CURRENT SCIENCE

Volume 100 Number 9 **10 May 2011**

EDITORIAL

Elements: Impending Scarcity

Chemistry is a curious word, pregnant with many meanings. In one of the endlessly contentious, shrill and, at times, unedifying television discussions on corruption in public life, a visible and voluble politician held forth on the ‘chemistry between lawyers and the judiciary’, which apparently seemed to influence the outcome of legal proceedings. The use of the word ‘chemistry’, by someone unlikely to be schooled in the discipline seemed a clear indication of a widely held perception that the subject involved the study of ‘good’ and ‘bad’ interactions between substances or materials; an extension to human behaviour seems both inevitable and justified. The noisy discussion on corruption faded, leaving me to puzzle over the subject of chemistry; a topic that seemed especially relevant in a year that has been formally dedicated to the celebration of the subject. Chemistry is, almost always, introduced to students by describing the elements and the Periodic Table. Mendeleyeev’s recognition of the periodicities in the properties of elements known in the mid-19th century and his conception of the ‘Table’ must surely rank as one of the pillars on which the edifice of modern science has been raised. But, the definition of the term ‘element’ has often troubled beginning students, most of whom forsake the subject at an early opportunity. Indeed, the word ‘element’ is used in many different contexts in English, outstripping ‘chemistry’ in its versatility. Arthur Conan Doyle made the derivative ‘elementary’ famous, in Sherlock Holmes’ explanations for his many success: ‘Elementary, my dear Watson.’ ‘Simple’ seemed the synonym.

The elements when introduced in chemistry courses indeed seem simple, leaving unwary students quite surprised by the complexities that follow. The elements, the basic constituents of all matter seemed even simpler to early civilizations, where the material world really seemed to be largely composed of earth, air, water and fire. Paracelsus thought of the world in terms of salt, sulfur and mercury, in simpler times. Robert Boyle writing in *The Sceptical Chymist*, in 1661, began to herald the dawn of modern definitions of the elements: ‘. . .certain primitive and simple, or perfectly unmingled bodies, or of one another, are the ingredients of which all those perfectly mixt bodies are immediately compounded and into which they are ultimately resolved’. Modern chemistry was to emerge two centuries later when Dalton and Mendeleeyev midwifed atoms and the Periodic Table into the modern age. Even definitions of elements in modern chemistry textbooks sometimes seem ambiguous and incomplete: ‘A chemical element is a substance that cannot be broken down by chemical means.’ A qualifying sentence is invariably added: ‘Elements are defined by the number of protons they possess.’ This apparent quibble acknowledges the enormous progress in understanding the nature of the atom and the discovery of isotopes. The elements, inevitably gold, attracted the alchemists in the 17th and 18th centuries; Newton amongst them. Transmutation seemed a most desirable goal. In a BBC program entitled ‘Chemistry: A Volatile History’, Jim Khaleeli, a theoretical physicist presents an engaging account of the road to the elements. He waxes eloquent when he says: ‘Chemistry was forged in the furnaces of the alchemists.’

Should one even consider a subject so elementary on the editorial pages of a scientific journal? What indeed is the provocation for this column? *Nature Materials* (2011, **10**, 157) in a recent editorial entitled ‘Elements in short supply’ noted that ‘when we think of scarce natural resources, the availability of oil is the main one that comes to mind’. In noting that many scarce materials are ‘valuable because of the chemical elements they contain’, the editorial notes ‘that oil is a molecule that is valuable for the energy stored in it and not for its carbon and hydrogen atoms’. Chemistry courses often focus on relatively few elements in Mendeleeyev’s Table; organic chemists being especially choosy, while their inorganic counterparts range somewhat more widely. What are the elements that are valuable and scarce, whose looming shortages must worry governments and policy makers? To answer this question, I turned to a report produced by the US Department of Energy (DOE) (Dec. 17, 2010), which outlined a ‘critical materials strategy’. Fourteen elements in the Periodic Table were marked as ‘key materials’. These are: lithium (Li), cobalt (Co), yttrium (Y), gallium (Ga), indium (In), tellurium (Te), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), terbium (Tb) and dysprosium (Dy). The last seven elements, beginning with lanthanum, belong to the class of elements called ‘rare earths’, which are often intensely disliked by many students of chemistry. There is a certain monotony of properties that are normally discussed, which quickly induce a sense of boredom. Current discussions of ‘critical’ and ‘strategic’ elements are fuelled by the Chinese restricting rare earth exports, after having become the major supplier of these materials, mining as much as '97% of the global rare earth material supply'. The device of 'squeezing any competition out of the market' by pricing ore very cheaply and then imposing export restrictions appears to have adversely affected global supply. The fourteen elements listed in the DOE report are crucial for 'clean energy' technologies, which are being so intensely sought. Solar cells (photovoltaic films) require indium, gallium and tellurium; magnets for both wind turbines and electric vehicles require praseodymium, neodymium, samarium and dysprosium; batteries for energy storage need lithium, cerium, praseodymium, neodymium, lanthanum and cobalt; phosphors in efficient fluorescent lighting require lanthanum, cerium, europium, terbium and yttrium. It appears clear that a clean future which minimises the use of fossil fuels, relies heavily on elements whose supply (and cost) is likely to be affected by looming shortages. The US DOE report does not discuss the actinide elements, uranium, plutonium and thorium amongst them, which are crucial to nuclear energy programs.

