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

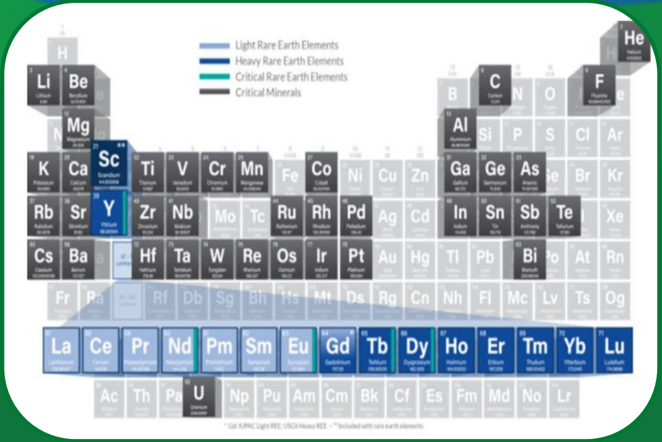
Beyond Combustion – Coal in the 21st Century

Evan J. Granite

Resource Sustainability Review Meeting

April 2, 2024





Carbons from Coal

Numerous Possibilities

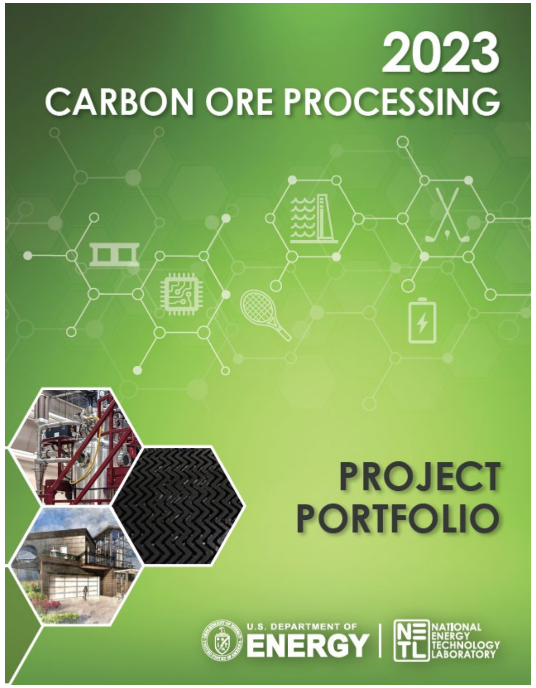
- Activated Carbons and Supercapacitors
- Coke
- Chars
- Graphite and Carbon Electrodes
- Graphene
- Nanocarbons
- Composites and Alloys
- Carbon Fibers, Blocks, Roof Shingles, Deck Boards, Pipes
- Carborundum (Silicon Carbide), Diamond

Program Overview

- Current and Recent Projects (49) – 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

DOE Carbon Ore Portfolio

- 23 active in 2024 and 2025
- https://netl.doe.gov/node/2476?list=Carbon%20Ore%20Processing
- Graphite
- Nanocarbons
- Supercapacitors
- Activated Carbons
- Silicon Carbide
- Building Materials
- Composites
- **Moving Towards High Value Products**



2023
CARBON ORE PROCESSING

PROJECT
PORTFOLIO

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

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

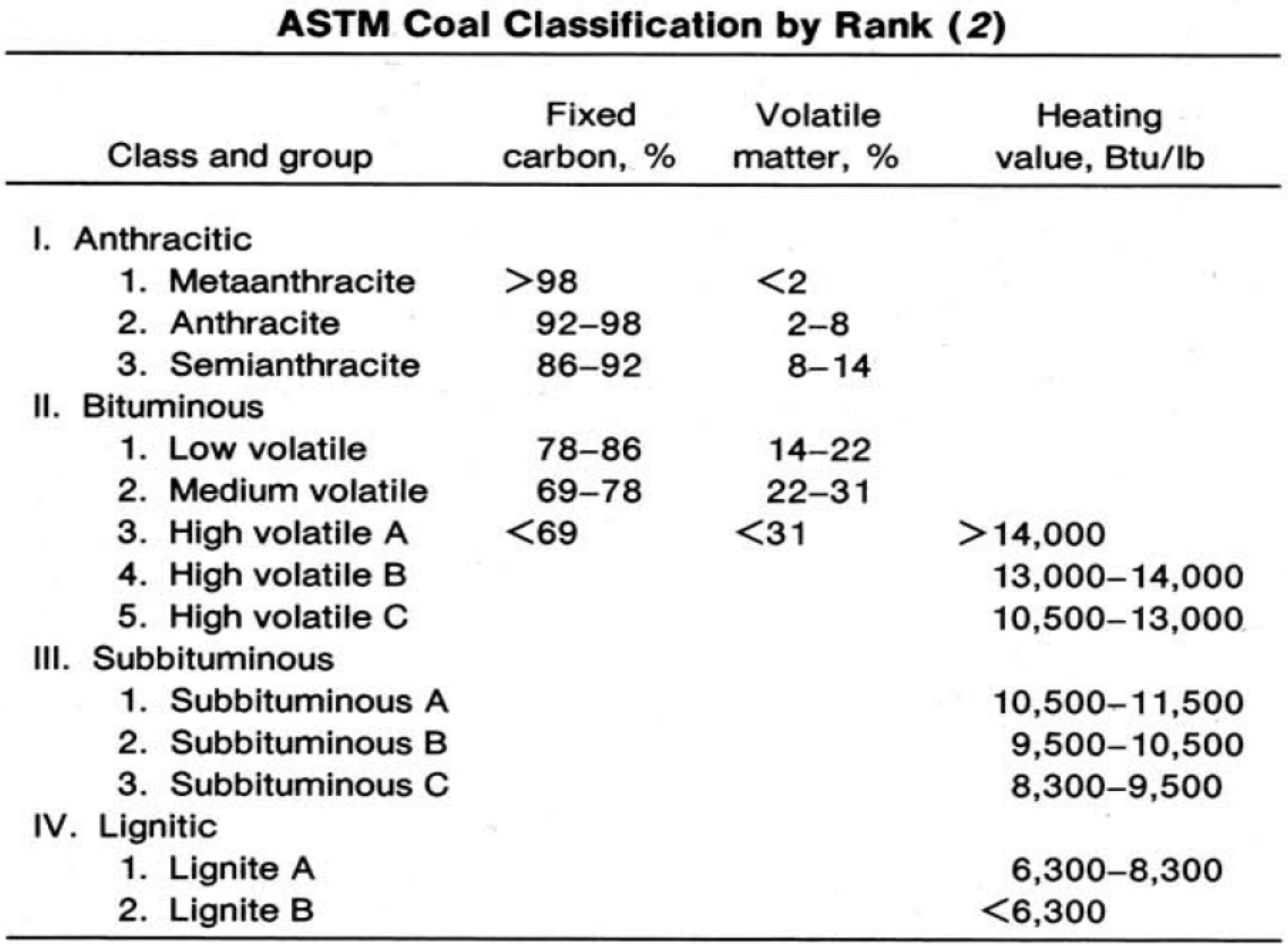
Classic Analysis – Moisture, Volatile Matter, Fixed Carbon, Ash

