Sustainability Aspects of Uranium Mining : Towards Accurate Accounting ?

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Abstract

The mining and milling of uranium ore in Australia has long been a controversial public issue. Over the past year a renewed debate has emerged on the potential for nuclear power to help mitigate against future greenhouse emissions and subsequent climate change. The central thesis of pro-nuclear advocates is the low 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 with respect to unit 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.

1 Introduction and Background

The nuclear industry has long been a controversial issue, commonly linked to issues such as nuclear weapons and nuclear waste. In Australia, the primary debate has often centred on uranium mining as we have significant economic resources – seen by some as worthy of export for financial return or simply to maintain our position in the global nuclear fraternity.

At present there is vigorous global debate about the perceived potential for nuclear power to reduce greenhouse gas emissions – the central hypothesis put forward by pro-nuclear advocates being the apparent low carbon intensity of nuclear power compared to fossil fuels. From an environmental sustainability perspective, it is critical to evaluate accurately the true life cycle costs of all forms of electricity production, especially with respect to greenhouse emissions. For nuclear power, a significant proportion of greenhouse emissions are derived from the fuel supply, including uranium mining, milling, enrichment and fuel manufacture. However, there are only limited data reported by uranium miners with respect to greenhouse emissions. Further to this, additional issues that need to be considered for uranium mining include the extent of economic resources known and the average ore grade of these resources. These aspects are critical in assessing the long-term ability of nuclear power to reduce greenhouse gas emissions.

This paper compiles and presents the available data on uranium mining, with a particular emphasis on historical production trends, known economic resources and greenhouse gas emissions, as well as water and energy consumption. This is then placed within the context of sustainability analyses of uranium mining.

2 Methodology and Data Sources

The various aspects of sustainability investigated in this paper are assessed through the compilation of detailed data sets on :

- **Uranium mining and milling** – historical government series/periodicals on mining;
- **Uranium resources** – historical government series/periodicals on mining as well as recent company annual financial or technical reports;
- **Energy and water consumption** – recent company annual sustainability or technical reports;
- **Carbon dioxide emissions** – recent company annual sustainability or technical reports.

Select sustainability data for the last two points are only available for a few uranium mines, namely Rössing in Namibia, McLean Lake and Cluff Lake in Canada, and Ranger, Beverley and Olympic Dam in Australia (the latter being a poly-metallic Cu-U-Au-Ag mine).

2.1 Data Sources : Uranium Mining and Milling

The data on uranium mining and milling are available for :

- **Canada** – 1959 to 2003 (NRC, var.), 2004 to 2005 (Cameco, var.; Cogema, 2005; Denison, var.);
- **United States** – 1948 to 2005 (EIA, var.) (especially the 1992 report);
- **South Africa** – 1953 to 2005 (CMSA, 2004) (including the CMSA website for 2005 data);
- **Australia** – 1954 to 2005 (Mudd, 2006);
- **Namibia** – 1976 to 1985 (Freeman & Vernon, 1986; OECD-NEA & IAEA, var.; USBoM, var.) (includes some estimated/cross-calculated data), 1986 to 1994 courtesy of Uranium Information Centre (‘Reviewing Rössing 1994’), and 1995 to 2005 (Rössing, var.);
- **Mongolia** – 1988 to 1996 (Mays, 1998).

2.2 Data Sources : Uranium Resources

Various uranium ore deposits were compiled by country, based on numerous company annual or other reports, plus the following :

- **Australia** – 1945 (Dickinson, 1945), ~1952 (Cawte, 1992), 1958 to 1960 (NRC, var.), 1987 (Battey *et al*, 1987), 2001 (McKay & Miezitis, 2001), 2005 company reports and (Mudd, 2006);
- **Canada** – 1957 to 1963 (NRC, var.), 2005 company reports (eg. (Cameco, var.; Cogema, 2005);
- **United States** – 1958 to 1960 (NRC, var.), 1992 to 2003 (EIA, var.), 2005 company reports;
- **South Africa** – 1958 to 1960 (NRC, var.), 2005 company reports (incomplete country resources);
- **Namibia** – 1958 to 1960 (NRC, var.), 2005 company reports (incomplete country resources);
- **Kazakhstan, Malawi, Mongolia, Niger, France, Zambia, Brazil, Argentina, Central African Republic and Russia** – 2005 company reports (often incomplete country resources).

