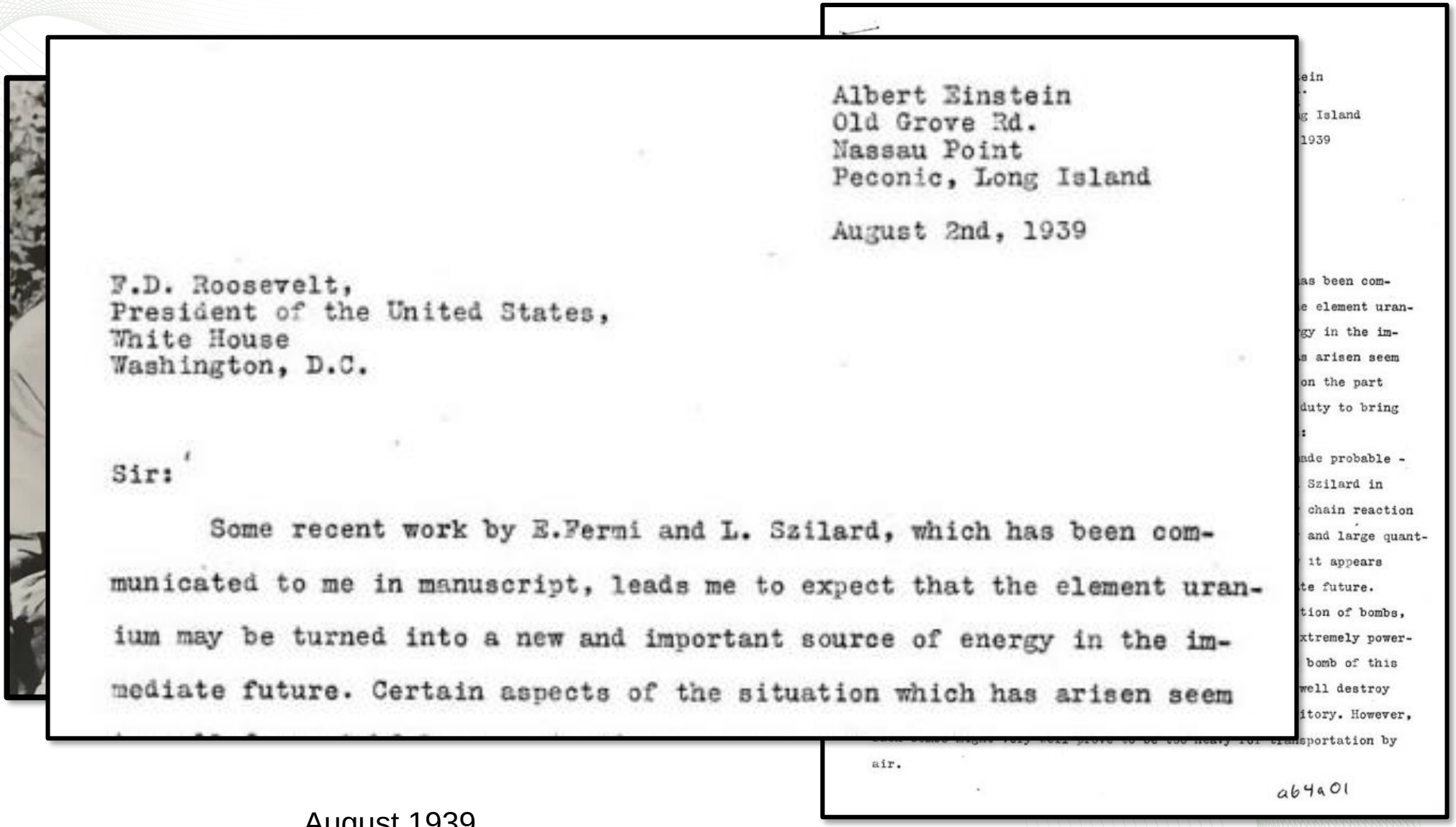
Opportunities for Enabling the Use of Coal as a Precursor for Value-Added Products

Edgar Lara-Curzio
Oak Ridge National Laboratory

Unites States Energy Association
August 9, 2018

The Beginning: Einstein's Letter



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

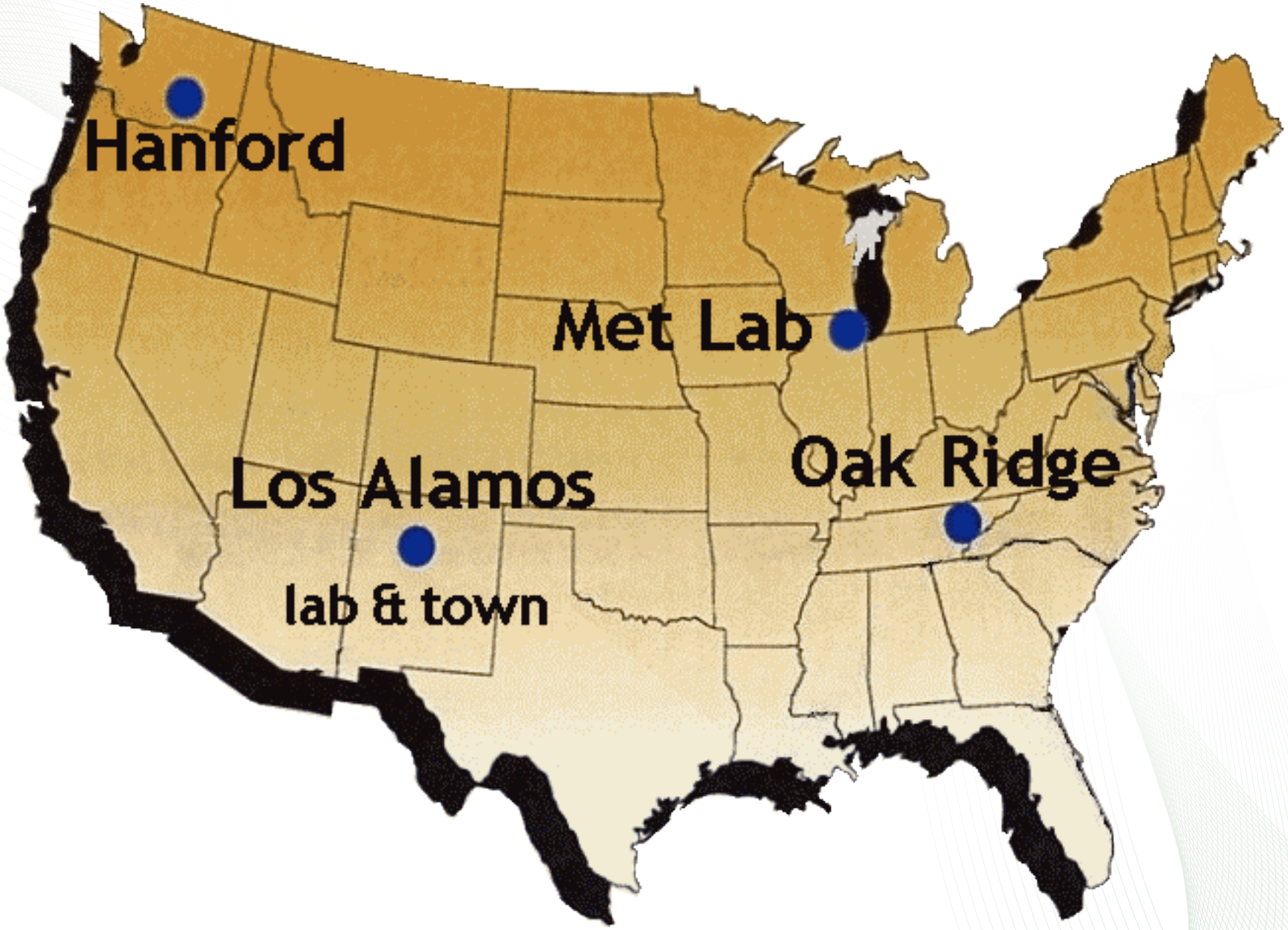
F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

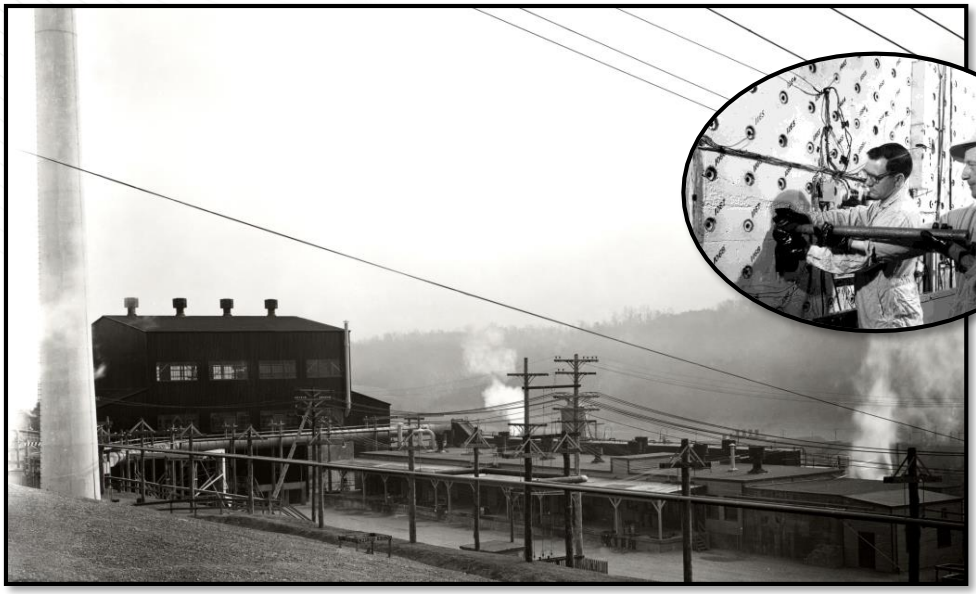
Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem

August 1939

Places of the Manhattan Project



Oak Ridge National Laboratory evolved from the Manhattan Project



The Clinton Pile was the world's first continuously operated nuclear reactor

Chemical processing techniques were developed to separate plutonium from irradiated fuel

Office of Science Laboratories

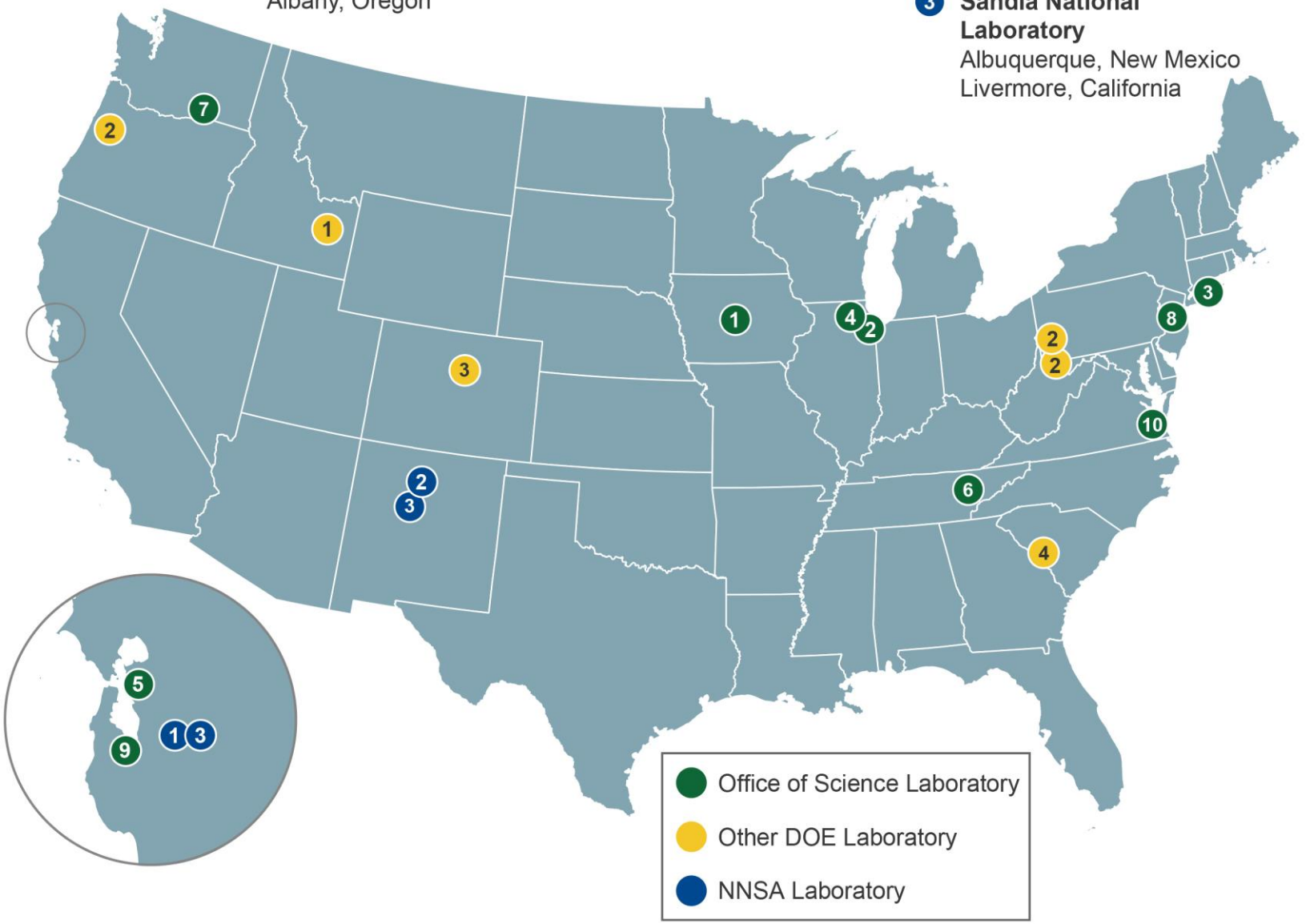
1. **Ames Laboratory**
   Ames, Iowa
2. **Argonne National Laboratory**
   Argonne, Illinois
3. **Brookhaven National Laboratory**
   Upton, New York
4. **Fermi National Accelerator Laboratory**
   Batavia, Illinois
5. **Lawrence Berkeley National Laboratory**
   Berkeley, California
6. **Oak Ridge National Laboratory**
   Oak Ridge, Tennessee
7. **Pacific Northwest National Laboratory**
   Richland, Washington
8. **Princeton Plasma Physics Laboratory**
   Princeton, New Jersey
9. **SLAC National Accelerator Laboratory**
   Menlo Park, California
10. **Thomas Jefferson National Accelerator Facility**
    Newport News, Virginia

Other DOE Laboratories

1. **Idaho National Laboratory**
   Idaho Falls, Idaho
2. **National Energy Technology Laboratory**
   Morgantown, West Virginia
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. **National Renewable Energy Laboratory**
   Golden, Colorado
4. **Savannah River National Laboratory**
   Aiken, South Carolina

NNSA Laboratories

1. **Lawrence Livermore National Laboratory**
   Livermore, California
2. **Los Alamos National Laboratory**
   Los Alamos, New Mexico
3. **Sandia National Laboratory**
   Albuquerque, New Mexico
   Livermore, California



ORNL's mission

Deliver scientific discoveries and technical breakthroughs that will accelerate the development and deployment of solutions in clean energy and global security, and in doing so create economic opportunity for the nation

Signature strengths

- Computational science and engineering
- Materials science and engineering
- Neutron science and technology
- Nuclear science and technology

ORNL innovations have had billion dollar impacts

- $1B domestic investment in additive manufacturing
- Fueleconomy.gov: $1B in fuel cost savings
- New gas turbine composite material
- Lab-on-a-chip: Caliper sold for $0.6B
- Cesium extraction: Basis for $1.3B waste processing
- Reactor life extension: $20B cost avoidance
- Advanced alloys: Chrome-moly steel in widespread use
- Ion implantation: Integrated circuits and medical implants
- Cryopreservation (mouse embryos): Frozen embryo (livestock reproduction)
- Centrifuge technology: Basis for vaccine purification and US enrichment industry
- Instrumentation: >$1B in products and spinoffs from ORTEC and TENNELEC
- Reactor technology: Concept technology for light water, high temperature, molten salt reactors
- PUREX: Basis for nuclear fuel reprocessing techniques used worldwide
- Radioisotopes: Multibillion dollar industry (>100 million procedures per year)

1940s **Today**

7

ORNL innovations have had billion dollar impacts

Coal-to-High Value-Added Products

Lab-on-a-chip: Caliper sold for $0.6B

Coal Power Plant Life Extension Enabled by Data Analytics, HPC, Advanced Materials and Thermal Storage Solutions

Ion implantation: Integrated circuits and medical implants

Cryopreservation (mouse embryos): Frozen embryo (livestock reproduction)

Centrifuge technology: Basis for vaccine purification and US enrichment industry

Instrumentation: >$1B in products and spinoffs from ORTEC and TENNELEC

Reactor technology: Concept technology for light water, high temperature, molten salt reactors

PUREX: Basis for nuclear fuel reprocessing techniques used worldwide

Radioisotopes: Multibillion dollar industry (>100 million procedures per year)

