Energy and Materials:
Can’t Have One Without the Other

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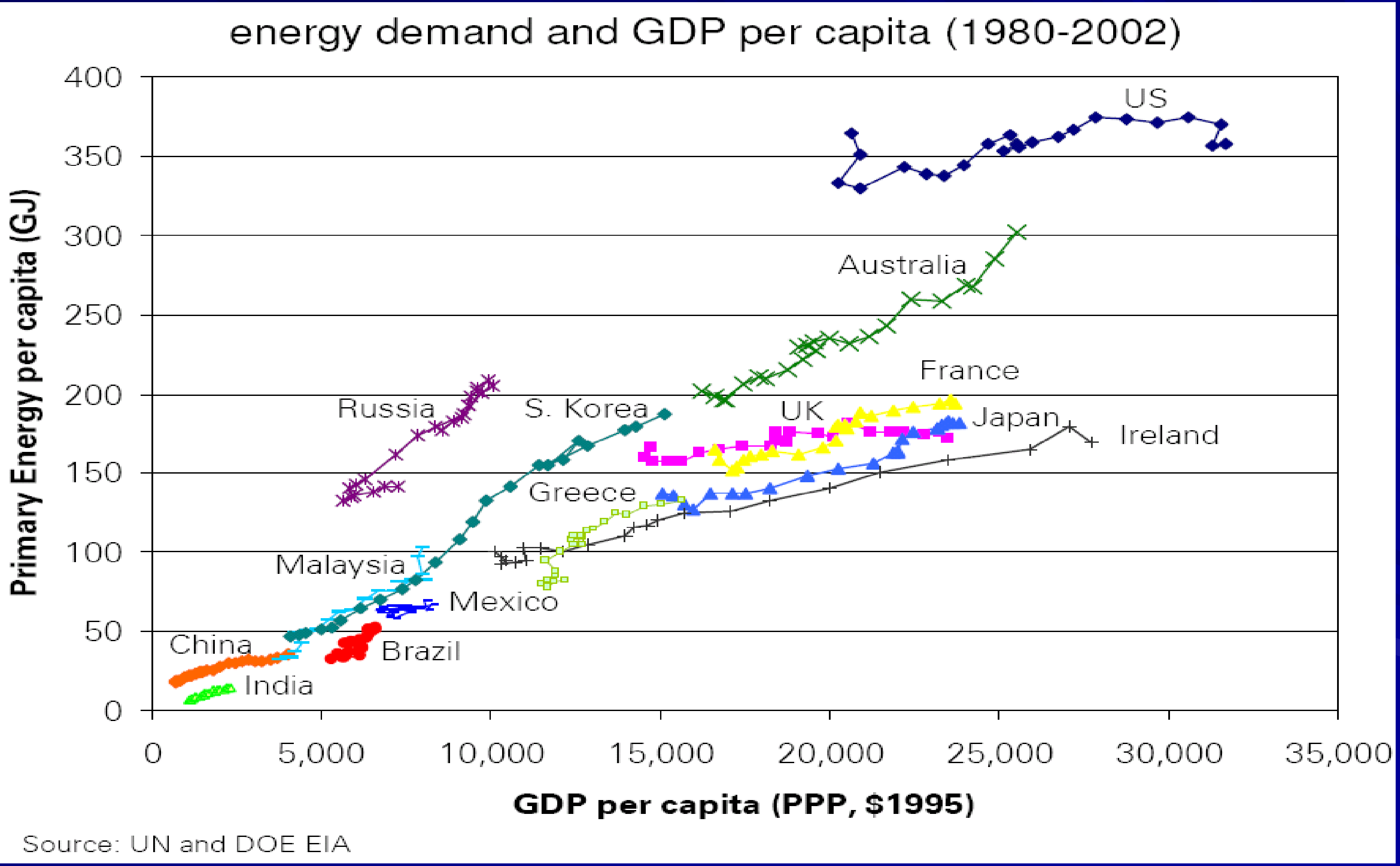
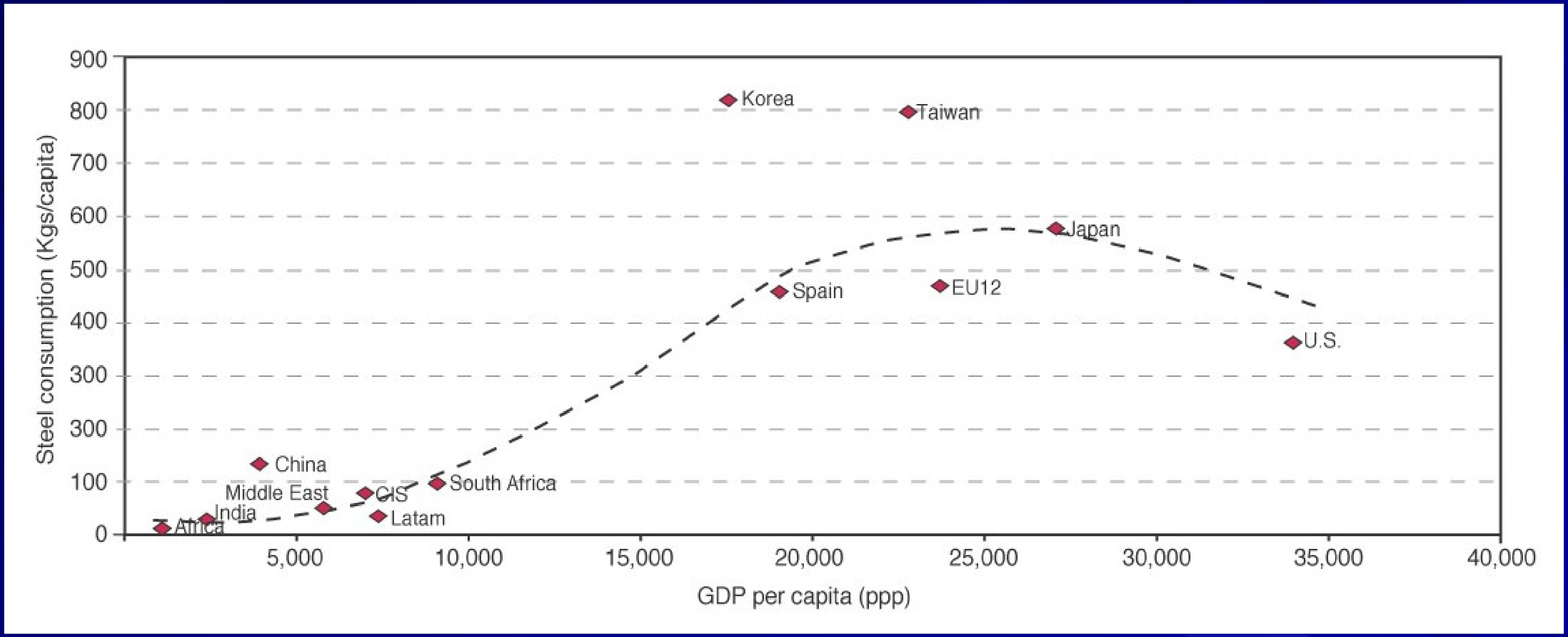
Penn State University, September 2006