All data above were summed to compare calculated totals with country resources reported by the 2005 Edition of (OECD-NEA & IAEA, var.).

2.3 Data Sources : Environmental Aspects of Uranium Mining and Milling

At present, there are only limited publicly reported data on energy and water consumption in uranium mining and milling and greenhouse gas emissions. Some companies, eg. Cameco and BHP Billiton, report company totals and not site specific data. Data available include :

- **Rössing, Namibia** – open cut mine and adjacent mill, 1995 to 2005 (Rössing, var.);
- **Ranger, Australia** – open cut mine and adjacent mill, 1996 to 2005 (ERA, var.);
- **Beverley, Australia** – acid in situ leach project, 2003 to 2005 (HR, var.);

- **Olympic Dam, Australia** – underground mine, adjacent mill and smelter complex, 1991 to 2004 (WMC, var.) (Note : Olympic Dam is a poly-metallic project producing refined copper, calcined uranium oxide concentrate, as well as gold and silver bullion);
- **McLean Lake, Canada** – open cut mine and adjacent mill, 2002 to 2005 (Cogema, 2005);
- **Cluff Lake, Canada** – open cut mine and adjacent mill, 2002 (Cogema, 2005) (Note : closed in early 2003 and now in rehabilitation);

All data have been normalised to consumption per unit uranium oxide (U_3O_8) production, with greenhouse gas emissions calculated from input fuels if carbon dioxide emissions were not reported.

To account for the fact that the Olympic Dam project is poly-metallic (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 and metallurgical smelting process, which is obviously impracticable. The factor of 20% is adopted as this is the average proportion of revenue from uranium at Olympic Dam (Mudd, 2006).

3 Results

3.1 Global Uranium Mining Production

The global production of uranium began in large scale following World War 2, initially to supply the nuclear weapons programs of the times, but switching to the emerging civil nuclear power industry from the late 1960s. Total production has been dominated by Canada, United States, (former Eastern) Germany, South Africa, Australia, Czech Republic, Niger, Namibia, and France as well as smaller production from countries (2005 Edition) (OECD-NEA & IAEA, var.). Complete production data are not available for all of these countries, however, a significant portion is available, especially for several of these principal producers.

In total, the compiled data totals 1.2 Mt U_3O_8 and accounts for more than half of estimated total global uranium production (~2.2 Mt U_3O_8) and most of the western world's total uranium production (~1.6 Mt U_3O_8) (2005 Edition, (OECD-NEA & IAEA, var.). The average ore grade for milling over time for the above countries is shown in Figure 1, with the estimated global data for ore milled, ore grade and production in Figure 2. The estimated percentage of global uranium production, which the compiled data represents, 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 mine production was excluded). Given the data include the current major producers, Canada, Australia and Namibia, the data provide a reasonable representation of the global uranium industry. Two peaks of uranium production are clearly evident in Figure 2 – firstly the weapons phase (peaking in 1959) followed shortly by the civil phase (peaking in 1988).

3.2 Global Uranium Mining 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, at the start of the nuclear arms race in the 1940's, uranium was considered to be extremely scarce, yet rapid and wide-ranging exploration soon proved an abundance of uranium far in excess of that required (Mogren, 2002).