1940s **Today**

8

The Rare Earth Minerals Crisis

The New York Times

ENERGY & ENVIRONMENT

China Weighs Tighter Controls on Rare Elements

By Chinese Leader Denies Using Mineral Exports for Political Ends

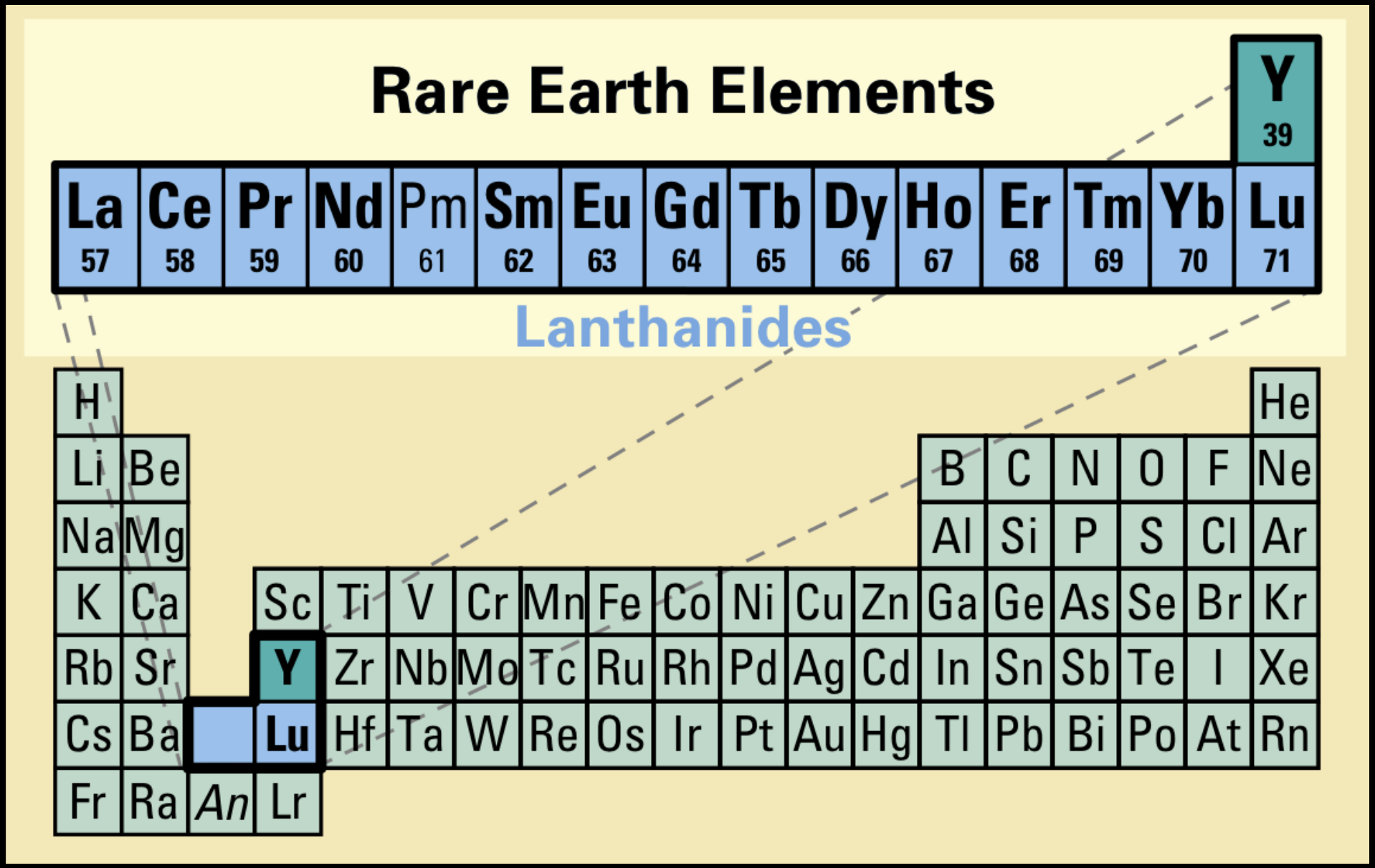
By Japan Calls on China to Resume Rare Earth Exports

By U.S. Called Vulnerable to Rare Earth Shortages

By China Consolidates Grip on Rare Earths

By KEITH BRADSHER SEPT. 15, 2011

BEIJING — In the name of fighting pollution, China has sent the price of compact fluorescent light bulbs soaring in the United States.


Rare Earth Elements
Y 39
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Lanthanides
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
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Ca
Sc
Ti
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Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Tc
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Po
At
Rn
Fr
Ra
An
Lr

What are the Rare Earth Elements?

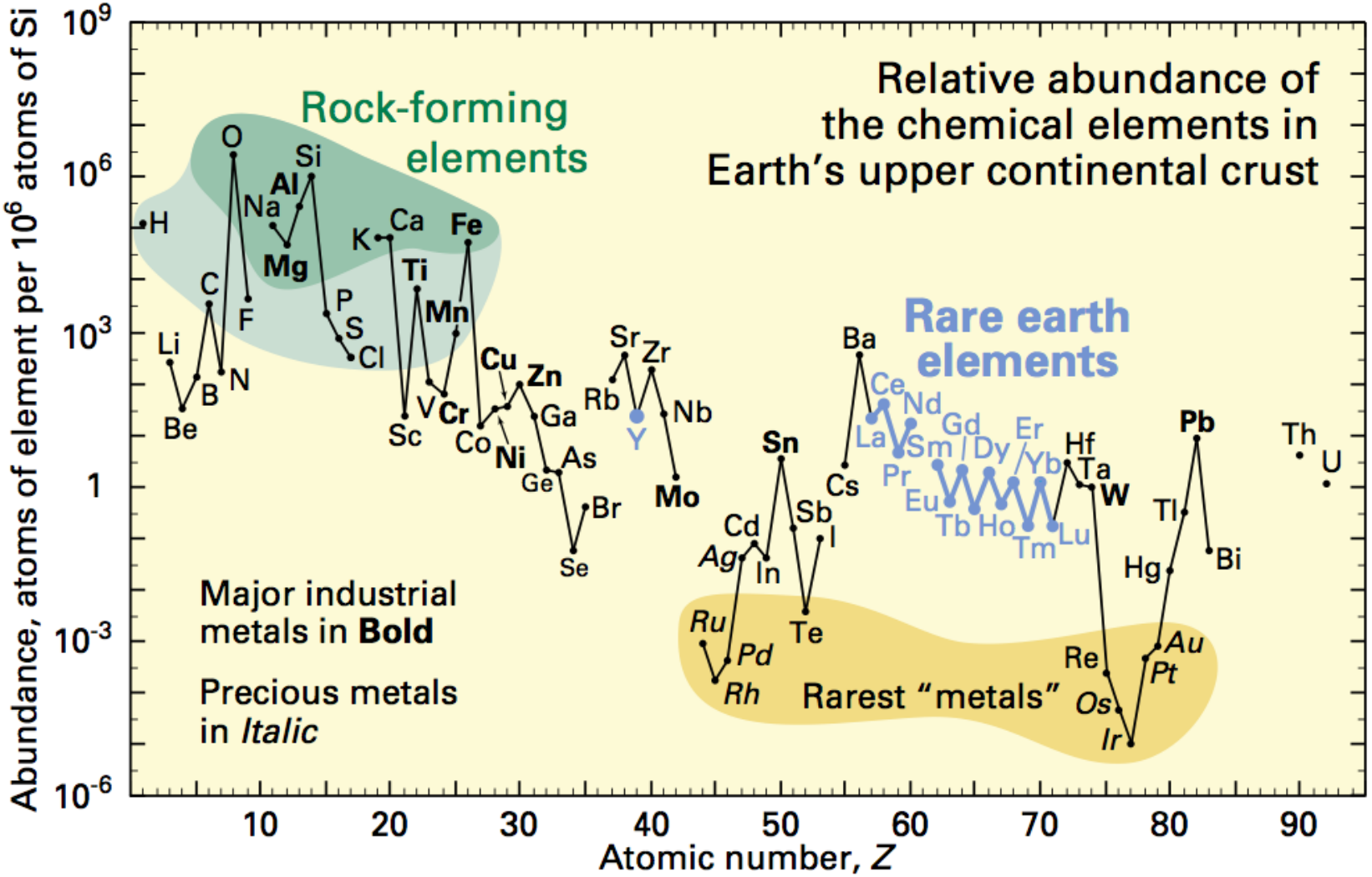
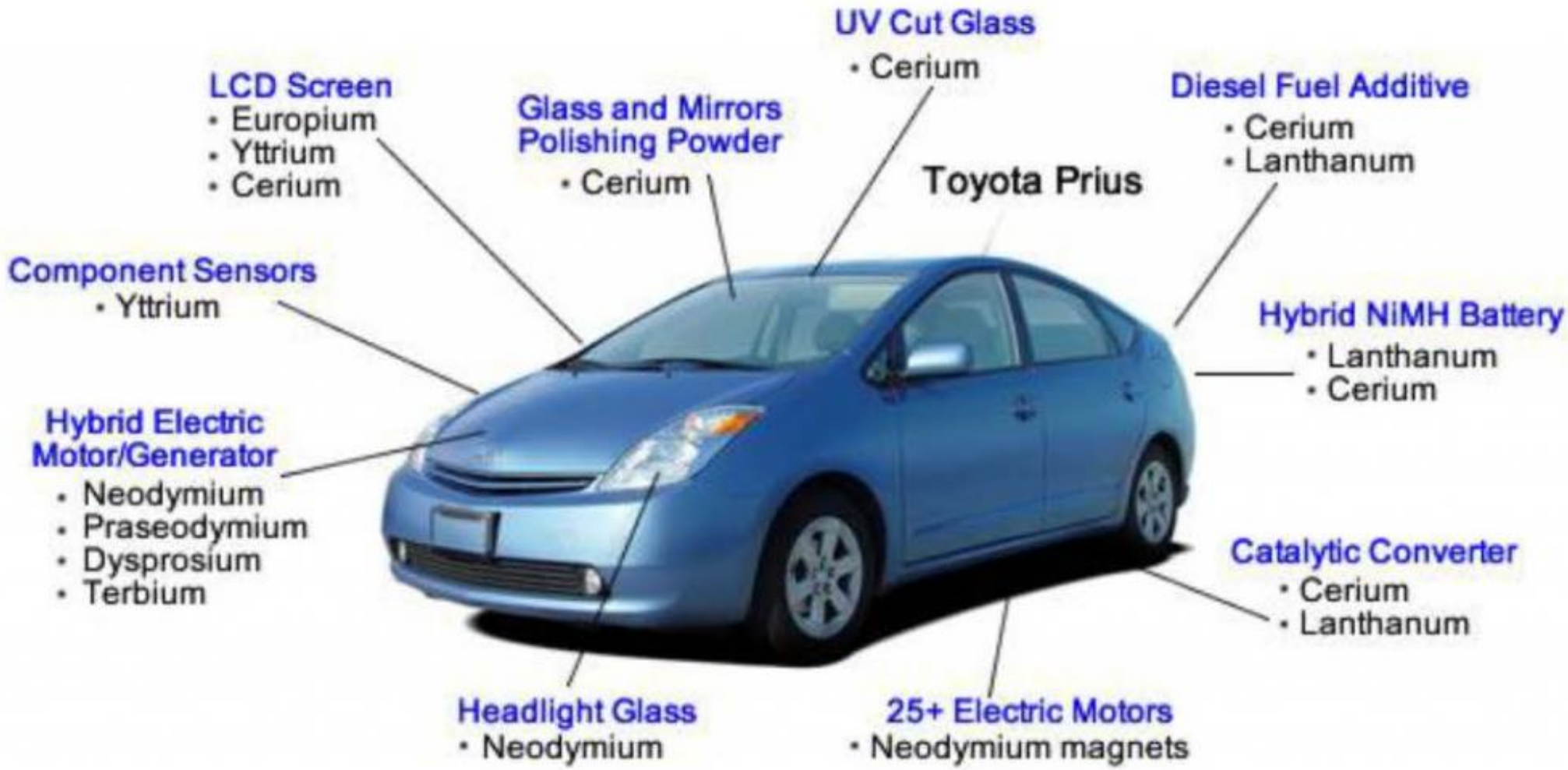


Figure 4. *Abundance (atom fraction) of the chemical elements in Earth's upper continental crust as a function of atomic number. Many of the elements are classified into (partially overlapping) categories: (1) rock-forming elements (major elements in green field and minor elements in light green field); (2) rare earth elements (lanthanides, La–Lu, and Y; labeled in blue); (3) major industrial metals (global production ≥3×10^7 kg/year; labeled in bold); (4) precious metals (italic); and (5) the nine rarest "metals"—the six platinum group elements plus Au, Re, and Te (a metalloid).*

Rare Earth Elements in Toyota's Prius



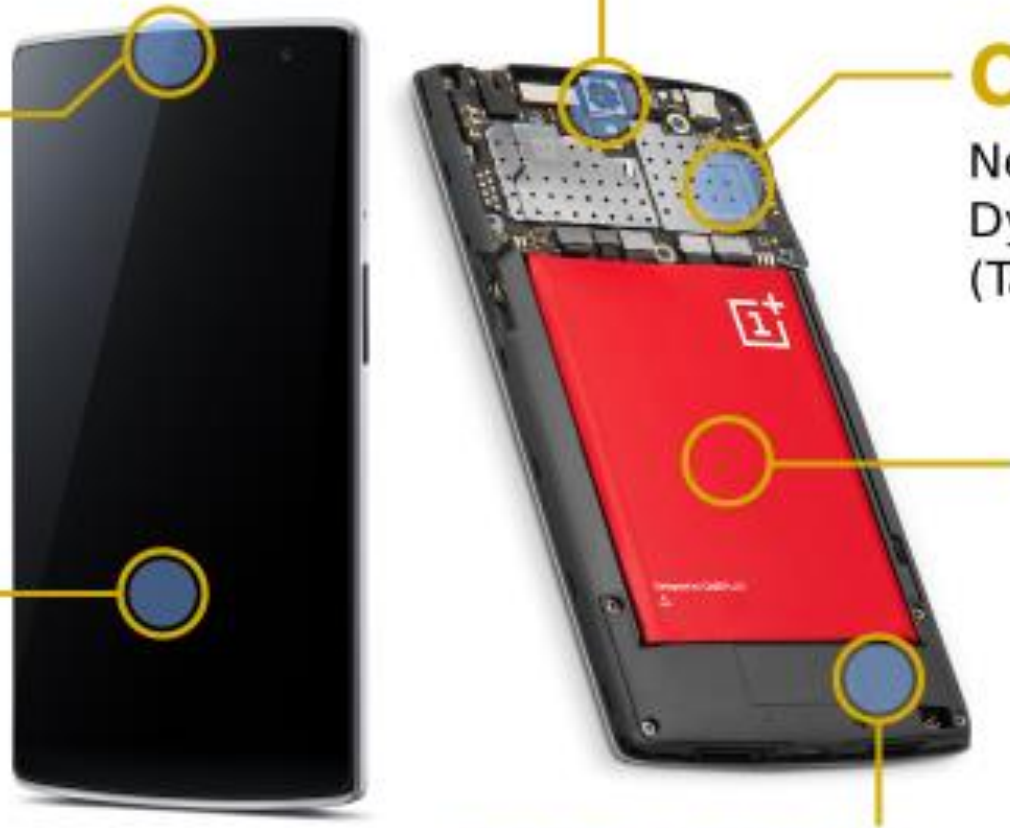
Lara-Curzio E. USEA Seminar. August 9, 2018

http://www.insightsonindia.com

http://cen.acs.org/

Rare Earth Elements in Smartphones

REE in different parts of a phone. Other scarce elements indicated within brackets.



CAMERA

Lanthanum
Yttrium

CIRCUITRY

Neodymium
Dysprosium
(Tantalum)

SPEAKERS

Praseodymium
Neodymium
Gadolinium

BATTERY

Lanthanum
Praseodymium
(Lithium)

COLOUR SCREEN

Yttrium
Europium
Gadolinium
Terbium

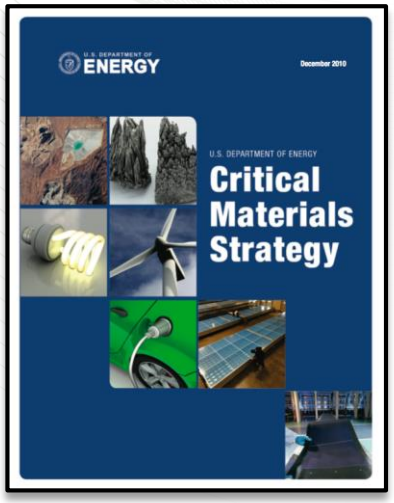
VIBRATION

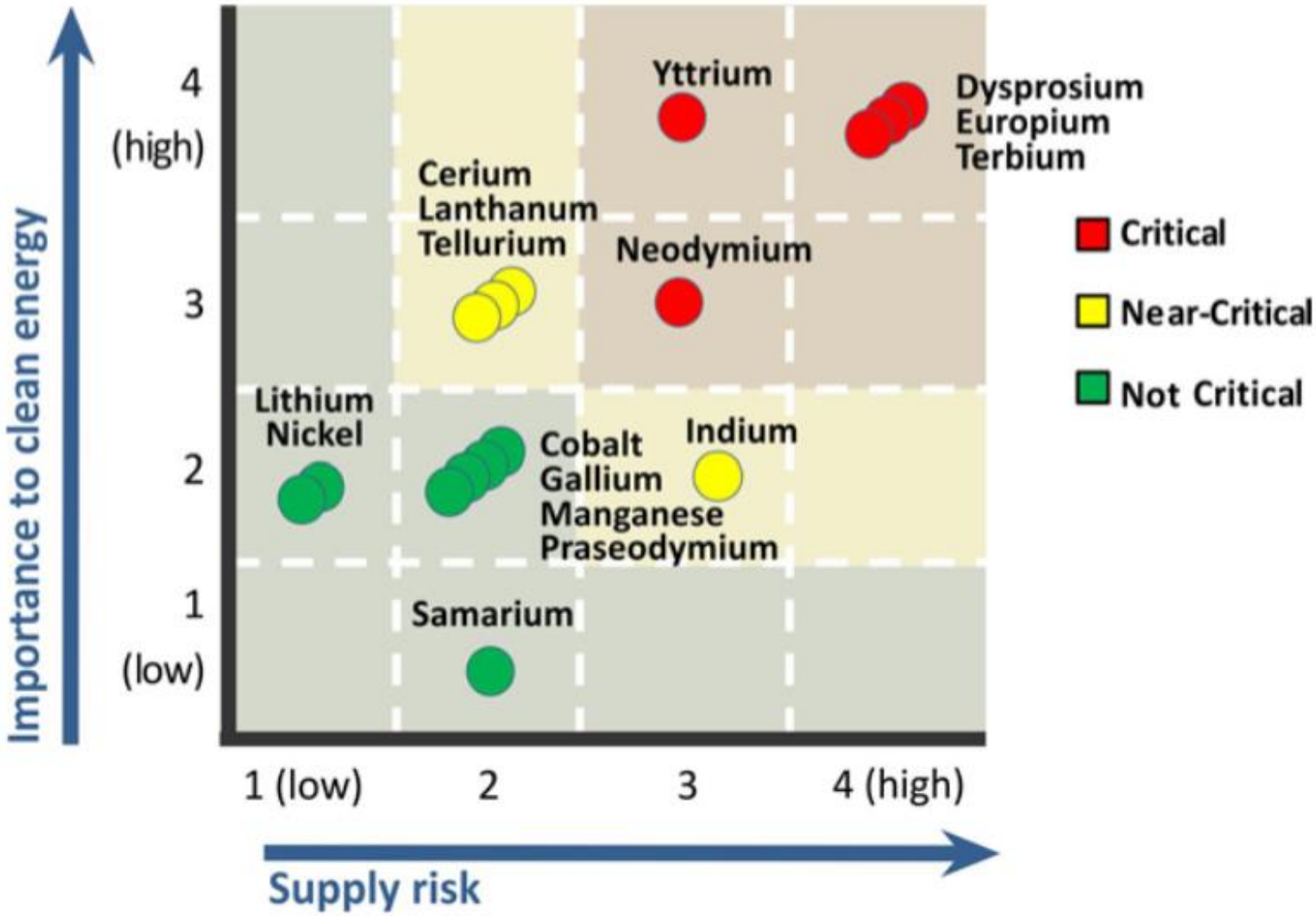
Neodymium
(Tungsten)