Energy Consumption Relates to Societal Well-being



Steel Consumption Also Relates to GDP



If China were to rise to South Korean steel consumption levels, the demand would be strong for 25 years at 5% growth!

www.usfunds.com

The Energy – Steel Connection

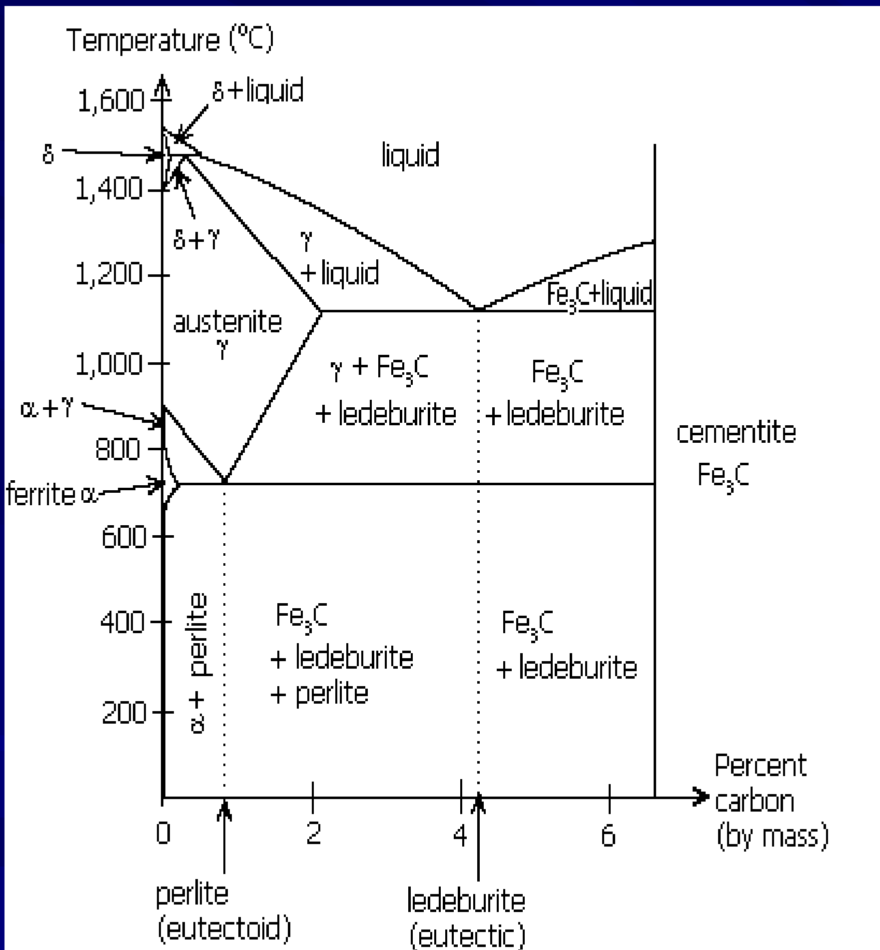
- The relationship between per capita steel consumption and energy has a strong, positive correlation. A high level of commercial energy consumption implies machinery, consumer durables, appliances and automobiles; all of this means steel.

