DOE Critical Minerals & Materials

Domestic Wastes and Byproducts – A Resource for Critical Material Supply Chains

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United States Department of Energy

Alaska Core-CM Stakeholders Meeting

September 2023

"Dynamic Dozen" Critical Materials

G O A L S

● 100% clean electricity by 2035: 30 GW offshore wind by 2030 ●
● Zero-emission transportation: 50% EV adoption by 2030 ●

- Neodymium, Praseodymium and Dysprosium for magnets → Magnets enable efficient electric machines including wind generators, electric and fuel cell vehicle motors, industrial motors
- Lithium, Cobalt, Nickel, Graphite, and Manganese for energy storage → Batteries are needed for electric vehicles and grid storage to enable high penetration of zero-emission transportation and intermittent clean power generation
- Iridium & Platinum for electrolyzers; Platinum for fuel cells → Iridium and platinum for electrolyzers are needed for green hydrogen production and platinum for fuel cells used in transportation and stationary energy storage.
- Gallium for wide bandgap semiconductors, LEDs → Wide bandgap power electronics enable high voltage power generation (like wind) to connect to the grid
- Germanium for microchips (semiconductors) → Microchips for sensors, data, and control play an important role in SMART manufacturing, which will be needed to increase efficiency and minimize waste (inclusion GHGs); Fiber and infrared optics

America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition

Introducing The Electric Eighteen

Critical Materials for Energy

- Aluminum
- Cobalt
- Copper
- Dysprosium
- Electrical Steel* (grain-oriented steel, non-grain-oriented steel, and amorphous steel)
- Fluorine
- Gallium
- Iridium
- Lithium
- Magnesium
- Natural Graphite

Introducing The Electric Eighteen

Critical Materials for Energy

- Neodymium
- Nickel
- Platinum
- Praseodymium
- Silicon
- Silicon Carbide
- Terbium

- "Critical Materials Assessment", USDOE, July 31, 2023, available on-line https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf

Characteristics of Wastes and Byproducts of Interest

- Voluminous
- Preferably Currently Produced
- Accessible
- Opportunities for Environmental Remediation
- Known and Elevated Concentrations of Critical & Valuable Elements
- Known pH Data – for Extraction of CM (acidic) or Carbon Dioxide Capture (basic)
- Preferably Easily Extractable
- Multiple Salable Products
- Critical Materials Are Concentrated In Many Wastes and Byproducts

Potential Wastes and Byproducts of Interest

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- Coal, Waste Coal, Acid Mine Drainage - Many Critical Materials
- Ash Impoundments – Many Critical Materials
- Petroleum Refinery Wastes (Desalter, Coke) – Ni, V, Mo – heavy crudes
- Steel Slag
- Red Mud (Bauxite Residue) – Rare Earths
- Smelters – Many Critical Materials Within Flue Dust and Slags
- Mine Tailings – Many Critical Materials
- Asbestos
- Produced Waters from Oil and Gas Production - Lithium
- Municipal Solid Waste – Source of Critical Materials
- Municipal Sludge – Potential Source of Platinum Group Metals
- E-Waste – Source of Platinum Group Metals and Critical Materials

Potential Wastes and Byproducts of Interest

- Coal, Acid Mine Drainage – Pilot Efforts (FECM)
- Ash Impoundments – Treasure Chest of Critical Elements, Pilots (FECM)
- Petroleum Refinery Wastes (Desalter, Coke) – FECM, USGS, CANMET
- Steel Slag
- Smelters – Ores Can Contain Critical Elements – **Heat is our Friend !**
- Mine Tailings – Ores Can Contain Critical Elements
- Red Mud – Can Contain 0.1 – 1% Rare Earths
- Asbestos
- Produced Waters – New Efforts Within FE & EE
- Municipal Solid Waste – 1 ton/person/ per year – estimated 1- 17 wt.% metals
- Municipal Sludge – Great Excitement in 2015, ES&T Paper Valuable Metals
- E-Waste – Platinum Group Metals, Nickel, Lithium, Cobalt

Heat is Our Friend

Concentration of Critical Metals

- Coal Combustion – Fly Ash and Bottom Ash
- MSW Energy Recovery/Incineration - Fly Ash and Bottom Ash
- Sewage Sludge Incineration - Fly Ash and Bottom Ash
- Smelter - Flue Dusts
- Steel - Slags
- Petroleum Refinery - Cokes and High Boiling Distillation Fractions
- **Volatility** – Melting and Boiling Points of Elements and Compounds
- Critical Elements Typically Concentrate in High Temperature Products
- Ashes, Flue Dusts, Slags, Cokes and High Boiling Fractions
- Happy Accident !
- **Heat Concentrates CM in Numerous Abundant Solid Wastes – "Granite Equation"**

Average Concentrations in Domestic Coal

• Nd	9.5 ppm	(COALQUAL analysis Lin, Granite)
• Dy	3.39 ppm	(COALQUAL analysis Lin, Granite)
• Li	16 ppm	(Finkelman 2018)
• Co	6.1 ppm	(Finkelman 2018)
• Ni	14 ppm	(Finkelman 2018)
• Ir	0.002 ppm	(World Coal Lin, Granite 2018)
• Pt	0.035 ppm	(World Coal Lin, Granite 2018)
• Ga	5.1 ppm	(Lin, Granite 2018)
• Ge	7.2 ppm	(Lin, Granite 2018)

Rough Quantities in US Legacy Waste Coal (OME)

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Nd	38,000 tons
Dy	13,600 tons
Li	64,000 tons
Co	24,400 tons
Ni	56,000 tons
Ir	8 tons
Pt	140 tons
Ga	20,400 tons
Ge	28,800 tons

- Within Four Billion Tons of Waste Coal, Scattered Across 1,000 Sites

Estimated Average Concentrations in US Coal Ash

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• Nd	86 ppm
• Dy	31 ppm
• Li	144 ppm
• Co	55 ppm
• Ni	126 ppm
• Ir	0.02 ppm
• Pt	0.3 ppm
• Ga	10 ppm
• Ge	65 ppm

Rough Quantities in US Legacy Coal Ash (OME)

U.S. DEPARTMENT OF ENERGY

Nd	172,000 tons
Dy	62,000 tons
Li	288,000 tons
Co	110,000 tons
Ni	252,000 tons
Ir	40 tons
Pt	600 tons
Ga	20,000 tons
Ge	130,000 tons

- Within Two Billion Tons of Ash, Scattered Across Over 1,300 Sites

Potential Supply in US Legacy Coal Ash, At Current Rates of Consumption

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• Nd	172,000 tons	~ 40-year supply (estimate)
• Dy	62,000 tons	~ 14-year supply (estimate)
• Li	288,000 tons	130-year supply
• Co	110,000 tons	15-year supply
• Ni	252,000 tons	1.1-year supply
• Ir	40 tons	15-year supply
• Pt	600 tons	15-year supply
• Ga	20,000 tons	1,100-year supply
• Ge	130,000 tons	3,900-year supply

U.S. Geological Survey, 2022, Mineral Commodity Summaries

Next Steps

Producing Estimates on Extent of Potential Resource

- Petroleum Refinery Wastes (Desalter, Coke)
- Steel Slag
- Red Mud
- Smelters
- Mine Tailings
- Asbestos
- Produced Waters
- Municipal Solid Waste
- Municipal Sludge
- E - Waste
- Preparing Reports and Notes for Journals

