The Sustainability of Uranium Mining: The Growing Implications of Known Mineral Resources and Eco-Efficiency

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ABSTRACT

The mining of uranium in Australia has long been a controversial public issue. Over the past year, a renewed debate has emerged on the perceived potential for nuclear power to help mitigate against future greenhouse emissions and subsequent climate change. The central thesis of pro-nuclear advocates is the lower carbon intensity of nuclear energy compared to fossil fuels. There remains very little detailed analysis of the true carbon costs of nuclear energy, however, despite this being a fundamentally critical aspect of the debate. In this paper, we compile and analyse a range of data on uranium mining and milling, analysing available data on reported uranium resources, as well as important sustainability metrics, such as energy and water consumption and carbon emissions per unit of uranium production. This is arguably the first time that such analyses have been compiled and presented for modern uranium projects. Overall, the data clearly show the sensitivity of sustainability assessments to the ore grade of the uranium deposit being mined and also that significant gaps remain in the full accounting and assessment of the sustainability (or otherwise) of the nuclear energy path. The paper is a case study of the energy, water and carbon costs of uranium mining within the context of the nuclear energy chain. Although the extent of uranium resources remains open to conjecture, gradually declining ore grades will most likely lead to an increasing ecological footprint from uranium mining in the nuclear fuel chain.

1. INTRODUCTION

The sustainability debate about energy sources is a critical challenge. At present, Australia is heavily reliant on fossil fuels, such as coal, oil and gas, which are potent contributors to greenhouse emissions. A number of groups, along with the Commonwealth Government, are strongly advocating the development of nuclear energy in Australia. There is intense debate about whether nuclear power, and its associated uranium mining, can be argued as a long-term, viable and truly sustainable energy source.

The two most critical aspects in this debate are the perceived low carbon intensity and the extent of net energy produced by the nuclear power chain. Life-cycle assessments (e.g., ISA, 2006) have shown that one of the major contributors to total life-cycle carbon emissions and energy costs is the mining of the uranium for nuclear fuel. These studies, however, have often used approximations for the mining stage and have not used reported data now available in sustainability reports by certain uranium mining operations.

This paper compiles and presents key data on the sustainability of uranium mining, with a particular focus on environmental costs and mineral resource issues.

2. METHOD: QUANTIFYING SUSTAINABILITY

Mining requires considerable inputs of energy, reagents and water resources and generates significant amounts of pollutant emissions but especially solid wastes (tailings and waste rock). For mining, the continued extent of known economic mineral resources is critical, but trends in processing and resource inputs and outputs are just as critical.

Detailed datasets for resources over time, mining production and reported sustainability data have been compiled. The data are presented in terms of links between critical sustainability and mining production aspects. In this way, future sustainability can be more accurately assessed by recognising long-term trends and the possible future implications for carbon and energy intensity. The uranium producers include Ranger, Beverley and Olympic Dam in Australia, Rössing in Namibia, and limited data from Canadian mines. Specific aspects and the associated literature used include :

- **Uranium Mining and Production** – NRC (various), Cameco (various), Cogema (2005), Denison (various), EIA (various), CMSA (2005) (including the CMSA website for 2006 data), Mudd (2007), Freeman and Vernon (1986), Johnson (1990), OECD-NEA and IAEA (various), USBoM (various), Rössing (various), and Mays (1998).
- **Uranium Resources** – Dickinson (1945), EIA (various), NRC (various), OECD-NEA and IAEA (various), Battey *et al.* (1987), McKay and Miezitis (2001), Cameco (various), Cogema (2005), Mudd (2007), and numerous 2005 mining company annual reports.
- **Sustainability Aspects** – **Rössing**, Namibia, open cut mine and mill, 1995 to 2006 (Rössing, various); **Ranger**, Australia, open cut mine and mill, 1983/84 to 1987/88 (OSS, various) (note: data are provided for 1981/82. but as this was the first year of operations. it is excluded as an outlier) and 1996 to 2006 (ERA, various); **Beverley**, Australia, acid in situ leach project, 2003 to 2005 (HR, various); **Olympic Dam**, Australia, underground mine, adjacent mill and copper smelter/refinery complex, 1991 to 2004 WMC, various) and 2004/05 (BHPB, 2005) (note: Olympic Dam is a polymetallic project producing refined copper and uranium oxide, as well as gold and silver bullion); **McLean Lake**, Canada, open cut mine and mill, 2002 to 2005 (Cogema, 2005); **Cluff Lake**, Canada, open cut mine and mill, 2002 (Cogema, 2005) (note: closed in early 2003 and now in rehabilitation).

