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Life Cycle Cost Analysis of MinEx CRC's Downhole LIBS Sensor

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Declaration

I, Jiahang Tang, confirm that the work presented in this thesis is my own.
Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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........Jiahang Tang...............	Jiahang Tang	....28/08/2024.......
Student's Name	Student's Signature	Date

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Table of contents

Abstract

This dissertation presents a detailed life cycle cost (LCC) analysis of the downhole Laser-Induced Breakdown Spectroscopy (LIBS) tool being developed by MinEx CRC. The cutting-edge tool designed for real-time geochemical analysis down a drill hole in the exploration and mining sectors.

The study systematically examines the costs associated with the development, production, operation, and eventual disposal of the LIBS sensor, aiming to identify the key economic factors that influence its overall lifecycle. The analysis reveals the significant impact of operational and maintenance costs on the total cost of the sensor, highlighting areas where efficiency improvements could lead to substantial savings, such as energy costs and labor costs. The findings emphasize the importance of strategic planning in the early stages of development to optimize the cost-effectiveness of this technology, ensuring its viability and sustainability in long-term field applications.

1 Introduction

Global demand for metals continues to grow, fueled by population growth and the development of new industries and technologies (e.g., renewable technologies, electric vehicles: Ali et al., 2017; Agusdinata, et al., 2022). Activities such as metal recycling, re-mining mine wastes, and the search for new deposits can partially address these needs (Pollmann et al., 2018). However, none of these methods alone will resolve the emerging supply-demand gap (Giles et al., 2014). In the context of exploration for new deposits, enhancing the ability to explore and successfully discover mineralisation is crucial; however, is challenging as explorers are required to search for deposits in areas that are completely hidden and buried beneath the surface (Fontana et al., 2023a). The process of mineral exploration currently faces shortcomings, including the time-consuming and costly nature of sampling and drilling, as well as the lengthy duration required to send samples to laboratories for geochemical analysis (Giles et al., 2014), which commonly takes ~3 months. Consequently, there is an urgent need to develop methods for rapid and accurate geochemical analyses at the drill site and significantly reduce the time to generate key data such as geochemistry so that the data can be used to inform drilling programs as they are happening.

The need for efficient data generation at the drill site is driving the development of geochemical analysis techniques using laser-induced breakdown spectroscopy (LIBS) for collection of geochemical data within a drill hole (Fontana et al., 2023a, 2023b). The LIBS instrument is currently being developed within the Mineral Exploration Cooperative Research Centre (MinEx CRC) Project 3: Real-Time Downhole Assay (https://minexcrc.com.au/projects/project-3/) project to provide near real-time geochemical data in boreholes. Compared to other portable devices, LIBS offers several advantages including detection of light elements, simple setup, deployment in harsh environments, and real-time data analysis (D. Cremers and Radziemski, 2013; Du et al., 2020; Lanza et al., 2015; Harmon and Senesi, 2021). Instrument development is at a Technology Readiness Level 6 (Table 1), with a prototype having been tested within a controlled environment in a real drill hole. As this instrument is developed, it is significant to understand the cost distribution of its life cycle. However, there is little research on the life cycle cost of downhole exploration equipment in the current academic circle, and there is a lack of a mature model to explore the life cycle cost of downhole exploration equipment in the existing literature.

Table 1 Technology Readiness Levels (TRL) By NASA (NASA, 1995)

TRL Level	**Description**
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations

The aim of this paper is to identify the whole life cycle cost (LCC) of downhole LIBS sensor and determine the key economic contributors to the LCC of the LIBS downhole geochemical analysis tool. The LCC of the downhole tool is calculated based on published life cycle cost analysis models. Sensitivity analysis is used to explore how the fluctuation of key economic factors will impact on the LCC. The LIBS tool LCC is compared with that of a portable X-Ray Fluorescence (pXRF) analyser, which is a similar portable geochemical analysis tool. Trade-offs between cost and data quality are considered.