- The level of consumption of steel per capita can be used as an indicator for a country's development. This indicator is not as representative as it once was, since aluminum and plastic have replaced steel in certain sectors of the construction industry.

Iron Smelting in the Hittite Empire

- The Hittites were the first (?) people to develop the art of iron smelting.
- Primitive furnaces did not reach temperature sufficient to melt iron (1535 ºC).
- The early product was wrought iron.

The Empirical Discovery of the Effect of Carbon



- Hittites learned that "carburizing" the iron substantially reduced its melting point.
- This was done by running the furnace with a 6-fold excess of charcoal.
- Today, we can understand this effect from the iron-carbon phase diagram.

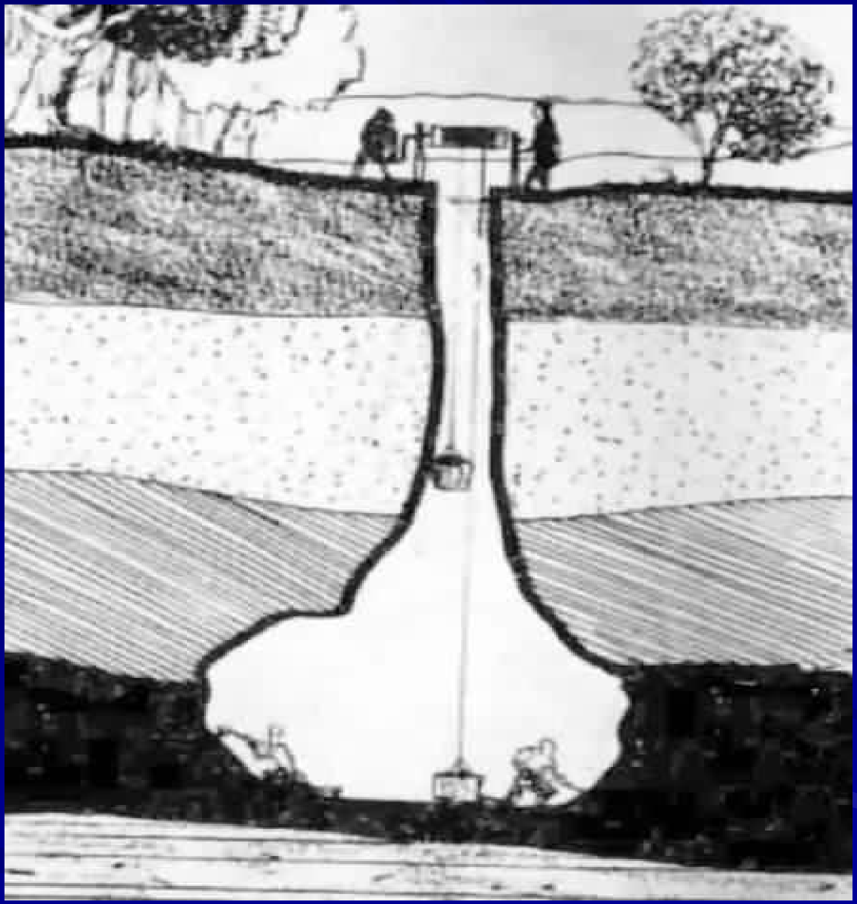
The Hittite Energy Crisis

- Running carbon-rich produces iron that can be melted and poured (1130 ºC): cast iron or pig iron. But…
- It takes about five tons of wood to make one ton of charcoal. This results in rapid deforestation.
- “It was the practice to cut clean… No ironmaster ever conceded that he had enough ‘coal’ land.”*
- The loss of availability of a necessary energy resource results in an *energy crisis*.

