OPEN PIT DEWATERING AND DEPRESSURISATION OF THE LIHIR GOLD MINE, PAPUA NEW GUINEA

P.F. BIXLEY\(^1\), S.J. LBBCH\(^2\), S.P. WHITE\(^3\) & B.R. BERRY\(^4\)

\(^1\)Century Resources Ltd, Wairakei, New Zealand
\(^2\)Lihir Management Company Ltd, Papua New Guinea
\(^3\)Industrial Research Ltd, Lower Hutt, New Zealand
\(^4\)Lihir Management Company Ltd, Papua New Guinea

SUMMARY - The open pit at Lihir Gold Mine is planned ultimately to reach more than 200 metres below sea level. Cooling and depressurisation of the geothermal resource associated with the gold mineralisation is an essential part of the mining operation. To investigate geothermal conditions beneath the mine pit, eight deep deviated geothermal wells were completed during 1999. Information from the deep well programme, together with information from the shallower mineral exploration wells drilled and tested in the 1980's has been used to develop a new numerical model which incorporates the development of the mine pit, shallow groundwater, interaction with the sea and the deep geothermal resource. This model has been calibrated using dewatering well information and is now being used to examine geothermal production scenarios required to rapidly depressurise and cool the shallow formations beneath the mine pit.

1.0 INTRODUCTION

The Lihir Group consists of four islands, of which Lihir (or Niolam) is the largest. Lihir Island is located about 700 km NE of the national capital, Port Moresby, and forms part of the New Ireland Province of Papua New Guinea (Figure 1).

![Location map](image)

Figure 1: Location map

Lihir experiences a high rainfall, averaging about 3.7 metres per annum, with mean relative humidity of 80%. Air temperature varies between 20 and 35°C. Being situated only 3° south of the equator Lihir is not subjected to the effects of cyclones. Natural vegetation is predominantly tropical rain forest.

1.1 Geology

Lihir is made up of five Miocene-Pleistocene volcanic units, three of which are recognizable volcanic craters, including the Luise Caldera, which is the youngest major volcanic centre on Lihir (refer Figure 2).

The Lihir Gold Project mineral deposits are located within the Luise Caldera, which is considered the remnant of an extinct volcano (Davis and Ballantyne, 1987). The Caldera is well defined, with the rim rising steeply to over 600 m above sea level in places. It is open to the northeast where it is breached by the sea to form Luise Harbour. Defined gold mineralisation occurs within an area of about 2 by 1.5 km.

Exploration work since 1983 has defined a number of adjacent and partly overlapping mineral deposits within the Luise Caldera, the principal ones being Leinetz, Minihie and Kapil, with definition of the latter being restricted due to near surface geothermal conditions.

At the end of 1999 the total gold ore resource was calculated at 93.1 Mt with an average grade of 3.74 g/t.

12 Mine Production

Open pit mine production began in late 1996. By the end of 1999 the base of the pit was about 70 m BSL. Total material movement at this time was about 82 Mt, 18 Mt of which was a combination of direct feed high grade ore and stockpiled low grade ore.

The main production mining equipment fleet consists of 3 diesel hydraulic shovels with 24 m\(^3\) buckets and 24 diesel hydraulic trucks each with a nominal capacity of 136 t.

Open pit mining is scheduled to be completed by about 2012, at which point pit dimensions will be about 2 by 15 km and extend to a depth of 200 - 250 m BSL.
1.3 Process Plant
The first ore was treated in May 1997. By the end of 1999 the Plant had processed 4.3 Mt of high grade ore and produced 1.36 million oz of gold.

On cessation of open pit mining in 2012, it is planned that the Process Plant will treat the stockpiled low grade ore for the next 22 years.

1.4 Power Source
The operations and associated infrastructure are supplied electricity from 11 heavy fuel oil fired generators. At any one time 9 generators are online, producing about 58 MW.

1.5 Geothermal Manifestations
Geothermal manifestations are common within the Luise Caldera and in places overlap the mineralised area. The geothermal surface manifestations include fumaroles, chloride springs and hot springs on the shoreline and offshore. The natural heat flow through the system is in the order of 50 MW(th).

2.0 MINE DEWATERING

2.1 Objectives
The ultimate pit will be immediately adjacent to the sea and will extend to depths of 200-250 mBSL. To allow successful progression of the mining schedule the shallow geothermal and groundwater system will need to be dewatered by 200-250 m.

The primary objectives of the mine dewatering system currently in place and planned are as follows:

- Depressurisation and cooling of the “shallow” geothermal reservoir.
- Interception of seawater recharge from Luise Harbour.
- Enhancing the stability of pit slopes by reducing pore pressures in the rock mass.
- Depressurisation of the “steam cap” as rapidly as possible in the vicinity of the mining area.
- Minimise the geothermal hazard for operational personnel and mining equipment.

