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On the current and future availability of gallium

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ABSTRACT

By-product availability curves were constructed for the production of gallium from bauxite, sulphidic zinc ores and coal. They were used to assess the nature of the current supply regime, as well as its potential future development. Not only was the current situation found to be firmly in the elastic supply regime for all three raw materials, indicating that significant future increases in primary gallium production are possible without increases in the production of the corresponding main products, but it was also found that current supply potential from bauxite and sulphidic zinc ores alone is at least five times higher than current primary production. Coal offers a significant additional supply potential (currently at least ~1.3 times primary gallium production). An extrapolation of growth trends for the primary production of bauxite, zinc and gallium into the future indicates that the minimum supply potential will not be utilised completely before 2050. Once this point is reached, additional increases in primary gallium production relative to the production of bauxite and zinc will still be possible via decreases in the relevant cut-off grades for extraction from these raw materials. No persistent shortages are expected in the foreseeable future. Short-term shortages might, however, occur but will not be due to geological factors. Our results clearly refute the notion that the supply of all by-product high-tech metals is currently restricted by their physical abundance in associated main products. Rather, the chief limitation appears to be installed production capacity.

1. Introduction

Gallium, a soft white metal, was discovered as a trace constituent in sphalerite (ZnS) in 1875 (Lecoq de Boisbaudran, 1875). It is named after the native country of its discoverer, France (Latin: *Gallia*). Remaining of little commercial interest up to the 1960s, some of its compounds have now found a number of important applications in the high-tech sector. The use of gallium arsenide (GaAs) and gallium nitride (GaN) in integrated circuits accounts for about 74% of total U.S. gallium consumption, while most of the remainder is due to optoelectronic devices such as solar cells, LEDs and photodetectors (Jaskula, 2015a). Integrated circuits based on GaAs or GaN offer lower energy consumption and higher computation speeds than standard silicon products and are therefore chiefly employed in mobile telecommunications and military applications. Gallium also finds minor use as a component in various low-melting-point alloys, as well as the plutonium alloy commonly used in nuclear weapons (Edwards et al., 1968; Hecker, 2000). Of scientific interest and historic importance is its application in neutrino detectors (e.g. Altmann et al., 2005).

Because its major applications are considered crucial for the functioning of modern economies (Angerer et al., 2009), and there are concerns about the security of its supply, gallium was identified as a 'critical' raw material by a number of recent studies (Erdmann and Graedel, 2011; European Commission, 2014). Gallium production has been growing at an average rate of 7.4% p.a. for the past 40 years (Fig. 1), much faster than most industrial metals (cf. data in Kelly and Matos (2013)). It will likely need to continue this growth in order to satisfy the rapidly increasing demand from its main applications (Angerer et al., 2009). Assuming similar future recycling rates as today and continued growth at a rate of 7.4% p.a., this means a more than tenfold increase in primary production might be required by 2050, raising the important question whether this trend is sustainable. Concerns over the future availability of gallium are due particularly to its importance in the production of thin-film photovoltaics (e.g. Fizaine, 2013).

Gallium is won as a by-product from both zinc and alumina production (Jaskula, 2015a), the latter being the most important

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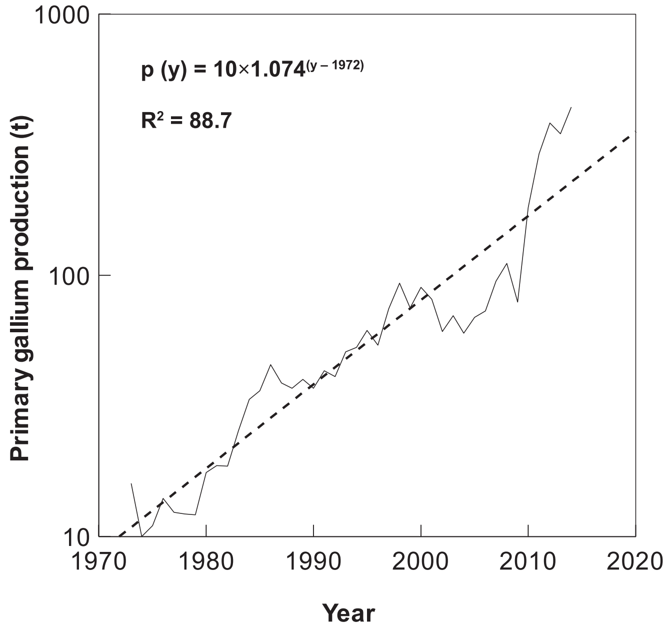

Fig. 1. Evolution of primary gallium production from 1973 through 2014. Data from Kelly and Matos (2013) and Jaskula (2015a). The fitted line corresponds to an exponential growth curve. *p* – primary gallium production, *y* – year.

source. Since the value of gallium contained in the corresponding ores is small compared to that of the main product (e.g. Wellmer et al., 1990; Andersson, 2000), the capacity for gallium production is ultimately limited by the production of the main products (cf. Campbell, 1985).[1] To adequately assess future supply risks, estimates of gallium availability should take this limitation into account and refer to annual potential rather than total reserves or resources (cf. Frenzel et al., 2015a). In the short term, installed production capacity will also be an important limitation, but this will not be considered here because we are mainly interested in the medium to long term.

