CHAPTER 2: EXPLORATION, EXTRACTION AND MILLING

The activity under consideration is the expansion of the current level of exploration, extraction and milling of minerals containing radioactive materials in South Australia.

WHAT ARE THE RISKS?

9. Exploration activities for all minerals are most commonly undertaken by remote geophysical reconnaissance and low-density soil/ rock geochemical methods, which pose low environmental risks. Where drilling occurs, the existing administrative and regulatory processes, if properly applied, are sufficient to manage the environmental and other risks.

Most modern exploration methods cause little environmental disturbance, as they involve geophysical data collection, surface sampling and stream sediment analysis.[1]

In the case of uranium, the exploration process is similar to that for any other mineral commodity. Geophysical surveys are used to detect characteristics associated with uranium mineralisation, including anomalies in measured radioactivity, magnetism, gravity and electrical conductivity. They are first performed from the air to identify sites of interest, which are then surveyed on the ground.[2] Surface features of the site, such as soil, stream sediment and geology, are sampled and analysed to obtain further information about the underlying geology and potential mineralisation.[3]

Depending on the results of the geophysical surveys and surface exploration, physical investigation of the underlying geology is undertaken. This involves borehole drilling into the ground to obtain a sample of rock material.[4] Technical analysis of the sample provides information about gamma radiation, groundwater and other physical characteristics, and chemical analysis is undertaken to quantify the geochemistry.[5]

These characteristics can then be used to model the framework of the underlying geology and identify further targets for exploration.[6]

More significant environmental impacts associated with mineral exploration may arise from the use of borehole drilling, which can directly affect surface water, groundwater, soil, flora and fauna.[7] When a site is selected for exploration drilling, it is cleared of vegetation. Depending on the density of that vegetation and the topography of the area, this can be done with minimal impact, although drilling areas may require heavy machinery to excavate sumps, as well as to clear tracks and drill pads.[8] Drilling activity may cause other impacts that require monitoring and management, including light, dust, vibration and noise.[9]

Exploration for minerals in South Australia is undertaken in accordance with licences issued by the state government. A program for environment protection and rehabilitation (PEPR) approved by the Department of State Development (DSD) is also required before activities commence.[11] A PEPR provides details about the mineral commodity targeted by an exploration company and the proposed exploration program, including landowner and native title holder engagement strategies and environmental management measures. The PEPR approach requires companies to take account of environmental risks before, during and after exploration.[12]

When exploration programs finish, a company is required to return the sites to their natural, pre-exploration state, as far as possible[13], for example, by 'ripping' tracks, which loosens compacted topsoil to promote regeneration of the native vegetation.[10] If exploration activities are likely to cause a significant environmental disturbance or are to occur in sensitive environmental areas, for example, national parks, there are provisions for the state government to require financial bonds.[14]

Once DSD is satisfied with the PEPR, a tenement area will be granted for a specified term of up to five years.[15] A radiation management plan (RMP), prepared in accordance with guidelines issued by the South Australian Environment Protection Authority (EPA), is also required to ensure adequate radiation protection of workers, the public and the environment.[16] The EPA is South Australia's independent environmental regulator.

In South Australia, uranium exploration has a history of compliance with environmental protection measures, although there have been instances where this has not occurred. For example, in 2008, Marathon Resources was found to have inappropriately disposed of wastes at sites where it had undertaken exploratory drilling. The regulator required the company to undertake rectification works, which were appropriately completed and independently verified.[17]

10. Mining and milling activities for all minerals pose risks to human health and the environment, which need to be managed. If expanded, uranium mining and milling activities in South Australia would create similar risks to those arising from current uranium mining activities.

The methods used in Australia to mine uranium are underground, in-situ leaching (ISL), also known as in-situ recovery, and open-cut.[18] There are other extraction methods, such as acid heap leaching, not currently used commercially in Australia.[19]

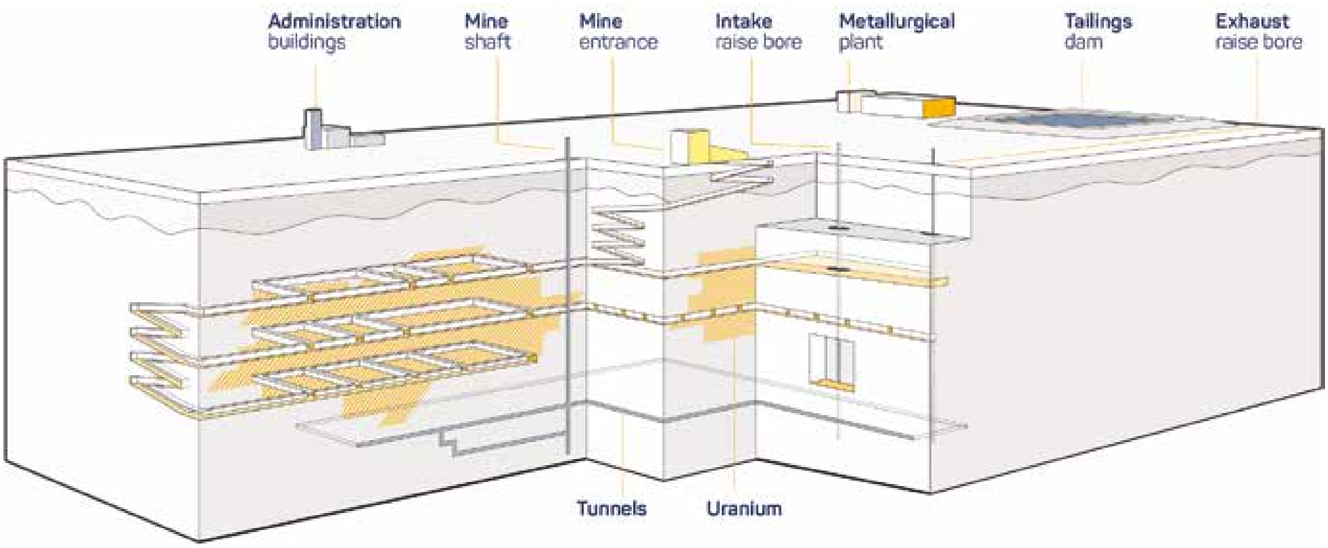

Figure 2.1: A cross-section of an underground mine

Olympic Dam in South Australia, which is owned and operated by BHP Billiton, is an underground mine that uses a sub-level open stope method (see Figure 2.1). This method is complex and requires extensive infrastructure.[20] In addition to the mine (see Figure 2.2), the operations at Olympic Dam include tailings storage dams, waste rock storage areas, product storage areas, an ore processing plant, administrative and residential buildings, and infrastructure to facilitate transport and the supply of utilities.

Operations at underground mines pose risks to workers, the environment and, potentially, members of the public.[21] If appropriate risk management strategies are not implemented, mining operations might result in underground collapse, rock fall, dust and noise pollution, and exposure to radiation and other radioactive particulates, causing harm to workers and the public, or environmental contamination.[22] Prevention and mitigation measures are used to reduce the risks of underground mining activities in accordance with regulatory requirements.[23] This would continue to be the case if underground operations using the present mining method were to be expanded.

Some of the environmental impacts identified in current and former mines elsewhere in Australia are more challenging than in the arid conditions of South Australia. The geochemical composition of a uranium ore body, in particular the presence of sulphides, increases the potential for uranium to migrate through the environment. That migration is assisted by water in areas of wetter climatic conditions.[24] As a result, strategies for managing the environmental impacts of uranium mining activities need to consider not only the nature of the extraction method, but also local climatic and geochemical conditions.

MINE WASTES

Uranium mining requires a radioactive waste management plan (RWMP) that is approved by the EPA and updated as requested by the operator or the regulator. A RWMP outlines how a proponent will manage risks to the environment resulting from mining processes, including the production and management of radioactive wastes.[25]

Mine wastes, known as tailings, comprise solid and liquid chemical wastes generated through milling and leaching processes. They often include fine suspended particles of rock mixed with acids and other chemicals. In the context of uranium mining, tailings generally contain radioactive elements, including radium and radon.[26] However, inadequate containment at tailings dams is a more significant hazard than the radioactivity level.[27]

A loss of containment has the potential to result in tailings breaching the dam containments and seeping into underlying geology and aquifers. If breaches occur, the tailings can render groundwater unsafe for use by humans and fauna. For these reasons, tailings dams and facilities are engineered and reinforced to avoid seepage or structural collapse. Tailings dam engineering plans must be reviewed by DSD before approval is given to start mining activities.[28] Mining companies are required to monitor and report annually on the integrity of their tailings dams and their retention

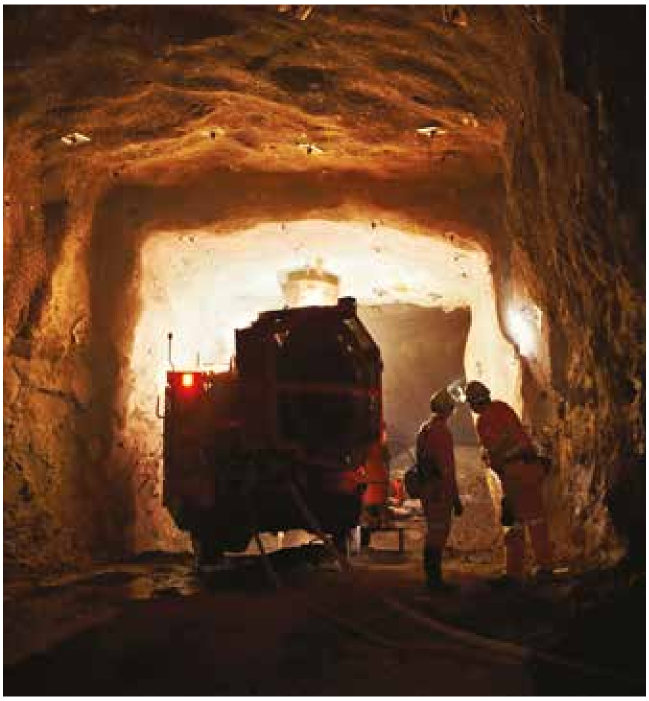

Figure 2.2: Underground mining at the Olympic Dam mine

Image courtesy of BHP Billiton

performance. In its most recent environmental protection and management program report, BHP Billiton stated there had been no recent embankment failures and that the groundwater beneath the tailings storage facility had not reached a level where it interacts with vegetation, indicating that any potential seepage was being managed.[29]

Other general and mine-related wastes, both liquid and solid, are generated during mining activities and, once the mine has closed, are retained on the mine site.[30] If these wastes interact with surface or groundwater, they can produce leachate, which can infiltrate and contaminate the underlying groundwater.[31] Leachate can contain contaminants, including radionuclides, heavy metals and acids, which can render the groundwater unusable. Waste and tailings facilities must be suitably lined with clay or geotextile fabrics to prevent their interaction with the surrounding environment.[32] At the end of mining operations, tailings dams are required to be capped to ensure that wastes are contained and risks to the environment are managed.

