"Relating the Increasing Scarcity of Mineral-Based Materials to the Materials Science Curriculum"

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Abstract: A new course was developed and offering as a senior technical elective or beginning graduate course with the title" Strategic Metals and Materials for the 21st Century" with the stated objective of creating an understanding of the role of mineral-based materials in the modern economy focusing on how such knowledge can and should be used in making strategic choices in an engineering context. The success at garnering student attention will be discussed. A novel aspect of this course is the use of current literature (including 'business news') used to demonstrate the connectedness of materials availability and the development and sustainability of engineering advances. The concept of strategic recycling, including design for recycling and waste stream management will be considered and, in particular, how it relates to traditional topics such as extractive metallurgy also will be discussed in terms of how it might rejuvenate a field of study.

Introduction: It can be argued that engineers have at their disposal three things: energy, materials, and information. Combinations thereof can be employed to fulfill the mission of the profession. That is, these are the prime elements through which engineering becomes "the discipline, art and profession of acquiring and applying technical, scientific, and mathematical knowledge to design and implement materials, structures, machines, devices, systems, and processes that safely realize a desired objective or invention."

However, it would be fair to say that intimate relationship of materials to the economy (both that of the US and that of the world) is underappreciated. Furthermore, the typical engineering student and, often, university researcher gives far less thought to the cost and availability of materials than to the performance metrics of a given material or system.

Thus, the motivation for developing and offering a course entitled "Strategic Metals and Materials for the 21st Century" was two fold. The first goal may be accurately expressed as a set learning outcomes, i.e., students will:

- Be able to gain accurate and timely information regarding the current and future availability of mineral-derived materials and use this information in the context of materials-constrained design,
- Appreciate when opportunities for materials substitution and possible and appropriate, as well as when it is not (i.e., intrinsic materials properties are unique),
- Understand the ethical implications of materials choices in designs and devices, particularly in the context of a globalized economy,

- Synthesize information obtained from historical sources, technical literature, business writings, and current news.

It was recognized from the beginning that the course would not have a "home," in that it was not replacing a well-established element in the curriculum. Three conscious choices were made in the introduction of the course. The first was to offer the course both as an upper level undergraduate technical elective and an introductory graduate level course. (The faculty of the department of Materials Science and Engineering approved both.) The second was to advertise the course broadly amongst the engineering student body in the interest of getting the attention of engineering students in other majors. Lastly, the course was promoted through signage with specific placement in areas frequented by students in the management school. Despite this enrollment was very low. The course was therefore adapted and offered as a "reading course." In this mode work is divided and weekly meetings are held to review progress for critical review and information sharing.

Implementation: To introduce the conceptual approach the initial phase of the course utilized three illustrative examples. The first was a set of references from the United States Geological Survey and the National Academies [1-8]. Key figures from these references clearly establish that the U.S. economy is intensive in its use of mineral-derived materials. Consider Figs. 1 and 2 from ref. 1, and Fig. 3 derived from data in ref. 3.