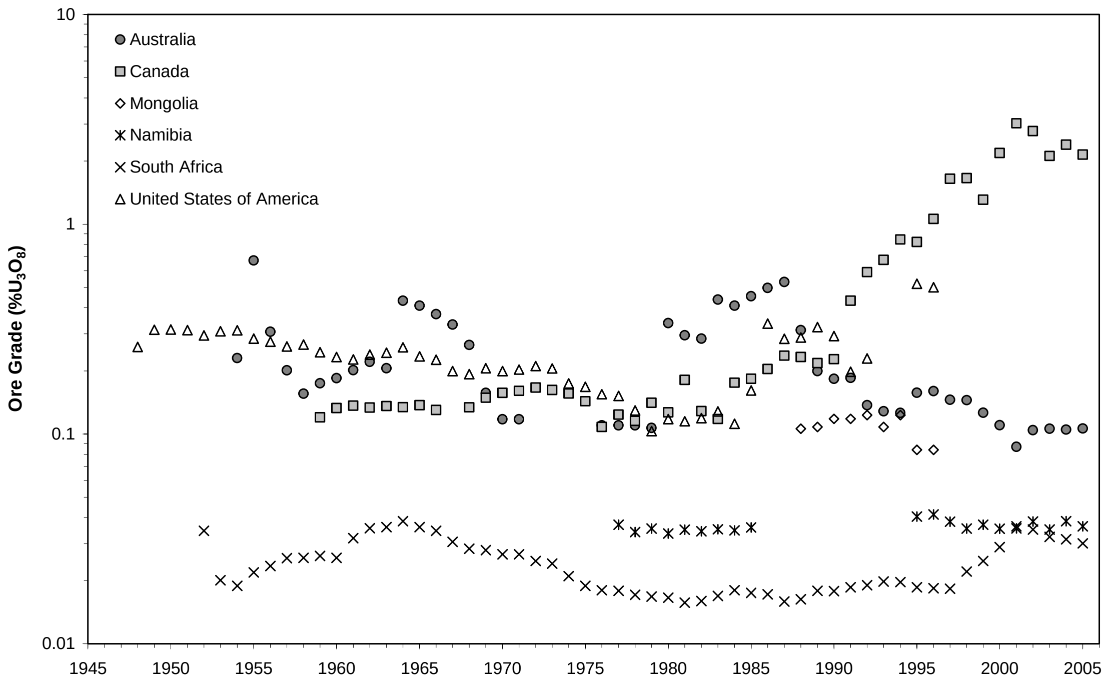

Figure 1 – Average Uranium Ore Grade in Milling Over Time

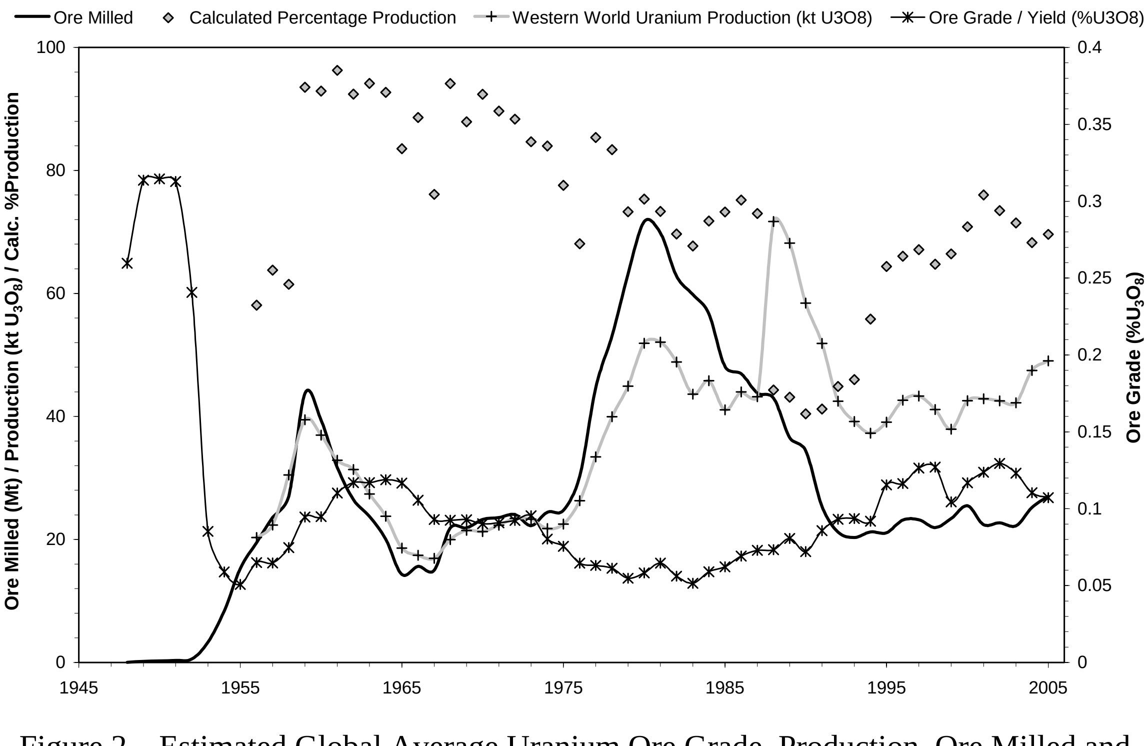

Figure 2 – Estimated Global Average Uranium Ore Grade, Production, Ore Milled and Calculated Percentage of Production

The second period of uranium mining (for civil nuclear power) also faced this same dilemma in the 1960's, but exploration again found additional uranium resources, particularly in Australia and Canada. The principal aspects of economic resources include the estimated contained uranium as well as the average ore grade of an individual deposit. Although country resources over time are compiled and analysed by (OECD-NEA & IAEA, var.), the ore grades and other salient statistics of the numerous deposits are invariably never presented.