Lara-Curzio E. USEA Seminar. August 9, 2018
http://www.insightsonindia.com

http://cen.acs.org/

DOE's Critical Materials Strategy (2010)





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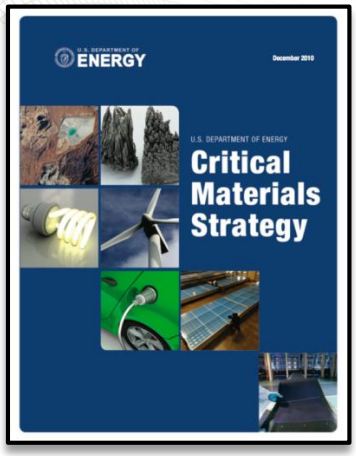


UPSTREAM — DOWNSTREAM

Extraction | Processing | Components | End-Use Technologies | Recycling and Reuse

Risks and Constraints

- Reserve Locations
- Export Quotas
- Environmental Impacts
- Geopolitical Volatility
- Market Volatility
- Capital Requirements
- Supplier Partnerships
- Technical Capability
- Economic Viability
- Intellectual Property
- Demand Uncertainty
- Technical Barriers
- Cost Effectiveness
- Waste Regulations

Opportunities

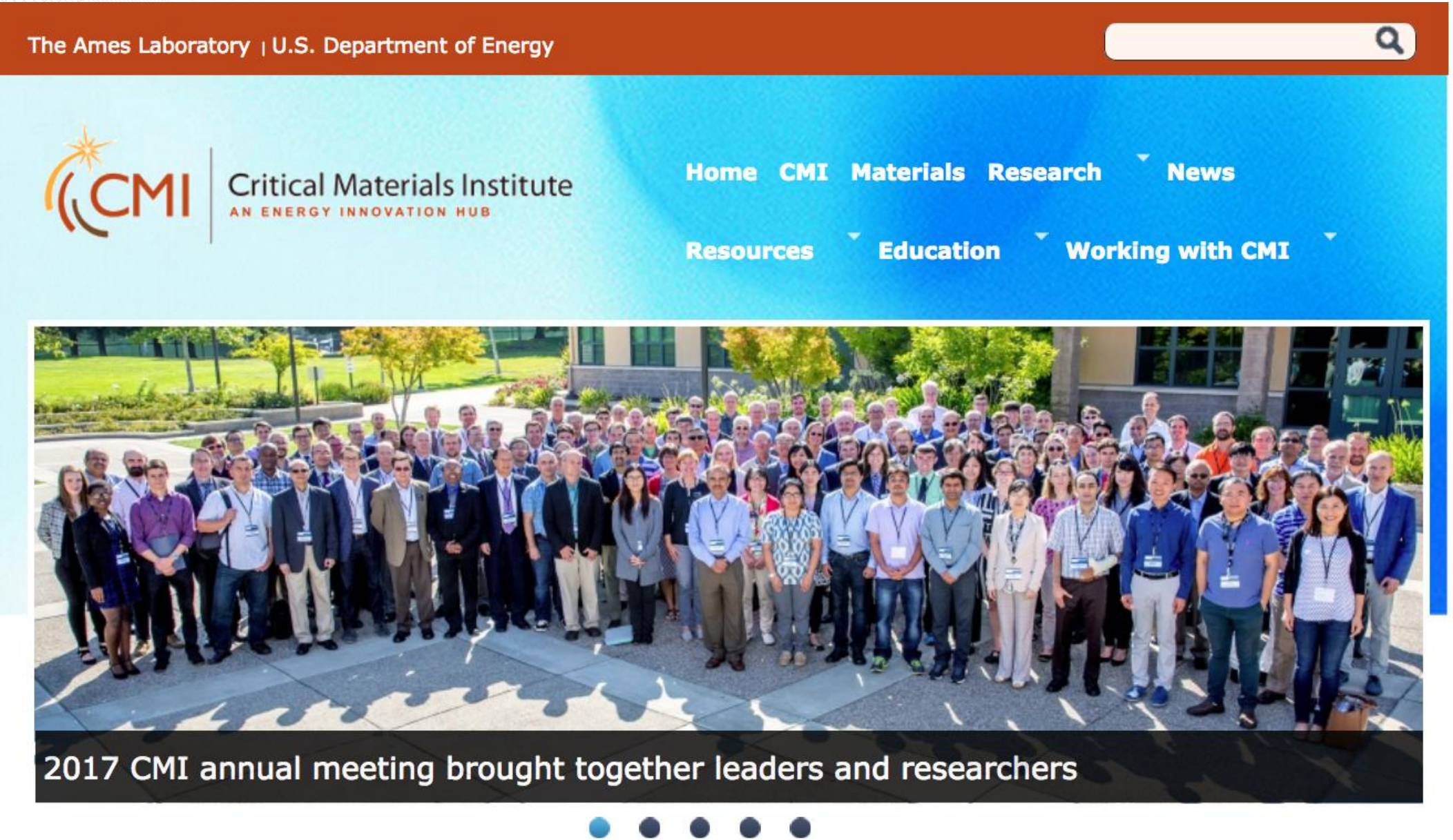
- New Mining and Separation Technologies
- Efficient, Less Toxic Processing
- Substitutes
- Recycling Technologies
- Design for Recycling

- Improved Permitting
- Stockpiles
- Recycling Policies

Program and Policy Directions

Integrated Research and Development
Education and Workforce Training
Enhanced Data and Information Gathering
Financial Assistance
Diplomacy

DOE's Critical Materials Institute (CMI)



DOE's Critical Materials Institute (CMI)

The Critical Materials Institute is a partnership of industries, universities and national laboratories that seeks ways to:

- diversify and expand the availability of these materials throughout their supply chain
- to reduce demand by identifying substitutes for critical materials, and
- to reduce wastes by increasing the efficiency of manufacturing and recycling.

After three years, CMI has issued 47 invention disclosures, 13 patent applications, two technology licenses, two open-source software packages, and over 80 refereed publications. Industrial collaborators are incorporating these accomplishments in their products and processes.

DOE's Critical Materials Institute: Team

U.S. DEPARTMENT OF
ENERGY

Public-Private Partnerships involving the National Laboratories

The Critical Materials Institute is an example of a successful **public-private partnership**, involving the DOE National Laboratories, that is developing innovative solutions to maintain our nation's economic growth and national security.

Rare Earth Elements from Coal and Coal by-Products

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U.S. DEPARTMENT OF ENERGY

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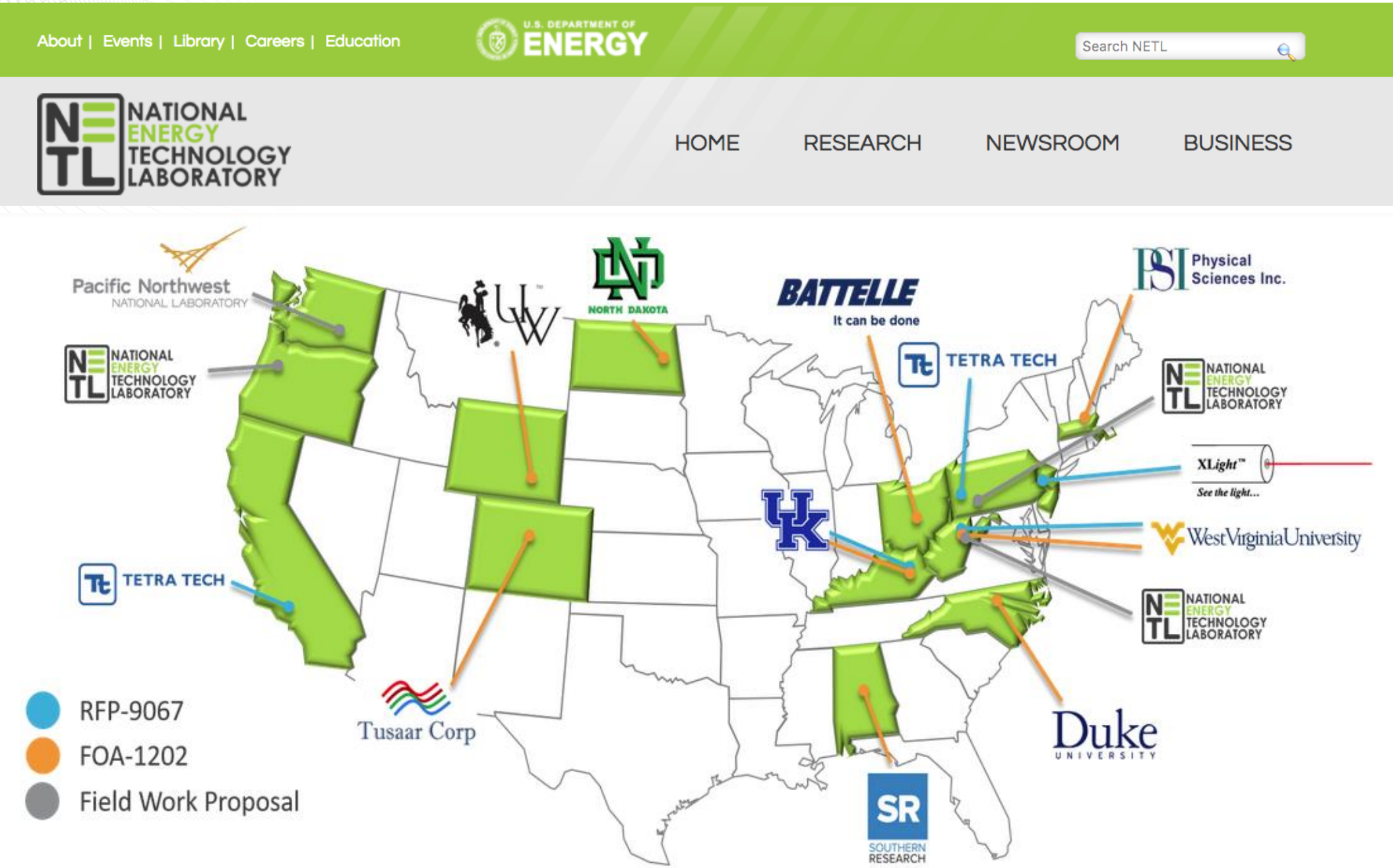
NATIONAL ENERGY TECHNOLOGY LABORATORY

HOME RESEARCH NEWSROOM BUSINESS

Comprising 17 elements from the periodic table, the group known as rare earth elements (REEs) provide significant value to our national security, energy independence, environmental future, and economic growth. REEs are important elements used in high-technology products such as catalysts, cell phones, hard drives, hybrid engines, lasers, magnets, medical devices, televisions, and other applications. The development of an economically competitive domestic supply of REEs will help to maintain our nation's economic growth and national security.

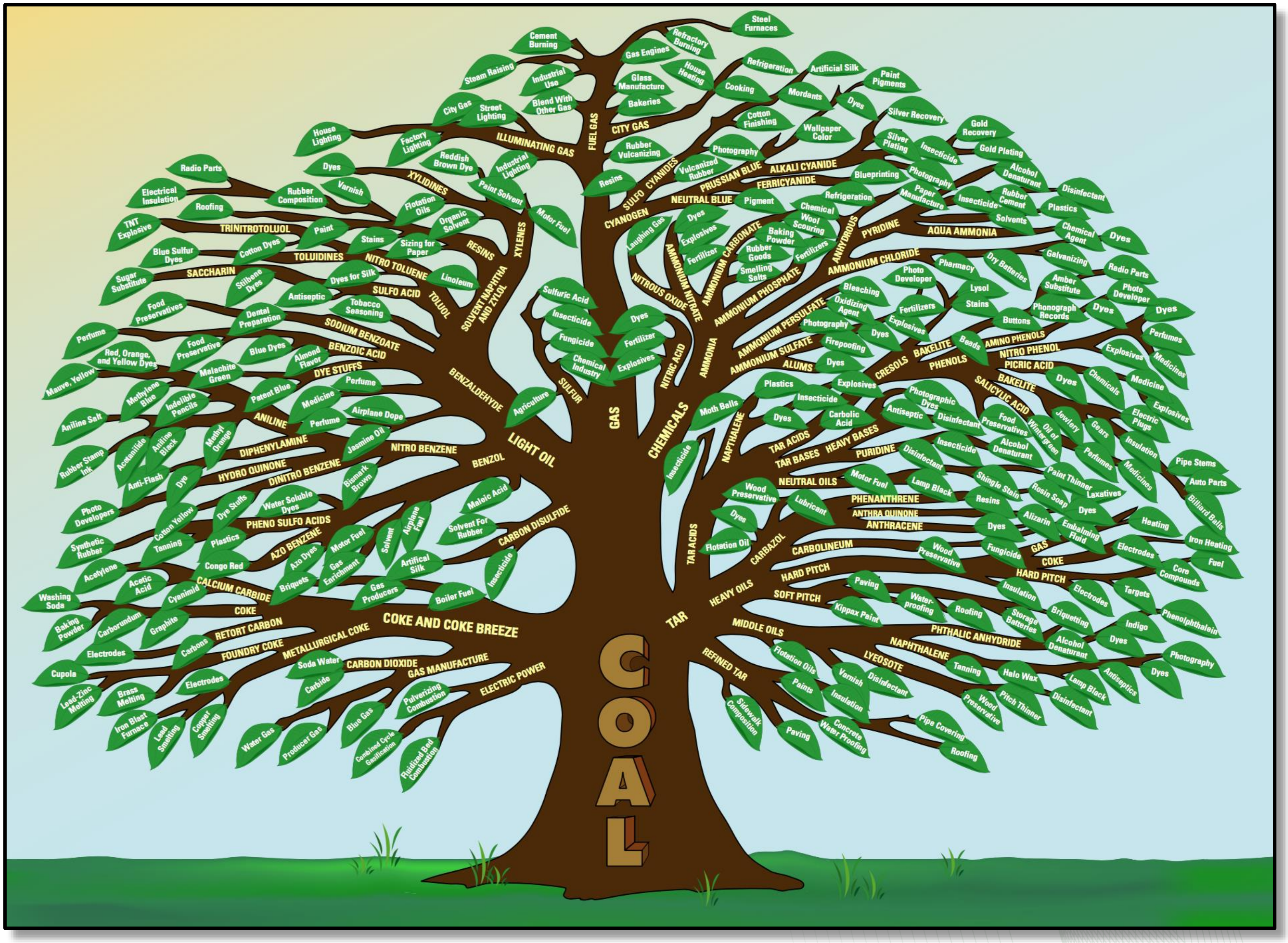
America's vast coal resources contain quantities of REEs that offer the potential to reduce our dependence on others for these critical materials and create new industries in regions where coal has played an important economic role. To support these needs, NETL has created a collaborative R&D program to develop technologies for the recovery of REEs from Coal and Coal By-Products.

