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The omnivorous diet of modern technology

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ABSTRACT

Two centuries ago the diet of technology (the diversity of materials utilized) consisted largely of natural materials and a few metals. A century later, the diversity in the diet had expanded to perhaps a dozen materials in common use. In contrast, today's technology employs nearly every material in the periodic table, a behavior illustrated in this paper by the material evolution of electronics, medical technology, and the jet engine. Geological deposits in a given country or region tend to have only minimal to moderate elemental diversity, however. As a result, an extensive and diverse metal trade is required if modern technology is to be sustained. Some recent industry responses to elemental scarcity and implications for corporate and governmental policy are discussed.

1. The materials of early technology

Materials diversity in manufacturing is a modern development. Historically, materials were employed more or less as nature had provided them – stone, wood, mud, thatch. Early metallurgy was able to use tin and copper ores to fashion bronze objects. Much later, in the Middle Ages, rudimentary forms of iron and steel were fashioned; these became stronger and easier to produce when the Bessemer Furnace was invented and improved upon in the late 18th and early 19th centuries. By 1900, industrial employment of mineral resources constituted perhaps a dozen elements, only a few of which were used widely.

It was not until the investigations of the analytical geochemists of the mid to late 19th century that most of the elements of the periodic table were identified. Nonetheless, they remained largely laboratory curiosities until modern materials science began in the last few decades to employ them for their specific physical and chemical properties. The trend continues today, with virtually no part of the periodic table left untouched.

As the material diet of technology has become more and more omnivorous, the trade of metals worldwide has noticeably escalated, such that a manufacturing company in one region of the world customarily employs materials from most other world regions. In a world with increasing population, increasing wealth, and declining ore deposits, it is reasonable to wonder if problems could lie ahead for today's most sophisticated technologies and technologically-advanced countries, or whether a materials science can be fashioned that returns to the use of the most abundant resources while maintaining and improving product function. These are the issues explored in this paper.

2. Examples of technological evolution

Technology innovators, whether they are companies or individuals, are continually seeking to improve the performance and reliability of their products, as well as to create new products for new applications. The pursuit of innovative products may involve new processes, new ideas, and in many cases new materials and elements. Each element has a unique suite of fundamental properties, including strength, conductivity, corrosion resistance, melting point, resistance to oxidation, magnetic strength, dielectric constant, and even radioactive half-life. A particular product type will place emphasis on one of these properties, or perhaps some optimal combination. As industries mature, they tend to seek out very specialized properties and to require specialized elements or combinations of elements. It would appear, based on recent history, that expanded sophistication of technology fundamentally requires more elements. To illustrate this, we consider the evolution in the use of elements for three applications: jet engines, medical technology, and electronics.

2.1. Evolution of jet-engine superalloys

Jet engines are one area of technology in which material elemental composition has clearly increased in complexity over time. The hotter an engine burns the more efficient it can be, and so engines require materials that have excellent strength and corrosion resistance at increasingly high temperatures. A class of

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materials referred to as superalloys has been used to provide these properties. The 20th century saw continual improvements (through elemental additions, among other factors) in these materials.

Superalloy development can be traced to the beginning of the 20th century with the discovery of austenitic stainless steel consisting of iron, chromium, and nickel. The high-temperature strength of stainless steel was quickly outgrown, however, and in 1929 nickel–chromium alloys utilizing aluminum, titanium, and niobium elements were first created (Sims, 1984). The late 1930s also saw the invention of the Vitallium alloy, a cobalt-based alloy that contains chromium and molybdenum.

Additional elements continued to be added in the next few decades, with tungsten added in the MAR-M-200 alloy to improve strength. The element tantalum was also added for similar purposes (Sims, 1984). In the late 1960s/early 1970s superalloys were further modified by the addition of the element hafnium to improve ductility (Donachie and Donachie, 2002).

In the late-1980s, alloys containing the additional element rhenium first started to appear (Walston et al., 1996). Rhenium is used to improve the temperature creep strength of superalloys, and its use as an alloy component distinguished "second-generation" single crystal alloys from "first generation" alloys. Increased concentrations of rhenium further distinguished third-generation alloys from those of second generation. Rhenium is by itself a very interesting and rare metal. It is not mined as a primary product, but rather is only recovered as a byproduct of molybdenum, which in turn is often a byproduct of copper. Fig. 1 depicts the trends in jet engine alloying elements over time and the resultant increased alloy strength at extreme temperature that resulted.

