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The criticality of four nuclear energy metals

E.M. Harper[a,*], Zhouwei Diao[a], Stefania Panousi[a], Philip Nuss[a], Matthew J. Eckelman[b], T.E. Graedel[a]

[a] *Center for Industrial Ecology, School of Forestry and Environmental Studies, Yale University, 195 Prospect Street, New Haven, CT 06511, United States*
[b] *Civil and Environmental Engineering Department, Northeastern University, 360 Huntington Avenue, Boston, MA 02115, United States*

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ABSTRACT

Concerns about the future balance between the supply and demand of metals have inspired research to define and assess metal criticality. Here we apply a comprehensive criticality methodology to four metals with uses in nuclear energy: zirconium (Zr), hafnium (Hf), thorium (Th), and uranium (U). 2008 criticality assessments for these metals were made on the national level for the United States and on the global level. The results and uncertainty estimates in three-dimensional "criticality space" are comprised of supply risk (SR), vulnerability to supply restriction (VSR), and environmental implications (EI) axes. The SR score is the highest for zirconium over both the medium term (i.e., 5–10 years) and the long term (i.e., a few decades). The cradle-to-gate EI score is highest for uranium, followed by hafnium and then thorium, with impacts due to a combination of on-site emissions and upstream burdens from the use of energy and materials during mineral processing and refining. Uranium has the highest VSR score at the national level, and the second highest at the global level. Zirconium is the most vulnerable at the global level. In general, SR for the four metals are reasonably high for the United States and more moderate for the planet, while EI and VSR scores are low to moderate. Overall, the criticality of the metals analyzed appears not to be of high concern, either nationally or globally.

1. Introduction

Energy is now a crucial part of the infrastructure and maintenance of society in almost all countries. As more concerns have appeared in recent years concerning the reliability of supplies of traditional energy resources, and the climate change issues connected with fossil fuels, nuclear energy has remained an alternative. Although many countries postponed their nuclear development after Japan's Fukushima Disaster of 2011 and Germany decided for a stepwise phase-out of nuclear energy to be completed by 2022 (Jahn and Korolczuk, 2012), others continue to construct new nuclear power plants for civilian use.

In the United States, there are 104 commercial nuclear reactors in operation at 65 sites, generating approximately 20% of electricity (USEIA, 2014b). Worldwide and in 2010, nuclear reactors supplied approximately 10% of the world's electricity, and is one of the fastest-growing sources, with an annual increase in generation of 2.5% (USEIA, 2013). Some countries rely on nuclear power for the majority of their electricity generation (such as France, USEIA, 2014a). Over 70 new reactors are currently under construction in 15 countries, indicating ongoing investment in this sector (IAEA, 2014). Nuclear reactors are not limited to electricity generating stations, but are also used to power large military vessels and are vital in the provision of radioactive isotopes for a wide range of medical uses, especially imaging technologies. An aspect of nuclear technology that is often overlooked is that it requires a set of unique metals for its construction and operation, and the routine availability of those metals is thus a topic of interest, as any uncertainty in their supply may have relevance to the energy security of the world.

In 2008 the United States National Research Council (NRC) published a structured assessment of the criticality of non-renewable resources, which evaluates both the risk of unreliable supply of metals and minerals and the impact of such a restriction on the organization being assessed (NRC, 2008). A number of other research efforts (e.g., Morley and Eatherley, 2008; European Commission, 2010, 2014; British Geological Survey, 2011, 2012 have built upon that beginning, but they produced different results due to differences in methodology and perspective (Erdmann and Graedel, 2011). Some of the efforts in criticality research specifically evaluate elements used in the energy industry, with different scopes and methodologies (Moss et al., 2011, 2013; USDOE, 2010).

Our research group created a detailed methodology to generate assessments of the criticality of metals based upon the

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[*] Corresponding author. Tel.: +1 203 228 2902.
E-mail address: ermelinda.harper@yale.edu (E.M. Harper).

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NRC's conceptual foundation but employing enhanced levels of scope, rigor, and transparency. We display the results on a three-dimensional criticality plot, comprised of supply risk, environmental implications, and vulnerability to supply restriction (Graedel et al., 2012). This methodology was first applied to the geological copper family (Nassar et al., 2012), and a slightly modified methodology was later applied to the zinc, tin, lead geological family (Harper et al., 2015); to iron and its alloying elements (Nuss et al., 2014); to the rare earth elements (Nassar et al., 2015); and to a group of specialty metals (Panousi et al., 2015).

In the present work, we assess the criticality of four metals that are central to modern nuclear energy technology: zirconium, hafnium, thorium, and uranium. We group the metals by their unique and crucial functions in the nuclear energy industry rather than by a reflection of their geological occurrence. Uranium and thorium are known for their applications as energy sources for nuclear power generators, with uranium being the major energy source used in this way. Thorium's main uses are in gas mantles for lighting applications, refractory applications, and with tungsten in welding electrodes, although it has the potential to be used in nuclear power generators (Cuney, 2012). Zirconium is used in ceramics, refractories, foundry molds, and, for purposes of this paper, hafnium-free zirconium metal is used to clad nuclear fuel rod tubes. Hafnium has diverse uses that include its use as a thermal neutron absorber in nuclear power reactors. A number of metals that have more varied industrial uses are also employed in nuclear energy facilities, including iron, tungsten, chromium, and nickel for properties such as shielding. We have addressed those metals in other studies similar to that of this paper (e.g., Nuss et al., 2014). Restrictions to the availability of any of these elements have the potential to constrain the development of nuclear energy and other related industries, and an assessment of their criticality is, therefore, of significant interest to countries with civilian nuclear facilities.

