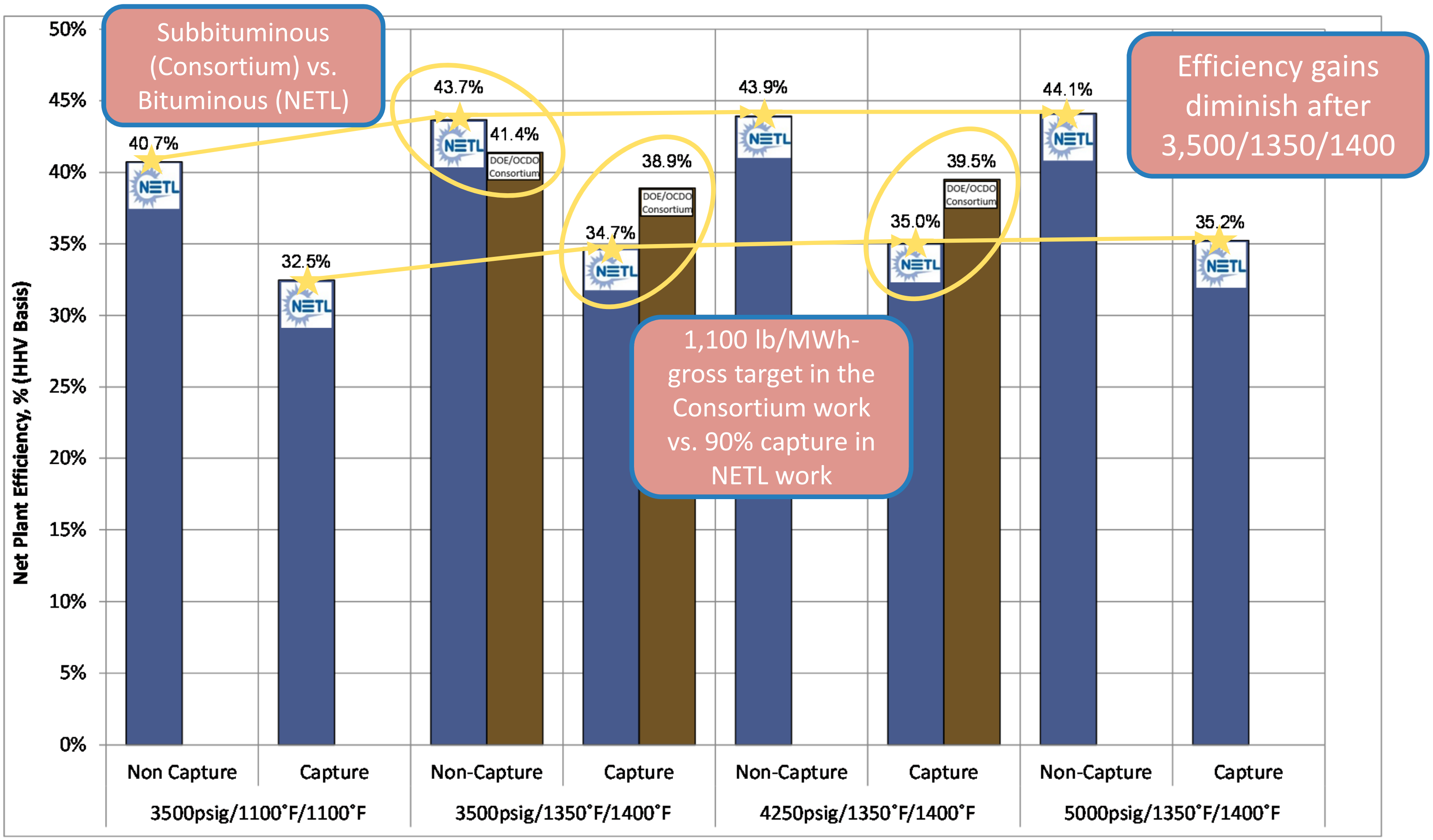
AUSC PC Plant Performance Results

Net Plant Efficiency



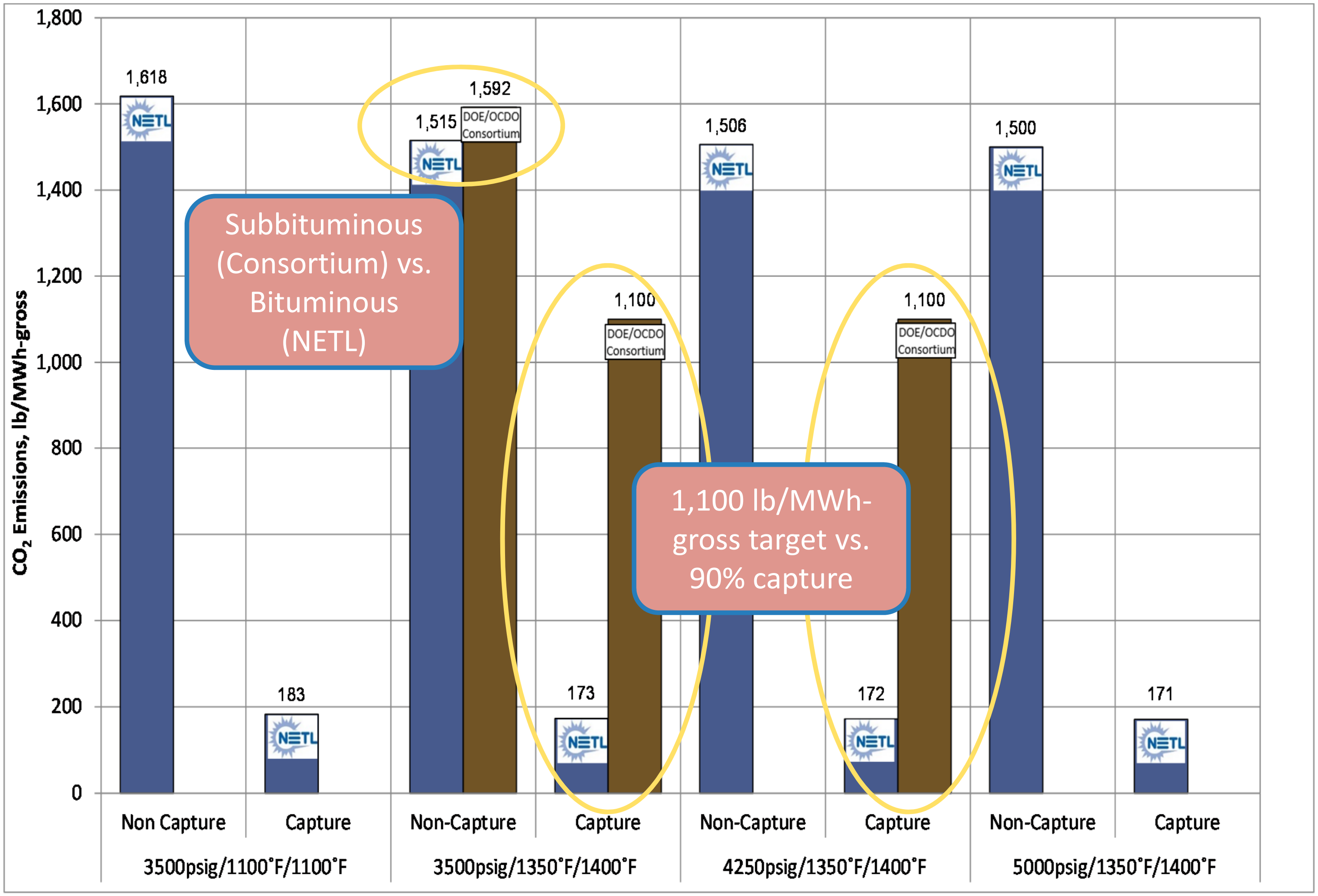
Slide 34

STR7 A lot of mixing of bases here. I wouldn't present either slide 11 or 12. Just a table of the results in comparison to B11A/B, B12A/B.