Coatings for the superalloys, used as a thermal barrier to increase operating temperatures, have themselves evolved to contain a number of uncommon elements. Yttrium is key among these, used because it improves adhesion of the oxide scale. Zirconium is another common coating element, used as a grain boundary strengthener.

The high temperature-strength materials have come a very long way in both performance and complexity from the stainless steels of the early 20st century. The jet engine of today contains a variety of different superalloys for different purposes within the engine, and thus a variety of elements. Fig. 2 depicts elements employed in one engine component, the turbine blade. Today's jet engine not only uses these more complex alloy systems, but also uses them in larger quantities. According to Donachie and Donachie (2002), the typical jet engine in 1950 contained 10% superalloys by weight; by 1985 that number had increased to 50%.

Finally, so-called "fourth generation" superalloys that add ruthenium as an additional alloying element have been developed in research labs (Koizumi et al., 2003). This indicates that the continual desire to improve superalloys is likely to involve additional elements in the future, if it is economically feasible to do so.

2.2. Evolution of nuclear medicine and medical imaging

Nuclear medicine is the use of radioactive substances for both the diagnosis and the treatment of disease. The field originated in the 1930s and 1940s, with the earliest clinical therapeutic application taking place in 1936 when John Lawrence used phosphorus-32 to treat leukemia (Society of Nuclear Medicine, 2012). Since that time the field has rapidly expanded, both in terms of the number of practitioners and in the variety of technologies and elements used. Today, over 200 radioisotopes are commonly employed for a variety of different medical purposes (World Nuclear Association, 2012).

Iodine-131 followed phosphorus-32 as an isotope utilized early in the history of nuclear medicine, with its first published clinical use occurring in 1939 (Society of Nuclear Medicine, 2012) and first application to thyroid cancer therapy in 1946 (Turner, 2012). This isotope was and still is used to treat thyroid cancer and to image the thyroid, along with other applications such as diagnosis of abnormal liver function. As is the case for several radioactive isotopes, the parent element can be different from the isotope element. In this case, most iodine-131 is produced from tellurium.

Table 1
The evolution of isotopes for use in nuclear medicine: a sampling.

Date	Isotope	Use
1936	Phosphorus-32	Lukemia treatment
1936	Sodium-24	Lukemia treatment
1939	Iodine-131	Thyroid imaging and treatment
1957	Xenon-133	Lung ventilation studies
1964	Technetium-99	Wide variety of imagining applications, especially skeleton and heart muscle
1973	Thallium-201	Diagnosis of coronary artery disease other heart conditions
1978	Fluorine-18	PET scans for studying brain physiology
1989	Rubidium-82	Myocardial perfusion imaging
1990	Indium-111	Brain studies, infection and colon transit studies
1991	Samarium-153	Pallative medicine, especially for bone cancers
1995	Holmium-166	Treatment of myeloma in bone marrow. Also being developed for liver tumors
2003	Yttrium-90	Cancer brachytherapy and pain relieve of arthritis
2006	Rhenium-188	Treatment and pain relief of skeletal metastases
2008	Lutetium-177	Prostate cancer applications

Later, in the mid-1960s through the early 1970s, the isotope technetium-99 was developed for medical purposes, and today this is the dominant isotope in use in nuclear medicine. Technetium is particularly well suited for medical imaging applications due to the emission spectrum of its radiation and its short half-life, which keep total patient radiation exposure low. The element is typically derived as a fission product of uranium through a molybdenum-99 intermediate. Xenon-133 was also developed for medical purposes around the same time period, and is used for pulmonary (lung) ventilation studies.

In the late 1970s and early 1980s new techniques in medical imaging were being developed, one important example being positron emission tomography (PET). In the PET scanning process, radioisotope decay can image a target tissue very precisely. The most important clinical role for PET scans is in oncology, but they are also used in cardiac and brain imaging. They thus provide additional imaging capabilities to the medical community using isotopes that include carbon-11, nitrogen-13, oxygen-15, and fluorine-18 (Hoh, 2007).

Many other isotopes have been developed for a variety of medical purposes. One area where additional isotopes are used is in palliative, or pain-relieving, treatments. Strontium-89 and samarium-153 have been used for the relief of cancer-induced bone pain, for example (Turner, 2012). Rhenium-186 is an isotope also used for this purpose.