Rare Earth Elements from Coal and Coal by-Products



Using Coal as a Precursor for High Value-Added Products

The Idea of Using Coal as a Precursor for Products is not New



Coal—A Complex Natural Resource
U.S. Geological Survey Circular 1143 (2002)

OAK RIDGE National Laboratory

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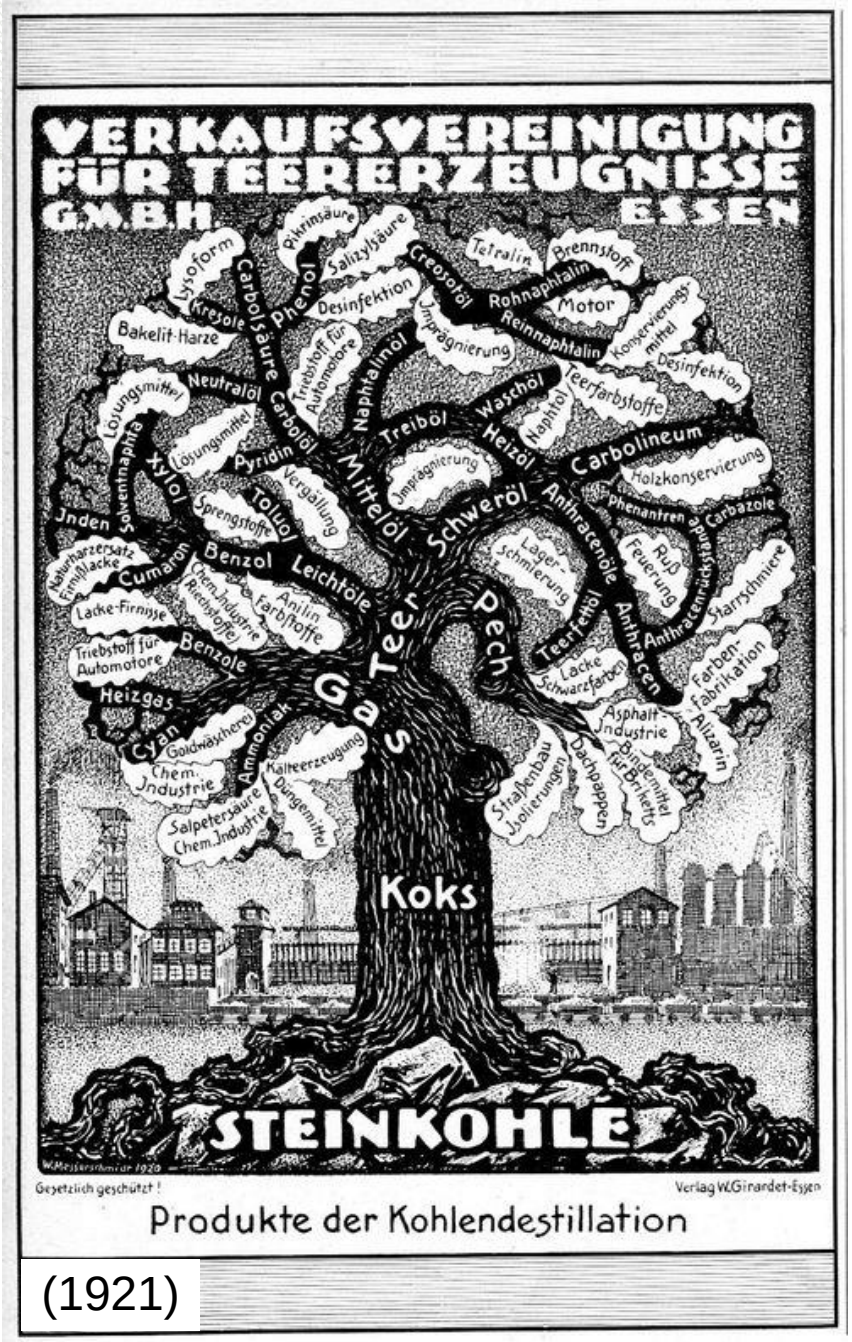
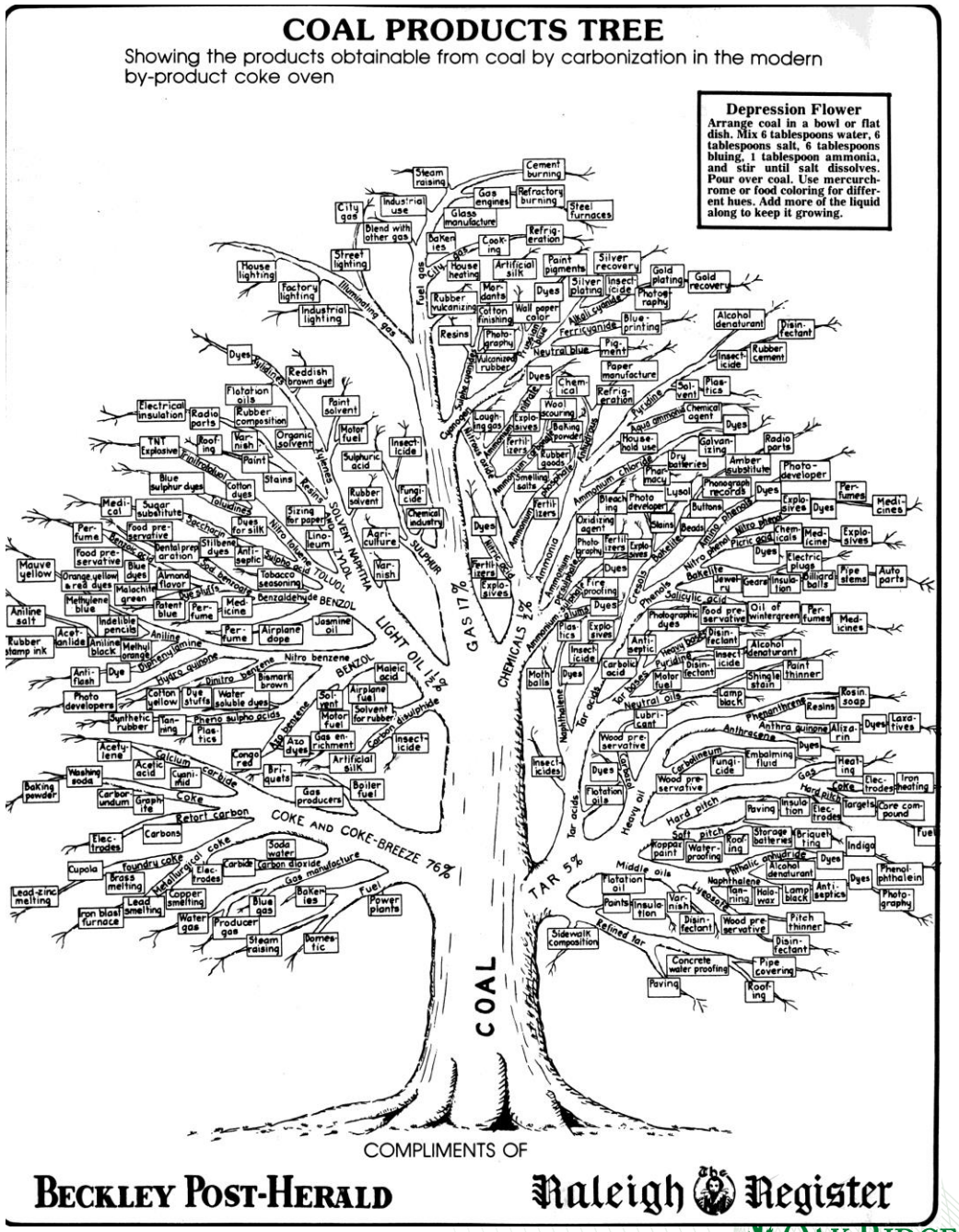


(1921)



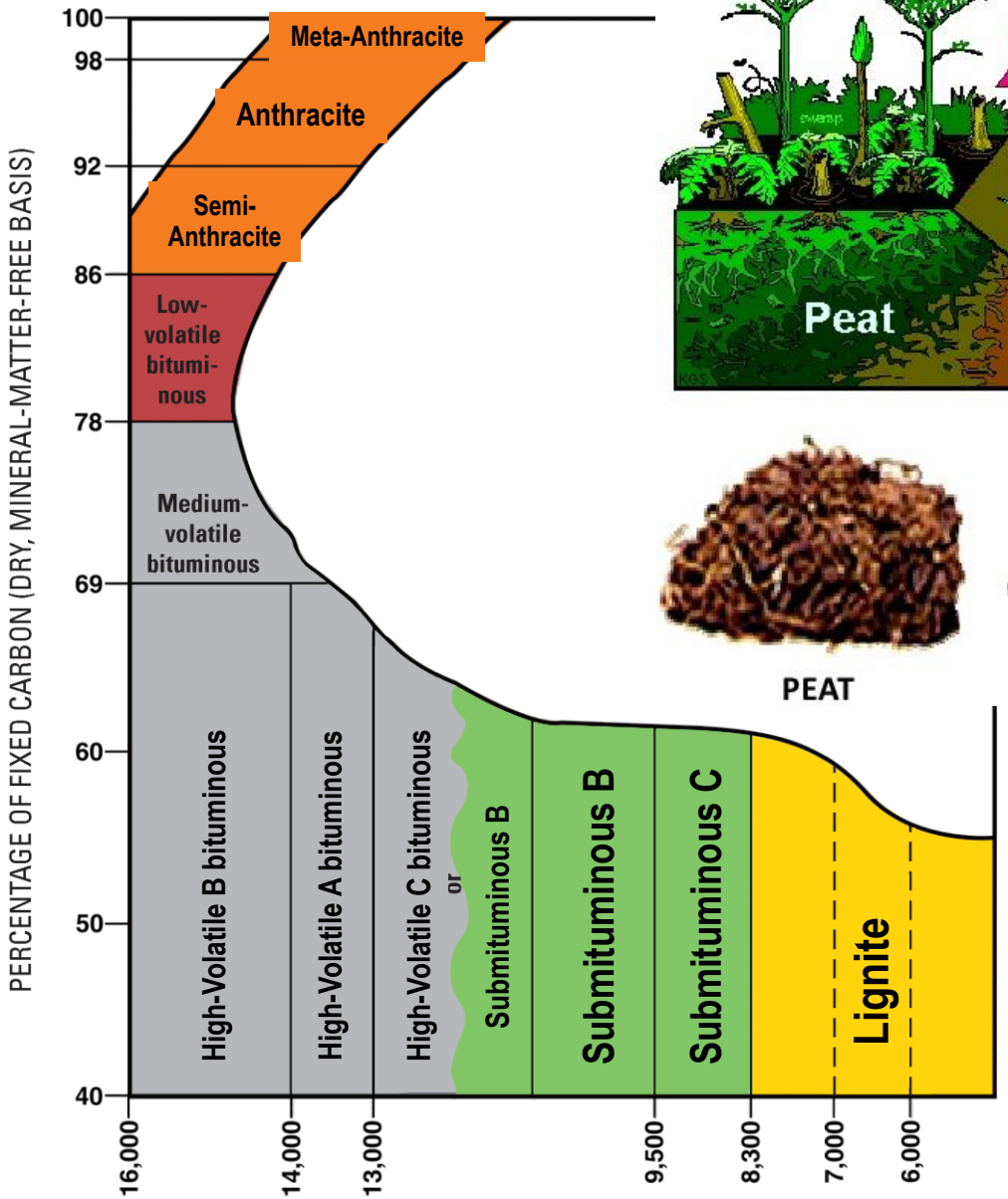
What is new are the capabilities and expertise at National Laboratories and Universities that were not available 15 years ago!!

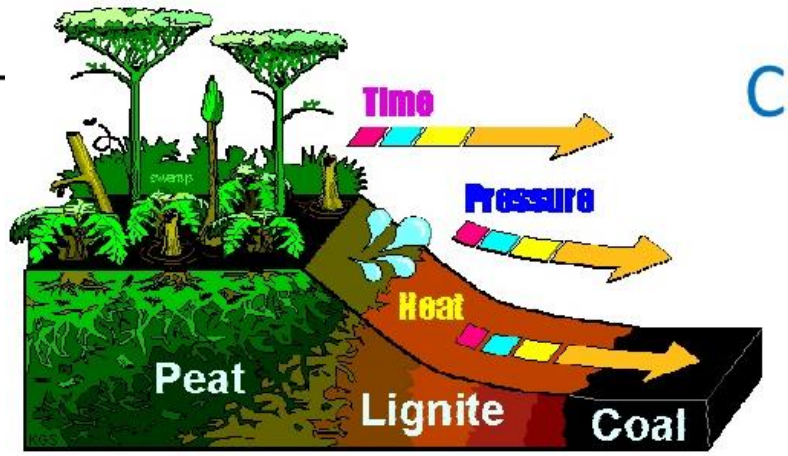
- World's fastest supercomputers
- Electron microscopes capable of imaging single atoms
- High-throughput characterization
- Light and neutron sources

These tools could be used to develop optimized physical and chemical separation processes in a shorter period of time

Not all wines are the same!

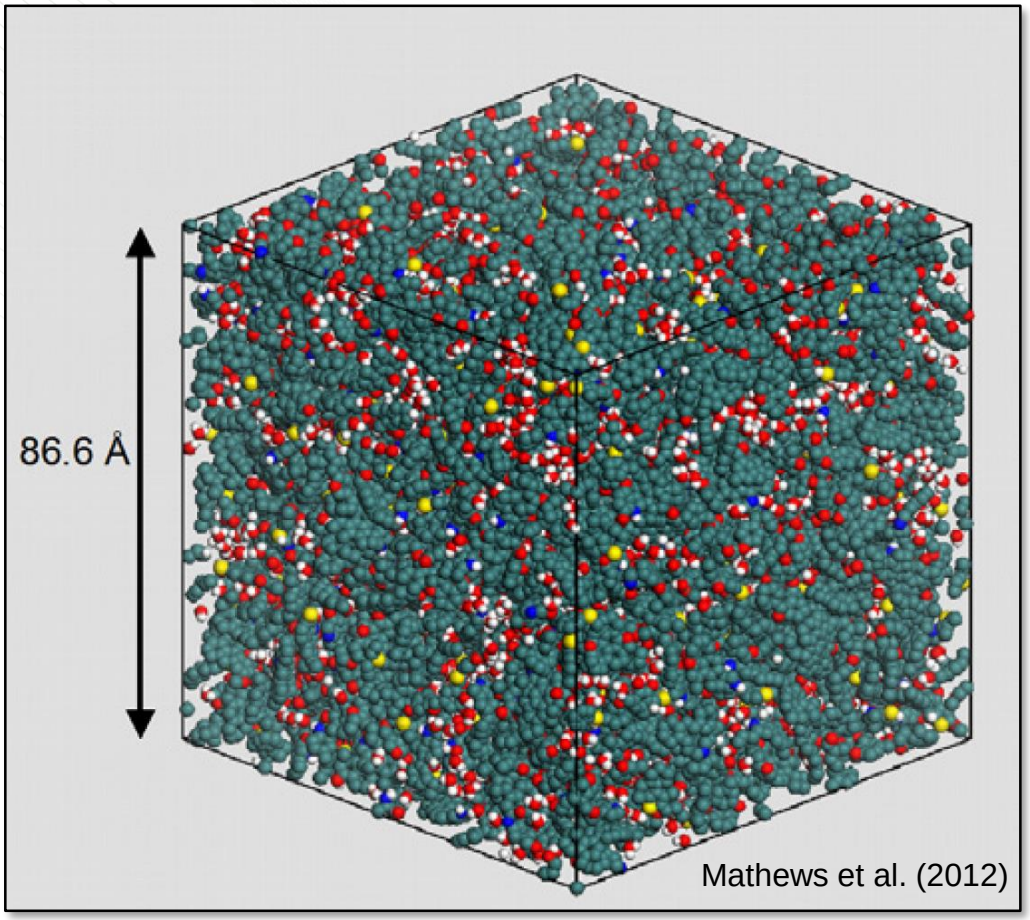
Not all coals are the same!





Coal – Stages of Formation

The Molecular Structure of Coal
A Genomic Approach



Mathews et al. (2012)

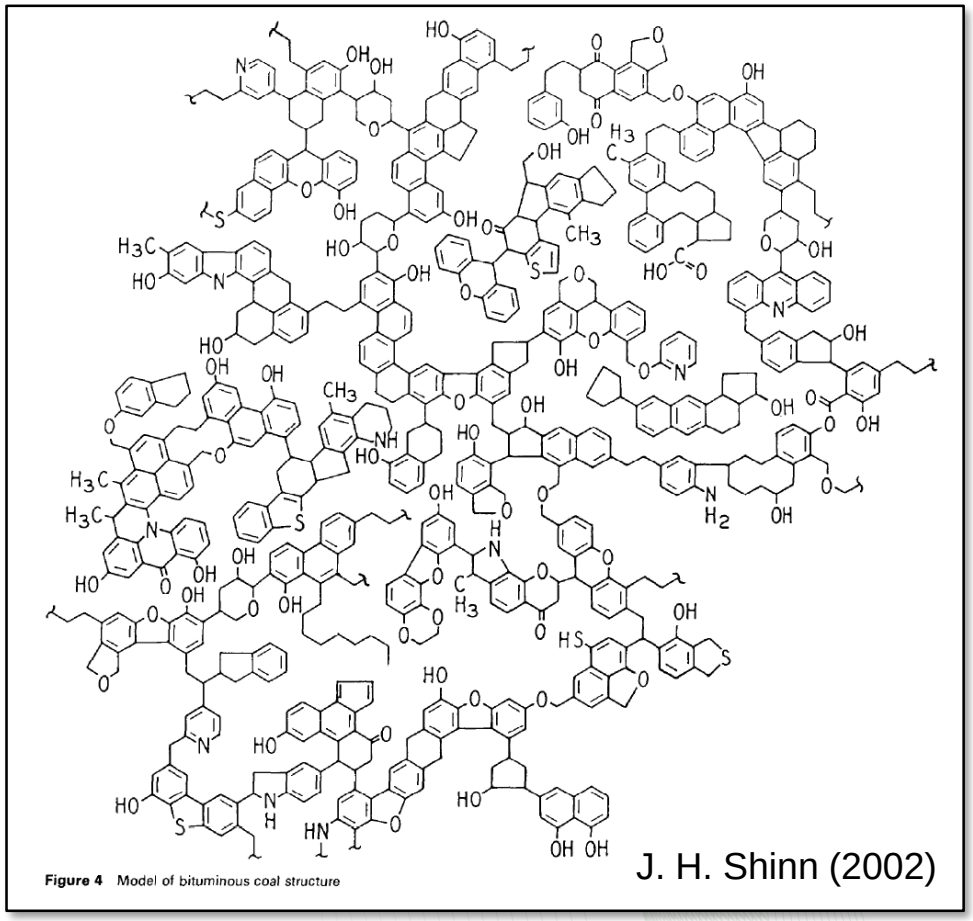
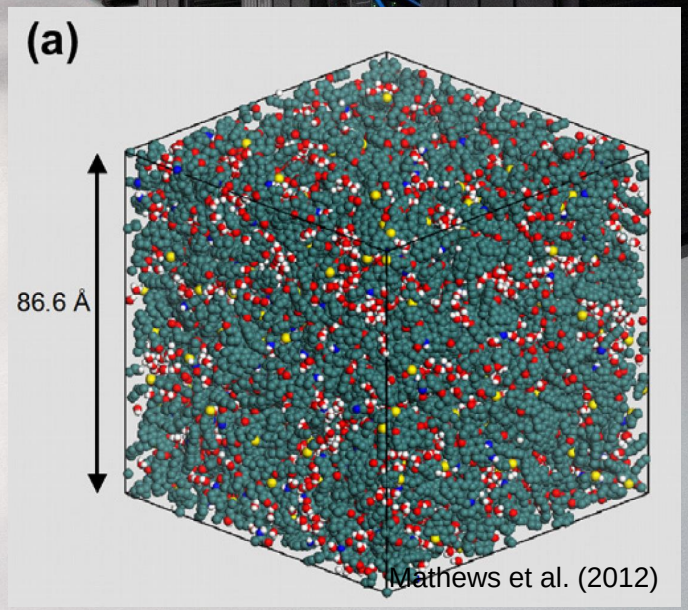