Shultz, Travis R. , 4/5/2016

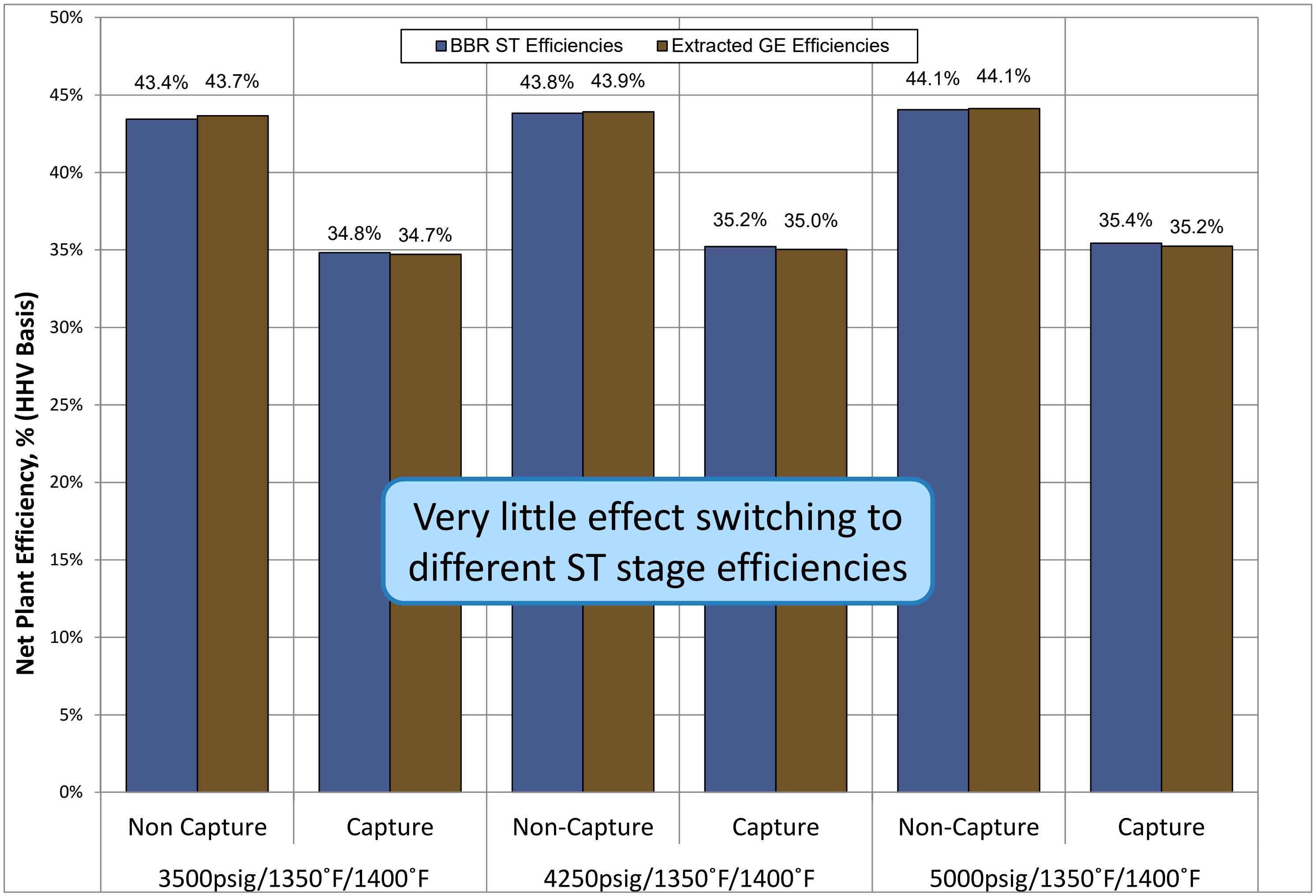
AUSC PC Plant Performance Results

CO_2 Emissions



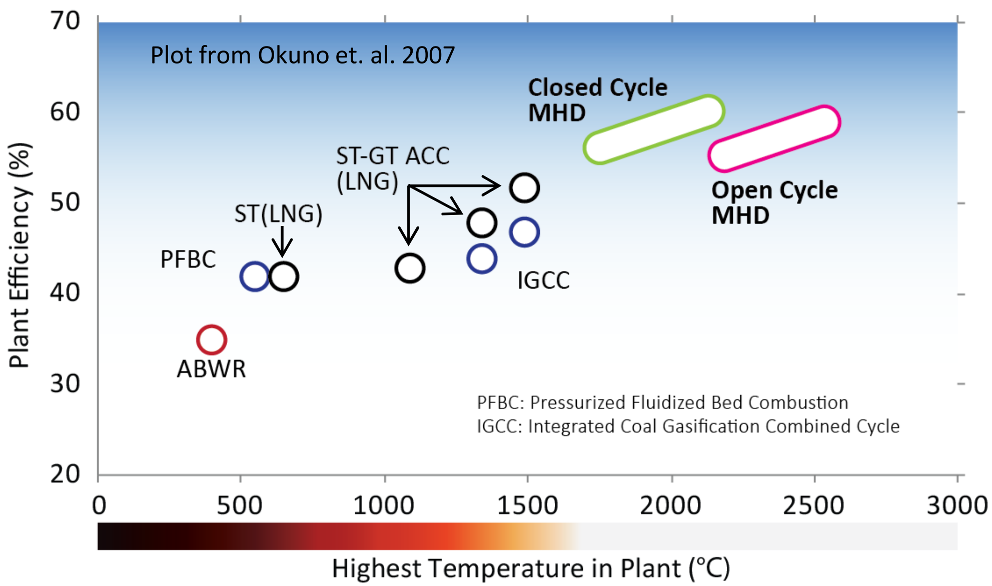
Performance Results

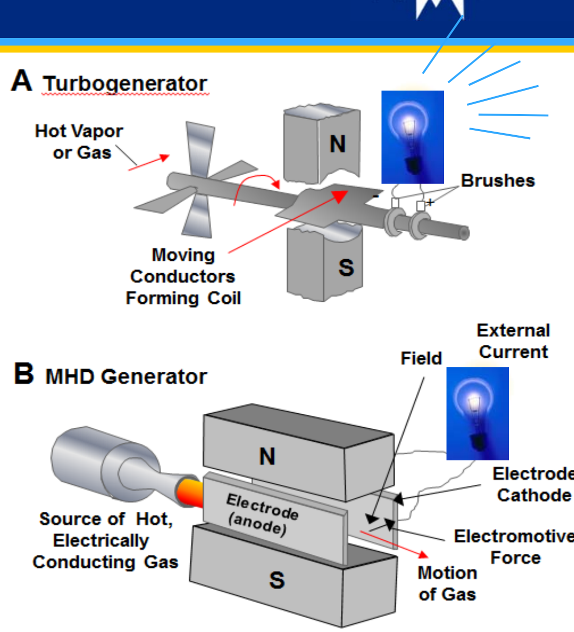
Net Plant Efficiency (HHV%)

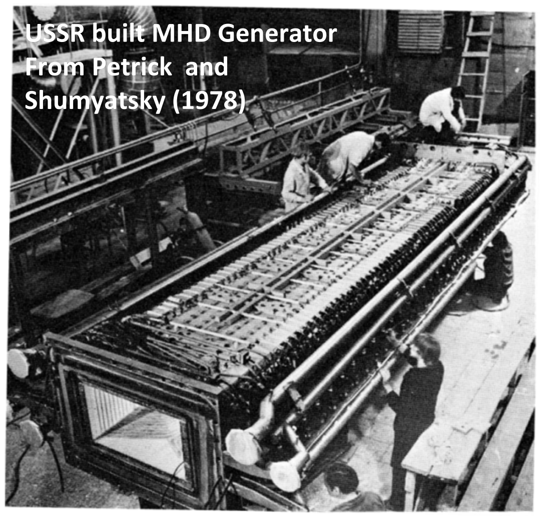


Direct Power Extraction (via MHD)

- **Magnetohydrodynamic (MHD) Power Generator:**
  - Use a strong magnet and convert kinetic energy of conductive gases directly to electric power
- **Higher thermal efficiency via higher temperatures**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS
- **MHD cycle: turns efficiency disadvantage (oxygen production) to efficiency advantage(power production)!**







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