All data have been normalised to consumption per unit of uranium oxide (U_3O_8) production. If input fuels such as diesel were reported, energy and greenhouse gas emissions were calculated using AGO (2005).

To account for the fact that the Olympic Dam project is polymetallic (Cu-U-Au-Ag), data are presented in terms of attributing either all energy and water consumption and carbon dioxide emissions to uranium production or only 20%. Although assuming 100% is clearly unrealistic, the recent average ore grade at ~0.08% U_3O_8 is higher than the Rössing uranium mine's at ~0.04% U_3O_8. The full energy accounting for direct uranium production at Olympic Dam would need to consider a detailed analysis and breakdown of the milling, metallurgical and smelting process, which is obviously impracticable. The factor of 20% is adopted as this is the long-term average proportion of revenue from uranium at Olympic Dam (Mudd, 2007).

3. RESULTS

3.1 Global Uranium Mining and Production

The global production of uranium began in large scale following World War II, initially for nuclear weapons programs but switching to the emerging nuclear power industry from the late 1960s. In total, the compiled data represent 1.27 million tonnes of uranium oxide (Mt U_3O_8) and account for more than half of estimated total global uranium production (~2.25 Mt

U_3O_8) and most of the western world's total uranium production (~1.6 Mt U_3O_8) (OECD-NEA and IAEA, various).

The average ore grade for milling over time available for some countries is shown in Figure 1, with the estimated global data for ore grade and production in Figure 2. The estimated percentage of global uranium production, which the compiled data represent, is shown also, demonstrating that the data generally represent >80% of western world uranium production in the 1960s and greater than 60% since the 1970s. In situ leach (ISL) mine production was excluded due to the difficulty of equivalence between ISL and hard rock mining. Given the data include the current major producers, Canada, Australia and Namibia, the data provide a reasonable representation of the global uranium industry.