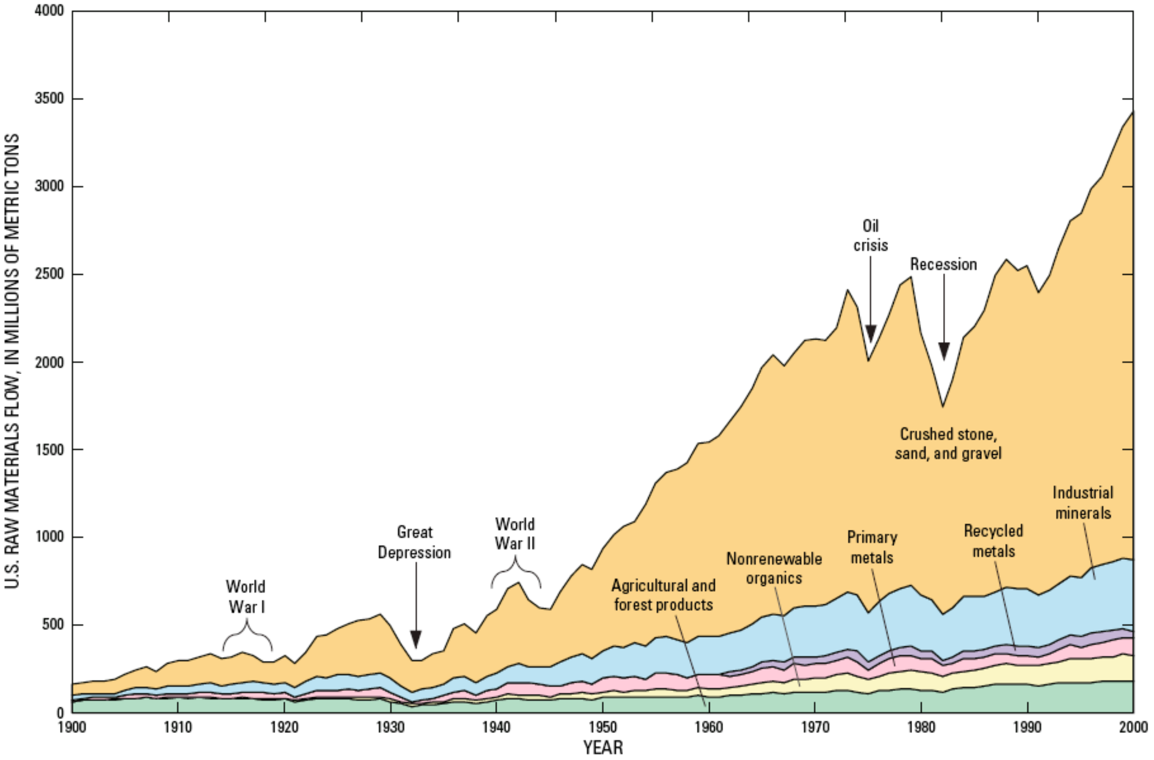