Municipal Solid Waste

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- Approximately 300 Million Tons/Year ~ 1 ton/year/person
- “8 % metals” – Crude Composition - EPA (yard waste, food, paper, cardboard, plastics, wood, metals,...)
- Really ~ 1 - 17% metals (other waste categories contain embedded metals)
- Unfortunately Includes Some E - Wastes
- **A Great Opportunity for CMs**
- **Landfills**
- **MSW Incinerator (Energy Recovery) Ashes**
- **https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials**
- **https://archive.epa.gov/epawaste/nonhaz/municipal/web/html/**
- EPA and Literature for Detailed Compositions

Municipal Sewage Sludge

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- Excitement on PGM Contents ~ ppm levels Pt, Pd, Rh
- Source - Road Dusts – Catalytic Converters
- Significant Literature on PGMs in Sewage Sludge
- Yale 2015 ES&T
- Quantities and Processing of Sewage
- https://www.epa.gov/biosolids/basic-information-about-biosolids
- https://www.epa.gov/biosolids/sewage-sludge-surveys
- https://www.epa.gov/sites/default/files/2021-04/documents/tnsss-appendix-elemental-analyses-report.pdf

- EPA and Literature for Detailed Compositions

Red Mud

- Voluminous Byproduct of Aluminum Production
- Stoichiometry of Bayer Process
- 1 – 2 Times as Much Red Mud Produced versus Alumina
- USGS Statistics Aluminum Production (USGS Mineral Commodity Summaries 2022)
- ~ 1.1 Million Tons Aluminum Produced in US in 2021
- Sodium Hydroxide – Bauxite Ore
- Highly Alkaline
- Enriched in Rare Earths – **0.1 – 1 % by weight**
- **Perhaps Enough to Supply Annual US Demand for Rare Earths (10,000 tons/year)**
- **A Fantastic Opportunity for RE and Carbon Dioxide Capture/Sequestration**
- **At Least 10% of Annual US Demand, From Currently Produced Red Mud**
- **Additional Rare Earths from Legacy Impoundments**
- **Current ARPA-E Research - Doug Wicks from DOE**

Steel

- Approximately 90 million tons Steel Produced/year in US
- Recent Thesis – Recover Valuable Elements from Slag
- "Sustainable Valorization of Steelmaking Slag: From Metal Extraction to Carbon Sequestration", PhD Thesis, Jihye Kim, Department of Chemical Engineering and Applied Chemistry, University of Toronto, 2021
- Obtaining Slag Compositions and Production Statistics

Petroleum

- Refine Approximately 18 Million barrels Petroleum/Day in US (USDOE - EIA)
- Heavy Crudes Contain Valuable Metals
- Roughly 1/3 US Crudes are "Heavy"
- Nickel, Vanadium and Molybdenum
- Other Valuable Metals are Present as Well (PGMs, Co)
- Concentrations up to 500 ppm V, 20 ppm Ni, 1 ppm Mo
- Concentrate in the Petroleum Coke at Refinery
- "Processing of Petroleum Coke for Recovery of Vanadium and Nickel", Hydrometallurgy, P.B. Queneau, R.F. Hogsett, L.W. Beckstead, D.E. Barchers, 22(1-2), 3-24, 1989
- EIA, USGS, CANMET, Exxon-Mobil & NIST for Detailed Petroleum Compositions

E - Wastes

- Computers, Televisions, Phones, ….

Crude Compositions:

Cu	15%,
Al	4.7%
Fe	3.1%
Pb	2.8%
Sn	1.8%
Ni	1.6%
Zn	1.2%
Ag	0.06%
Au	0.03%

“Bio-extraction of precious metals from urban solid waste”, AIP Conference Proceedings 1805, 020004 (2017); https://doi.org/10.1063/1.4974410, Published Online: 20 January 2017
Subhabrata Das, Gayathri Natarajan and Yen-Peng Ting

- EERE and EPA for Volumes & Detailed Compositions

Smelter Wastes

- Flue Dusts
- Slags
- Extensive Literature for Copper, Zinc, Nickel
- USGS Statistics on Domestic Production (2023 Mineral Commodity Summaries)
- Developing Estimates

Mine Wastes

- Domestic High-Quality Ores Depleted over Time
- Cut-Off Grades for Most Metals have been Reduced
- Many Mine Tailings and Waste Rocks Now Contain Economically Recoverable Concentrations of Metals
- Tailings, Waste Rock
- Rock – Ore Ratio (USGS) Publications
- USGS
- Peer-Reviewed Literature, Especially for Cu, Zn, Ni
- Rio Tinto - Efforts to Recover Tellurium and Copper from Mine Wastes and Tailings
- Developing Estimates

Produced Waters and Leachates

- **Enormous Quantities - 20 – 25 billion barrels produced water/year in US**
- **USGS Database on Produced Waters**
- Engle, M. A., Saraswathula, V., Thordsen, J. J., Morrissey, E. A., Gans, K. D., Blondes, M. S., Kharaka, Y. K., Rowan, E. L., & Reidy, M. E. (2019). U.S. Geological Survey National Produced Waters Geochemical Database v2.3 [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7J964W8
- "Incomplete"
- Literature
- **Lithium is a Focus**
- **Leachates from Waste Impoundments**
- Possibilities for CMs (FECM)
- DOE to Invest More Than $18 Million to Treat Wastewater, Recover Valuable Minerals – Announcement 2/10/23 https://netl.doe.gov/node/12321

