

No molecule left behind or toward zero waste mining

Coal Beneficiation

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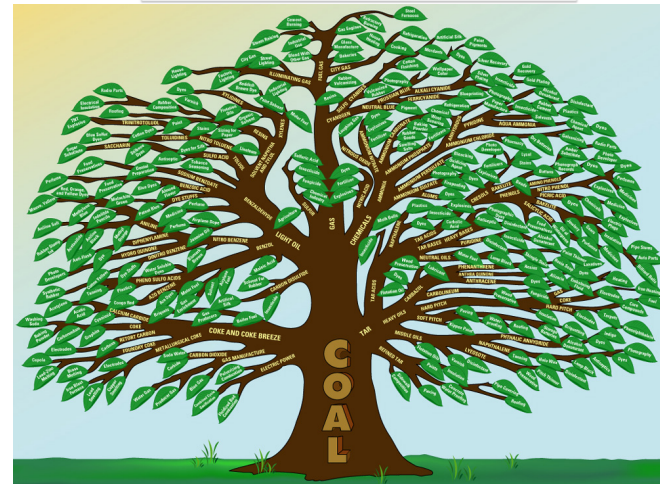
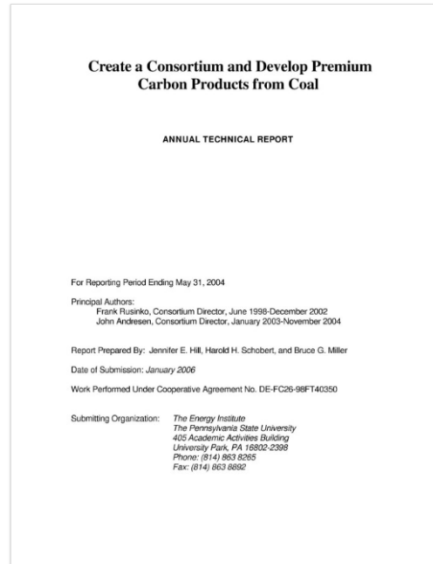
2018 President, Society for Mining, Metallurgy and Exploration, Inc.

President, PrepTech Inc., Apollo, PA



Coal Beneficiation

- No molecule left behind—US DOE
- Toward zero waste mining—Canada Mining Innovation Council
- New products from coal may require new coal specifications that can be achieved through coal beneficiation (AKA coal cleaning or preparation)



Consortium for Premium Carbon Products from Coal

These projects resulted in many potential applications for coal-derived feedstocks. These include:

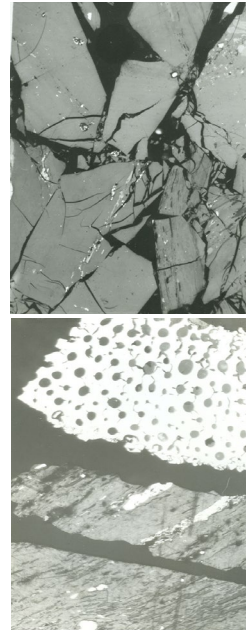
- (1) Use of anthracite as a *sorbent to capture CO₂ emissions*;
- (2) Use of anthracite-based carbon as a *catalyst*;
- (3) Use of processed anthracite in *carbon electrodes and carbon black*;
- (4) Use of raw coal refuse for producing *activated carbon*;
- (5) Reusable PACs to *recycle captured mercury*;
- (6) Use of combustion and gasification chars to *capture mercury from coal-fired power plants*;
- (7) Development of a synthetic *coal tar enamel*;
- (8) Use of alternative binder pitches in *aluminum anodes*;
- (9) Use of Solvent Extracted Carbon Ore (SECO) to fuel a *carbon fuel cell*;
- (10) Production of a low cost coal-derived turbostratic *carbon powder for structural applications*;
- (11) Production of high-value *carbon fibers and foams* via the co-processing of a low-cost coal extract pitch with well-dispersed carbon nanotubes;
- (12) Use of carbon from fly ash as *metallurgical carbon*;
- (13) Production of bulk carbon fiber for *concrete reinforcement*; and
- (14) Characterizing *coal solvent extraction* processes.