All publicly listed mining companies, at least in western-style economies, are generally bound by codes or law to report accurately on economic ore resources they control. Given the largely western economic control of the global uranium industry, it is therefore possible to compile an up-to-date assessment of recent uranium deposit resource statistics. This can then be compared to the limited earlier data available.

In total, the compiled data totals 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, (OECD-NEA & IAEA, var.). 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.

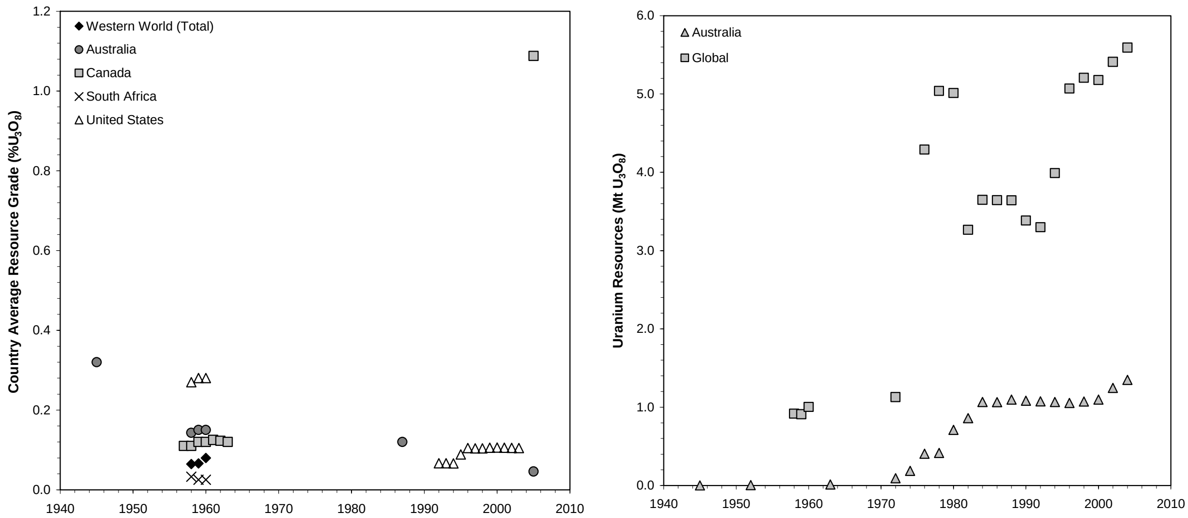

Figure 3 – Average Ore Grade of Select Country Uranium Resources (left) and Global and Australian Known Economic Uranium Resources (right) Over Time