Figure 4 Model of bituminous coal structure

J. H. Shinn (2002)

HPC Applied to Coal Processing: Finding the Most Energetically Favorable Pathways for Breaking down Coal into Products and Precursors



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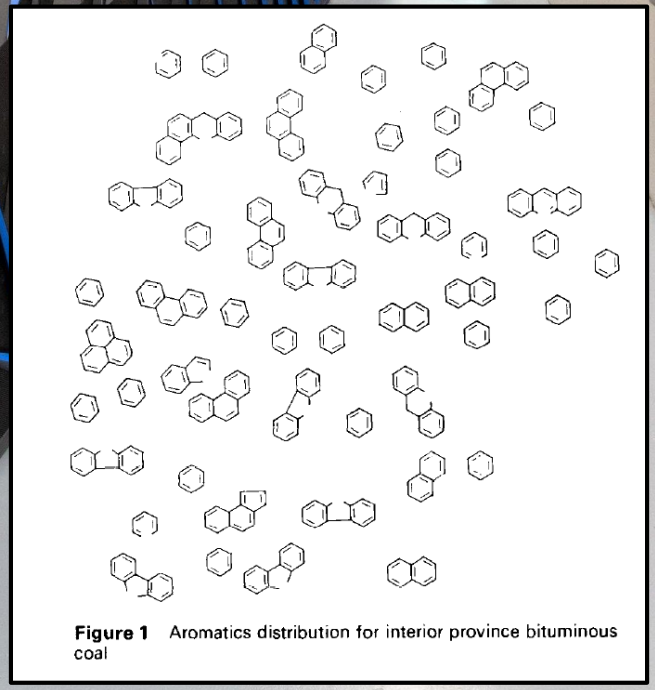
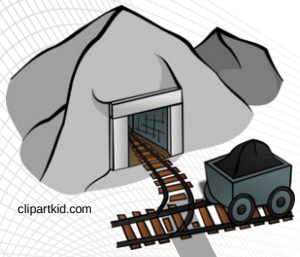
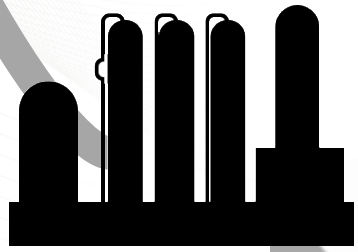


Figure 1 Aromatics distribution for interior province bituminous coal

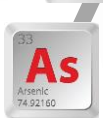
Coal as a Precursor for High Value-Added Products



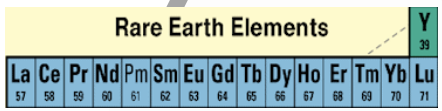
Coal Mine



Coal “Refinery”



water



Lara-Curzio et al. (2016)

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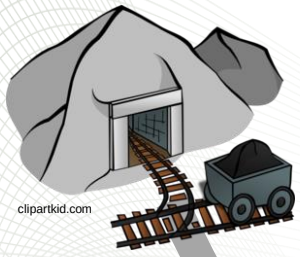

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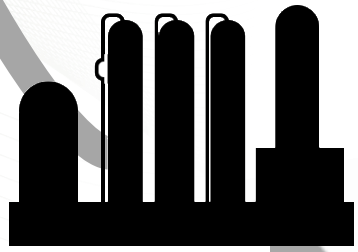
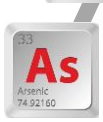


Coal “Refinery”

chemicals



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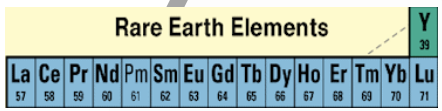

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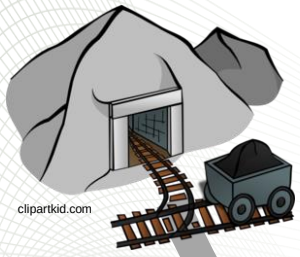

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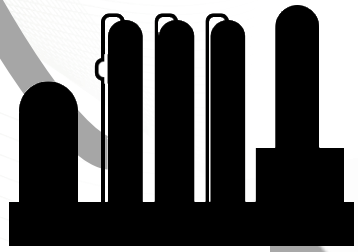

Coal “Refinery”

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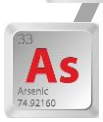
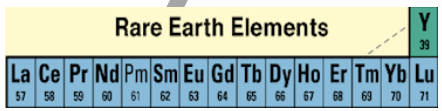


water

activated carbon



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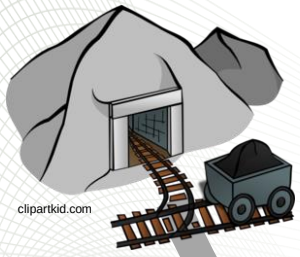

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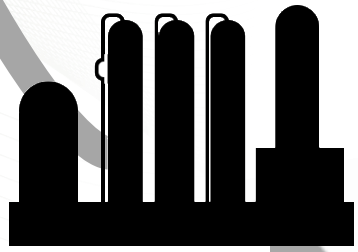

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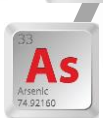
chemicals



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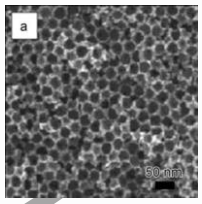
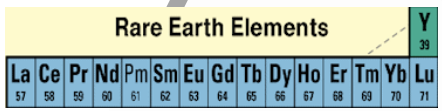
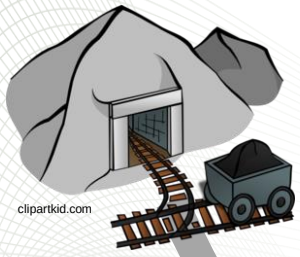


mesoporous carbon



Lara-Curzio et al. (2016)

Coal as a Precursor for High Value-Added Products



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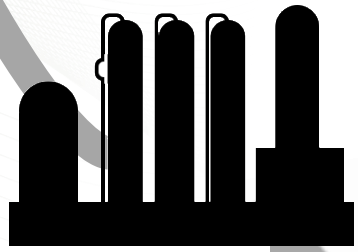
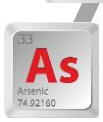


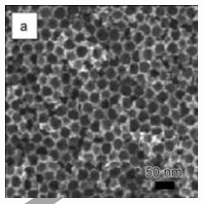
Coal “Refinery”

chemicals



water

activated carbon



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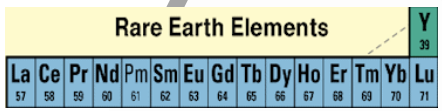

metallurgical coal

Lara-Curzio et al. (2016)

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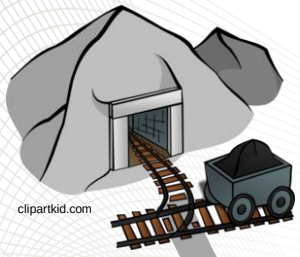

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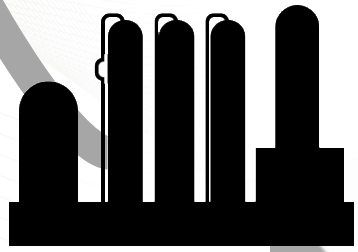

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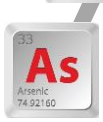

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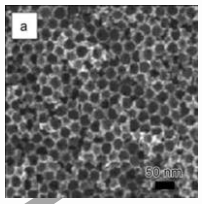

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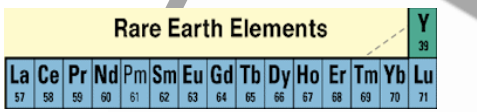


metallurgical coal

carbon fibers

Lara-Curzio et al. (2016)

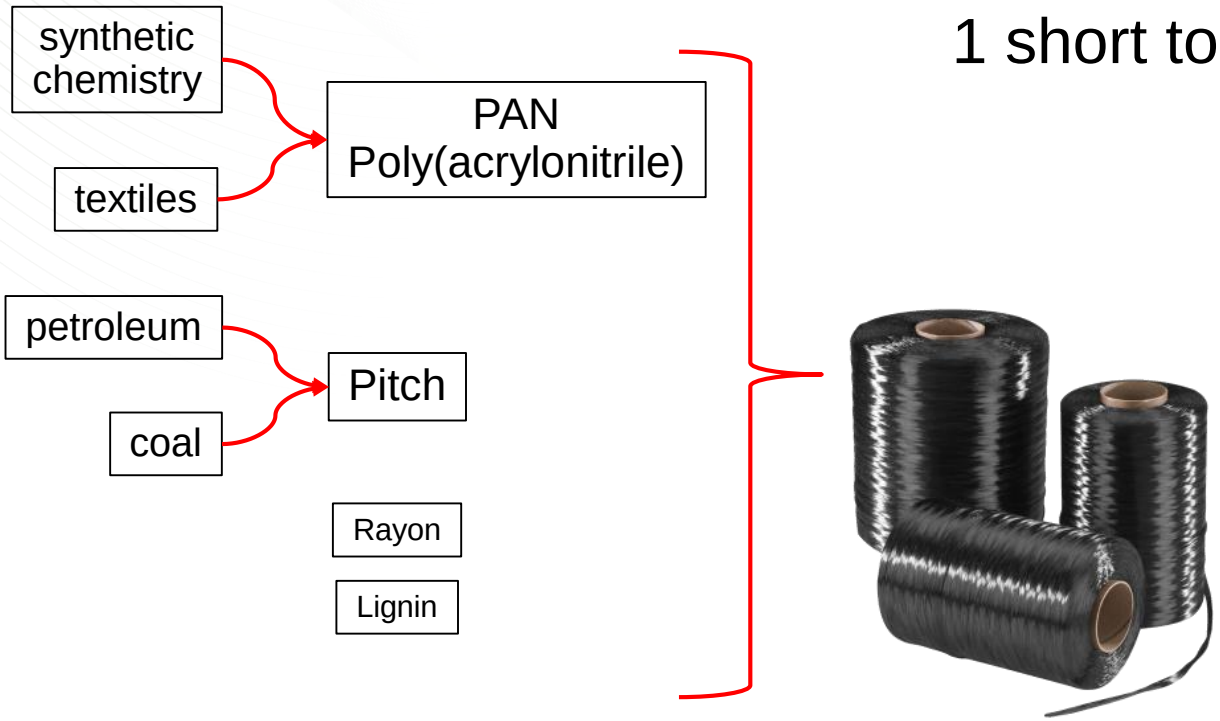
Carbon Fibers

1 short ton of coal ~ $50

value-added

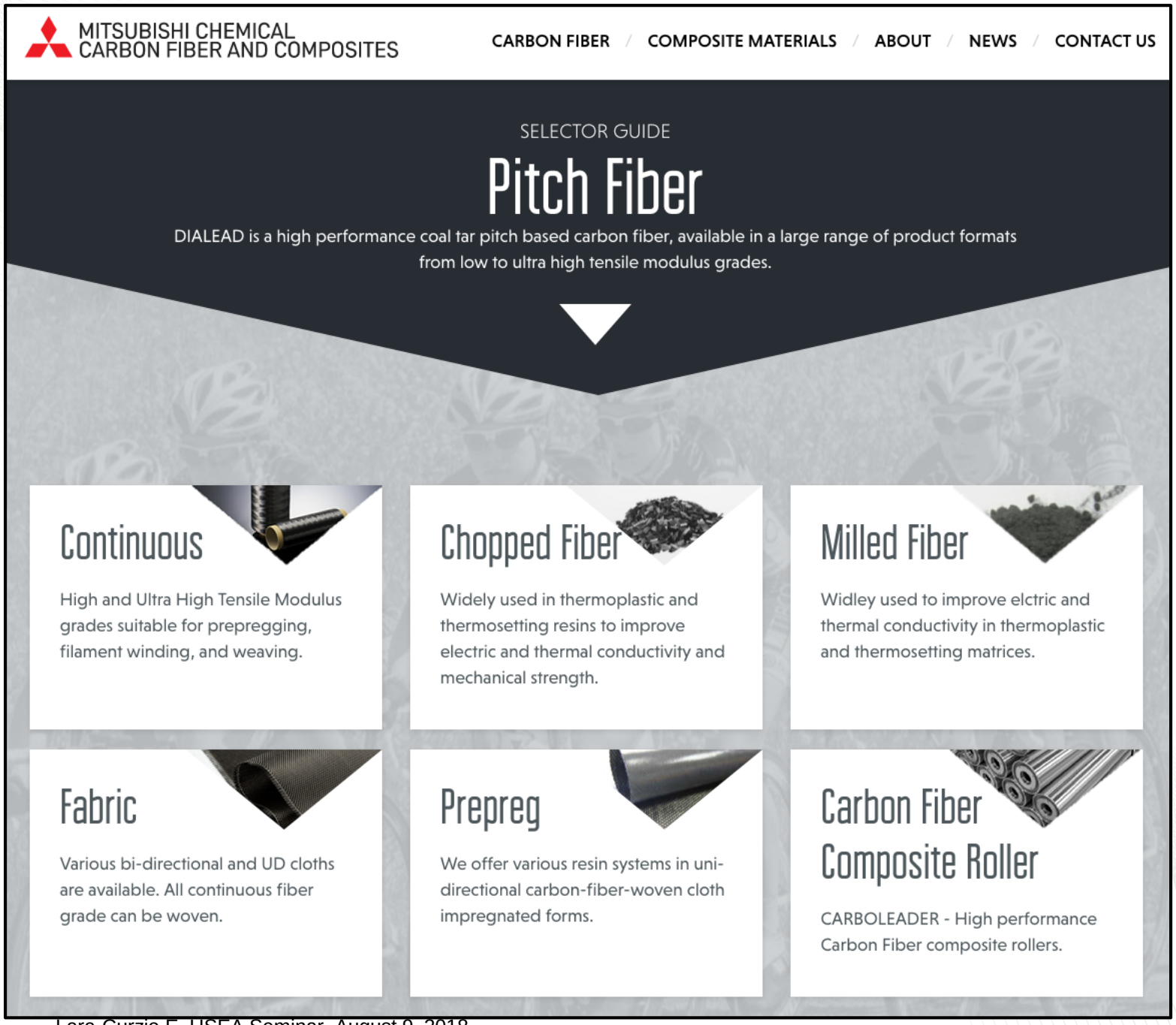
1 short ton of carbon fibers ~ $18,000 ($20/kg)

Precursors

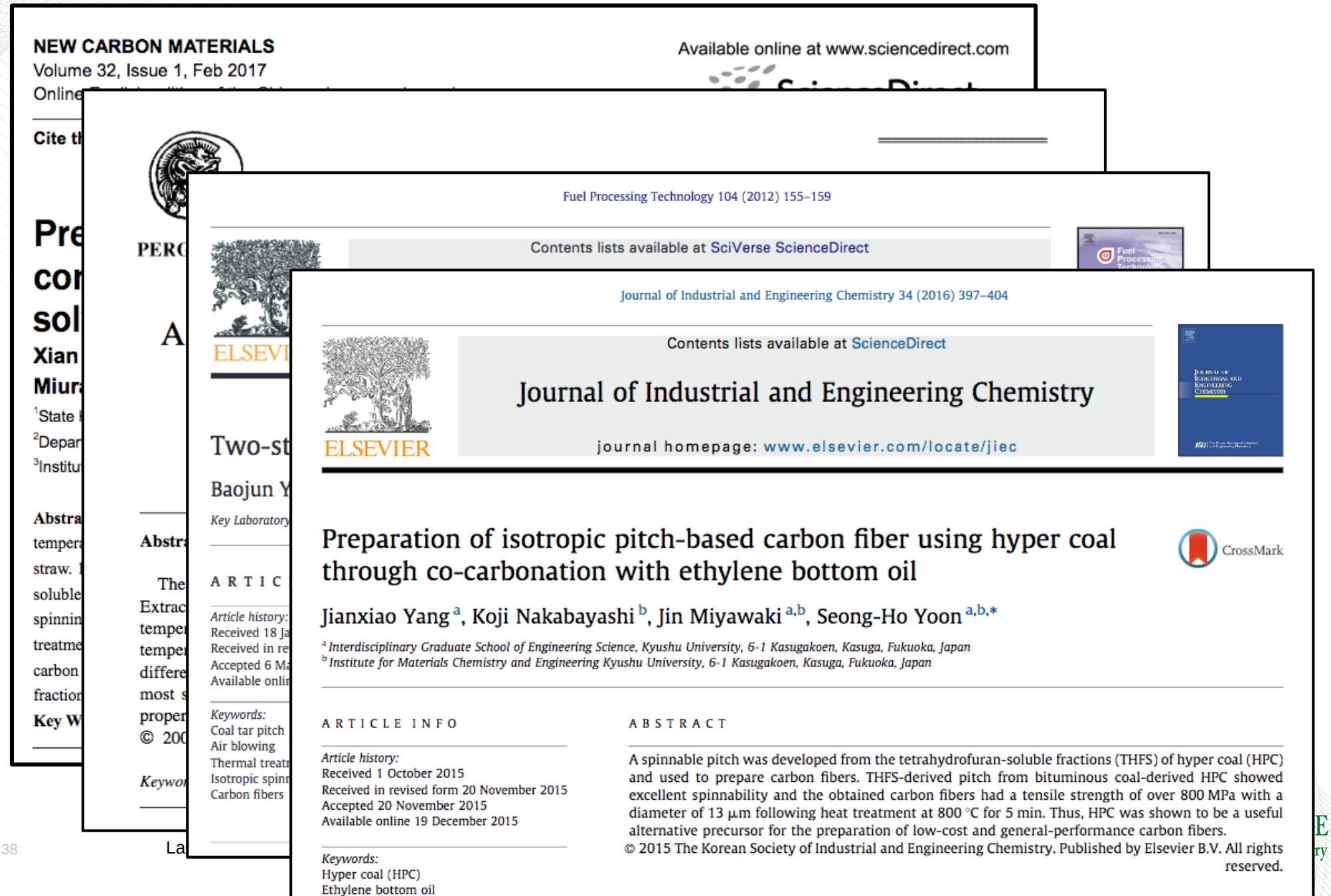


ORNL is developing technologies to reduce the cost of making carbon fibers to $10-$14/kg, which would enable widespread utilization in automobiles and trucks

Coal-derived Carbon Fibers have been commercialized



Several groups are trying to develop new coal-derived Carbon Fibers



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Journal of Industrial and Engineering Chemistry 34 (2016) 397–404

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/jiec

ELSEVIER

Preparation of isotropic pitch-based carbon fiber using hyper coal through co-carbonation with ethylene bottom oil

Jianxiao Yang [a], Koji Nakabayashi [b], Jin Miyawaki [a,b], Seong-Ho Yoon [a,b,*]

[a] Interdisciplinary Graduate School of Engineering Science, Kyushu University, 6-1 Kasugakoen, Kasuga, Fukuoka, Japan
[b] Institute for Materials Chemistry and Engineering Kyushu University, 6-1 Kasugakoen, Kasuga, Fukuoka, Japan

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Hyper coal (HPC)
Ethylene bottom oil

ABSTRACT

A spinnable pitch was developed from the tetrahydrofuran-soluble fractions (THFS) of hyper coal (HPC) and used to prepare carbon fibers. THFS-derived pitch from bituminous coal-derived HPC showed excellent spinnability and the obtained carbon fibers had a tensile strength of over 800 MPa with a diameter of 13 μm following heat treatment at 800 °C for 5 min. Thus, HPC was shown to be a useful alternative precursor for the preparation of low-cost and general-performance carbon fibers.

