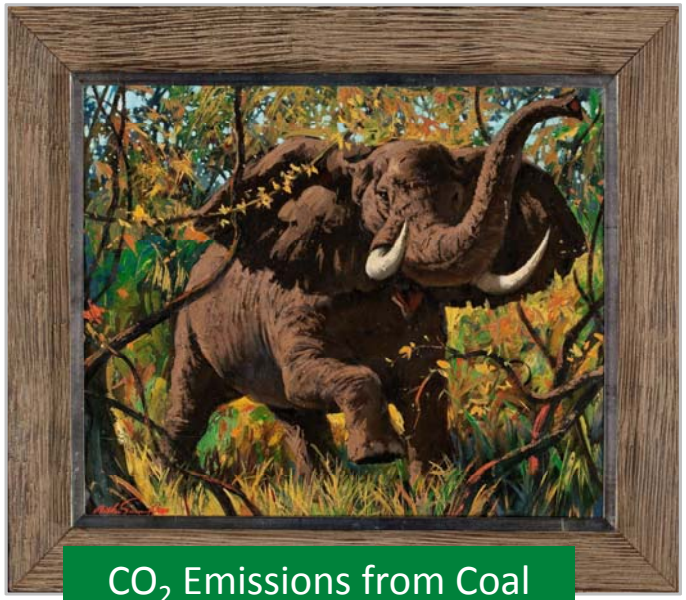
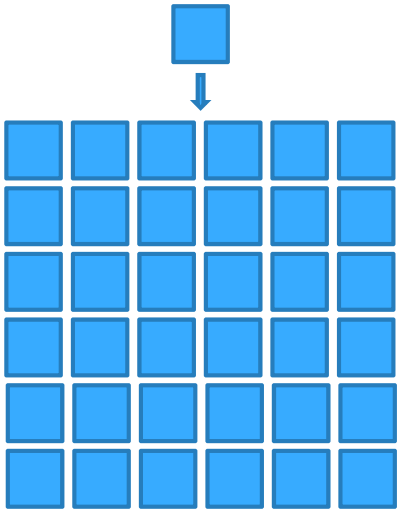
Driving Innovation ♦ Delivering Results