New isotopes with specific medical properties continue to be employed. Lutetium-177, for example, an isotope identified for medical uses in the early 21st century (Turner, 2012), emits just enough gamma radiation for imaging and enough beta radiation to perform therapy on small tumors. Its half-life is long enough to allow sophisticated preparation for use (World Nuclear Association, 2012). This isotope complements yttrium-90, which was used for similar applications. Other commonly used isotopes include bismuth-213, palladium-103, dysprosium-165, erbium-169, holmium-166, ytterbium-169, and many more (World Nuclear Association, 2012). Table 1 provides a summary of some of the key

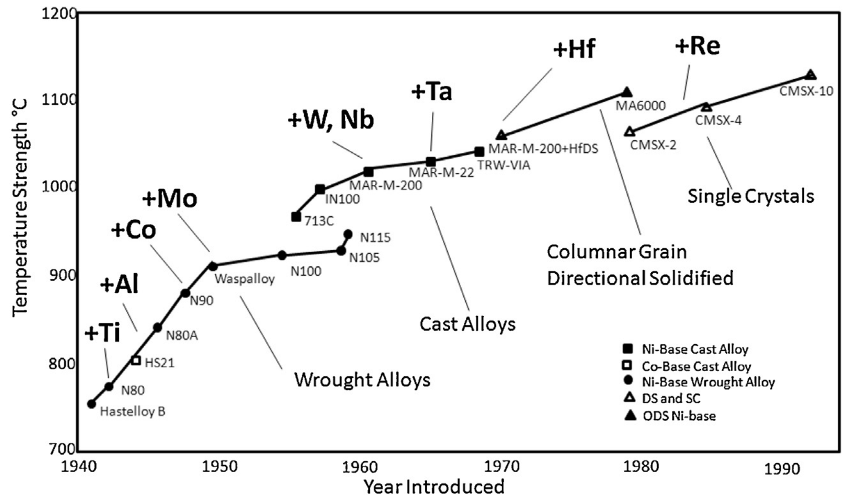

Fig. 1. Trend of superalloy strength with additional alloying elements. The "temperature strength" is the highest temperature at which the alloy maintains satisfactory physical properties for at least 100 h at 140 MPa pressure.
Adapted from Donachie and Donachie (2002).

radioactive isotopes along with their approximate date of introduction.

The nuclear medicine industry today is quite pervasive, with around 20 million procedures per year in the US alone (Fahey et al., 2011). The field continues to grow at a rate of about 10% per year. In order to perform these procedures, nuclear medicine has utilized an increasing number of elements with specialized radioactive properties, as outlined above. In addition to highly specialized elements, nuclear medicine also relies upon specialized processing to produce the radioisotopes, a reliance which was highlighted by the 2009–2010 medical isotope shortage caused by the unexpected shutdown of the CANDU reactor (Zakzouk, 2009).

Other applications of medical technology, such as magnetic resonance imaging (MRI), also contain a large and expanding number of elements. MRI machines need hundreds of pounds of magnets, and rare earth magnets have generally replaced earlier magnet technology in MRI machines. Fig. 3, focusing on elements used in GE Health Care products, shows the breadth of elements used over the broad health care technology segment.

2.3. Evolution of the electronics industry

The progress of the electronics industry over the 20th century and early 21st century has been profound, so much so that it could not have been foreseen even by some of its founding scientists and engineers (Kilby, 2000). Increasing material complexity has accompanied this progress, as the industry has used ever more elements and alloys in its continual drive to improve a variety of properties including magnetic strength, electrical conductivity, and capacitance, to drive down costs, and to decrease product size.