* Hopewell Furnace National Historic Site

Ironmaking in Ancient China

- Chinese ironmaking also initially relied on wood. (Technology transmitted from Hittites?)
- Loss of wood resource led to the response of fuel switching.
- Some Chinese ironmaking sites began to use anthracite as fuel.



Iron-making in 17th-Century England

- English iron-makers used charcoal from oak as the fuel of choice in smelting.
- As in the past, the increased demand for iron led to extensive cutting of oak forests.
- In this case, there was also a competing application for oak: naval vessels.

The 17th Century Energy Crisis

Deforestation due to increasing demand for oak led to a genuine resource shortage *and* government mandates to reserve oak for naval use. This is an example of a second mechanism that can lead to an energy crisis.

Hot Shortness

- With the switch to the direct use of coal, iron pieces would tear or break apart when being worked at high temperature.
- This problem was called hot shortness, or sometimes "hot shorts."
- Eventually, it was realized that this is due to precipitation of FeS as the molten metal solidifies. FeS segregates in grain boundaries and causes sites of weakness.

Sulfur Evolution During Slow Heating of Coal

Sulfur is driven off by at least two mechanisms:

$$FeS_2 + 2\,H\bullet \rightarrow \text{“FeS”} + H_2S\uparrow$$

$$R\text{-}S\text{-}R' + 4H\bullet \rightarrow RH + R'H + H_2S\uparrow$$

The H_2S interacts with the iron

$$Fe + H_2S \rightarrow FeS + H_2$$

and the FeS precipitates in grain boundaries.

Coal-to-Coke Transition

- Slow heating of some types of coal in absence of air leads to formation of strong, porous, carbon-rich coke.
- This coke became the dominant fuel for iron smelting.

The Steady Decline in Coke Production

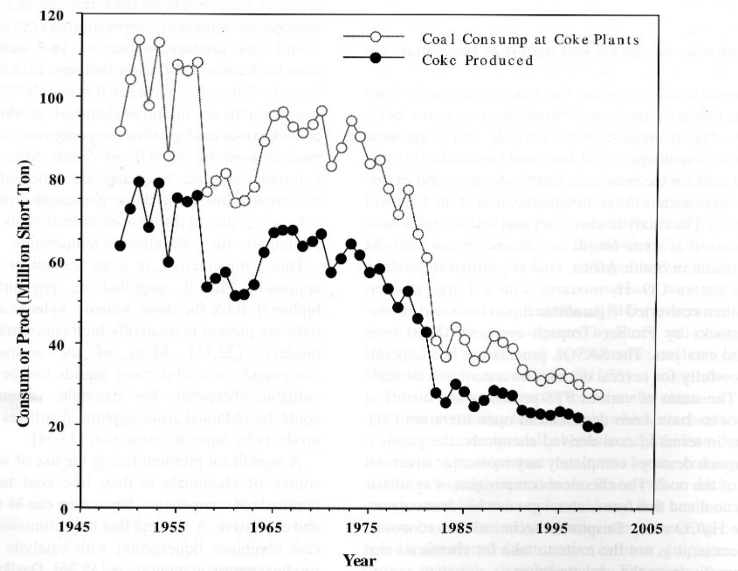


Fig. 6. US coal consumption at coke plants and metallurgical coke production during 1945–1999 (1 short ton = 0.907 metric tonne).

Song and Schobert, 2002.

Coke production has declined for two reasons:

- Steady improvement in the "coke rate" of blast furnaces, and
- A switch to electric arc furnace technology…

Which leads to a new materials challenge.