Carbon Fiber Composites are widely used in Aerospace Technologies

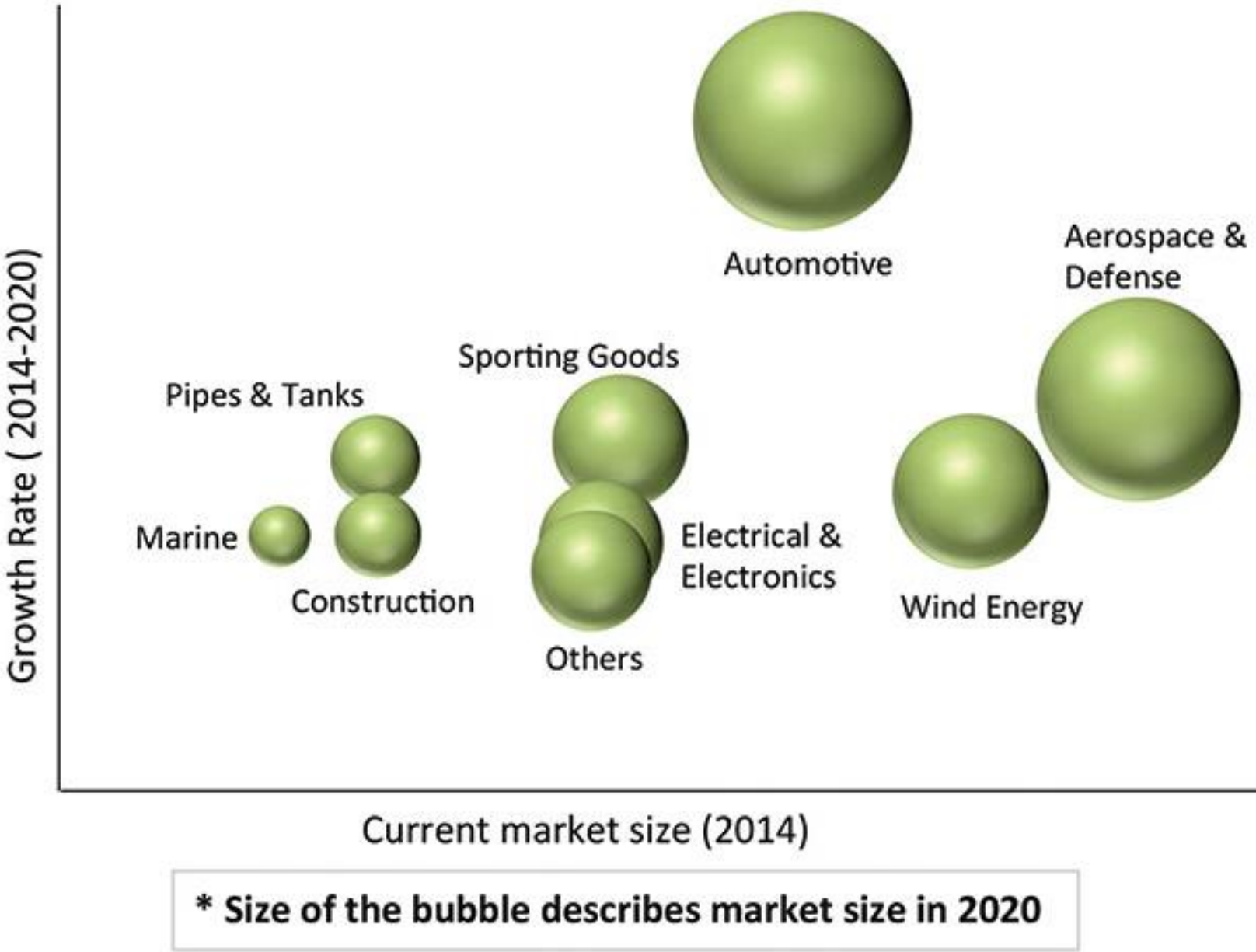
Boeing 787 fuselage

OAK RIDGE National Laboratory

Carbon fiber composites have started to be used in high volume in automobiles: BMW i3: mass-produced carbon fiber cars finally come of age

Lara-Curzio et al. (2016)

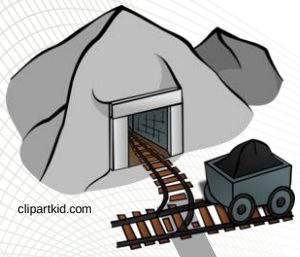
Potential of Carbon Fiber Composites Market Growth



Lara-Curzio et al. (2016)

Lara-Curzio E. USEA Seminar. August 9, 2018
www.marketsandmarkets.com.

Coal as a Precursor for High Value-Added Products



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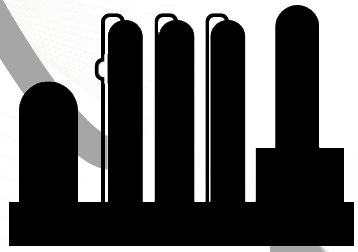
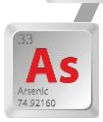


Coal “Refinery”

chemicals



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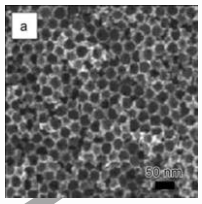
activated carbon



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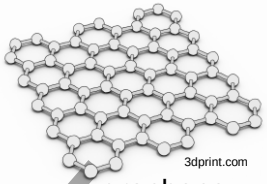
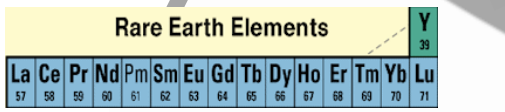
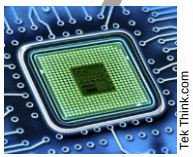


graphene



metallurgical coal

carbon fibers



electronic devices including photovoltaics

Lara-Curzio et al. (2016)

Coal can be used to fabricate Photovoltaics

Carbon Emerges as New Solar

Nanocarbon-Based Photovoltaics

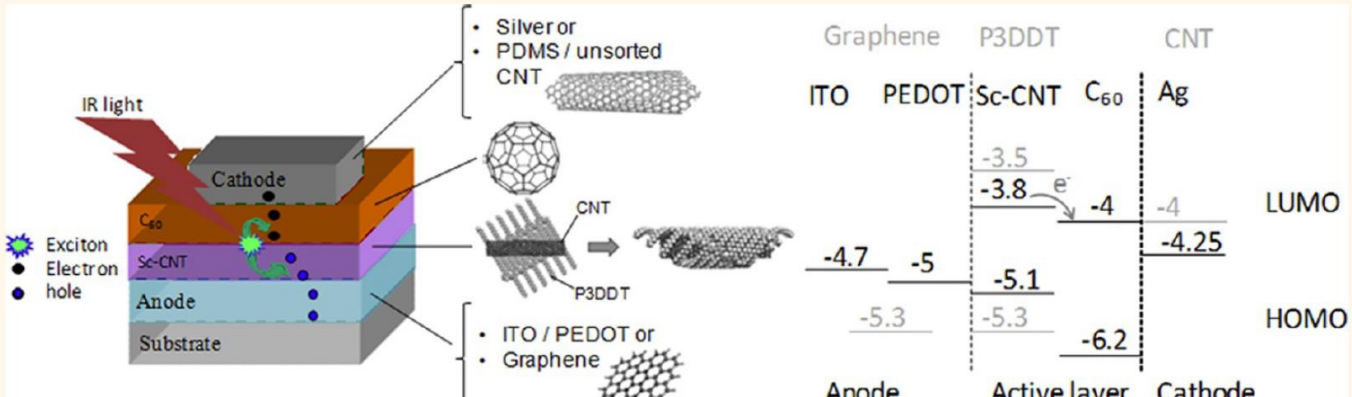
ARTICLE

Evaluation of Solution-Processable Carbon-Based Electrodes for All-Carbon Solar Cells

Marc P. Ramuz,[†,‡] Michael Vosgueritchian,[†,‡] Peng Wei,[†] Chenggong Wang,[§] Yongli Gao,[§] Yingpeng Wu,[⊥] Yongsheng Chen,[⊥] and Zhenan Bao[†,*]

[†]Department of Chemical Engineering, Stanford University, 381 North-South Mall, Stanford, California 94305, United States, [§]Department of Physics and Astrophysics, University of Rochester, Rochester, New York 14627, United States, and [⊥]Institute of Polymer Chemistry, Nankai University, Weijin Road 94, Tianjin 300071, China. [‡]These authors contributed equally to this work.

ABSTRACT



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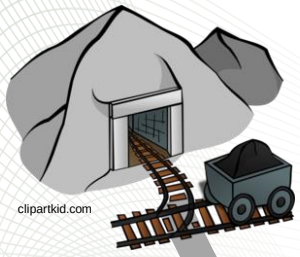

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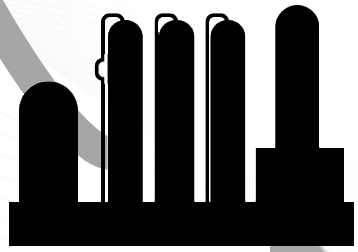
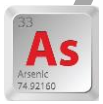


Coal “Refinery”

chemicals



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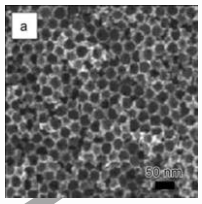

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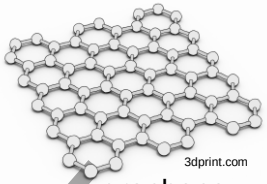

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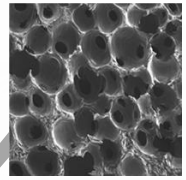
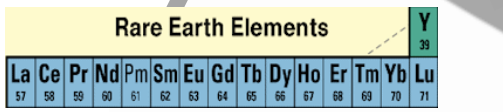


thermal conduction

thermal insulation



metallurgical coal

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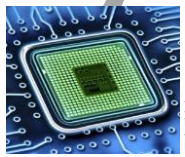

electronic devices including photovoltaics

Lara-Curzio et al. (2016)

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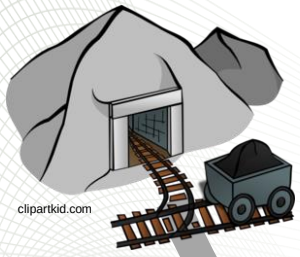

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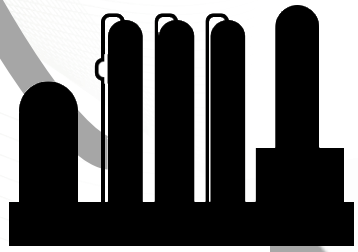

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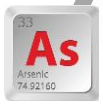

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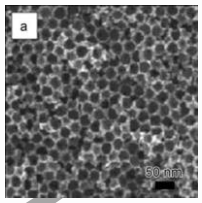

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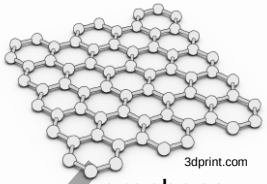
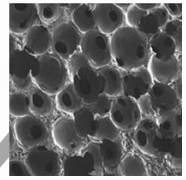


graphene

thermal management



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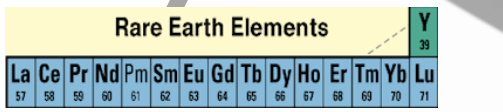

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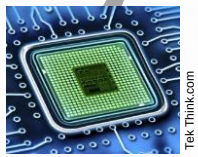
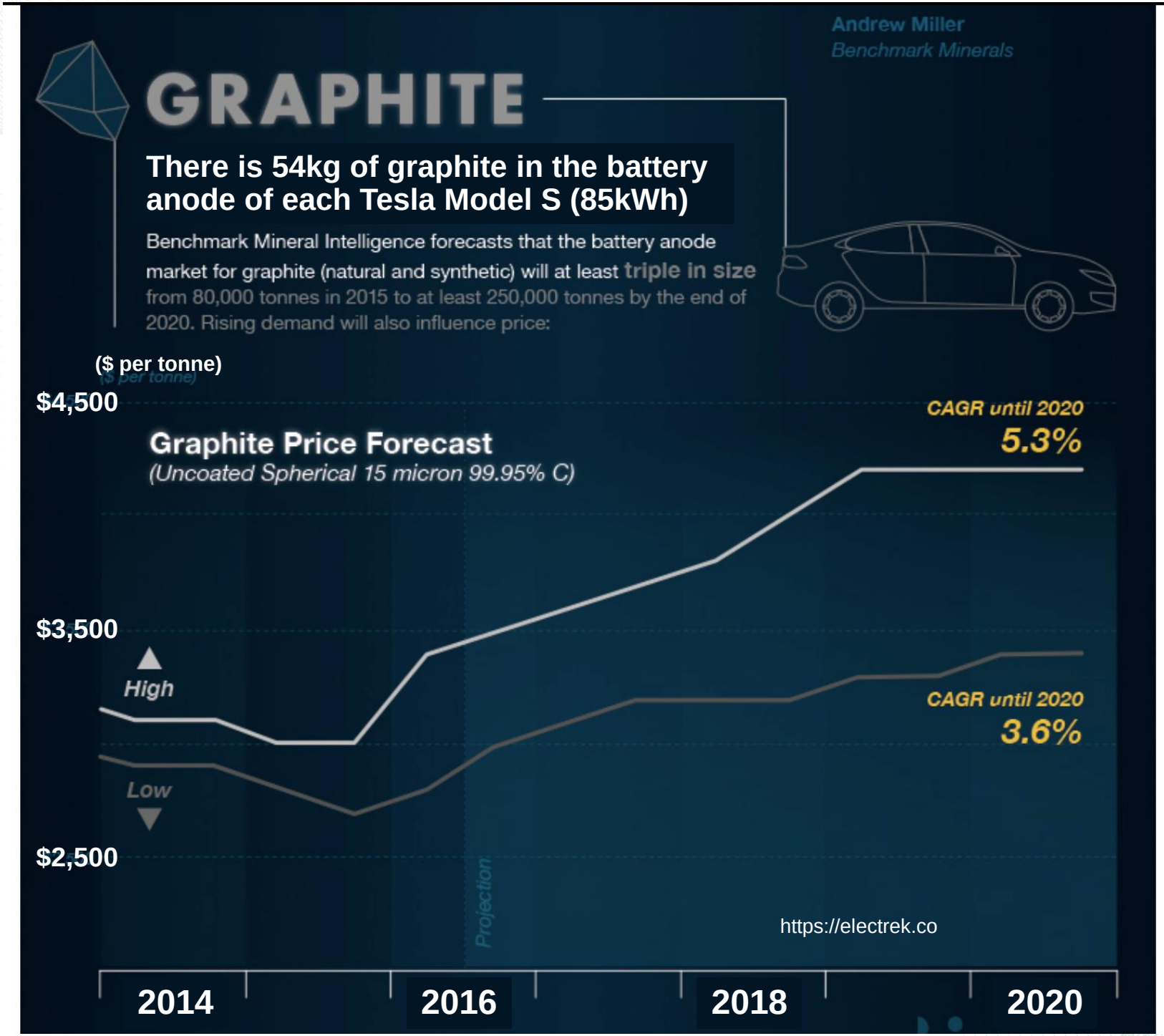


electronic devices including photovoltaics

Electrodes for Li-ion batteries and supercapacitors

Lara-Curzio et al. (2016)