Magnetic hard-drives, for example, have seen incredible performance gains over the latter half of the 20th and early 21st centuries. In 1956, IBM sold its first hard drive, which stored 5 MB of data, at a cost of $50,000 dollars (Farrance, 2012). It was as large as two refrigerators. Today's standard PC hard drives hold 5–6 orders of magnitude more data and cost a tiny fraction of the price. These performance and cost improvements were achieved by the introduction of additional specialized elements and alloys, among other technological and process innovations. For

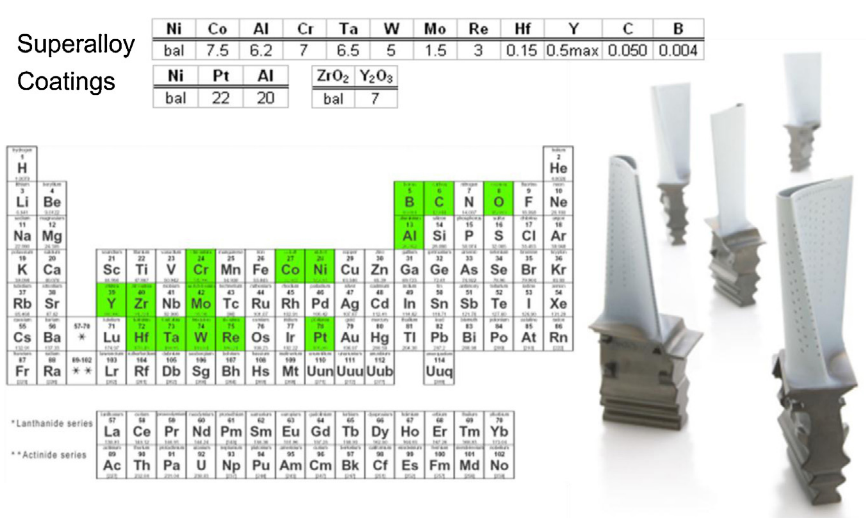

Fig. 2. Elements used in modern jet engine turbine blade superalloys and coatings (alloy Rene N5) (Duclos et al., 2010).
Figure courtesy of D.M. Lipkin, General Electric Central Research Laboratories (2010).

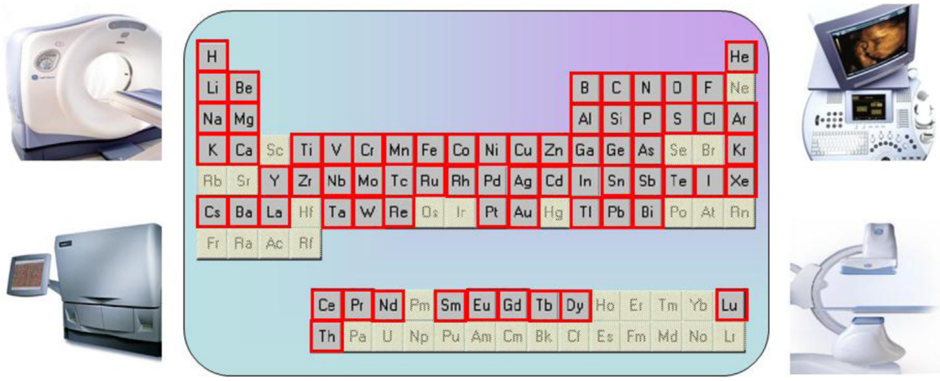

Fig. 3. GE Healthcare products use nearly all elements in the periodic table.
Courtesy of D.M. Lipkin, General Electric Central Research Laboratories (2010).

example, the magnetic material currently used in hard-disk heads is a neodymium–iron–boron alloy (NIB). This magnet type was first commercialized in 1983 and largely displaced another rare earth magnet, the samarium–cobalt magnet developed in the 1960s (Enokido, 2010). Although magnetically strong, NIB magnets are prone to oxidation due to the high iron content, and so additional elements such as nickel, copper, zinc, gold, silver, tin, titanium, and chromium are used as coatings to reduce corrosion (E-Magnets UK Limited, 2012). Another rare earth element, dysprosium, was later added to increase the performance of the magnet at elevated temperatures.

Integrated circuits, the core electronics processing components, have themselves undergone a large increase in material complexity in the drive to maximize the number of electronic constituents that could be integrated. Pecht and Prabhu (2006) provide an overview of some of the more common materials used today in these devices. These include silicon, gallium arsenide, indium phosphide, and germanium as semiconductor material; alumina, beryllia, copper, tungsten, and molybdenum for IC substrate materials; gold-tin, gold-germanium, and organic polyimide as attachment materials; gold, aluminum, copper, and silver as wire attachment materials; and tin-lead, antimony, bismuth, silver, and tin-indium for solder materials. The recent history of one IC component, digital random access memory (DRAM), is reviewed by Gerritsen et al. (2005). This history shows a trend (Fig. 4) from more common dielectric materials such as silicon dioxide in the 1980s to tantalum oxide, hafnium oxide, and zirconium oxide in the 2000s. The electrode material has also continued to evolve.