CO_2 Emissions from Coal
The Elephant in the Room

Modular Approach
Revolutionary Engineering



Revolutionary Materials
to support
Revolutionary Engineering

Gasification Systems and Coal Biomass to Liquids Programs

Ongoing R&D and Changing Focus

Jenny Tennant
DOE Technology Manager
Coal Gasification and Fuels Production

October 7, 2015

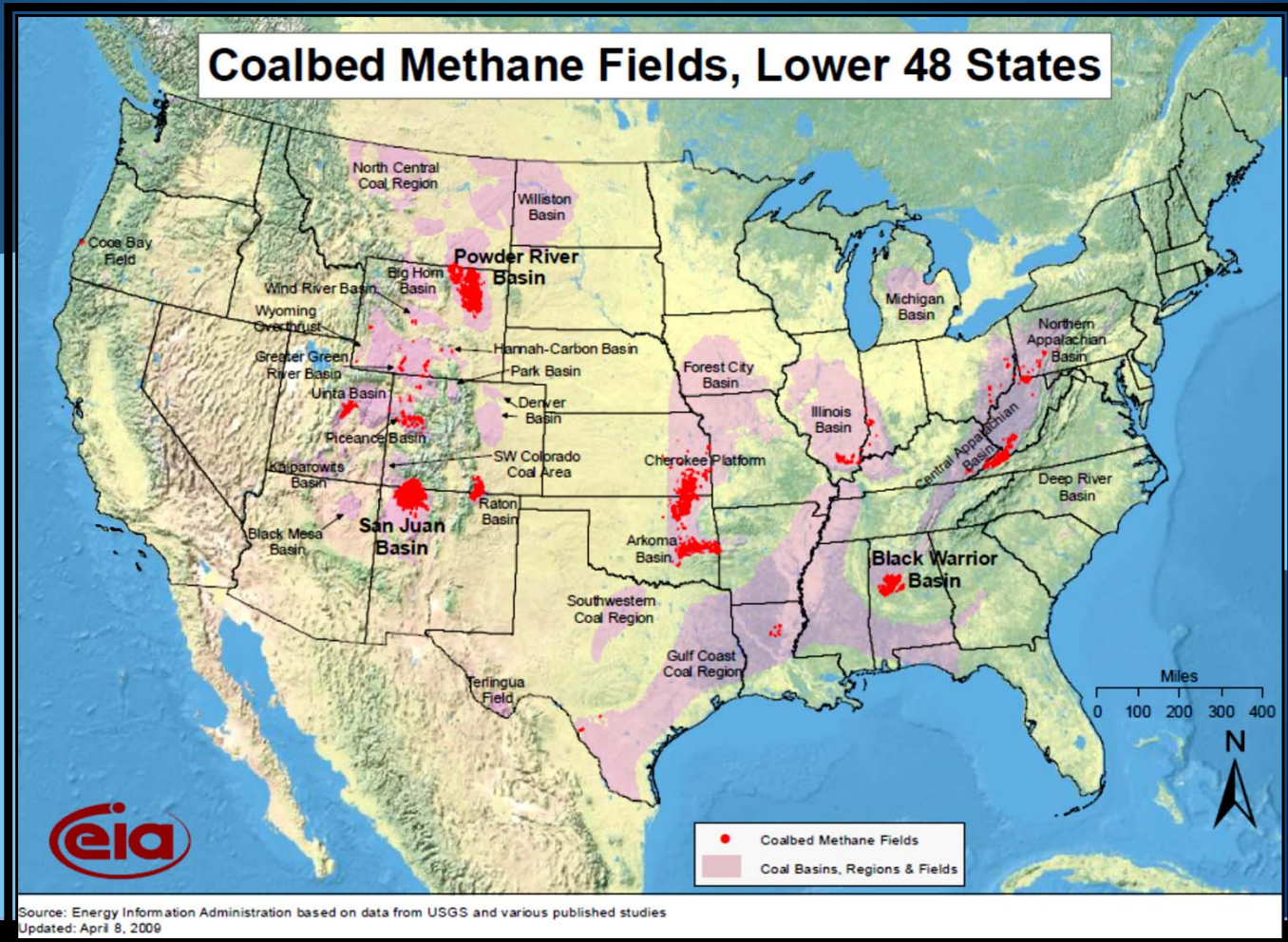
Ongoing Projects

- **Two direct coal chemical looping projects, and one to create hydrogen from syngas**
- **Seven oxygen production projects**
- **Four biogasification projects**
- **Two projects on using red mud as a gasification catalyst**

and more

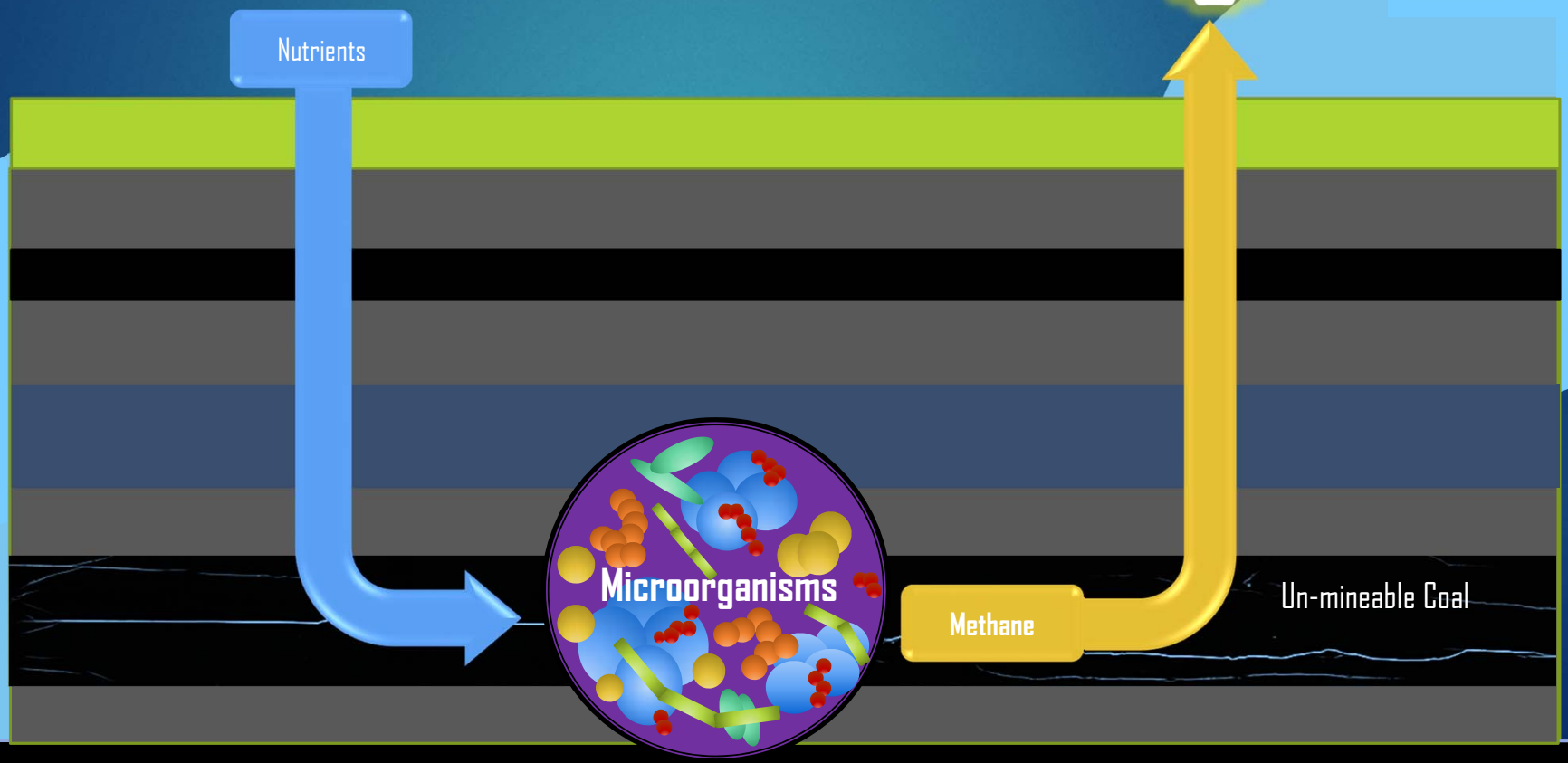
A sampling of these technologies and projects follows

Genetic Characterization of Native Microbial Communities In "Un-mineable" Coals



Future Direction

This technology's competition is the natural gas market



American Recovery and Reinvestment Act Success!

