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Uranium Mining, Nuclear Power and Sustainability: Rhetoric versus Reality

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ABSTRACT

The major greenhouse gas emissions from coal combustion are leading certain people to argue for uranium mining and nuclear power to meet these challenges. Although there is considerable rhetoric around promoting nuclear power as 'green' due to its relatively lower greenhouse intensity, a careful study of the data is required to properly understand the sustainability of uranium mining and nuclear power, and whether it can or should have a role in future energy supply scenarios. This paper presents detailed research and analysis on uranium mining, focusing on known economic resources, production, solid waste and water management, pollution issues as well as energy and greenhouse aspects. A particular focus will be on Australia and its operating and prospective uranium mines. Overall, the paper raises fundamental issues concerning the long-term sustainability of uranium mining and nuclear power, and documents the greenhouse intensity of uranium production and the nuclear fuel chain.

Keywords: uranium mining, nuclear power, sustainable mining, greenhouse gas emissions, environmental impacts

INTRODUCTION

Despite the utopian promise of electricity 'too cheap to meter'[1], nuclear power remains a minor source of electricity worldwide. In 2007 nuclear power accounted for 5.87% of total primary energy supply and was responsible for 13.7% of global electricity supply. This percentage contribution has been declining through the 2000s (IEA, 2009). Concerns about hazards and unfavourable economics have stopped the growth of nuclear energy in all but two Western countries, Finland and France. In the USA, no orders for nuclear power stations placed after 1978 have been completed and all plants ordered after 1973 have been cancelled. However, there is still growth in nuclear energy in several countries, notably China, Russia, India and South Korea. Over the next 15–20 years, many more nuclear power stations will reach retirement age than those contracted for actual construction (Schneider *et al.*, 2009).

World primary energy production and electricity generation are given in Table 1, including the International Energy Agency's (IEA) projection of world energy and electricity demands in 2030. It can be seen that nuclear energy's share of primary energy and electricity are predicted to decline by 2030 – and yet we are led to believe that it is the saviour of the world's power hungry demands. Also of note is the massive proportional increase in renewable energy-derived electricity. By 2030 all renewable electricity sources (wind, solar, hydro, geothermal and biomass) will more than double, especially led by hydro, wind and solar-derived electricity. There are more radical scenarios for 100% renewable energy on a global scale (Jacobson & Delucchi, 2009; Sørensen & Meibom, 2000), 100% renewable energy for the European Union (Zervos *et al.*, 2010) and 100% renewable electricity for New Zealand (Mason *et al.*, 2010), among others.

There are numerous critical issues facing the energy and electricity sectors globally, such as:

- greenhouse gas emissions released by fossil fuel sources contributing to anthropogenic climate change;

[1] Although this statement was made by Lewis L. Strauss on 16th September 1954 mainly in reference to the future potential of hydrogen fusion power, it was made during the early years of the Cold War when nuclear fission power was being actively promoted through the 'Atoms for Peace' program and remains a useful metaphor generally.

- peak oil, the end of the era of cheap conventional oil, together with concerns about energy security, especially ongoing supply issues and maintaining resources.

It is argued by some that nuclear power can effectively address these problems on the basis that it has lower carbon intensity than fossil fuels, is largely independent of oil or coal supplies and, if plutonium breeder reactors can be made commercial, could provide a substantial energy resource which could last a considerable period of time (centuries or more).

In this context we ask, what is the basis upon which nuclear power could be argued to increase beyond the IEA's current projections? In other words, can the nuclear fuel chain be considered a sustainable option for future electricity generation? These questions are more than of minor consequence to address. The contribution of nuclear power to nuclear weapons proliferation remains paramount and urgent (eg. North Korea, India, Pakistan, Iran, etc.) and nuclear reactor safety and long-term stewardship of nuclear waste (ie. for greater than 100,000 years) still represent fundamental concerns, especially when comparing these risks to energy efficiency and various renewable energy technologies such as solar thermal technologies, solar photovoltaics, wind and so on.

This paper presents a detailed study of the ability for uranium (U) mining and resources to meet possible future scenarios for expanded nuclear power. An extensive array of data is compiled and analysed, including known economic resources, production, solid waste burdens, water management, pollution issues as well as energy and greenhouse aspects. The extent of sustainability reporting by U mining companies is also reviewed, since this is a strongly growing basis for reputable mining companies to report and transparently demonstrate their overall sustainability performance (Mudd, 2009).

The paper thus provides a detailed case study of the U sector of the global mining industry, which, albeit a somewhat small player in value terms, attracts significant political and corporate support while remaining deeply controversial in public debate.

URANIUM RESOURCES, MINING AND MILLING

Uranium Resources

Since the discovery of radioactivity in 1896, there have been arguably four major phases of U mining – the 'radium' phase from ~1900 to 1940, the Cold War or military phase from 1941 to the 1960s, the civilian phase from the 1970s to the mid-1990s, followed most recently by a resurgence in interest in U exploration and mining since about 2003. At the start of each major phase, substantial concerns were raised about the extent of U resources – that is, the ability to meet rapidly growing demands. Very quickly, however, for each of the first three phases, new deposits and major fields were discovered that quickly led to new supply. Given the current hype around nuclear power and U mining, has the fourth phase been different? Has there been a wave of new discoveries in Australia, Canada or elsewhere, which can underpin the hoped for expansion in nuclear power over coming decades? To address the fundamental issue of U resources over time, a range of data have been compiled and updated, including an extensive database of U deposit statistics for critical countries.

Uranium resources can be found in a wide variety of deposit types, mainly related to its geochemical versatility. According to the International Atomic Energy Agency (IAEA), there are eleven primary types of U deposits: (1) unconformity-related; (2) sandstone; (3) hematite breccia complex; (4) quartz-pebble conglomerate; (5) vein; (6) intrusive; (7) volcanic and caldera-related; (8) metasomatite; (9) surficial; (10) collapse breccia pipe; and (11) phosphorite (IAEA, 2009b). In addition, minor deposit types include metamorphic, limestone-paleokarst and U-enriched coal deposits (IAEA, 2009b). Historically, most U production has been derived from sandstone, unconformity and quartz-pebble conglomerate deposits. It is common for a country to be dominated by a single deposit type (eg. South Africa by quartz-pebble conglomerates; Kazakhstan by sandstones), but not always (eg. numerous types in the USA and Australia).

Given the political prominence of U as a strategic national resource, especially during the Cold War years, there is a reasonable amount of data on U resources since 1950. Major publications include:

- *Uranium : Resources, Production and Demand* (aka the 'Red Book', published every 2 years since 1965) (OECD-NEA & IAEA, var.);
- *Canadian Minerals Yearbook* (1944 to present) (NRC, var.);
- US Bureau of Mines' *Minerals Yearbook* (1933 to 1993) (USBoM, var.);
- US Department of Energy's *Uranium Industry Annual* (1992 to 2005) (EIA, var.); and
- South African Chamber of Mines' *Facts and Figures* (CMSA, 2008).

In addition, other reports also provide data (eg. Australia, Battey *et al.*, 1987; Dickinson, 1945; McKay & Miezitis, 2001; Mudd, 2010). Numerous U companies also publish their reserves and resources in annual corporate reports, as required for publicly-listed companies in developed countries (eg. Cameco, BHP Billiton, Rio Tinto, Uranium One, Paladin Energy, Denison Mines, Areva and others).

Based on methodology adopted by the 2007 Edition of the OECD/IAEA Red Book, U resources are classified slightly different to the normal 'reserves and resources' (eg. JORC Code; AusIMM *et al.*, 2004), instead using 'identified resources' which consists of 'reasonably assured resources' (RAR) and 'inferred resources' with deposits categorised into predicted cost ranges (eg. <US$40/kg U, <US$80/kg U, <US$130/kg U). Although there are differences in the various codes or standards for reporting U resources, they are broadly similar and provide a realistic basis for comparison. It must also be stated that there are legitimate technical concerns regarding the reliability and accuracy of Red Book U resource data (see Dittmar, 2009), although we will assume Red Book data is sufficiently accurate for this paper.

The trends in remaining economic resources and country average ore grades are shown in Figure 1, with Red Book and national resource data for 2007 in Table 2. A compilation of reported U resources by individual projects is given in Table 3. There are two main trends evident: (i) global economic U resources have continued to grow over time; and (ii) most countries, except Canada, show declining average ore grades with time. The rise in the average ore grade in Canada in the 1990s is mainly due to the large, high-grade deposits discovered at McArthur River and Cigar Lake (see Table 3), although recent years has seen a declining trend emerge as lower grade deposits such as Kiggavik-Sissons Schultz and others (Table 3) are now considered as potential economic prospects. The 1950s -60s resources in Canada were dominated by the Elliot Lake district of northern Ontario, which produced ~165 kt U_3O_8 from ore averaging ~0.11% U_3O_8 by field closure in 1996. Substantial mineralised ore remains at Elliot Lake, given that only some half of the identified ore has been mined (based on 1957 ore resource estimates of 342 Mt while ore production totalled ~156 Mt). Whether the remaining Elliot Lake ore could be classified as economic is speculative (see Cochrane & Hwozdyk, 2007).

Canadian U resources are very much dominated by two classes – the super-rich deposits of northern Saskatchewan's Athabasca Basin, especially McArthur River and Cigar Lake, but also the numerous low grade deposits still known in Elliot Lake in northern Ontario, the Baker Lake district of Nunavut containing the undeveloped Kiggavik-Sissons Schultz deposits or the unusually low grade Hidden Bay deposits of Saskatchewan. As visible in Figure 1, when all known U deposits are included in Canada's resources, the total significantly exceeds the national estimate – largely since Natural Resources Canada (NRC) only include operating mines and those committed to development in their national resource estimates – but also that the average Canadian ore grade declines significantly.

The extent of U resources in Australia is increasingly dominated by the giant Olympic Dam deposit in South Australia. The Olympic Dam copper-U-gold-silver (Cu-U-Au-Ag) project is based on an underground mine, concentrator, U-Cu hydrometallurgical complex, Cu smelter and Cu refinery. The most recent reported mineral resource is 9,080 Mt ore grading 0.86% Cu, 0.027% U_3O_8, 0.32 g/t Au and 1.50 g/t Ag (Table 3) – giving a contained U of some 2,445 kt U_3O_8. At present, there are plans being assessed to convert Olympic Dam to a large open cut project, whereby some U would be produced locally but a significant portion would be contained in U-rich Cu concentrates proposed to be exported to a new, specially constructed Cu smelter in China (see BHPB, 2009) – for total production of 19 kt U_3O_8 per year.

In general, based on deposit data in Table 3, there remain extensive U resources identified in existing producer countries, but almost all of these resources are low grade (0.02-0.05% U_3O_8). In the longer term, continuing U demand will have to mean mining of these lower grade U ore resources with resulting large increase in CO_2 emissions (see below). Furthermore, while the total of 6,278 kt U_3O_8 is close to the 2007 Red Book estimate of 6,448 kt U_3O_8 (see Table 2), major deposits and/or countries are missing (eg. Kazakhstan, China, Russia), as well as numerous small deposits <5 kt U_3O_8.

A plot of ore tonnage versus ore grade for all resources from Table 3 is given in Figure 2, showing a broad inverse correlation – as grade declines, tonnage tends to increase. The Olympic Dam, McArthur River and Cigar Lake deposits are clearly unusual in a global sense, given their relationship to all other U resources.