Thomas Hobbes on Graphite Electrodes

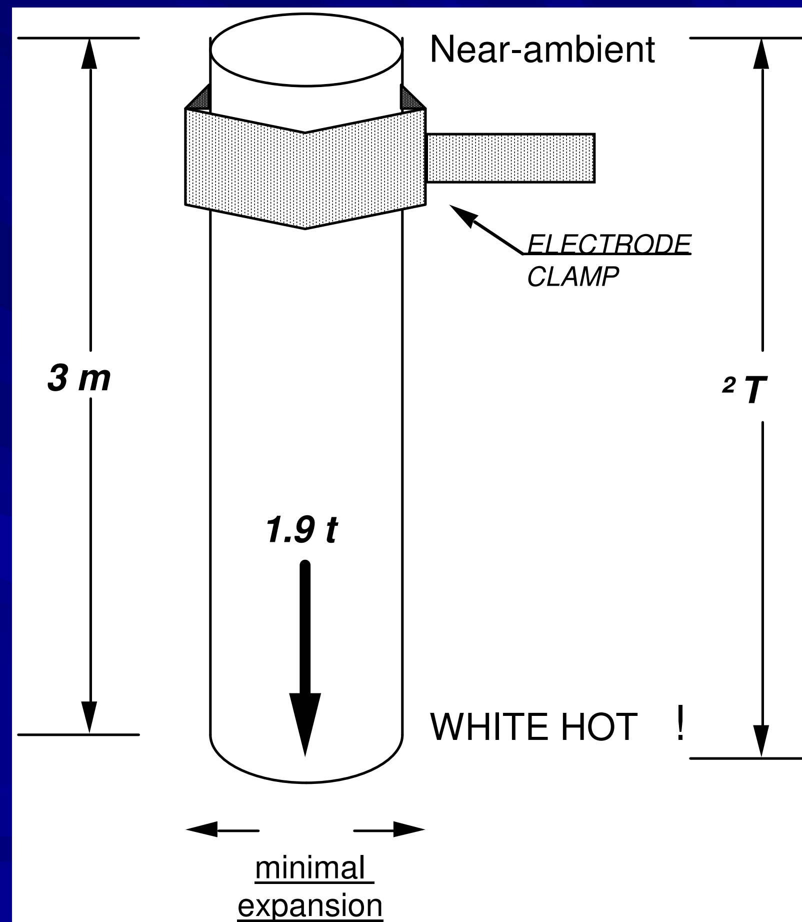
"… a life that is nasty, brutish, and short…"*

*Hobbes, *Leviathan*

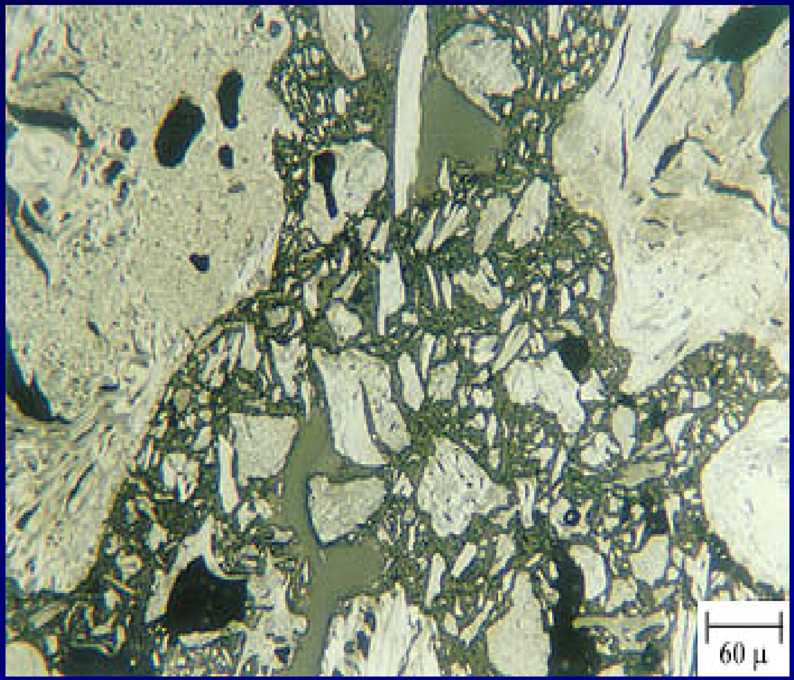
The Graphite Electrode as a Triumph of Materials Engineering

Requirements include

- mechanical integrity
- low CTE
- ability to sustain enormous ΔT
- oxidation resistance