Research Triangle Institute's Syngas Cleanup Technology

- ARRA funding enabled accelerated testing from successful 0.3 MWe tests to 50 MWe at a Tampa Electric Company's Polk Power Station -- *a 167-fold increase in scale*
- Accumulated more than 1,500 total hours of operation, achieving greater than 99.7-99.9 % total sulfur removal (for both H2S and COS)

RTI President Wayne Holden, DOE PDAS Julio Friedmann, TECO Vice President Tom Hernandez

- Project was completed under budget
- Follow-on project planned to achieve at least 5,000 hrs of test time
- Expected to be demonstrated by industry without DOE support

back

Ion Transport Membrane (ITM)

~~*Air Products and Chemicals, Inc*~~. *???*

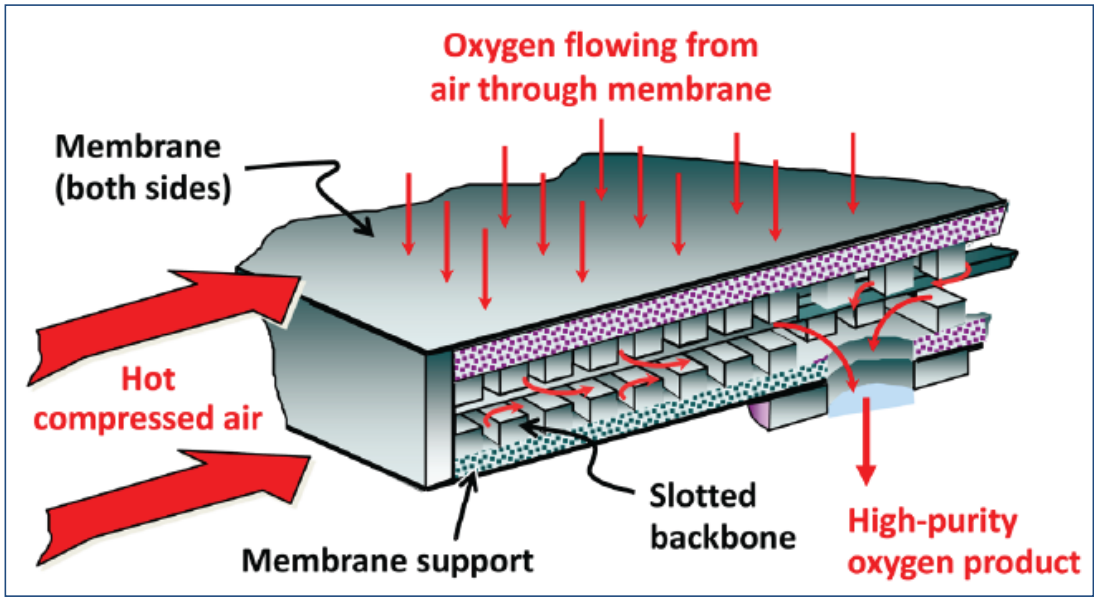
Ion Transport Membrane (ITM)