Uranium Mining, Milling and Production

The U industry uses conventional mining and milling methods, and has also been a pioneer in developing new technologies in the mining industry, such as solvent extraction and in situ leaching. Mining is typically through open cut or underground methods, depending on depth, size and other factors (eg. rivers or lakes). Given it is common for a U deposits to occur in clusters, as in the Athabasca Basin of Canada or Colorado

Palteau of the USA, a central mill can often process ores from a variety of mines. Milling begins with fine grinding, followed by either acid or alkaline leaching, solvent extraction, chemical precipitation and finally calcination to produce uranium oxide (ie. U_3O_8). Acid-based leaching is most common, as it is faster and often achieves a more complete extraction, as well as being a relatively cheaper reagent. Alkaline leaching is suited for particular ore types which contain significant calcite (or limestone), the most common of which is surficial (or carnotite) type deposits. Further discussion of U ore mining and milling is given by IAEA (1993, 2009a), OECD-NEA & IAEA (1999), and Özberk & Oliver (2000).

In situ leaching (ISL) is a very specialised form of U production, and is commonly only suitable for sandstone type deposits. The process of ISL involves drilling hundreds of groundwater bores into the sandstone ore, using some as injection bores and most as extraction bores. The reagents are added to the re-circulating solutions, including an acid (eg. sulfuric acid) or alkali (sodium bicarbonate) plus a strong oxidant (eg. oxygen, hydrogen peroxide, or hypochlorate), thereby dissolving the U ‘in situ’ in the ore formation and bringing it to the surface in the extracted solutions. Although ISL used to be a relatively minor U source, restricted to a handful of mines throughout the world, the rapid growth of ISL mines in Kazakhstan in the past few years has seen ISL begin to rival conventional sources – reaching about 36% of global U production in 2009 (WNA, 2010). A major issue with ISL is the challenge of remediating impacted groundwater resources after mining, with the extent of groundwater contamination often severe at Cold War-era acid ISL sites (Mudd, 2001a, b) – although civilian-era alkaline sites have also proved much more difficult to remediate than anticipated (see Hall, 2009; Otton & Hall, 2009).

Historical U production by country is given in Figure 3, showing the major dominance of a select handful of countries such as Canada, the United States, Germany (dominantly East), the former Soviet Union and its now component states since 1992 (eg. Kazakhstan, Uzbekistan etc), Niger and Australia. By the collapse of the Soviet Union in 1991, it is interesting to note that the USSR, USA, Canada and Eastern Germany had each produced 445.2, 397.5, 292.2 and 256.5 kt U_3O_8, respectively. Total world production by 2009 has been approximately 2,903 kt U_3O_8 (which compares to the 6,448 kt U_3O_8 of resources reported by the 2007 Red Book; Table 2).

A compilation of production statistics for U projects around the world is given in Table 4, showing the dominance of a small number of mines (the Top 5 mines, McArthur River, Ranger, Rössing, Kraznokamensk and Olympic Dam, produced 42% of 2009 global production) as well as the popularity of ISL for sandstone ores (especially Kazakhstan despite numerous mines not reporting production data). The more than two orders of magnitude difference in ore grades, from McArthur River at ~15% U_3O_8 before blending at Key Lake to ~0.04% U_3O_8 at Rössing, is extremely unusual in global mining (compared to say maximum and minimum Cu or Au ore grades), and highlights the decidedly variable nature of individual U projects (scale, technical challenges, economics, ore processing, environmental issues, etc.). Another important aspect of the data in Table 4 is that not all companies report complete mining and milling statistics. For example, most mines do not report waste rock (even open cut mines) – despite this often being a major portion of mine waste, and some do not report complete mill data (eg. ore milled, ore grades, U extraction, or solution volumes and concentrations for ISL).

The available data for average country ore grades over time is compiled in Figure 4, showing the relative magnitude of different countries such as Namibia versus Australia, as well as the increasing ore grades in Canada as the dominance of Saskatchewan's rich deposits grows (especially the start of the high grade McArthur River project in 2000). Given the increasing proportion of low grade projects under development in Canada, Australia and Namibia, and especially ISL production in Kazakhstan, the overall global average ore grade will continue to decline over time.

A rarely analysed issue of U production is the consistency of various publications and data sources. Given the prominence of non-proliferation issues globally and international treaty requirements for safeguards to ensure that U is used for civilian purposes, accurate statistics are an obvious necessity. Production is variably reported by companies and state or federal agencies, sometimes as contained t U or t U_3O_8, but also as U ore concentrate (or 'UOC'). Furthermore, some groups report sales (or deliveries) only, and not production. A detailed case study of Australia's recent U reporting is compiled in Table 5 for production and in Table 6 for exports. As can be seen, there is significant inconsistency in reported production – perhaps due to Olympic Dam reporting UOC and not contained U_3O_8. According to production data reported by AUA (var.), who correct UOC to t U, UOC is typically some 98% pure U_3O_8. Further complications arise due to the differences between 'exports' and deliveries, the difference usually being one of timing. Overall, it can be seen that the variability in reported production and exports (/deliveries) is easily of the order of several tens to hundreds of tonnes or more, which is more than can be attributed to merely rounding errors or UOC v U_3O_8. Such a situation does not instill confidence of U accounting with respect to nuclear non-proliferation.

In an era of continuing grave concerns over proliferation of fissionable materials and nuclear weapons technology (eg. Iran, North Korea, India, Pakistan, Israel), amongst other concerns of nuclear power, it is imperative that accurate and public accounts of U production and all related materials be maintained.

Uranium Mine Rehabilitation: Australia's Status

Although many of the aspects and challenges of U mine rehabilitation are similar or analogous to conventional hard rock mining such as copper or gold, the radioactive nature of U mine wastes and former facilities leads to additional requirements. Based on modern environmental regulation and community expectations, since about 1970 in most developed countries, all former U projects are required to be rehabilitated after completion of mining and milling. During the Cold War era U mines were often abandoned or at best only given a cursory rehabilitation – leading to a major and substantial legacy of environmental and/or radiological impacts (as discussed by Waggitt, 2007). For example, the US Department of Energy has taken on the rehabilitation of all former U mines from which they obtained material for the Cold War, a program which has cost literally billions of dollars but remains only partially documented (certainly no substantive overview paper or compilation report appears to have been published). One of the 'costs' of the reunification of Germany was for the West German government to accept all liabilities and remediation costs for the former U industry of the old East Germany (the German Democratic Republic or GDR) – in December 1991 this program amounted to a budget of some 13 billion deutsche marks (equal to €6.6 billion) (Hagen & Jakubick, 2005). In many parts of the world, the legacy of unrehabilitated U mining and milling continues.

In Australia, there is often a widely held belief that we have been successful in rehabilitating our legacy U projects – but invariably this view is held by those who have never visited these sites. In brief, the major Cold War-era U mines in Australia were the Mary Kathleen, Rum Jungle, Radium Hill-Port Pirie and the Upper South Alligator Valley, with the latter rehabilitated only in the 2000s (after the Coronation Hill saga) while all others were rehabilitated in the mid-1980s. Further small U projects were also developed at Pandanus Creek-Cobar 2, Fleur de Lys, George Creek, Brock's Creek and Adelaide River in the Northern Territory and Myponga in South Australia (Mudd, 2010), though no substantive rehabilitation work is known for each site. The Nabarlek project, which operated from 1979 to 1988, was a 'modern U mine' and approved and operated under strict regulations and supervision, being rehabilitated in the mid-1990s. Other 'modern U mines' are still in operation at Ranger, Olympic Dam and more recently Beverley.

At present, there is no former U project in Australia which can be claimed as a successful, long-term rehabilitation case study – all still require ongoing monitoring and maintenance, and some remain mildly to extremely polluting. While this may be rather surprising to many in the general mining industry, there is strong evidence to support such a view:

- *Rum Jungle* – despite some $20 million of works, the site remains a major source of extreme acid and metalliferous drainage (AMD) to the Finniss River, as shown in Figure 5, as well as a host ongoing problems such as erosion, weeds, site security and so on. A detailed review of the rehabilitation work, subsequent monitoring and strong evidence of failure is given by Mudd & Patterson (2010).

- *Mary Kathleen* – the rehabilitation project won an Australian engineering excellence award in 1986, based on predictions of no AMD, low ongoing tailings dam seepage and associated impacts, erosional stability and no metal and radionuclide uptake by vegetation (amongst other aspects). Recent research has shown these assumptions over-estimated the long-term success of rehabilitation, with AMD, tailings seepage, erosion and/or metal-radionuclide uptake impacts now prevalent across relevant parts of the site (see Figure 5) (Lottermoser *et al.*, 2005).

- *Radium Hill* – although the waste rock and tailings at Radium Hill are very low in specific activity (~0.04% U_3O_8), physical dispersal has been occurring despite rehabilitation (Lottermoser & Ashley, 2006) and the site requires ongoing monitoring and maintenance (see Figure 5) (McLeary, 2004b).

- *Port Pirie* – this site treated ~152 kt of ore concentrate from Radium Hill, grading about ~0.7% U_3O_8, and like Radium Hill, still requires ongoing monitoring and maintenance (McLeary, 2004a).

- *Upper South Alligator Valley* – about 13 U mines and 2 U mills were merely abandoned in the mid-1960s, leaving indigenous (Jawoyn) people and tourists to southern Kakadu at risk of radiation exposure or safety hazards, as well as localised AMD at some former mines (mainly Rockhole). Minor rehabilitation works were undertaken in the late 1980s but were not tasked with complete rehabilitation. Following the blocking of the re-mining of Coronation Hill in 1991 and after considerable negotiation with Jawoyn elders, all rehabilitation work in the valley was finally completed in 2009. The test of time will reveal its degree of success (or otherwise).

- *Nabarlek* – a U mine/mill opened in the modern era of strict environmental regulations, and yet despite closing in 1988 the site was not rehabilitated until 1995. Although post-closure assessment has shown a reduction in average radon flux from the former ore zone (Mudd, 2007), gamma radiation rates have increased across many parts of the site which formerly showed effectively background levels (Martin, 2000; Mudd, 2002). Some residual infrastructure still remains idle at Nabarlek, as well as major impacts from weeds and the destruction of the revegetation during recent cyclonic storms.

The saga of the radium era waste (ie. 1910s-20s) in suburban Hunters Hill in Sydney, still not fully remediated and appropriately managed nearly a century later (GPSC5, 2008), is also another telling tale of Australia's failure to manage U mining and milling wastes – even for extremely small sites in full public eye (Mudd, 2005a).

At acid in-situ leach projects in South Australia, regulatory approvals allow companies to ignore groundwater remediation after mine closure despite never validating key scientific assumptions and claims concerning groundwater impacts (Mudd, 2001a, 2005b).

Australia's track record on U mine and mill rehabilitation is therefore far from acceptable, and remains distant from reasonable expectations of all sites and wastes being physically, chemically, biologically and radiologically stable such that we can be confident of no further monitoring or maintenance.