GENERATION OF DUST AND HANDLING OF ORES

Underground and open-cut mining poses a risk to workers through exposure to radioactive dust particulates and radon gas[33], particularly due to the use of explosives, heavy machinery and processing equipment, and other ground disturbances.[34] There is a known association between exposure to these sources and historical experience of lung cancers in workers in uranium mines, where those mines operated with limited or no protective measures for workers.[35]

In modern uranium mining operations, such as those at Olympic Dam, the EPA-approved RMPs contain measures to protect the health of workers. A key control is to minimise direct handling of materials containing uranium. This is achieved through the use of machinery and automation, for example, in uranium oxide packing facilities. Other controls include dust suppression by wetting dry surfaces, ventilation to remove radon gas, real-time air quality monitoring, and filtration systems, including in the cabins of trucks used underground. For workers, measures include wearing personal protective equipment, cleaning uniforms and showering.[36]

The radiation exposure of employees is monitored and doses are compiled in reports to the EPA, which are publicly available.[37] Data on radiation doses to uranium mine workers in Australia is collated by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in the Australian National Radiation Dose Register (ANRDR).[38] As set out in Chapter 7: Radiation risks, the data shows that the exposure of workers is significantly lower than the regulated limit.

In a submission to the Commission, it was asserted that the RMP at Olympic Dam had not been updated between 1998 and 2013.[39] The implication was that protection measures in mining operations had not been effectively regulated by the regulator or managed by the operator. The evidence is that at all times there was an effective RMP at Olympic Dam that had been approved by the EPA, the regulator. During the period in question, the EPA had not needed to amend the plan and the measures in the plan were implemented, as evidenced by the EPA's regular inspection of the mine's radiation safety measures.[40] Therefore, the criticism made is not a basis for suggesting that radiation protection could not be effectively managed at Olympic Dam or elsewhere in the future.

IMPACTS ON FAUNA

Tailings fluids are acidified and contain other harmful chemicals. In an arid environment, the water held in tailings dams can attract native fauna. When fauna access tailings dams, the result can be illness or death. Significant numbers of birds and mammals have perished in the past in tailings facilities at Olympic Dam.[41] BHP Billiton has since implemented measures to minimise the interaction between the fauna and tailings dam water, including fencing and light and noise-deterrent systems, which have reduced but not eliminated the risks.[42] Netting of the dams has also been proposed.[43]

RISKS TO WATER SOURCES

Water is required during mining operations for minerals processing, dust suppression and equipment washing. As mines tend to be located in remote areas, away from major pipeline infrastructure, water is a critical resource. It can be sourced from the surface, including lakes and rivers, or from aquifers. In so doing, there is the potential for over-extraction of groundwater. As well as depleting water resources, this could cause soils and remnant water to become saline.

The water requirements at Olympic Dam are substantial, with operations using an average of 37 megalitres of groundwater a day.[44] Water is primarily supplied to operations from Wellfields A and B, which draw from the Great Artesian Basin, and are located 120 kilometres (km) and 200 km respectively north-east of operations.[45]

The quantity of water used is limited by BHP Billiton's operating licence, which is issued by the South Australian Department of Environment, Water and Natural Resources. A monitoring program is incorporated in the licence to track water use. The quantities of water extracted are recorded and are publicly available in annual reports. Current extraction is within the regulated limits.[46]

Concerns have been expressed in the past that water consumption at Olympic Dam was having a negative effect on the environmentally sensitive Mound Springs, where water from the Great Artesian Basin reaches the surface.[47] However, ongoing monitoring has not identified any changes in the springs beyond those predicted when Olympic Dam was established and those stated in the 1997 environmental impact statement. This is demonstrated by measurements of the rate of flow and monitoring of flora communities.[48]

Figure 2.3: The Four Mile ISL wellfield, with inset showing pipework linking into a well-house

Image courtesy of Heathgate Resources

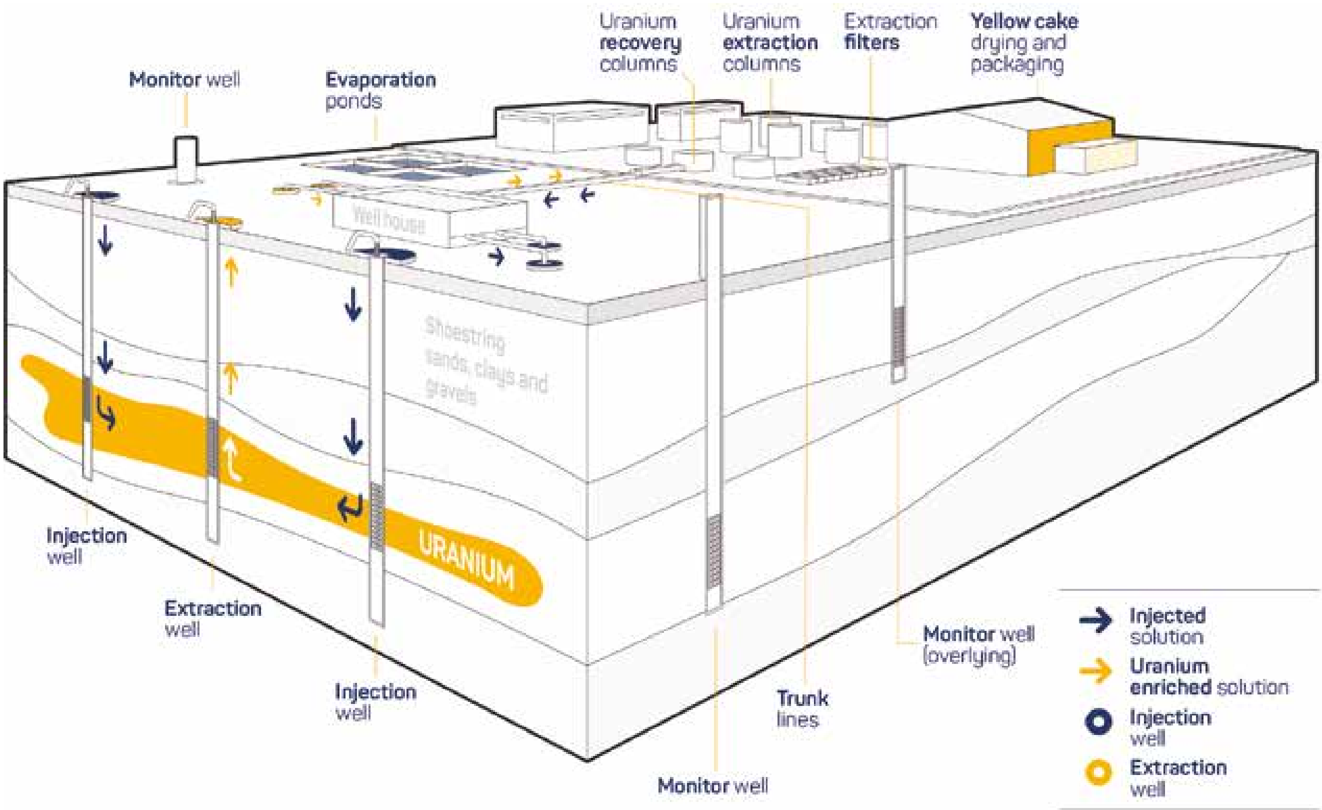

Figure 2.4: A cross-section of an in-situ leach uranium mine

11. In-situ leach (ISL) mining in South Australia is conducted in aquifers, which, because of their natural salinity and radon content, have no human or stock use. As in underground mining, the risks of ISL mining are managed by operators under the supervision of regulatory authorities.

ISL mining recovers uranium from permeable sandstone deposits by continuously recirculating a leaching solution through mineralised ore zones, mobilising the uranium and then recovering and concentrating the uranium at surface facilities.[49]

The type of leaching solution used—whether acidic or alkaline—depends on the composition of the geology and environmental considerations. The South Australian ISL mines—Beverley, Beverley North and Four Mile—use dilute sulphuric acid and hydrogen peroxide to extract the uranium from the host rock.[50]

ISL mines require both extraction and monitoring wells, as well as a system to transport the solution containing uranium to a processing plant. Unlike underground or open-cut mining, the uranium is extracted with minimal ground disturbance. This is indicated in Figure 2.3, which shows the wellfields at Four Mile and the above-ground pipework, which ultimately leads to the associated processing plant. When mining operations conclude, it is possible to remove all above-ground facilities and remediate the site as close as possible to its form before mining.

ISL mining produces a range of potential environmental risks that are specific to this particular form of extraction. These are discussed below. In South Australia, ISL activities are presently undertaken in aquifers that have no human or stock use because of their high natural salinity and radon content (a natural breakdown product of uranium).[51]

POTENTIAL CONTAMINATION OF NON-TARGET AQUIFERS

ISL mining requires the injection and extraction of a leaching solution at pressure into the underlying target aquifer (see Figure 2.4).[52] It is necessary to manage the potential for the migration of leaching solutions to areas outside the designated extraction zone, such as underlying or overlying aquifers. As part of this, the movement of fluids within a target aquifer is modelled to enable the planning of the rates and location of injection and extraction.

The risk of migration is managed through constant monitoring and modelling of underground movements of leaching fluids.[53] This is done through a ring of nearby monitor wells, which are installed beyond the mining zone.[54] Water samples are taken regularly from these wells to allow for the early detection of any unplanned migration of mining fluids.[55]

In leaching the uranium, some solution is removed from the extraction circuit to ensure that the target aquifer does not become over-pressurised, as this could cause the solution to migrate. The removed fluid, known as the 'bleed', is stored as liquid waste awaiting disposal.

SOLID AND LIQUID WASTES

ISL mining produces both solid and liquid wastes. The liquid wastes include the bleed solution and other solutions resulting from the recovery of uranium at the processing plant. They are saline, moderately acidic and contain some unrecovered uranium. These liquid wastes are held in evaporation ponds to reduce their volume before disposal into a designated aquifer, in accordance with the approved RWMP.[56]

The long-term impact of the injection and disposal of fluids into an aquifer is presently understood to be mitigated by the process of natural attenuation, which neutralises contaminants in groundwater over time without the need for further intervention.[57] The process takes place due to chemical interactions between the groundwater and underlying geology.[58]

ISL miners in South Australia plan to remediate post-extraction groundwater at their operations through natural attenuation.[59] Where this occurs, the mechanisms and rate at which the remediation will occur should be supported by laboratory tests and modelling.[60]

Heathgate Resources, the operator of the Beverley and Beverley North mines, is planning to undertake a trial program of remediation by natural attenuation.[61] The trial would require demonstration before the post-extraction stage in line with EPA approvals and, should natural attenuation not be demonstrated to be occurring, the company would be required to undertake alternative measures to remediate the affected aquifers.[62] At the Beverley and Four Mile mines, there is evidence to suggest that natural attenuation will take place over the long term in accordance with the modelling to date.[63]

ISL mines also produce solid low level radioactive wastes, such as used equipment from processing and laboratory activities. However, these wastes are produced in smaller quantities at ISL operations than at underground mines. The wastes are managed in purpose-built repositories that are regulated by the EPA and operated in accordance with ARPANSA requirements.[64]

RISKS FROM RADIOACTIVE MATERIALS

Heathgate Resources has an EPA-approved RMP, which identifies the potential pathways through which workers could be exposed to radiation as radon decay products, radioactive dust, gamma radiation and surface contamination.[65] Radiation protection measures include the use of personal protective equipment and hygiene practices.[66]

Further, operational areas are monitored for the presence of radioactive materials and workers are required to wear thermoluminescent dosimeter badges, which measure their external exposure to gamma radiation.[67] Mine operators calculate annual doses to workers and include this information in an annual report to the EPA.[68] The data is also provided to ARPANSA for inclusion in the ANRDR.[69]

12. The lessons that have emerged from the state-owned uranium mine at Radium Hill, which closed in 1961, and the associated treatment plant at Port Pirie have been incorporated into current regulatory frameworks.