The Graphite Electrode and the Law of Unintended Consequences



Gray and Crelling, *Petrographic Atlas*

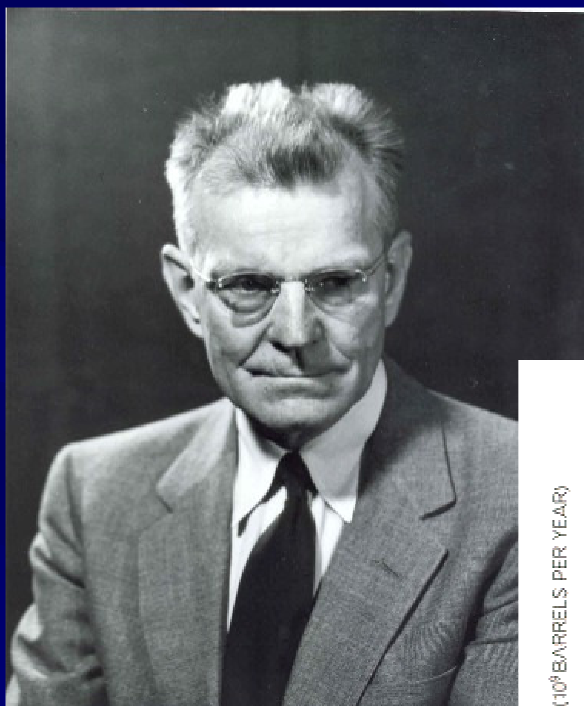
- Graphite electrodes are produced from two components: petroleum coke and *coal tar* pitch.
- But coal tar pitch is a by-product of the metallurgical coke industry.
- The increase in graphite electrode usage reduces coke demand, and thus reduces coal tar pitch availability.
- Materials challenge: find a suitable replacement for coal tar pitch.

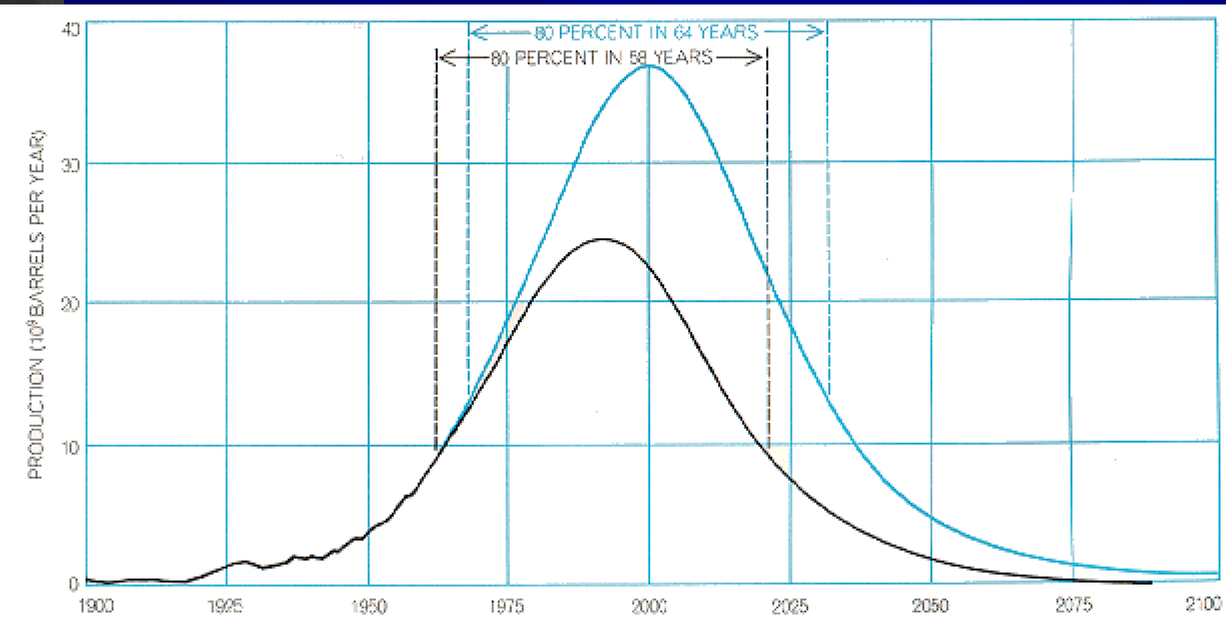
Petroleum:
Are We in an Energy Crisis Now?

- Extensive, potentially explosive, turmoil in many petroleum-producing regions of the world.
- China is now an aggressive and voracious player in world petroleum markets.
- Saudi production is likely “max-ed out.”
- Domestic oil production peaked in 1970.

M. King Hubbert

"Our ignorance is not so vast as our failure to use what we know."





CYCLE OF WORLD OIL PRODUCTION is plotted on the basis of two estimates of the amount of oil that will ultimately be produced. The colored curve reflects Ryman's estimate of $2,100 \times 10^9$ barrels and the black curve represents an estimate of $1,350 \times 10^9$ barrels.

So Now What?

