Olympic Dam Expansion

a case study

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Note

In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

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Part I View of BHPBilliton on Olympic Dam Expansion ODX

http://odx.bhpbilliton.com/.weblog downloaded 29 August 2007

The Expansion Project

Imagine ...

BHP Billiton's Olympic Dam mine is already big. It is the world's fourth largest copper deposit, the largest uranium deposit and also produces more gold and silver than most other mines in Australia. It is the biggest underground hard rock mine in Australia. It is already complex. The polymetallic resource yields copper, uranium, silver and gold. The process route employs both hydrometallurgical and pyro-metallurgical techniques on a significant scale to extract refined copper, silver and gold metal and uranium oxide. All this on-site at Olympic Dam situated 570 kilometres north-west of South Australia's capital, Adelaide.

Now think bigger

The proposed expansion, which is likely to see operations converted to open pit, will be one of the biggest of its type in the world. Establishing the open pit will require the removal of around a million tonnes of over burden every day for four years. Once completed, the expanded mine will produce around 40 million tonnes of ore to the new processing plant each year. The plant will produce significantly more metal in each of the commodity groups using similar technologies to those currently employed. The Prefeasibility Study, which is now underway, will take two years to complete. The study will produce an estimate of the capital cost of the expansion.

There are around 20 diamond drill rigs on site now. They are carrying out resource definition drilling to infill the resource model that underpins the Prefeasibility Study. There is also a large geotechnical program as well as sterilisation drilling to determine final positions of infrastructure. Specialised rigs are probing the depth of the ore body with some holes planned to go more than two kilometres deep.

An Environmental Impact Study is being produced as part of the project to analyse the projected impacts of the expansion. One impact will be the growth of the town of Roxby Downs, where most mine and plant employees are based. It is expected that the town will more than double in size to a population of about 10,000.

BHP Billiton is making a major investment in the study phase to collect and model data and carry out mining, processing and infrastructure engineering studies. To do this it requires people. The people who work on this project will have a unique experience working with a world class team to build a world class operation.

Olympic Dam Overview

History

Olympic Dam is Australia's largest underground mine. When it began producing copper in 1988 it had an annual output of 45,000 tonnes. Today the mine produces more than 200,000 tonnes of copper each year along with uranium, gold and silver as bi-products.

It's the only mining operation in Australia that delivers ore to a fully integrated processing facility all located on a single site.

The composition of mineralisation is remarkable. While the geological team which discovered the ore body was looking for – and found – copper, they also uncovered a veritable treasure trove of minerals not previously found together in such large concentrations anywhere else in the world.

Apart from containing the fourth largest known copper deposit in the world, Olympic Dam (some 570km north-west of Adelaide) is by far the world's single largest known uranium ore body, the tenth largest gold reserve and one of the largest known silver deposits.
Timeline

* 1975 Ore body discovered by Western Mining Corporation (WMC)
* 1979 Joint venture with BP
* 1982 Indenture Agreement with SA Government. Whenan Shaft completed
* 1983 EIS (Environment Impact Statement) approved to 150,000t/a Cu
* 1988 Mine production began at 45,000t/a Cu and 1,000t/a U
* 1992 Optimisation #1 – 66,000t/a Cu and 1,500t/a U
* 1995 Optimisation #2 – 84,000t/a Cu and 1,500t/a U
* 1996 Announcement of major expansion to achieve 200,000t/a Cu
* 1997 EIS submitted and approved for 350,000t/a Cu. Commencement of major expansion to 200,000t/a Cu
* 2000 First full year of 200,000t/a Cu and 4,600t/a U production
* 2001 Major expansion feasibility announced
* 2002 Optimisation #3 completed to 235,000t/a Cu
* 2003 EPE Commissioning and Smelter 2 Shutdown
* 2004 CSX successfully commissioned
* 2005 BHP Billiton acquisition of WMC Resources

Production

Production began in 1988 at 45,000 tonnes of copper a year. In 2006 Olympic Dam aims to mine close to 10 million tonnes of ore.

The Process
The Olympic Dam site is divided into two parts – the mine where the underground mining occurs, and the Process Plant where ore is processed into its final saleable products.

The Olympic Dam mining operation is highly mechanised, with an automated rail operation and underground crushing. The primary method of ore extraction is long hole open stoping with cement aggregate fill. This method allows for large equipment to achieve high productivity and maximum ore recovery.

Ore is hoisted to the surface by the Whenan (5,000t/day) and Clarke (25,000t/day) systems where it is fed to one of two grinding circuits. After grinding, the resultant slurry passes to a flotation circuit where a series of flotation stages and a further regrinding activity produce a copper concentrate. The concentrate then passes through a leaching circuit which is principally designed to extract uranium from the copper minerals. Uranium is extracted in a solvent extraction plant, producing yellow-cake, which is subsequently calcined to produce uranium oxide concentrate and then packaged in drums for export sales.

After drying, copper concentrate is fed to an Outokumpu flash furnace smelter, which produces blister copper and flash furnace slag. Blister copper is transferred to anode furnaces for fire refining. Anode copper is transported to the refinery where the ISA electro-refining process is used to produce copper cathodes. The slimes from this process are treated separately to recover gold and silver.

People
Currently approximately 3000 people work at Olympic Dam (divided approximately equally between permanent employees and contractors.)

The majority of the workforce reside in Roxby Downs, built to support the mine and opened in 1988. Some 16km from Olympic Dam, Roxby Downs has a population of approximately 4,500 and boasts one the highest birth rates in Australia.

The town of Roxby Downs has an Administrator appointed by the South Australian Government in consultation with BHP Billiton who provides the Local Government function for the town.

Olympic Dam & The Expansion

BHP Billiton is considering a major expansion of its Olympic Dam operations to more than double current production capacity.