The Radium Hill mine was operated by the South Australian Government from 1954 until November 1961. Uranium ore was extracted and transported by rail to the Rare Earths Treatment Plant at Port Pirie, also operated by the state government. At the treatment plant, the ore concentrate was processed into uranium oxide concentrate through an acid leach and ion exchange process. The treatment plant ceased uranium processing activities in 1962, although the site was subsequently used for other commercial activities. The state government continues to manage the sites of those facilities.

The activities on those sites were not planned, operated, regulated or decommissioned in accordance with current practice, nor would they have been permitted under the current regulatory framework. Typical of the conduct of mining activities in that era, operations were primarily focused on orderly production and without any evident contemplation of environmental impacts.[70] Risks to the health of workers were considered, although radiological risks were not prioritised.[71]

The lack of environmental consideration is demonstrated by numerous characteristics of each site. In the case of Radium Hill, crushed waste rock containing traces of radioactive ore was used to construct roads and other infrastructure.[72] Closure of the site simply involved the removal and sale of plant.[73] The tailings dam, which was not an engineered

Figure 2.5: From left, the Radium Hill tailings dam in 1964; in 1980 before rehabilitation; and in 2015

Images on left courtesy of the Department of State Development

structure but was built using uncompacted tailings, was not capped when the mine closed. As a result the wind dispersed tailings into the surrounding landscape.[74]

In the 1980s the government capped the tailings dam at Radium Hill; however, this was only a short-term solution to the problem of dispersion. Figure 2.5 shows that subsequent erosion is occurring and the tailings are being exposed, although to a lesser extent than before they were capped.[75] In future, it will be necessary to increase the capping thickness and reduce the angle of the dam walls to stem erosion.[76]

At the Port Pirie treatment plant, the tailings dams were built on tidal mud flats, a sensitive marine environment, and are uncapped. Although mitigated by levees, the risk remains for further dispersion of radioactive materials and metallic elements during flooding caused by king tides.[77]

The failure to consider the environment in the planning, operating and decommissioning of these facilities has resulted in ongoing management challenges. Although subsequent assessments of both sites show they do not pose a serious radiological risk to the health of visitors to the sites[78], the state government is required to continue to monitor and manage potential environmental contamination. Environmental reports in relation to both sites identify the need for longer-term management plans, although these are yet to be completed.[79]

These experiences have fed into today's regulatory frameworks for mines, which are directed towards protecting the environment using management and preventative measures.

The current regulatory regime requires:

- the environmental consequences of mining activities to be addressed in the establishment and operation of mines and associated facilities. The licensing process for new mines requires comprehensive environmental impact statements, involving associated investigation and testing to ensure the risks are properly characterised and can be appropriately managed[80]
- the remediation of mine sites as part of their planned closure, to minimise ongoing risks to the environment. To avoid environmental legacy issues and associated costs, the PEPR must be approved by regulators before the mine starts operating and is regularly updated during the life of the mine[81]

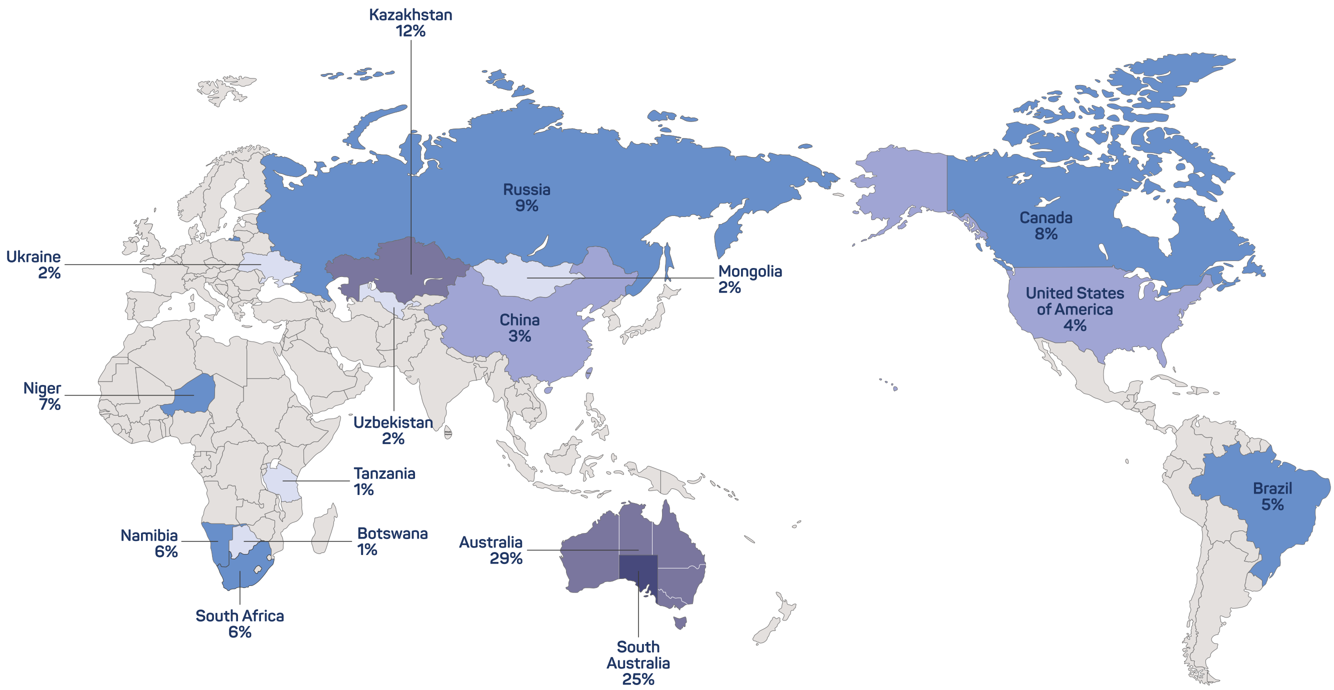

Figure 2.6: Economically viable global uranium resources

Data supplied by the Department of State Development

- the physical separation of mines and mineral processing facilities from sensitive environments.[82] Current planning and environmental regulation requires both DSD and the EPA to assess proposed mining and mineral processing operations. Proposals are also released for public consultation. These processes would not permit current similar developments in environmentally sensitive areas or near large population centres[83]
- an independent regulator to monitor and enforce compliance with regulatory requirements, which are in accordance with internationally accepted standards.[84] As South Australia's independent environmental regulator, the EPA is responsible for protecting people and the environment from harm associated with radioactive substances and setting standards relating to other environmental impacts, such as site contamination and waste. An EPA-approved licence, requiring compliance with national radiation safety measures and enforceable penalties in the event of a breach, is a prerequisite for radioactive mineral extraction and processing.[85]

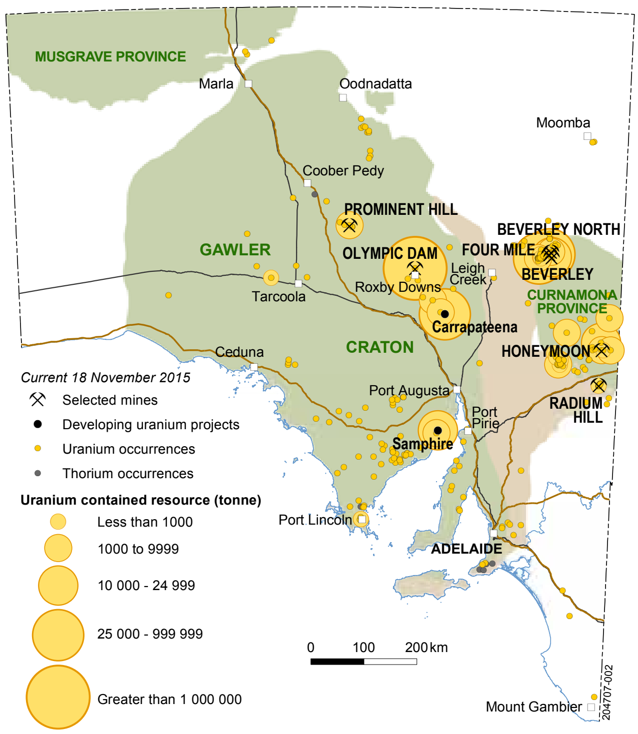

Figure 2.7: Uranium mines and mineral resources in South Australia

Map supplied by the Department of State Development

13. Generally, the risk of post-closure impacts from exploration and mining is addressed by a regulator holding a financial security or bond. The amount of the bond reflects the estimated cost of remediation and is usually adjusted over the mine's operational life.

The South Australian Government seeks financial assurances in the form of bonds or bank guarantees from mining companies and, in some cases, exploration companies to cover the costs of environmental remediation should the company not be able to do so adequately.[86] DSD calculates the value of the assurance based on its assessment of the greatest amount of environmental disturbance that could occur, and, depending on its level of confidence in the assessment, may include a contingency.[87] DSD engages quantity surveyors to assist in accurately estimating the cost of remediating each aspect of the project, and it may review the estimate if operations change significantly.[88]

The bond system was not standard practice when Olympic Dam, the state's largest mining project, was established [89], thereby making it an exception. BHP Billiton has made an internal financial provision to address estimated remediation and closure costs for the mine.[90] Any future expansion of Olympic Dam would come under a new indenture that would take account of the bond requirement; however, this would not be implemented until a decision was made to proceed with the expansion.[91]

ARE THE ACTIVITIES FEASIBLE?

14. Given the detailed knowledge of uranium deposits in South Australia, the similarity of geological characteristics in the north of the state, and what is known about the development of mineral systems, there are good reasons for concluding that new commercial uranium deposits can be found in the state.

South Australia has approximately 25 per cent of the world's known uranium resources, or about 80 per cent of Australia's uranium resources (see Figure 2.6).[92]

There are a range of well understood primary and secondary uranium deposits in South Australia. Figure 2.7 shows the identified deposits and their relative size.

Olympic Dam is the largest known uranium deposit in the world.[93] It is a primary uranium deposit associated with copper, iron oxide, gold, silver and rare earth elements, and is hosted in the 1.5 billion-year-old Hiltaba Suite Granite.[94] Other primary deposits have been located in South Australia, most recently at Carrapateena.[95]

Primary uranium deposits are known to have formed through hydrothermal systems or the movement of magmatic fluids from deep within Earth's crust. These fluids moved under pressure through the underlying geology, transporting uranium and other minerals, and consolidated closer to the surface.[96] Experience from discoveries of deposits in other mineral systems has shown that where one primary mineral deposit is discovered, other deposits of the same mineral composition are likely to exist. The process of formation also can indicate the size of related deposits. A large primary deposit may be associated with numerous smaller deposits. This inference can be shown as a Zipf curve.[97] Figure 2.8 plots on a Zipf curve South Australia's primary uranium deposits. Based on these, there is likely to be a range of undiscovered significant uranium deposits.