Current Customer Specifications

- Power Plants
 - Transportation/efficiency specifications: ash (typically **10-12 %** for US Eastern bituminous coal), Btu
 - Handling specifications: particle size (topsize and limit on fines), moisture (typically ~7-8% for US Eastern bituminous coal)
 - Mineral composition for slagging/fouling: ash fusion temperatures, ash constituents
 - Efficient combustion in general: moisture, ash, Btu, grindability
 - Environmental: sulfur, ash, trace elements
 - Every power plant has its own specification

Customer Specifications

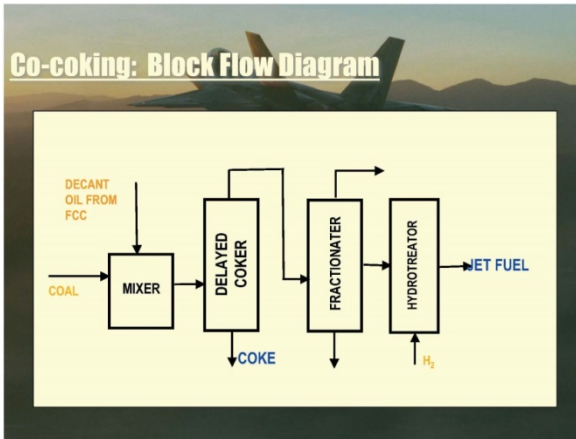
- Metallurgical
 - Transportation specifications: ash (typically 8-10 % dry in US)
 - Handling specifications: particle size (topsize), moisture
 - “Coke button”—thermoplastic properties
 - Macerals
 - Vitrinite reflectance
 - Related to achieving coke quality (carbon), coke strength, minimize slag (ash content), low sulfur (1-1.5 % dry), phosphorus, other alkalis
 - Generally very sophisticated blending



New Products—New Coal Specifications

- Can be achieved through coal beneficiation or coal cleaning technologies—some tried and true, some improved technologies, some new technologies
- Look at the coal data—size analysis and washability data, etc.

Example—Jet Fuel



- Produced 2% ash clean coal from a WV coal sample and 6% ash clean coal from a PA coal sample using froth flotation
- Goal to produce jet fuel plus a premium coke for the aluminum industry

Example—Silicon Smelting

- Silicon smelting, for example, typically uses charcoal @ <0.3% ash
 - Blue Gem coal (naturally low ash/minimal cleaning needed) has been used
 - Sinosi Group (China) for silicon metal smelting includes a coal specification of 4% max. ash, 12-15% VM, 3% max. H₂O, 6-30 mm particle size

There is no such thing as coal, there are coals (Luckie)

Table 1. Classification of Coals by Rank (Annual Book of ASTM Standards, Section 5, "Gaseous Fuel; Coal and Coke," Volume 05.05, ASTM, Philadelphia, PA)

Class	Group	Fixed Carbon Limits, % (Dry, mineral-matter-free basis)		Volatile Matter Limits, % (Dry, mineral-matter-free basis)		Gross Calorific Value Limits, Btu/lb (Moist, mineral-matter-free basis)	
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than
1. Anthracite	1. Meta-anthracite	98	--	--	2	--	--n
	2. Anthracite	92	98	2	8	--	--n
	3. Semianthracite	86	92	8	14	--	--n
2. Bituminous	1. Low volatile bituminous coal	78	86	14	22	--	--c
	2. Medium volatile bituminous coal	69	78	22	31	--	--c
	3. High volatile A bituminous coal	--	69	31	--	14000	--c
	4. High volatile B bituminous coal	--	--	--	--	13000	14000c
	5. High volatile C bituminous coal	--	--	--	--	11500 10500	13000c 11500c
3. Subbituminous	1. Subbituminous A	--	--	--	--	10500	11500n
	2. Subbituminous B	--	--	--	--	9500	10500n
	3. Subbituminous C	--	--	--	--	8300	9500n
4. Lignite	1. Lignite A	--	--	--	--	6300	8300n
	2. Lignite B	--	--	--	--	--	6300n