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

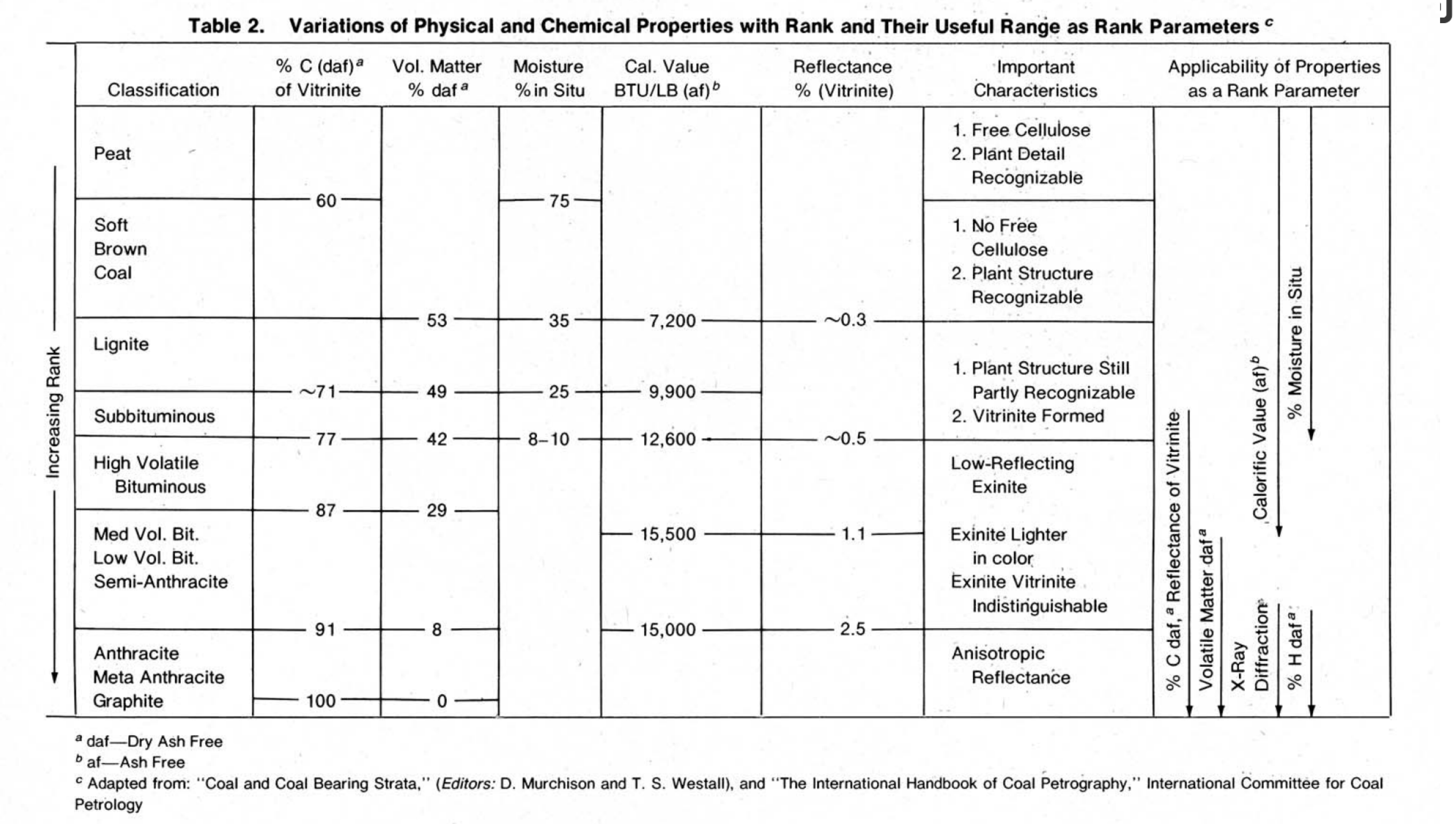


Table 2. Variations of Physical and Chemical Properties with Rank and Their Useful Range as Rank Parameters [c]

Increasing Rank

Classification	% C (daf)[a] of Vitrinite	Vol. Matter % daf [a]	Moisture % in Situ	Cal. Value BTU/LB (af) [b]	Reflectance % (Vitrinite)	Important Characteristics	Applicability of Properties as a Rank Parameter
Peat						1. Free Cellulose 2. Plant Detail Recognizable	Calorific Value (af)[b] % Moisture in Situ
	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							% C daf,[a] Reflectance of Vitrinite
	77	42	8–10	12,600	~0.5		
High Volatile Bituminous						Low-Reflecting Exinite	
	87	29					
Med Vol. Bit. Low Vol. Bit. Semi-Anthracite				15,500	1.1	Exinite Lighter in color Exinite Vitrinite Indistinguishable	Volatile Matter daf[a] X-Ray Diffraction % H daf[a]
	91	8		15,000	2.5		
Anthracite Meta Anthracite Graphite						Anisotropic Reflectance	
	100	0					

[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.
- "The Geochemistry of Coal – Part II. The Components of Coal", Harold H. Schobert, Journal of Chemical Education, 290-293, 1989.

Abundant Domestic Coal – Largest World Reserves

Abundant Coal Reserves in the U.S.