The Olympic Dam orebody is massive. An open pit mine is the current preferred option to achieve the proposed capacity increase because of the scale of the ore body,

BHP Billiton is undertaking a two year Prefeasibility Study, which includes the examination of a broad range of alternatives. An Environmental Impact Statement (EIS) is being prepared for the Australian and South Australian Governments. Further information about the Environmental Impact Statement is available at: www.olympicdameis.com.
ODX Timeline Targets

The Olympic Dam Expansion project is split into five key stages and is scheduled over a seven year timing plan.
Stage 1: Concept
Understanding the potential and the possibility

Stage 2: Pre-feasibility
Rigorously examine development alternatives and analytically select a preferred development plan

Stage 3: Feasibility
Refine and optimize the single go-forward case

Stage 4: Execution
Construct and commission

Stage 5: Operation
Ramp-up to full scale production

Timeline

Once the Prefeasibility Study and EIS are complete and the EIS is approved by both governments, the Board of BHP Billiton will review the findings and determine whether or not to proceed to the next stages of project. These include the final Feasibility Study, a mine pre-strip and the final execution phase of the project.

This entire process will take more than seven years and the input of thousands of people so a separate organisation, ODX, has been established within the BHP Billiton Base Metals (Australia) Adelaide office to undertake the studies and plan and execute the project.

Mine Development

The ODX project base case is an open pit mining operation that will be larger than any existing open pit mine operation in Australia and will rival BHP Billiton's giant Escondida copper mine in northern Chile.

The Mine Development team will eventually top 100 employees and will make up about half of the total ODX project team.

The key challenges for the Mine Development team will be to complete a pre-feasibility and feasibility study of one of the world's top mining operations. The mining equipment and ore processing technology harnessed for this expansion will be world's best, applied at the largest scale.

The scope of Mine Development includes all technical aspects from exploration and resource drilling through geology, mine planning and incorporating geotechnical, hydrogeology and geometallurgy. In addition the Mine Development group covers all aspects for an operating mine site including mine operations, training, mine maintenance & support.

Another significant challenge for the Mine Development team is that the mining area has no open pit history. Therefore all open pit infrastructure will be planned as though it were a greenfields site. At the same time plans must be developed to expand current mill processing and refinery systems to cope with the greatly increased ore tonnages produced by an open pit development.

Developing an extremely large open pit mine adjacent to a large underground operation that is already in full production, provides unique challenges from a design, scheduling and pit optimisation point of view.

For most personnel involved in the job this will be the largest project they will ever work on – a true career building opportunity.

Mine Operations

The proposed mining operation will require the removal of a significant quantity of overburden to expose the ore at a depth of approximately 350 metres. The pre-mine pit is in flat lying sedimentary cover including lime stone and sandstone. Once ore has been exposed then it is anticipated a sequence of push-backs will be used for the continued operation.
The mine

* Estimated one million tonnes of total movement per day (around 350 million tonnes of total movement a year).
* Estimated 100,000 tonnes per day of ore to the plant once commissioned.
* 15-18m benches.

* 65m wide ramps (2 lanes up for traffic management).

Drill and blast

Large drills will be used for the mining operation. It is anticipated there will be a drill per shovel to ensure that blasted floor stocks will be available for each shovel. In addition to the production drills there is a need for pre-split drilling to aid in blasting control on the walls of the pit.

Dewatering

Minimal dewatering of the proposed mining area is expected although at least two rock units contain water and will need dewatering pre-mining. As much as is practicable all water will be re-used in the mining operation. Management of dust is important to the operation and infrastructure needs to be in place to support this.

Equipment Selection & Commissioning

The mine operations group will assist in the selection and commissioning of the mining fleets as part of the project. All equipment and support that is required needs to be determined and the schedule for implementation is to be clearly determined and then completed. It is anticipated that activities in the mining area will commence following all government and BHP Billiton's approval being received. This is currently targeted for the second half of calendar 2008. In-order to meet this target all selection and start up work need to be completed by the end of calendar 2007. It is expected that the first shovel delivery will occur in late 2008 with a commissioning and commencement of mining in early 2009.

Prior to mining commencement all required surface mining infrastructure must be constructed including all shift change and support buildings. At the same time a pre-mine will be completed that includes the pioneering works, establishing access and clearing topsoil and the pre-strip that is the first mining with a requirement to establish shovel mining faces and space.
Operations Training & Development

In order to support the start up of the mining operations a training and development group will be established. It is anticipated that a significant training facility will be constructed. The project will need to recruit and train a significant number of operators, some of whom will have relevant experience but many may not. There will be a commitment made to a best practice style of training facility that is likely to include simulators.

Technical Services

Surface Drilling Program

The pre-feasibility surface drilling program currently being undertaken at Olympic Dam comprises some 569 holes that total approximately 488 km. The area to be drilled is approx 110 km2. Along with resource definition holes, significant geotechnical, metallurgical and sterilisation drilling is required.

Water drilling will be required to understand hydro-geological dynamics.

Some 20 rigs with 4 different contractors and other service providers are employing nearly 200 personnel for the exploration program. The number of rigs is being stepped up to increase the rate of data collection.

The drilling programme is a significant undertaking, with some 350m of flat lying sediments over the Breccia Complex that contains mineralisation.

Existing underground and the proposed open-cut mining operations will run concurrently for a number of years. The ultimate open pit mine is expected to be about 1200 metres deep with the dimensions of the pit at the surface being about 3.5 by 4.5 kilometres.

The initial "Starter Pit" will be about 450 metres deep and have a diameter at the surface of about 1.7 kilometres. The Starter Pit is larger than final size of most existing open pit mines in Australia.

Designing such a large open pit mine requires detailed studies of the geology and geological structures, and the geotechnical and hydrogeological parameters of the rock mass.

Geotechnical work will focus on delivering parameters such as slope angles to be used in mine planning. Test work and analysis including hydrological data will be used to develop designs.
Hydrogeology

Hydrogeological studies will be carried out to provide the data required to prepare a hydrogeology model for an extended area around the proposed open pit mine. Deliverables include dewatering, water supply, environmental monitoring and interaction with the geotechnical group.