SUSTAINABILITY METRICS OF URANIUM PRODUCTION

Sustainability Reporting

A welcome trend across all sectors of global industry is the strong emergence of sustainability reporting over the past decade. Numerous mining companies have certainly been at the forefront of this change in corporate accountability by publishing annual sustainability reports alongside statutory financial reports (Mudd, 2009). The most popular protocol is the Global Reporting Initiative (GRI, 2006) – a coalition of the United Nations, industry, government and civil society groups. The use of the GRI for reporting is (still) voluntary, and it includes core and voluntary indicators covering economic, social, environmental, human rights and labour aspects of an organisation's activities, with some being qualitative while others are quantitative. A specific sector supplement was recently finalised to facilitate improved and more relevant sustainability reporting for mining (GRI, 2010). Some mining companies continue to rely on internally developed systems for sustainability reporting, with variable comparison to the GRI. The extent to which a report meets GRI requirements can also be assessed, giving a company's report an 'application level', essentially a measure of thoroughness or quality assurance. The issue of external auditing is emerging as a key test regarding the credibility of reports (Fonseca, 2010) – that is, the old 'spin versus substance' debate.

This paper will only focus on the most critical environmental GRI indicators, which include:

- EN3/EN4 – direct/indirect energy consumption by primary energy source (*both core*);
- EN5, EN6, EN7 – energy savings and efficiency, renewable energy initiatives (*all voluntary*);
- EN8 – total water withdrawal by source (*core*);

- EN9 – water sources significantly affected by withdrawal of water (*voluntary*);
- EN10 – percentage and total volume of water recycled and reused (*voluntary*);
- EN16, EN17 – total direct and indirect greenhouse gas emissions by weight (*core*);
- EN18 – initiatives to reduce greenhouse gas emissions and reductions achieved (*voluntary*);
- EN19 – emissions of ozone-depleting substances by weight (*core*);
- EN20 – NO_x, SO_x, and other significant air emissions by type and weight (*core*);
- EN21 – total water discharge by quality and destination (*core*);
- EN22 – total weight of waste by type and disposal method (*core*);
- EN23 – total number and volume of significant spills (*core*).

In addition, the GRI mining sector supplement also recommends the following indicators as replacements or complementary to the main protocol:

- MM1 – amount of land (owned or leased, and managed for production activities or extractive use) disturbed or rehabilitated (*core*);
- MM2 – the number and percentage of total sites identified as requiring biodiversity management plans according to stated criteria, and the number (percentage) of those sites with plans in place (*core*);
- MM3 – total amounts of overburden, rock, tailings, and sludges and their associated risks (*core*);
- MM11 – programs and progress relating to materials stewardship (*core*).

A detailed compilation of the extent of sustainability reporting by U companies for 2008 is given in Table 7. In comparing Tables 4 and 7, it is clear that several major U producers do not even publish annual sustainability reports. For those who do publish such reports, the extent of actual site data is minimal, and certainly only a minor proportion of the core GRI indicators. Common problems include the tendency to produce group only or corporate reports which publish data for a company as a whole, with virtually no site-specific data, as well as the lack of data tables (some reports just show relative change from the previous year or a pre-defined baseline year, in either percentage terms or in low resolution graphs). Although it is relatively rare for targets to be set for aspects such as energy, water or emissions, the Rössing mine does include graphs of performance over time with respect to targets, shown in Figure 6. The gradual rise in unit metrics is a clear reminder of the challenge of declining ore grades and/or increasing mine waste – that is, despite efficiency measures, unit production costs continue to gradually rise over time. The Rössing mine, however, does deserve credit as one of the few U projects in the world to continue to release detailed site-specific data in their annual reporting (as opposed to BHP Billiton, who discontinued such reporting by WMC for Olympic Dam after their successful 2005 takeover of WMC).

Other issues in sustainability reporting include timeliness and fragmentation. It is still a widespread problem that sustainability reports are not prepared and published at the same time as annual, statutory corporate reports, sometimes being released several months later – although this is a generic challenge and certainly not unique to U mining (see Mudd, 2009). In Australia, there is significant fragmentation of statutory environmental reporting under a variety of different policies and systems. For example, energy consumption by site is reported to the Australian Government under the *Energy Efficiencies Opportunities Act 2006* ('EEO'), including energy efficiency actions underway and their success (or otherwise) – most mining companies make their EEO reports available online. EEO reports do not separate direct and indirect energy either, further complicating any use of the data. Although greenhouse gas emissions are also reported to the Australian Government, site-based data is considered confidential and only published in sustainability reports if a company so chooses. There are no compulsory requirements to report annual mine waste volumes or water consumption or site water balances publicly. It would appear that Canada is in a similar position to Australia, although most other countries are not even close to such statutory reporting regimes.

As such, although some companies may choose to adopt the Global Reporting Initiative for sustainability reporting, as can be seen from Table 7, there is still a long way to go before regular, site-specific data is consistently reported which makes analysing environmental performance more robust, reliable and comparable across sites, companies and countries.

Sustainability Metrics

The environmental sustainability metrics of U production are compiled in Table 8, including recent and additional data since Mudd & Diesendorf (2008). The data is presented as two metrics – unit input/output per t ore processed and unit input/output per t U_3O_8 produced. The unit metrics versus U ore grade are given in Figure 7, including unit water versus unit energy consumption.

For Olympic Dam, metrics are calculated on the basis that 20% of revenue is derived from U production, with energy, water and CO_2 emissions therefore taken as 20% of totals. Although it is conceivable that Olympic Dam ore could be processed for U alone, given it's large size and slightly higher ore grade than Rössing, at present a considerable proportion of inputs and outputs are associated with Cu-Au-Ag production.

As could be expected, there is considerable variability in the unit metrics for the different U projects. For example, unit water, energy and CO_2 metrics vary from 29.4 to 1,768 kL/t U_3O_8 (excluding ISL, which was 6,704 to 10,590 kL/t U_3O_8), 96.6 to 822 GJ/t U_3O_8 and 8.0 to 74.7 t CO_2/t U_3O_8, respectively. Based on production weighted averages, the unit water, energy and CO_2 metrics of U production are 692 kL/t U_3O_8, 260 GJ/t U_3O_8 and 30.8 t CO_2/t U_3O_8, respectively.

The variability between projects is probably a function of deposit characteristics and average ore grade, mine type, process configuration, climate and other factors. For example, the super-rich grades at the McArthur River project require highly specialised remote mining techniques in conjunction with ground freezing to prevent groundwater inflows (the operational difficulty of such techniques has already seen one major flood at McArthur River in 2003, closing the mine for several months, followed by a severe flooding of the Cigar Lake project in 2006 during development – leading to several years delay). As such, the unit water requirements at McArthur River are extremely high despite the high ore grade. Another aspect is energy consumption, with most projects only reporting total energy consumption and not direct and indirect energy sources as required by the GRI. A critical issue in this regard is the split between diesel inputs, used dominantly in mine trucks, and electricity, used mainly in the mill. By reporting both direct and indirect energy consumption by their respective sources (eg. hydro- or coal-based electricity) allows a more accurate picture of the mining and milling steps to be developed, especially with respect to ore grades and emissions profiles. Based on the available data (Table 8), electricity used in milling shows both economies of scale (eg. Rössing has a low unit electricity input of 19.5 kWh/t milled) or mine complexity (eg. McArthur River has a very high unit electricity input of 1,083 kWh/t milled).

A less obvious problem is the accuracy of reported data. Although it is assumed in this paper that all data is complete, accurate and therefore comparable, this is not always clear or even true. For example, the water consumption at the Ranger project is potable (drinking) water only (P. Varris, pers. comm., 16 June 2008) and not process water consumption. Thus although Ranger looks like a highly water efficient U producer, its reported water data is arguably less than 1% of its water throughput or annual water account (eg. contrast Rössing's water account in Figure 6).

In general, there is an approximately inverse relationship between the U ore grade and the respective unit metric, meaning that as ore grades decline the unit metrics will most likely increase. This is a typical expectation for mining in general (eg. Norgate & Jahanshahi, 2010), but importantly this generic relationship formed a fundamental basis for the 'World3' systems model used in 'The Limits to Growth' study of 1972 which predicted that business as usual would see global collapse by about 2050 (Meadows *et al.*, 2004). By contrasting the ore grades of U projects in Table 8 with those from Tables 3 and 4, it can be seen that a major proportion of any future growth in U production has to come from projects with ore grades at or lower than existing projects – and certainly lower than the 'tipping point' of ~0.1% U_3O_8 where unit costs begin to increase substantively (cf. Figure 7).

In addition, the data presented herein does not include the energy requirements and CO_2 emissions associated with the chemicals, reagents and other inputs to keep a U project operating. This includes aspects such as acids (eg. sulfuric acid), alkalis (sodium bicarbonate), oxidants (pyrolusite, hydrogen peroxide), numerous reagents (ammonia, organic solvents, amines, lime, etc.) as well as steels, concrete, explosives, and the extensive amount of materials and energy required to manufacture the mine trucks, transport fleet and so on. For example, according to reporting by explosives manufacturer Dyno Nobel, the average energy cost for ammonium nitrate fuel oil (ANFO) explosives is 7.81 GJ/t ANFO as well as 1.75 t $CO_{2\text{-}e}$/t ANFO (DN, 2006). The typical unit consumption rate for explosives in open cut mines around the world is 0.27 kg ANFO/t rock (unpublished data by authors). Therefore, at Rössing in 2009, it can be estimated that the explosives consumed were 13,875 t ANFO (for 51.4 Mt rock) – the manufacture of which led to about 24,300 t CO_2 of emissions.

Finally, a major aspect which has not been analysed is other pollutants, such as particulates, carbon monoxide, sulfur dioxide (SO_2), nitrogen oxides (or 'NO_x'), heavy metals and such. In Australia, Canada the United States, there are statutory national pollutant release inventories which require public reporting of such emissions to land, air and water. To date, it is extremely rare that U companies have included such data in their reporting, leaving another major gap in understanding the full implications of emissions and pollutant issues associated with U mining and milling.

DISCUSSION: RHETORIC VERSUS REALITY

Projecting Uranium Resources and Production

As noted in the introduction, there is only a modest growth in nuclear power predicted by the IEA by 2030, under both low and high growth scenarios (Table 1). Based on IEA data for nuclear power growth and U requirements, the low and high growth scenarios were projected for U requirements, shown with historical U production and civilian reactor requirements in Figure 8. Assuming that new mine production supplies all U requirements from 2015, this means that by 2030, the low and high growth scenarios project cumulative U requirements of 2,018 and 2,373 kt U_3O_8, respectively. Both estimates are well within known low cost U resources (ie. <US$40/kg U; Table 2), however, given the sluggish growth in western U production, this places more pressure on countries such as Kazakhstan which have seen considerable growth in ISL-based U production over the past several years (see Figure 3). In addition, this requires new production from the numerous low grade projects of South Africa and Namibia, with grades ranging as low as 0.015% U_3O_8 at Trekkopje – which is being developed as a heap leach project especially with a seawater desalination plant to provide its water supply. It is possible, based on operating sites, resource data from Table 3 and assumptions regarding the sequence of developing mines, to project the future ore grade out to 2030, but the high uncertainty in doing such estimates precludes any meaningful insight. For example, new deposits could be discovered (or increases to existing ones), the development sequence could vary, economics could radically alter prices and supply-demand balances, decommissioned nuclear weapons material could be delivered into the civilian market, or even nuclear power could decline and not grow at all. On the other hand, some countries could use imported U to free up local sources of U to increase their nuclear weapons production.