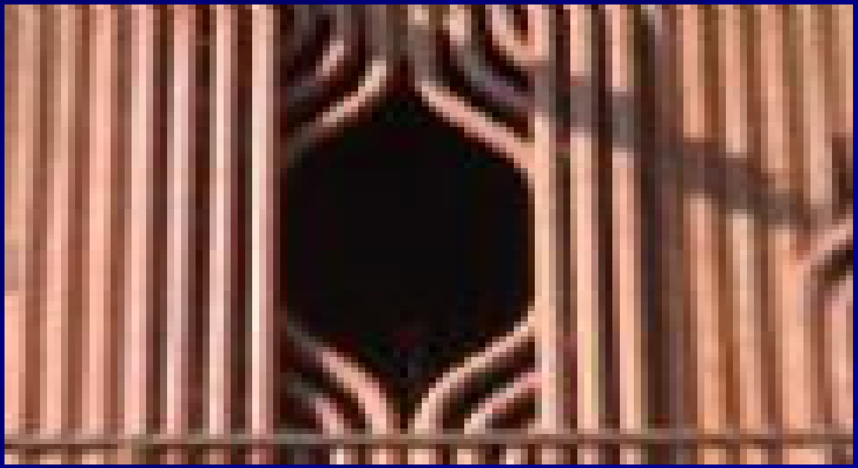
Conservation and efficiency.

The absolutely best source of “new” energy is to do a better job of conserving the energy resources we now have, and to make more efficient use of those resources.

Carnot and Energy Efficiency

$$\text{Efficiency} = \frac{T_H - T_L}{T_H}$$

Carnot's Challenges to Materials Science



- High-temperature superalloys for turbine blades and other components; e.g., oxide-dispersion strengthening in combustion turbines.
- Superalloys for "ultrasupercritical" steam cycles in power generation. 50% increase in pressure, 150 ºC more temperature with thinner-wall, smaller-diameter tubes.

A Few Additional Materials Challenges

- Improved batteries and fuel cells
- Novel capacitors and other energy storage devices
- Materials for turbine or turboshaft engines
- Microturbines
- High-power solid-state switches
- Advanced superconductors
- Hydrogen storage materials
- Gas separation materials

What Forms of Energy Are Available?

- Fossil (derives from biomass, which derives from solar)
- Biomass (derives from solar)
- Wind (from differential heating of atmosphere by the sun)
- Hydropower (from the hydrological cycle driven by solar water evaporation)

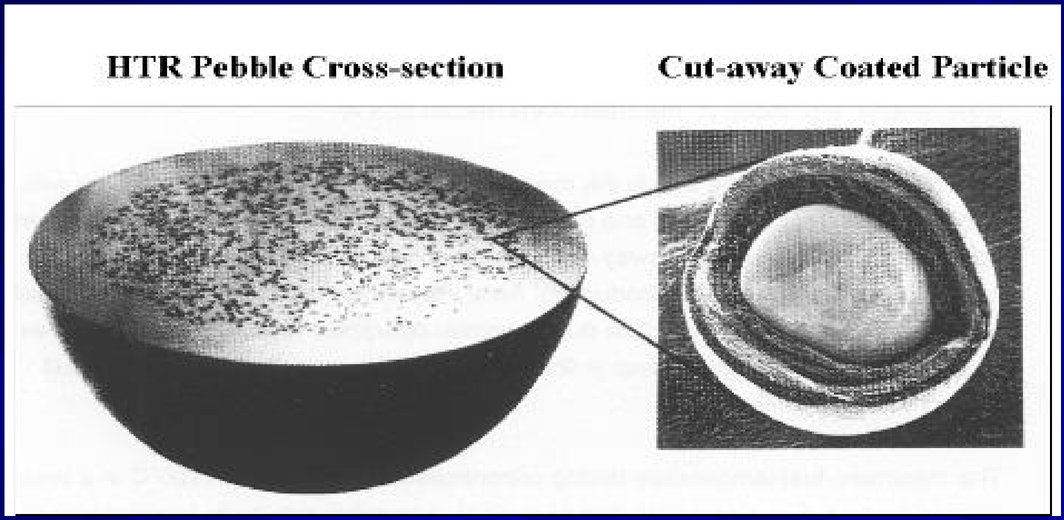
➢ Solar

➢ Nuclear

Graphite Materials in Nuclear Energy

- Graphite has been an essential component of reactor technology, beginning with Fermi's hand-built reactor in 1942.
- Graphite is not without problems: e.g., thermal expansion (Sellafield) and combustion (Chernobyl).
- Newer, safer reactor designs will still rely on specially designed carbon materials.