One of the challenges for the proposed open-pit mine is to understand and manage the pore pressures associated with a deep large mine. Studies and test work will be carried out to help determine the parameters to be included in the geotechnical designs to ensure an effective mine design.
Underground Bulk Sample

In addition to the surface works part of the Mine Development team is focussed on an underground bulk sample project. A section of disused access in the underground mining operations has been rehabilitated to regain access. This will allow a bulk sample to be collected for various tests. Providing real data on the mineralisation, and access for an underground drill programme.

This project presents challenges for the team working underground and on-surface support. There is a commitment to Zero Harm in the project and the BSD plays an important part in achieving this.

Geology

During the early 1970's Western Mining Corporation established a project generation team which targeted South Australia for world class sediment-hosted copper deposits.

The Stuart Shelf of northern South Australia was selected as it was crossed by major lineaments and regional geophysical, gravity and magnetic results indicated that there may be significant volumes of mafic volcanic rocks.
In June 1975 an exploration drilling programme commenced over the two coincident magnetic and gravity anomalies; Olympic Dam and Acropolis.

RD1 drilled through 335m of flat-lying Proterozoic and Cambrian sediments before passing through an unconformity into haematite altered basement rocks. In theory the copper mineralisation was supposed to be in the overlying sediments but assays revealed fine-grained hypogene chalcocite in the basement. RD1 returned 38m @ 1.05%Cu, which was considered uneconomic at these depths at this time, but RD10 changed that with an intersection of 170m @ 2.12%Cu and 0.58kg/t U3O8 and is considered the "Discovery Hole".

However, following initial underground development in 1985-1987, it became apparent that none of the mineralisation was stratabound and that it was hosted in a highly variable magmatic-hydrothermal breccia complex that displays multiple brecciation, diatreme intrusions, mafic and ultramafic dyke intrusions along with interpreted gravity collapse of high level volcanic edifice material. The deposit is considered to be a member of the Iron Oxide Copper Gold (IOCG) family of deposits and has a close temporal and spatial association with the Hiltaba Suite of granites, dated at 1590Ma and more specifically the more fractionated and oxidised Roxby Downs subsuite (1588Ma).

The main lithologies at Olympic Dam comprise a continuum of breccias starting at the periphery with granite clasts set in little haematite matrix progressing into the centre where the clasts are wholly haematite in a haematite matrix. The principal gangue minerals are haematite, sericite and quartz. Minor gangue minerals include; siderite, chlorite, fluorite and barite.

The dominant sulphide minerals are chalcopyrite, bornite, chalcocite and pyrite. Minor sulphides include; carrolite, cobaltite, galena, sphalerite and molybdenite. Other minerals of interest are; metallic copper, electrum, Ag-, Hg-, Pb-, Bi-selenides and tellurides. The uranium at Olympic Dam occurs mostly as uraninite, coffinite or brannerite with trace amounts in zircon, monazite, florencite and bastinite.

Geometallurgy

“Predicting and Planning for Future Mineral/Metal Recovery”

The recovery of metals from ore bodies is fundamentally controlled by how the metals occur (i.e. mineralogy), the size of the minerals, and the intergrowth relationships of the economic minerals with gangue (or uneconomic) minerals. Historically, Geology focused on producing Resource Models based on detailed metal grades, with little or no information about mineralogy. Providing a ‘representative’ ore sample, or samples, for metallurgical testing was always a challenge. Often, process plants were designed and built based on metallurgical test results derived from samples that were not ‘representative’ of ores which would be encountered over the life of the mine. The rapidly emerging field of Geometallurgy bridges the disciplinary gap between geology and metallurgy. The purpose of geometallurgy is to define and quantify all ore properties (e.g. physical, chemical, mineralogical) which may impact on the mining and processing of the ore over the life of the mine.

The Olympic Dam Fe-oxide Cu-U-Au-Ag ore body formed in a ‘shallow level’ magmatic-hydrothermal breccia complex. Coeval felsic, mafic, and ultramafic volcanism is an integral part of the ore formation process.

All base metal ore deposits contain minerals which are not homogeneously distributed throughout the ore deposit, Olympic Dam is no exception. At Olympic Dam, the breccia types, economic mineralisation, and gangue minerals are spatially ‘zoned’ across the deposit. More than sixty minerals have been identified at Olympic Dam which can be grouped according to their recovery properties:

* Sulfide Minerals - concentrate grade, tails leach Cu recovery, smelter throughput
* Uranium Minerals - Uranium Recovery
* Gangue minerals (hem, qtz, seri, bar) - Mill Power Consumption
* Siderite, chlorite, fluorite - Acid Consumption and Uranium Recovery
* ‘Deleterious’ As, Se, Bi, Te, Sb-bearing minerals - Cathode Quality
* Au, Ag, REE, Co, Zn, Pb- bearing minerals
* Plus other ‘gangue’ minerals

The GEOMET model is based on a robust assay database. All mineralogy and metallurgy data will be linked back to the assays. Mineralogical and metallurgical samples will be collected across the deposit to ensure that all possible ‘ore types’ are tested.

Ore processing

The ore processing team is part of the wider project owner’s team, and will eventually top 45 members. It will be developing a Processing facility incorporating minerals processing, hydrometallurgy, refining and smelting to extract copper, uranium, silver and gold.

The ODX project’s ore processing team faces one of the world’s most challenging planning exercises. Currently the team is specifying and supervising a range of metallurgical and process test work to provide data for settling on a final process route and to assist in predicting key project parameters. A number of studies are being undertaken to test process options as part of the decision analysis component of the Prefeasibility Study. Preliminary engineering is under way to determine the capital and operating costs for the ore processing component of the project.

Producing and compiling technically rigorous and compelling prefeasibility and feasibility study documents for this project is the first stage. Once the project receives Board sanction, this will be followed by finalisation of engineering design and then the massive task of turning the plans into plants. The challenge arises from both the scale of the project, which is one of largest ore processing projects ever undertaken, and the process complexity of integrating five different processing steps to produce final metal in copper, gold and silver and uranium oxide. The opportunity to take a project like this from concept to commissioning will make for an unparalleled experience.