The potential for primary uranium deposits suggests there are likely to be many secondary deposits, which are formed within ancient river systems (paleochannels). The uranium-enriched fluids that are derived from the erosion of a primary deposit are transported by groundwater, where they eventually accumulate due to a change in water or rock chemistry. Those deposits are localised and generally contain small quantities of uranium.[98] The uranium in the Frome Embayment at Beverley is a secondary deposit hosted within sandstone as a series of uranium roll-fronts, derived through the weathering of the exposed uranium-enriched rocks of the northern Flinders Ranges.[99]

15. Despite reliable estimates that further commercial deposits of uranium exist in South Australia, there are numerous barriers to the successful exploration for those deposits. These barriers are shared with exploration projects for other minerals.

Exploration for uranium is similar to other minerals and is conducted only when a number of conditions are satisfied. An exploration company will carefully assess these conditions before seeking an exploration licence.

A market for a mineral commodity must exist or be reasonably likely to exist, although opportunities for uranium in particular can be difficult to assess given the prevalence of long-term contracts in that market.[100] Access to investment is also required before exploration activities start.[101] Once an ore body is identified, an exploration company will quantify that deposit, including its mineral characterisation, location and economic potential.[102] Specific aspects, such as recovery costs, are also generally quantified in the business case for exploring for a particular deposit.

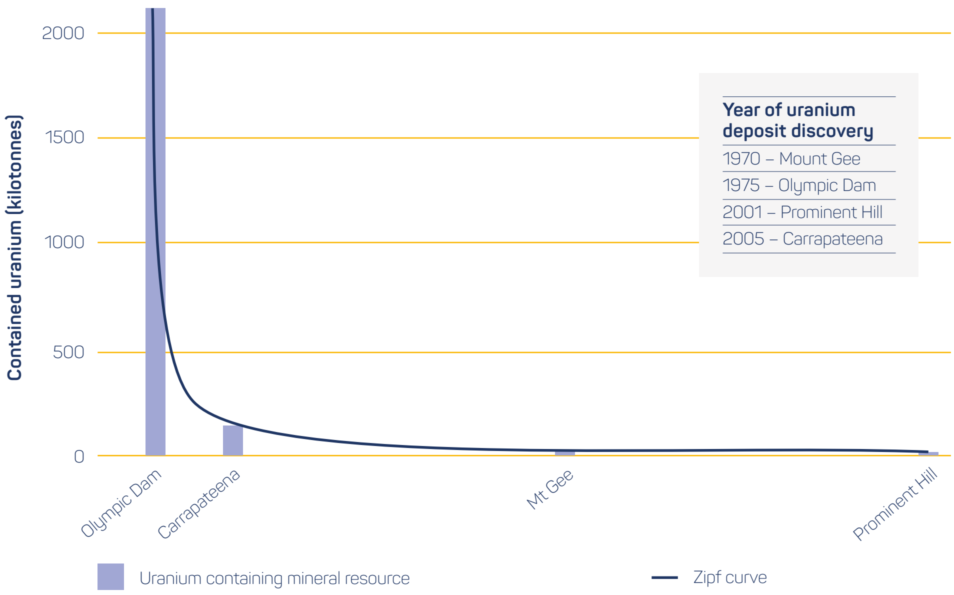

Figure 2.8: Known uranium deposits containing mineral resources and reserves in South Australia

Data supplied by the Department of State Development

Consistent with other minerals, the successful development of a uranium deposit requires access to supporting infrastructure, such as roads, railways, airfields and ports, and services, including electricity, water and gas.[103]

In South Australia, minerals explorers are required by their licence conditions to report their exploration expenditure to DSD. That information shows that uranium exploration expenditure has decreased significantly in the past decade from a high of $118 million (m) in 2007/08 to $2.3m in 2014/15 a 98 per cent reduction — see Figure 2.9. There has been a decrease in expenditure of about 77 per cent since 2012/13.[104]

EXTENT AND THICKNESS OF COVER

In significant parts of South Australia, crystalline rock-bearing minerals underlie a deep layer of sedimentary cover (see Figure 2.10).[105] Depending on the depth of that cover, the geochemistry of uranium and other minerals is obscured and cannot be properly detected through remote-sensing techniques. In some cases, the only way to accurately understand the underlying geology is by drilling, which only provides data for a small area. This poses a technical challenge to identifying the locations of mineral-bearing rock and, if discovered, to economically extracting the ore.[106]

That challenge is recognised by government, industry and academic institutions, with a range of strategies being developed to support an increase in exploration. A prominent national strategy is UNCOVER, which seeks to promote more collaboration and information sharing to address a common set of key issues associated with extensive cover.[107] UNCOVER has led to the development of further policies, including the National Mineral Exploration Strategy, by the state and federal governments and the Industry Roadmap by the exploration industry.[108] Although these policies indicate there is broad agreement as to what could be done to overcome this barrier to exploration, and initiatives such as South Australia's Plan for Accelerating Exploration (PACE) are consistent with the identified priorities[109], the full benefits of the implementation of UNCOVER are yet to be realised.[110]

COST OF DRILLING ACTIVITIES

Exploration drilling programs are expensive: about $500 /metre using diamond drilling methods.[111] If the target mineralisation were hosted in crystalline basement geology (see Figure 2.10) overlain by barren sedimentary rock, the cost to drill down to the uranium-bearing minerals would be significant.[112]

The Adelaide-based Deep Exploration Technologies Cooperative Research Centre (DET CRC) is conducting research into lowering the cost of exploration drilling and acquiring data.[113] This has led to the development of the Coiled Tubing Drilling Rig for mineral exploration, complemented by the Lab-At-Rig® continuous geochemical

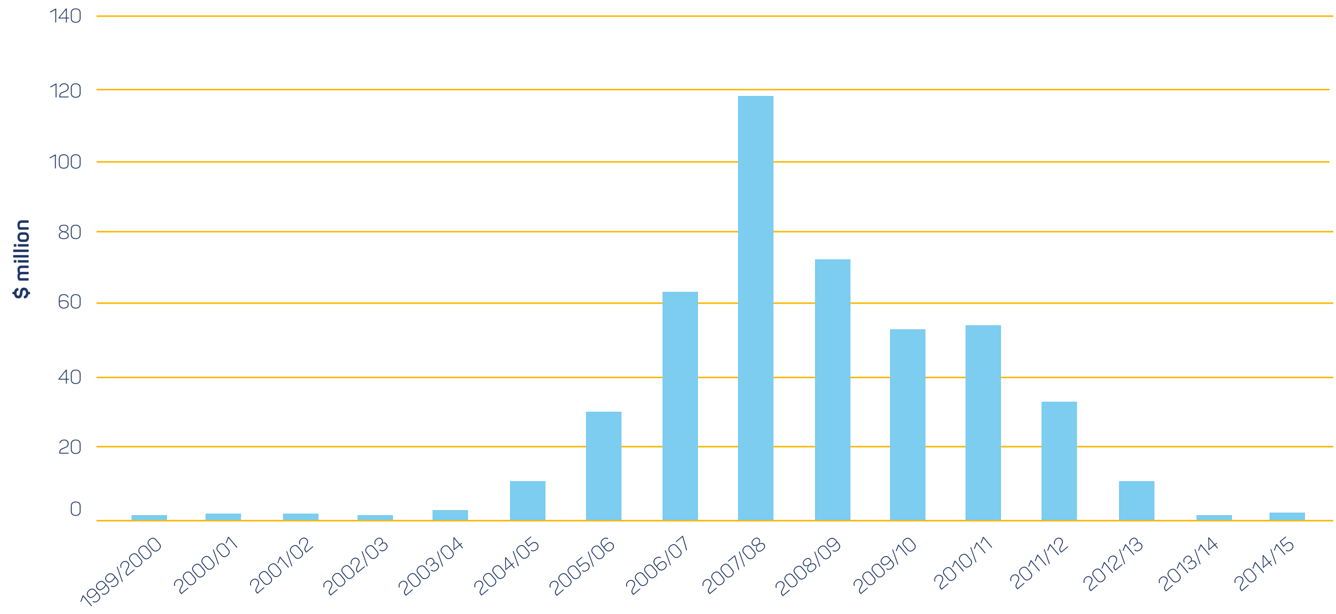

Figure 2.9: South Australian uranium exploration, 1999/2000 to 2014/15

Data supplied by the Department of State Development

testing attachment.[114] These innovations are designed to facilitate better characterisation of the geophysics and geochemistry of the geology being drilled, assisting geologists to tailor drilling strategies for greater efficiency.

LOW PROBABILITY OF SUCCESS IN DRILLING AT GREENFIELD LOCATIONS

Exploration companies target regions of known mineral potential (brownfield exploration) to increase the likelihood of discovering an economic mineral deposit (see Figure 2.11).[115]

There is greater risk associated with exploration in greenfield locations, which have not been surveyed before.[116] When combined with the high cost of exploration, this lower probability of success makes greenfield exploration less attractive. To offset risk, greenfield exploration requires technical skill and knowledge of the target mineralisation. This involves interpretation of high-resolution geoscientific data and experience in locating mineral deposits.

In addition to the expense associated with drilling, these issues have led to a paucity of drilling data across large areas of South Australia.[117] An example is the Pandurra Formation (extending from Whyalla towards Coober Pedy in central South Australia), which is considered prospective for uranium. It is estimated that only 27 holes penetrating the basement geology have been drilled within a 40 000 square kilometre area.[118]

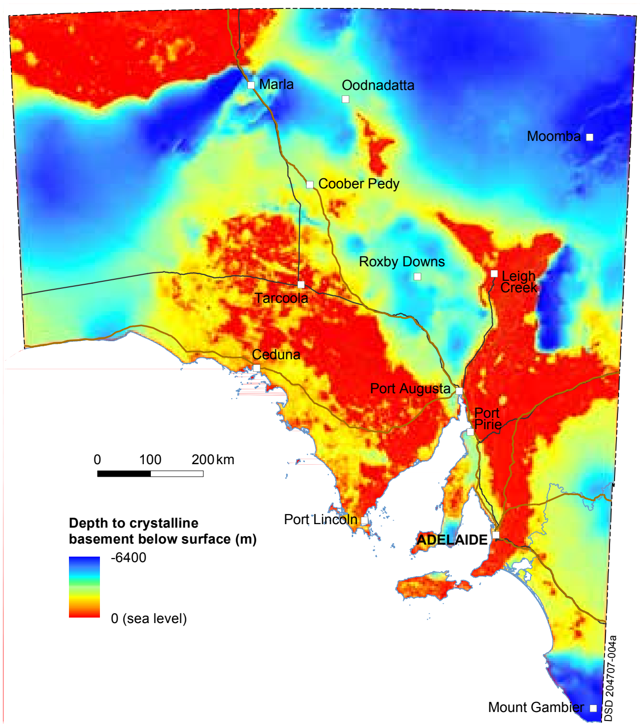

Figure 2.10: Depth to crystalline basement in South Australia

Map supplied by the Department of State Development

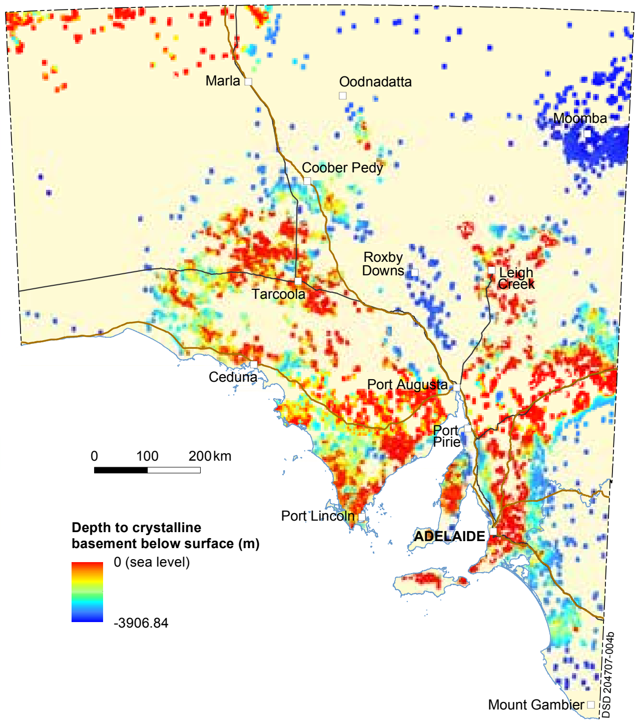

Figure 2.11: Drill core locations and measured depth to crystalline basement in South Australia

Map supplied by the Department of State Development

Figure 2.11 shows the drilling locations in South Australia and demonstrates that large parts of the state are under-explored, with no drilling or only shallow drilling.