Pebble-bed Reactor Fuel

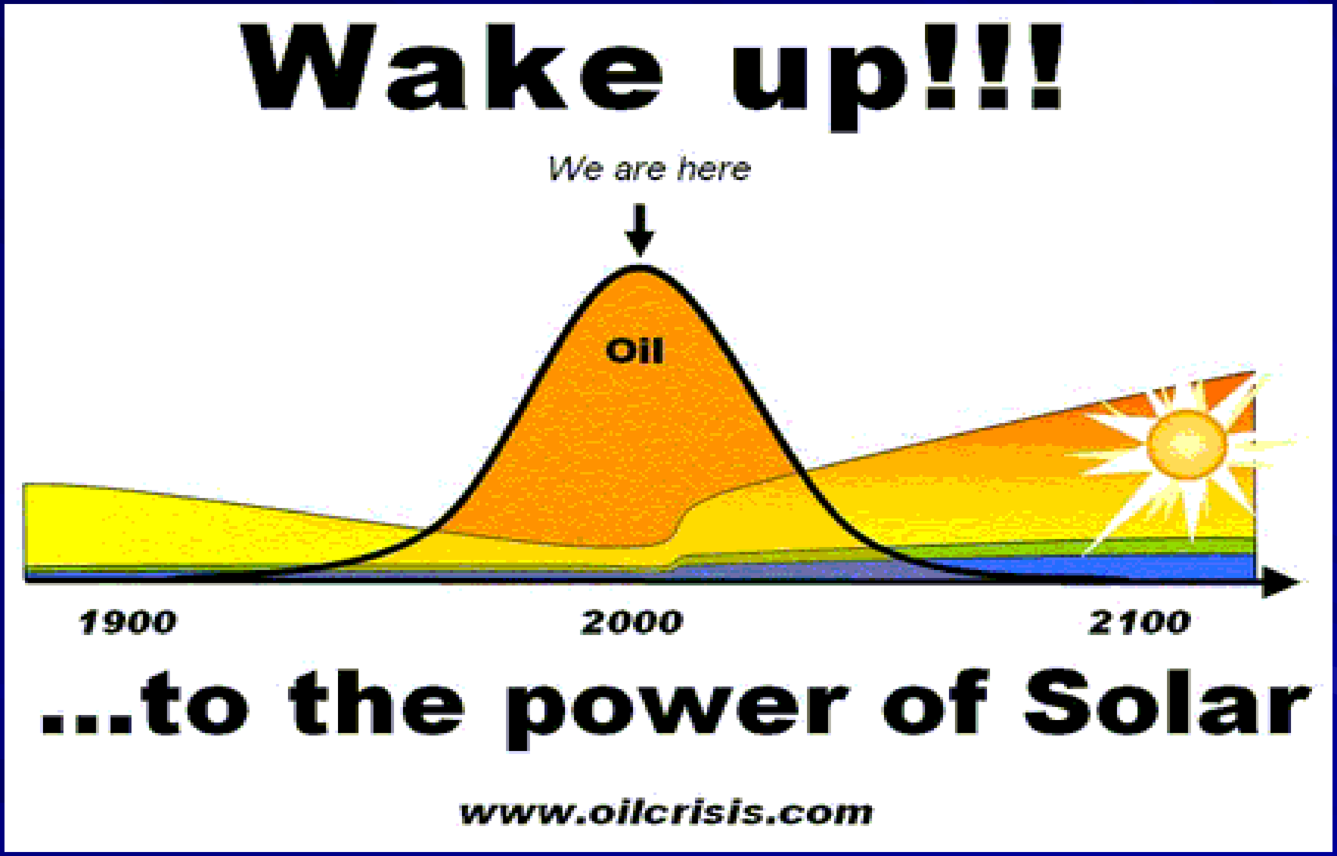


- The fuel for a pebble-bed reactor consists of a 0.5 mm sphere of UO_2 surrounded by porous carbon buffer, inner layer of isotropic pyrolytic carbon, barrier layer of SiC, outer layer of isotropic pyrolytic carbon.
- Challenges include surviving radiation flux, high temperatures, and mechanical strength in a 1 mm particle.

Some Materials Challenges in Solar Energy

- Finding low-cost routes to “solar-grade” silicon.
- New solar cell materials better than amorphous Si but without components having environmental issues.
- Why do solar cells lose effectiveness after long-term exposure?
- Photocatalysts for effective conversion of water to H_2 and CO_2 to methane.

Ultimately, It's All Solar…



Concluding Remarks

- We *are* in an energy crisis. It's going to get worse before it gets better.
- The efficient use of energy requires continued development of improved materials and their applications.
- The efficient production of materials requires continued development of improved energy utilization.