It is important to point out in the context of this work that the word "criticality" is used here in a way different from that often encountered in the physical sciences, where the associated word "critical" can be employed to indicate a transition from one state of a system to another (as in "critical point" or "critical angle", where "critical" is an adjective). In contrast, in this paper and elsewhere (e.g., National Research Council, 2008; United States Department of Energy, 2010; European Commission, 2010, 2014), "criticality" sees use as a noun that refers to the degree to which a given resource has high importance of use and potentially restricted availability. In this usage, a transition from one state to another is not implied, although boundaries have sometimes been imposed (EC, 2010, 2014) to designate some materials as "critical" from importance and availability perspectives.

2. Materials and methods

Criticality is dependent upon a number of diverse factors that span, for example, the topics of geology, regulation, geopolitics, and material science. Some factors are quantitative, while others require a more qualitative evaluation. We evaluate metals in three-dimensional "criticality space" where one axis is supply risk (SR), another is environmental implications (EI), and the third is vulnerability to supply restriction (VSR). Each axis is composed of equally weighted components that, in turn, are composed of equally weighted indicators whose quantification is discussed in detail in previous publications (i.e., Graedel et al., 2012; Harper et al., 2015) (see the Supporting information for criticality diagrams at the global and national levels).

All indicators are transformed to a 0–100 scale (transformations are provided in the Supporting information). Indicators are weighted equally, and all data and results are for year 2008. We explicitly estimate a quantitative uncertainty by Monte Carlo analysis for each indicator included in the three dimensions. Each indicator was varied over its assigned uncertainty range for 10,000 iterations, resulting in an "uncertainty cloud" in criticality space (further details provided in the supporting information). Global and national (i.e., United States) analyses were considered, and figures displaying the methodology are in the supporting information. Additionally, a list of acronyms and abbreviations for the components and indicators is provided as an Appendix to this manuscript.

2.1. Supply risk for the four nuclear energy metals

SR consists of three equally weighted components – geological, technological, and economic (GTE), social and regulatory (S&R), and geopolitical (GP)–that, in turn, are comprised of indicators, also equally weighted. Unequal weighting is an option for analysts to adjust if desired. The evaluation of each indicator is transformed to a 0 to 100 scale, which represents low to high SR. The indicators are fully described in Graedel et al. (2012), and are briefly addressed here.

GTE is comprised of depletion time (DT) and companion metal fraction (CF) indicators. DT is an estimate of the geological abundance and abundance of available end-of-life scrap of each metal relative to current production rate, while CF represents the percentage of the metal mined as a companion (i.e., recovered as a byproduct from the ore of a host metal, rather than mined for itself). Note that the geological supply refers to terrestrial supplies. In the case of uranium, there is a longstanding trend to cite large quantities of uranium in seawater as a potential supply source (e.g., Davies et al., 1964; Rogner et al., 2012), and research efforts that focus on its efficient extraction from seawater are currently underway (e.g., Lu, 2014). The DT evaluation considers historical models of use so that losses during each metal's production, as well as the secondary end-of-life supply of each metal, may be considered (details in the Supporting information).

S&R is composed of policy potential index (PPI) (McMahon and Cervantes, 2011) and human development index (HDI) (UNDP, 2012). McMahon and Cervantes indicate that PPI represents "a report card to governments on how attractive their policies are from the point of view of an exploration manager" (McMahon and Cervantes, 2011). HDI is a summary measure of human development based upon a measure of health, education, and living standards (UNDP, 2012). Our evaluation of HDI is based upon the premise that a high level of human development would result in a dispreference for intrusive industrial development.

GP is composed of worldwide governance indicators – political stability and absence of violence/terrorism (WGI-PV) (World Bank, 2012), and global supply concentration (GSC) based on the Herfindahl–Hirschman index (HHI) (United States Department of Justice and Federal Trade Commission, 2006). HHI is a metric commonly used to measure market concentration, and is included to address the risk of mining or refining production being concentrated in a small number of countries (United States Department of Justice and Federal Trade Commission, 2006).

Several SR indicators – PPI, HDI, and WGI-PV – were weighted by each metal's production on a country basis. For all indicators that were weighted, each except for PPI was weighted using either the metal's mining or refining production, whichever yielded the higher risk score. In this way, the production step that has the higher risk as the "bottleneck" most likely to cause a supply constraint. This selection of the higher risk production weighting was not used for PPI, because PPI is inherently based on mining factors and thus should only be based on mining considerations.

In cases in which a metal is a companion of another metal (a host metal), the host metal's mine production data may be utilized to