The breadth of elements used across the whole of the integrated circuit is depicted in Fig. 5, which shows the evolution in the elements used in an Intel printed circuit board over the past three decades. Beginning in the 1980s with only twelve elements in use, tantalum, tungsten, bromium, and titanium were added in the 1990s. In the 2000s, however, the elemental diversity exploded to the sixty or more used today – nearly every element that is not radioactive, water-soluble, or gaseous.

3. The geography of mineral deposits

As noted in the above examples, modern industry is dependent on access to a large spectrum of elements. Individual business entities must ensure that they have a reliable source of these raw materials. Raw material availability is a function of various factors, from geophysical (deposit quality) to political (export quotas). Recent work has sought to characterize this "supply risk" of material availability at a national as well as individual business level (Graedel et al., 2012). One aspect of this work focuses on the distribution of mineral deposits across different countries.

Nature is whimsical in the geography of ore deposits. Some countries and regions are richly endowed with a great diversity of resources, some have large deposits but of only a few different resources, some have very little at all. The situation can be demonstrated by examining the Mineral Reserve statistics for a wide variety of mineral commodities. The US Geological Survey defines Mineral Reserves as the in-place demonstrated mineral deposits that can be economically extracted at the present time. The degree to which deposits of a particular mineral are concentrated can be indicated by the Hershman-Hirshenfeld Index (U.S. Department of Justice and Federal Trade Commission, 2006), given by

$$\mathrm{HHI}_j = \sum_i (f_{i,j})^2$$

where f is the percentage of the global Mineral Reserves of mineral j in country i. (Note that if the entire Mineral Reserve is in a single country, HHI = 100^2 = 10,000, and if the Mineral Reserves are divided into three countries on a 50%/25%/25% basis then HHI, $50^2 + 25^2 + 25^2$, 3750.) A second variant of the HHI for a particular mineral commodity can be calculated from Mine Production statistics rather than Mineral Reserve statistics. Differences between these two variants of HHI indicate the possibility of evolution in mineral sourcing.

The HHI results for twenty select elementary mineral commodities are shown in Fig. 6, as calculated from U.S. Geological Survey data (USGS, 2012). HHI values above 3000 indicate that the mineral is dominated by one or two major countries. The figure shows both HHI variations; Mine Production and Mineral Reserves. It is interesting to note the minerals with the highest HHI according to Mine Production. These include the rare earths (elements vital to modern electronics), niobium (a critical element in steels and superalloys), antimony (used for a variety of purposes such as flame retardants), and platinum group metals (used as catalysts in the automotive and petrochemical industries). A new or sharply-expanding use for any of these resources would create an economic windfall for the countries hosting major deposits, should they choose to exploit their resource position.

The differences between Mine Production HHI and Mineral Reserve HHI for these high HHI mineral commodities contains some interesting information. For example, for the rare earth elements, although the mine production HHI is high the Mineral Reserve HHI is considerably lower. This indicates that additional rare earth deposits could be brought to the market (as is now beginning to happen) should the dominant country exploit its current market position. In contrast, the platinum group metals have a significantly lower Mine Production HHI than Mineral Reserve HHI. This may

Increasing elemental complexity →

Dielectric	SiO_2	NO	Si_3N_4	Ta_2O_5	Al_2O_3; HfO_2; ZrO_2
Electrode	Poly-silicon		HSG	TiN	WN ;TaN; Ru