Supported thin-film, ceramic planar devices

Fast, solid state electrochemical transport of oxygen

Pressure-driven; compact

All the layers are composed of the same ceramic material

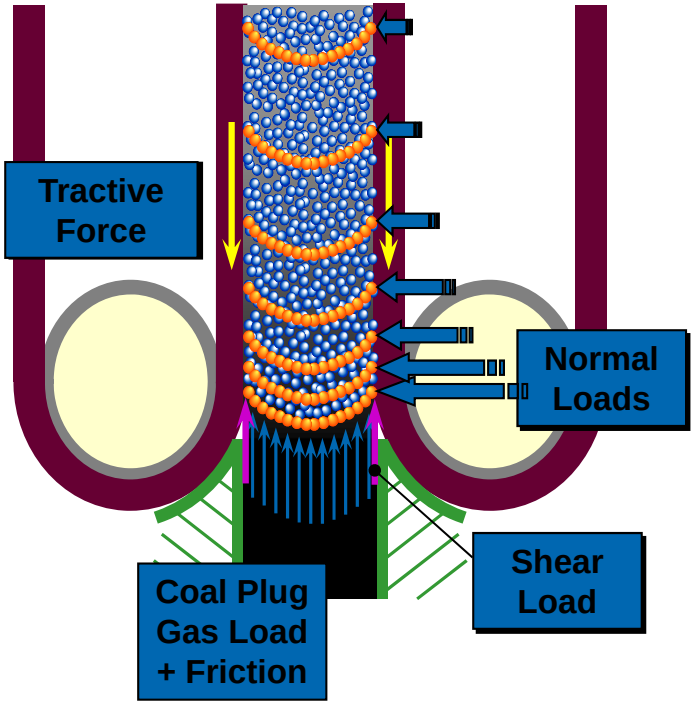


1.0 TPD Stack

High Pressure Solids Pump

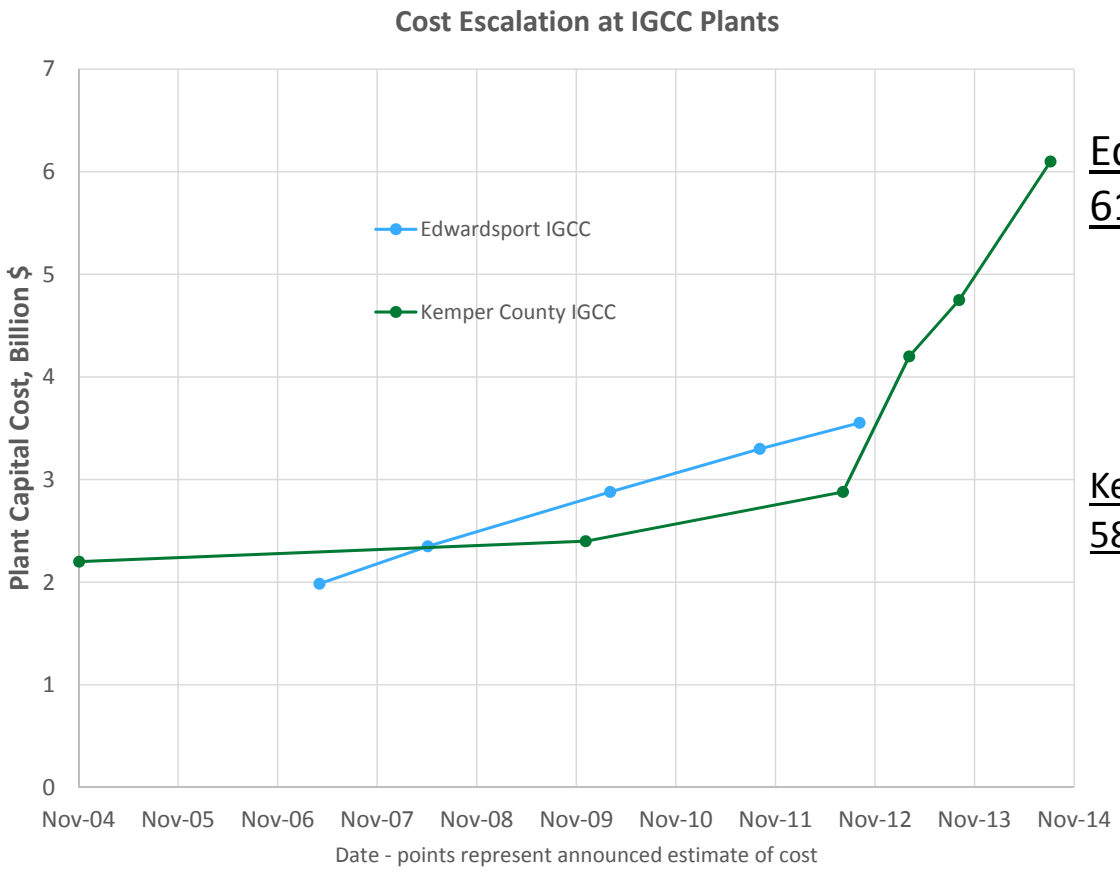
~~Aerojet Rocketdyne~~ Gas Technology Institute

- Pump operation relies on ability of bulk solids to form multiple stable "bridges" or arch between parallel wall structure, bridges can support very large loads
- Increasing load is transferred to sidewalls, making the bridge more stable, further increasing load will ultimately fail the sidewall
- Extrusion or "pumping" occurs when sidewalls are moved mechanically and material is released by separating the walls



In "lock-up" there is no "slip" or relative motion between material and moving walls, device exhibits "positive displacement" with a volumetric displacement of unity

Edwardsport IGCC and Kemper County IGCC Plant Capital Costs



<u>Edwardsport IGCC – 618 MW (no carbon capture)</u>

Initial Cost Estimate - $1,985M ($3,200 per kW)

Final Cost - $3,554M ($5,700 per kW)

<u>Kemper County IGCC – 582 MW (65% carbon capture)</u>

Initial Cost Estimate - $2,200M ($3,800 per kW)

Final Cost Estimate - $6,100M ($10,500 per kW)

Coal is being Crushed Between CO_2 Emissions and Low Prices for Oil and Natural Gas

To Transportation Fuel

Without CO_2 capture and storage

A 50,000 barrel per day plant will emit 2.3 times more CO_2 in the atmosphere every day than conventional oil refining

A 50,000 barrel per day plant will be economically competitive when oil is $120 per barrel

We need to think about coal conversion in different terms

NETL Ongoing Efforts:

Survey of U.S. coal conversion needs

- Appalachia included

Survey of U.S. coals and high value products from past R&D

Systems Analysis geared up to focus on optimizing systems that will focus on most compelling needs

Existing Coal R&D

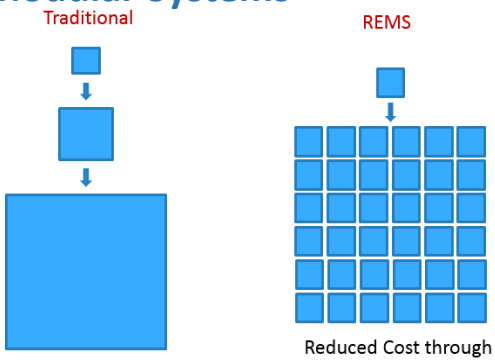
- At least 3 companies engaged in active R&D
- Several larger-scale targeted technologies will apply even better to smaller systems
- Actively seeking other ongoing R&D work and potential collaborations
- New NETL initiative: Radically Engineered Modular Systems (REMS)

NETL Supercomputer

and expertise on coal kinetics and reactor behavior

Like personal computing, modeling gas-particulate reactions is becoming increasingly powerful

Modular Systems



Less expensive products the bigger the plant gets

- Funding difficulties
- Biomass use infeasible

Reduced Cost through Advanced Manufacturing

- Any size for any application
- Repeated designs mean faster replacements and less plant down-time
- More plant flexibility: feed and products

Advanced Manufacturing

- Reduced reactor and plant capital costs
- Decreased plant down time
- Increased product value

By 2020 hope to build prototype REMS mine mouth economically viable pilot-scale plant