2.2 Methods of Dewatering
To achieve the required levels of dewatering, the following methods are used:

- Horizontal drainholes drilled from within the open pit.
- Deep geothermal wells.
- Steam relief wells.
- Pumped dewatering wells.

3.0 GEOTHERMAL RESERVOIR

3.1 Mineral Exploration Well Information
As part of mineral resource evaluation, more than 1000 exploration and development wells were drilled, with 300 of these wells more than 200m deep. Temperature profiles were measured on many of them and allowed quite detailed temperature mapping of the shallow part of the geothermal resource - down to 200-300 metres depth. While there was unusually detailed temperature information (compared with “normal” geothermal developments) over part of the hot resource, from the geothermal perspective the detailed information covered only the SE flank of the high temperature resource and considerable uncertainty remained with regard to its full extent. Electrical geophysical surveys have been carried out, but provided limited information due to rugged local topography, the massive sulphide orebody and relatively high salinity groundwater adjacent to Luise Harbour.

Extensive testing of the shallow aquifers near the planned mine area was done during the exploration phase. This detailed information extends down to about 300 metres and covers the southeastern flank of the geothermal resource.

Interpreted temperatures at 200 metres below sea level are plotted on Figure 4, together with the planned ultimate pit outline. The natural piezometric surface for the geothermal resource is about 10 metres above sea level. The contours on Figure 2 indicate there are zones where temperatures at 200 mBSL were close to boiling-point-for-depth (BPD) conditions and existed before development started (At this elevation BP is about 215°C based on reservoir pressure). Other parts of the field have depressed temperatures with complicated patterns due to mixing of the deeper geothermal water and shallow infiltrating groundwater.
As the ultimate pit will extend about 200 metres below sea level, correct management of the dewatering operation was recognised as an important part of the mine operation. Extensive monitoring and interference testing was done on the shallow exploration wells to determine the characteristics of the shallow groundwater aquifers and the nature of links between these aquifers and the sea. As part of the mine feasibility study the groundwater system and the deep geothermal system were separately modelled using the information collected from the monitoring and interference testing.

![Image: Interpreted temperatures at 200m below sea level.](3)

3.2 Geothermal Drilling

In 1999 eight deep geothermal wells were drilled. These were standard geothermal completions with 9-5/8" production casing and 7" slotted liners. Because of restricted access due to the local topography and mining operations, and to keep the wellheads outside the final pit boundaries, all the wells were drilled from two adjacent pads located near the SW comer of the mine. The deep wells were designed to explore geothermal conditions under the pit and to try and locate the source area for the high temperature upflow. The first well was vertical and all other wells were deviated, usually by 60-70°, The initial vertical well was later sidetracked and recompleted as a directional well. Measured well depths are 1260-1790m, achieving true vertical depths of 1120-1400m and horizontal throws of 570-970m from wellhead.

![Image: Conceptual Model](4)

3.3 Results

The 1999 deep drilling program has helped to define the deep pressure profile and to locate the area of upflow supporting the shallow manifestations.

In wells drilled to the north, maximum well temperatures are 240-260°C, associated with higher permeability at about 1000 mBSL. The southern wells are cooler, 220-230°C and have relatively poor permeability.

All of the deep wells have been discharged vertically and five of the wells connected up for long term discharge to atmospheric separators. Average production flows are about 70 t/h with wellhead enthalpy 1200-1600 kJ/kg. By September 2000 almost 500,000 tonnes of reservoir fluids had been produced.

The produced fluid is a little unusual with high pH, high chloride and high sulphates. Weirbox water commonly has a pH about 9, with chloride contents of about 30,000 ppm and sulphate 40,000 ppm. Chemistry data indicate the deep fluid cannot be derived by simple mixing with seawater and that there is likely to be a magmatic component in the deep fluids.

From the production perspective, this unusual chemistry has associated problem with the formation of mineral deposits in the wellbore and in some discharge pipelines. To date this has been confined to predominantly calcite scale in the wellbore and silica scale in pipelines and the separator.

3.4 Conceptual Model

The conceptual understanding for the shallow part of the geothermal resource remains much the same as that detailed in the Feasibility Report.
Figure 5: Schematic model of the Lihir geothermal system natural state
(Kennecott, 1992). That model was derived using a combination of:

- downhole temperature and water level measurements,
- pumping/interference and tidal response tests,
- fluid chemistry,
- geology,
- estimated surface infiltration,
- estimated outflow from the system

In the Feasibility Study conceptual model the geothermal system was seen as a permeable bathtub, mounted on three sides by low permeability rock (outside the caldera boundary), and on the fourth side by the sea. There was a connection to the sea at shallow levels where most of the natural flow exits the system, while at deeper levels the sea was isolated from the geothermal reservoir by low permeability rock. For the undisturbed reservoir this arrangement allows outflow of hot fluids to the sea and minimal recharge to the geothermal reservoir from the sea at depth, where the hydrostatic pressure is significantly greater than inside the geothermal reservoir.