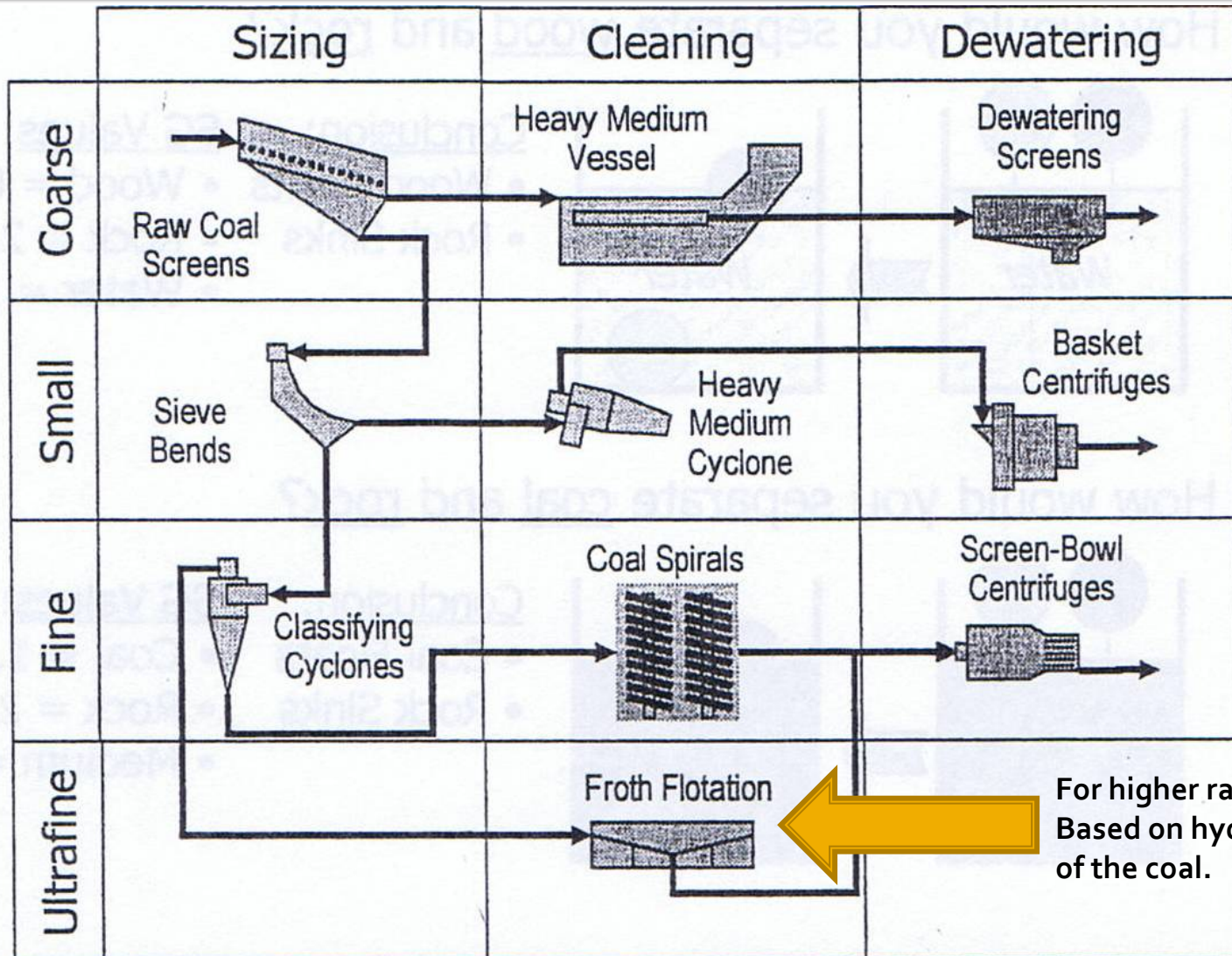
Agglomerating character:

n - nonagglomerating

c - commonly agglomerating

a - agglomerating

Coal Beneficiation Overview (Luttrell and Honaker)



For higher rank coals only.
Based on hydrophobicity
of the coal.