2 Background

2.1 Necessity of Geochemical Data Collection

The collection of geochemical data is an important part of understanding and analysing minerals. Geologists collect geochemical data to identify the composition and concentration of elements within rock, soil, and water samples. This information is crucial for understanding geological processes and the history of the Earth's crust (Cremers and Radziemski, 2013). Additionally, geochemical data helps in locating and assessing the economic potential of mineral deposits (Ali et al., 2017). Such data guides exploration activities, reducing the risks and costs associated with drilling and mining (Giles, Hillis, and Cleverley, 2014).

2.2 Established Geochemical Assay Methods

Two well-established methods to analyse geochemical data are laboratory whole rock geochemistry and pXRF. Laboratory assays involve collecting samples from the field and sending them to a laboratory for detailed analysis. The method provides highly accurate and precise measurements of elemental concentrations for all elements on the period table (Staveley and Thow, 2010). Laboratory analysis offers true volumetric data representation of the bulk rock chemistry. Techniques used include XRF, mass spectrometry (MS), atomic absorption spectroscopy (AAS), and inductively coupled plasma optical emission spectroscopy (ICP-OES). However, laboratory assays is time-consuming, requires sophisticated equipment, and trained personnel. There are also logistical challenges in sample transport (Pollmann et al., 2018), which may cause damage to samples during transit. The cost of laboratory assays varies depending on the number of elements being analysed and the technique(s) being used.

Portable X-ray fluorescence (pXRF) allows for on-site analysis of samples, providing immediate data. It is easy to use and can analyze a wide range of elements directly in the field (Fisher et al. 2014; Lanza et al., 2015). This reduces the need for extensive sample preparation and transport to laboratories. pXRF is particularly useful for preliminary surveys and rapid decision-making during exploration activities. However, it has limitations in sensitivity, especially for elements lighter than Mg, and can be less accurate compared to laboratory assays (Du et al., 2020). Moreover, both laboratory and portable methods may require complementary techniques to provide a complete geochemical picture.

2.3 Application of LIBS

LIBS is a spectroscopic analytical technique that uses a high-powered laser to ablate a small portion of the sample. The laser pulse generates a plasma on the sample surface and the emitted light from the plasma is analyzed to determine the elemental composition (Cremers and Radziemski, 2013). LIBS is capable of detecting a wide range of elements, including those that are difficult to detect with other methods (Harmon and Senesi, 2021). It provides real-time in-situ analysis of samples in various environments (e.g., provide one or two examples and references).

2.3.1 LIBS in Geoscience

In the geoscience sector, LIBS is used for rapid on-site geochemical analysis of rock, soil, and mineral samples (Lanza et al., 2015). It is employed in field surveys and exploration to quickly identify areas of interest for further investigation (Harmon and Senesi, 2021). LIBS is also useful in environmental monitoring to detect contamination and assess soil quality. In addition, LIBS can be used for analysis of geological material in extremely harsh environments, which makes it stand out in two application scenarios: integration into robotic systems for planetary exploration, such as the Mars rover missions (Du et al., 2020); and deployment in the deep sea to detect geological features in cold seeps and hydrothermal vents (Fabre et al., 2020).

Recent developments have seen the application of LIBS in real-time downhole assays to provide geochemical data within drill holes. This technique enables continuous monitoring and analysis of drill cores without the need to bring samples to the surface (Harmon and Senesi, 2021). It improves the efficiency of drilling operations by providing immediate feedback on the mineral content of the borehole (Cremers and Radziemski, 2013). This advancement has the potential to revolutionize mineral exploration by reducing costs and increasing the speed of obtaining critical data.

2.4 Life Cycle Cost Analysis

The entire cost of facility ownership can be evaluated using life-cycle cost analysis (LCCA: Fuller, S., 2010). An LCCA is used to assess the total cost of project alternatives and choose a design that will guarantee the facility has the lowest total cost of ownership while maintaining its quality and functionality. To guarantee a decrease in life-cycle costs (LCC), the LCCA should be carried out early in the design phase when there is still opportunity to improve the design.