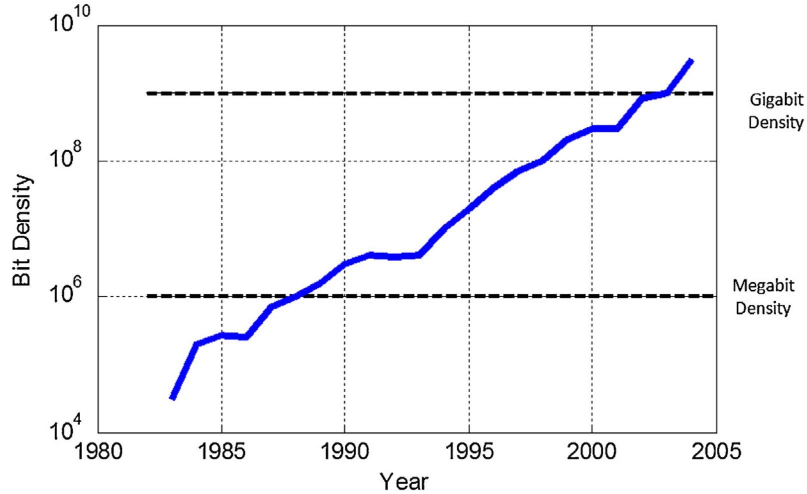

Fig. 4. Dynamic random access memory (DRAM) components in integrated circuits have used additional elements to improve performance. Bit density is the number of bits on an industry standard chip of area 65 mm^2.
Adapted from Gerritsen et al. (2005), see also Itoh (1990).

indicate that the production of these minerals will become more concentrated in the future.

Other minerals, including widely used metals such as aluminum and copper, are much more widely distributed than the high HHI minerals discussed above. These minerals have formed the backbone of technology since the Industrial Revolution, partly because of their ubiquity, partly because of their ability to be processed into useful forms by relatively uncomplicated procedures.

A second analysis of Mineral Reserve data that is useful is to look at deposit concentrations not by element, but by country. This can be done by determining for each country how many of its Mineral Reserve values fall into the top three countries in which deposits of that mineral occur. The results of that analysis for twenty selected mineral commodities are shown in Fig. 7. It is striking that of the 20 minerals whose HHIs appear in Fig. 6, the country with the largest number of significant domestic deposits (Australia) has only slightly more than 50%. Thus, although such countries as China, South Africa, Russia, and Australia could certainly be termed "mineral rich", even those countries do not possess anything like the full palette of elements employed by modern technology. For other countries, Mineral Reserves are significantly less diverse (as India) or minimal (as Germany). These latter countries,

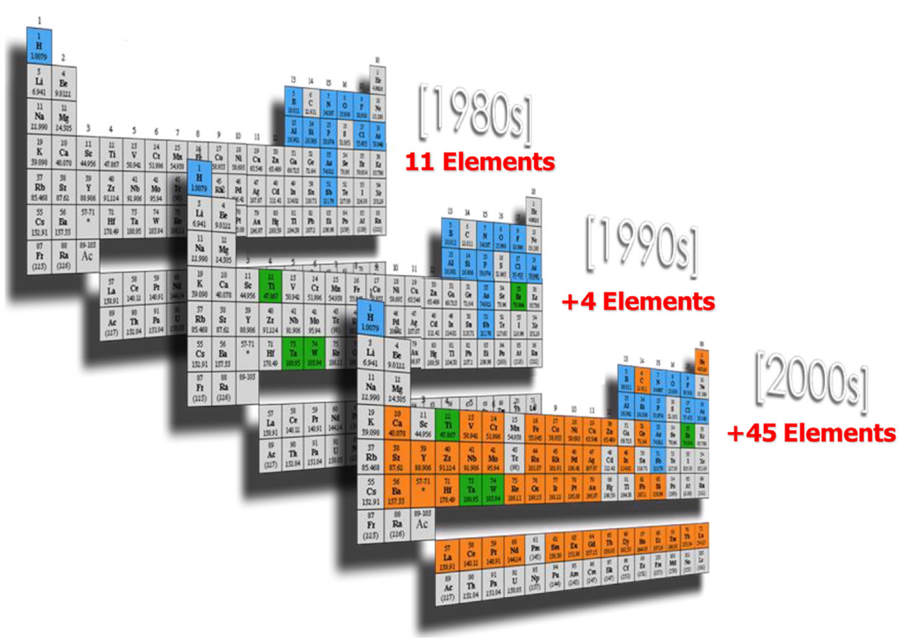

Fig. 5. The number of elements used in Intel products (shown by shading) has expanded rapidly.
Adapted from a figure courtesy of T. McManus, Intel Corporation (2006).