USGS Data Produced Waters and Brines - Lithium

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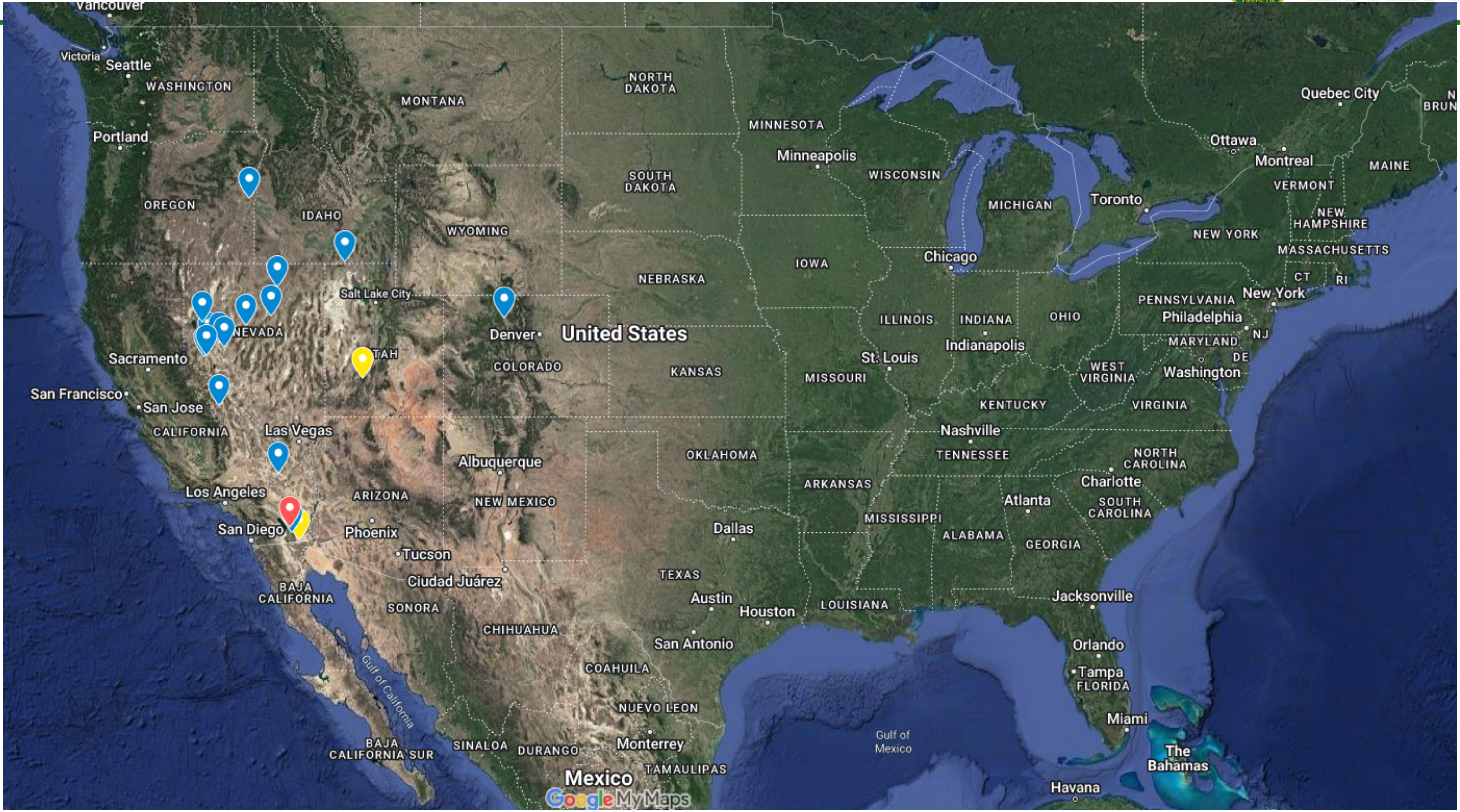

Lithium – USGS Produced Waters Database

Domestic Sources of Li - Google My Maps   Blue < 20 ppm, Yellow 20 - 80 ppm, Red > 80 ppm Lithium, Courtesy of Naomi Akiyama

Lithium extraction from oilfield brine, Pamela Daitch, University of Texas at Austin, MS Thesis, 2018.   Lithium extraction from oilfield brine (utexas.edu)

- The U.S. Geological Survey National Produced Waters Geochemical Database was utilized to identify lithium-rich brine from wells across the U.S.   The volume and concentration potential of the most promising lithium-enriched geologic formation were calculated.
- Advanced technology offers the advantage of recovering Li from concentrations as low as 70 mg/L.   Of the produced water samples, only 344 samples had Li concentrations greater than or equal to 70 mg/L.

Other Non-Traditional Sources

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Outer Space

- Recent Dissertations on Meteorites, Asteroids, Moon, and Mars as Sources of Critical Materials – NASA is Part of Intergovernmental Efforts Led by DOE – “Space Mining”

Ocean Floor

- Seabed Minerals – DOE Leading This Effort

Arctic Region

- www.arctic.gov Challenging Region – but See Others

Ocean Waters

- A Long-Held Dream – Quantities Enormous, But Concentrations are Low
- Example - Lithium – 1 ppm
- Could Co-Production of Metals and Potable or Useable Water Aid Economics?

Ash Impoundment Leachates

- Digested/Extracted Materials ala Acid Mine Drainage Efforts

Other Non-Traditional Sources

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Garnet Abrasives and Sands

- Garnet – Used as Industrial Abrasives
- Approximately 100,000 tons Produced Annually in United States
- Recent Papers from Oak Ridge and Jacobs University in Germany
- **Suggest High Rare Contents – As Much as 0.1 – 1% by Weight Total REY+ Sc**
- **Particularly for Heavy Rare Earths and Scandium**
- Unfortunately, Extraction Seems Difficult
- "Potential of garnet sand as an unconventional resource of the critical high-technology metals scandium and rare earth elements", Franziska Klimpel, Michael Bau, Torsten Graupner, Scientific Reports, 11:5306, 2021
- "Industrial garnet as an unconventional heavy rare earth element resource: Preliminary insights from a literature survey of worldwide garnet trace element concentrations", N. Alex Zirakparvar, 2022, Ore Geology Reviews, in press, available on-line, July 22, 2022

Other Non-Traditional Sources

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Phosphogypsum

- Rare earths are often found in nature as the phosphate monazite
-
- Phosphogypsum wastes are byproducts of phosphoric acid or fertilizer production
- Much of the original rare earth elements originally present with the phosphate rocks are concentrated in the phosphogypsum
- DOE-supported research is currently examining the potential of these wastes for recovery of the rare earths

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Questions

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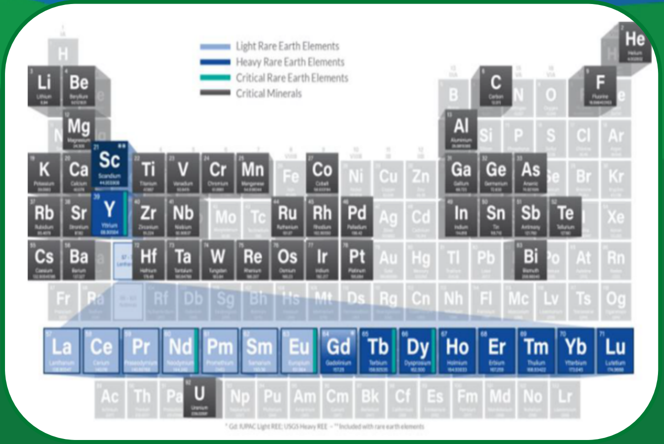
ENERGY
Fossil Energy and
Carbon Management

Beyond Combustion – Coal in the 21st Century

Evan Granite

Alaska Core-CM Stakeholders Meeting

September 2023



Carbons from Coal

Numerous Possibilities

- Activated Carbons
- Coke
- Chars
- Graphite and Carbon Electrodes
- Graphene
- Nanocarbons
- Composites and Alloys
- Carbon Fibers, Blocks, Roof Shingles, Deck Boards, Pipes
- Carborundum (Silicon Carbide), Diamond

Program Overview

- Current and Recent Projects (41) – Covering Building Materials (Bricks, Blocks, Deck Boards, Roof Shingles), Silicon Carbide, Beneficiation, Graphite, Carbon Fibers, Nanomaterials, Activated Carbons, Composites
- Completion of Current Projects
- Focus on Clean Energy High Value Materials
- High Volume Materials
- Graphite is a Critical Material
- Use of Byproduct Carbons from Critical Material Recovery
- Many Synergies with Critical Materials Program

Motivation for the Program

- Develop Clean Energy & Novel High Value Carbon Products to Incentivize and Facilitate Clean-Up of Waste Coal and Coal Byproduct Impoundments
- Use of Byproduct Carbons from Critical Material Recovery
- Focus on Clean Energy & Highest Value Products Such as Graphene, Nanocarbons, Graphite, Battery Electrodes, Specialty High Surface Area Activated Carbons, Novel Alloys, Fibers
- Develop High Volume Products Such as Building Materials
- Bricks, Blocks, Roof Shingles, Pipes, Deck Boards

What is Coal ?