The ODX project will result in an operation with the potential to rival Escondida and Kennecott’s Bingham Canyon mine, with a working life expected to extend up to 70 years or more.

The project will demand intellectual flexibility and team work to challenge existing design and construction paradigms and deliver final solutions that are economic and practical.

It is an opportunity to build a career with one of the world’s biggest mining companies, working on a world-scale project with an opportunity to have an influence on decisions that will shape operations for a generation.

Existing Olympic Dam processes

Olympic Dam is a rare operation. It is one of the few resource businesses in the world that convert mined ore to four final metal products on one site, using a range of metallurgical techniques incorporating minerals processing, hydrometallurgy, pyrometallurgy and electrometallurgy.

Ore from the mine is currently fed to conventional grinding circuits using autogenous grinding mills. After grinding, the resultant slurry passes to a flotation circuit where the combination of a series of flotation stages and regrinding produce a copper concentrate. The concentrate is then upgraded through a leaching circuit prior to being sent to the smelting operation. After drying, copper concentrate is fed to an Outokumpu flash furnace smelter, producing blister copper. This copper is fire-refined in an anode furnace prior to presentation to the refinery as an anode where the ISA electro-refining process is used to produce copper cathodes. The slimes from this process are treated separately to recover gold and silver.

The tailings from the flotation circuit also pass through a leaching circuit to provide copper and uranium in solution for feed to respective solvent extraction plants. Copper recovered through solvent extraction is plated as cathode via the electro-winning process. Uranium recovered through solvent extraction is subjected to precipitation and calcination to produce uranium oxide concentrate and then packaged in drums for export sales.

Download the Process Flow diagrams:

- Ore Processing Flow (PDF 579KB)
- Smelter Process Flow (PDF 330KB)
- Concentrator Process Flow (PDF 993KB)
- Hydromet Process Flow (PDF 1 MB)
- Refinery Process Flow (PDF 1 MB).

The existing Olympic Dam plant provides a unique opportunity for metallurgists to develop a broad range of skills, ranging from refining and smelting operations to hydrometallurgy and minerals processing, while continuing to work at the same operation.

The ODX project offers an even greater opportunity as the development team works on plans to take the already significant 235,000 tonne capacity operation up to approximately 500,000 tonnes – a world-scale operation in any terms and one that will be producing copper, uranium, gold and silver.

In terms of copper cathode production there will be few larger operations in the world.

Part II Process analysis of ODX

1 Uranium reserves and resources of Olympic Dam

Olympic Dam, in the south of Australia, is the largest uranium deposit known in the world. Today it is an underground mine with copper as main product and uranium as co-product. In addition relatively small amounts of gold and silver are extracted from the large mineralisation. The owner of Olympic Dam, BHPBilliton, is considering to convert the underground mine into a huge open pit mine. In this report the so-called Olympic Dam Expansion, or ODX, is addressed by means of a process analysis.

The uranium resources and reserves of Olympic Dam as published by the IAEA, OECD/NEA [Q90] and UIC [Q211] are listed in Table D.13. The corresponding uranium content, mass of ore and volume of the ore are added by the author. To calculate the volume of the corresponding ore bodies an average density of d = 2.7 Mg/m^3 is assumed (the average density of granite).
In its Annual Report 2007 [Q361] BHPBilliton published new, greatly upgraded figures. We return to the new data in a later section. The next sections are to show the close relationship between the reported resource figures and some basic arithmetic based on other data from BHPBilliton.

The uranium resources and reserves of Olympic Dam as published by the IAEA, OECD/NEA and UIC are listed in Table 1. The corresponding uranium content, mass of ore and volume of the ore are added by the author. To calculate the volume of the corresponding ore bodies an average density of d = 2.7 Mg/m^3 is assumed (the average density of granite).

Table 1

Uranium reserves and resources of Olympic Dam. The data of the first three columns are from Red Book 2006 [Q90] and UIC-emine 2005 [Q211]. The volume of the ore is based on an assumed density of d = 2.7 Mg/m^3.

Olympic Dam	$m(U_3O_8)$ Mg	G % U_3O_8	m(U) Gg	m(ore) Tg	V(ore) 10^6 m^3
Proven reserves	71000	0.06	60	118	44
Probable reserves	321000	0.05	272	642	238
Measured resources	325000	0.05	276	650	241
Indicated resources	568000	0.04	482	1420	526
Inferred resources	522000	0.03	443	1740	644
Sum Olympic Dam	1807000	–	1532	4570	1693

Table 2

Various combinations of resources and reserves of Olympic Dam

Olympic Dam	m(U) Gg	m(ore) Tg	V(ore) 10^6 m^3
Inferred + indicated resources	924	3160	1170
Inferred + indicated + measured resources	1200	3810	1411
Inferred + indicated + measured resources + probable reserves	1472	4452	1649

Mg = megagram = 10^6 g = 1 metric tonne
Gg = gigagram = 10^9 g = 1000 metric tonnes
Tg = teragram = 10^{12} g = 1 million metric tonnes

2 Data from BHP BIlliton

Open pits

source: BHPBIlliton 2007 [Q354]
Excavating the 'Starter Pit', with a depth of 350 m and a diameter at the surface of 1700 m, wil take four years at a movement of estimated 350 million tonnes overburden a year.
Once completed, the expanded mine will produce around 40 million tonnes of ore to the new processing plant each year.
The pit is in flat lying sedimentary cover including limestone and sandstone.
At a depth of 350 m the ore (Breccia Complex) will be exposed.
The final depth of the Starter Pit will be 450 m.
15-18 m benches
65 m wide ramps (2 lanes up for traffic management).
Estmated 100 000 tonnes per day of ore will be transported to the processing plant once commissioned.

Existing underground and the proposed open-cut mining operations will run concurrently for a number of years.

The ultimate open pit will be about 1200 m deep and with dimensions at the surface of about 3.5 by 4.5 km.

Processing capacity.
Current capacity close to 10 million tonnes ore a year.
The ODX will result in an expected working life extension up to 70 years or more.