Source: Fletcher & Baylis/Science Source

Estimated Recoverable Reserves

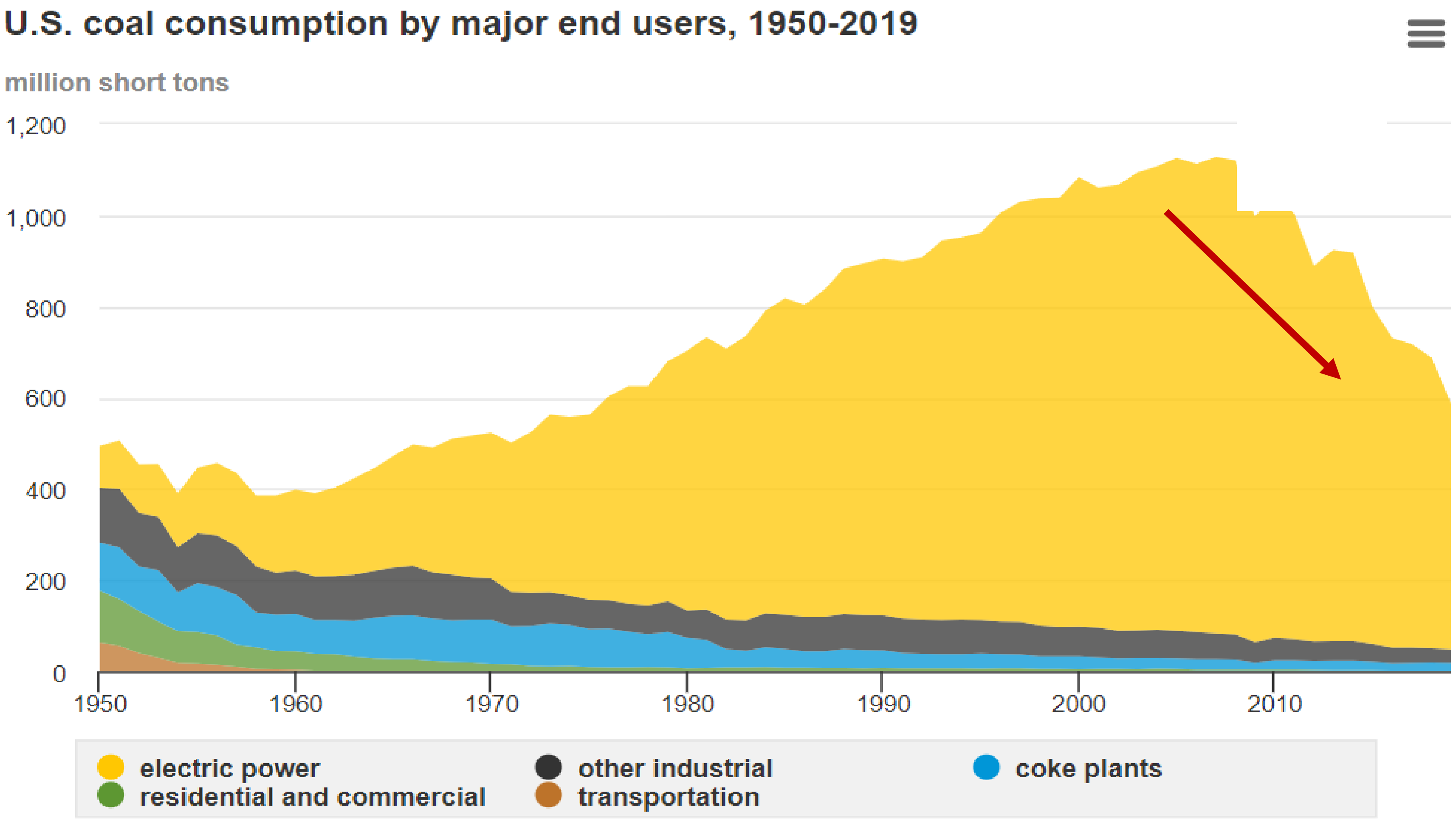
- Coal that can *currently* be mined
- 253 billion short tons

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



U.S. coal consumption by major end users, 1950-2019

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

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

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)
- 577 Million Tons in 2021; 594 Million Tons in 2022 (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

Unconventional & Secondary Sources

Extraction, Separation, and Processing of REEs and Critical Minerals

Manufacturing of Hive Value, High Growth Carbon Products

How Do We Process/Utilize of Coal?