Where is the low ash coal?

- EPRI/CQ Inc. Coal Cleaning Test Facility data from US and Canadian coals
- Low gravity separation opportunities, especially for the coarser coal fractions

Where is the low ash coal?

RAW-COAL COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% KITTANNING (MIDDLE)

Size Fraction PLUS 0
Proportion of Total Coal (Wt %) 100.0

		Direct				Cumulative Float			
Specific Gravity		Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)	Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)
Sink	Float								
	1.25	2.4	1.98	1.08	14027	2.4	1.98	1.08	14027
1.25	1.30	29.5	3.62	1.50	13862	31.9	3.50	1.47	13856
1.30	1.35	14.7	7.83	2.51	13175	46.5	4.86	1.80	13626
1.35	1.40	7.2	13.20	3.23	12300	53.7	5.98	1.99	13449
1.40	1.60	14.3	25.63	3.25	10399	68.0	10.10	2.25	12809
1.60	1.80	4.1	38.64	3.66	8216	72.1	11.72	2.33	12548
1.80	2.00	5.6	43.63	2.45	7089	77.7	14.02	2.34	12154
2.00	2.45	7.4	67.12	3.84	3542	85.0	18.63	2.47	11407
2.45		15.0	86.23	7.51	860	100.0	28.74	3.22	9829

Where is the low ash coal?

RAW-COAL COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% FREEPORT (UPPER)

Size Fraction PLUS 325M
Proportion of Total Coal (Wt %) 94.6

		Direct				Cumulative Float			
Specific Gravity		Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)	Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)
Sink	Float								
	1.25	0.6	1.52	0.84	15390	0.6	1.52	0.84	15390
1.25	1.30	30.8	2.82	0.82	14863	31.4	2.80	0.83	14873
1.30	1.35	15.4	7.81	1.06	14240	46.8	4.45	0.90	14678
1.35	1.40	7.7	11.89	1.55	13511	54.4	5.50	0.99	14514
1.40	1.45	4.1	15.02	2.00	12986	58.6	6.17	1.06	14407
1.45	1.50	3.3	20.48	2.36	12033	61.9	6.94	1.13	14278
1.50	1.60	4.2	27.28	2.55	10869	66.1	8.24	1.22	14061
1.60	1.70	2.8	36.37	2.53	9221	68.9	9.39	1.28	13863
1.70	1.80	2.2	44.01	2.28	7914	71.2	10.46	1.31	13678
1.80	1.90	2.1	50.76	2.17	6745	73.3	11.62	1.33	13479
1.90	2.00	2.0	55.87	2.17	5902	75.3	12.81	1.36	13276
2.00	2.10	2.1	62.43	2.05	4816	77.4	14.18	1.38	13042
2.10	2.17	1.8	67.31	2.06	4004	79.2	15.40	1.39	12835
2.17		20.8	83.21	3.30	1359	100.0	29.48	1.79	10452

Where is the low ash coal?

RAW-COAL COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% POCAHONTAS #3

Size Fraction PLUS 0
Proportion of Total Coal (Wt %) 100.0

		Direct				Cumulative Float			
Specific Gravity		Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)	Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Heating Value (Btu/lb)
Sink	Float								
	1.25	0.0	1.01	0.67	15637	0.0	1.01	0.67	15637
1.25	1.30	35.1	1.48	0.64	15556	35.1	1.48	0.64	15556
1.30	1.35	19.2	4.06	0.78	15120	54.3	2.39	0.69	15404
1.35	1.40	6.2	6.99	1.08	14507	60.5	2.86	0.73	15313
1.40	1.60	6.8	14.51	1.65	12987	67.3	4.04	0.82	15078
1.60	1.80	2.4	33.03	1.68	9646	69.7	5.05	0.85	14887
1.80	2.00	3.0	49.48	1.35	6900	72.7	6.89	0.87	14557
2.00	2.45	8.8	74.36	0.82	2791	81.5	14.19	0.87	13285
2.45		18.5	91.27	0.82	323	100.0	28.43	0.86	10890

Where is the low ash coal?