Power.
OD is connected tot the state electricity supply grid with an average total load of 120 MW. The proposed development may require 300-400 MW of additional power.

Water.
The current operation uses about 32 ML (million liters) a day (= 32 000 m^3/day). The proposed development requires about 120 ML/day (= 120 000 m3/day) of additional water. Feasibility investigations are underway of a coastal desalination plant ((Upper Spencer Gulf) to meet long-term water demand.

Transport.
About a million tonnes of material is currently transported to and from Olympic Dam each year by road. The proposed expansion is likely to increase this to about 2.2 million tonnes of material per year.

Geology

Following initial underground development in 1985-1987, it became apparent that none of the mineralisation was stratabound and that it was hosted in a highly variable magmatic-hydrothermal breccia complex that displays multiple brecciation, diatreme intrusions, mafic and ultramafic dyke intrusions along with interpreted gravity collapse of high level volcanic edifice material. The deposit is considered to be a member of the Iron Oxide Copper Gold (IOCG) family of deposits and has a close temporal and spatial association with the Hiltaba Suite of granites, dated at 1590Ma (million years) and more specifically the more fractionated and oxidised Roxby Downs subsuite (1588Ma).

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uraninite = UO_2
coffinite = $U(SiO_4)_{1-x}(OH)_{4x}$
brannerite = $(U,Ca,Ce)(Ti,Fe)_2O_6$

3 Assumptions in this study

The text published by BHP Billiton [Q354] gives only a few details, so a number of assumptions must be made to estimate the amounts of materials

- The overburden consists of sedimenatry rock, including limestone (d = 2.68-2.76 Mg/m^3) and sandstone (d = 2.14-2.36 Mg/m^3, according to Handbook of Chemistry and Physics 75th ed). The mean density of the waste rock is assumed to be d = 2.5 Mg/m3.

- The mean density of the ore is assumed d = 2.7 Mg/m^3 (the average density of granite).

- The average slope angle of the pit is assumed to be 45° (see Figure 1). Much steeper or much shallower slopes seem not likely, judging from photographs of other open-pit mines, including BHP Billiton‘s Escondida mine in Chili (see the photograph of Figure 2).

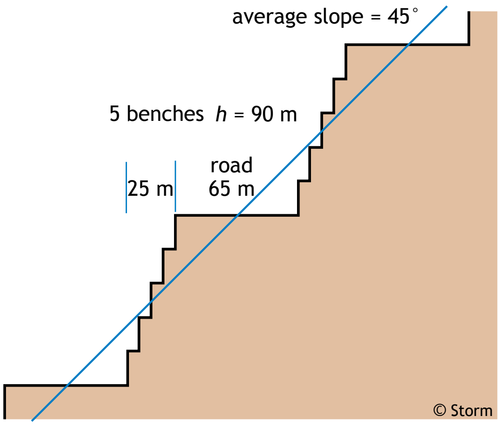

Figure 1
Possible configuration of an ODX open pit mine, with benches of 18 m high. The average slope angle of the pit is 45°.

Figure 2
BHP Billiton's Escondida copper mine in Chili, world's largest copper mine. Source: BHP Billiton 2007 [Q354]. Would the final pit of Olympic Dam Expansion look like this mine?

- The haul distance is difficult to estimate. If we assume an average slope of the ramp to the surface of 10%, the minimum haul distance from the bottom to the surface of the starter pit would be some 4.5 km and of the final pit some 12 km.

The total haul distance from the pit bottom to the waste rock dump area is assumed to be at least 20 km for the starter pit and 30 km for the final pit. The empty return trip of the dump trucks is considered to be equivalent to some 5 km loaded and is included in above figures.

- The final pit is assumed to encompass the complete mineable ore body.

- To approximate the maximum amount of ore in situ, the mineable ore body is assumed to be a homogeneous ellipsoid with semi-axes a, b and c. The values of the semi-axes are determined by the dimensions of the final pit, and are graphically derived (see Figure 3).

Possible geometry of ODX

Based on above assumptions a possible geometry of the ODX can be conceived, as illustrated by Figure 3. The pits are considered to be inverted truncated cones: the starter pit circular and the final pit elliptical. The volume of a frustum can be calculated by the equation 1 in Figure 4. The volumes of the three open pits, as illustrated by Figure 3, and the volumes of the rock to be excavated, are compiled in Table D.15.
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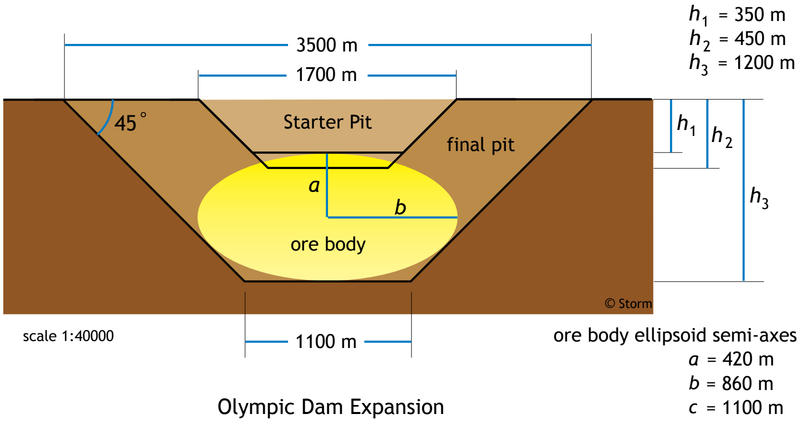
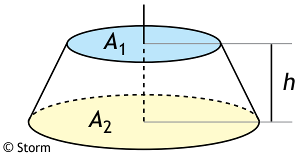


Figure 3

Estimated geometry of the starter pit, final pit and the mineralization body of the Olympic Dam mine.