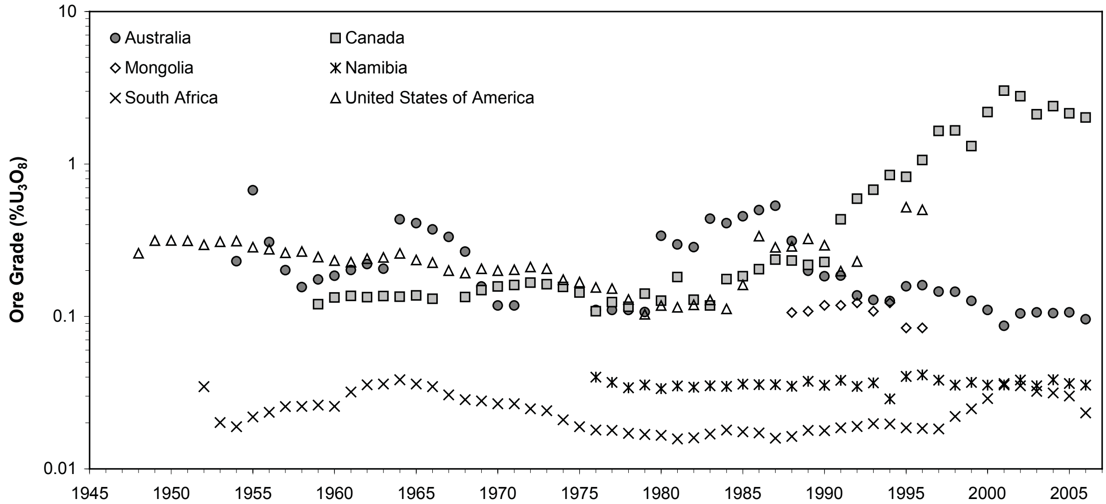


Figure 1. Average uranium ore grade in milling over time by country

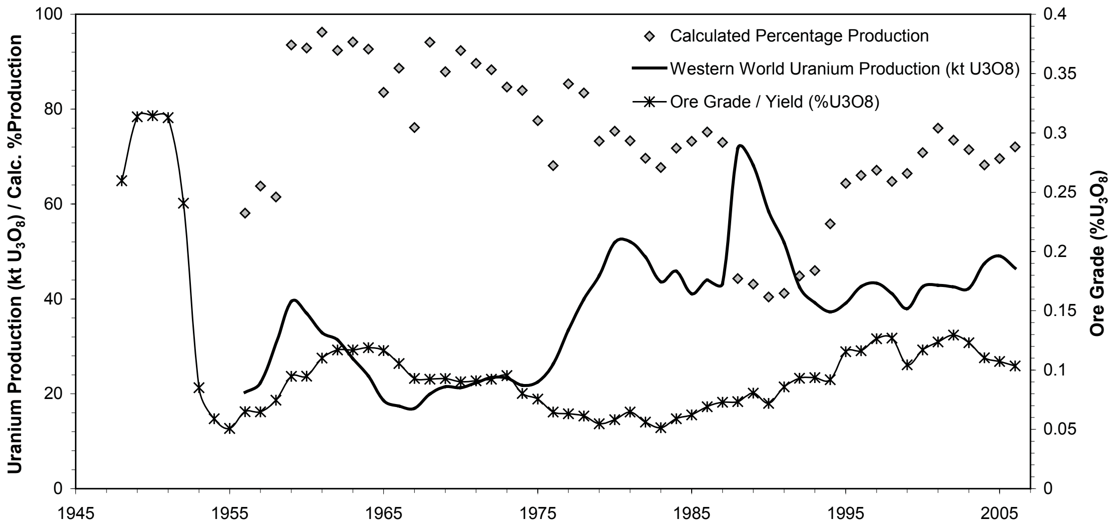


Figure 2. Estimated global average uranium ore grade, production and calculated percentage of production

3.2 Global Economic Uranium Resources

It is commonly perceived that uranium is a finite resource. The known availability of uranium has been considered to be limited in the past, with further exploration work leading to further resources being found. For example, the nuclear weapons era in the late 1940s and the nuclear power era from the late 1960s both started with the belief of uranium scarcity, yet rapid and wide-ranging exploration soon proved an abundance of uranium far in excess of that required (Mogren, 2002). The principal aspects of economic resources include the contained uranium, as well as the average ore grade of an individual deposit. Although country resources over time are compiled bi-annually and analysed by OECD-NEA and IAEA (various), the ore grades and other salient aspects of the numerous deposits are rarely presented. All publicly listed mining companies, at least in western-style economies, are generally bound by voluntary codes and/or the law to report accurately on economic mineral resources they control. This can be compared to the limited earlier data available.

The compiled data total 3.8 Mt U_3O_8 of uranium resources and accounts for more than half of estimated total global uranium resources (5.5 Mt U_3O_8, 2005 edition of OECD-NEA and IAEA, various). The ore grade of select country uranium resources over time and global and Australian known economic uranium resources are given in Figure 3, with numerous individual deposits by ore grade and contained uranium compiled in Figure 4 by country.