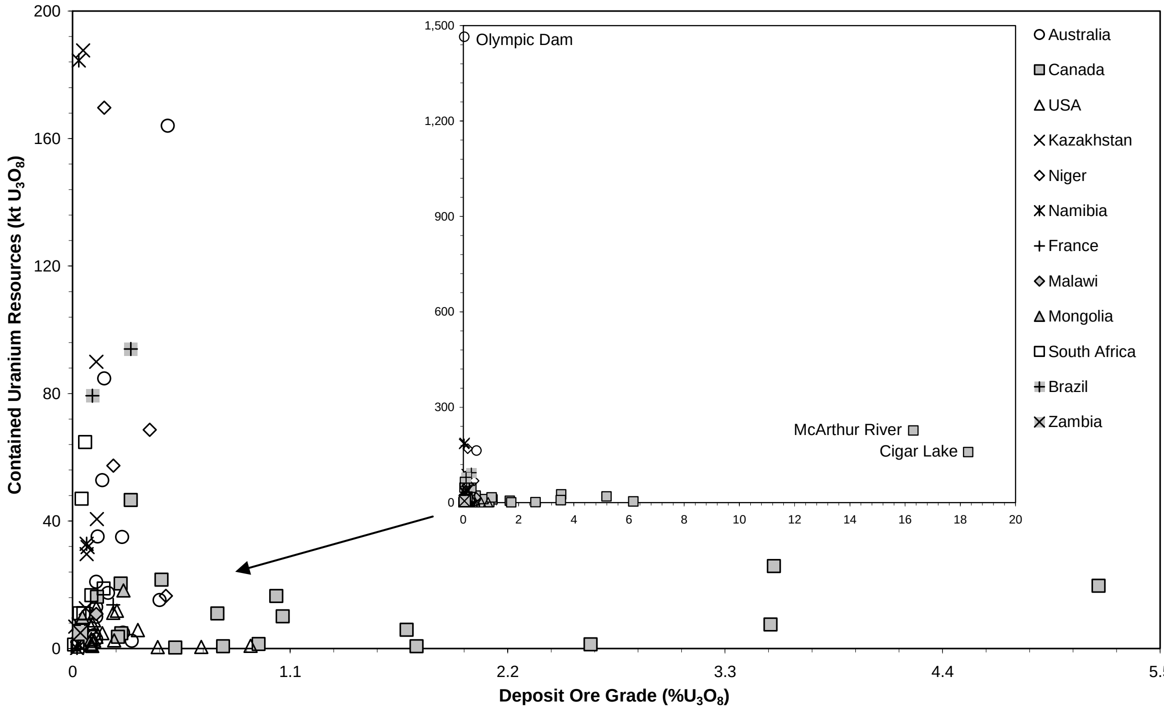

Figure 4 – Contained Uranium Resources versus Ore Grade : Individual Deposits by Country