The pits are considered to be inverted truncated cones: the starter pit circular and the final pit elliptical. The volume of a frustum can be calculated by the equation 1 in Figure 4. The volumes of the three open pits, as illustrated by Figure 3, and the volumes of the rock to be excavated, are compiled in Table 3.



$$V = \frac{1}{3} h \left(A_1 + \sqrt{A_1 A_2} + A_2\right)$$

eq 1

Figure 4

Truncated cone (frustum) and its volume. The top and bottom areas can be either circular, elliptical (provided both ellipses have the same a/b ratio) or polygonal (truncated pyramid). A1 and A2 are the areas of the top and bottom of the frustum respectively.

To approximate the maximum volume of an ore body fitting within the boundaries of the final pit we assumed it to be an ellipsoid. In Figure 3 the semi-axes of that ellipsoid are deduced: a = 420 m, b = 860 m and c = 1100 m. The volume of an ellipsoid with semi-axes a, b and c can be calculated by equation 2:

$$V_{\text{ellipsoid}} = \frac{4}{3} \pi\, a\, b\, c$$

eq 2

The volume of the estimated ore body is $V_{\text{ore}} = 1.66 \bullet 10^9\ \text{m}^3$, or 1.66 km^3.
At a depth of 350 m the ore body will be exposed (BHP Billiton). We assume that the volume difference ($\Delta V = V2 - V1$) of pits 1 and 2 contains ore (see Table 4). Figure 3 shows this is a rough approximation of the

segment of the ore ellipsoid falling within that part of pit 2. As the ore body is a highly variable complex no better estimate seems possible.

Table 3

Dimensions and volumes of the proposed open pits of ODX. The figures in the columns h, a1 and b1 are from BHP Billiton, the last 5 columns are based on above assumptions.

pit	h m	a1 m	b1 m	a2 m	b2 m	A_1 10^6 m^2	A_2 10^6 m^2	V 10^6 m^3
Starter pit	350	850	850	500	500	2.270	0.785	512
Starter pit	450	850	850	400	400	2.270	0.503	576
Final pit	1200	1750	2250	550	1050	12.37	1.814	7569

Table 4

The four main parts of the ODX rock bodies, as estimated in Figure 3.

part	Depth m	designation	V 10^9 m^3	m(content) 10^9 Mg	d Mg/m^3
Pit 1	350	V1	0.512	1.28	2.5
Pit 2	450	V2	0.576	1.44	2.5 *
Pit 3	1200	V3	7.57	18.9	2.5 *
Ore ellipsoid		V4	1.66	4.49	2.7
First ore		V2 – V1	0.064	0.173	2.7
Overburden final mine		V3 – V4	5.90	14.8	2.5

* Supposed this volume would consist of waste rock only. A part of this volume comprises ore, so the real mass will be higher. The content of pit 2 would have a mass of $m = 1.28 + 0.17 = 1.45 \bullet 10^9$ Mg and of pit 3: $m = 14.8 + 4.5 = 19.3 \bullet 10^9$ Mg.

The ore from pit 2, 173 Tg, would contain about 69 Gg U_3O_8, assumed an average ore grade of $G = 0.04\%$ U_3O_8, or 58.7 Gg uranium. The current world uranium consumption (2007) amounts to some 68 Gg/a.
As the expanded processing plant would process about 40 Tg ore each year, pit 2 would produce ore for 4 years at that rate. The whole ore ellipsoid, as conceived in Figure 3, would contain some 4500 Tg, enough for more than a 100 years production. BHP Billiton cites a production period of 70 years, indicating an ore body of about 2800 Tg, or a higher production rate in the future.

Table 5

Overburden ratio (stripping ratio)

- First ore volume rV = 0.512/0.064 = 8.0
  mass rm = 1.28/0.160 = 8.0
- Final ore volume rV = 5.90/1.66 = 3.6
  mass rm = 14.8/4.49 = 3.3

Evaluation

The volume and mass of the estimated ore ellipsoid come strikingly close to the official figures from Table 2, see Table 5. The results indicate that the conceived geometry of ODX in Figure 3 might be plausible.

Table 6
Comparison of the geometrically estimated ore body mass and volume with the figures deduced from Q90 and Q211.

Olympic Dam Expansion	m(ore) Tg	V(ore) 10^6 m^3	source
Estmated ore body ellipsoid	4494 *	1664	this study
Inferred + indicated + measured resources + probable reserves (see Table 2)	4452	1649 *	Q90 + Q211

* Assumed average density of the ore d = 2.7 Mg/m3.

According to BHP Billiton [Q354] it would take about 4 years to remove the overburden of the Starter Pit, at a rate of 350 million tonnes a year, or a total of about 1400 million Mg. This mass corresponds with the content of pit 1 (V1) in Figure 3 and in Table 4.

4 Revised resource data of Olympic Dam (September 2007)

In its Annual Report 2007 [Q361] BHPBilliton published greatly upgraded figures of its resources, see Table 7.

Table 7
Uranium reserves and resources of Olympic Dam, according to BHPBilliton 2007 [Q361].
The volume of the ore is based on an assumed density of d = 2.7 Mg/m^3.

Olympic Dam	m(ore) Tg	G % U_3O_8	m(U_3O_8) Gg	m(U) Gg	V(ore) 10^6 m^3
proved ore reserve	61	0.063	38.4	32.6	23
probable ore reserve	339	0.057	193.2	163.9	126
total reserve	399		232	196	148
measured resource	1311	0.036	472	400	486
indicated resource	3129	0.029	907	770	1159
inferred resource	3298	0.026	857	727	1221
total resource	7738		2237	1897	2866
sum Olympic Dam	8538		2469	2093	3014

Table 8

Uranium ore reserve and secource of OD, about fitting within the dimensions of Figure D.9 and Table D.18.

Olympic Dam	m(U) Gg	m(ore) Tg	V(ore) 10^6 m^3
Total reserve	196	339	148
Measured resource	400	1311	486
indicated resource	770	3129	1159
sum	1366	4779	1793

Very likely the figures published on the dimensions of ODX in the first half of 2007 were based on the most recent figures of reserves and resources. As Table 8 shows, the sum of the reserve, measured resource and indicated resource comes close to the figures in Table 6. If so, this would imply that the plans for ODX exclude the Inferred Resource, the least assured and leanest ore resource. This part of the ore body may lay deeper or may extend horizontally. In both cases exploitation of that part might require a far larger open pit and so a larger overburden ratio. The energy consumption of mining and milling per kg uranium of that part may rise substantially.