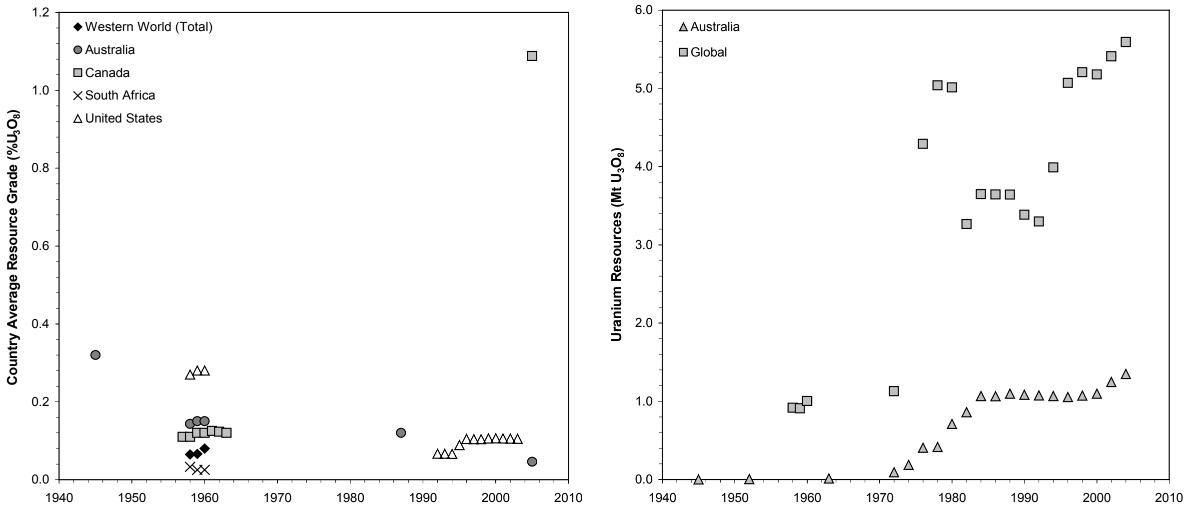


Figure 3. Average ore grade of select country uranium resources (left) and global and Australian known economic uranium resources (right) over time