Two Typical Routes

- **1. Combustion**

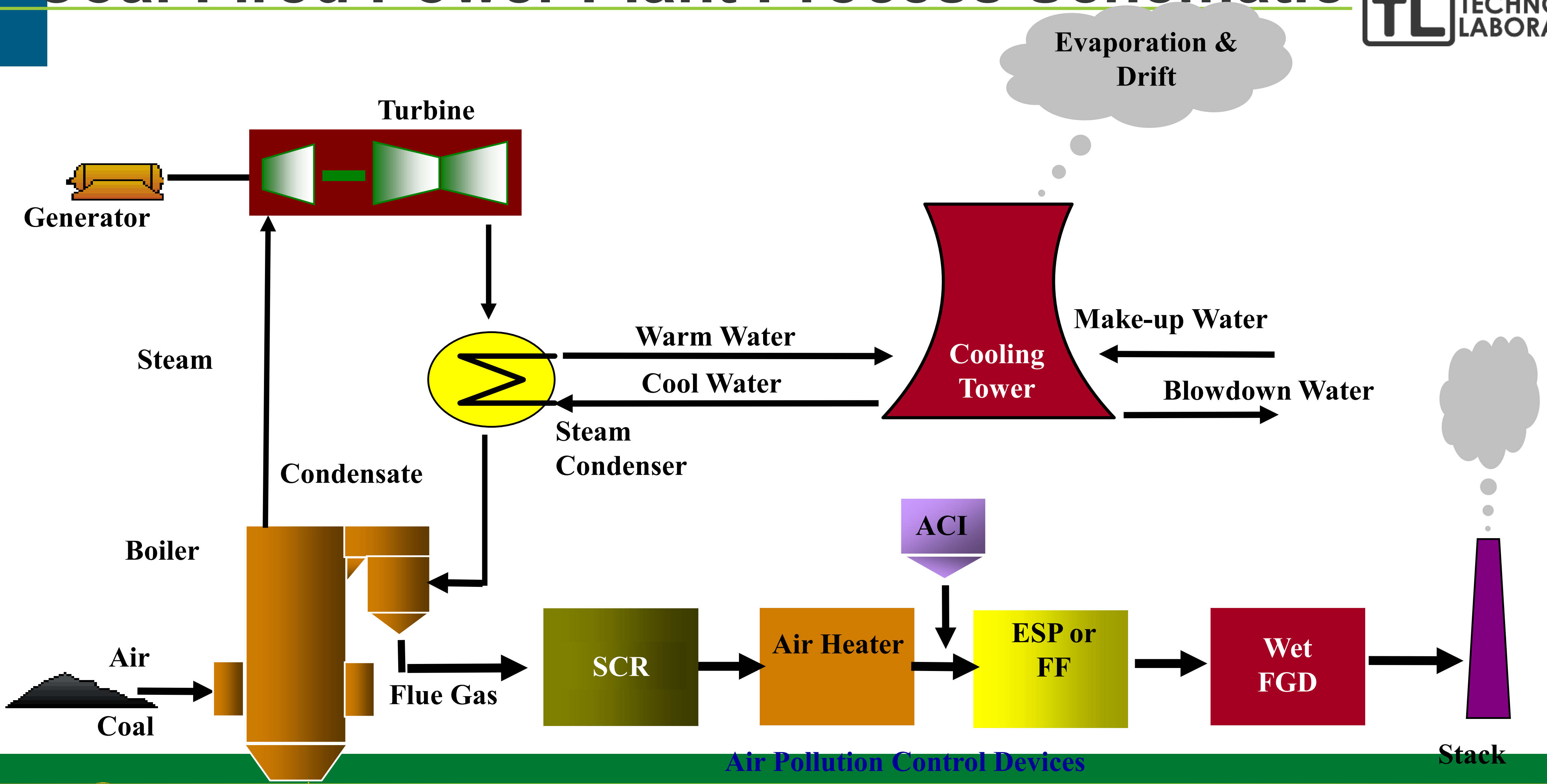
  Power Generation, Heat

- **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

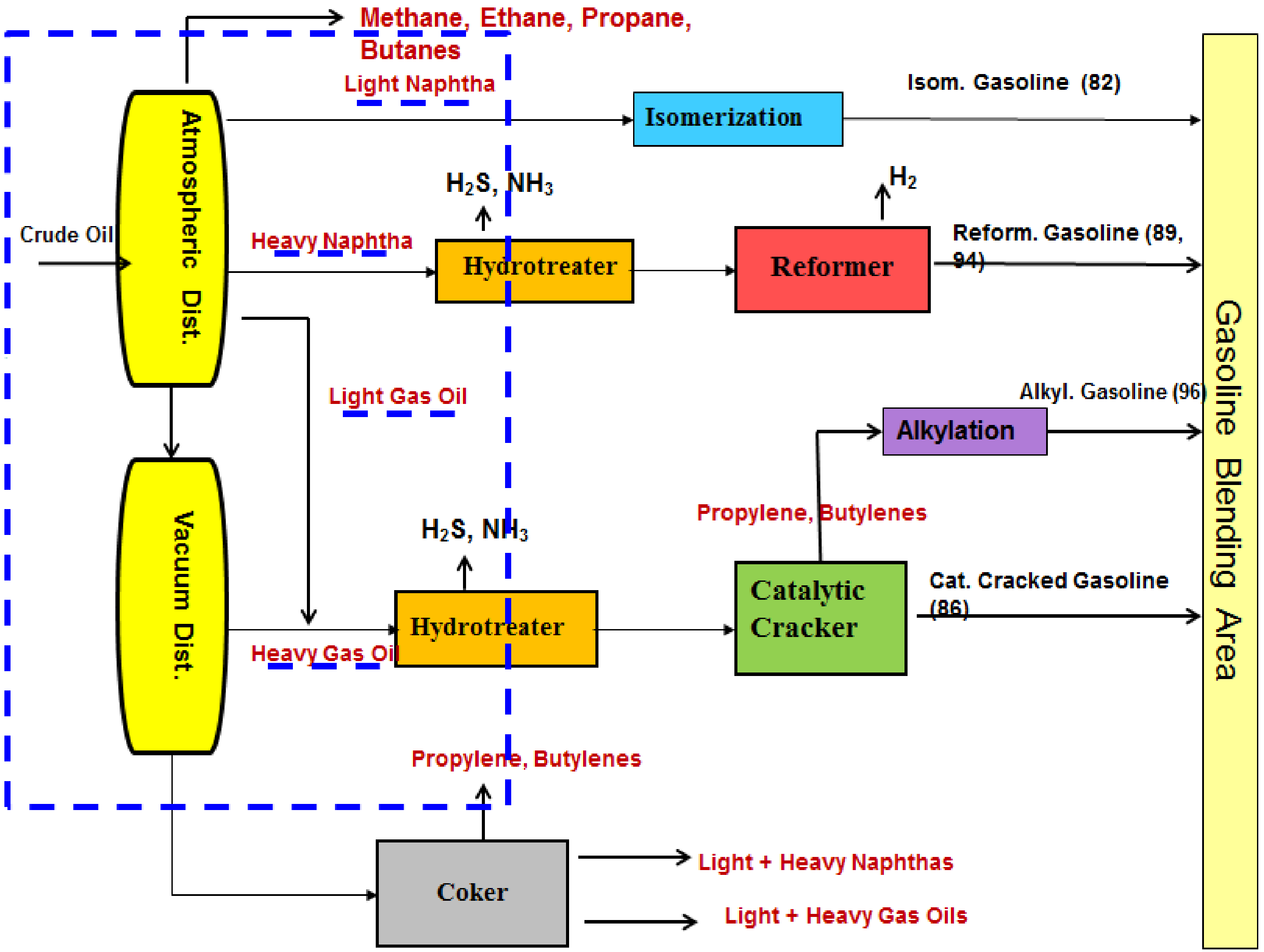
Major Products

- 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 and University of Kentucky Projects

FWP-FEAA155 – C4AWAR

- “Coal Conversion for Carbon Fibers and Composites”
- Graphite, Fibers, and Composites

FWP-FEAA157

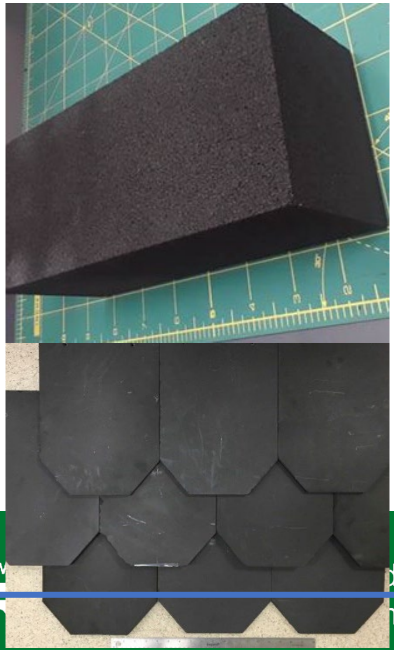
- “Scale-up Production of Graphite and Carbon Fibers from Coal and Coal Refuse”
- Scale-Up at Oak Ridge Carbon Fiber Pilot Facility
- Carbon Fibers Envisioned for Lightweight Automobiles
- Graphite for Batteries (New ORNL Technology for Graphite)

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

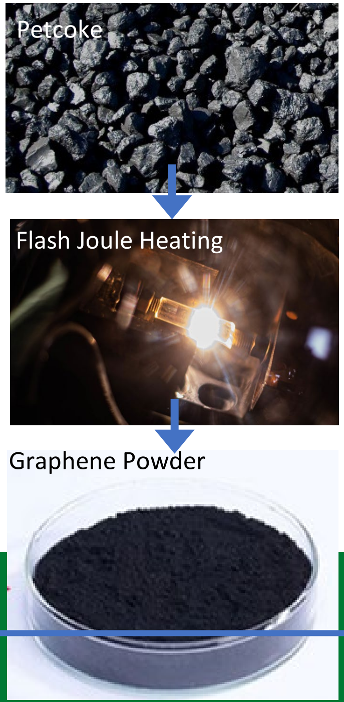
- Generated predominantly from ***coal waste and refuse*** – toward remediation
- Enable domestic manufacturing of strategic materials to encourage job creation
- Ensure the health and safety of the environment and people around the use and disposal of carbon-based products