RAW-COAL COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% ILLINOIS NO. 6

Size Fraction PLUS 200M
Proportion of Total Coal (Wt %) 96.7

		Direct				Cumulative Float			
Specific Gravity				Heating				Heating	
Sink	Float	Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Value (Btu/lb)	Weight (Wt%)	Ash (Wt%)	Sulfur (Wt%)	Value (Btu/lb)
	1.25	1.4	2.12	2.35	13565	1.4	2.12	2.35	13565
1.25	1.30	25.1	3.51	2.61	13700	26.5	3.44	2.59	13693
1.30	1.35	32.7	7.43	2.87	13092	59.2	5.64	2.75	13361
1.35	1.40	15.3	13.12	3.22	12189	74.6	7.18	2.84	13120
1.40	1.45	7.3	17.11	4.20	11532	81.9	8.06	2.97	12978
1.45	1.50	2.8	20.40	5.11	10915	84.7	8.47	3.04	12910
1.50	1.60	3.1	25.37	6.71	10151	87.7	9.07	3.17	12813
1.60	1.70	1.7	33.05	7.08	8858	89.4	9.51	3.24	12740
1.70	1.80	1.3	37.83	7.04	7944	90.7	9.92	3.29	12671
1.80	2.00	1.6	43.67	8.38	6872	92.3	10.50	3.38	12570
2.00	2.20	0.8	57.41	11.40	4889	93.1	10.91	3.45	12503
2.20	2.50	2.0	75.86	8.31	2110	95.1	12.27	3.55	12286
2.50		4.9	70.07	23.16	2228	100.0	15.10	4.51	11794

Where is the low ash coal?

RAW-COAL COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% KENTUCKY NO. 11

Size Fraction PLUS 200M
Proportion of Total Coal (Wt %) 82.0

		Direct				Cumulative Float			
Specific Gravity		Weight	Ash	Sulfur	Heating	Weight	Ash	Sulfur	Heating
Sink	Float	(Wt%)	(Wt%)	(Wt%)	Value (Btu/lb)	(Wt%)	(Wt%)	(Wt%)	Value (Btu/lb)
	1.30	43.8	3.71	2.92	13732	43.8	3.71	2.92	13732
1.30	1.35	12.7	6.94	3.54	13241	56.5	4.44	3.06	13622
1.35	1.40	4.0	8.19	3.51	12865	60.5	4.69	3.09	13571
1.40	1.45	3.7	11.61	3.91	12330	64.2	5.09	3.14	13499
1.45	1.50	1.7	18.26	4.63	11410	65.9	5.42	3.17	13447
1.50	1.60	2.0	24.13	5.01	10441	67.9	5.98	3.23	13357
1.60	1.70	1.1	32.49	5.71	9044	69.0	6.40	3.27	13287
1.70	1.80	0.8	39.70	6.23	5422	69.8	6.78	3.30	13198
1.80	2.17	2.1	54.12	7.09	3965	72.0	8.18	3.42	12925
2.17		28.0	85.40	6.28	804	100.0	29.84	4.22	9525

Where is the low ash coal?