5 Energy consumption and CO_2 emission at ODX

The main product of Olympic Dam is copper, uranium is by-product as are gold and silver. That may imply that the separation processes following the mill are optimized to extract copper. The consumption of energy and auxiliary materials by OD to run the separation processes surely will be higher than if uranium were the only product. Without detailed data on the separation processes it is difficult to estimate the fraction of the energy and material consumption which should be attributed to the uranium extraction. Mudd & Diesendorf 2007 [Q338] adopt a fraction of 20%, based on the average proportion of revenue from uranium at OD. From a physical/chemical point of view this criterion may not be very solid, but without sufficient process data there seems to be no other choice.

To get an impression of the energy quality of the ore of OD, we assume it to be exclusively a uranium ore. The calculation of the energy consumption and CO_2 emission are based on the specific energy requirements listed in Table 9, which are used in this study. The process analysis of the Ranger mine shows that the used values may lead to a slight underestimation, rather than overestimation.

Table 9

Specific energy equirements of mining and milling hard uranium ores, considered to be world average values.

mining	Jth + Je = 1.06 GJ/Mg ore	R = Jth/Je = 8.0
milling hard ores	Jth + Je = 4.49 GJ/Mg ore	R = Jth/Je = 0.1
reclamation mine	Jth + Je = 4.2 GJ/Mg ore	R = Jth/Je = 8.0

The thermal inputs of the processes are assumed to be supplied by diesel fuel. The specific CO2 emission of burning diesel is taken at 75 g/MJ (heat), or 0.075 Tg/PJ.

In Table 10 the energy requirements, thermal and electrical separately, and CO_2 production of the exploitation of the complete ore body of Olymic Dam (8538 Tg of ore) are listed. Evidence from the past shows that the nuclear industry tends to easily adopt favourable figures, how insecure they may be, as facts to base on their prognoses.
In the last three columns (E, F and G) of Table D.22 the CO_2 production are calculated, assumed that the electrical component of the energy consumption is generated by diesel-fuelled power plants, with an electrical/thermal efficiency of 40% (which may be a high estimate).

Table 10

Energy requirements and CO_2 production of the mining and milling of the full mass of ore of Olympic Dam, amounting to 8538 Tg, plus mine reclamation. The columns E, F and G refer to the case the electrical component is supplied by diesel-fuelled power generation.

8538 Tg ore process					Assumed diesel-generated electrity, efficiency = 0.40		
	A	B	C	D	E	F	G
	$E_{th}+E_e$ PJ	E_{th} PJ	E_e PJ	$m(CO_2)$ B•0.075 Tg	$E_e \rightarrow E_{th}$ C/0.40 PJ	$m(CO_2)$ E•0.075 Tg	$m(CO_2)$ D + F Tg
Mining	9050	8045	1006	603	2514	189	792
Milling	38336	3485	34851	261	87126	6535	6796
Sum mine+milling	47386	11530	35856	865	89640	6723	7588
Reclamation mine	35860	31875	3984	2391	9961	747	3238
Sum m+m+reclam	83246	43405	39841	3255	99601	7470	10725

To give an impression of the electric power consumption of the mining and milling, excluding mine reclamation, the following example. Assume an operational life of 100 years of ODX, then the average electricity consumption would be 359 PJ a year, corresponding with a continuous power consumption of 11.4 GW.

As pointed out above, the total energy consumption of ODX will be significantly higher than the figures from Table 10, for the extraction and processing of copper, gold and silver are not included. The energy consumption to be attributed to the uranium extraction alone might be considerably lower than the figures of Table D.22.
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6 Energy potential from ODX

How much electricity could be generated from the uranium ore reserves and resources? The answer is not as simple as it may seem, for the amount of uranium extractable from the 8538 Tg of ore depends on the extraction efficiency, which in turn depends on several factors, such as ore grade and mineralogy of the uranium in the ore.

The mineralogy of the uranium in the ore body of ODX tends to become increasingly refractory with depth, due to an increasing proportion of the refractory uranium minerals brannerite and coffinite, and a decreasing proportion of the easily processible mineral uraninite.

uraninite = UO_2
coffinite = $U(SiO_4)_{1-x}(OH)_{4x}$
brannerite = $(U,Ca,Ce)(Ti,Fe)_2O_6$

A higher fraction of refractory minerals implies higher consumption of energy and materials per kg recovered uranium and lower extraction yield due to greater losses. In addition to a decreasing ore grade with depth, the ore gets harder to process. Both effects cause a declining energy quality of the ore with increasing depth.

In 2006 10 million tonnes of ore have been processed at a uranium grade of 0.06% U_3O_8 (proven reserves), with an uranium production of 3916 Mg U_3O_8 (BHP BIlliton Annual Report 2006). This figures point to a net extraction effiency of 0.66 (66%). The historical extraction efficiency for uranium of OD is 0.653 and is expected to decline to 0.50-0.40 for ODX, according to Mudd 2007 [Q362].
Likely, the historical value of Y = 0.653 refers to the proven reserve of OD, with an ore grade of G = 0.063% U_3O_8, for these ore are mined first. In Figure 5 two curves, A and B, are added to the Y-logG curve which is used in this study to assess the world uranium resources. Both curves start from the emprirical point at G = 0.063% U_3O_8. The extraction yields at OD will go down when the average ore grade decreases.
Curve A represents the same relationship between yield and grade as the blue main curve in Figure D.11, the only difference being the lower starting point.
Curve B is based on the assumption that the yield Y declines to 0.40 at G = 0.026% U_3O_8. There are reasons to suppose a more steeply declining yield at lower grades than curve A, in view of the increasingly refractory character of the ore when going to deeper and poorer deposits.