Next-Gen Construction & Infrastructure Materials

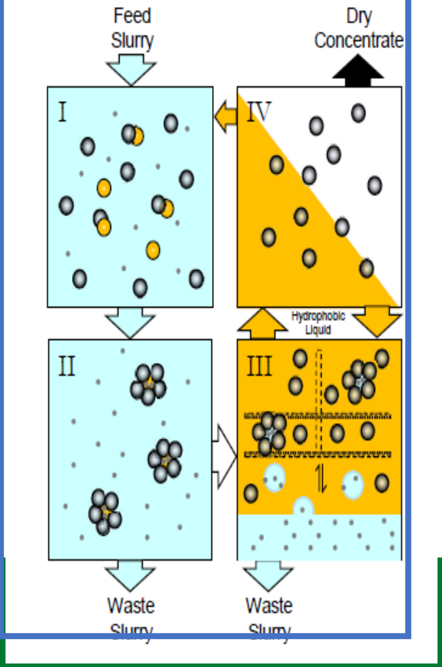


Carbon Fibers from Coal Tar Pitch

Nanomaterials

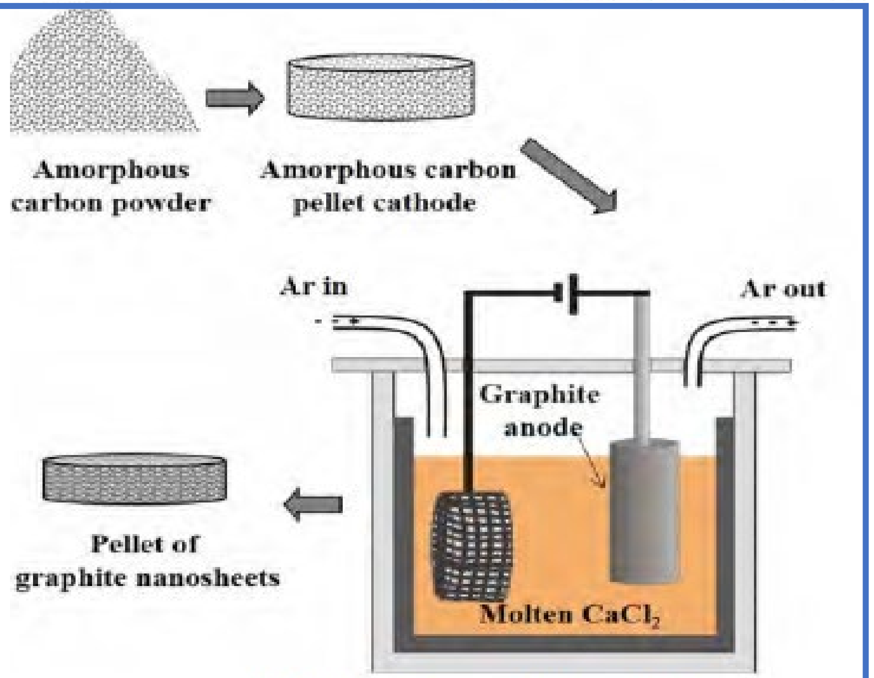


Waste Recovery

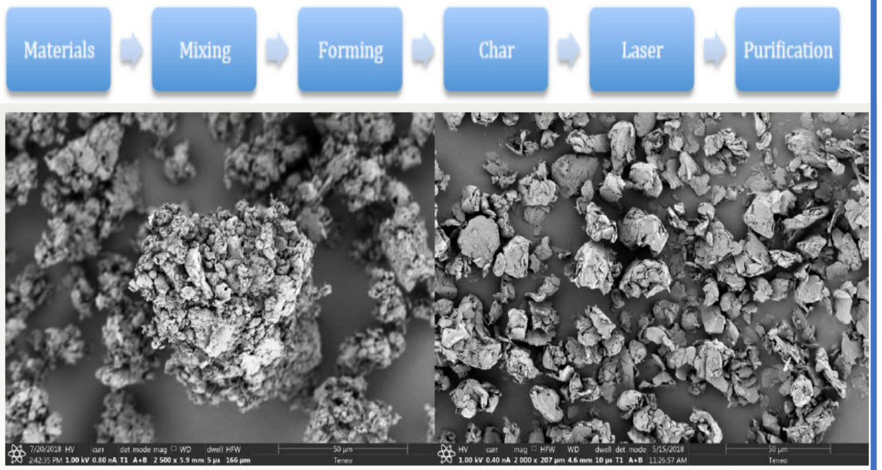


Transformation of Carbon Ore to Graphite

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

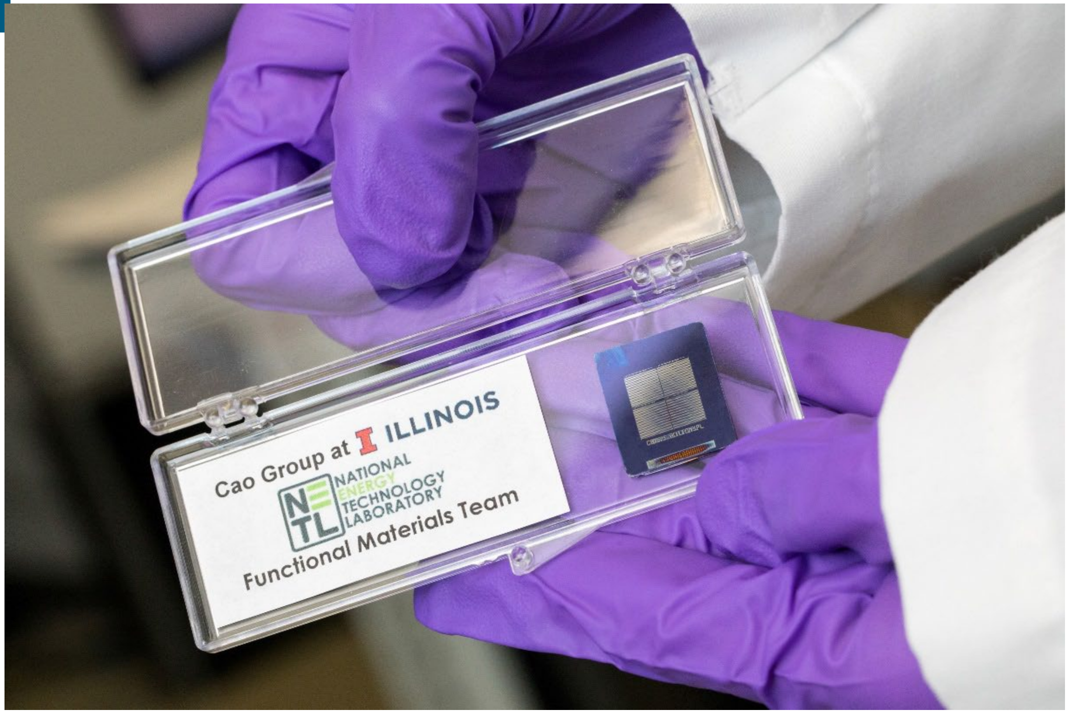


Graphite from Lignite Hitachi MagE3 Graphite

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

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

Carbon Electronics: Memristor Computer Memory



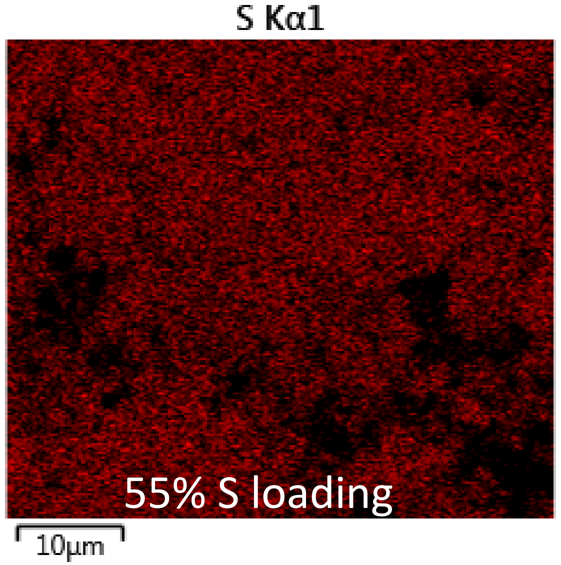
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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

