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Shifts and trends in the global anthropogenic stocks and flows of tantalum

Nedal T. Nassar*

National Minerals Information Cente, U.S.Geological Survey, USA

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ABSTRACT

The supply and demand of tantalum has undergone a number of significant shifts over the past few decades. The purpose of this work is to quantify how these shifts have affected tantalum's global material cycle. A global stocks and flows model for tantalum has thus been developed for the years 1970–2015. The results indicate that the overall quantity of tantalum prompt scrap generated during manufacturing has increased notably due to tantalum's increased use as an alloy additive and sputtering target. In contrast, the amount of tantalum contained in recycled obsolete scrap, mainly in the form of used carbides, is estimated to have remained relatively constant since the late-1980s. Moreover, tantalum's overall end-of-life recycling rate (EoL-RR) seems to have declined from a high of 22–25% in the 1990s to approximately 18% today. This decline is also attributable to the shift in tantalum's use from carbides to sputtering targets and chemicals that, along with tantalum's use in capacitors, have not been recycled at the end-of-life (EoL) in significant quantities. The results also indicate that 21–25% of tantalum produced since 1970 is still in use today, with the remainder having been lost during processing, manufacturing, use, or at the EoL. However, a portion of the EoL "discards" may actually still be retained by the end-user as "hibernating" stocks that could potentially be recycled if the economic, technical, and behavioral challenges of recycling obsolete electronics are overcome.

1. Introduction

Superior acid corrosion resistance, ductility, wear resistance, biocompatibility, high melting point, high strength at elevated temperatures, and the ability to efficiently and reliably store and release electrical charge are just a few of the properties that have made tantalum (Ta) the element of choice for a multitude of highly specialized applications in a wide range of industries including automotive, aerospace, chemical processing, defense, electronics, medical, and metallurgy. Despite the significance of tantalum to a number of strategic industries, the tantalum industry itself has traditionally been "shrouded in secrecy" (Papp, 2011). Indeed, tantalum is noted as one of a handful of commodities for which the information and data necessary for developing detailed material flow analyses (MFAs) are most limited (Risk and Policy Analysts Limited, 2012). The lack of transparency is due, in part, to the fact that tantalum mineral concentrates are not traded on commodity exchanges but are instead sold under fixed-price contracts through a network of dealers (Bleiwas et al., 2015; Burt and Schwela, 2013). Furthermore, the tantalum supply chain is dominated by a small number of processors (the tantalum equivalent to smelters) that act as a "pinch point" of the supply chain (Burt and Schwela, 2013).

What is known about the tantalum industry is that there have been a number of significant shifts in both its supply and demand over the past few decades. On the supply side, tantalum primary production (i.e., tantalum mine production and tantalum recovered from tin slags) has undergone two major shifts since the 1970s. The first was the decline in the relative contribution of tantalum recovered from tin slags to the global tantalum supply. The second was the shift from "industrial" or "conventional" mining operations in developed countries like Australia to artisanal mining operations in the Democratic Republic of the Congo (D.R. Congo) and Rwanda (Bleiwas et al., 2015). On the demand side, the tantalum market has also undergone a number of notable changes over the past few decades including a number of boom-and-bust cycles, a shift away from the use of tantalum in carbides (mainly due to substitution) to an increased use in alloy additives, chemicals, and sputtering targets, as well as an overall trend toward industry consolidation and restructuring. A detailed narrative of these supply and demand shifts in presented in Appendix A.

These changes and shifts in tantalum's supply and demand patterns have been reflected in recent assessments of its "criticality." Indeed, tantalum's categorization as a "critical" metal has varied by not only the methodology employed but also the timeframe utilized by these analyses. For example, the U.S. National Research Council (NRC) report did not consider tantalum as one of the more critical commodities examined due to a relatively "moderate" supply risk (US National Research Council, 2008). The NRC report was, however, published in

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* Correspondence to: 12201 Sunrise Valley Dr MS 988, Reston, VA 20192 USA.
E-mail address: nnassar@usgs.gov.

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Table 1
Summary information on the major tantalum applications.