Overall, it can be concluded that sufficient low cost U resources are already known to meet the IEA's projected growth in nuclear power to 2030 – the question is not a matter of 'how much', but the actual production rates and from which deposits or mines that nuclear reactor requirements will be met.

Environmental Costs of Uranium Production

Given that U resources are not a major obstacle to IEA's projected nuclear power growth by 2030, we discuss two environmental impacts, CO_2 emissions and water consumption, over the nuclear fuel chain as a whole and U mining and milling in particular. Both aspects are already significant for the current U industry, and are expected to become more acute if the industry grows as projected.

CO_2 emissions

One of the key factors in determining the CO_2 emissions from the nuclear fuel chain is the U ore grade (Storm van Leeuwen & Smith, 2005), referred to hereinafter as 'SvLS'. Following SvLS, we define 'high-grade' U ores to be those with at least 0.1% U_3O_8. In simple terms, for each tonne of high-grade ore mined, at least 1 kg U_3O_8 can be extracted. For high-grade ores, such as most of those being mined in Australia and Canada, the fossil energy inputs and associated emissions from U mining and milling are small compared with those from the construction and decommissioning of the nuclear power station and total emissions from the nuclear fuel chain are much less than those of electricity from natural gas, the least greenhouse-intensive of the fossil fuels, as shown in Table 9.

SvLS define 'low-grade' U ores to contain less than 0.01% U_3O_8. To obtain 1 kg U_3O_8 from low-grade ore, at least 10 tonnes of low-grade ore has to be mined and milled. This entails an order-of-magnitude increase in the fossil energy required for mining and milling the ore and managing the mountains of mine-wastes. SvLS find that the fossil energy consumption for these steps in the nuclear fuel chain becomes so large that the nuclear fuel chain emits total quantities of CO_2 that are comparable with those from an equivalent combined cycle gas-fired power station, about 600 g CO_2/kWh.

SvLS's work has been critiqued by Lenzen (2008) who argues that a more accurate approach is needed and then shows that his approach gives much lower values of CO_2 emissions from the construction and decommissioning of nuclear power stations. Lenzen also rejects SvLS's requirement that the mine waste should be buried and covered, on the debatable grounds that this recommended safe practice was not carried out for most former mine sites. This value judgment is equivalent to neglecting the risks to future generations of the release of low-level radiation when integrated over 100,000 years (see Mudd, 2007).

Table 9 compares Lenzen (2008)'s results for total CO_2 emissions from the nuclear fuel chain for a light water reactor with those of SvLS, incorporating Lenzen's corrections to SvLS for construction and decommissioning. Emissions from the construction of large wind turbines (cf. Table 1, Lenzen & Munksgaard, 2002) are included in the table for comparison, along with natural gas-derived electricity (ISA, 2006).

Comparing columns 2 and 3 from Table 9, it can be concluded that Lenzen confirms SvLS's qualitative result that has been ignored or obscured by nuclear power proponents – namely that there is a big jump in CO_2 emissions from the nuclear fuel chain in going from high-grade to low-grade U ores. Furthermore, both Lenzen and SvLS find that CO_2 emissions from nuclear power are much greater than those from wind power when U ore-grade is low. If we require that mine waste should be covered, but not to the extent of SvLS, then the emissions from the nuclear fuel chain could lie between the results of Lenzen and SvLS, at about 300 g CO_2/kWh. These are sufficiently high to provide the basis for the case that nuclear energy, based on existing commercial technology, cannot be a long-term energy/electricity solution to global climate change.

Water consumption

Two stages in the nuclear fuel chain consume large quantities of water: U mining and the operation of nuclear power stations.

As shown in the sustainability metrics section, there is a wide variation in water consumption per tonne of U oxide produced. The Olympic Dam project in South Australia currently consumes 12.3 billion litres (GL) or 12.3 Mt of water per year, although it is a combined producer of Cu, U_3O_8, Au and Ag. Data is available for the Ranger (~0.3% U_3O_8), Rössing (~0.035% U_3O_8) and Beverley (~ 0.12% U_3O_8) U mines. Both Ranger and Rössing are conventional open cut mines while Beverley is an acid in situ leach mine. The water consumption for Ranger, Rössing and Beverley is 60, 877 and 8,520 kL/t U_3O_8, respectively (Table 8). The reason Beverley is so high is that it is an ISL or solution mining project – a mining process based entirely on pumping water and chemicals to mine the U in situ. Given that Ranger and Rössing are both open cut mines with conventional processing mills with similar production scale, it is clear that the average ore grade is critical in the environmental costs of U production (including energy costs).

Nuclear power stations use the heat from nuclear reactions to boil water to produce steam to turn turbines that turn generators to produce electricity. Like most coal-fired power stations, nuclear power stations require large quantities of water to condense the steam back to liquid water. However, for the same type of cooling system, a nuclear power station typically uses 20-80 per cent more water than a coal station with the same electricity generation. This is because the steam in nuclear power stations is at lower temperatures and pressures and hence nuclear power is generally less thermally efficient. In other words, a smaller fraction of the heat production in a nuclear station is converted into electricity. For evaporative cooling (the most common type in Australia), a typical 1000 megawatt coal station consumers about 14 GL per year, while an equivalent nuclear station consumers about 20 GL per year (PL, 2006; Rose, 2006).

For comparison, the drinking water consumption of Canberra (population 350,000, latitude 35º) varies within the range 50–60 GL per year (ActewAGL, 2008).

It is of course preferable that large power stations be cooled with seawater, instead of scarce freshwater. This would entail siting nuclear power stations near the coast, the zone that is often most densely populated. Air-cooled nuclear power stations could be located inland, but these are less efficient and hence produce significantly more expensive electricity than water-cooled. Thus there may be limited sites for nuclear power stations in countries such as Australia (Mackintosh, 2007).

Greenhouse Accounting: The Old 'Pea & Thimble' Trick

There is a rarely acknowledged but irreconcilable conflict of interest when the mining industry on the one hand calls for expanded nuclear power to help reduce greenhouse gas emissions, while on the other hand the same companies producing U in Australia are even more rapidly expanding their coal mines in eastern Australia. That is, the two dominant U exporters, BHP Billiton from Olympic Dam and Rio Tinto through their majority (~68%) share of Energy Resources of Australia who operate the Ranger mine in the Northern Territory, both earn considerably more profits from coal than they do from U exports.

Over the past decade, Australia's coal exports have soared from 169.4 Mt in 1998/99 (worth $9.24 billion) to 261.6 Mt in 2008/09 (worth $54.66 billion) (ABARE, 2009). Based on energy factors from ABARE (2010), coal exports in 2008/09 contained ~7.39 billion GJ (ie. 7.39 exajoules or EJ). In the same period, U exports grew from 5,989 t U_3O_8 in 1998/99 (worth $288 million) to 10,114 t U_3O_8 in 2008/09 (worth $990 million) (ABARE, 2009). According to ABARE (2010), 1 t U_3O_8 contains 470,000 GJ of useable energy, giving the contained energy content of U exports in 2008/09 as 4.75 EJ. However, from the 2007 Red Book (OECD-NEA & IAEA, 2008), nuclear power in 2006 generated 2,675.08 TWh of electricity from 78,404 t U_3O_8 –

giving a much smaller useable energy factor of 122,830 GJ/t U_3O_8, and therefore only 1.24 EJ of U energy exports. Although this is most likely due to theoretical considerations of contained energy versus converted electrical energy, this significant inconsistency remains unresolved. Consistent and reliable energy conversion factors for U remain elusive.

It is often selectively claimed that Australia's U exports offset or magically even prevent some 400 Mt of CO_2 emissions compared to coal (eg. AUA, 2010). However, if one optimistically assumes that all nuclear electricity replaces coal and based on typical factors from (DCC, 2009) and IEA data (IEA, 2009), Australia's U exports at their most could only displace 310 Mt of CO_2 emissions – certainly not the 400 Mt CO_2 claimed by the industry. It has to be stated that no coal-fired power station is shut down to allow nuclear power the stage – and coal exports continue their inexorable rise. In countries such as China, nuclear power is a supplement only. Nuclear power is currently only 2% of electricity generation and even in China's long-term planning, it will only grow to 4-5% by 2020. Coal-based electricity remains China's dominant supply choice.

Australia's coal exports in 2008/09 were responsible for ~660 Mt CO_2 of emissions (using factors from DCC, 2009) – which when compared to the supposed 'credit' claimed by U exports, a major debt of some 350 Mt CO_2 shows Australia is still in the red if both coal and U exports were counted as part of Australia's national greenhouse accounts, rather than in the country of use. Thus Australia cannot blindly use U exports as a smokescreen to hide from the global responsibility associated with our coal exports and climate change action.

Based on current mining industry and government plans and aspirations (eg. ABARE, 2010), it is clear that U will remain a poor cousin to old King Coal. Claiming illusory CO_2 savings from U exports while U producers/exporters significantly increase coal exports is very reminiscent of the old pea and thimble trick. Meanwhile, greenhouse gas emissions will undoubtedly continue to rise in Australia and around the world, and the prospect of serious, irreversible climate change impacts looms.

CONCLUSIONS

This paper has provided an extensive review of the mining and milling of uranium (U) ore in the context of perceived increase in global nuclear power. Despite its early promise, nuclear power remains a minor source of primary world energy supplies as well as electricity – and its share is projected to continue to decline, especially as renewable energy sources enter substantial growth in the coming decades. Although the detailed evaluation of known U resources shows that there is sufficient low cost U to meet expected nuclear power demands by 2030, this will increasingly have to be from lower grade deposits. A detailed compilation and analysis of the sustainability metrics of U production, such as energy and water inputs and greenhouse gas emission outputs, shows that they are inversely related to ore grade – meaning that as global average ore grades decline the unit intensity of U production will increase. This means that greenhouse emissions from U mining will begin to increase significantly over this time frame, effectively reducing any perceived benefit of nuclear power as a low carbon intensity electricity source. When accounting for this trend in full life cycle assessment of the nuclear power chain, it can be seen that nuclear power begins to approach gas-based electricity. Given Australia's major role as a coal exporter, and that the two dominant U producers make more profits from coal than U, it is hypocritical for Australia to use climate change as a basis for arguing for nuclear power. Overall, when moving beyond simple rhetoric and considering the factual implications of the sustainability of U mining and nuclear power, reality clearly demonstrates that nuclear power is not a viable strategy to address burgeoning global greenhouse gas emissions and the serious risks of climate change.

FIGURE CAPTIONS

Fig 1 – Remaining economic resources (left) and country average ore grades (right).

Fig 2 – Tonnage-grade plot for uranium deposits from Table 3.

Fig 3 – Uranium production by country (1945-2009) (data from OECD-NEA & IAEA, 2006, var.; WNA, 2010).

Fig 4 – Average country U ore grades over time.

Fig 5 – Australian U mine rehabilitation: less than desirable success.

Fig 6 – Environmental aspects of sustainability reporting by Rössing Uranium Ltd.

Fig 7 – Sustainability metrics U production: unit energy versus U ore grade (top left), unit CO_2 emissions versus U ore grade (top right), unit water consumption versus U ore grade (bottom left); unit water versus unit energy consumption (bottom right).

Fig 8 – Historical and projected U production and reactor requirements (IEA scenarios).

TABLE CAPTIONS

Table 1 – World primary energy supply and electricity generation.