RAW-COAL
COMPOSITE WASHABILITY ANALYSIS

Seam Proportions and Name(s) 100.0% PITTSBURGH

Size Fraction PLUS 0
Proportion of Total Coal (Wt %) 100.0

		Direct				Cumulative Float			
Specific Gravity		Weight	Ash	Sulfur	Heating	Weight	Ash	Sulfur	Heating
Sink	Float	(Wt%)	(Wt%)	(Wt%)	(Btu/lb)	(Wt%)	(Wt%)	(Wt%)	(Btu/lb)
	1.25	0.6	3.54	3.09	14309	0.6	3.54	3.09	14319
	1.25	22.8	2.90	2.21	14245	24.3	3.90	3.21	14241
	1.30	19.5	7.18	4.07	13750	43.8	5.35	3.59	14023
	1.35	9.9	10.81	5.84	13105	53.7	6.36	4.01	13854
	1.40	9.7	18.93	6.93	11784	63.4	8.28	4.45	13538
	1.60	2.7	35.49	5.54	9045	66.0	9.37	4.49	13357
	1.80	4.9	52.10	3.40	6303	70.9	12.34	4.42	12867
	2.00	3.9	62.37	3.10	4616	74.8	14.92	4.35	12442
	2.20	2.7	76.97	4.18	2369	77.5	17.08	4.34	12091
	2.45	22.5	88.46	4.80	489	100.0	33.14	4.45	9481

PC Boiler Fuel
39.1 wt %, 11.01% ash, 13,099 Btu/lb

FBC fuel
11.5 wt %, 49.34% ash, 6,375 Btu/lb

True refuse
25.2 wt %, 530 Btu/lb

Specialty fuel or other product feedstocks
~4% ash

Note: oversimplification of real separations in a coal cleaning plant

Don't forget rare earth elements in the middlings/refuse streams, especially in the fine clays! And many on the Critical Minerals list!

Conventional Coal Beneficiation

- **Coarse and intermediate size coal** would require multiple processing steps to produce coal for:
 - Specialty markets
 - PC boiler fuel
 - FBC fuel
- Minimal refuse disposal at the coal mine/ processing plant site. Ash disposed of at power plants or for beneficial use (concrete additives, for example).



American Coal Ash Association
www.acaa-usa.org
Beneficial use of coal combustion
products



**Coal Ash Is Not Hazardous Waste
under U.S. Agency Rules**

The new label means that states, not the EPA, will be the primary enforcer of rules regarding coal ash, a byproduct of coal-based power production containing toxic materials such as arsenic and lead

EPA, Dec 2014

Conventional Coal Beneficiation

- **Fine size coal** could also require multiple processing steps to produce coal for:
 - Specialty markets
 - PC boiler fuel (though sending this fraction to a PFBC would eliminate issues with moisture and fines content)
 - PFBC fuel (handles low BTU, dewatered fines @~25% moisture)
- Minimal refuse disposal at the coal mine/processing plant site. Ash disposal at power plants. **Think rare earth/critical elements or beneficial use of ash for soil supplements.**

New Fine Coal Processes for Fine Waste

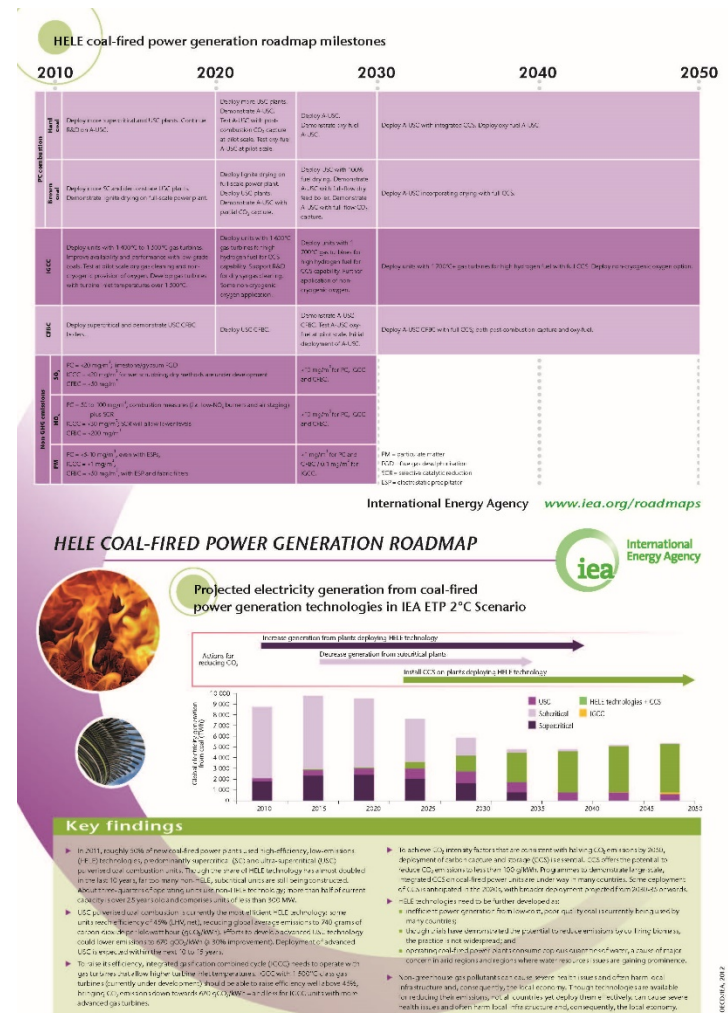
- OMNIS/CONSOL Energy—creating low ash pellets from thickener underflow; using remaining **minerals as a soil amendment** (pilot)
- Arq/Peabody Energy—low ash, clean coal fines combined with crude oil for use by refineries (construction of commercial plant)
- HHS—Minerals Refining Company—coal fines cleaned and dewatered in one step then pelletized (design of commercial plant) to produce low ash product