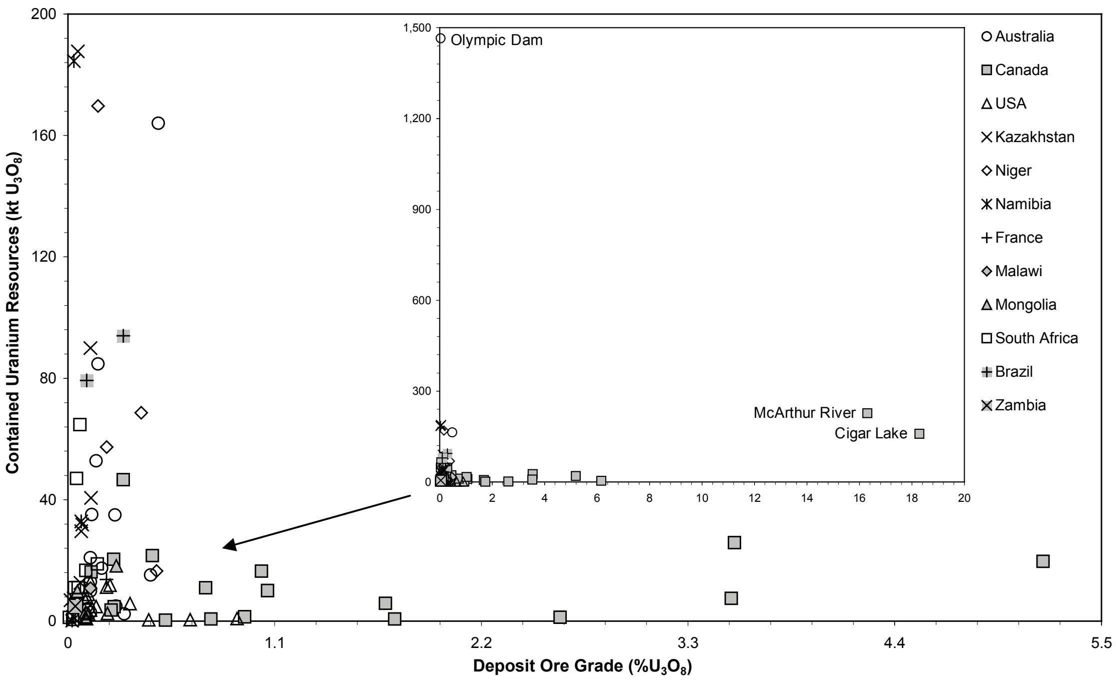
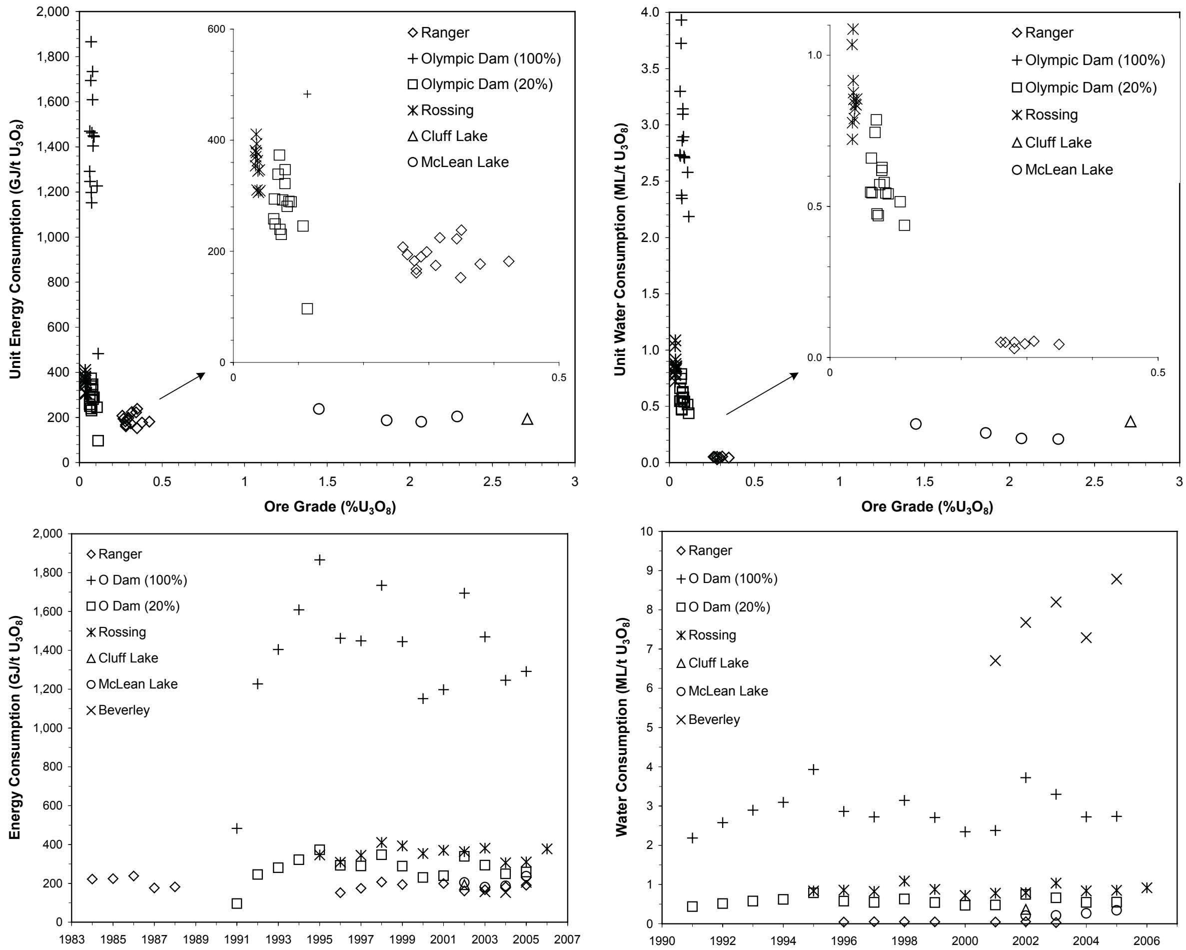


Figure 4. Contained uranium resources versus ore grade : individual deposits by country

3.3 Energy and Water Consumption and Carbon Dioxide Emissions in Uranium Mining

The compiled data for energy and water consumption per unit of uranium oxide production with respect to ore grade and time are shown in Figure 5. The compiled data for carbon dioxide emissions per unit of uranium oxide production with respect to ore grade and over time are shown in Figure 6. As can be seen, using a 20% factor places Olympic Dam within the same order of magnitude as Rössing. The higher water consumption of Beverley is due to the fact it is an in situ leach mine. Data are summarised in Table 1.