Table 2 – Economic uranium resources (kt U_3O_8) by country and ore types, comparing Red Book (2007 Edition, OECD-NEA & IAEA, var.) and national data (2007 data).

Table 3 – Uranium resources by individual project (2009 data; >5 kt U_3O_8 only).

Table 4 – Uranium production by project, mine type and ore type (2009 data).

Table 5 – Inconsistencies in Australian uranium production reporting by source (2004-2008).

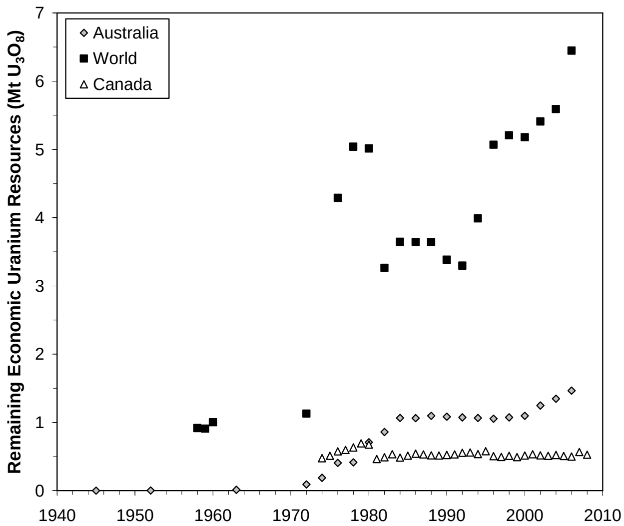
Table 6 – Inconsistencies in Australian uranium exports reporting by source (2005-2009).

Table 7 – State of sustainability reporting for environmental indicators by major uranium companies.

Table 8 – Environmental sustainability metrics for certain U projects (±1 standard deviation; years of data in brackets)

Table 9 – Total CO_2 emissions (g CO_2/kWh) from nuclear fuel chain according to Lenzen or SvLS for high-grade and low-grade uranium ore, including wind and natural gas for comparison.

FIGURES



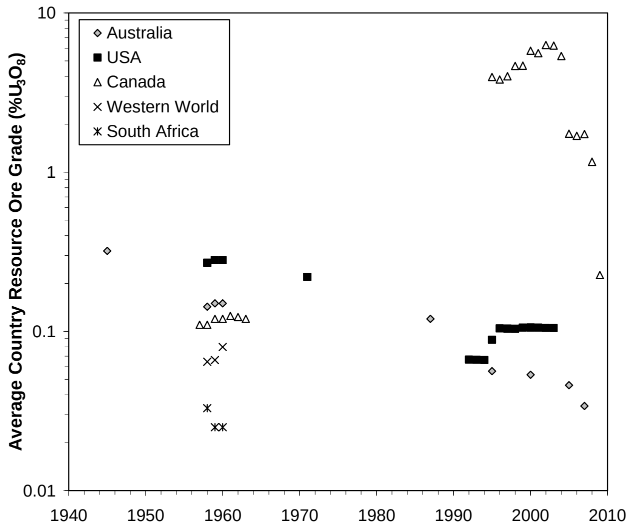


Fig 1 – Remaining economic resources (left) and country average ore grades (right).

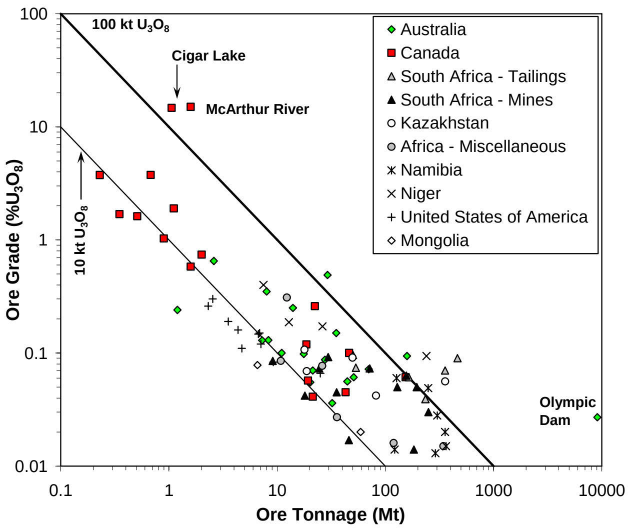


Fig 2 – Tonnage-grade plot for uranium deposits from Table 3.

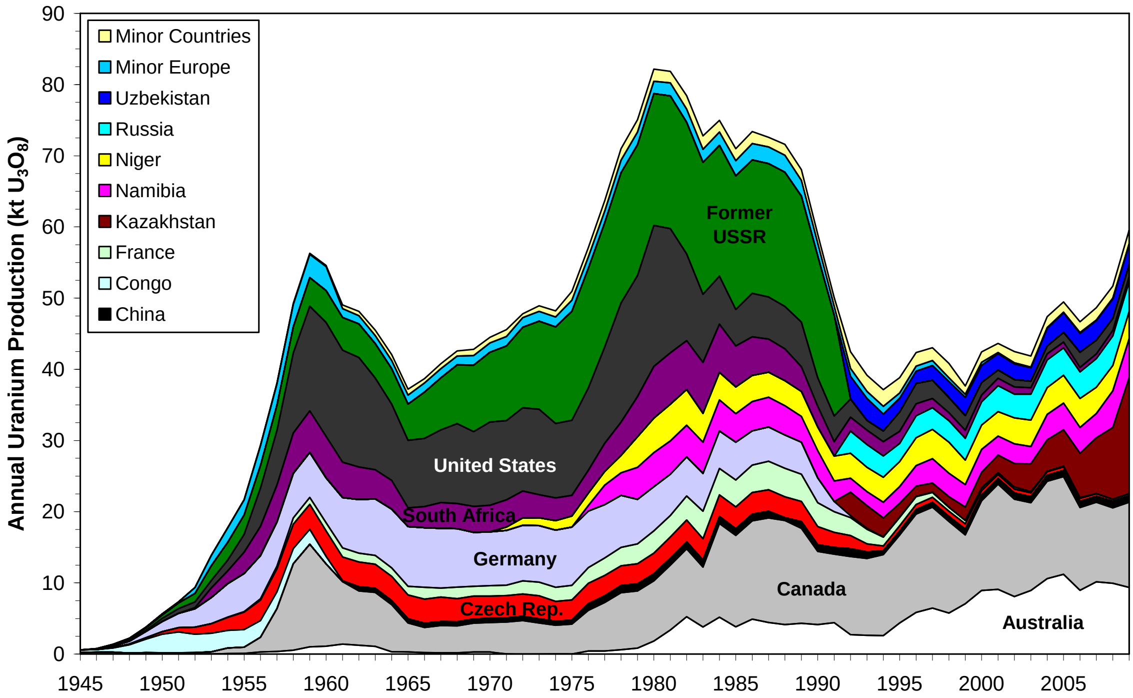


Fig 3 – Uranium production by country (1945-2009) (data from OECD-NEA & IAEA, 2006, var.; WNA, 2010).

Notes: Minor Countries – Argentina, Brazil, Gabon, India, Iran, Japan, Madagascar, Mexico, Mongolia, Pakistan, Ukraine; Minor Europe – Belgium, Bulgaria, Finland, Hungary, Poland, Portugal, Romania, Spain, Sweden, Yugoslavia; Germany includes West and East Germany; Czech Rep. includes Czech Republic and Czechoslovakia.

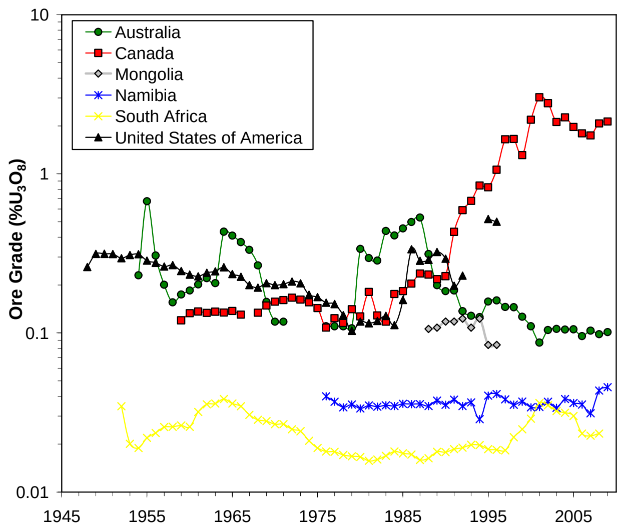


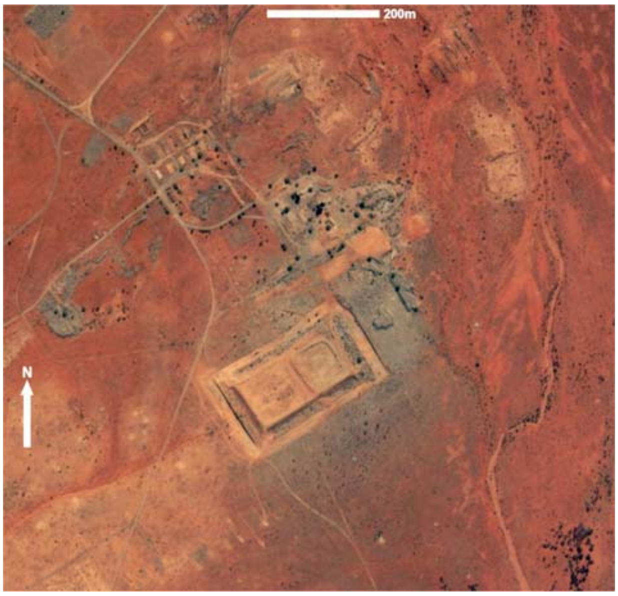
Fig 4 – Average country U ore grades over time.

White's waste rock dump (WRD) leaking AMD in the dry season, Rum Jungle, July 2007

Adjacent Finniss River at Rum Jungle, showing continuing and extreme impacts of AMD, July 2007

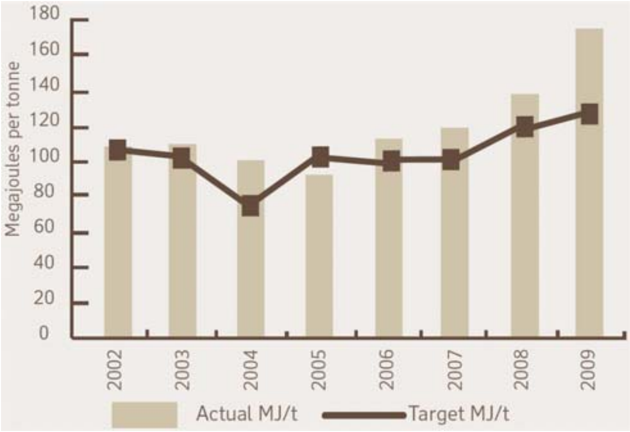
AMD seeping from the *rehabilitated* tailings dam, Mary Kathleen (Lottermoser & Ashley, 2005)

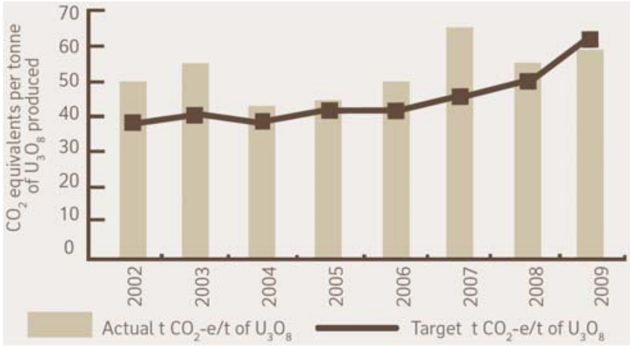
Seepage impacts at the tailings dam, including cattle footprints, Mary Kathleen, April 2010 (photo author)



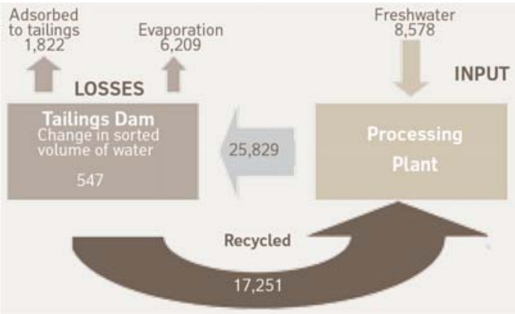
Rill erosion exposing tailings (grey), Radium Hill (top left, Lottermoser & Ashley, 2005); Similar erosion scar, ~2.5 m (bottom left); physical dispersal of pale grey-blue tailings at Radium Hill (above; Lottermoser & Ashley, 2005)

Fig 5 – Australian U mine rehabilitation: less than desirable success (photos author unless noted).