Beneficiation Processes for Low Rank Coals

- Low rank coals have high inherent moisture/low heating value content
- Reduction of moisture prior to combustion provides higher combustion efficiency
- Several technologies have been developed to reduce this moisture (and some capture the water for beneficial use)
 - ZEMAG Clean Energy Technology, Germany
 - Coldry Process, ECT Limited, Australia
 - RWE-WTE = RWE (Rhenish-Westphalian Electric) WTE technology
 - HTFG = Delta Drying Technology Ltd
 - WEC-BCB = White Energy Company, Binderless Coal Briquetting
 - UBC = Upgraded Brown Coal Process, Japan Coal Energy Center & Kobe Steel Ltd.
 - Exergen company, Continuous Hydrothermal Dewatering technology
 - MTE = Mechanical Thermal Expression, developed by the CRC for Clean Power
 - KFUEL = Koppelman Fuel, Evergreen Energy, Denver, Colorado, USA
 - LCP = LiMaxTM Coal Process Technology, developed by GB Clean Energy

What about HELE Coal-Fired Power Plants?

- International Energy Agency HELE Road Map 2014 (www.iea.org/roadmaps)
 - New coal specifications needed?
 - Can lower quality coal be used?
- More efficient (increase from ~33 to 40 %), therefore, inherent CO₂ reduction for supercritical and ultra-supercritical units (2-3 % reduction for every 1 % increase in efficiency); leave room for carbon capture technologies to be installed when commercial. Current power plants can be repowered now to reduce CO₂!
- That's two gigatonnes of CO₂ worldwide. In addition, there are reductions in NO_x, SO₂, and particulate matter. (worldcoal.org)



Summary

- Coal beneficiation, both conventional and new technologies, can be used to produce multiple products—low ash coal for specialty markets, traditional or higher ash for coal-fired power plant markets, ash markets (including beneficial use and source of rare earth/critical elements)
- Coal can be part of an economical reduced CO₂ power generation strategy!

Opportunities

- Test different coal qualities for new markets (need small scale test facility, maybe up to 50-100 tph, to produce sufficient materials for testing—a new Coal Cleaning Test Facility) in order to develop Coal Quality Impact Models to optimize coal specifications for these new markets
- Revisit the EPRI/DOE Coal Quality Impact Model (CQIM™) or Coal Quality Expert (CQE™) and expand for new products from coal
- Continue identifying coals and coal products with high levels of rare earth elements and developing processes to recover the REEs/critical elements

Opportunities

- Develop new rugged sensors to work in wet, sometimes dusty or sometimes muddy environments
- Develop smart manufacturing technologies, such as AI and VR, to work in concert with online analyzers to better control coal quality, especially for multiple product plants
- Develop image analysis techniques beyond froth flotation
- Develop better procedures for relating coal beneficiation performance to drill core data
- Better understand the change in moisture content of coal, especially lower rank coal



Thank you!