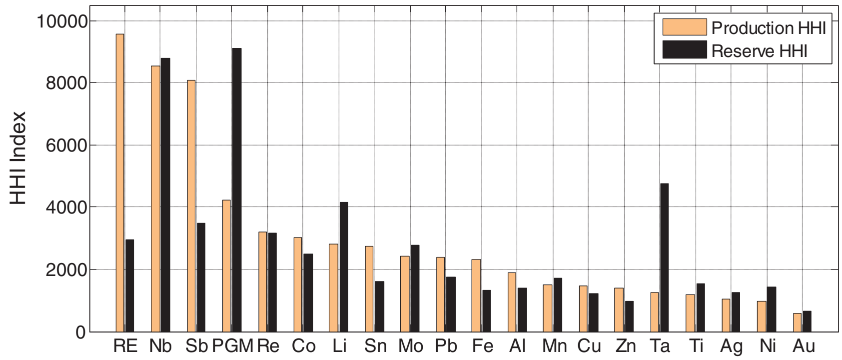

Fig. 6. HHI ratings indicate that certain elements are highly concentrated in a few countries (left bar – Mine Production HHI, right bar – Mineral Reserves HHI).

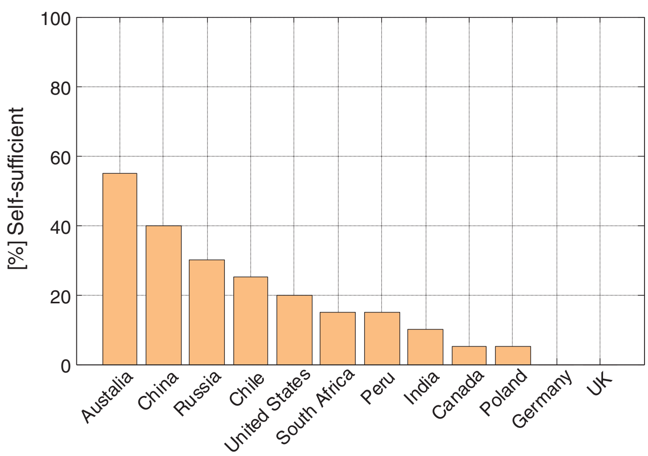

Fig. 7. For selected countries, the fraction of Reserves of 20 major mineral commodities whose magnitudes are among the top three in the world.

which may be capable of quite advanced technological economies, are very dependent on global trade to prevent elemental scarcity from becoming a problem for them.

4. Recent industry response to elemental scarcity

In some cases, elemental scarcity becomes a concern due to biophysical, political, or other causes. Recent export quotas on Chinese rare earths, where the elements are today mined nearly exclusively, constitute one such case. Technology companies must respond to such scarcity and the resultant changes in availability and price of raw materials in order to keep their products competitive, and have done so in a variety of ways. In this section, we consider two examples of companies responding to elemental scarcity in the 21st century in order to illustrate some of the possible approaches.

In the first example, we consider General Electric (GE), one of the major producers of aircraft jet engines. In 2006, the company recognized that demand for the critical alloying element rhenium was on pace to significantly outstrip the supply available for use (Fink et al., 2010). This, in turn, was expected to lead to a significant increase in rhenium prices. In order to minimize the company's exposure to these challenges, a rhenium reduction program was instituted which consisted of 4 strategies: *revert*, *recycle*, *recover*, and *reduce*.

The *revert*, *recycle*, and *recover* strategies all involve the collection of waste material containing rhenium, followed by the extraction of the rhenium for future use. In the case of *revert*, the collected material is waste material from the alloy foundry. *Recovery* relates to collecting grinding "swarf" from the engine parts manufacturing process. In the case of *recycling*, the collected material is previously fielded turbine hardware. Foundries already efficiently collect their waste material, so GE's focus was primarily on recovery of rhenium from swarf. Pilot research was conducted by GE to investigate various methods (pyrometallurgic and hydrometallurgic) to extract rhenium from the swarf, and a pilot process was developed and applied. The company reported that 90 kg of rhenium was recovered through 2009 by these actions (Fink et al., 2010).

The *reduce* strategy involved a redesign of the alloys used by GE, with the goal of maintaining their desirable properties while using less rhenium. GE also wanted to avoid introducing additional exotic elements when redesigning the alloy, as this could create other element scarcity problems in the future. After conducting an extensive development and test program, GE was able to develop two new alloys, one of which used a reduced amount of rhenium, and one which used no rhenium. Testing consisted of validating a wide variety of mechanical characteristics such as creep rupture and oxidation resistance, as well as ensuring that the alloy was compatible with manufacturing techniques. This testing represents a significant investment of time and money, but the investment has been rewarded as the alloy has now gone into service in the CFM56 engine.