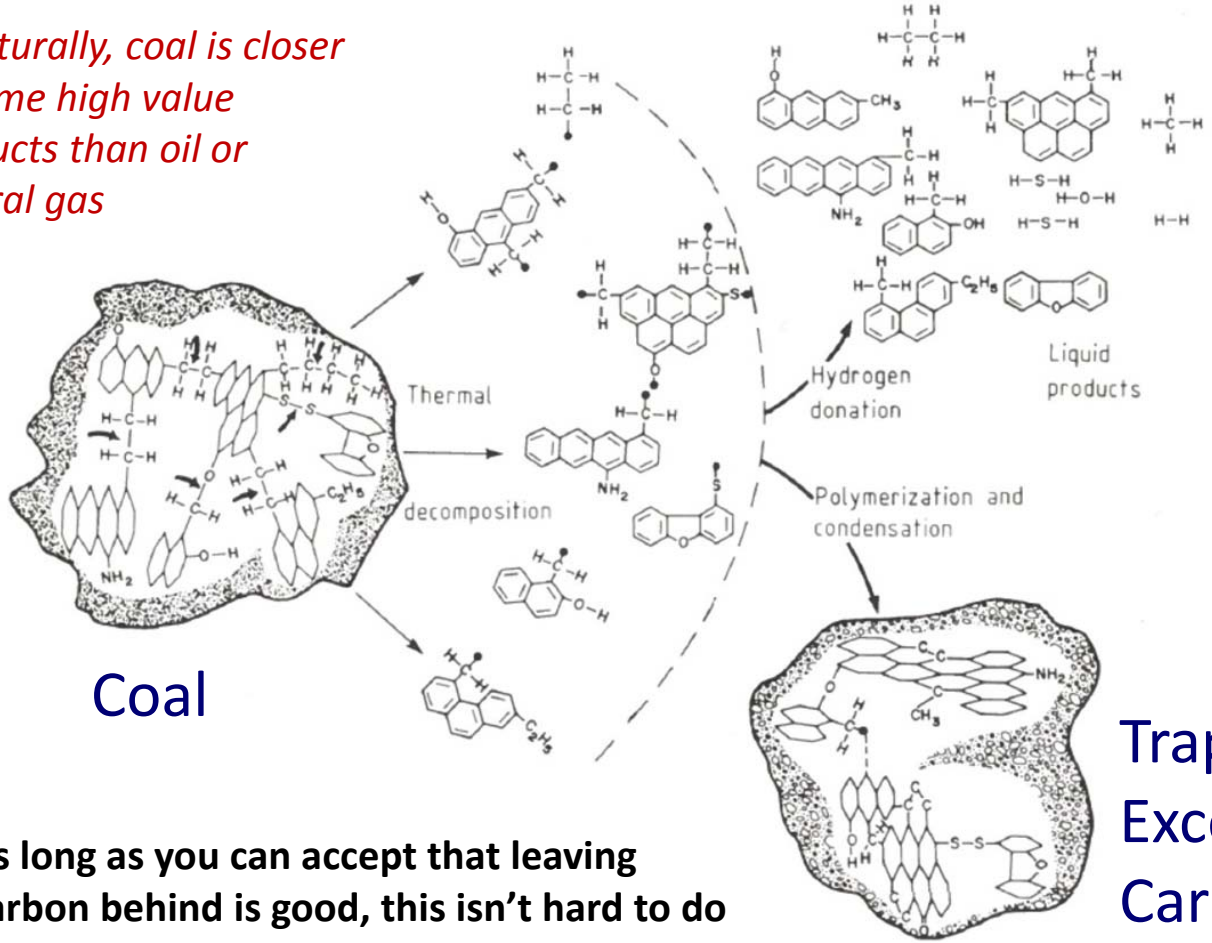
✓ Use coal prep plant fines as feedstock

✓ Go after highest value products

By 2030 achieve a coal conversion revolution by manipulating coal at the particulate level. Expand reach to bigger markets.

Consider Removing Excess Carbon as a Solid

Structurally, coal is closer to some high value products than oil or natural gas



Coal

High Value Products

Trapped Excess Carbon

As long as you can accept that leaving carbon behind is good, this isn't hard to do

Frank Derbyshire and David Gray, Ullman's Encyclopedia of Industrial Chemistry, Vol A7, 1986

Biomass

If we also use biomass, we should be able to create liquid fuels that *emit less CO_2 than oil refining*
<u>without gaseous CO2 capture and storage</u>

- We'd need smaller plants since transporting biomass is expensive

Power Generation:

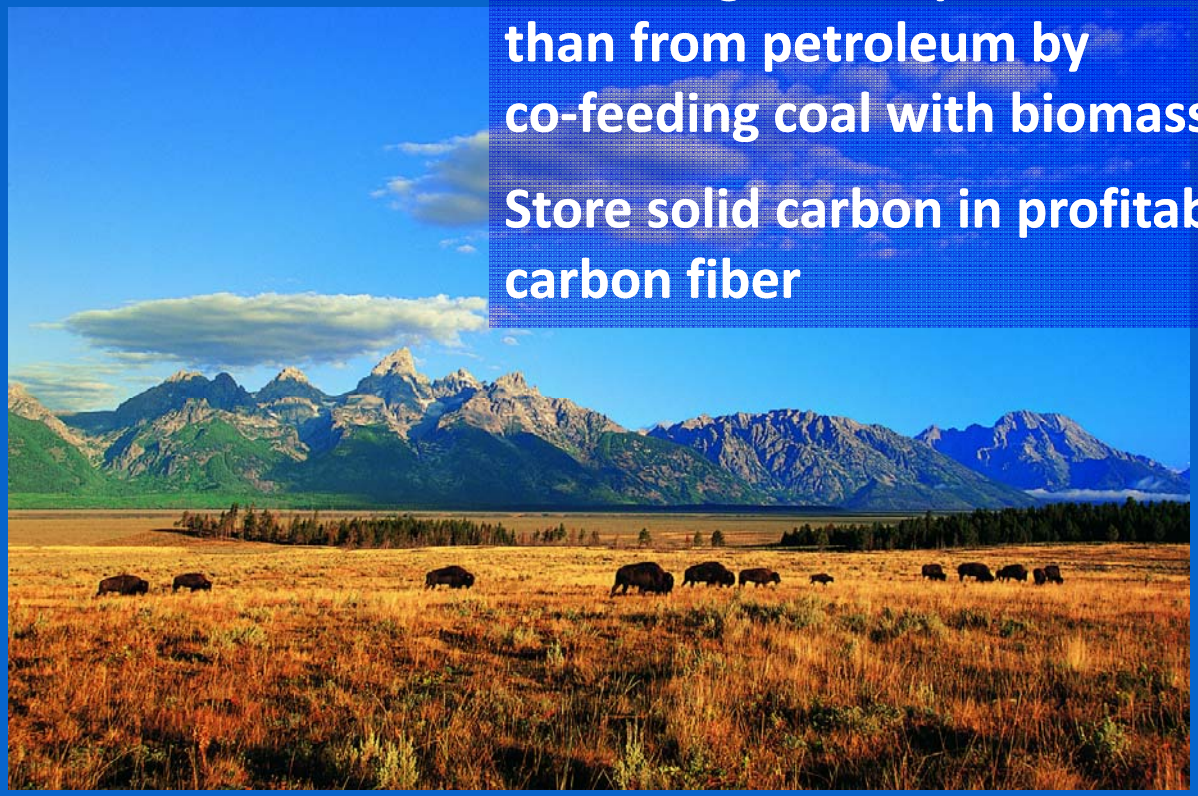
- Integration with Fuel Cells
- Niche markets with high power costs
- Plant power in poly-generation applications