LCCA has a wide range of application scenarios, from various types of products to internal costs within a particular organisation (Arditi, D., & Messiha, 1999). Construction and transport are the areas where LCCA is used the most. In these two areas, there are well established LCCA models for research, such as the Queue and User Cost Evaluation of Work Zones model (QUEWZ) for life cycle cost analysis of pavements (Memmott & Dudek, 1984). In recent years, consumer LCCA models have also been used in the study of products and consumer behavior (Kara, S., et al., 2017).

3 Methodology

3.1 Life Cycle Cost Model

In the retrospective study of the LCC model by Durairaj et al. (2002), seven models related to life cycle cost were mentioned. One of those models is Fabrycky and Blanchard's LCCA model, which is the basis of all LCCA models (Fabrycky and Blanchard, 1991). Fabrycky and Blanchard (1991) disassembled the life cycle cost into four parts: research and development, production and construction, operation and maintenance, and scrapping and disposal. This model is the most general and can be applied to most systems or product LCCA. As the LIBS downhole sensor is still in the stage of development and testing and has yet to be formally put into mass production or entered the market, this study uses basic LCCA model of Fabrycky and Blanchard (1991). The overall analysis process is carried out according to the sequence shown in Figure 1.

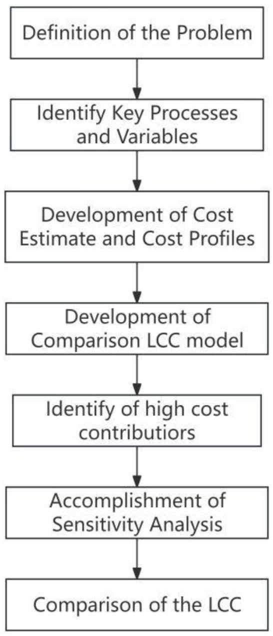

Figure 1. Workflow depicting the life cycle analysis method used in this study. Image taken from Fabrycky and Blanchard (1991).

3.2 Development of the LCC model

3.2.1 Definition of the structure

Using the "cradle to grave" approach, the analysis divides the life cycle of the downhole LIBS sensor into four stages: development, production, operation, and disposal. Based on the life cycle process and LCCA model, this study divides the life cycle cost of the downhole LIBS probe into four parts: initial research and development cost, production and construction cost, operation and maintenance cost, and scrapping and disposal cost. Figure 2 illustrates the research framework of this study.

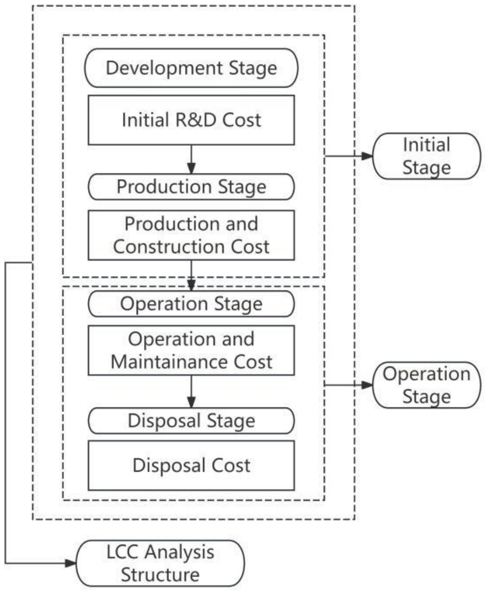

Figure 2. LCCA Structure for the downhole LIBS tool??.

3.2.2 Data collection

As the downhole LIBS sensor is not yet in production, the data for the downhole LIBS sensor development is provided by the MinEx CRC Project 3: Real-time Downhole Assay team. This information and data are based on experimental work within the project as well as the downhole tool field trials conducted by the MinEx Project 3 team at the Australian Automation and Robotics Precinct (AARP: www.theaarp.com.au) in early July 2024.

3.3 Assumption of the study

3.3.1 Equipment life

The most critical component that determines the service life of the downhole LIBS sensor is the laser. The life of diode pumped solid state laser's service life is about 10,000-30,000 hours (Gray, T., & Frederickson, C.,1990; Šulc, J., & Jelínková, H., 2013). In this study, the maximum expected service life, 30,000 hours, is used as the life expectancy of the downhole LIBS sensor. For the convenience of calculation, the hours are converted into years in this study, so the life of the downhole LIBS device is estimated to be 3 years.