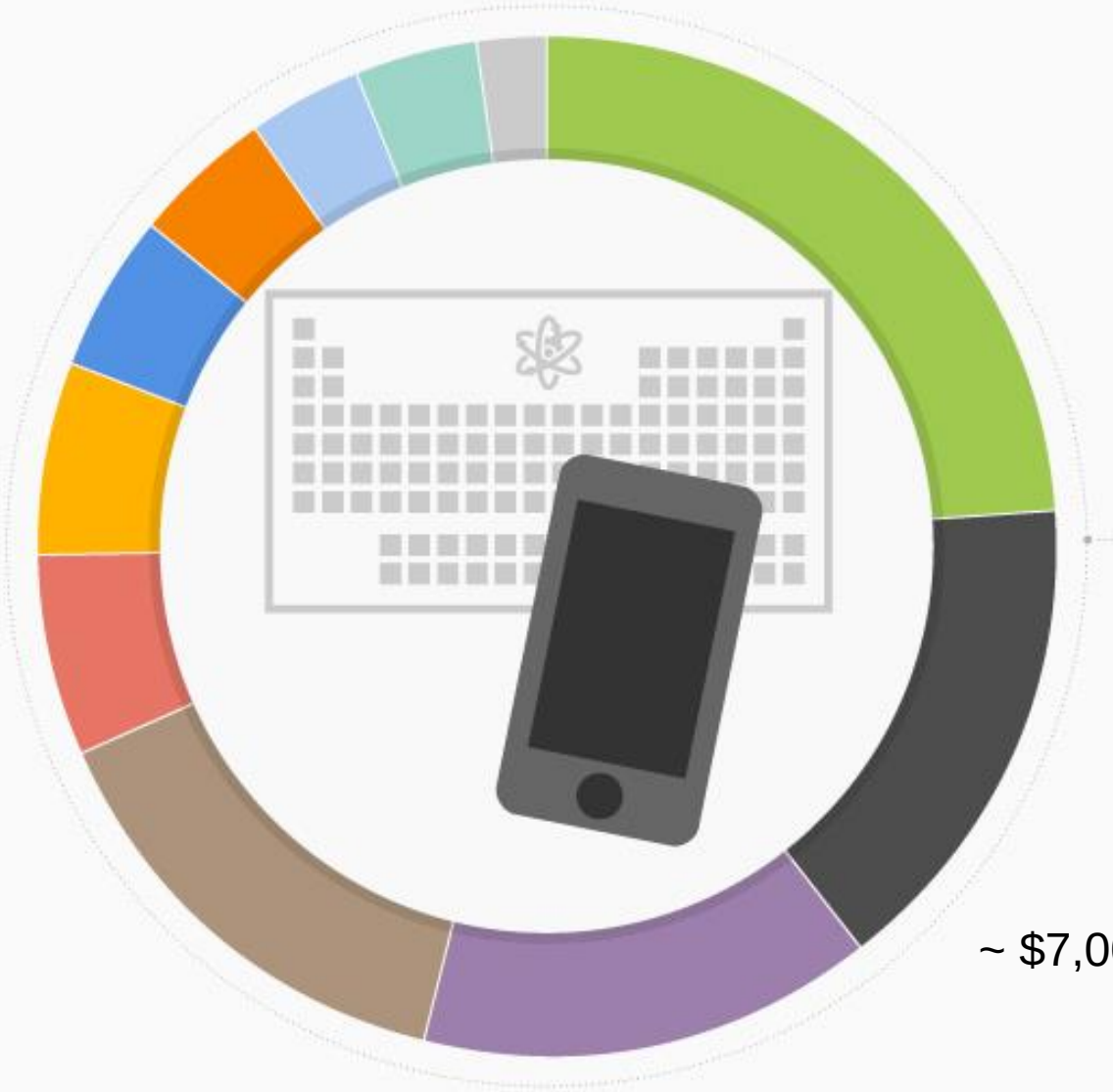
Carbon is used for anodes of most Li-ion batteries



129 Grams: The Materials That Make Up The iPhone

Materials used in iPhone 6, 16GB model

- 31.1 g Aluminium
- 19.9 g Carbon
- 18.7 g Oxygen
- 18.6 g Iron
- 8.1 g Silicon
- 7.8 g Copper
- 6.6 g Cobalt
- 5.5 g Hydrogen
- 4.9 g Chrome
- 4.9 g Others
- 2.7 g Nickel
- 129.0 g Total

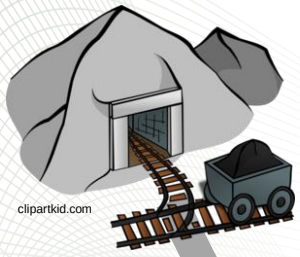


Total value of elements
$1.03

~ $7,000 per short ton

Source: 911 Metallurgist

Coal as a Precursor for High Value-Added Products



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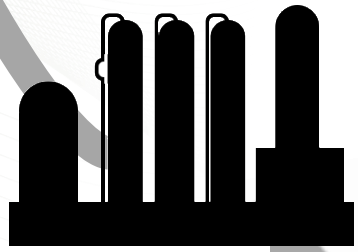

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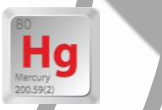

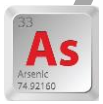

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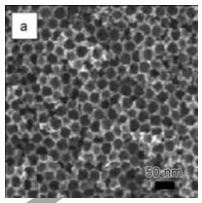

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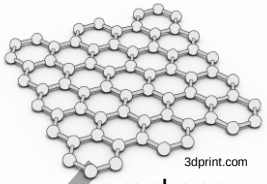

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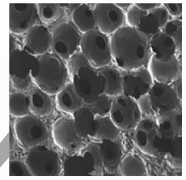

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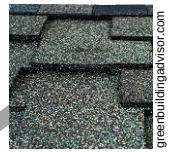
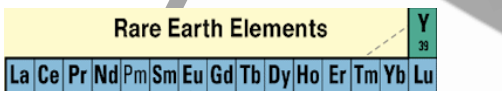
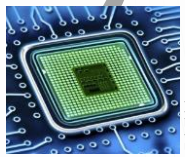




metallurgical coal

carbon fibers



electronic devices including photovoltaics

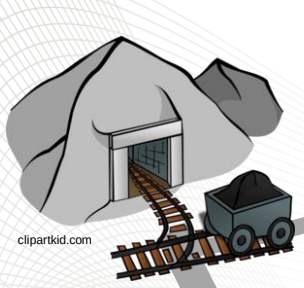
Electrodes for Li-ion batteries and supercapacitors

building and construction materials

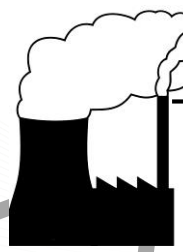
Lara-Curzio et al. (2016)

OAK RIDGE National Laboratory

Coal as a Precursor for High Value-Added Products



Coal Mine



carbon capture

- ethanol
- building materials
- value-added products

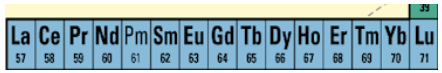
heat and power

Coal "Refinery"

chemicals

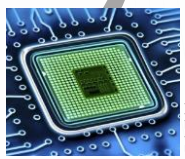
Finding use for every molecule that is mined.

No molecule left behind!



metallurgical coal

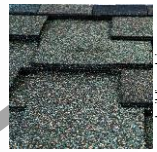
carbon fibers



electronic devices including photovoltaics

Electrodes for Li-ion batteries and supercapacitors

thermal insulation



building and construction materials

Lara-Curzio et al. (2016)

Edgar's Letter

Edgar Lara-Curzio
Oak Ridge National Laboratory
Oak Ridge, TN 37831

D. J. Trump
President of the United States,
White House
Washington, D.C.

Sir:

The National Laboratories are ready to collaborate with the Coal Industry and Academia to develop the underlying and translational science that will enable the development and deployment of energy-efficient and cost-effective processes for: recovering rare-earth elements from coal and converting coal into high value-added products thus enabling the creation of new manufacturing industries and well-paying jobs in coal communities across the U.S

DOE's Fossil Energy Program sponsors workshop

OAK RIDGE National Laboratory

Workshop Report in Preparation

OAK RIDGE National Laboratory

DOE's Fossil Energy Program sponsors Technoeconomic Analysis

STATEMENT OF WORK

Techno-Economic Analysis of the U.S. Value-Added Coal Product Industry

April 2018

Prepared by
Sujit Das
Senior R&D Staff Member
Energy & Transportation Science Division
Oak Ridge National Laboratory (ORNL)
Oak Ridge, Tennessee 37831

ORNL is collaborating with Ramaco, WRI, MIT and the University of Wyoming to turn coal into high value-added products

‘Too Valuable to Burn’: Ramaco to Turn Coal from Wyo. Mine into Car, Plane Parts

February 24, 2017

SNL, Taylor Kuykendall, 2/23/2017

Ramaco Carbon LLC is aiming to “fundamentally diversify the future of the coal industry” with a “coal to cars” mine, research center and industrial park.

The facility is a partnership of the Ramaco Resources Inc. affiliate as well as national research teams from the Massachusetts Institute of Technology, Grossman Group for Advanced Materials, Oak Ridge National Laboratory, Duke University, Southern Research Institute and the Western Research Institute. The group is aiming to divert “a significant amount of thermal coal production” away from coal-burning utilities and into the creation of other products using coal as a base.

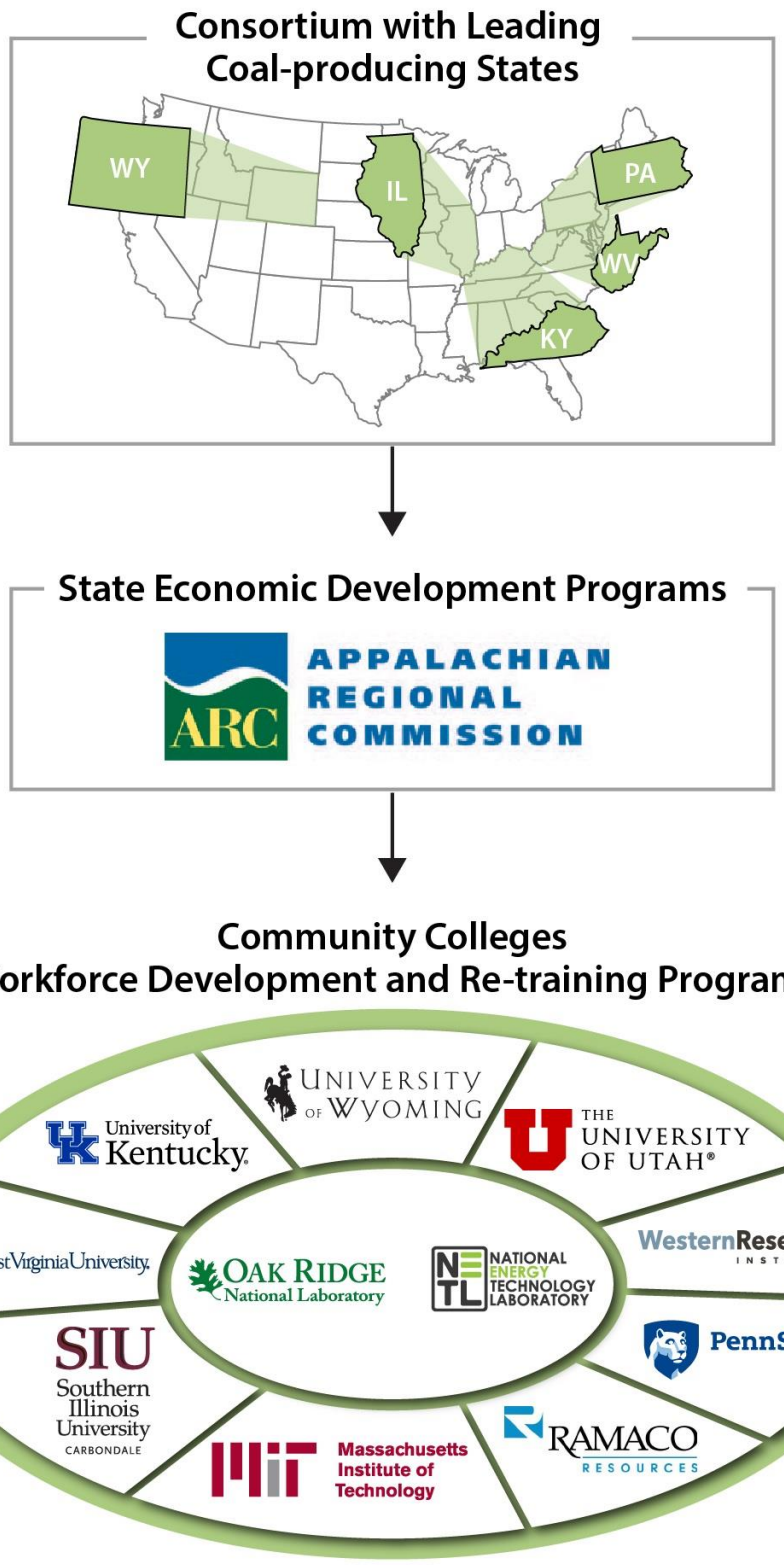
The group plans to start with carbon fiber parts for cars, airplanes and other products. Ramaco Carbon said the company expects that its Powder River Basin coal reserves and operations will now separately serve as the nucleus of a “coal to products&quo t; technology company with a focus on manufacturing high-value industrial products.

Social & Economic Perspective

The Sweat of their Face: Portraying American Workers,”

National Portrait Gallery

“Mine America’s Coal”
Norman Rockwell



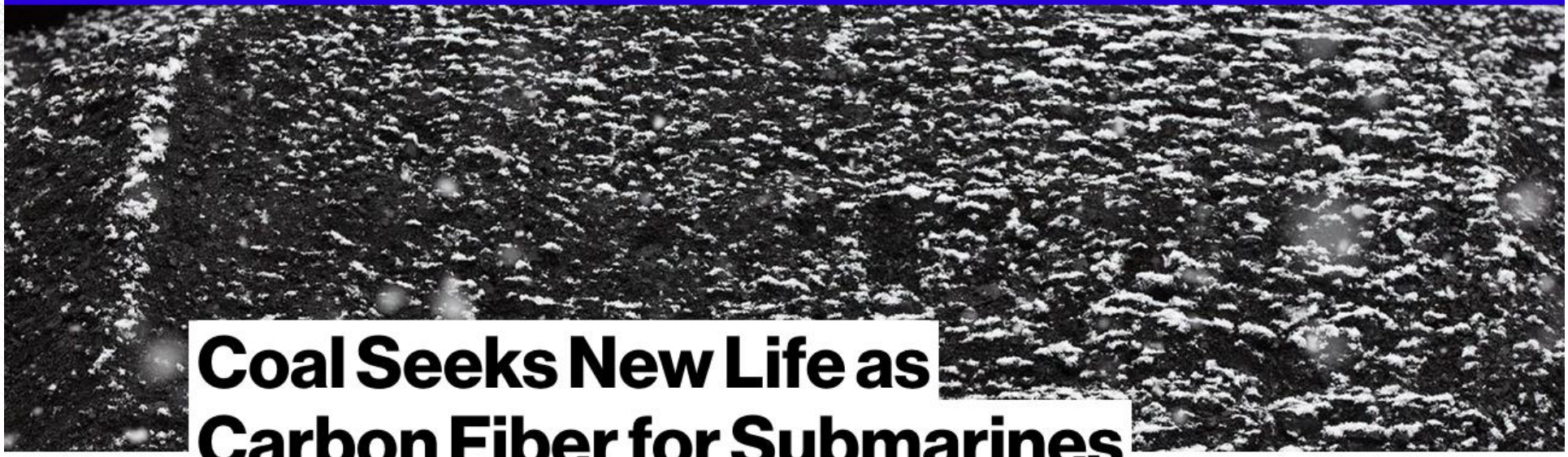
Bringing Manufacturing Jobs to Coal Communities

Opportunities for retraining and work force development

In analogy to the Critical Materials Institute, could we establish a public-private partnership to develop the underlying science that will enable the development of energy-efficient and cost-effective separation processes to obtain from coal, precursors for manufacturing high value-added products?

Questions?

Additional Slides



Coal Seeks New Life as Carbon Fiber for Submarines

By **Tim Loh** and **Patrick Martin**
September 13, 2017, 7:00 PM EDT *Updated on* September 14, 2017, 9:53 AM EDT
From **Climate Changed**

- One of many uses scientists study as U.S. utilities burn less
- New markets won't restore lost mine jobs, but may halt slide

The 30-foot hull of an experimental mini-sub is helping to show how the U.S. may be able to redeploy the mountain of coal that power plants are no longer burning.

Researchers at the Oak Ridge National Laboratory in Tennessee used carbon fibers to build the submersible for the U.S. Navy with a 3-D printer, demonstrating the promise of new manufacturing techniques that are faster, cheaper and more flexible. But it also offers inspiration to scientists looking to turn America's vast reserves of coal into advanced materials, including carbon fibers now made using petroleum-based polymers.