LACK OF WIDESPREAD APPLICATION OF NEW SENSING TECHNOLOGY

Geophysical surveying of South Australia has been conducted on a wide scale by the South Australian Government and other research organisations, including the collection of magnetic, radiometric and gravity data.[119] This data provides a general characterisation of the state's surface geology (to a depth of about 30 cm) and, to a lesser extent, the underlying geological structures.[120] Exploration companies and research organisations conduct geophysical surveys on a finer scale directly on the Earth's surface using methods such as 'magnetotellurics', a technique that measures electrical and magnetic fields to understand geophysical structures.[121]

The larger the range of the geophysical survey, the larger the resolution, so a detailed survey is required to identify subtle geological features. Geophysical surveying on a detailed scale is not used often, as it is costly to commission.[122] This has led to gaps in the high-resolution geoscientific data sets available for some parts of the state.

THE NEED TO ENHANCE THE STATE'S HIGH-RESOLUTION GEOSCIENTIFIC DATASET

Extensive geoscientific data has been collected throughout the state, which can assist in identifying areas with mineral potential. The data is consolidated in the South Australian Resource Information Geoserver, a public electronic database administered by the state government, which comprises data contributed by past exploration companies, research organisations and its own surveys. Despite there being gaps in the overall coverage of the state, this comprehensive dataset is high quality and is internationally well-regarded.

However, there is potential to further enhance the utility of this dataset to explorers. In practice, each geophysical technique is employed independently and provides information about a specific geophysical aspect, whereas the characteristics of many aspects are relevant to a commercial decision to investigate an area's mineral potential.[123]

To that end, combining the different aspects of the dataset into a single comprehensive framework would further enhance the system and its potential to deliver benefits.[124] Although this would present challenges[125], ongoing technological developments associated with the collection of geophysical data, including cheaper instrumentation and higher data storage and processing capacity[126], make integration more feasible. Given that the South Australian Government already maintains a substantial central repository for geoscientific data obtained by other entities, it is logical that it would take a leading role in both integrating the data and making it accessible to the public.[127]

16. The South Australian Government's Plan for Accelerating Exploration (PACE) has led to increased investment in mining exploration. Counter-cyclical investment will leave South Australia better placed to take advantage of subsequent recoveries in the markets for minerals commodities.

PACE was devised to support increased exploration investment in greenfield drilling activities. Through the program, the state government offers a financial contribution to an explorer to assist in meeting the costs of drilling activities. In return, the explorer provides the geological samples collected during drilling to the government for consolidation in the Drill Core Reference Library, which promotes greater understanding of areas where little exploration has occurred in the past.[128]

This co-investment strategy has underpinned an additional $700m in private mineral exploration investment over 10 years and has increased South Australian mining revenue by $2400m.[129] It also contributed to the significant

discoveries of the Carrapateena, Four Mile and Prominent Hill deposits.[130] Although optimistic economic circumstances and encouragement from other discoveries also impact significantly on increased exploration expenditure in South Australia, it is evident that PACE made a strong contribution in supporting that growth.[131] In November 2015, the South Australian Government invested a further $20m in a new two-year cycle of PACE, known as PACE Copper, which provides financial support for greenfield drilling activities.[132]

These outcomes show that the mineral exploration industry is better placed to take advantage of upward trends in the markets for their targeted commodities when they invest in projects during less favourable economic conditions. It is ideal for government to support that investment on a 'counter-cyclical' basis, that is, at a time when overall exploration expenditure is low.[133] Such a strategy could alleviate some of the challenges associated with developing viable mining operations that are discussed in this chapter, namely the significant length of time required to establish a mine. Therefore, it is necessary to consider the means by which support for greenfield drilling projects can be sustained over the longer term.

IN WHAT CIRCUMSTANCES ARE THE ACTIVITIES VIABLE?

17. Consistent with mineral exploration, there are significant barriers to the viability of new uranium mine developments in South Australia.

The average price of South Australian uranium (U_3O_8) during the past decade has been about $70 a kilogram (kg) (see Figure 2.12), although it recently increased.[134] The current price of about $80 per kg is considered too low by some companies to develop or operate a mine.[135]

Exploration for any new mineral deposit is high-risk and success is limited.[136] Globally, there have been fewer than 10 newly identified greenfield resources for uranium in the past decade.[137] There is also considerable risk in converting a deposit into a mine.[138] As well as investment hurdles, there can be technical difficulties with the mineralogy and dispersion of the ore in the deposit.[139] Deposits are often deep, requiring underground infrastructure to be built to access the deposit, increasing the time to extraction.[140] It can take up to 20 years from discovery to extraction for large-scale mines.[141]

Navigating state and federal government processes to obtain new uranium mine approvals in South Australia and other Australian jurisdictions can take a long time.[142] For example, it has taken Toro Energy more than 10 years to be in a position to develop the uranium deposit at Wiluna in Western Australia.[143] Proposals require long-term, detailed scientific and engineering investigation and analysis in the form of an environmental impact statement, which can take considerable time and expense to collate.[144] In some instances, the commodity market for uranium has decreased to the extent that a mine considered financially viable at the outset of the process is no longer viable by the time it is approved.[145]

Approvals for new mines are usually handled exclusively by the relevant state or territory government. However, because federal legislation (the *Environment Protection and Biodiversity Conservation Act 1999*) refers to uranium mining as a 'nuclear action'[146], there is a requirement for Australian Government approval before a licence is granted. Whether any added environmental benefit flows from this duplication in process has been questioned by numerous organisations.[147]

Federal and state governments have sought to address these issues through administrative arrangements that establish agreed criteria sufficient to meet the requirements of both levels of government. An 'assessments bilateral' has been agreed that specifies the requirements for assessing the environmental impacts of new mines, such

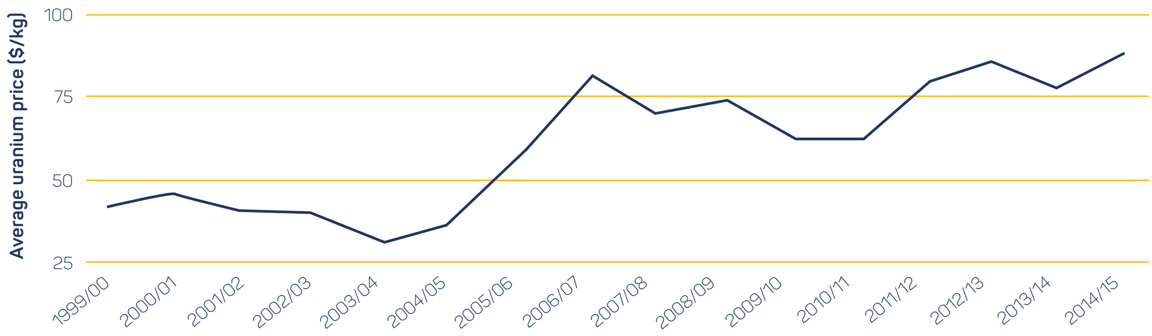

Figure 2.12: Average prices of South Australian uranium, 1999/2000 to 2014/2015

that proponents need to meet one set of criteria rather than two.[148] A bilateral arrangement relating to approvals, through which an approval by the state could be used as the basis for an Australian Government approval, is being negotiated between the federal and South Australian governments.[149]

Even if the administration of the processes could be coordinated, they remain separate, have different timeframes and may still require different information—despite their common purpose. These parallel processes can result in differing conditions being imposed on the same activity, or duplicated conditions, which effectively require the same studies to be undertaken twice to demonstrate compliance. This has increased the anticipated costs of, and timeframes required for, regulatory approval for new uranium mines.[150]

18. Increases in the uranium price will not occur until existing global inventories are used. Recent commercial decisions in Australia by those currently operating or developing uranium mines do not offer any clear indication of the position in the longer term.

The international uranium market is currently oversupplied with uranium.[151] This has changed the way in which suppliers and customers have traditionally transacted, as customers move to purchase uranium on the spot market rather than entering into long-term contracts.[152] It is unlikely that demand will increase, with a corresponding price rise, until at least 2018.[153] The potential for a future increase is contingent on several factors, including the extent to which Japan restarts its nuclear reactors following the Fukushima Daiichi nuclear accident and China's decisions as to its sources of uranium.[154]

Uranium is produced either alone or, as is the case at Olympic Dam, as a by-product during the recovery of other minerals.[155] The uranium price has minimal impact on the production of uranium at Olympic Dam, as the mine's principal source of revenue is copper, to which uranium production is tied.[156] BHP Billiton's decision in 2012 to postpone a planned expansion of Olympic Dam and investigate less capital-intensive designs was principally related to activity in the global copper market, not uranium.[157]

Mines using the ISL technique have been established at four locations in South Australia: Beverley, Beverley North, Four Mile and Honeymoon. Although these mines produce uranium exclusively, Four Mile is the only operation that is currently extracting uranium.[158] The Beverley wellfields are currently under care and maintenance. At Beverley North, the Pepegoona satellite plant is offline pending infrastructure modifications aimed at increasing future production.[159]

Uranium recovered at Four Mile is pumped to the Pannikin satellite plant at Beverley North, before being transported to the Beverley plant for further processing.[160] Operations at the Honeymoon ISL mine were suspended in 2013 due to high production costs and ongoing difficulties in achieving design capacity.[161]

Outside South Australia, the Ranger mine in the Northern Territory has been operational since 1981, but in recent years has decreased its production of uranium, as it has shifted from direct ore extraction to processing stockpiled ore.[162] Production in 2014 was 1165 tonnes (t) uranium oxide concentrate (UOC) due to an incident at the mine in December 2013.[163] In 2015 it rose to 2005 t.[164] Plans to develop an underground mine on the Ranger Project Area have been suspended, with the owner citing the current operating environment and the end, in 2021, of its mining authority as reasons.[165] If a final investment decision is made to develop the Wiluna deposit in Western Australia, the mine is predicted to produce 695 t of uranium a year.[166] Mines at the Kintyre and Yeelirrie deposits, also in Western Australia, are planned, although final investment decisions are yet to be taken.[167]

19. In recent years, the annual output of South Australian uranium mines has been between 4000 and 5000 tonnes UOC. Increasing output beyond those levels would require the reinstatement of production at some mines, and to be substantially increased, would require investment in the development of new production capacity.