Note: Beverley is excluded from ore grade due to the uncertain nature of the actual ore grade being mined by acid leaching. Prior to mining, resources were estimated at 9.7 Mt at 0.18% U_3O_8 (see Mudd, 2007).

Figure 5. Energy and water consumption per unit of uranium oxide production versus ore grade and time

4. DISCUSSION

The data compiled and presented within this paper provide support for a number of key aspects of uranium mining, centred around known economic resources, ore grades of resources and production, energy and water consumption per unit of uranium oxide production, and greenhouse emissions (carbon dioxide) per unit of uranium oxide production.

The extent of economic uranium resources has generally increased over time, coincident with the major periods of exploration. In Canada, the Elliot Lake region of Ontario provided most resources during the 1950s and 1960s, switching to Saskatchewan from the 1970s. The extremely high-grade deposits of Cigar Lake and McArthur River were discovered in 1981 and 1988 with grades of 18.3% and 14.3% U_3O_8, respectively. Although new prospects

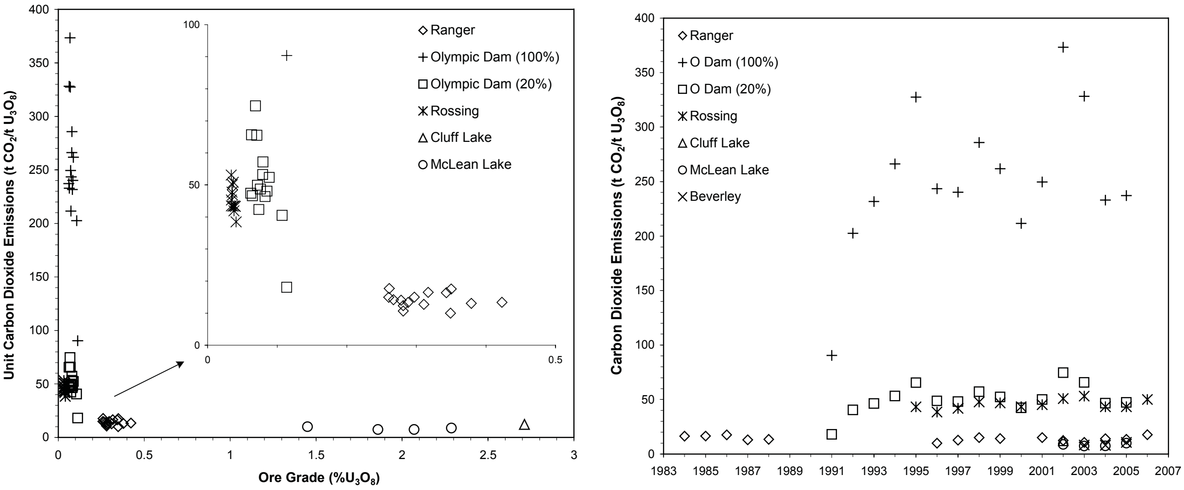


Figure 6. Carbon dioxide emissions per unit of uranium oxide production versus ore grade and time

Table 1. Summary of normalised energy and water consumption and carbon dioxide emissions for select uranium mines (average ± standard deviation, number of years in brackets)

Uranium Project	Typical Ore Grade %U_3O_8	Annual Prod. t U_3O_8	Consumption: Water kL/t U_3O_8	Consumption: Energy GJ/t U_3O_8	Emissions: Carbon Dioxide t CO_2/t U_3O_8
Ranger	0.28-0.42	~5,000	46.2 ± 8.2 (7)	191 ± 25 (14)	14.1 ± 2.3 (15)
Olympic (100%)	0.064-0.114	~4,300	2,888 ± 487 (15)	1,382 ± 325 (15)	252 ± 65 (15)
Olympic (20%)			578 ± 97 (15)	276 ± 65 (15)	50.4 ± 13.0 (15)
Rössing	~0.034-0.041	~3,700	868 ± 104 (12)	356 ± 34 (12)	45.7 ± 4.2 (12)
Cluff Lake	2.71	(closed)	365 (1)	194 (1)	12.1 (1)
McLean Lake	1.45-2.29	~2,750	257 ± 62 (4)	202 ± 25 (4) †	8.4 ± 1.2 (4)
Beverley	~0.18	~1,000	7,731 ± 802 (5)	172 ± 29 (3) ‡	8.9 ± 1.5 (3)
Niger #	~0.2-0.5	~3,100	*no data*	~204	*no data*
Cameco §	~0.9-4.0	~8,500	*no data*	~178	*no data*