Palette with Many Possibilities

Lignite Subbituminous Bituminous Anthracite

Low-ranking → High-ranking

Classic Analysis – Moisture, Volatile Matter, Fixed Carbon, Ash

Sequentially Dry, Pyrolyze and Burn Coal

Weight Loss From Each Step Yields – Moisture, VM, FC, and Ash (balance)

Source: Zazzeri, G. et al. (2016*). Atmos. Chem. Phys*. (16), 13669-13680. 10.5194/acp-16-13669-2016., Adapted from https://creativecommons.org

Coal Classifications

ASTM Coal Classification by Rank (*2*)

Class and group	Fixed carbon, %	Volatile matter, %	Heating value, Btu/lb
I. Anthracitic			
1. Metaanthracite	>98	<2	
2. Anthracite	92–98	2–8	
3. Semianthracite	86–92	8–14	
II. Bituminous			
1. Low volatile	78–86	14–22	
2. Medium volatile	69–78	22–31	
3. High volatile A	<69	<31	>14,000
4. High volatile B			13,000–14,000
5. High volatile C			10,500–13,000
III. Subbituminous			
1. Subbituminous A			10,500–11,500
2. Subbituminous B			9,500–10,500
3. Subbituminous C			8,300–9,500
IV. Lignitic			
1. Lignite A			6,300–8,300
2. Lignite B			<6,300

Graphitization in Nature – Coal and Graphite

Table 2. Variations of Physical and Chemical Properties with Rank and Their Useful Range as Rank Parameters [c]

Classification (Increasing Rank ↓)	% C (daf)[a] of Vitrinite	Vol. Matter % daf[a]	Moisture % in Situ	Cal. Value BTU/LB (af)[b]	Reflectance % (Vitrinite)	Important Characteristics
Peat						1. Free Cellulose 2. Plant Detail Recognizable
	60		75			
Soft Brown Coal						1. No Free Cellulose 2. Plant Structure Recognizable
		53	35	7,200	~0.3	
Lignite						1. Plant Structure Still Partly Recognizable 2. Vitrinite Formed
	~71	49	25	9,900		
Subbituminous						
	77	42	8–10	12,600	~0.5	
High Volatile Bituminous						Low-Reflecting Exinite
	87	29				
				15,500	1.1	
Med Vol. Bit. Low Vol. Bit. Semi-Anthracite						Exinite Lighter in color; Exinite Vitrinite Indistinguishable
	91	8		15,000	2.5	
Anthracite Meta Anthracite Graphite						Anisotropic Reflectance
	100	0				

Applicability of Properties as a Rank Parameter: % Moisture in Situ; Calorific Value (af)[b]; % C daf,[a] Reflectance of Vitrinite; Volatile Matter daf[a]; X-Ray Diffraction; % H daf[a]

[a] daf—Dry Ash Free
[b] af—Ash Free
[c] Adapted from: "Coal and Coal Bearing Strata," (*Editors:* D. Murchison and T. S. Westall), and "The International Handbook of Coal Petrography," International Committee for Coal Petrology

Graphitization in Nature – Coal and Graphite

Table 1. Coal and Coal-Related Carbonaceous Materials in Nature (from Schobert 1989)

Muck

Peat

Lignite ↑ closer to surface ↓ increasing age, fixed carbon & graphitization

Subbituminous Coal

Bituminous Coal

Anthracite

Graphitization in Nature – Coal and Graphite

Graphite Formed in Nature

- Elevated Temperatures/Pressures
- Or Contact with Hot Magmatic Fluids
- Typically, Over Eons ("Coalification/Graphitization")
- Muck – Peat - Lignite – Subbituminous – Bituminous – Anthracite – Meta Anthracite – Graphite
- "The Geochemistry of Coal – Part I. The Classification and Origin of Coal", Harold H. Schobert, Journal of Chemical Education, 242-244, 1989.
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Abundant Domestic Coal – Largest World Reserves

Abundant Coal Reserves in the U.S.