Elements and minerals from which they may be extracted are unevenly distributed across the globe. Not all known deposits can be easily mined. Extraction and processing can be both expensive and environmentally harmful. The DOE report summarizes information on many key elements, comparing both production and reserves in major producers. Interestingly, the US data for lithium and tellurium is listed as 'withheld', presumably for strategic reasons. Indeed in this area data is often 'proprietary' and not available. China holds an almost complete stranglehold on rare earth production and is also a major producer of lithium, cobalt and gallium. India is listed only as a minor producer of rare earths, a clear indication of scarcities which may loom in the future. The DOE report presents an interesting 'criticality matrix' where the 'supply risks' and importance to clean energy are mapped for both a short term assessment (0–5 years) and a long term projection (5–15 years). The rare earths, europium, yttrium, neodymium, dysprosium and terbium appear to have the highest supply risk and also the greatest importance to clean energy technologies. While the DOE report presents an American perspective, large countries like India which lack a substantial base of natural mineral resource may need to constantly assess strategies to deal with impending scarcities.

Japan, a technologically advanced but resource strapped country, has evolved long term strategies. In a commentary entitled 'Managing the scarcity of chemical elements', E. Nakamura and K. Sato discuss Japan's 'Element Strategy' (*Nature Materials*, 2011, **10**, 158). They characterize the period from the 1960s to 1980s as 'an era when pioneers were racing through the unexplored and fertile wilderness of the periodic table'. The many new materials 'found in this "element hunt" have been successfully used in high-tech products that now play an indispensable role in our lives'. These authors highlight the fact that 'element hunters' were not only materials scientists but even included the organic chemists. They provide the 2010 Nobel prize in chemistry awarded to Heck, Negishi and Suzuki as an example; a case where 'the properties of palladium, zinc and boron were used to the full'. Although much of the world focus is on rare earths and the elements listed in the DOE report, Nakamura and Sato point out that even phosphorus is 'considered to be in possible danger of depletion'. A scenario may unfold over the next fifty years where 'a shortage of phosphorus fertilizer would cause significant damage to agriculture'. Uneven distribution of scarce but critical elements will raise complex issues of politics and trade. The authors note that 'the production of the platinum group metals, important as catalysts, is concentrated in South Africa and Russia; niobium which is used as a steel additive, is mostly produced in Brazil and Canada. The tantalum used in capacitors is almost exclusively produced in Australia and Brazil'. The fact, that India with its enormous population is almost completely absent from the list of countries with some strategic resources, must be a matter of concern in the long run.

Are there solutions in sight to address the problems of looming element scarcity? Nakamura and Sato strike an optimistic note reminding us of the Haber–Bosch ammonia synthesis which used 'nitrogen in the air' and led to the fertilizer revolution in agriculture. Scientific advance may be anticipated, catalysed by a crisis. The Japanese 'Element Strategy Initiative' is based on the premise 'that where resources are scarce but high technology is abundant, necessity is the mother of invention'. The strategy rests on 'four pillars: substitution, regulation, reduction and recycling'. The drive to find substitutes will undoubtedly provide a motivating factor for future chemical research. Organic semiconductors which have made a beginning will have to be evaluated not only in terms of 'energy policy but also in terms of the element strategy'. Nakamura and Sato list many novel examples, including the organic ferroelectric, croconic acid ($C_5O_5H_2$), which contains none of the scarce and exotic elements. While regulation and reduction of scarce element usage will undoubtedly form an important part of any 'element policy', recovery and recycling must also be central to a long term strategy. The authors quote a study by the National Institute for Materials Science in Japan which estimates element content in 'urban mines' which contain 'discarded high tech devices'. The numbers are staggering: '6800 tons of gold (16% of the world reserves), 60,000 tons of silver (22%) and 1700 tons of indium (15.5%)'. Recycling by microbial leaching may assume importance in future.

The elements form the core of chemistry. The rarest amongst them are sometimes central to the modern world. Addressing the problems posed by the looming scarcity of the most critical elements of modern technology will be anything but elementary.

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