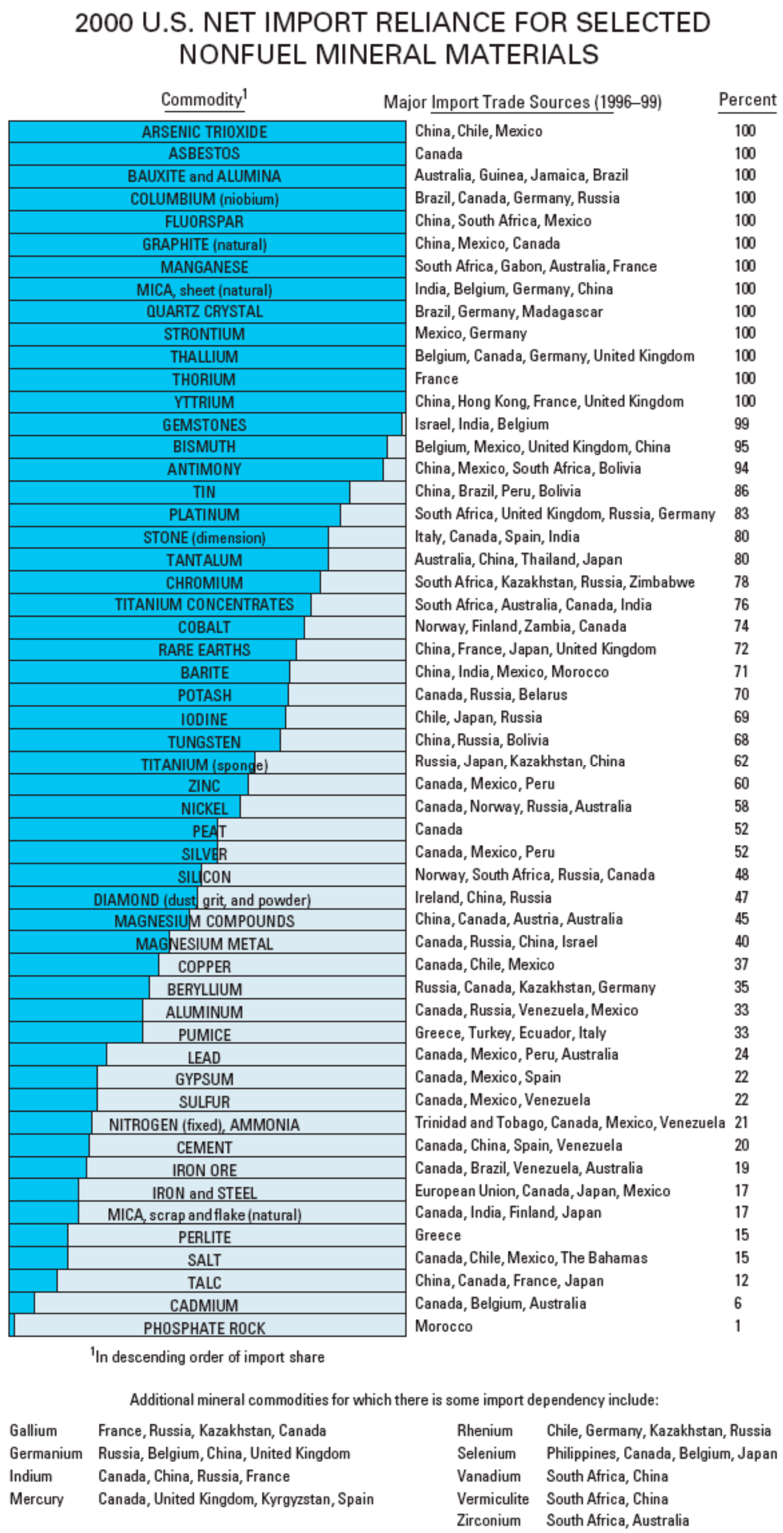