As a second example, we consider TDK, one of the world's largest electronic component manufacturers. TDK has had a long history of development of magnetic materials since its founding in 1935, and in recent years has focused on reducing the dysprosium content in its neodymium–iron–boron (NIB) magnets (Enokido, 2010). As in the rhenium example, the desire to reduce the magnet's dysprosium content was driven by the scarcity of the element and the resultant impacts on availability and price.

TDK's solution to reduce its dependence on dysprosium (Dy) was largely one of process redesign. In an older process, low Dy and high Dy alloys were mixed together and baked at high temperatures to uniformly spread dysprosium throughout the crystalline particles that make up the structure of the magnet. TDK was able to develop a new process that diffuses Dy directly onto the surface of crystalline particles through a low-temperature heat treatment. In this way, it was found that 20–50% less Dy could be used than the previous process, and the magnet's properties were improved as well (Enokido, 2010).

Thus, several forward-looking technology corporations have recently focused on reducing their dependence on elements perceived as scarce. In the two examples surveyed, strategies to reduce dependence consisted of collection and reuse of various waste materials (GE), redesign of an alloy product (GE), and redesign of a manufacturing process (TDK). These examples illustrate some of the possible strategies available to technology companies as they focus on element scarcity as well as product performance in their business decisions.

5. Discussion

Modern industry and technology have evolved to require a full palette of materials, and yet geological deposits of different minerals are widely dispersed. This situation implies that modern technology renders no region of the world independent of other regions. Future developments in high-temperature technology, in energy technologies such as solar cells and wind power, and in specialty areas as in the electronics and medical imaging can be expected to further increase this interdependence. In a connected world many different factors, from domestic mineral supplies to international export quotas, can lead to disruptive material and element shortages. It is thus important for all countries and corporations to consider strategies to mitigate possible shortages.

One initial step is to quantify the level of interdependence for mineral commodities though the HHI metric discussed above. This metric indicates the degree to which supply is concentrated in the hands of a small number of countries, and thus may be prone to restriction. Market power due to supply concentration may allow a country to raise prices opportunistically to take advantage of a weak buyer. Once high HHI elements are identified, policy makers may choose to take action to diversify sources of elements by providing incentives for domestic production, for example, or by supporting expanded production in developing countries prior to a price signal reaching a product manufacturer.

The degree of concentration of elements is one important factor in insulating technology from raw material and element shortages, but not the only one. The criticality work discussed in Graedel et al. (2012) and the methods developed by the National Research Council (2008a) are both directed toward creating a framework for understanding overall element criticality more broadly. The methodology developed in these works is based on multiple criteria for metal criticality that capture geophysical availability, political considerations, and substitutability, as well as environmental impacts. Studies specific to particular industries, such as clean energy technologies (U.S. Department of Energy (2010) and military hardware National Research Council (2008b), are also important in understanding the detailed implications of particular elements to specific sectors.

Product design and manufacturing is an additional tool to minimize the disruption of industry due to raw material shortages. This work reviewed recent industry responses by GE to reduce rhenium through alloy redesign and rhenium recovery from scrap materials in several life cycle stages, as well as process changes made by TDK to reduce the amount of dysprosium required to make its rare earth magnets. These strategies are applicable to other technology areas as well. For corporations concerned about supply risk, designing away from elements with high HHIs is also a useful strategy, especially if the countries containing the large mineral fractions are viewed as potentially problematic.

As we begin the 21st century, we find modern technology utilizing the full spectrum of elements, both geologically rare, and geologically more common. International trade supplies these elements from every corner of the globe to appropriate markets. It is interesting to think about long-term sustainability questions and strategies regarding this full utilization of elements. In particular, if the geological availability of rare elements becomes a concern, one long-term strategy could be to minimize the use of these elements in design, focusing instead on achieving better material properties through more clever combinations of common elements. Another strategy could be further geological exploration for rare elements combined with better reuse/recycling of these elements. Industries that utilize rare elements may not be able to formulate a long-term strategy (20–50 year time spans) based on the limits of geologic availability, but instead could focus on short-term economic projections. Notwithstanding these approaches, it is clear that the time when ready availability of the full spectrum of elements can be assumed may be coming to an end. With product design under the shadow of material constraints likely to be increasingly common in the future, the prospects for materials supply and demand need to be part of the thinking of every product development team from this point forward.

Acknowledgement

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