Source: Fletcher & Baylis/Science Source

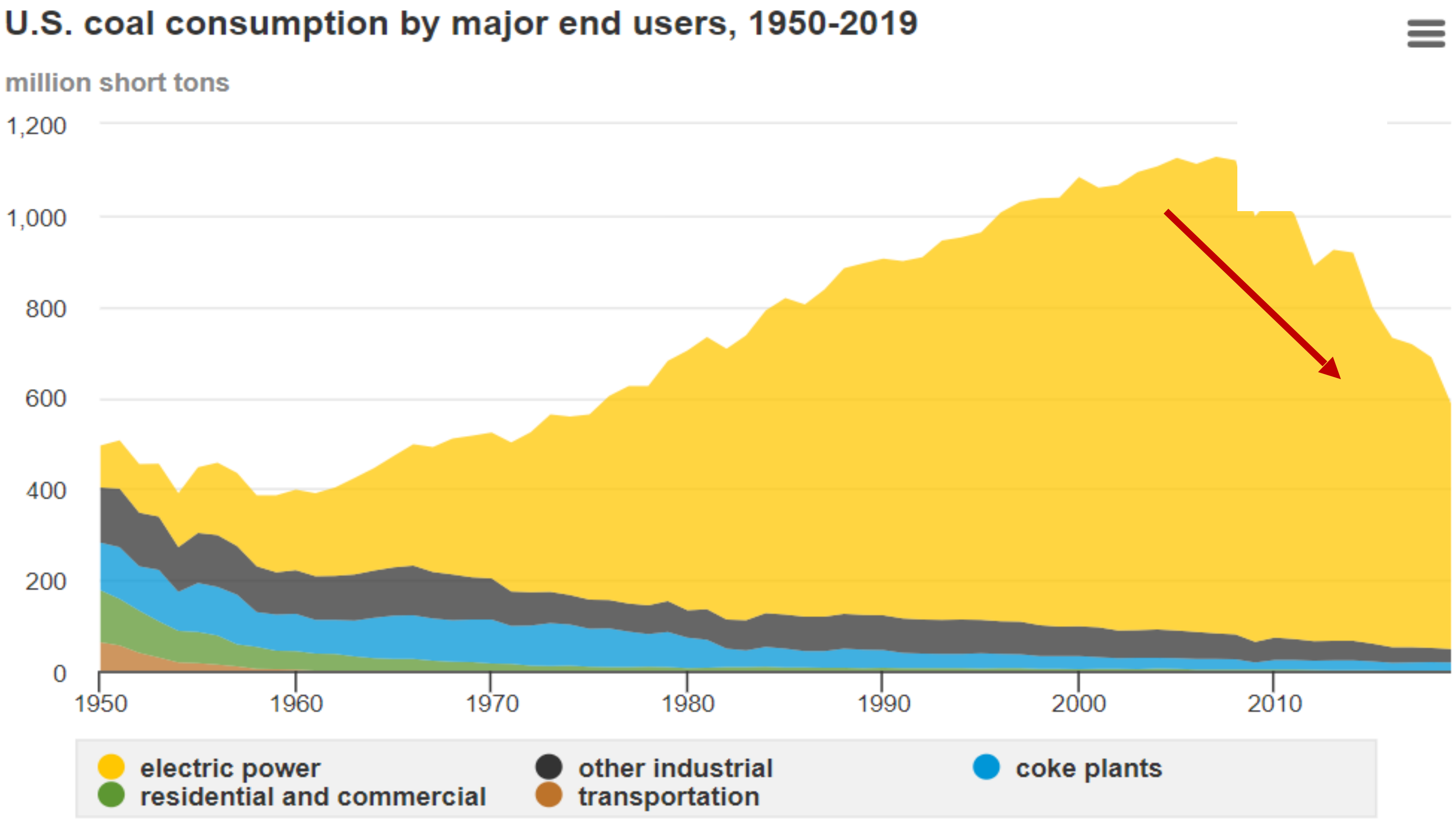
Estimated Recoverable Reserves

- Coal that can *currently* be mined
- 253 billion short tons

Demonstrated Reserve Base

- Total amount of coal that could *feasibly* be mined
- 474 billion short tons

Declining Domestic Production and Consumption
Trends in U.S. Coal Consumption



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 6.2, May 2020

Declining US Coal Production

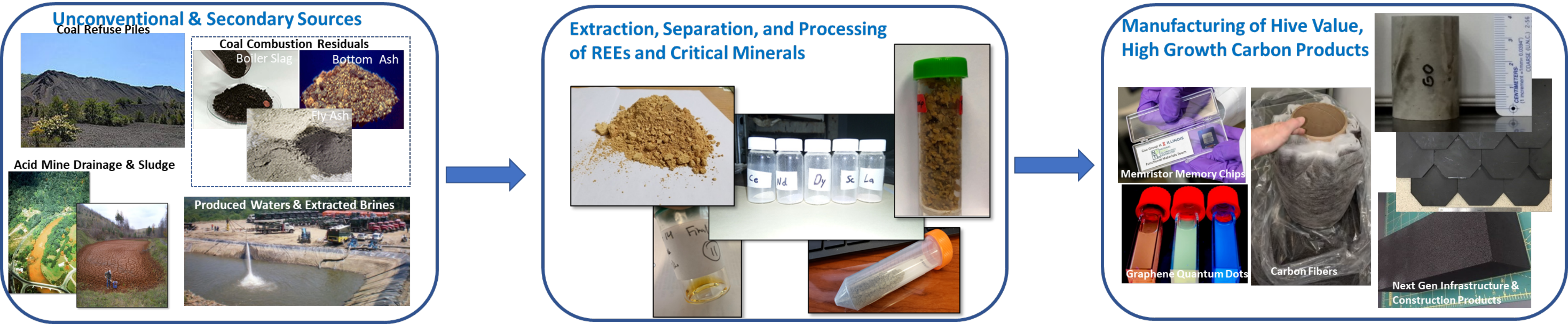
Coal and Waste Coal – Resource

- US Has 250 – 300 Year Supply Coal
- Largest in the World by a Wide Margin
- Approximately 1 – 1.1 billion tons/year Produced from 1990 – 2014 (EIA)
- 535 Million Tons in 2020; 578 Million Tons in 2021 (EIA)
- US Coal – Most Used for Generation Electricity
- Retirements of Older Coal-Burning Power Plants
- Inexpensive Natural Gas
- Activated Carbons, Chemicals, Tars, Steel, Exports
- We Can Do So Much More with Coal, Waste Coal and Byproducts

Principles of Waste Minimization and Circularity

Reclaiming, recycling waste materials

Maximizing use of feedstock materials



How Do We Process/Utilization of Coal

NATIONAL ENERGY TECHNOLOGY LABORATORY

Two Typical Routes

- **1. Combustion**

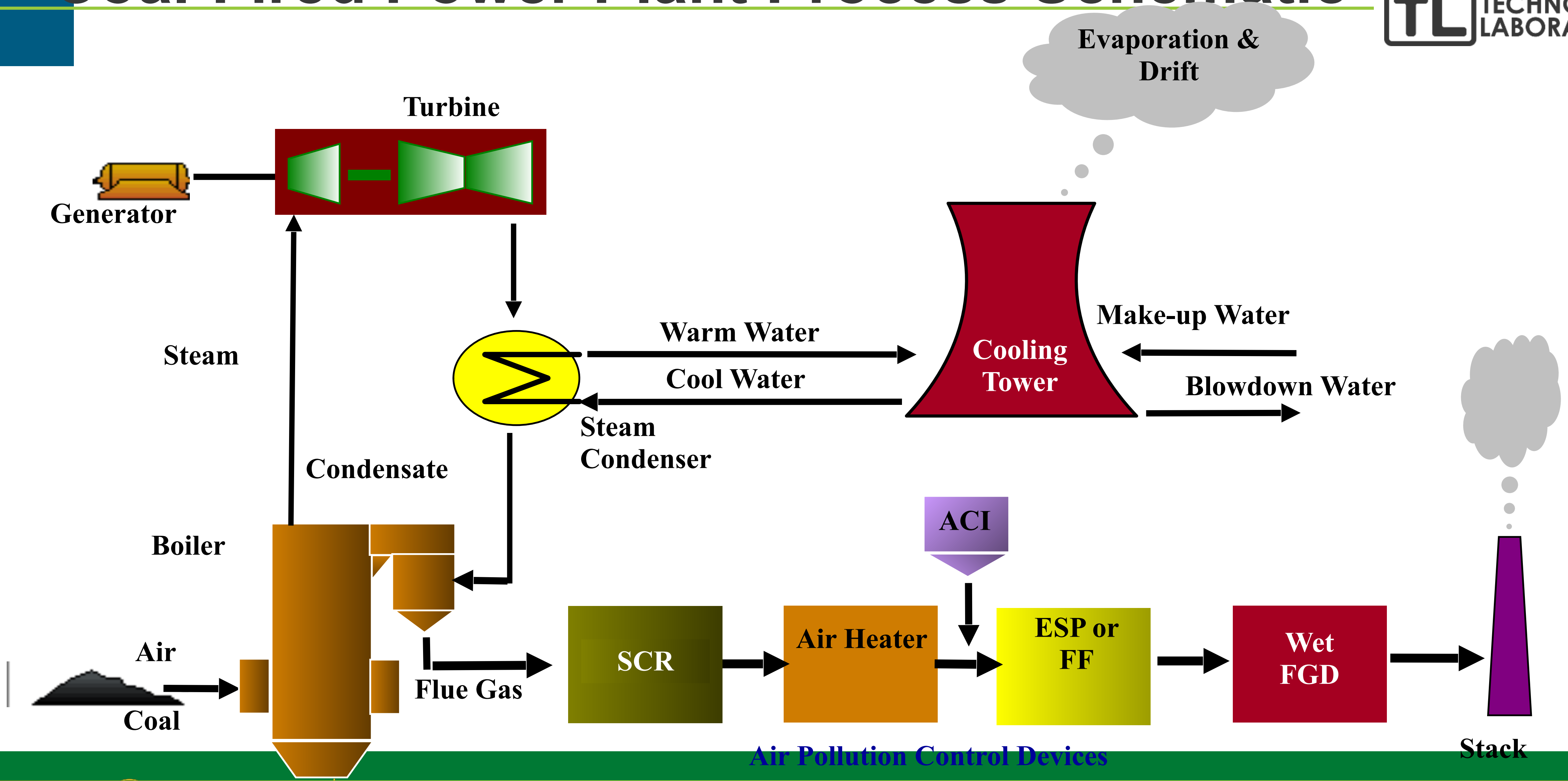
  Power Generation, Heat

- **2. Pyrolysis and Gasification**

  Chemicals, Tars, Liquid Fuels, Activated Carbons, Power Generation

Under Carbon Ore – Novel Carbons, Typically by Pyrolysis

Coal-Fired Power Plant Process Schematic



What is Gasification?