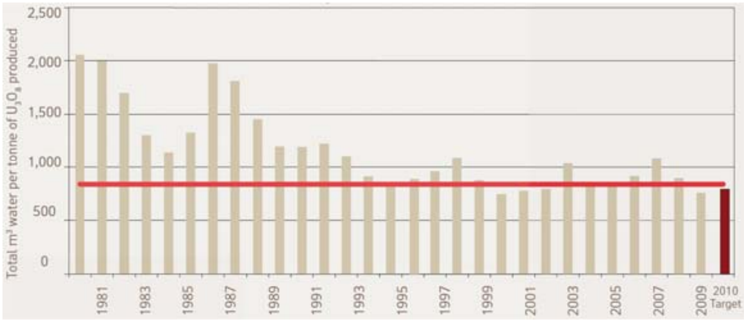




Unit CO_2 emissions in U production (above); unit energy consumption in U ore processing (left)



Site water balance, Rössing U project



Unit water consumption in U production

Fig 6 – Environmental aspects of sustainability reporting by Rössing Uranium Ltd (adapted from 2009 Edition, Rössing, var.)

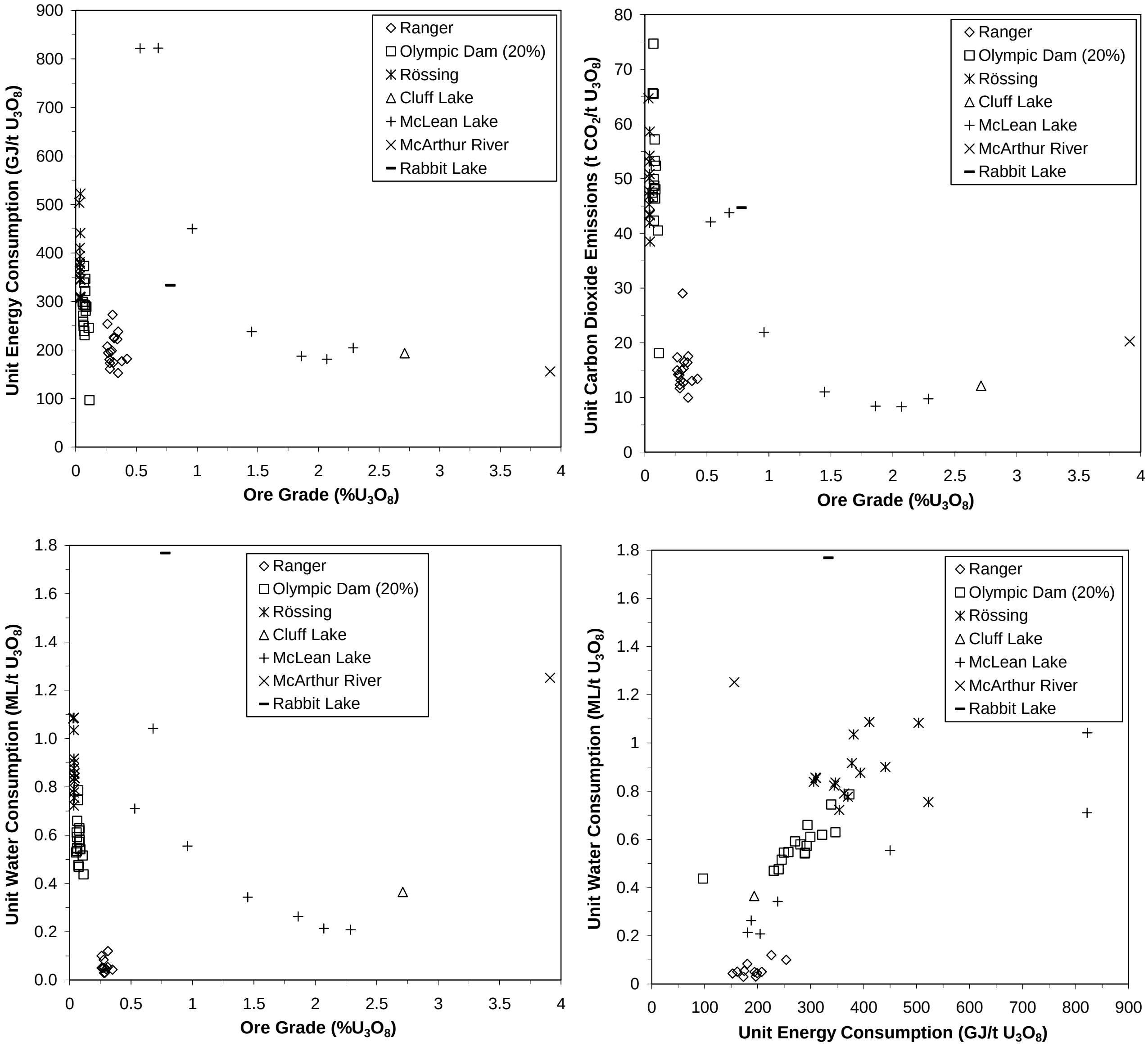


Fig 7 – Sustainability metrics U production: unit energy versus U ore grade (top left), unit CO_2 emissions versus U ore grade (top right), unit water consumption versus U ore grade (bottom left); unit water versus unit energy consumption (bottom right).

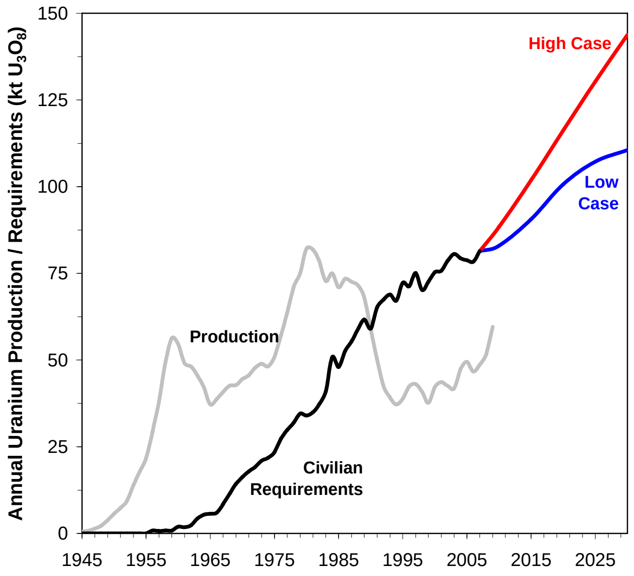


Fig 8 – Historical and projected U production and reactor requirements (IEA scenarios).

TABLES

Table 1 – World primary energy supply and electricity generation, 2007 and projected 2030 (IEA, 2009).

	Primary Energy Demand				**Electricity Generation**	
Source	**2007 (EJ, %)**	**2030 (EJ, %)**		**Source**	**2007 (TWh, %)**	**2030 (TWh, %)**
coal	133.3 (26.50%)	204.6 (29.11%)		coal	8,216 (41.59%)	15,259 (44.50%)
natural gas	105.2 (20.91%)	149.1 (21.21%)		gas	4,126 (20.88%)	7,058 (20.58%)
crude oil	171.4 (34.07%)	209.7 (29.84%)		oil	1,117 (5.65%)	665 (1.94%)
biomass & other	49.2 (9.79%)	67.2 (9.55%)		biomass	259 (1.31%)	839 (2.45%)
nuclear	29.7 (5.90%)	40.0 (5.69%)		nuclear	2,719 (13.76%)	3,667 (10.69%)
hydro	11.1 (2.21%)	16.8 (2.39%)		hydro	3,078 (15.58%)	4,680 (13.65%)
other renewables	3.1 (0.62%)	15.5 (2.20%)		wind	173 (0.88%)	1,535 (4.48%)
				geothermal	62 (0.31%)	173 (0.50%)
				solar	5 (0.03%)	402 (1.17%)
EJ – exa (10^{18}) joules; TWh – tera (10^{12}) watt-hours.				tidal & wave	1 (0.01%)	13 (0.04%)

Table 2 – Economic uranium resources (kt U_3O_3) by country and ore types, comparing Red Book (2007 Edition, OECD-NEA & IAEA, var.) and national data (2007 data).

Country	Cumulative	RAR + Inferred	RAR + Inferred	RAR + Inferred	RAR + Inferred	National	Major Ore
	Prod. (to 2009)	<US$40/kg U	<US$80/kg U	<US$130/kg U	Total	Estimate	Types
Australia	193.8	1,410.1	23.6	31.8	1,465.5	1,614	unconformity, HB, sandstone
Kazakhstan	78.9	609.9	276.2	77.5	963.6		sandstone
Russia	61.8	98.6	485.5	59.3	643.4		sandstone, VC, metasomatite
South Africa	190.2	276.7	127.9	108.4	513.0	341	quartz pebble cong.
Canada	514.4	415.5	83.5	0.0	499.0	568.3	unconformity
United States	430.3	0.0	116.7	283.0	399.7	403.7	sandstone, surficial, CBP
Brazil	3.6	164.6	107.8	55.9	328.2		metasomatite, intrusive
Namibia	117.8	137.2	134.3	52.7	324.2		intrusive, surficial
Niger	130.3	40.3	48.3	234.4	323.0		sandstone
Ukraine	17.8	40.2	176.9	18.2	235.2		metasomatite, sandstone
Jordan	0	131.8	0.0	0.0	131.8		phosphorite
Uzbekistan	44.1	101.6	0.0	29.2	130.9		sandstone, vein
India	11.2	0.0	0.0	85.9	85.9		vein, intrusive, metasomatite
China	37.9	46.3	26.6	7.1	80.1		sandstone, VC, L-PK
Mongolia	0.6	19.2	53.9	0.0	73.1		VC, sandstone
Rest of World	1,070	9.5	91.3	150.4	251.2		
World Totals	**2,903**	**3,501.6**	**1,752.5**	**1,193.7**	**6,447.8**		

HB – hematite breccia; CBP – collapse breccia pipe; VC – volcanic and caldera-related; L-PK – limestone-paleokarst.