South Australian uranium production in 2014/15 was valued at about $346.5m (see Figure 2.13). Average production of UOC during the past decade was 4438 t per year, with an average annual value of about $321m.[168] Since 2012/13, production volumes have decreased by 17 per cent, with a corresponding decrease in royalties payable to the state government from $17.8m to $15.9m in 2014/15.[169]

In 2014/15, Olympic Dam produced 3144 t UOC and Four Mile produced 922 t.[170] Increasing the state's uranium output beyond current levels would require bringing the mines presently under care and maintenance back into production.

However, significant increases in production levels could only be achieved through substantial investment in new capacity. A new ISL mine could be established more quickly than an underground or open-cut mine, although as production levels from South Australian ISL mines indicate, its impact on overall production would not be as substantial.[171]

BHP Billiton is currently investigating the benefits of incorporating another uranium ore processing method, heap leaching, into its processing flow at Olympic Dam.

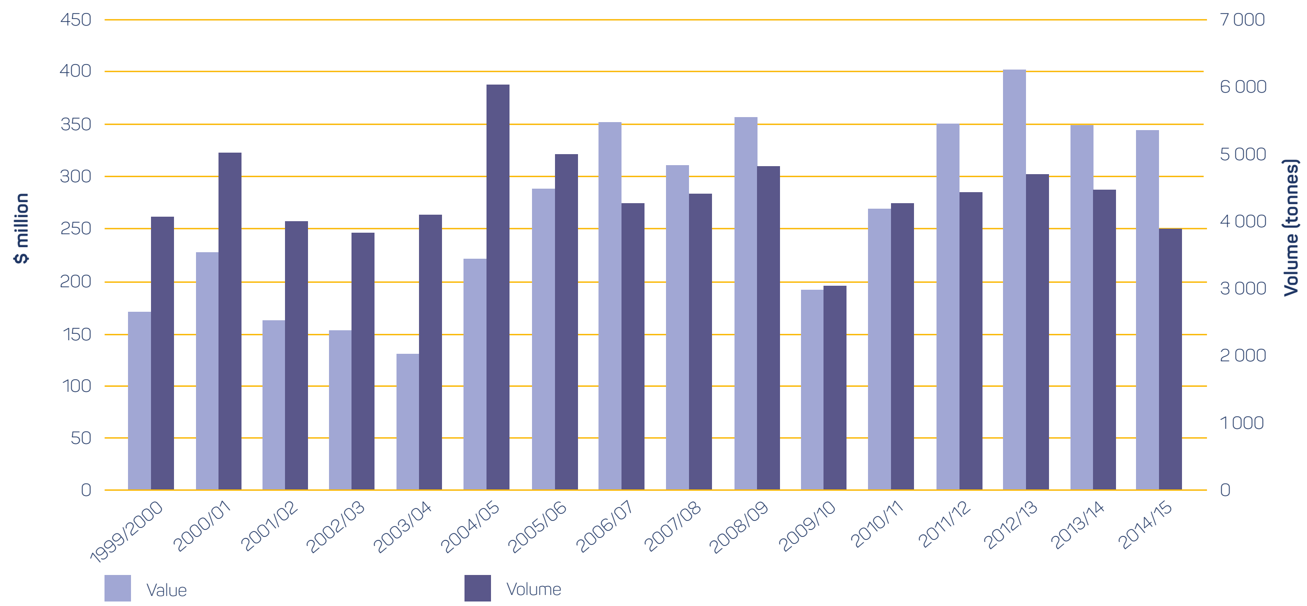

Figure 2.13: South Australian uranium production, 1999/2000 to 2014/15

Data supplied by the Department of State Development

This method involves treating the mined ore with an acid solution over about a year so that uranium and some copper may be extracted more efficiently during later stages of the process.[172] While uranium ore could be processed more efficiently if these trials prove successful, it is unclear whether this would have any impact on a decision to increase output.

20. Uranium production has produced benefits to the South Australian economy, and will continue to do so.

21. An expansion of uranium production would add value to the economy, but expectations should be tempered. Even were production to increase to meet very optimistic demand forecasts prompted by strong climate action policies, the value of production over the long term and associated royalties are relatively small in terms of the state's total revenues.

South Australian uranium production has, considering its aggregate value over the past 15 years, made a substantial economic contribution: see Figure 2.13. In 2014/15, South Australia's uranium exports met about 4.5 per cent of global demand.[173] This is the lowest level since 2010/11.[174]

It is difficult to predict long-term uranium demand given its dependence on a variety of factors, including the structure of global policy measures to reduce greenhouse gas emissions and the extent to which nuclear energy plays a part in those measures. However, should there be a significant increase in global demand for nuclear energy, the contribution that uranium production could potentially make to future prosperity in South Australia can be placed in some context.

The International Energy Agency (IEA), in anticipation of the 2015 United Nations Climate Change Conference in Paris, released forecasts on future electricity demand and the potential growth of low-carbon energy sources if action is taken to address greenhouse gas emissions and to limit global average temperature to 'well below 2 °C' above pre-industrial levels. The scenario developed by the IEA assumes that nuclear capacity will be expanded substantially by 2030, resulting in additional capacity of 274 gigawatt electrical (GWe).[175] It also estimated that installed capacity could be between 520 GWe and 837 GWe in 2040.[176]

If this scenario were to be realised, global demand for UOC would be expected to be about 130 kilotonnes (kt) in 2030 and about 170 kt in 2040.[177] If South Australia were to maintain its current share of the global uranium market, and assuming that production capacity could be expanded, its UOC production would increase to about 6100 t of uranium by 2030 and about 7700 t by 2040.[178]

If that expansion were to occur, and the UOC price were to increase and stabilise at about $128 per kg in 2030 and beyond, the total revenue from South Australia uranium sales would be about $770m in 2030 and about $980m in 2040.[179] At current rates, the South Australian Government

would receive royalties of $40m in 2030 and $50m in 2040.[180] To place these values in context, the total mineral and petroleum royalty received in 2014 was $237.5m.[181]

Therefore, the increased royalties that would flow from greater uranium production, even at very optimistic levels, would not have a significant impact on South Australia's economy.

Other views have been expressed about the economic potential that increased uranium production might offer to the Australian economy, including what would occur if Australian producers were to capture a greater share of an expanding world market for uranium.[182] The economic benefits described would be significant if they were realised. However, it is important to place those projections in context. To realise the potential benefits would require both substantial investment to expand production capacity well beyond present levels by 2040, as well as substantial increases in installed nuclear capacity internationally.

The situation would be different if South Australia were to take further steps in processing uranium into fuel for nuclear reactors. The value that can be derived from those activities is higher than that associated with uranium exports. The potential viability of facilities undertaking those activities is addressed in Chapter 3: Further processing and manufacture.

22. Energy generation technologies that use thorium as a fuel component are not commercial and are not expected to be in the foreseeable future. Further, with the low price of uranium and its broad acceptance as the fuel source for the most dominant type of nuclear reactor, there is no commercial incentive to develop thorium as a fuel. Although South Australia possesses numerous thorium deposits, it does not have a competitive advantage in that resource as it does with uranium.

Thorium is common in the earth's crust (about three to five times more abundant than uranium) and is principally associated with monazite, a by-product of heavy mineral sands mining.[183] There is a mineral sands mine near Ceduna in South Australia. However, operations at that mine were suspended in February 2016 due to market conditions.[184]

The identified global thorium resource is estimated at about 6212 kt[185], of which Australia's total proven thorium reserve is approximately 595 kt.[186] Thorium is not currently mined in Australia.[187]

The long-term outlook for the thorium market will be tied to developing a technology that can consume thorium as a fuel in nuclear reactors.[188] No commercial nuclear fuels based on, or containing, thorium are currently available[189], although some prototype reactors exist, and organisations in Canada, China, India and Norway are undertaking research.[190] Despite research efforts aimed at developing thorium into a viable nuclear fuel, it is unlikely to be used in commercial nuclear activities in the foreseeable future.[191]

Even if thorium-bearing fuels were developed for commercial use, the quantity of thorium required in a fuel source would be much less than the quantity of uranium required to produce the same amount of energy.[192] This being so, there is unlikely to be significant increased demand for thorium and no appreciable increase in investment in extraction operations.

NOTES

1 Transcript: Tyne & Marshall, p. 1141. International Atomic Energy Agency (IAEA), *Advances in airborne and ground geophysical methods for uranium exploration*, IAEA nuclear energy series no. NF-T-1.5, IAEA, Vienna, 2013, p. 5; Department of State Development (DSD), *Mineral exploration reporting guidelines for South Australia*, minerals regulatory guidelines (MG13), DSD, February 2015, pp. 18–19; Department for Manufacturing, Innovation and Trade, *Generic program for environment protection and rehabilitation—low impact mineral exploration in South Australia*, ministerial determination 001, South Australian Government Gazette, 30 June 2011.

2 Transcripts: Giles, pp. 214–215; Heinson, pp. 221–222, 232; Hill, pp. 241–242, 254. IAEA, *Advances in airborne*, pp. 1, 5–14; DSD, *Mineral exploration reporting guidelines*, pp. 14, 15–17; DSD, *Guidelines for conducting mineral*, p. 16; DSD, *Guidelines: landowner rights and access arrangements in relation to mineral exploration and mining in South Australia*, minerals regulatory guidelines (MG4), July 2014, p. 26.

3 Transcript: Hill, p. 248. DSD, *Mineral exploration reporting guidelines*, pp. 14, 18–19.

4 Transcripts: Giles, pp. 214–216; Hill, p. 244; Heinson, p. 221. DSD, *Guidelines for conducting mineral*, p. 12; DSD, *Mineral exploration reporting guidelines*, p. 19.

5 Transcript: Hill, p. 245. IAEA, *Advances in airborne*, pp. 5, 13–14, 23.

6 Transcripts: Heinson, p. 224; Hill, p. 246. IAEA, *Advances in airborne*, pp. 1, 5–6; DSD; J Duke, *Government geoscience to support mineral exploration: public policy rationale and impact*, report prepared for Prospectors and Developers Association of Canada, Canada, 2010, pp. 17–24; DSD, *Landowner rights and access arrangements*, pp. 26–27.

7 Transcript: Guthrie, pp. 1115–1116. DSD, *Guidelines for conducting mineral*, pp. 15–17, 28, 29–30, 37; DSD, *Statement of environmental objectives*, pp. 1–7.

8 DSD, *Statement of environmental objectives and environmental guidelines for mineral exploration activities in South Australia*, Earth Resources Information Sheet (M33), Government of South Australia, 2004, pp. 1, 3–14, 6–17 DSD, *Guidelines for conducting mineral*, pp. 29–30, 32–33. BHP Billiton, *Olympic Dam annual environmental protection and management program report 1 July 2013–30 June 2014*, p. 23.

9 Transcripts: Tyne & Marshall, p. 1146. DSD, *Statement of environmental objectives*; Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD–NEA), *Managing environmental and health impacts of uranium mining*, NEA no. 7062, OECD, 2014, pp. 30, 53.