Gasification

- Carbon – Steam or Carbon – Carbon Dioxide Reactions
- $C + H_2O \rightarrow CO + H_2$ $C + CO_2 \rightarrow 2\ CO$
- To make Syngas (Fuel Gas)
- Primarily CO and H_2
- Burn to Make Electricity
- Convert to Chemicals and Fuels
- FT Process
- Methanol, Synthetic Gasoline, Waxes,…….

What is Gasification & Fuel Gas (Syngas)?

- Carbon-Steam Reaction
- Pyrolysis – “Thermally Neutral” – ΔH Small
- Combustion
- Elevated Pressure

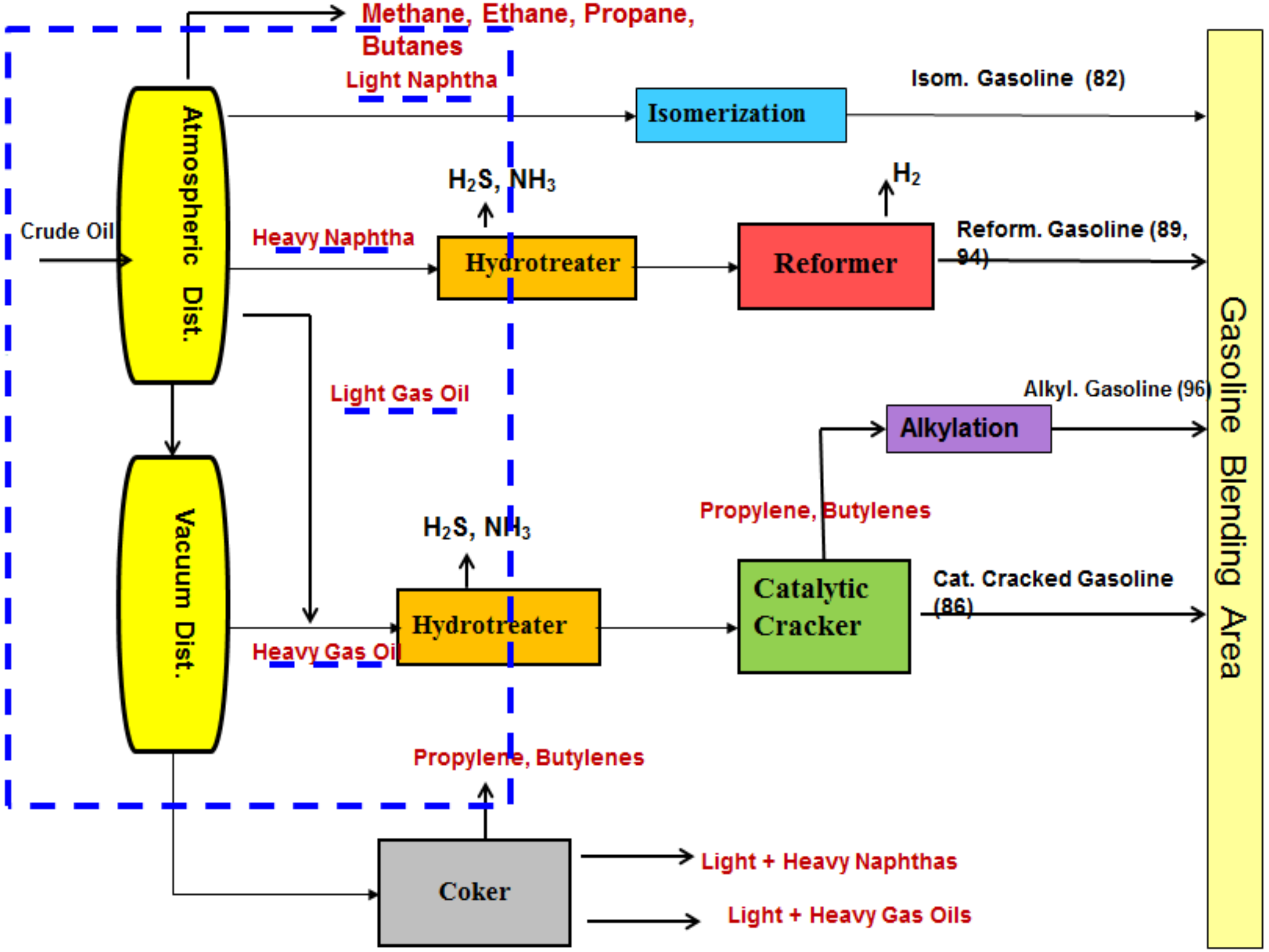
Major Products

- CO, H_2, CO_2, H_2O, Tars & HCs, Chars

Minor Products

- NH_3 , HCl, Cl_2 and particulates
- H_2S, COS, CS_2
- Trace Contaminants: Hg, AsH_3, H_2Se, and PH_3

Petroleum Refinery – Uses Every Part of the Fossil Fuel



ORNL Projects

FWP-FEAA155 – C4AWAR

- "Coal Conversion for Carbon Fibers and Composites"
- 10 MM Graphite, Fibers, and Composites – Lab-Scale R&D

FWP-FEAA157

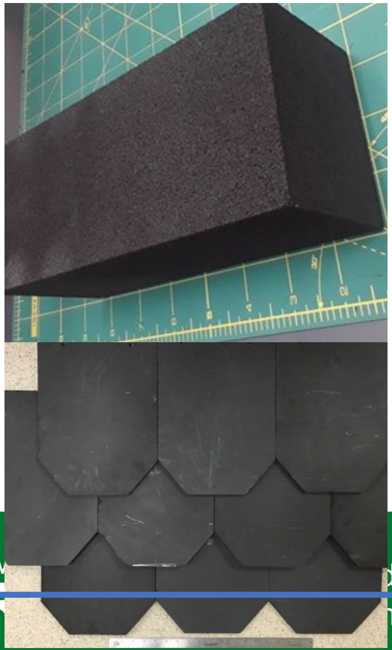
- "Scale-up Production of Graphite and Carbon Fibers from Coal and Coal Refuse"
- 10 MM Scale-Up at Oak Ridge Carbon Fiber Pilot Facility
- Carbon Fibers Envisioned for Lightweight Automobiles
- Graphite for Batteries (New ORNL Technology for Graphite)

Carbon Ore to Products: Opportunities Toward a Clean Energy Transition

Advanced processing of carbon ore and associated by-products for the development of everyday and high value carbon products

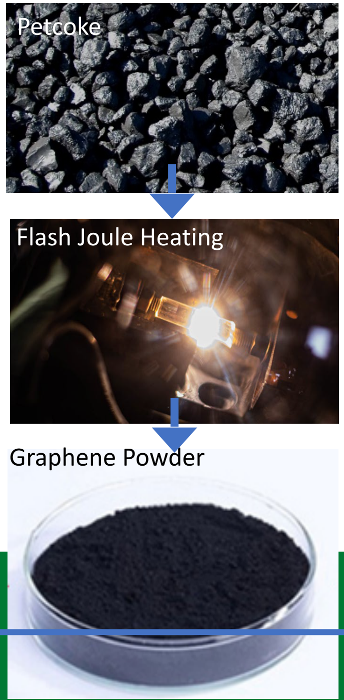
- Generated predominantly from ***coal waste and refuse*** – toward remediation
- Enable domestic manufacturing of strategic materials to encourage job creation
- Ensure the health and safety of the environment and people around the use and disposal of carbon-based products