Reduce capital costs and new technology costs by using advanced tools

- Modular systems and advanced manufacturing
- Advanced computer programs

Use the benefit of complex coal structure to create high value products, with a lower carbon footprint than from petroleum by co-feeding coal with biomass

Store solid carbon in profitable ways: perhaps making carbon fiber



Carbon Fiber House – Oak Ridge

New Message to the Public:
Coal Can Make Low CO_2 Emission Products

Happy Elephant

Coal Scientists

NETL intends to issue Requests for Information in the near future:

- *Technologies to produce high value products with solid carbon capture*
- *Ongoing R&D to develop less expensive ways of turning coal into carbon fiber*

Back Up Information

2015 Gasification Systems and Coal & Coal-Biomass to Liquids Workshop – Day 1

- **Monday, August 10, 2015**
- Welcome and Introduction
  Jenny Tennant, Technology Manager for Gasification and C&CBTL
  U.S. Department of Energy, National Energy Technology Laboratory
- Wyoming Coal's Role in the World–Recent Past, Present and Future
  Don Collins, CEO of the Western Research Institute
- **SESSION I**
- Chemical Looping Gasification for Hydrogen Enhanced Syngas Production
  Liang-Shih Fan, The Ohio State University
- Limestone Chemical Looping
  Armand Levasseur, Alstom Power, Inc.
- **SESSION II**
- Radically Engineered Modular Systems
  Christopher Matranga, U.S. Department of Energy, National Energy Technology Laboratory
- Praxair's Oxygen Transport Membrane Technology for Syngas and Power Applications
  Juan Li, Praxair, Inc.
- Advanced Reactor Design for Integrated WGS/Pre-Combustion CO_2 Capture
  Gokhan Alptekin, TDA Research, Inc.
- **SESSION III**
- Sorbent-Based Oxygen Production for Energy Systems
  Vijay Sethi, Western Research Institute
- Cost-Effective Air Separation System
  Gokhan Alptekin, TDA Research, Inc.
- A Cost-Effective Oxygen Separation System Based on Open Gradient Magnetic Field by Polymer Beads
  Raghuvir Singh, ITN Energy Systems, Inc.
- Production of High-Purity Oxygen via Membrane Contactor with Oxygen Carrier Solutions
  Shiguang Li, Gas Technology Institute
- Intermediate Temperature Nano-Structured Ceramic Hollow Fiber Membranes for Oxygen Separation
  Xingjian Xue, University of South Carolina
- **SESSION IV**
- Advanced Gasifier and Water Gas Shift Technologies for Low-Cost Coal Conversion to High Hydrogen Syngas
  Don Stevenson, GTI
- Scale-Up of High Temperature Syngas Cleanup Technology
  Raghubir Gupta, RTI International
- Dry Solids Pump Coal Feed Technology
  Timothy Saunders, GTI
- Breakthrough Hybrid CTL Process Integrating Advanced Technologies for Coal Gasification, NG Partial Oxidation, Warm Syngas Cleanup, and Syngas-to-Jet Fuel
  John Carpenter, RTI International

http://www.netl.doe.gov/events/conference-proceedings/2015/gas-ccbtl

Workshop Day 2

- **Tuesday, August 11, 2015**
- Coal Conversion – A Global Perspective
  David Denton, Gasification Technologies Council and RTI International
- **SESSION I**
- Indirect Liquefaction of Coal-Biomass Mixtures for Production of Jet Fuel with High Productivity and Selectivity
  Santosh Gangwal, Southern Research Institute
- Technology for Cost-Competitive Jet Fuel Production Using CTL
  Joseph Hartvigsen, Ceramatec, Inc.
- New Advances for Fischer-Tropsch Catalysis
  Christopher Matranga, U.S. Department of Energy, National Energy Technology Laboratory
- **SESSION II**
- Application of Chemical Looping with Spouting Fluidized Bed for Hydrogen- Rich Syngas Production From Catalytic Coal Gasification
  Kunlei Liu, University of Kentucky-Center for Applied Energy Reseach
- Development of Coal to Liquids Pilot Facility and Lessons Learned
  Andrew Placido, University of Kentucky-Center for Applied Energy Reseach
- Coal to Desired Fuels and Chemicals
  Maohong Fan, University of Wyoming
- Bio Gasification Panel
  MODERATOR: Djuna Gulliver, U.S. Department of Energy, National Energy Technology Laboratory
  Yael Tucker, U.S. Department of Energy, National Energy Technology Laboratory
  Yanna Liang, Southern Illinois University Carbondale
  Matthew Fields, Montana State University
  Taylor Sparks, University of Utah
- **SESSION III**
- Design/Cost Study for Synthetic Jet Fuel Production at a Mississippi Site from Lignite Woody Biomass with CO_2 Capture and Storage via EOR
  Eric Larson, Princeton University
- Multiphase Flow Science at The National Energy Technology Laboratory
  William Rogers, U.S. Department of Energy, National Energy Technology Laboratory
- **SESSION IV BREAK OUT DISCUSSIONS**
- **Radical Reactor Concepts**
  Jenny Tennant, U.S. Department of Energy, National Energy Technology Laboratory
  George Richards, U.S. Department of Energy, National Energy Technology Laboratory
- Performing a Techno-Economic Analysis (TEA)
  James Fisher, U.S. Department of Energy, National Energy Technology Laboratory
- **New Coal and Biomass to Liquids Concepts**
  Dushyant Shekhawat, U.S. Department of Energy, National Energy Technology Laboratory
- **Biogasification Field Site Deployment Goals and Challenges**
  Djuna Gulliver, U.S. Department of Energy, National Energy Technology Laboratory