10 DSD, *Statement of environmental objectives*, p. 4

11 Transcript: Tyne & Marshall, pp. 1140–1141. *Mining Act 1971* (SA) pts 10A, 10B; DSD, *Guidelines for conducting mineral*, pp. 13–14.

12 DSD, *Landowner rights and access*; DSD, *Preparation of a program for environment protection and rehabilitation (PEPR) for low impact mineral exploration in South Australia*, Minerals Regulatory Guidelines (MG8), Government of South Australia, 2015; DSD, *Guidelines for conducting mineral*, p. 13.

13 ranscripts: Guthrie, pp. 1111, 1116–1117; Tyne & Marshall, pp. 1144–1146. DSD, *Guidelines for conducting mineral*, pp. 8–14

14 Transcript: Tyne & Marshall, pp. 1140–1143, 1146. *Mining Act 1971* (SA) s. 62; DSD, *Guidelines for conducting mineral*, pp. 13–14.

15 Transcript: Tyne & Marshall, pp. 1128, 1143. DSD, 'Exploration licensing', *Minerals*, 2014, http://www.minerals.statedevelopment.sa.gov.au/exploration/exploration_licensing

16 Radiation Protection Division, *Radiation protection guidelines on mining in South Australia: Mineral exploration*, Environment Protection Authority (EPA) (SA), Adelaide, February 2010, pp. 7–8.

17 Parsons Brinckerhoff Australia, *Independent verification of rectification works EL 3258*, Marathon Resources Limited, 16 February 2009, pp. v–vi, 1–6.

18 Submission: Engineers Australia, p. 6. IAEA & OECD–NEA, *Uranium 2014: Resources, production and demand*, OECD, 2014, pp. 150–151.

19 Transcript: McGill, p. 668. IAEA & OECD–NEA, *Uranium 2014*, p. 151.

20 BHP Billiton Ltd, *Olympic Dam expansion draft environmental impact statement*, BHP Billiton, 2009, p. 37.

21 OECD–NEA, *The safety of the nuclear fuel cycle*, 3rd edn, 2005, pp. 113–115.

22 Transcript: McGill, pp. 661–663. OECD–NEA, *The safety of the nuclear*, pp. 113–115.

23 Transcript: McGill, pp. 661–663. DSD, *Guidelines for miners*.

24 Transcript: Ashley, pp. 589–592.

25 Transcript: Baldry, Bellifemine & Wigley, pp. 647–648.

26 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), *Code of practice for radiation protection and radioactive waste management in mining and mineral processing*, Radiation Protection Series No. 9, 2005, pp. 17, 29; IAEA, *Management of radioactive waste from the mining and milling of ores*, IAEA, Vienna, 2002, p. 16.

27 Transcript: Baldry, Bellifemine & Wigley, p. 642.

28 ibid., pp. 642–643.

29 BHP Billiton Ltd, *Annual environmental protection and management program report 1 July 2013–30 June 2014 – Olympic Dam*, pp. 133–135, 146–153.

30 IAEA, *Management of radioactive waste*, p. 19.

31 G Doka, *Non-radiological emissions from uranium tailings: a generic, global model for Life Cycle Inventory data*, report to PSI, Villigen, Doka Life Cycle Assessments, Zurich, February 2009, p. 15.

32 Transcript: McGill, p. 667.

33 OECD–NEA, *The safety of the nuclear*, pp. 113–115.

34 Transcript: Baldry, Bellifemine & Wigley, p. 646.

35 A Woodward, D Roder, AJ McMichael, P Crouch & A Mylvaganam, 'Radon daughter exposures at the Radium Hill uranium mine and lung cancer rates among former workers, 1952–87', *Cancer Causes and Control 2*, 1991, p. 213.

36 Transcript: McGill, pp. 662–663. BHP Billiton Ltd, *Radiation management plan – Olympic Dam*, BHP Billiton, 2013, pp. 9–15.

37 EPA, Uranium, http://www.epa.sa.gov.au/environmental_info/radiation/mining_and_mineral_processing/uranium

38 Transcript: Baldry, Bellifemine & Wigley, p. 650.

39 Submission: Conservation Council of SA (CCSA), Australian Conservation Foundation (ACF) & Friends of the Earth (FoE), p. 39.

40 K Baldry (EPA), letter to the Nuclear Fuel Cycle Royal Commission, 28 April 2016.

41 BHP Billiton Ltd, *Annual environmental protection*, p. 154.

42 Transcript: McGill, p. 664. BHP Billiton Ltd, *Annual environmental protection*, p. 155.

43 BHP Billiton Ltd, *Olympic Dam expansion supplementary environmental impact statement*, BHP Billiton, 2011, p. 357.

44 BHP Billiton Ltd, *Olympic Dam expansion draft environmental impact statement*, BHP Billiton, 2009, p. 337.

45 BHP Billiton Ltd, *Olympic Dam expansion draft*, p. 45.

46 BHP Billiton, *Annual environmental protection*, p. 46.

47 Submission: CCSA, ACF & FoE, p. 64. GM Mudd, 'Mound springs of the Great Artesian Basin in South Australia: A case study from Olympic Dam', *Environmental Geology* 39, no. 5, 2000, pp. 463–476.

48 Transcript: Power & Sampson, pp. 300, 307–308; BHP Billiton, *Annual environmental protection*, pp. 46–52.

49 Transcript: Marsland-Smith, pp. 609–610.

50 ibid., p. 620.

51 Transcript: Baldry, Bellifemine & Wigley, p. 640; Marsland-Smith p. 619.

52 Transcript: Marsland-Smith pp. 607–610. Submission: Engineers Australia pp. 6–7. Geoscience Australia, *Australia's in situ recovery uranium mining best practice guide: Groundwater, residues and radiation protection*, Commonwealth of Australia, 2010, pp. 8–13.

53 Transcript: Marsland-Smith, pp. 621–624.

54 ibid., p. 621.

55 Heathgate Resources, *Four Mile uranium mine—Program for environmental protection and rehabilitation, and radioactive waste management plan*, Heathgate Resources, 2013, pp. 42, 61.

56 Transcript: Baldry, Bellifemine & Wigley pp. 641, 645. Heathgate Resources

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

Pty Ltd, *Beverley North Mine: Mining and rehabilitation program*, 2008.

57 EPA, 'Response to questions from the Nuclear Fuel Cycle Royal Commission—Natural attenuation and groundwater flow rates', EPA, December 2015, p. 4.

58 A Marsland-Smith, 'Natural attenuation and groundwater flow, response to questions from the Nuclear Fuel Cycle Royal Commission', Heathgate Resources Pty Ltd, 28 December 2015, p. 3.

59 Heathgate Resources, *Four Mile uranium mine—Program for environmental protection and rehabilitation, and radioactive waste management plan*, Heathgate Resources, 2013, p. 105; Uranium One Australia, *Honeymoon uranium mine—Program for environment protection and rehabilitation*, Uranium One Australia, 2015, p. 19.

60 Australian Government, *Australia's in situ recovery uranium mining best practice guide*, Geoscience Australia, 2010, p. 12.

61 Transcript: Marsland-Smith p. 630.

62 Transcripts: Baldry, Bellifemine & Wigley pp. 640–642; Marsland-Smith pp. 625–626, 630. A Marsland-Smith, 'Response to questions'.

63 Transcript: Baldry, Bellifemine & Wigley, p. 640. EPA, 'Response to questions'; A Marsland-Smith, 'Response to questions'; Umwelt und Ingenieurtechnik GmbH Dresden (UIT), 'Natural attenuation project from lab tests to FME aquifer—Geochemical Modeling', 2008.

64 Commonwealth Scientific Industrial Research Organisation (CSIRO), Review of environmental impacts of the acid in-situ leach uranium mining process, CSIRO Land and Water, 2004 pp. 35-36.

65 Heathgate Resources, Beverley & Beverley North Uranium Mines, *Annual occupational radiation monitoring report 2015*, February 2016, p. 8.

66 Submission: Engineers Australia, p. 6. Heathgate, *Beverley Mine: Radiation management plan*, document no. MP-12, Heathgate Resources Pty Ltd, Adelaide, 2009, pp. 43–52, 57–59; Safework Australia, *Managing risks of hazardous chemicals in the workplace: code of practice*, July 2012.

67 Beverley & Beverley North mines, *Annual occupational radiation monitoring report*, February 2016, p. 22.

68 Transcript: Baldry, Bellifemine & Wigley p. 650. K Pelgrim & R Calley, *Annual compliance report 2014*, Heathgate Resources Pty Ltd, 2014, pp. 35–48.

69 Transcript: Larsson, p. 906.

70 Transcript: Baldry, Palmer, Borysenko, Marshall & Ward, pp. 559, 564. DSD, 'Submission to the Nuclear Fuel Cycle Royal Commission in response to questions regarding lessons learnt from historical uranium extraction, milling and processing activities in South Australia', 2015, p. 6.

71 Transcript: Baldry, Palmer, Borysenko, Marshall & Ward, p. 555; Kakosche, pp 544–545.

72 Transcript: Ashley, p. 600. DSD, 'Submission to the Nuclear Fuel Cycle Royal Commission in response to questions', 2015, p. 7.

73 Transcript: Kakoschke, p. 548. DSD, 'Response to questions', 2015, p. 10.

74 Transcript: Kakoschke, p. 541, 543, 547; Baldry, Palmer, Borysenko, Marshall & Ward pp. 560–562. DSD, 'Response to questions', p. 7.

75 DSD, 'Response to questions', p. 14.

76 Transcript: Ashley, p. 601.

77 Transcript: Baldry, Palmer, Borysenko, Marshall and Ward, pp. 563. DSD, 'Response to questions', p. 8.

78 DSD, 'Response to questions', p. 11; EPA, 'Response to questions from the Nuclear Fuel Cycle Royal Commission regarding environmental impacts at the former Port Pirie uranium/rare earths treatment facility and Radium Hill mine site', 2015, pp. 10–12, 14.

79 Transcript: Baldry, Palmer, Borysenko, Marshall & Ward, p. 577.

80 ibid., pp. 578, 581, 583.

81 Transcript: Baldry, Palmer, Borysenko, Marshall & Ward, p. 581–582. DSD, 'Response to questions', p. 25.

82 Transcript: Baldry, Palmer, Borysenko, Marshall & Ward, p. 558.

83 ibid., pp. 584–586.

84 ibid., pp. 553, 578–579.

85 EPA, 'Response to questions', p. 17.

86 Transcripts: Baldry, Palmer, Borysenko, Marshall & Ward, p. 566; Tyne & Marshall, p. 1140. *Mining Act 1971* (SA) s 62.

87 Transcript: Tyne & Marshall, pp. 1140–1141.

88 Transcript: Tyne & Marshall, pp. 1144–1145, 1148; DSD, *Guidelines for miners*, pp. 13–14.

89 Transcript: Tyne & Marshall, p. 1146.

90 Transcript: McGill, p. 670. BHP Billiton Ltd, *Resourcing global growth: Annual report 2015*, BHP Billiton, pp. 225, 271, 274.