Figure 1. U.S. flow of raw materials by weight, 1900–98. The use of raw materials dramatically increased in the United States throughout the 20th century (from ref. 1, cited as modified from Matos and Wagner, 1998, fig. 3).



2000 U.S. NET IMPORT RELIANCE FOR SELECTED NONFUEL MINERAL MATERIALS

Commodity[1]	Major Import Trade Sources (1996–99)	Percent
ARSENIC TRIOXIDE	China, Chile, Mexico	100
ASBESTOS	Canada	100
BAUXITE and ALUMINA	Australia, Guinea, Jamaica, Brazil	100
COLUMBIUM (niobium)	Brazil, Canada, Germany, Russia	100
FLUORSPAR	China, South Africa, Mexico	100
GRAPHITE (natural)	China, Mexico, Canada	100
MANGANESE	South Africa, Gabon, Australia, France	100
MICA, sheet (natural)	India, Belgium, Germany, China	100
QUARTZ CRYSTAL	Brazil, Germany, Madagascar	100
STRONTIUM	Mexico, Germany	100
THALLIUM	Belgium, Canada, Germany, United Kingdom	100
THORIUM	France	100
YTTRIUM	China, Hong Kong, France, United Kingdom	100
GEMSTONES	Israel, India, Belgium	99
BISMUTH	Belgium, Mexico, United Kingdom, China	95
ANTIMONY	China, Mexico, South Africa, Bolivia	94
TIN	China, Brazil, Peru, Bolivia	86
PLATINUM	South Africa, United Kingdom, Russia, Germany	83
STONE (dimension)	Italy, Canada, Spain, India	80
TANTALUM	Australia, China, Thailand, Japan	80
CHROMIUM	South Africa, Kazakhstan, Russia, Zimbabwe	78
TITANIUM CONCENTRATES	South Africa, Australia, Canada, India	76
COBALT	Norway, Finland, Zambia, Canada	74
RARE EARTHS	China, France, Japan, United Kingdom	72
BARITE	China, India, Mexico, Morocco	71
POTASH	Canada, Russia, Belarus	70
IODINE	Chile, Japan, Russia	69
TUNGSTEN	China, Russia, Bolivia	68
TITANIUM (sponge)	Russia, Japan, Kazakhstan, China	62
ZINC	Canada, Mexico, Peru	60
NICKEL	Canada, Norway, Russia, Australia	58
PEAT	Canada	52
SILVER	Canada, Mexico, Peru	52
SILICON	Norway, South Africa, Russia, Canada	48
DIAMOND (dust, grit, and powder)	Ireland, China, Russia	47
MAGNESIUM COMPOUNDS	China, Canada, Austria, Australia	45
MAGNESIUM METAL	Canada, Russia, China, Israel	40
COPPER	Canada, Chile, Mexico	37
BERYLLIUM	Russia, Canada, Kazakhstan, Germany	35
ALUMINUM	Canada, Russia, Venezuela, Mexico	33
PUMICE	Greece, Turkey, Ecuador, Italy	33
LEAD	Canada, Mexico, Peru, Australia	24
GYPSUM	Canada, Mexico, Spain	22
SULFUR	Canada, Mexico, Venezuela	22
NITROGEN (fixed), AMMONIA	Trinidad and Tobago, Canada, Mexico, Venezuela	21
CEMENT	Canada, China, Spain, Venezuela	20
IRON ORE	Canada, Brazil, Venezuela, Australia	19
IRON and STEEL	European Union, Canada, Japan, Mexico	17
MICA, scrap and flake (natural)	Canada, India, Finland, Japan	17
PERLITE	Greece	15
SALT	Canada, Chile, Mexico, The Bahamas	15
TALC	China, Canada, France, Japan	12
CADMIUM	Canada, Belgium, Australia	6
PHOSPHATE ROCK	Morocco	1