Workshop Posters

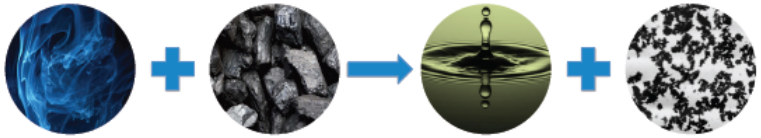
- Design and Fabrication of Novel Mixed Ion-Electron Conducting Membranes for Oxygen Separation
  Jiwen Wang, HiFunda, LLC.
- Economic and Environmental Analyses of Coal Biomass to Liquids: A Case Study In West Virginia
  Weiguo Liu and Jingxin Wang, West Virginia University
- Slag Management in Entrained Bed Gasification
  James Bennett, U.S. Department of Energy, National Energy Technology Laboratory
- Greenhouse Gas-Reduced Coal-and Biomass-to-Liquid-Based Jet Fuel (GHGR-CBTL) Process
  Mehdi Namazian, Altex Technologies Corporation
- Breakthrough Hybrid CTL Process Integrating Advanced Technologies for Coal Gasification, NG Partial Oxidation, Warm Syngas Cleanup, and Syngas-to-Jet Fuel
  John Carpenter, RTI International
- Microwave-Assisted Coal Gasification
  Dushyant Shekhawat, U.S. Department of Energy, National Energy Technology Laboratory
- Synthesis of the Encapsulated Porous Kaolinite Proppant with Spherification
  Kyu-Bum Han, University of Utah
- H S-Resistant Steam Reforming Catalysts for Upgrading Coal Derived Syngas for Coal-to-Liquids Production
  Andrew Lucero, Southern Research Institute
- Gasification and Pre-Combustion CO Capture Testing at the National Carbon Capture Center
  John Carroll, National Carbon Capture Center–Southern Company
- A Cost-Effective Oxygen Separation System Based on Open-Gradient Magnetic Field by Polymer Beads
  Raghuvir Singh, ITN Energy Systems, Inc.
- Synergy and Inhibition During Co-Gasification of Biomass-Coal Blends
  Pradeep Agrawal, Georgia Institute of Technology
- Wave Liquefaction™: The Novel Coal-Biomass-to-Liquids Process
  George Skoptsov, H Quest Vanguard, Inc.
- Direct Coal-to-Liquids (CTL) for Jet Fuel Using Biomass-Derived Solvents
  Satya Chauhan, Battelle
- NETL Crosscutting Technology Research for Sensors Applicable to Harsh Environments
  David Stopek, LTI and Robert Romanosky, U.S. Department of Energy, National Energy Technology Laboratory
- NETL Crosscutting Technology Research for High-Performance Materials
  David Stopek, LTI and Robert Romanosky, U.S. Department of Energy, National Energy Technology Laboratory
- NETL Crosscutting Technology Research for Simulation-Based Engineering
  David Stopek, LTI and Robert Romanosky, U.S. Department of Energy, National Energy Technology Laboratory
- Producing Methane from Coal Through Biogasification Identifying Suitable Nutrient Solutions for Enhancing Methane Yield
  Yanna Liang, Southern Illinois University Carbondale
- Poison Resistant Water-Gas-Shift Catalyst for Coal and Biomass Co-Gasification
  Gokhan Alptekin, TDA Research, Inc.
- Unconventional, Novel Coal-to-Liquids Process
  Francois Botha, Thermaquatica

Wave Liquefaction™
The Novel Coal-Biomass to Liquids Process

Example Poster

George Skoptsov george.skoptsov@h-quest.com
James Strohm james.strohm@h-quest.com
H Quest Vanguard, Inc
750 William Pitt Way : Pittsburgh, PA 15238

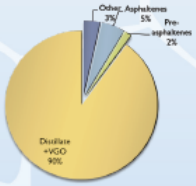
Wave Liquefaction™ combines gaseous and solid hydrocarbons to cleanly and efficiently produce liquid fuels or chemicals and carbon char.



With only 15% biomass feed and no CCS, lifecycle CO_2 emissions are 22% less than for transportation fuels from conventional oil refining.

SYNCRUDE COMPOSITION

Wave Liquefaction™ syncrude yields are 50%-65% wt (on dry, ash-free basis). Liquid product flows at room temperature, has API > 10, and < 50% aromaticity. Low asphaltene content reduces requirements for downstream hydrotreating needed to produce finished fuels.