91 Transcript: Tyne & Marshall, p. 1147.

92 DSD, *The Facts about uranium mining in South Australia*, Government of South Australia, p. 3.

93 IAEA & OECD–NEA, *Uranium 2014*, p. 150.

94 Transcript: Giles p. 202.

95 IAEA & OECD–NEA, *Uranium 2014*, p. 485.

96 Transcript: Giles, pp. 199–203.

97 ibid., pp. 203–205.

98 ibid., pp. 211–213.

99 ibid., Giles p. 213.

100 Transcript: Guthrie, p. 1109.

101 Submission: South Australian Chamber of Mines and Energy (SACOME), p. 8.

102 Transcript: Giles, p. 217.

103 Submission: SACOME, p. 15.

104 T Tyne (DSD), letter to the Nuclear Fuel Cycle Royal Commission, 2 February 2016.

105 Transcript: Hill, p. 240.

106 Transcript: Giles, p. 214; Hill, pp. 240, 244–245.

107 Transcript: Hill, p. 241. Australian Academy of Science, *Searching the deep earth: A vision for exploration geoscience in Australia*, Canberra, 2012.

108 Transcript: Hill, pp. 241, 255–256. Amira International, *Unlocking Australia's hidden potential: An industry roadmap*, Melbourne, 2015; *National Mineral Exploration Strategy*, 2012, available at https://scer.govspace.gov.au/workstreams/geoscience/national-exploration-strategy/

109 Transcript: Hill, p. 256.

110 ibid., p. 260.

111 Transcript: Giles, p. 215.

112 Transcript: Hill, p. 240.

113 Transcript: Giles, p. 217; Hill p. 249.

114 Transcript: Giles, p. 217. Deep Exploration Technologies CRC, *Coiled tubing drilling for mineral exploration*, accessed on 23 April 2016, http://detcrc.com.au/programs/program-1/project-1-1/; Deep Exploration Technologies CRC, Lab-at-Rig® for Mineral Exploration, accessed on 23 April 2016, http://detcrc.com.au/programs/program-3/project-3-2/

115 Transcripts: Heinson, p. 222; Tyne & Marshall, p. 1124.

116 Transcript: Hill, p. 249–250.

117 ibid., p. 249, 251–252.

118 Transcript: Giles, pp. 206–208.

119 Transcripts: Giles, p. 209; Heinson p. 222; Tyne & Marshall pp. 1132–1133.

120 Transcript: Giles, p. 216; Hill pp. 242–243.

121 Transcripts: Hill, pp. 247–248; Heinson, pp. 219–220.

122 Transcript: Heinson, p. 221.

123 ibid., pp. 224–225.

124 ibid., pp. 221.

125 Transcript: Hill, p. 246–247.

126 Transcript: Heinson, pp. 220–221.

127 Transcript: Hill, p. 247.

128 ibid., p. 252.

129 Economics Consulting Services, *The evaluation of the plan for accelerating exploration (PACE): Prospectivity, programs, promotion and people (PACE*

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions

review 2014), report for the Department of Manufacturing, Innovation, Trade, Resources and Energy, report book 2014/00014, 2014, p. 86.

130 Transcript: Hill, p. 253.

131 ibid., p. 259.

132 DSD, PACE Copper, accessed on 21 April 2016, http://www.minerals.statedevelopment.sa.gov.au/geoscience/pace/pace_copper; DSD, PACE discovery drilling 2016, accessed on 21 April 2016, http://www.minerals.statedevelopment.sa.gov.au/geoscience/pace/pace_discovery_drilling_2016

133 Transcript: Hill, p. 259.

134 Submission: Toro Energy, p. 10. DSD, *Minerals data 02/02/16*, excel spreadsheet prepared for the Nuclear Fuel Cycle Royal Commission, Adelaide, February 2016, http://nuclearrc.sa.gov.au/other-documentation/?search=Other%20 Documentation

135 Transcripts: Guthrie, pp. 1108–1109; Marsland-Smith, p. 614. Submissions: Areva, pp. 5–9, 10-11; Toro Energy, pp. 10. UX Consulting Co, *Uranium spot price 4 April 2016*, Cameco Corporation, 2016, https://www.cameco.com/invest/markets/uranium-price; Tradetech, *Uranium spot price 25 March 2016*, Cameco Corporation, 2016, https://www.cameco.com/invest/markets/uranium-price

136 Transcript: Giles, p. 208. Submissions: SACOME, pp. 10–14; BHP Billiton, p. 7. J Duke, *Government geoscience to support*, pp. 21, 24.

137 Transcripts: Hill, p. 249–251; Tyne & Marshall, pp. 1134. Submissions: Areva, pp. 5–9. OECD–NEA, *Uranium 2014: Resources, production and demand*, no. 7209, OECD–NEA, 2014, pp. 37–41.

138 Submissions: BHP Billiton, pp. 7–9; SACOME, pp. 10–14.

139 Transcript: McGill, pp. 659–660; Wigley, 634. Submissions: BHP Billiton, p. 10.

140 Transcripts: Heinson, p. 229.

141 Submissions: SACOME, pp. 10–14; Toro Energy, pp. 5, 10–11. AMIRA international, 'Unlocking Australia's hidden mineral potential: An industry roadmap – stage 1', corporate flyer, 2014, p. 1.

142 Transcript Guthrie, pp. 1110–1114; McGill, pp. 656–657; Tyne & Marshall, pp. 1137–1138. Submissions: Areva, pp. 4, 6–8, 10; BHP Billiton, pp. 4, 7–9; Minerals Council of Australia Issues Paper 1, pp. 13–16; SACOME, pp. 10–14; Toro Energy, pp. 12–17, 36-40. Deloitte, 'Review of regulatory efficiency in uranium mining', 2008, pp. 53–57.

143 Transcript: Guthrie, pp. 1111–1114. Submission: Toro Energy, pp. 1, 5, 8–9, 10, 12–17, 36–40.

144 Transcript: Guthrie, pp. 1111–1114. Submissions: SACOME, pp. 11–14; Toro Energy, pp. 5, 8–11, 35–40.

145 Transcript: Guthrie, pp. 1108–1109, 1112. Submissions: SACOME, pp. 11–14; Toro Energy, pp. 5, 8–9, 10–11, 35–40.

146 *Environmental Protection and Biodiversity Conservation Act 1999* (Cth) s 22.

147 Transcript: Guthrie, pp. 1110–1112; Submissions: BHP Billiton, p. 7; Minerals Council of Australia Issues Paper 1, pp. 11–12, 29; SACOME, pp. 13–14; Toro Energy, pp. 12–15.

148 Transcript: Tyne & Marshall, pp. 1139–1140, 1148.

149 ibid., pp. 1139.

150 Transcript: Guthrie, pp. 1111–1114. Submissions: SACOME, pp. 11–14; Toro Energy, pp. 12–13, 35-40.

151 Transcript: Guthrie, p. 1109.

152 ibid.

153 ibid.

154 Transcript: Guthrie, pp. 1109–1110; Tyne & Marshall, p. 1125.

155 Submission: Engineers Australia, p. 6.

156 Transcript: McGill, p. 655. Submission: BHP Billiton, pp. 3, 14.

157 Submission: BHP Billiton, pp. 10, 14.

158 DSD, Uranium, http://www.minerals.statedevelopment.sa.gov.au/invest/mineral_commodities/uranium

159 Transcript: Marsland-Smith, p. 615.

160 ibid., p. 609.

161 Uranium One, *Honeymoon project placed on care and maintenance*, media release, 12 November 2013.

162 Energy Resources Australia (ERA), *Annual Report 2014*, Energy Resources of Australia Ltd, 2014, p. 5.

163 ibid., p. 9

164 ERA, *ERA announces full year results for 2015*, ASX announcement, Energy Resources of Australia Ltd, 28 January 2016.

165 ERA, *Ranger 3 Deeps project update*, media release, 11 June 2015.

166 IAEA & OECD–NEA, *Uranium 2014*, p. 152.

167 Cameco, Kintyre, Cameco Corp, 2016, https://www.cameco.com/australia/kintyre/; Cameco, Yeelirrie, Cameco Corp, 2016, https://www.cameco.com/australia/yeelirrie/

168 T Tyne (DSD), letter to the Nuclear Fuel Cycle Royal Commission, 2 February 2016.

169 ibid.

170 BHP Billiton Ltd, *Resourcing global growth: Annual report 2015*, BHP, 2015, p. 96; Alliance Resources Limited, *Annual Report 2015*, Alliance, 2015, p. 1.

171 Heathgate Resources, *Four Mile Uranium Mine – Program for environmental protection and rehabilitation, and radioactive waste management plan*, Heathgate Resources, 2013, p. 13.

172 Transcript: McGill pp. 654–655.

173 World Nuclear Association, *The nuclear fuel report global scenarios for demand and supply availability 2015–2035*, 2015. Table 5.1, p.64. T Tyne (DSD), letter to the Nuclear Fuel Cycle Royal Commission, 2 February 2016.

174 T Tyne (DSD), letter to the Nuclear Fuel Cycle Royal Commission, 2 February 2016.

175 IEA, *Energy and climate change: world energy outlook special report*, annex A, IEA, Paris, 2015, p. 587.

176 ibid.

177 Ernst & Young, *CGE modelling assessment*, report to the Nuclear Fuel Cycle Royal Commission, February 2016, Section 4.1.

178 ibid.

179 ibid.

180 ibid.

181 DSD, *Mineral exploration in South Australia: Commodity highlights and achievements 2014*, Government of South Australia, 2015, p. 5.

182 S Davidson and A De Silva, *Realising Australia's uranium potential*, Minerals Council of Australia, 2015.

183 IAEA & OECD–NEA, *Uranium 2014*, pp. 37, 41; Y Mietzitis, 'Thorium', in Geoscience Australia, *Australia's identified mineral resources 2013*, Commonwealth of Australia, p. 123; Deloitte, *Review of regulatory efficiency in uranium mining — Final report: December 2008*, report to the Department of Resources, Energy and Tourism, p. 70.

184 Iluka Resources Limited, *Iluka suspends Jacinth-Ambrosia mining and concentrating activities*, Australian Securities Exchange notice, Iluka Resources, 16 February 2016.

185 IAEA & OECD–NEA, *Uranium 2014*, p. 38.

186 ibid., p. 40.

187 Mietzitis, 'Thorium', p. 127.

188 Mietzitis, 'Thorium', p. 122; IAEA, *Nuclear Technology Review 2015*, IAEA, Vienna, 2015, p. 13; IAEA & OECD–NEA, *Uranium 2014*, pp. 39, 41.

189 IAEA, *Nuclear Technology Review 2015*, p. 13; IAEA & OECD–NEA, *Uranium 2014*, p. 41; Mietzitis, 'Thorium', p. 122.

190 IAEA & OECD–NEA, *Uranium 2014*, pp. 39, 41.

191 Submission: Minerals Council of Australia Issues Paper 1, p. 10. IAEA & OECD–NEA, *Uranium 2014*, p. 41.

192 D Greneche, W Szymczak, J Buchheit, M Delpech, A Vasile & H Golfier, 'Rethinking the thorium fuel cycle: An industrial point of view', *Proceedings of the International Congress on Advances in Nuclear Power Plants*, Paper 7367, 2007, p. 7.

Transcripts and submissions can be found at the Nuclear Fuel Cycle Royal Commission's website:www.nuclearrc.sa.gov.au/transcripts and www.nuclearrc.sa.gov.au/submissions