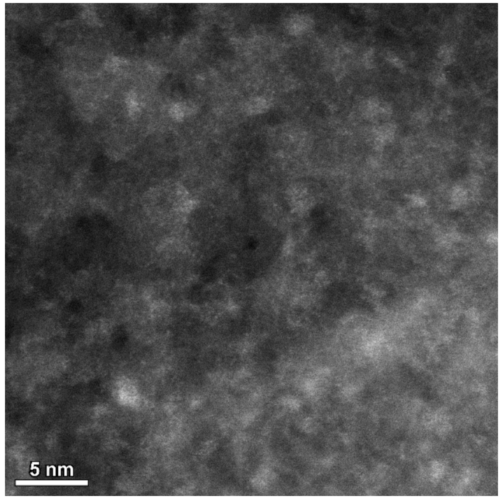
Porous carbons for energy storage, chemical processing, & filtration applications

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

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

Coal Materials: Porous Carbons, Nanoporous Membranes

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 Meetings

- Downtown Pittsburgh
- October 2022
- Over 40 Presentations on Carbon Ore Research
- Presentations are Available On-line
- https://netl.doe.gov/22RS-proceedings

- Today's Program Review
- April 2 – 4, 2024
- Pittsburgh
- https://netl.doe.gov/events/24RS

Acknowledgements

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- Brent Sheets
- Arctic Energy Office (Givey Kochanowski, Michael McEleney, Erin Whitney, Carolyn Hinkley)
- FECM – Julia Pizzutti, Gabe Hernandez, Brad Crabtree

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

Graphite and Carbon Electrodes

Graphite

- **Critical Mineral (USGS) and a Critical Energy Material (USDOE)**

Natural Graphite

- US Imported 84,000 Metric Tons in 2023
- **100% Import Reliance**
- Import Sources: (2019-2022) China 42%; Mexico, 16%; Canada, 15%; Madagascar, 12%; other, 15%.
- The major uses of natural graphite were **batteries**, brake linings, lubricants, powdered metals, refractory applications, and steelmaking.
- The number of lithium-ion battery manufacturing facilities in the United States increased to 10 in 2023 from 3 in operation during 2019.
- An additional 28 facilities were under development.
- U.S. Geological Survey, 2024, Mineral commodity summaries 2024: U.S. Geological Survey, 212 p., https://doi.org/10.3133/mcs2024.

Domestic Demand for Graphite Will Grow

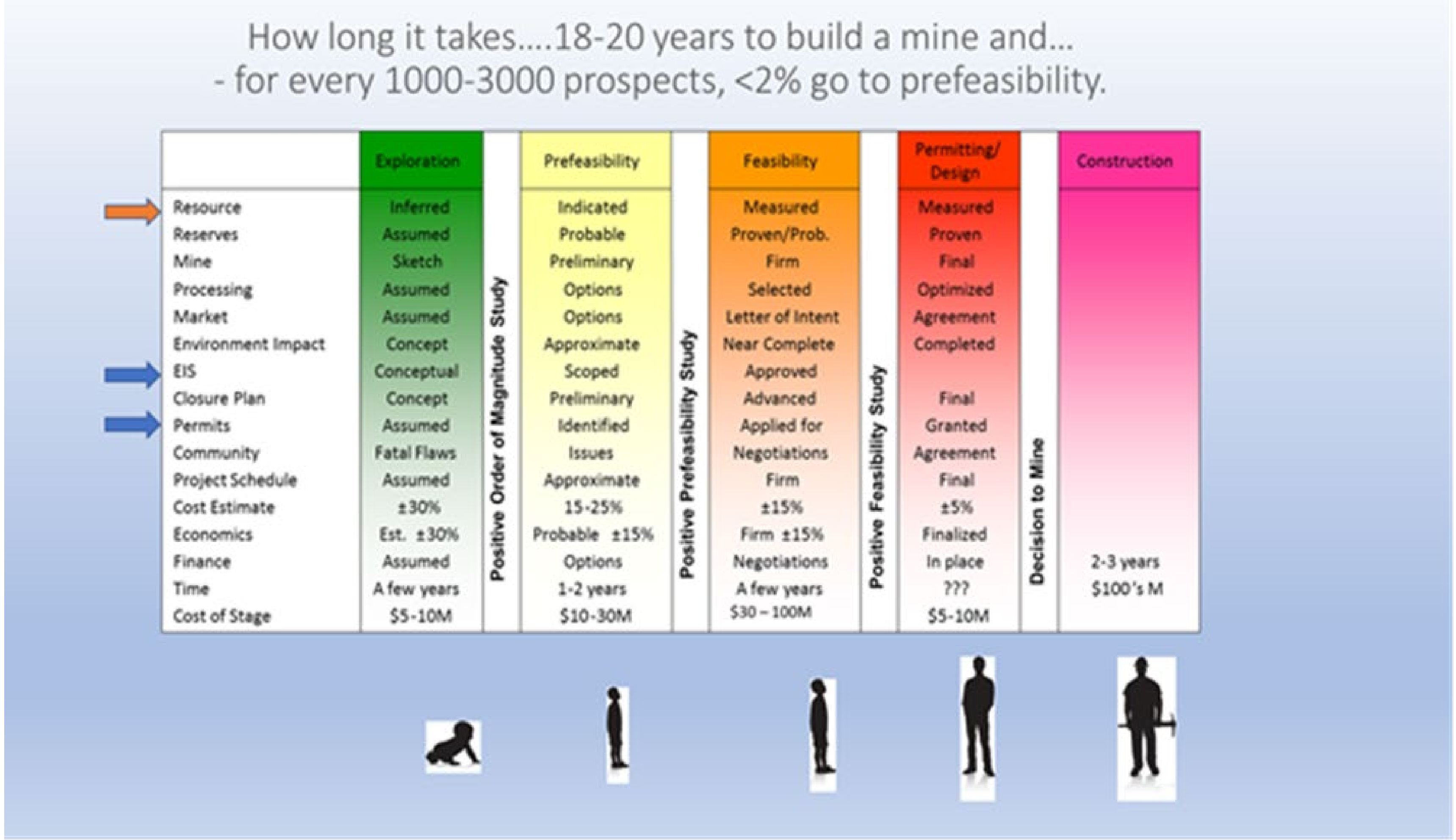
U.S. DEPARTMENT OF ENERGY

- “Very crude back of the envelope estimates for US EV market” – the current domestic annual automobile/SUV demand is around 15.5 million cars/year (2023). **The DOE has a goal of 50% EV adoption by 2030. Assuming this DOE goal is met,**
- EV car batteries contain approximately 150 lbs. of graphite. Assuming 3% annual increase in annual automobile demand (23% increase in automobile demand for 2030, 19 million cars/year in 2030):
- 19,000,000 cars sold in 2030/year * 0.5 EV * 150 lbs. graphite/electric vehicle * 1 ton/2,000 lb. = **713,000 tons graphite required for 2030 US EV demand**
- Versus 92,000 tons (84,000 metric tons) in 2023
- Not accounting for Electric Trucks, Consumer Batteries,……

What Can We Do to Meet Burgeoning Demand?