Application	Typical end-uses	Tantalum material
Capacitors	Electronics including: ● Communication (cellular phones) ● Computer and business machines (desktop and laptop computers, tablets, printers) ● Consumer electronics (video cameras, digital still cameras, digital audio players, flat screen televisions, game consoles, battery chargers), ● Medical devices (hearing aids, pace makers) ● Automotive components (airbag activation, engine management modules, global position systems) ● Other equipment (oil well probes, power rectifiers, cellular phone base stations)	Capacitor-grade powders and mill products in the form of wires as anode leads and sintering tray assemblies and shielding components for the anode sintering furnaces
Carbides	Cutting and boring tool inserts	Tantalum carbide (TaC)
Chemicals	Large variety of tantalum chemicals and compounds that are used in a wide range of applications including optoelectronics, optical glass, lead zirconate titanate ceramics, microwave ceramics, catalysts, pigments, metallurgy, chemical vapor deposition precursors, sol-gel, chemical and powder synthesis, and thin film resistors.	Examples include K_2TaF_7, Ta_2O_5, $TaCl_5$, $LiTaO_3$, $Ta(OC_2H_5)_5$, $Ta(OCH_2CH_2CH_2CH_3)_5$, $Ta(OCH_3)_5$, TaN, $TaSi_2$, $TaAl_3$, TaB_2, TaH, TaS_2, $TaBr_5$, TaF_5, Ta amides, and ferro-Ta alloys
Mill products	● Chemical processing equipment (pipe lining, cladding, tanks, valves, bayonet heaters, and heat exchanges) ● Cathodic protection for steel structures ● Corrosion resistant hardware (screws, nuts, bolts, and fasteners) ● Medical applications (prosthetic devices, hip joints, stents, implants, and suture clips) ● Military and aerospace applications (kinetic energy projectiles and aircraft flame shields) ● Nuclear applications (containers for nuclear waste and for melting and sintering of rare earths and plutonium)	Tantalum fabricated sheets, plates, rods, and wires, etc.
Alloy additives	Additive to certain nickel- and cobalt-based superalloys used mainly in aircraft engines and land-based gas turbines	Tantalum ingots, metallurgical-grade tantalum powders
Sputtering targets	Semiconductors, magnetic storage media, inkjet printer heads, logic circuitry, and flat panel displays	Tantalum ingots, metallurgical-grade tantalum, mill products

2008 using statistics from the year 2007 or before—a time period in which the majority of tantalum was being produced in countries that were deemed “reliable suppliers,” namely Australia, Brazil, and Canada. In contrast, the 2010 European Commission report on critical raw materials noted tantalum as “critical” for the European Union (European Commission, 2010). Tantalum was, however, dropped from the list in the updated 2014 report due to a reduced supply risk indicator score that was a result of changes in the concentration of tantalum primary production (European Commission, 2014). Other assessments (e.g., British Geological Survey, 2016; Graedel et al., 2015; U.S. National Science and Technology Council, 2016) have similarly provided varied results often due to the time period considered in the analysis.

A consistent need of these and other assessments is more rigorous and complete information on the sources, uses, losses, stocks, and recycling of the commodities examined. Providing insight on these factors helps address concerns regarding potential supply shortages, supply diversification and security, resource efficiency, and the potential for future recycling. By quantifying the anthropogenic flow of material through each stage of a commodity’s life cycle, MFAs have been used to provide such insights for a number of nonfuel mineral commodities including other refractory metals, such as tungsten (Harper and Graedel, 2008; Harper, 2008; Leal-Ayala et al., 2015; Shedd, 2011a, 2011b; Smith, 1994), and ferrous metals, such as cobalt (Harper et al., 2012 Shedd, 2004, 1993; Shedd, 1993), that are used in similar applications as tantalum.

A review of the literature yielded only five MFAs on tantalum: a global assessment focused mainly on tantalum’s use in capacitors and carbides in the mid-1990s (Hoppe and Korinek, 1995); an assessment of tantalum flows in the United States in the year 1998 (Cunningham, 2004); a global assessment of relative tantalum flows (no absolute quantities provided) in the year 2011 (Gille and Meier, 2012); a global assessment of tantalum flows in the year 2014 focused solely on the metallurgical processing stage of the life cycle (Achebe, 2016); and a detailed study on the flows of tantalum in Europe (Deetman et al., 2017). In addition to these five studies, there have also been a few efforts that have attempted to track tantalum along its supply chain (e.g., Bleischwitz et al., 2012; Soto-Viruet et al., 2013; Young, 2015). These studies provide a useful foundation for understanding the tantalum cycle. However, given that these studies are only single snapshots in time, they do not provide any insights as to how the significant shifts in tantalum’s supply and demand over the past few decades have affected its material flows. Moreover, to the author’s knowledge, no comprehensive global assessment of tantalum stocks in-use has been published in the literature. The goal of this work is, therefore, to provide a comprehensive quantification of the global anthropogenic flows of tantalum through its five main life cycle stages (primary production, processing, manufacturing, use, and end-of-life (EoL)) over a time period of several decades (1970–2015) and to provide estimates of global tantalum stocks in-use by application for the same time period.

2. Data and methods

2.1. Data

The construction of the global anthropogenic flows of tantalum through its five main life cycle stages involved the collection of supply and demand statistics from number of different sources in the literature, including various publications from the National Minerals Information Center at the U.S. Geological Survey (Bleiwas et al., 2015; US Geological Survey, 2017, 2016a, 2016b) and its predecessor at the U.S. Bureau of Mines (Cunningham, 1985; Griffith and Sheridan, 1970; Jones, 1980; Stipp, 1976), the British Geological Survey (Brown et al., 2016), the Tantalum-Niobium International Study Center (Burt and Schwela, 2013; Grey, 1990; Korinek, 1994, 1988; Linden, 2000, 1999, 1995, 1983; Tantalum-Niobium International Study Center, 2017), Roskill Information Services (Roskill Information Services Ltd., 2016; Roskill Information Services Ltd., 2012; Roskill Information Services