Since the potential for supply problems was hypothesised as early as 1975, a number of studies on gallium availability have already been conducted (Chin, 1975; Rosi, 1980; Watts et al., 1980; Katrak and Agarwal, 1981; Kramer, 1988; Andersson, 2000; Elsner et al., 2010; Zuser and Rechenberger, 2011; Butcher and Brown, 2014; Jaskula, 2015a; Licht et al., 2015). However, most of these constrain their detailed considerations to alumina and make unrealistically high-estimates based on overall gallium recoveries of >30–50% from bauxite (Rosi, 1980; Katrak and Agarwal, 1981; Kramer, 1988; Elsner et al., 2010). Others limit themselves to stating the total amount of gallium contained in global bauxite reserves or annual production (Chin, 1975; Andersson, 2000; Zuser and Rechenberger, 2011; Fizaine, 2013; Butcher and Brown, 2014; Jaskula, 2015a). Where sources other than bauxite were considered, this is usually limited to stating average concentrations and total amounts associated to reserves or annual production (e.g. Katrak and Agarwal, 1981; Andersson, 2000). Licht et al. (2015) assumed unrealistically high-recoveries from bauxite, zinc ores and coal, and also limited their considerations to mean concentrations. Statistical uncertainties were never considered. Løvik et al. (2015) recently made an improved estimate of the amount of gallium extractable from bauxite. However, they did not consider zinc ores and coal in detail, nor did they account for the effects of variable bauxite composition on the recovery of gallium.

In addition to studies focusing on extractable quantities contained in current process streams, two recent studies attempted an assessment via the evaluation of correlations between gallium and aluminium prices (Fizaine, 2013; Afflerbach et al., 2014). While their results have some relevance for the current situation, they do not provide the detailed quantitative understanding necessary to evaluate potential future developments.

The need for a detailed and realistic new estimate of the availability of gallium from various conventional and non-conventional resource types should therefore be apparent. Such an estimate should necessarily incorporate data on the processing behaviour of gallium to yield realistic scenarios for achievable recoveries. It should also incorporate considerations of statistical uncertainty. The aim of this article is to provide such an estimate and discuss its implications with respect to possible future developments in primary gallium production.

Bauxite, sulphidic zinc ores and coal will be considered as sources of by-product gallium. This choice reflects both current and past trends in production: the majority of all primary gallium is now produced from process solutions in the Bayer Process (alumina refining), while the remainder comes from zinc-smelter residues (Jaskula, 2015a, 2015b). In the past, coal-gasification fly-ash also constituted an important source (Clark, 1953).

Other sources of by-product gallium have been suggested in the literature: flue dusts from the pyrometallurgical smelting of phosphorus (Neylan et al., 1985) and alternative sources of alumina such as nepheline syenite (Roskill, 1997) and clay materials (Katrak and Agarwal, 1981). However, neither of these has ever been of commercial significance. The pyrometallurgical smelting of phosphorus has now been almost entirely replaced by hydrometallurgical alternatives (Gleason, 2007) where no comparable gallium-enrichment occurs. Without such enrichment, commercial extraction is not viable. Nepheline syenites and clay materials on the other hand are not expected to become important sources of alumina (and therefore gallium) until bauxite resources are exhausted. This is not expected to occur for at least 50 years (Meyer, 2004). For these reasons, neither phosphorus flue dusts nor alternative sources of alumina are considered.

In the following sections, we first summarise the general methodology we used for the estimation of current supply potentials and associated statistical uncertainties. We also show how these estimates can be adapted to changes in market conditions using by-product availability curves. We then discuss aspects specific to each raw material such as process routes, recoveries, and the data used for parameter estimation of the statistical models employed in our calculations. This is followed by a detailed presentation of results, a discussion of their significance, and a final summary of the conclusions from our work.

2. Data and methodology

The general method outlined in Frenzel et al. (2015a) was used to make estimates of the supply potential of gallium. Because this is a new method, a summary is given below to familiarise readers with the process. Since not all aspects can be adequately represented in such a small space, interested readers are referred to the original publication for further details (Frenzel et al., 2015a).

We start by defining the supply potential of gallium as that quantity which could be produced per year in an ideal market given current prices and state of technology. By an ideal market we mean a market in which each suitable volume of primary raw material is optimally treated for gallium extraction to maximise overall profits. Because real markets may for various reasons be

[1] Campbell (1985) defines a by-product as ‘a material that is recovered as a secondary product from the extractive process and has no effect on the decisions about the appropriate profit-maximising level of production for the mining operation.’ That is, by-products have no influence on planning decisions at the mine level, and therefore, do not influence the production level of the corresponding main products.