- **New Domestic Mines (Alabama, Alaska, Montana)**
- **New Domestic Processing Facilities (Cleaning the Natural Graphite)**
- This Takes Time
- On Order of 10 - 20 Years
- Resource Characterization – Extensive Sampling Program to Quantify
- Engineering Designs – Mining and Processing of Ore
- Financing – Many Millions of Dollars
- Permits – For Both Mining and Processing of Ore
- Construction and Shakedown

Typical Mine Project Timeline



How long it takes....18-20 years to build a mine and...
- for every 1000-3000 prospects, <2% go to prefeasibility.

	Exploration	Positive Order of Magnitude Study	Prefeasibility	Positive Prefeasibility Study	Feasibility	Positive Feasibility Study	Permitting/ Design	Decision to Mine	Construction
Resource	Inferred		Indicated		Measured		Measured		
Reserves	Assumed		Probable		Proven/Prob.		Proven		
Mine	Sketch		Preliminary		Firm		Final		
Processing	Assumed		Options		Selected		Optimized		
Market	Assumed		Options		Letter of Intent		Agreement		
Environment Impact	Concept		Approximate		Near Complete		Completed		
EIS	Conceptual		Scoped		Approved				
Closure Plan	Concept		Preliminary		Advanced		Final		
Permits	Assumed		Identified		Applied for		Granted		
Community	Fatal Flaws		Issues		Negotiations		Agreement		
Project Schedule	Assumed		Approximate		Firm		Final		
Cost Estimate	±30%		15-25%		±15%		±5%		
Economics	Est. ±30%		Probable ±15%		Firm ±15%		Finalized		
Finance	Assumed		Options		Negotiations		In place		2-3 years
Time	A few years		1-2 years		A few years		???		$100's M
Cost of Stage	$5-10M		$10-30M		$30 – 100M		$5-10M		

- Figure is courtesy of Lance Miller, Vice President, Natural Resources, NANA, from his presentation “Alaska Critical Mineral Resources”, DOE-DOD Seminar Series on Critical Materials, February 8, 2024.

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**

→ Similar to Acheson Process

Albeit Much Slower!

Synthetic Graphite

- Produced by Heating Carbonaceous Materials to 3,000 – 4,000^{o}C
- For Long Periods of Time
- Acheson Process - 1890
- Others (Petroleum Coke)
- Energy Intensive
- Polluting

- DOE is Seeking Alternative (Lower Temperature) Methods

Value-Added Products from Coal

Part 1. Graphite (and Carborandum)

- Multi-Billion Dollar Annual Industry
- Various Precursors
- Thermal Formation
- Edward Acheson 1890
- Making Silicon Carbide by Heating Coke and Sand to 3000^{o}C
- Form Graphite at Even Higher Temperatures (4000^{o}C)
- By Thermal Decomposition of Silicon Carbide
- Carbon + Sand → Silicon Carbide (Carborandum SiC) → Graphite
- Anthracite an Optimum Feed for His Process

Edward Acheson (1856-1931)

- Prolific Inventor (70 Patents)
- Western Pennsylvania
- Worked for Edison
- Interested in Making Diamonds
- Industrial Abrasive
- Through Heating Carbon at High Temperatures
- Ended Up Making Silicon Carbide
- And Graphite
- Processes Used to this Day

Catalysts for Thermal Graphitization

- **Abundant Literature**
- **Review – Rongyan Wang, "Catalytic Graphitization of Coal-Based Carbon Materials with Light Rare Earth Elements", Langmuir 2016, 32, 8583−8592**
- **La, Ce, Pr , Fe, Co, Ni, Si (Acheson), Ti, W, Mo, Cr**
- **Still Require High (Typically 2700°C) Temperatures**
- **One of the Best CeO_2 – $CaCO_3$ or MnO_2 US Patent 3,615,209**
- **2200°C – 88 - 100% Graphitization**
- **Fe catalysts - 1300°C**
- **"Fe based catalysts for petroleum coke graphitization for Lithium Ion battery application", Agung Nugroho, Materials Letters, 303, 130557, 2021**
- **Mechanisms: Carbide Formation (Acheson), Orientation, Nucleation**

Low Temperature Production of Graphite

Graphite can be synthesized from either coal or petroleum coke at high temperatures of 3000 – 4000 ^{o}C. These high temperatures make the production of synthetic graphite an expensive and environmentally damaging endeavor. The United States has over four billion tons of waste coals, scattered in over one thousand impoundments.

The DOE is investigating concepts for production of graphite from abundant waste coals, at temperatures below 1800^{o}C. This would facilitate clean-up of the waste coal sites and spur production of domestic graphite in a more environmentally friendly and economical manner.

Key Challenges in the Technology Area

- The impact of impurities in the waste coals on the formation of the graphite product.
- Disposition and mitigation of release of toxic elements within the coal such as mercury, arsenic, selenium, cadmium, phosphorus, antimony, sulfur, nitrogen, and halogens.
- Disposition of uranium and thorium present in the feed coal
- Mitigation of organic pollutants
- Economics of the lower temperature processes versus the commercial processes for production of graphite
- Verification of the final synthetic graphite product being highly suitable for use in batteries.
- Producing a brief techno-economic analysis showing creation of a significant number of stable domestic jobs.
- Demonstration of enhancing environmental justice for communities negatively impacted by the waste sites.