Referring to figures given by Bruker Corporation (2023a), portable XRF analyzers typically have a service life of 3-9 years. For the convenience of subsequent comparison, this study selected the same service life as the downhole LIBS sensor, a

3-year cycle, to estimate the cost of pXRF.

3.3.2 Assumptions about the labor force operating downhole LIBS equipment

This study assumes that two workers are required to operate the downhole LIBS equipment, and that a typical work schedule will be 7.5 hours a day for five days a week over the 3-year life of the equipment. Considering holidays and vacations, a rough estimate of 50 weeks of work per year would give the two workers 1,875 hours of work per year. At the same time, the study assumes that wages paid to workers remain constant over the lifetime of the equipment.

3.3.3 Fuel price estimation for downhole LIBS

Taking the average of the past 5 years diesel price in Australia as the set price ($149.8 per L) (AIP, 2024), this study assumes that the diesel price remain constant over the entire equipment life cycle. Since the study considers the daily operation of individual equipment, it can be assumed that the daily diesel price will be the same as the average annual oil price over the whole year, and the generator will provide power for 5 days, 50 weeks per year.

4 Results

4.1 Life cycle cost of downhole LIBS

Individual equipment and unit costs for participating in a single exploration activity are assessed and used to make scenario assumptions based on available data. All costs are given in Australian dollars.

4.1.1 Initial research and development costs

The research and development (R&D) phase of the LIBS downhole sensor has taken six years to date (Van der Hoek, B. pers. comm. 2024). Initial development costs, which include software development for researchers and staff and procurement of test equipment, are expected to total $3 million. The equipment to be purchased includes the components of the tool, including: a customized 532 nm Nd:YAG Montford Laser (maximum pulse energy of 40mJ at 5 Hz) (~$70,000); two high-resolution Ibsen Photonics spectrometers (wavelength ranges of 190 to 435 nm and 360 to 830 nm) (~$15,000); optics including a laser beam polarization splitter cube, focusing lens, collimator and a bifurcated multi-mode optical fiber (~$5,000). The downhole tool is operated as a wireline tool, meaning it is lowered into a drill hole on a wireline (steel) cable using a winch. Geochemical data is collected as the tool is pulled out of the drill hole. The winch system is estimated to cost $20,000.

4.1.2 Production and construction costs

Production and construction costs mainly include raw material and equipment placement costs. The cost of raw materials is assumed to be the cost of individual components of the tool as outlined in the initial R&D cost section above. Therefore, the resulting raw material cost for a single downhole LIBS device is estimated to be $90,000.

In terms of equipment placement costs, although the downhole LIBS tool does not require permanent placement, its operation requires infrastructure such as dedicated laser safety rooms. The placement cost of these facilities is estimated at $5,000 to $10,000 (Van der Hoek, B., 2024). The midpoint of the range of $7,500 is used here as placement costs. The price of purchasing and setting up the winch is also included here ($20,000 as mentioned in the R&D section).

4.1.3 Operating and maintenance costs

The downhole LIBS sensor involves the following major expenses in the operation process:

- *Labor costs:* Each unit is expected to require two people to operate. The average hourly wage for mining workers in Australia is AU $61.98 (Talent.com, 2024). Assuming that the 2 operators will work for 7.5 hours per day, and the total labor cost of ~$930/day

- *Energy costs:* The downhole LIBS sensor requires very little power. A single diesel generator was used during the July 2024 Project 3 field trials, and less than 10L of fuel was used per day to meet the energy requirements. The calculation section will introduce the assumption and fluctuation rate of diesel prices in detail.
- *Consumables cost:* As the downhole LIBS tool collects geochemical data directly from the drill hole wall, no sample preparation is required. The cost of consumables is therefore presumed to be $0 as deployment does not require consumables other than those already mentioned.

Since the downhole LIBS sensor has not been commercialized, the cost required for its maintenance in actual practice is unknown. Therefore, an estimate cost of the maintenance cycle is assumed based on the main components contained in the downhole LIBS sensor.