Most Read

1 A $150 Billion Misfire: How Disaster Models Got Irma Wrong
2 NFL TV Ratings Slump Again
3 Jamie Dimon Slams Bitcoin as a 'Fraud'
4 Pandit Says 30% of Bank Jobs May Disappear in Next Five Years
5 Apple Unveils IPhone X With New Display as Rivals Grow

ORNL innovations have had billion dollar impacts

Lab-on-a-chip: Caliper sold for $600M in 2011

Cesium extraction: Basis for $1.3B waste processing facility at Savannah River

Reactor life extension: $20B cost avoidance

Advanced alloys: Chrome-moly steel in widespread use

Cryopreservation of mouse embryos: Frozen embryo transfer for livestock reproduction

Ion implantation: Technology for integrated circuits and medical implants

Centrifuge technology: Basis for vaccine purification and US enrichment industry

Instrumentation: >$1B in products and spinoffs from ORTEC and TENNELEC

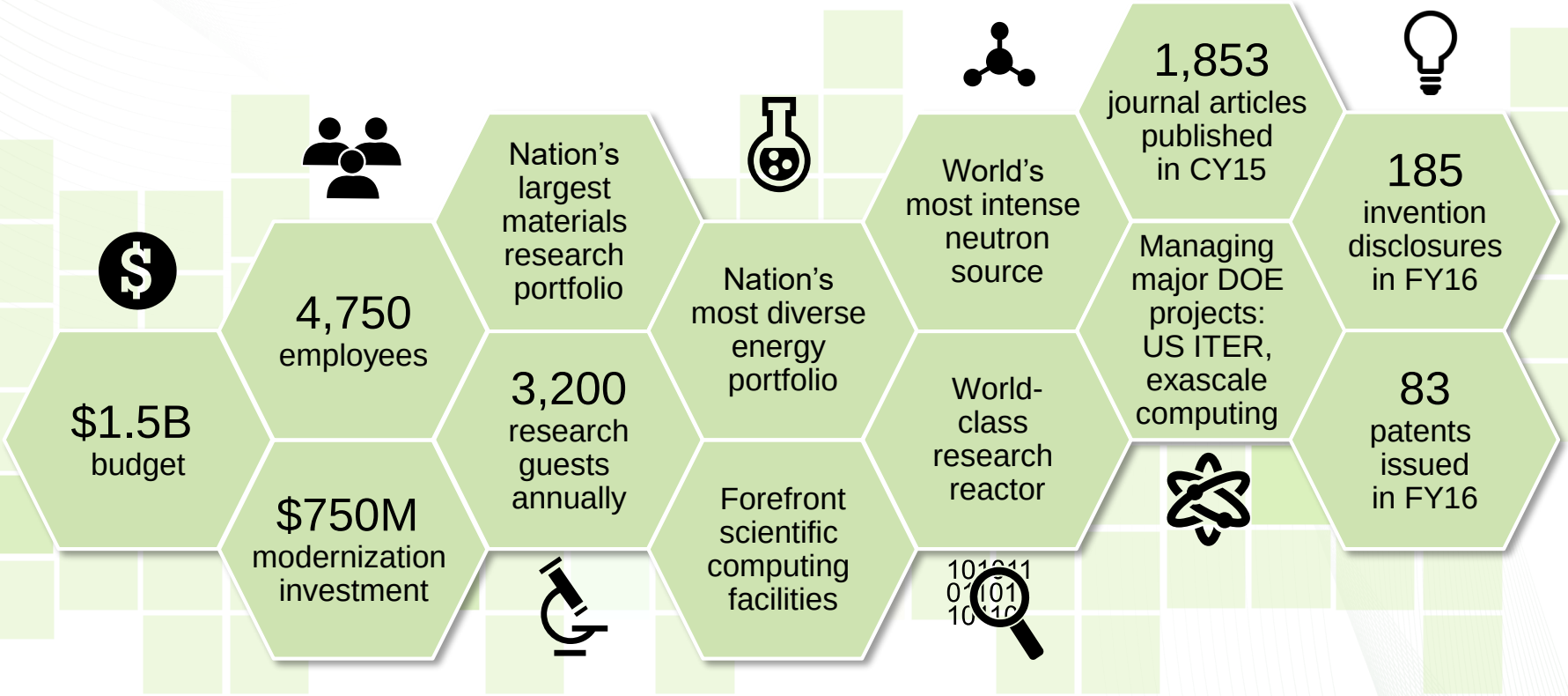
Reactor technology: Concept and technology development for light water, high temperature, and molten salt reactors

PUREX: Basis for nuclear fuel reprocessing techniques used worldwide

Radioisotopes: Multibillion dollar industry (>100 million procedures per year)

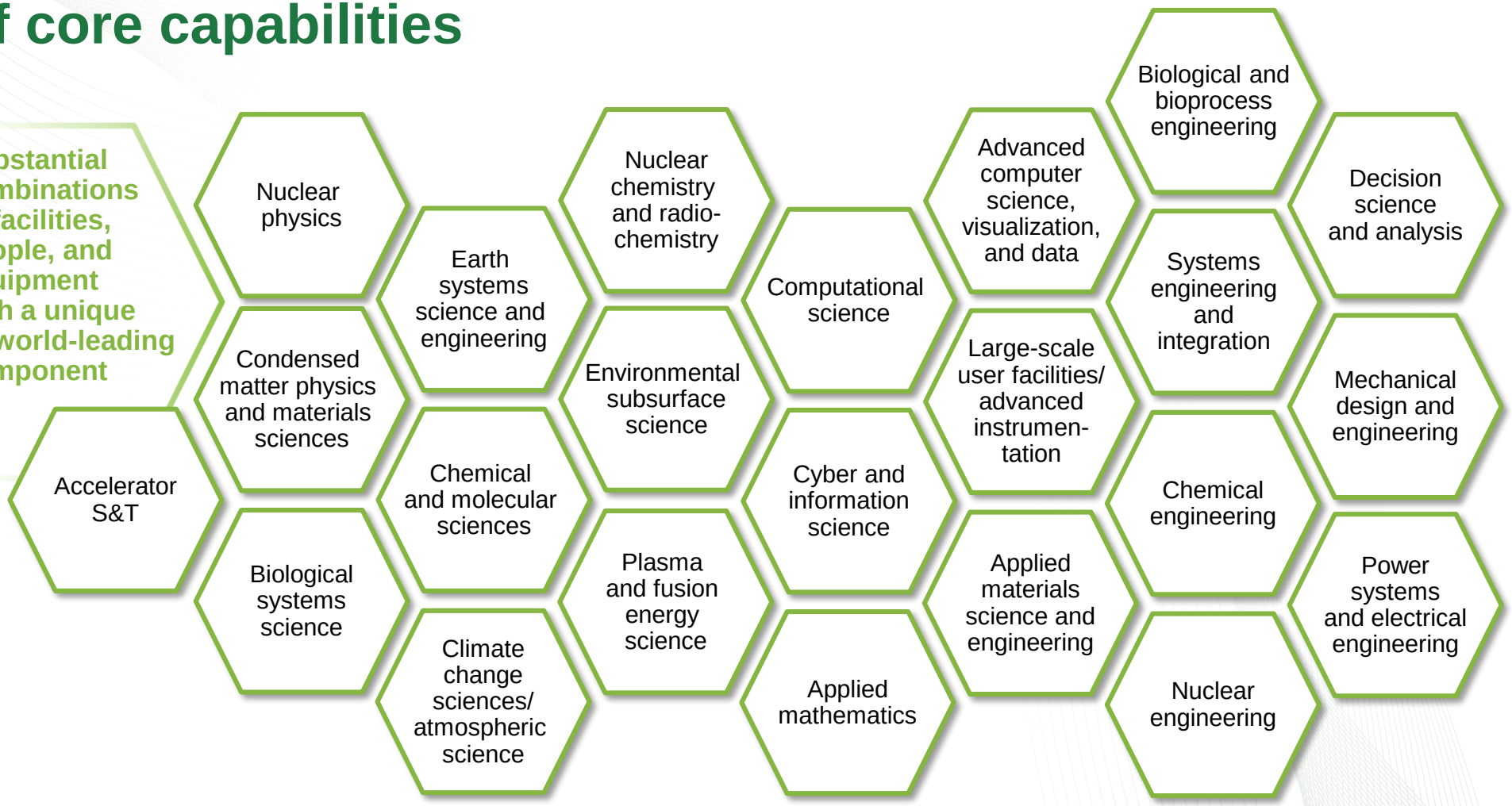
1940s 1960s 1980s 2000s

Today, ORNL is a leading science and energy laboratory

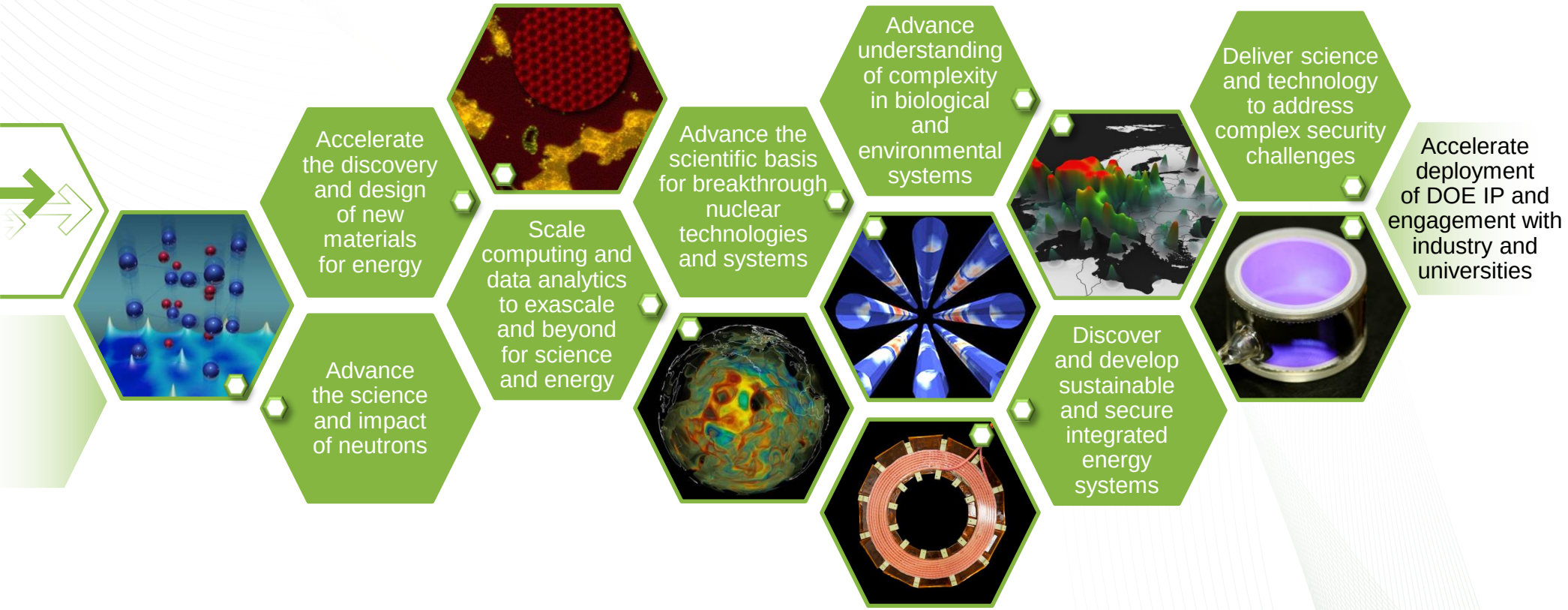


ORNL has an exceptionally broad set of core capabilities

Substantial combinations of facilities, people, and equipment with a unique or world-leading component



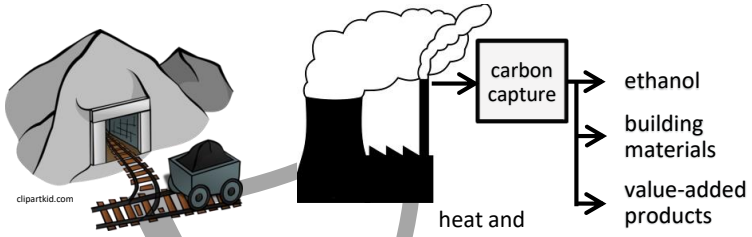
Our core capabilities position us to tackle compelling problems in science and technology



Converting Coal into High Value-Added Product

Finding use for every molecule that is mined. No molecule left behind!

Developing the underlying and translational science that will enable the development and deployment of energy-efficient and cost-effective processes for: recovering rare-earth elements from coal and converting coal into high value-added products thus enabling the creation of new manufacturing industries and well-paying jobs in coal communities across the U.S.

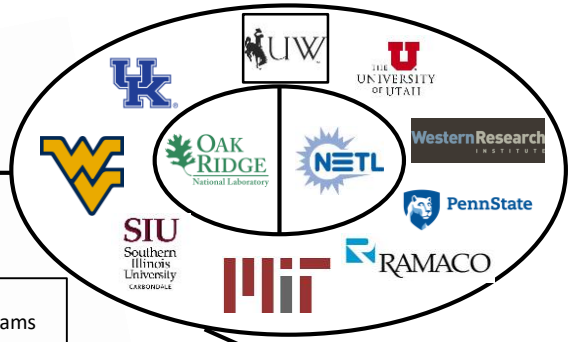



chemicals

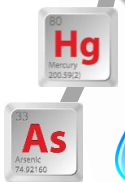
Consortium with leading coal-producing states

ARC Appalachian Regional Commission

State Economic Development Programs

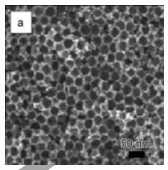


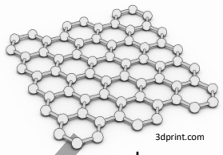
Community Colleges
Workforce Development and re-training programs

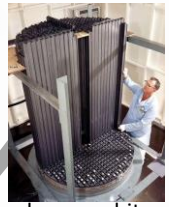


water

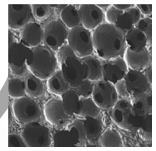
activated carbon


mesoporous carbon

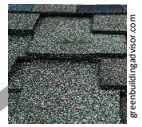

graphene


nuclear graphite

thermal management

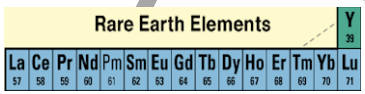

thermal conduction


thermal insulation



building and construction materials

Rare Earth Elements

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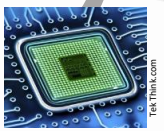


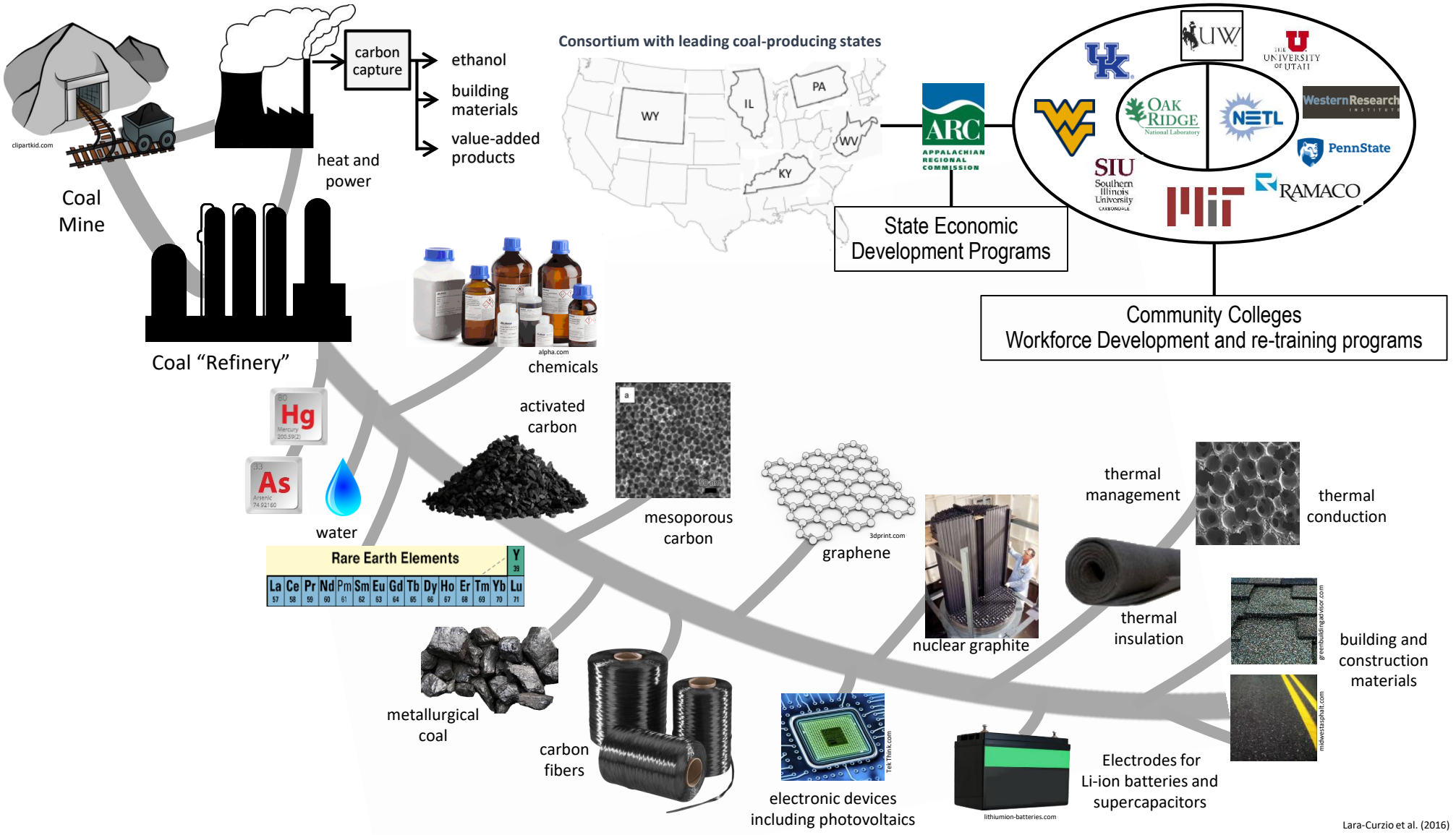
electronic devices including photovoltaics

Electrodes for Li-ion batteries and supercapacitors

Science & Technology Themes

- Separation science & technology
- Advanced characterization
- Catalysis
- Manufacturing
- Improving chemical transformations through high-performance computing
- Materials and infrastructure, including modular chemical reactor designs
- Energy, Economic and Life-Cycle Analysis, including integration of products (precursors and chemicals) into the existing supply infrastructure

Lara-Curzio et al. (2016)



Lara-Curzio et al. (2016)