The subsurface information at that time extended down to about 300 mBSL. The deep recharge temperature and gas content were unknown. The few wells deeper than 300 mBSL encountered low permeability in the anhydrite sealed zone.

Temperatures and permeability encountered by the deep wells drilled in 1999 confirmed widespread low permeability conditions down to 1000 mBSL. An area of better permeability and higher temperatures was found about 1000 mBSL beneath the Kapit-Leinaté area about 1 km northeast from the G-W-02 wellpad. Based on this information this area is assumed to be the deep upflow/fluid recharge zone for modelling purposes.

Even with new information on the deeper part of the resource, some of the previous uncertainties remain. The major uncertainty is the full extent of the high temperature source. The southeastern flank of the resource has been proven in some detail by the mineral exploration wells and by the deep wells, but there is no direct information available to reliably determine the location of the northern and western boundaries. The rim of the Lihir Caldera has been used to indicate the location of the western and northern boundaries of the high temperature resource – assuming lower permeability formations lie outside the caldera and/or enhanced permeability is present, associated with and inside a caldera boundary fault.

4.0 MODELLING

Modelling of the Lihir geothermal system is quite challenging because of the need to represent both the shallow groundwater system (to investigate dewatering scenarios) and the deep geothermal system (to investigate pressure — and cooling). Further complications are added by the need to include the changing topography of the ground surface as the pit is developed and the rock topography both above and below sea level. GeoCad software has been used to develop a TOUGH2 (Pruess 1991) model of this system, this simplified the inclusion of surface topography and time staging of the pit excavation. Figure 6 shows the volume modeled and the horizontal and vertical resolution. Over most of the pit area the horizontal resolution is 200 metres with a finer resolution of 60 m at the pit and the sea. The entire modelled region is divided into 24 layers and contains over 5500 elements.

![Figure 6: Representation of the TOUGH2 model.](image)

4.1 Model Verification

The parameters defining the model are:

- Magnitude, enthalpy and location of the sources representing the geothermal upflow into the reservoir
- Permeability, porosity, specific heat and density of each element in the model
- Magnitude and location of surface infiltration

These parameters are adjusted until the model calculates an acceptable match to a number of measured properties of the system.

The information used in calibrating this model was:

- Interpreted shallow temperature and pressure measurements taken from the Project Feasibility Report
- Pressure and temperature measurements from the recent deep drilling program
- Estimated inflow, recharges and outflow from the system
- Dewatering Row and drawdown in dewatering monitor wells to April 2000.
42 Shallow Model Refinement

An extensive program of dewatering and monitoring of groundwater levels has been underway since September 1997. The data from this program has been used to refine the permeabilities assigned to the shallow areas of the model.

The procedure used was to model the dewatering over the period from September 1997 to April 2000. This produced estimates of the pressure drawdown at each of the monitor wells. The permeability of regions affecting the calculated pressure drawdown was adjusted to improve the match to measurement and the process repeated. This procedure used the inverse modelling program ITOUGH2, which repeatedly adjusts parameters until an optimum match to measurement is obtained.

![Figure 7: Calculated contours of pressure drawdown in April 2000. The current pit outline is overlaid.](image)

![Figure 8: Calculated (solid line) and measured pressure drawdown at monitor well MB14D.](image)

Generally pressure drawdown at the monitor wells was well matched, the average mismatch being about 1 bar. This is probably about the best that can be done without refining the spatial resolution of the model, improving the approximation to pit excavation and reducing the uncertainty in the location of dewatering well feedpoints. Figure 7 shows the calculated pressure drawdown in April 2000 and Figure 8 a 'typical' match to dewatering monitor well pressure drawdown.

5.0 GEOTHERMAL POWER GENERATION

The potential to use the geothermal energy to replace the present fuel oil-fired generation plant is under investigation. Temperatures and permeability encountered to date by the deep geothermal wells are suitable for power generation and a feasibility study of the resource confirms that a small scale power plant is both technically and economically feasible, provided the well scaling technical problems can be overcome. As the resolution of these problems is necessary to enable sustained production for the depressurisation and dewatering programme, their associated costs do not impact on the power station economics. Based on the likely available fluid, plant sizes from 5-15 MW were considered.

Production operations using capillary tubing for downhole inhibitor injection are due to commence later in 2000. A new series of wells designed to produce from shallow, two-phase conditions are also being drilled at the present time.

A decision to pursue geothermal power as an energy option is likely once antiscalant trials in the wells have been completed. The scale of any future development will need to consider the sustainability of the geothermal resource, the needs of the depressurisation/dewatering programme and the "fit" of geothermal into the overall energy needs of LMC. The ability to source locally produced, non hydrocarbon derived electricity, offers Lihir Management Company significant opportunities to reduce energy costs and SO2 emissions.

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7.0 REFERENCES