3.3 Energy and Water Consumption in Uranium Mining

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

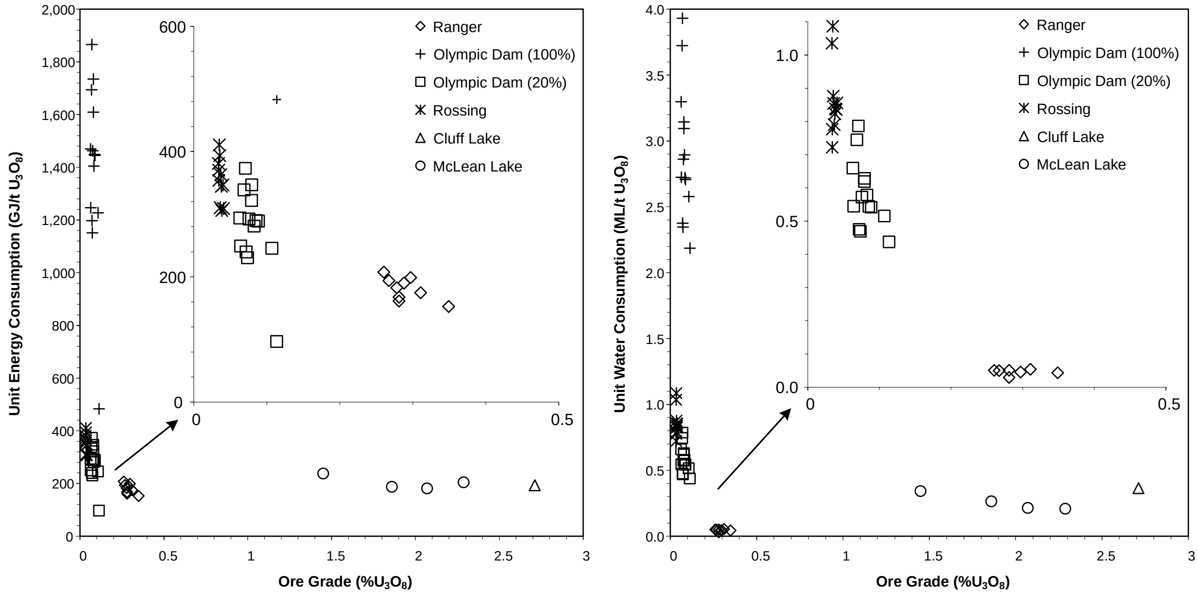

Figure 5 – Energy and Water Consumption per Uranium Oxide Produced versus Ore Grade

(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, containing about 21,000 t U_3O_8; see (Mudd, 2006)