Next-Gen Construction & Infrastructure Materials

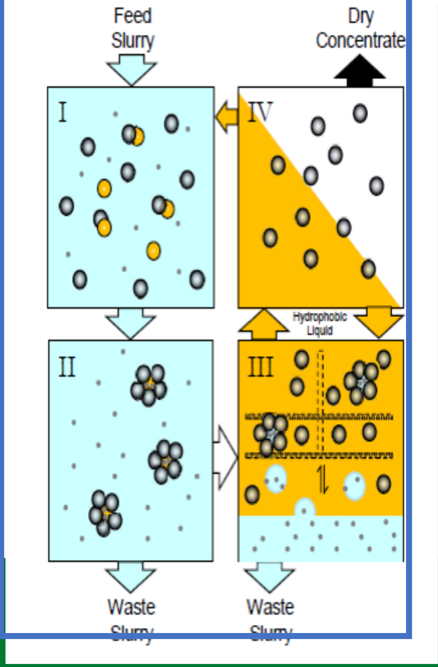


Carbon Fibers from Coal Tar Pitch

Nanomaterials

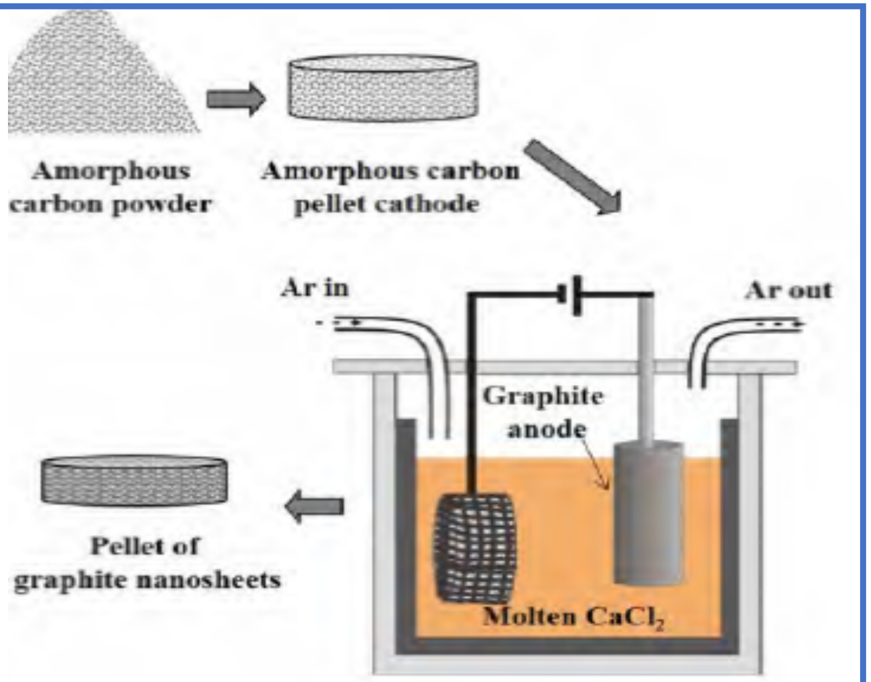


Waste Recovery

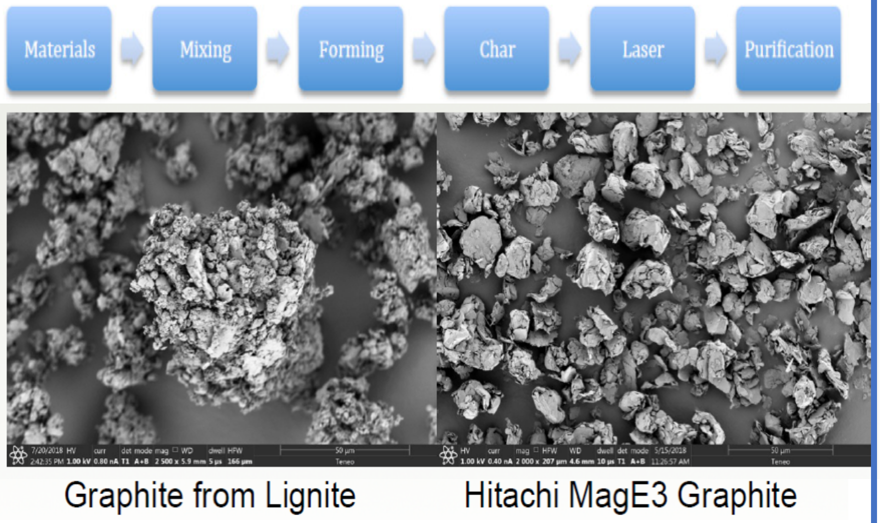


Transformation of Carbon Ore to Graphite

To address anticipated increase in demand, funding research on synthetic graphite



ORNL is investigating the conversion of coal char into graphite using a low-temperature electrochemical graphitization process

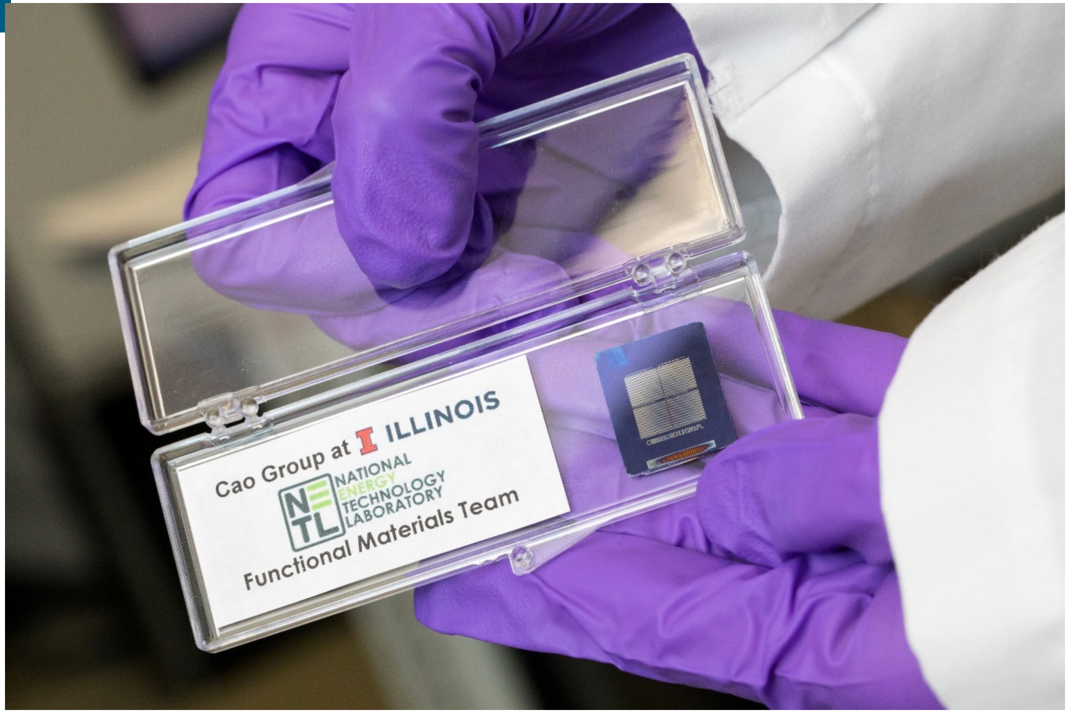


George Washington University is researching coal to Li-ion battery grade (potato) graphite