† Data given by WNA (2006) is 313 GJ/t U_3O_8.
‡ Data for 2004-05 are given by WNA (2006) for Beverley as 187 and 221 GJ/t U_3O_8, respectively, compared to data reported by HR (various) and used in graphs and table above.
# Data for 2000, for Areva's (formerly Cogema) two mine/mill complexes (Somair and Cominak) (WNA, 2006).
§ Data average over 1992 to 2001 for 'Cameco mines' (WNA, 2006).

are being found (e.g., Millenium), no deposits of the significance of Cigar Lake and McArthur River have been found in Canada since 1988. In Australia, despite broad-ranging exploration in the 1970s with associated spectacular results, there have only been two new deposits discovered since 1975 – Kintyre in 1985 and Beverley 4 Mile in 2002. All increases inresources between 1985 and 2005 have resulted from increased drilling and new assessments at known deposits, mainly Ranger and Olympic Dam. This pattern of no 'world-class' discoveries greater than 50 kt U_3O_8 in the past two decades is thought to be similar in other countries (see OECD-NEA and IAEA, various).

It is entirely possible that, with further exploration, new uranium deposits could be found; however, some issues need to be considered. Firstly, given the broad coverage of uranium exploration globally over the past fifty years, any new deposit discovered is most likely to be deeper than most current deposits. This trend is evident in Canada, where successive deposits discovered in Saskatchewan have each been deeper, and future deposits are expected to be found even deeper still. The deeper a deposit, the more energy that could be expected to be required to mine the resource. Secondly, the long-term trend over the past five decades has been a steady decline in most average country ore grades (even allowing for varying economic assessments of resources). This is particularly evident in Australia, where the increasing size of the Olympic Dam deposit now dominates Australia's total resources and average ore grade. The average country ore grade for the United States in the 1990s was typically 0.07% to 0.11% U_3O_8, which is about one third of that in the late 1950s of 0.28% U_3O_8. Canada is the only country that has seen a substantive rise in its average ore grade, due to the rich Athabasca Basin deposits of northern Saskatchewan. The average ore grade of the Elliot Lake district of northern Ontario, which generally contained more than 95% of Canada's resources in the 1950s to 1960s, was typically 0.11% U_3O_8 – compared to the estimated average of 1.1% U_3O_8 in 2005. These trends in average ore grade of country resources are reflected in the ore grades of as-milled production (Figure 1). It is worth noting that, despite the increasing ore grade in Canada, this has not significantly affected typical global average ore grade, which has remained between to 0.05% and 0.13% U_3O_8 over the past five decades. Finally, based on data for 93 deposits or fields compiled for this paper (Figure 4), there is an indicative relationship between ore grade and contained uranium. As ore grade declines, there is an increasing possibility of substantial tonnage. In terms of production capacity for an expanded nuclear power program, these larger-tonnage, lower-grade deposits would need to be developed, thereby balancing the rich Saskatchewan deposits.

A common issue raised with uranium resources is by-product sources, such as phosphate (e.g., Florida, USA) and gold ores. Virtually all of South African uranium has been derived as a by-product from gold mining in the Witwatersrand Basin. In the United States, some uranium was produced as a by-product of phosphate mining until the permanent closure of the uranium production capacity 2000 (capacity of about 1,150 t U_3O_8 at that time; 2001 edition of OECD-NEA and IAEA, various). The Olympic Dam project in Australia, containing copper, uranium, gold and silver, is the only current major producer not solely mining a deposit for uranium (though Olympic Dam is more correctly described as a co-product mine). Over recent years, only South Africa has continued to produce by-product uranium derived from gold ores. A detailed examination of OECD-NEA and IAEA (various) shows that by-product uranium has been a minor component of global uranium production to date (probably of the order of less than 20%). There is very little recent data on uranium resources from by-product operations, especially ore grades and quantity, nor information available to discern or allocate energy, water and reagent costs and pollutant emissions to the additional effort required for this by-product uranium.