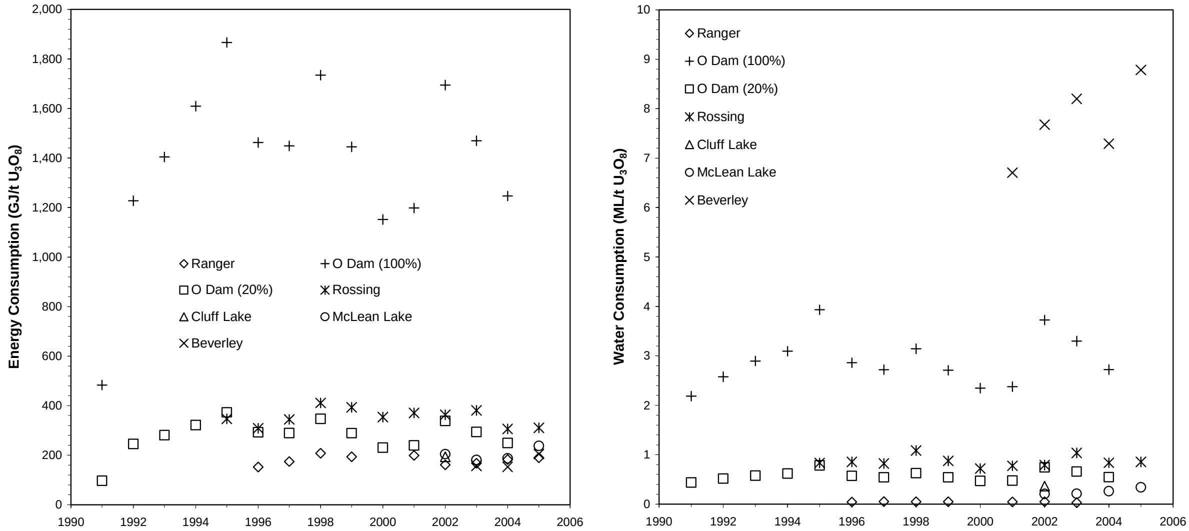

Figure 6 – Energy and Water Consumption per Uranium Oxide Produced versus Time

3.4 Carbon Dioxide Emissions From Uranium Mining

The compiled data for carbon dioxide emissions per unit uranium oxide production with respect to ore grade and over time are shown in Figure 7. As can be seen, using a 20% factor places Olympic Dam within the same order of magnitude as Rössing.

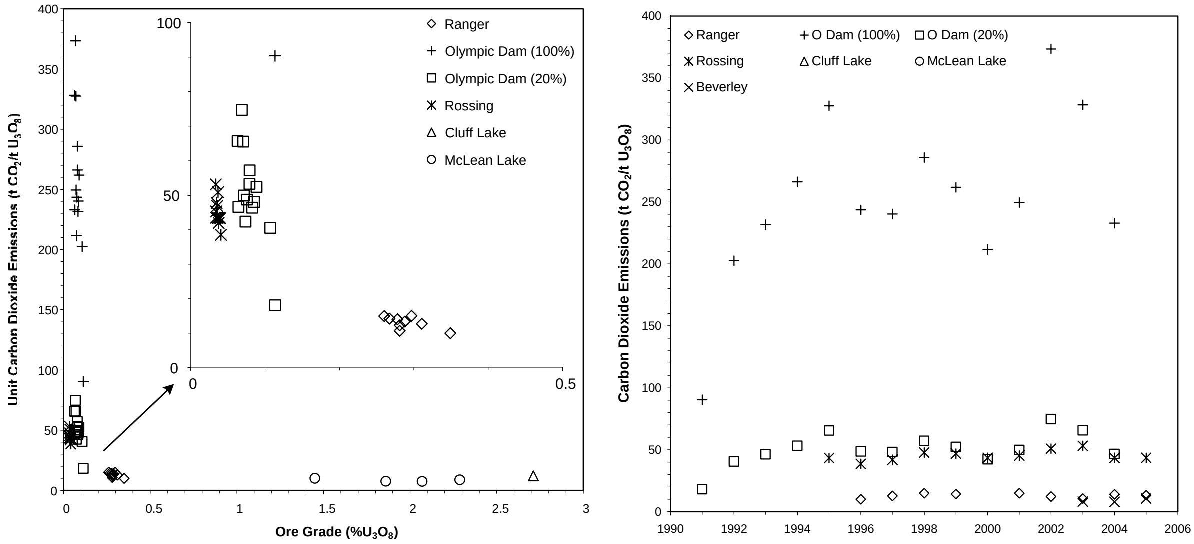

Figure 7 – Carbon Dioxide Emissions per Uranium Oxide Produced versus Ore Grade and Time

Table 1 – Summary of Normalised Energy and Water Consumption and Carbon Dioxide Emissions for Uranium Mines (Average ± Standard Deviation, number of years in brackets)

Uranium Project	Typical Ore Grade	Annual Prod.	Consumption		Emissions
			Water	Energy	Carbon Dioxide
	$\%U_3O_8$	t U_3O_8	kL/t U_3O_8	GJ/t U_3O_8	t CO_2/t U_3O_8
Ranger	0.28-0.35	5,000	46.2 ± 8.2 (7)	181 ± 18 (9)	13.0 ± 1.8 (9)
Olympic (100%)	0.064-0.114	4,300	2,899 ± 503 (14)	1,389 ± 336 (14)	253 ± 67 (14)
Olympic (20%)			580 ± 101 (14)	278 ± 67 (14)	50.6 ± 13.5 (14)
Rössing	~0.034-0.041	~3,700	863 ± 107 (11)	354 ± 35 (11)	45.3 ± 4.1 (11)
Cliff 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.
‡ Different data for 2004-05 is given by (WNA, 2006) for Beverley as 187 and 221 GJ/t U_3O_8, respectively, compared to data reported by (HR, var.) 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).