***FOA 2405:* "Advanced Coal Waste Processing**

Carbon Electronics: Memristor Computer Memory

NATIONAL ENERGY TECHNOLOGY LABORATORY

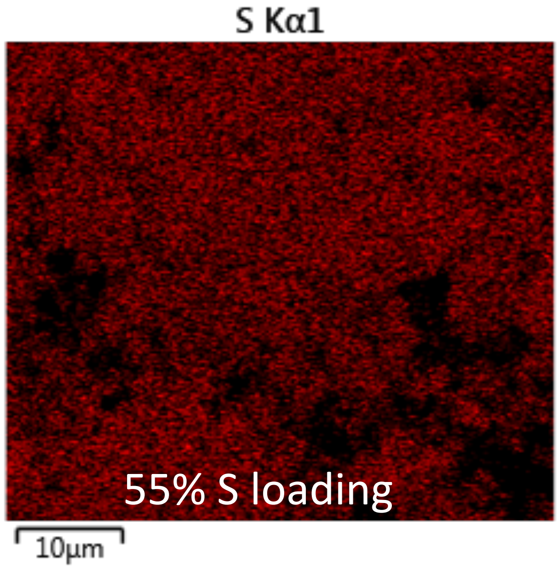


ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
Cao Group, Materials Science

- **Memristor computer memory devices:**
  - Emerging memory technology
  - Energy efficient (<pJ/operation)
  - High speed (10 ns)
  - Easily miniaturized (10 X 10 nm)
  - Integrable on logic chip
- **Coal carbons outperform other carbons and metal oxides:**
  - Lower cost fabrication method
  - Improved device-to-device reproducibility
  - Better long-term device stability

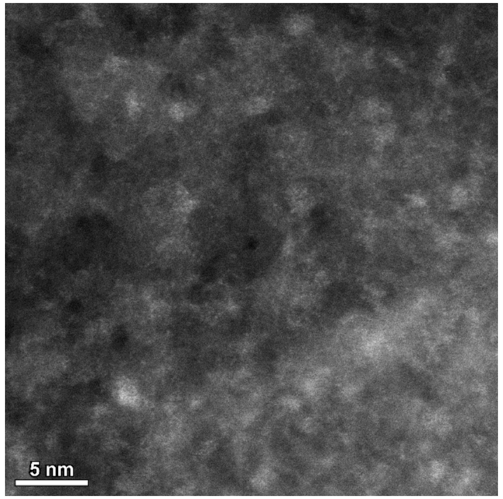
Porous carbons for energy storage, chemical processing, & filtration applications

Energy Storage



- Application: LiS battery
- 25-33% increase in S loading w.r.t. SOTA

Chemical Processing



- Applications: CO_2 Utilization, Chemical processing, synthetic fuels
- Single metal atoms dispersed on carbon
- Unprecedented activity for , H_2 , O_2 , CO, CO_2, organic decomp

Filtration & Membranes

Massachusetts Institute of Technology

- Ideal pore size for water desalination, testing in progress at NETL
- Solid carbon membranes w/ MIT

Current Portfolio – Pyrolysis of Coal
Waste Minimization

- Pyrolysis – Heat Coal in Absence of Air
- Outstanding Strategy for Upgrading Coal
- Thermally Neutral : $\Delta H_{\text{Reaction Pyrolysis}}$ is Small
- Decomposition of Volatile Matter & Graphitization of Carbon
- Produce Char, Tar and Gases
- Focused Upon Char or the Tar (For Carbon or Pitch)
- Results in Wasted Gas, Tar and/or Char
- Future Work – Utilize All of The Pyrolysis Products
- No Wasted Molecules

X-MAT – Tour April 7, 2022

X-MAT – Tour April 7, 2022

FOA 2620

- Released July/August 2022
- AO1: Graphite (Synergy with Critical Materials)
- AO2: Composites and Novel Alloys
- 6 MM Total
- Selections Announced
- https://www.energy.gov/fecm/articles/doe-invests-6-million-develop-useful-products-coal-and-coal-wastes-support-clean
- DOE Invests $6 Million to Develop Useful Products from Coal and Coal Wastes in Support of a Clean Energy Economy
- February 16, 2023

Future Research

- a) **High Value Products for Clean Energy Economy** - Carbon Nanomaterials, Graphite, Specialty Ultra-High Surface Area Activated Carbons, Fibers, Composites, Novel Alloys, Diamonds

- b) **Utilization of Entire Coal Value Chain** – Volatile Matter (Tars and Pitch – Fibers; Gases - Chemicals), Mineral Matter (Critical Minerals), Fixed Carbon (Carbon Nanomaterials, Graphite, UHSAAC) – No Wasted Molecules – Multiple Products - Better Process Economics – Greater Incentive to Clean-Up Coal Impoundments
  - **Utilize Byproduct Carbons from Recovery of CMs**
- c) **Tracking and Removal of Harmful Trace and Minor Element Species – Zero Emissions**

In the News

- https://www.netl.doe.gov/node/12705

- A technology, developed by XMAT with support from DOE, uses coal waste as an anode material in lithium-ion batteries.

- https://www.energy.gov/fecm/articles/doe-announces-6-million-develop-useful-products-coal-and-coal-wastes

- FOA 2620

Annual Review Meeting

- Downtown Pittsburgh
- In Person
- October 2022
- Over 40 Presentations on Carbon Ore Research
- Presentations are Available On-line
- https://netl.doe.gov/22RS-proceedings
- Next Program Review
- April 2 – 4, 2024
- Pittsburgh

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- Savannah Rice
- Acqueetta Ragland-Higdon

Additional Information

- **Much additional information is available on the NETL Carbon Ore website:**
- **https://netl.doe.gov/Carbon-Ore-Processing**

- **A factsheet is also available:**
- **https://netl.doe.gov/sites/default/files/2022-11/Program-151_0.pdf**

U.S. DEPARTMENT OF
ENERGY
Fossil Energy and
Carbon Management

Questions

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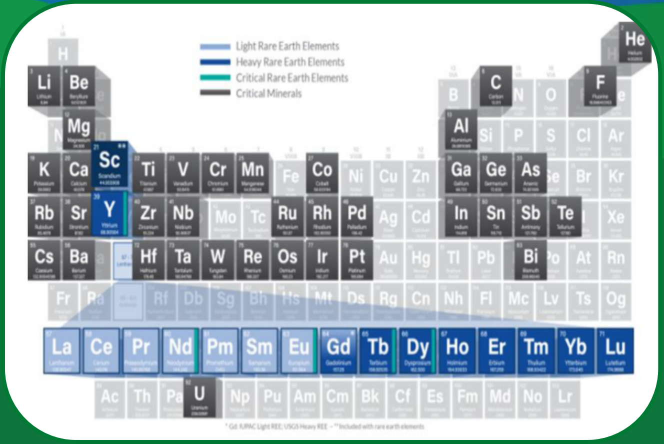

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