Recent Technical Accomplishments – Carbon Ore

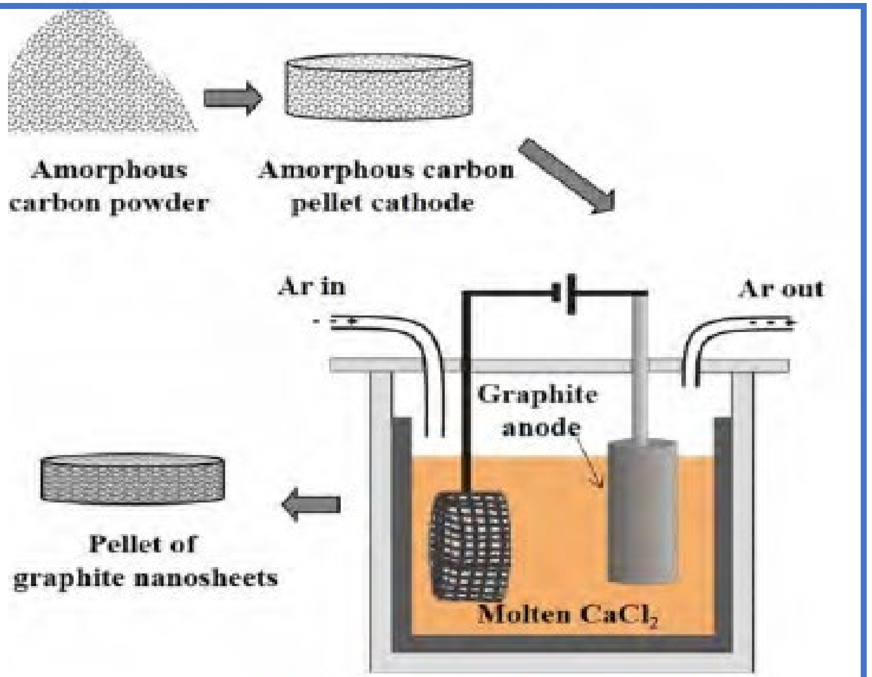
Low Temperature Production of Graphite

Graphite can be synthesized from either coal or petroleum coke at very high temperatures of 3000 – 4000°C. These high temperatures make the production of synthetic graphite an expensive and environmentally damaging endeavor. NETL showed iron is an effective **catalyst for converting coal to graphite at much lower temperatures of around 1500°C.** Additionally, both the catalyst & acid used to recover it can be recycled and reused to produce graphite that performs well in lithium-ion battery tests. This effort has significance for utilizing abundant domestic waste coals for fabricating battery anodes, at large-scales. https://www.netl.doe.gov/node/12897 September 19, 2023, NETL website

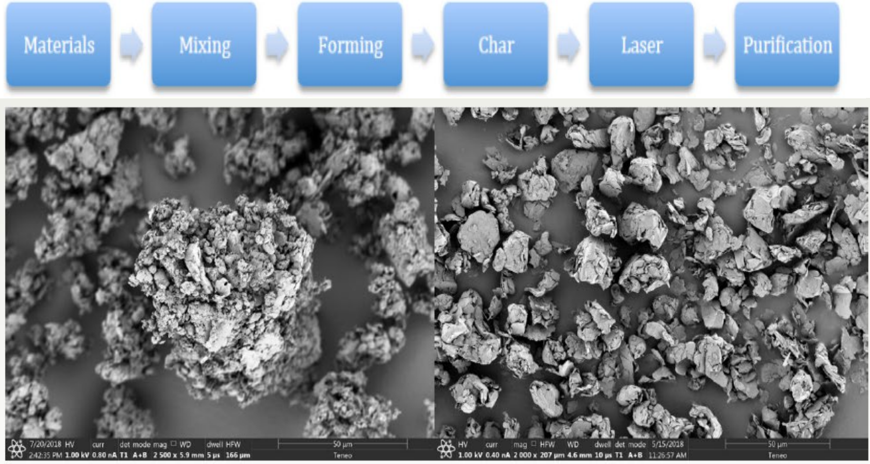
- **Other Significant Breakthroughs by George Washington University and ORNL**
- **Laser Method, Electrochemical Cell**

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



Graphite from Lignite

Hitachi MagE3 Graphite

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

FOA 2405: _“_Advanced Coal Waste Processing

Technology Disruptions

New Battery Electrodes

- **Carbon, but not Graphite**
- Such as Carbon Silicon Materials

- **Adoption of Non-Graphite Carbons Would Disrupt Projections for Graphite Demand**
- **DOE Research**

SBIR Topic

Direct Use of Coal or Carbonaceous Coal Wastes as Lithium-Ion Battery Anodes

- Potential SBIR Topic
- Maximum Phase I Award Amount: $250,000
- Maximum Phase II Award Amount: $1,600,000
- Less Expensive Alternative to Graphite
- 50% Coal or Waste Coal Content
- May Use Silicon or Other Materials
- Projected Explosive Demand for Carbon Electrodes in Lithium Batteries
- FY24-Phase-I-Release-2-TopicsV612082023.pdf (osti.gov)
- **Posted January 18, 2024; Applications Due in March 2024; Awards in June**
- Accepting SBIR Phase I Applications: YES
- Accepting STTR Phase I Applications: YES

Recent Technical Accomplishments – Carbon Ore

Coal-Derived Battery Anodes Show Great Commercial Promise

https://netl.doe.gov/node/12705 July 19, 2023, NETL website news item

DOE supported R&D of Semplastics' technology to utilize domestic, abundant, and inexpensive coal-derived lithium-ion battery anodes as an alternative to graphite. This technology received the Voltage Award from the Battery Innovation Center, which recognizes an emerging company and/or technology with the highest potential to make a difference in batteries and electrification. Under this agreement, coal-derived lithium-ion battery anodes have been tested extensively in 18650 cells, an industry standard size used in BEVs such as the Tesla Model S & X.

Technology Disruptions

New Battery Chemistries and Materials

- **Nearly Infinite Number of Possibilities/Combinations**
- EMF Series – Thermodynamics of Oxidation/Reduction - Suggests Possible **Electrodes**
- **Electrolytes** – Aqueous, Solid, Ions,……
- Issues – Energy Density, Lifetime, Charge/Recharge Cycles and Kinetics, Safety, Cost, Material Availability, Fabrication, Geometry, Electrode Morphologies, …..
- **Typically Takes Years of Testing to Perfect**
- Microsoft and PNNL AI Initiative to Speed Up Battery Development
- https://quantum.microsoft.com/en-us/our-story/quantum-elements-overview
- https://cloudblogs.microsoft.com/quantum/2023/08/09/accelerating-materials-discovery-with-ai-and-azure-quantum-elements/
- **Adoption of New Batteries Would Disrupt Future Need for Graphite**
- **DOE Research**

Conclusions/Future Work

- **Acheson Process and Recent Variations - Great Success**
- **Carbon + Sand → Silicon Carbide (Carborundum SiC) → Graphite**

Challenges

- **Energy Intensive (3000-4000°C)**
- **Slow (Heating in Two Steps: 1000°C, 3000-4000°C)**
- **Impurities in Coal (and Cokes)**

Future Work (Synthetic Graphite)

- **Reduce Required Temperatures, Reaction Times, and Energy**
- **Produce Other Value-Added Carbons and Products**
- **Capture and Account for the Pollutants**
- **Routes: Catalysts, Electrochemical (ORNL), Laser Heating (GWU), Thermal (UKY)**

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

Questions

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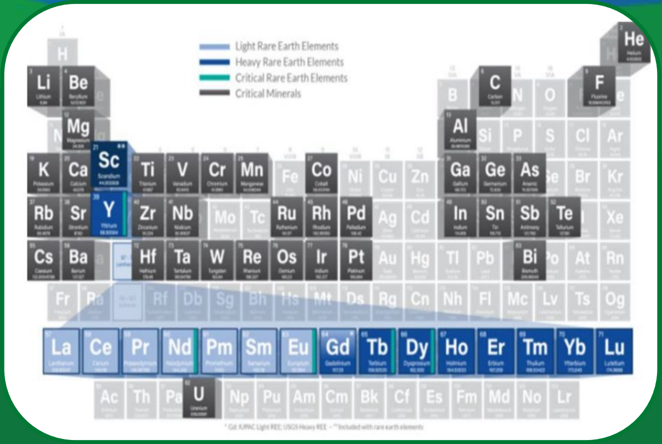

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