[1] In descending order of import share

Additional mineral commodities for which there is some import dependency include:

Gallium	France, Russia, Kazakhstan, Canada	Rhenium	Chile, Germany, Kazakhstan, Russia
Germanium	Russia, Belgium, China, United Kingdom	Selenium	Philippines, Canada, Belgium, Japan
Indium	Canada, China, Russia, France	Vanadium	South Africa, China
Mercury	Canada, United Kingdom, Kyrgyzstan, Spain	Vermiculite	South Africa, China
		Zirconium	South Africa, Australia

Figure 2. 2000 U.S. net import reliance for selected nonfuel mineral materials (from ref.1).

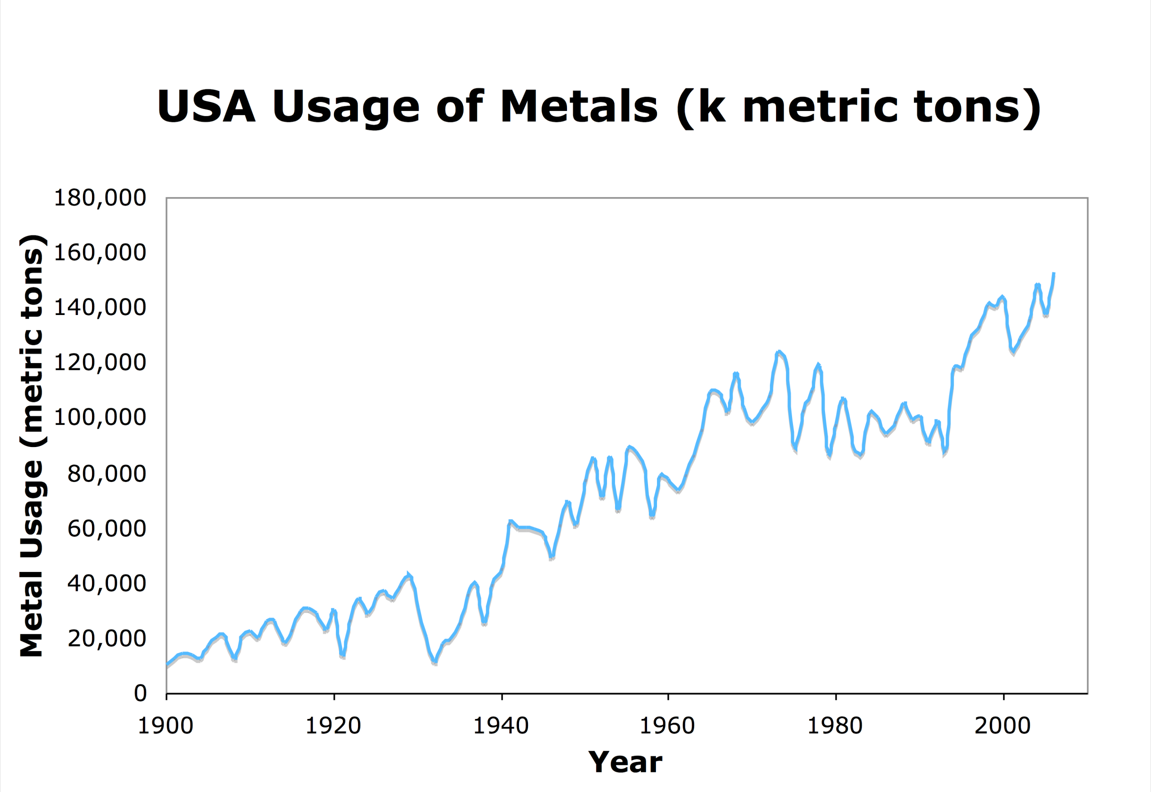


Figure 3. 2000 U.S. net import reliance for selected nonfuel mineral materials (from ref.1).

The second element was to introduce the notion of a "cycle" to the usage of metals. Students are, of course, very familiar with the concept of the water cycle and increasing familiar with the carbon cycle. A few have been exposed to geochemical cycles, but very few materials science and engineering students are familiar with the cycles associated with industrial usage of materials, in general, or metals, in particular. The copper cycle was used as there are several references [e.g. 6-7] that examine it and the data appears relatively robust. A schematic of a materials flow appears in Fig. 4 (from ref. 1).

In the class the copper cycle was analyzed in detail. Noting such startling facts as 90% of all the copper ever produced was done so in the 20th century (bronze age notwithstanding); 70% of that being in the last 50 years (the lifetime of the instructor) and 50% being only in the past 25 years (the lifetime of current graduate students) [ref. 6]. Furthermore, an estimated 85% of all the copper ever produced is still in use (much of it in the built infrastructure as, for example, wiring and plumbing) – thus **not** available to be recycled [ref. 6].

Furthermore, a best effort was made to construct such flow diagrams from USGS data. When the documents alone were insufficient or unclear, direct contact was made with appropriate USGS staff. Direct student contact was preferred and was successful. This process also was very helpful at making evident where there were holes in the data – for example when industry intentionally failed to report data for "competitive reasons."