Note: National estimates sourced from – Australia (GA, var.); Canada (NRC, var.); South Africa (SADGCIS, 2009); United States (2003 only, this the most recent data available) (EIA, 2004). Additional information sourced from IAEA (2009b).

Table 3 – Uranium resources by individual project (2009 data; >5 kt U3O8 only).

Mine/Deposit (status)	Mt ore	%U_3O_8	kt U_3O_8	Company
Olympic Dam (*producing*)[&]	9,080[&]	0.027	2,445	BHP Billiton
Ranger (*producing*)	158.1	0.094	149.4	Energy Resources of Australia[§]
Jabiluka (deposit)	29.2	0.49	142.0	Energy Resources of Australia[§]
Yeelirrie (deposit)[#]	35.2[#]	0.15[#]	52.5[#]	BHP Billiton
Valhalla Field (deposit)	70.1	0.072	50.6	Paladin Energy[91.03%]
Kintyre (deposit)[#]	~14[#]	0.25[#]	36[#]	Cameco[70%]-Mitsubishi[30%]
Mt Gee (deposit)	51.0	0.061	31.4	Marathon Resources
Beverley Four Mile (deposit)	8.0	0.35	28	General Atomics[75%]-Alliance Resources[25%]
Mulga Rock (deposit)	44.6	0.056	24.8	Energy & Metals Australia
Westmoreland (deposit)	27.7	0.087	24.1	Laramide Resources
Gould's Dam (deposit)[#]	17.6[#]	0.098[#]	18.0[#]	Uranium One
Koongarra (deposit)[#]	2.6[#]	0.65[#]	16.9[#]	Areva
Manyingee (deposit)	21.3	0.07	14.6	Paladin Energy
Beverley (*producing*)	*nd*[†]	*nd*[†]	*~14*[†]	General Atomics
Lake Maitland (deposit)	32.3	0.036	11.8	Mega Uranium
Wiluna (deposit)	20.2	0.055	11.1	Toro Energy
Angela-Pamela (deposit)[#]	11[#]	~0.1[#]	~11[#]	Cameco[50%]-Paladin Energy[50%]
Oobagooma (deposit)	8.3	0.13	10	Paladin Energy
Bigrlyi (deposit)	7.27	0.129	9.4	Energy Metals[53.7%]-Paladin Energy[42.1%]
Honeymoon (2010 start)	1.2	0.24	2.9	Uranium One[51%]-Mitsui[49%]
Australia Total	**9,640**	**0.032**	**3,104**	
McArthur River (*producing*)	1.59	15.02	238.2	Cameco[55.8%]-Areva[16.2%]-UEM[27.9%]
Cigar Lake (developing)	1.06	14.70	156.1	Cameco[50.0%]-Areva[37.1%]-Idemitsu[7.9%]-TEPCO[5%]
Denison-Elliot Lake (deposit)	154.0	0.061	93.1	Denison Mines
Kiggavik-Sissons Schultz (deposit)	22.35	0.259	58.0	Areva[64.8%]-JCU[?%]-Daewoo[?%]
Michelin-Jacques Lake (deposit)	46.35	0.10	44.5	Aurora Energy Resources
Millenium (deposit)	0.68	3.76	25.7	Cameco[42%]-JCU[30%]-Areva[28%]
Hidden Bay (deposit)	18.67	0.119	22.3	UEX
Midwest (developing)	1.11	1.90	21.2	Areva[69.16%]-Denison[25.17%]-JCU[5.67%]
Eco Ridge-Elliot Lake (deposit)	42.94	0.045	19.3	Pele Mountain
Rabbit Lake (*producing*)	2.01	0.74	14.8	Cameco
Dieter Lake (deposit)	19.31	0.057	11.0	Fission Energy Corp
Angilak-Lac Cinquante	0.9	1.03	9.3	Kivalliq Energy Corp
Matoush (deposit)	1.59	0.58	9.2	Strateco Resources
Amer Lake	21.4	0.041	8.8	Uranium North Resources
Tamarack (deposit)	0.23	3.74	8.6	Cameco[57%]-Areva[43%]
McLean Lake (*producing*)	0.51	1.62	8.2	Areva[70%]-Denison[22.5%]-OURD[7.5%]
Dawn Lake (deposit)	0.35	1.69	5.9	Cameco[57%]-Areva[43%]
Canada Total	**335**	**0.226**	**754.2**	
Ezulwini Tailings (*producing*)	356.3	0.07	246.6	First Uranium
Driefontein Tailings (deposit)	164.7	0.061	100.5	Gold Fields
Ezulwini (*producing*)	156.5	0.063	99.1	First Uranium
Springbok Flats (deposit)	~195	0.050	96.6	HolGoun Investment Holdings
Kloof Tailings (deposit)	234.9	0.039	91.6	Gold Fields
Potchefstroom (deposit)	250.0	0.030	75.0	Wits Gold
Rietkuil-Dominion (closed)	128.7	0.050	64.8	Uranium One
South Deep (Au mine, U deposit)	71.6	0.073	52.3	Gold Fields
Driefontein (Au mine, U deposit)	50.2	0.096	48.2	Gold Fields
Free State Tailings (deposit)	463.7	0.09	42	Harmony Gold
South Deep Tailings (deposit)	53.4	0.074	39.5	Gold Fields
Moab Khotsong (*producing*)	29.61	0.092	27.2	AngloGold Ashanti

Southern Free State (deposit)	183.2	0.014	25.6	Wits Gold
Kopanang (*producing*)	24.47	0.073	17.9	AngloGold Ashanti
Kloof (Au mine, U deposit)	35.5	0.045	16.0	Gold Fields
Ruyst Kuil (deposit)	9.10	0.085	9.1	Areva$^{74\%}$
Mponeng (U not extracted)	46.02	0.017	7.8	AngloGold Ashanti
Great Noligwa (*producing*)	18.06	0.042	7.6	AngloGold Ashanti
South Africa Total	**2,471**	**0.058**	**1,067**	
Inkai (*producing*)	357.5	0.056	199.9	Cameco$^{60\%}$-KazAtomProm$^{40\%}$
Katco (*producing*)	49.8	0.091	45.5	Areva$^{51\%}$-KazAtomProm$^{49\%}$
South Inkai (*producing*)	82.1	0.042	34.7	Uranium One$^{70\%}$-KazAtomProm$^{30\%}$
Karatau (*producing*)	17.9	0.107	19.1	Uranium One$^{50\%}$-KazAtomProm$^{50\%}$
Akdala[‡] (*producing*)	18.8[‡]	0.069[‡]	13.0[‡]	Uranium One$^{70\%}$-KazAtomProm$^{30\%}$
Kazakhstan Total	**526.1**	**0.059**	**312.2**	
Bakouma (dep.) ***(Cent. Afr. Rep.)***	12.3	0.309	38.0	Areva
Kayelekera (*producing*) ***(Malawi)***	26.1	0.077	20.1	Paladin Energy$^{85\%}$-Malawi Government$^{15\%}$
Mutanga (deposit) ***(Zambia)***	35.7	0.027	9.7	Denison Mines
Faléa (deposit) ***(Mali)***	10.8	0.085	9.2	Rockgate Capital Corp
Rössing South	249	0.049	121.4	Extract Resources
Rössing (*producing*)	301.7	0.028	85.2	Rössing Uranium[§]
Langer Heinrich (*producing*)	127.1	0.06	76.3	Paladin Energy
Etango (deposit)	355.7	0.020	72.5	Bannerman Resources
Trekkopje (deposit)	363.4	0.015	55.0	Areva
Valenica (deposit)	290	0.013	36.9	Forsys Metals Corp
Marenica (deposit)	122	0.014	17.3	Marenica Energy
Namibia Total	**1,809**	**0.026**	**464.4**	
Imouraren (deposit)	239.9	0.094	226.1	Areva$^{63.4\%}$-ONAREM$^{36.6\%}$
Somair (*producing*)	26.23	0.172	45.2	Areva$^{63.4\%}$-ONAREM$^{36.6\%}$
Cominak (*producing*)	7.48	0.399	29.8	Areva$^{34\%}$-ONaReM$^{31\%}$-OURC$^{25\%}$-ENuSA$^{10\%}$
Arlit (deposit)	12.85	0.187	24.1	Areva
Niger Total	**286.5**	**0.113**	**325.2**	
Letlhakane (deposit)	344.2	0.015	52.5	A-Cap Resources
Serule (deposit)	119.5	0.016	19.1	A-Cap Resources
Dulaan Uul (deposit)	59.04	0.020	11.8	Areva
Hairhan (deposit)	6.57	0.078	5.16	Denison Mines
Smith Ranch-Highland (*producing*)	25.08	0.066	16.6	Cameco
Nose Rock (deposit)	6.89	0.15	10.3	Uranium Resources
Crow Butte (*producing*)	6.69	0.147	9.82	Cameco
Churchrock (deposit)	7.08	0.12	8.49	Uranium Resources
West Largo (deposit)	2.54	0.3	7.62	Uranium Resources
North Butte-Brown Ranch (deposit)	9.22	0.083	7.61	Cameco
Crownpoint (deposit)	4.35	0.16	6.97	Uranium Resources
Roca Honda (deposit)	3.54	0.19	6.72	Uranium Resources
Tony M-Southwest (deposit)	2.31	0.26	5.91	Denison Mines
Mancos (deposit)	4.72	0.11	5.19	Uranium Resources
United States Total	**72.4**	**0.118**	**85.2**	
World Total	**15,754**	**0.042**	**6,278**	

[&]Olympic Dam ore resources also include 0.86% Cu, 0.32 g/t Au and 1.50 g/t Ag; [§]Majority own by Rio Tinto (~68%); [‡]July 2006 data; [†]Since General Atomics are privately owned, they are not required to report annually on reserves and resources, 14 kt U_3O_8 based on 1998 data minus cumulative production; [#]Older data since no 2009 resource is reported.

Note: all data sourced from respective company annual reports and/or websites.

Table 4 – Uranium production by project, mine type and ore type (2009 data).