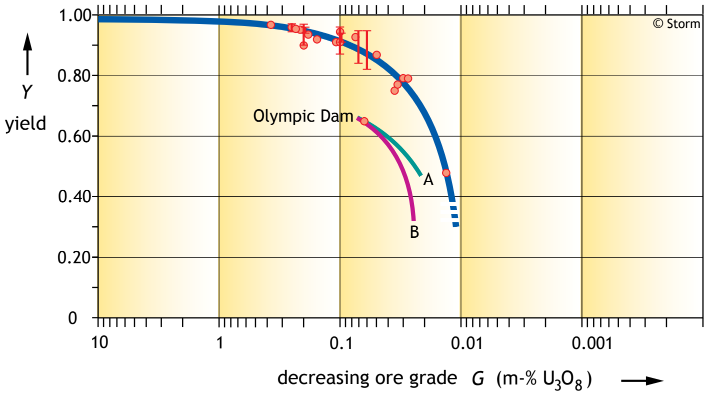

Figure 5

Extraction yields of Olympic Dam. The value at an ore grade of G = 0.0653% U_3O_8 (red dot) is the historic mean yield. Curves A and B represent two possible relationships between yield and lower ore grades and are explained in the text. The upper (blue) curve represents the Y-log G relationship as used in this study.

In Table 10 the recoverable amounts of uranium from the total reserve en resource of OD are listed. Column B gives the in situ amounts of uranium, column D gives the recoverable amounts assumed the yield declines according curve A and column F is based on curve B in Figure 5.
The values in columns D and F should be considered speculative, as no empirical data are available.

The reference reactor in this study, which comes close to the Generation III reactors, consumes 162.35 Mg natural uranium per reload period. During one reload period D (corresponding with one year at a mean load factor of 0.82) it produces a fixed gross amount of electricity of:

$$E_{gross} = 25.86 \text{ PJ/D} = 7.183 \bullet 10^9 \text{ kWh/D}.$$

Obviously, Olympic Dam will ultimately deliver less than 2093 Gg uranium, and likely less than 1156 Gg. An amount of close to 996 Gg seems more realistic. For comparison: the annual uranium consumption rate of today's world nuclear fleet is about 68 Gg/a.

Table 11

Masses of recoverable uranium from ODX, calculated at different extraction effiencies Y. Column C is based on the yield curve A in Figure 5 and column E on curve B.

Olympic Dam	A	B	C	D	E	F
	G % U_3O_8	in situ m(U) Gg	Y curve A	D=B•C recoverd m(U) Gg	Y curve B	F=B•E recoverd m(U) Gg
Proven reserves	0.063	32.6	0.653	21.3	0.653	21.3
Probable reserves	0.057	163.9	0.640	104.9	0.635	104.1
total reserve		196.4		126.2		125.3
Measured resources	0.036	400.2	0.580	232.1	0.545	218.1
Indicated resources	0.029	769.5	0.545	419.4	0.470	361.7
Inferred resources	0.026	727.1	0.520	378.1	0.400	290.9
total resource		1896.8		1029.6		870.6
Sum Olympic Dam		2093.3		1155.8		996.0

Table 12 compiles the gross electricity production possible from the amounts of recovered uranium (see columns D and F of Table 11), and the CO_2 emissions per kilowatt-hour. Columns C and D of Table 12 give the specific CO_2 emission if only the fossil fuel input is taken into account, as is done throughout this study (see Part C). In columns E and F of Table 12 the CO_2 emission is given when all electric energy inputs were to be generated from diesel fuel, with a thermal to electric efficiency of 40% and a specific CO_2 emission of 75 gCO_2/MJ(th). The last column gives the sum of both components.

Table 12

Specific CO_2 emissions of the recovery of uranium of Olympic Dam at two different recovery yield curves. The energy consumption and CO_2 emission is fully attributed to the recovery of uranium. For explanation: see text.

m(U) Gg	A	B	C	D	E	F	G
	n number of reloads D	Gross E product. 10^9 kWh	th m + m CO_2 g/kWh	th m+m + reclam CO_2 g/kWh	e › th m+m CO_2 g/kWh	e › th m+m + reclam CO_2 g/kWh	th+e›th m+m + reclam CO_2 g/kWh
1156	7119	51135	17	64	131	146	210
996	6135	44065	20	74	153	170	243

In Table 13 the CO_2 emission of the full nuclear chain is calculated, based on uranium from OD. In this table the energy consumption of mining and milling and mine reclamation is fully attributed to the uranium extraction, ignoring the production of copper, silver and gold. The total uranium production is assumed to be 996 Gg.

In Case A only the CO_2 emissions due to the thermal energy inputs of the nuclear chain are listed. In Case B the electrical inputs of OD are supposed to be generated by diesel-fuelled power stations. The electrical inputs of the other components of the chain are not converted and assumed to be supplied by nuclear power in a steady state.

The 'repayment' of the energy debt – construction, decommissioning and dismantling of the nuclear power plant – solely depends on the operational lifetime of the nuclear power plant. In this part an operational lifetime of 30 years at an average load factor of 0.82 is assumed. The other energy inputs with their CO_2 emissions are running inputs and are constant per reload period.

Table 13

The CO_2 emission of the full nuclear chain based on uranium from ODX, if all energy consumption is attributed to the uranium extraction. Assumed uranium production of 996 Gg. The term of 'repayment' of the energy debt depends on the operational lifetime of the nuclear reactor, here assumed to be 30 years at a mean load factor of 0.82.

Part of the nuclear chain	CO_2 emission (g/kWh)	
	Case A thermal input only	Case B thermal + electrical input *
mining + milling ODX	19.6	172.2 *
front end, excluding mining + milling	5.8	5.8
operation + maintenance + refurbishments	24.4	24.4
back end, excluding reclamation mine	11.3	11.3
reclamation mine ODX	54.3	71.2 *
'repayment' energy debt (average)	58.0	58.0
sum (rounded)	173	343

* Assumed the electrical inputs of OD (mining + milling and mine reclamation) are generated by diesel-fuelled power plants.

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