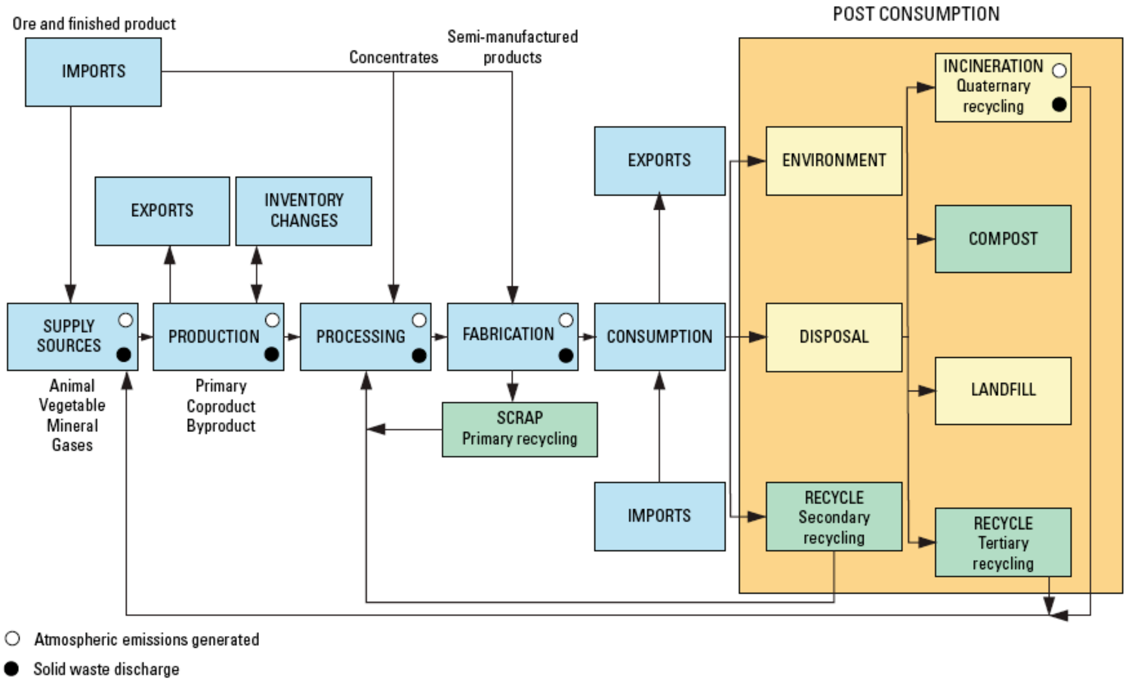


Figure 4. Schematic flow diagram for a metal (or other commodity). This diagram is far less complex than those presented in the literature for actual metals, yet still conveys the challenges associated with gathering and analysizing enough data to construct a meaningful diagram (from ref.1).

The third introductory element was the case study of tantalum capacitors as both a question of engineering ethics and supply chain risk. Tantalum capacitors are a minor component, but a major enabling element in portable electronics for personal, industrial, and medical electronics. In addition, tantalum carbide is an irreplaceable abrasive in industrial machining and it is a key alloying element in superalloys.

The case of tantalum is a helpful one in the classroom as it highlights the importance of not only understanding the technical applications, but also the supply chain. Using older trade publications it was possible to illustrate the vulnerability of a supply chain to a disruption of single component [8].

Secondly, the disparity of the annually updated information from the USGS on this metal and reality was only available by reference to the current popular and trade press. In particular, the latest USGS information available at the time of the class offering [9] states: *Tantalum ore and concentrate, metals, and waste and scrap were the leading imported tantalum materials, with each accounting for approximately equal amounts of tantalum. By weight, tantalum mineral concentrate imports for consumption were supplied 77% by Australia and 20% by Canada; metal, 24% by Brazil and 13% each by China and Japan; and waste and scrap, 18% by Australia, 14% by China, and 12% by Brazil.*

Furthermore it added: *Capital market problems and the subsequent economic slowdown were expected to result in reduced tantalum material consumption, price, and production*. Such information suggest neither availability or price would be a concern for an engineer designing with tantalum. However, immediately prior to class offering tremendous shifts occurred in the world situation. The worlds largest tantalum mine (in Australia) closed and operations were suspended in Canadian mines. These events were reported in the press [10-12] and the implications were discussed. This also provided an opportunity to discuss the importance of Internet information and methods to determine the pedigree of such information.

Finally, this case study allowed the ethical question of the minerals trade in the Democratic Republic of the Congo and its effect on internal military conflict with its associated horrors [13,14].

The balance of the course followed this pattern. That is, technical data and metallurgical uses of a metal were presented (in large part from metallurgical text books or papers published in archival or trade journals). Historical data was then made available (again a mix of both books and articles was employed). The student task became to obtain quantitative data to permit materials flow to be assessed (this included USGS, but also other sources when possible). Throughout the semester, future availability was predicted to the degree possible and alternative materials were considered. Finally, the use of the internet constrained to credible sources was consistently employed to obtain up-to-date information on the particular metal.

Summary: The course was not a success in terms of garnering a new population of students or of engaging a large number of students in a new topic. However, by all other measures it was highly successful. All learning objectives were met. The level of student engagement was high. Furthermore, the sought after synthesis of information from a variety of sources was accomplished with very little problem. The chief struggle was not to find sufficient information, but to vet the abundance of available information to get it down to a manageable size. Direct student interaction in this effort was very helpful in this initial offering, but this is expected to be a more challenging aspect of the course in the future as class size grows.

Finally, prior to future offerings more strategic positioning of the course will be attempted to ensure sustainable numbers of students are enrolled.

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