Mine/Deposit	**Mine Type**	**Deposit Type**	**Mt ore**	**%U_3O_8**	**t U_3O_8**	**Mt waste rock**	**Company**
Olympic Dam, Australia	underground	hematite breccia	8.105	0.056	3,515	*nd*	BHP Billiton
Ranger, Australia	open cut	unconformity	2.268	0.26	5,240	17.3	Energy Resources of Australia[§]
Beverley, Australia	in situ leach[‡]	sandstone	*nd*[‡]	~0.18[‡]	~658[#]	*nd*	General Atomics
McArthur River, Canada[†]	underground	unconformity	0.187[†]	4.68[†]	8,655[†]	*nd*	Cameco$^{55.8\%}$-Areva$^{16.2\%}$-UEM$^{27.9\%}$
Rabbit Lake, Canada	underground	unconformity	0.216	0.82	1,706	*nd*	Cameco
McLean Lake, Canada	open cut/ug.	unconformity	~0.172[€]	~1.0[€]	1,637[€]	*nd*	Areva$^{70\%}$-Denison$^{22.5\%}$-OURD$^{7.5\%}$
Hérault Division, France	*nd*	*nd*	*nd*	*nd*	9	*nd*	Areva
Akdala, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.069[‡]	*1,225*	*nd*	Uranium One$^{70\%}$-KazAtomProm$^{30\%}$
Karatau, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.107[‡]	*»66*[€]	*nd*	Uranium One$^{50\%}$-KazAtomProm$^{50\%}$
Kharasan, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.095[‡]	124	*nd*	Energy Asia$^{40\%}$-Uranium One$^{30\%}$-KazAtomProm$^{30\%}$
Katco, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.091[‡]	3,693	*nd*	Areva$^{51\%}$-KazAtomProm$^{49\%}$
Inkai, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.056[‡]	843	*nd*	Cameco$^{60\%}$-KazAtomProm$^{40\%}$
South Inkai, Kazakhstan	in situ leach[‡]	sandstone	*nd*	~0.042[‡]	980	*nd*	Uranium One$^{70\%}$-KazAtomProm$^{30\%}$
Zarechnoe, Kazakhstan	in situ leach[‡]	sandstone	*nd*	*nd*	289	*nd*	Priargunsky / ARMZ
Rössing, Namibia	open cut	intrusive	12.633	~0.039	4,150	38.76	Rössing Uranium[§]
Langer Heinrich, Namibia	open cut	surficial	1.727	0.096	1,304	»2.1	Paladin Energy
Cominak, Niger	underground	sandstone	*nd (~0.5)*[‡]	~0.399[‡]	1,692	*nd*	Areva$^{34\%}$-ONaReM$^{31\%}$-OURC$^{25\%}$-ENUSA$^{10\%}$
Somair, Niger	open cut	sandstone	*nd (~1.5)*[‡]	~0.172[‡]	2,131	*nd*	Areva$^{63.4\%}$-ONAREM$^{36.6\%}$
Priargunsky, Russia	underground	caldera/volcanic	*nd (~2)*[‡]	~0.2	3,542	*nd*	Priargunsky / ARMZ
Dalur, Russia	ISL	sandstone	*nd*	*nd*	545	*nd*	Priargunsky / ARMZ
Khiagda, Russia	ISL	sandstone	*nd*	*nd*	115	*nd*	Priargunsky / ARMZ
Vaal Rivers, South Africa	underground	quartz pebble	~2.5	0.0233	582	*nd*	AngloGold Ashanti
Smith Ranch-Highland, USA	in situ leach[‡]	sandstone	*nd*	~0.07[‡]	831	*nd*	Cameco
Crow Butte, USA	in situ leach[‡]	sandstone	*nd*	~0.15[‡]	351	*nd*	Cameco
Kingsville Dome, USA	in situ leach[‡]	sandstone	*nd*	~0.075[‡]	25	*nd*	Uranium Resources Inc
	Hard rock		~32	~0.115	30,612		
	ISL		*nd*	~0.086	»9,679	(grade is production weighted-average)	

nd – no data; [‡]Ore processed is not available, ore milled is an estimate only and grade data based on reported resources only (or IAEA, 2009b); [#]Approximate only, exact 2009 production not yet reported; [§]Majority own by Rio Tinto (~68%); [†]McArthur River ore is processed at the Key Lake mill through blending with low grade ore/waste from Key Lake; [€]Full 2009 production data not reported.

Note: all data sourced from respective company annual reports and/or websites.

Table 5 – Inconsistencies in Australian uranium production reporting by source (2004-2008).

	Ranger (NT)	Olympic Dam (SA)	Beverley (SA)	SA *(sum)*	Australia *(sum)*	PIRSA: SA	ABARE: SA	ABARE: NT
Type	t U_3O_8	U ore conc.	t U_3O_8	t U_3O_8	t U_3O_8	t U_3O_8	t U_3O_8	t U_3O_8
2004	5,137	4,370	1,084	5,454	10,591	5,052	5,487	5,136
2005	5,910	4,344	955	5,299	11,209	5,764	5,311	5,908
2006	4,748	3,398	824.6	4,223	8,971	4,172	4,216	4,750
2007	5,412	3,995	748	4,743	10,155	3,487	4,733	5,412
2008	5,340	3,990	659	4,649	9,989	5,622	4,648	5,339
Totals	**26,547**	**20,097**	**4,271**	**24,368**	**50,915**	**24,097**	**24,395**	**26,545**
Source	(ERA, var.-a)	(BHPB, var.-b)	(AUA, var.)			(PIRSA, var.)	(ABARE, var.)	

NT – Northern Territory; SA – South Australia; PIRSA – Primary Industry and Resources South Australia (state agency); ABARE – Australian Bureau of Agricultural & Resource Economics (federal agency).

Table 6 – Inconsistencies in Australian uranium exports reporting by source (2004-2008).

	ABARE: Exports	ASNO: Deliveries			ABARE: Exports
Type	t U_3O_8	t U_3O_8			t U_3O_8
2004	9,681	9,156.82		2003-04	9,099
2005	12,360	10,298.78		2004-05	11,249
2006	8,656	10,596.58		2005-06	10,253
2007	10,232	9,047.79		2006-07	9,519
2008	9,663	9,663.31		2007-08	10,139
Totals	**50,592**	**48,763**			**50,259**
Source	(ABARE, var.)	(ASNO, var.)			(ABARE, 2009)

ASNO – Australian Safeguards & Non-Proliferation Office; ABARE – Australian Bureau of Agricultural & Resource Economics (both federal agencies).

Table 7 – State of sustainability reporting for environmental indicators by major uranium companies.

Company	Published/ Year	Reporting Basis	Corporate/ Individual Site	EN3	EN4	EN5	EN6	EN7	EN8	EN9	EN10	EN16	EN17	EN18	EN19	EN20	EN21	EN22	EN23	MM1	MM2	MM3	MM11
Cameco	2007	Internal[#]	Corporate	X	X	*P*	X	X	X	*P*	X	*P*[§]	*P*[§]	*P*	X	*P*[§]	**Y**	*P*[§]	*P*[§]	X	X	*P*[§]	X
Energy Res. Aust.	2008	Internal	Site	*P*[§]	*P*[§]	*P*	X	X	X	*P*	X	*P*[§]	*P*[§]	X	X	X	*P*	*P*	X	X	*P*	X	*P*
Rössing Uranium	2009	Internal	Site	*P*[§]	*P*[§]	X	X	X	*P*	X	**Y**	*P*[§]	*P*[§]	X	X	X	X	X	X	**Y**	P	P	X
BHP Billiton	2009	GRI	Corporate	**Y**	**Y**	X	X	X	*P*	X	**Y**	*P*[§]	*P*[§]	X	**Y**	**Y**	*P*	**Y**	P	**Y**	**Y**	X	**Y**
BHPB Olympic Dam	2008	Internal	Site	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Areva	2008	Internal[#]	Corporate	*P*[§]	*P*[§]	*P*	*P*	*P*	*P*	X	X	**Y**	X	**Y**	X	X	X	*P*	X	X	X	X	X
Areva Res. Canada	2009	Internal	Corporate	**Y**	**Y**	X	X	X	X	*P*		X	X	X	X	*P*	*P*	X	X	X	X	X	X

Companies with no formal sustainability reporting: Paladin Energy, Uranium One, Priargunsky / ARMZ, Kazatomprom, Heathgate Resources/General Atomics, Cotter Corporation/General Atomics and Uranium Resources Inc.

X – not reported; P – partial reporting or discussion; Y – reported. All based on most recent company sustainability report (or website information).

[#]Still has some cross-referencing or partial use of the Global Reporting Initiative, but is mainly the company's protocol/system. [§]Reported as total only and not as direct / indirect or by type.

Note: (1) In Australia, energy efficiency measures and savings are reported separately under the *Energy Efficiency Opportunities Act 2006*, though these are yet to be incorporated into sustainability reports by Australian mines or companies. (2) BHP Billiton no longer publish site-based reports, hence the Olympic Dam report is the most recent available.

Table 8 – Environmental sustainability metrics for certain U projects (±1 standard deviation; years of data in brackets)

Project	Grade	Water	Water	Electricity	Energy	Energy	CO_2	Emissions
	$\%U_3O_8$	kL/t ore	kL/t U_3O_8	kWh/t ore	MJ/t ore	GJ/t U_3O_8	t CO_2/t ore	t CO_2/t U_3O_8
Olympic Dam[20%,§]	0.054-0.114	0.282±0.05 (19)	575±88 (19)	93.1±7.7 (6)	136±29 (17)	277±61 (17)	25±3.6 (17)	50.9±12 (17)
Ranger	0.260-0.423	0.153±0.08 (11)	60±29 (11)	*nd*	563±118 (17)	202±33 (17)	42±12 (17)	15.1±4.1 (17)
Rössing	~0.03-0.04	0.268±0.03 (15)	877±113 (15)	19.5±0.8 (5)	117±19 (15)	382±65 (15)	15±1.7 (15)	48.4±7.0 (15)
Beverley (ISL)	~0.18	-	8,520±1,500 (7)	-	-	216±63 (5)	-	11.2±3.3 (5)
McArthur River	3.91	48.4 (1)	1,252 (1)	1,083 (1)	6,027 (1)	156 (1)	20 (1)	782 (1)
Rabbit Lake	0.78	13.32 (1)	1,768 (1)	438 (1)	2,513 (1)	334 (1)	45 (1)	337 (1)
McLean Lake	0.53-2.29	4.85±0.87 (7)	476±312 (7)	249±17 (7)	4,078±647 (7)	415±293 (7)	198±43 (7)	20.7±16 (7)
Cluff Lake	2.71	9.79 (1)	365 (1)	*nd*	5,187 (1)	194 (1)	325 (1)	12.1 (1)
Production Weighted Average		**2.67**	**692**		**834**	**260**	**74.4**	**30.8**

nd – no data; [§]Olympic Dam is presented on the basis of attributing 20% of inputs and outputs to U production, since this is the long-term average proportional revenue from U (see (Mudd, 2010).

Notes: (1) All data is obtained from the respective company annual sustainability or environmental management reports (ARC, var.; BHPB, var.-a; ERA, var.-b; HR, var.; Rössing, var.; WMC, var.), unless otherwise noted; (2) *Australia* – 1980s Ranger energy data from (OSS, var.), with CO_2 factors assumed from DCC (2009); (3) *Canada* – some site-specific data for McArthur River (including milling at Key Lake) and Rabbit Lake is taken from Nilsson & Randheim (2008); energy and CO_2 emissions factors are sourced from MAC (2009); Cluff Lake is final year of operations.

Table 9 – Total CO_2 emissions (g CO_2/kWh) from nuclear fuel chain according to Lenzen or SvLS for high-grade and low-grade uranium ore, including wind and natural gas for comparison.

U ore grade	(excluding mine rehabilitation)		(with mine rehabilitation)	Wind[c]	Natural
(%U_3O_8)	Lenzen[a]	SvLS[b]	SvLS[b]		Gas[d]
0.15	60	107	117	10-20	491-577
0.01	131	220	437	10-20	491-577

[a]Lenzen (2008) excludes significant emissions from the clean-up of mine waste.

[b] We have modified SvLS's results as presented in column 3 to incorporate Lenzen's corrections for emissions from construction and decommissioning, while keeping SvLS's own results for high-level nuclear waste management. SvLS's results are reproduced unchanged in column 4.

[c]Data from Lenzen (2008).

[d]Data from ISA (2006).

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