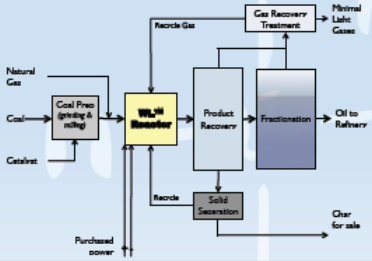
COALS TESTED

More than a dozen coals ranging from lignite to low-volatile bituminous as well as a pine/coal mixture were shown to have high liquid yields with Wave Liquefaction™. Selected results are shown below:

Feedstock Type	Coal Seam	Liquid yield with hydrogen (% wt)	Liquid yield with methane (% wt)
low-volatile bituminous	Pocahontas #3 (VA)	67%	51%
high-volatile bituminous	Pittsburgh #8 (PA)	56%	45%
	H Queen #1 (Russia)	66%	71%
	Bled Canyon (UT)	68%	60%
	Illinois #6 (IL)	72%	61%
subbituminous	Wyodak (WY)	67%	61%
	Wyodak, dry (WY)	57%	45%
lignite	Beulah (ND)	29%	30%
	Victoria Brown (Aus.)	76%	52%
biomass-coal blend	Bled Canyon (UT) / Pine	52%	40%

PROCESS DIAGRAM

Wave Liquefaction™ converts coal and natural gas in a simple, continuous process into synthetic crude and an added-value char product. No coal preparation apart from sizing is needed.



BACKGROUND

Wave Liquefaction™ process was originally developed with the specific goal of establishing the vast US coal resources as an alternative, cost-effective domestic source of military jet fuel with the lifecycle greenhouse gas emissions below those of a conventional crude oil refining process. Blending coal with 15% biomass by weight will decrease lifecycle CO_2 emissions by more than 20% relative to conventional gasoline production without use of any carbon capture or sequestration solutions.

Wave Liquefaction™ is a rapid, efficient, continuous process, with a compact footprint, high feedstock flexibility, and liquid yields exceeding 50% wt (d.a.f.) for most coals tested. It has a low environmental impact, with little to no CO_2 emissions or water consumption. Production costs of synthetic crude with the current coal, natural gas and electricity prices are estimated to be as low as $30 per barrel.

With natural gas co-feed, methane is activated and converted into hydrogen within the reactor without use of steam-methane reforming or other GHG-intensive solutions. Excess hydrogen can be produced for downstream processing of synthetic crude into finished products. The process rejects carbon in the form of a solid, added-value char, which has a wide range of potential applications.

HOW IT WORKS

Wave Liquefaction™ combines low-energy gas ionization and rapid microwave pyrolysis in a novel direct coal liquefaction process.

- Solid hydrocarbon particles are rapidly and selectively heated to pyrolytic temperatures (over 1000°C within 100 milliseconds).
- Pyrolysis products (liquids) are immediately hydrogenated in-situ with ionized and activated hydrogen-rich transport gases.
- Hydrogenated liquids are quenched by cool (< 300°C) transport gases, stopping further reactions, preventing gas production and maximizing yields of high value products.
- High thermal efficiencies (~80%) and material throughputs dramatically reduce reactor footprint and energy requirements.
- High liquid yields enable conversion of 1 ton of coal into 3-4 barrels of synthetic crude oil or finished fuel products.
- Excess hydrogen production enables downstream oil upgrading to finished fuel products with dramatically reduced GHG emissions.

With no intrinsic CO_2 output or water use, Wave Liquefaction™ can efficiently convert a blend of coal and biomass into cost-competitive net carbon-neutral or carbon-negative transportation fuels.

TECHNOLOGY VERSATILITY

Properties of the Wave Liquefaction™ liquid product (aromaticity, density, H:C ratio) can be widely varied by adjusting energy input, feedstock and gas composition. The product aromaticity can be made close to 100%, with as much as 20% of the liquid yield consisting of the BTEX fraction. Industrial non-fuel uses for these liquid and solid products include:

Carbon pitch for production of aluminum smelting anodes: e.g. ALCOA needs worldwide are >500,000 metric tons/year

Creosote for wood preservation (railroad ties, poles)
Pavement sealants and roof coatings.
Carbon black, graphite and anthracene oil.

Napthalene and other chemicals and precursors.
BTEX (single-ring aromatics) for the plastics industry.

Activated carbon applications (e.g. mercury removal)
Electric arc furnace and PCI applications.

LOW GREENHOUSE GAS EMISSIONS

Wave Liquefaction™ produces little to no CO_2 emissions from both the conversion and from the excess hydrogen production. When deployed with a non-fossil source of electricity, both process and lifecycle emissions are significantly lower than for conventional oil refining processes.

	Current State of the Art Technologies			Wave Liquefaction™		
	Conventional Petroleum	Indirect Coal Liquefaction	Direct Coal Liquefaction (CMSL)	Purchased Power	Integrated Power from Natural Gas	Integrated Power from Char
Operating Pressure		10-69 bar	170 bar	1 bar		
Feedstock Oil Cost $/bbl	>$60/bbl	<$40/bbl	>$50/bbl	<$40/bbl		
Capital Cost $/bbl	$54-18K	~$80K	$50-58K	$18K	$28K	
Liquid Yield bbl/ton coal		2.4	3.0	3-4		
Thermal Efficiency	>90%	48%	60%	52%		
Water Consumption bbl/bbl	2.5 (net)	7	0.6	< 0.65		
CO_2 Process Emissions g/g_{fuel}	33	708	454	13	<90	190
Well-to-Wheels CO_2 $g/(ton\cdot km)$	88	185	157	69	94	111
Technology Readiness	9	7-8	6-7	3-4		

Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels, R. M. Stratton, H.M. Wong, J. I. Hileman, 2010

Wave Liquefaction™ can enable not only production of liquid transportation fuels with 22% less lifecycle CO_2 emissions than conventional oil refining, but also clean, sustainable production of chemical feedstocks and solid carbon materials, which can significantly improve sustainability and emissions metrics of the downstream processes and industries.