With respect to energy, gradual increasing trends are apparent for Olympic Dam, Beverley, Ranger and McLean Lake, although Rössing shows a slight decreasing trend over time. The compiled data are only based on direct fuel inputs, such as diesel or electricity. There appears to be little difference in energy costs per unit of uranium production above an ore grade of about 0.5% U_3O_8. Given the small number of points greater than 0.5%, however, this interpretation requires caution. A curious fact shown by the data above is that the energy cost of Beverley, an acid in situ leach project, is similar to that for Ranger, a large open cut mine/mill complex. For Beverley, a recent energy efficiency audit in 2004 showed that the wellfield and mill consumed 44.9% and 41.6% of electricity usage, respectively, or, in terms of activities, that pumping consumed 80.7% of electricity usage (HR, various). The energy cost of drilling at Beverley remains unquantified; and, with large numbers of bores, it should not be ignored.

Critically, the data for all mines do not account for the additional embodied energy required for reagents, such as solvents (e.g., kerosene, amine), sulfuric acid, oxidants (e.g., hydrogen peroxide, manganese dioxide (MnO_2), lime and so on. This would add further energy costs to uranium production. For example, data for the Ranger mine from 1988/89 to 1996/97 (OSS, various) suggest that each tonne of uranium oxide production requires about 320 litres of kerosene, 12.7 litres of amine, 460 kilograms of ammonia (NH_3), 1.75 tonnes of oxidant (as t MnO_2), 15 tonnes of acid (as t H_2SO_4) and 5.9 tonnes of lime. For kerosene, the embodied energy is estimated as 36.6 GJ/kL (AGO, 2005), thereby adding about 60,000 GJ to Ranger's energy requirements for some 5,000 tonnes of U_3O_8 annual production. This would add approximately 11.7 GJ/t U_3O_8, or 6%, to the 191 GJ/t U_3O_8 presently reported. Unfortunately, more recent annual data since the 1997 mill expansion at Ranger are not available. It is clear that full life-cycle accounting and sustainability reporting needs to include reagents with major embodied energy costs.

For water, gradual increasing trends are apparent for Olympic Dam, Beverley and McLean Lake, although Ranger and Rössing show a slight decreasing trend over time. There are marked differences in water consumption, due in large part to the major differences between these various projects. For example, although Ranger and Rössing are somewhat similar in terms of uranium production and scale for open cut mining, Rössing has an ore throughput about fivefold that of Ranger, as well as an ore grade some eight times lower. The sensitivity of normalised water consumption to ore grade is apparent. Further characterising water issues based on water quality and recycling is not possible based on the available data.

The direct emission of carbon dioxide (and equivalents) is an issue of critical importance, especially in the context of the current debate over greenhouse emissions from the nuclear chain. As with energy and water consumption, gradual increasing trends for normalised emissions are apparent for all mines. The data in terms of carbon dioxide emissions per tonne of ore milled, although not presented within the space of this paper, show that Olympic Dam and McLean Lake are gradually declining over time, while Ranger and Rössing are increasing. The declining trends are most likely related to the recent expansion of Olympic Dam and increasing throughput at McLean Lake.

5. CONCLUSION

The extent of economically recoverable uranium, although still uncertain, is related to exploration effort and economics but is also inextricably linked to environmental costs, such as energy, water, and chemicals consumption and greenhouse emissions, as well as broader social and political issues. As shown within this paper, these crucial environmental aspects of resource extraction are only just beginning to be understood in the context of more complete life-cycle analyses of the nuclear chain and other energy options. There still remains incomplete reporting, however, especially in terms of data consistency between mines. It is clear that there is a strong sensitivity of energy and water consumption and greenhouse emissions to ore grade and that ore grades are likely to continue to decline gradually in the medium to long term. These issues are critical to understanding the current debate over nuclear power and greenhouse emissions, especially with respect to ascribing sustainability to such activities as uranium mining and milling.

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