4 Discussion

The data compiled and presented within this paper provides 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 uranium oxide production and greenhouse emissions (carbon dioxide) per uranium oxide production.

The extent of economic uranium resources has generally increased over time, co-incident with the major periods of exploration. In Canada, the Elliot Lake region of Ontario provided most resources during the 1950's-60's, switching to Saskatchewan from the 1970's. 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 (prior to mining) (Cameco, var.). Although new prospects are being found, only the Millenium prospect from late 2002 has to date proven substantive (about 26 kt U_3O_8 at ~3.55% U_3O_8; 2005 Edition, (Cameco, var.). No deposits of the significance of Cigar Lake and McArthur River have been found since 1988.

In Australia, despite broad ranging exploration in the 1970's with associated spectacular results, there has only been one new deposit discovered since 1975 – the modest Kintyre in 1985. All increases in uranium resources since this time have resulted from increased drilling and new assessments at known deposits, mainly Ranger and Olympic Dam. This pattern of no 'world-class' discoveries in the past two decades is thought to be similar in other countries.

Although beyond the scope of this paper, significant additional uranium resources are likely to be available as a by-product from phosphate ore resources (eg. Florida, USA), which have produced uranium in the past. 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 50 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 (eg. (Macdonald, 2001). The deeper a deposit the more energy which can 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 average country ore grade (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 1990's was typically 0.07-0.11% U_3O_8, which is about one third of that in the late 1950's of 0.28% U_3O_8. Canada is the only country which has seen a substantive rise in its average ore grade, due to the rich Athabasca Basin deposits of northern Saskatchewan (eg. McArthur River, Cigar Lake, Midwest). The average ore grade of the Elliot Lake district of northern Ontario, which generally contained more than 95% of Canada's resources from the 1950's to 1960's, was typically 0.11% U_3O_8 – compared to the estimated average of 1.1% U_3O_8 in 2005 (based on resource data compiled for this paper). 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 0.05-0.13% U_3O_8 over the past five decades (even allowing for incomplete production). Finally, based on data for 93 deposits/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 major production capacity for any proposed nuclear power program, it is clear that these larger tonnage, lower grade deposits would need to be developed, thereby continuing to balance the rich Saskatchewan deposits into the future.

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 (excluding the single year for Cluff Lake). The data reported for these select mines and compiled herein is only based on direct fuel inputs, such as diesel and/or electricity. Given the data provided, there appears to be little difference in unit energy costs per uranium oxide 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 well field and mill consumed 44.9% and 41.6% of electricity usage, or in terms of activities pumping consumed 80.7% of electricity usage (2004 Edition, (HR, var.). Critically, the data for all mines does not account for the additional embodied energy required for reagents such as solvents (eg. kerosene, amine), sulfuric acid, oxidants (eg. hydrogen peroxide), lime and so on. This would add significant energy costs to uranium production.

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 (excluding the single year for Cluff Lake). 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 five-fold that of Ranger as well as an ore grade some eight times lower, thereby leading to significant demands for water. The general sensitivity of normalised water consumption to ore grade is also apparent.

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 (excluding the single year for Cluff Lake). The data in terms of carbon dioxide emissions per tonne of ore milled, although not presented within the space of this paper, shows 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. The general sensitivity of normalised water consumption to ore grade is also apparent.

5 Conclusion

The extent of economically recoverable uranium, although still effectively unknown, is linked to exploration effort and economics but is inextricably linked to environmental costs such as energy and water consumption and greenhouse emissions. 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 and site-specific data for numerous individual mines and mills. 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 understand in 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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