The optical components on the LIBS sensor will age with time. As mentioned in the initial cost, these optics cost about $5000. They usually have a replacement cycle of 1-3 months (Van der Hoek, B., 2024). This study takes the middle of this range and assumes that these optical elements must be replaced every two months. Since estimating the labor costs to be considered for a specific replacement machine is difficult, this study assumes that the replacement cost will be the same as the purchase cost, which is $5,000.

Lasers may degrade over time and fail but are unlikely to be included in the spare parts package of the study budget due to procurement costs. Therefore, it is assumed that there is no cost for replacement of a laser within the downhole LIBS system over the life of the equipment. Similarly, spectrometers does not need to be maintained during their life cycle (Van der Hoek, B., 2024).

4.1.4 Disposal costs

The specific dismantling and transportation costs of the downhole LIBS tool cannot be estimated as the instrument has not been put into market operation. However, since the downhole LIBS sensor is not a physically large fixed asset, the removal and transportation costs are expected to be minimal.

The instrument scrapping cost includes the declaration and environmental management cost of some components that require special treatment at the end of the life cycle of LIBS sensors. The Montford laser within the downhole LIBS tool may need to be declared and managed by the radiation management department in Australia during the retirement stage. Since the process from development to testing of the downhole LIBS tool has been carried out in South Australia, this study will refer to the cost data provided by the Environmental Protection Agency (EPA) of South Australia to estimate the cost of its declaration.

The EPA requires persons who use or handle radioactive materials, operate ionizing radiation equipment, or possess radiation sources in South Australia to have a radiation permit issued by the EPA (Environment Protection Authority South Australia, 2021). The application fee for a permit mainly consists of two parts: submission fee and assessment fee, of which the submission fee is $245. The assessment fee is 20% of the activity with the highest environmental Management fee (EMF) component. According to EPA's criteria for waste recycling facilities listed in the Environmental Protection Regulations 2023 - Schedule of Environmental Management Fees, there is one fee unit for 1,000 tons or less of waste per year. Since we only consider the cost of a single piece of equipment, this study assumes that waste weighs less than 1,000 tons in the year the equipment is retired. Then, the environmental management cost of a unit is $964 (Environmental management component = A$964 / expense unit) (EPA SA, 2023). The assessment fee is, therefore, $192.8. In summary, the declaration fee is $450, while the environmental management fee is $960.

4.2 Life cycle cost of pXRF

The cost-effectiveness of the downhole LIBS sensor was estimated by comparison with a portable X-Ray Fluorescence instrument, which is a portable geochemical analysis tool commonly used in the exploration and mining industry (e.g., Fisher et al. 2014). Compared with the laboratory method, pXRF, as a portable detection tool, has a higher degree of similarity in cost structure with the LIBS sensor, so this device was selected for comparative analysis in this study.

No detailed and comprehensive disclosure is currently given by suppliers regarding the costs of pXRF instruments at various stages of the life cycle, therefore the parts of the life cycle costs of the pXRF that can be estimated by reasonable assumptions or for which information can be found are presented here.

Regarding initial development costs, the existing major pXRF suppliers do not provide specific expenses for developing such equipment. Furthermore, this cost cannot be reasonably estimated due to the lack of publicly available information. Therefore, the initial R&D costs of pXRF are not considered here and are not included in the comparison with the LIBS sensor.

In terms of production and construction costs, no company has publicly disclosed how much it costs them to build a pXRF device. However, a rough estimate may be determined by considering the cost of the raw materials used in the critical components of the pXRF. These components include X-Ray Tubes, silicon drift sensor, graphene window, case and shield, lithium-ion battery and electronic components. Detailed cost estimates of the components based on market industry information are shown in Table

2.

Table 2 Estimation of the cost and replacement cycle of components in a pXRF. Data sourced from Bruker Corporation (Bruker, 2023a).

Item	**Cost (AUD)**
Rh target X-Ray Tubes	8000
Silicon Drift sensor (SDD)	10000
Graphene Window (20 mm^2)	1500
Electronic Components	3000
Case and Shield	1000
P/N 160.0009 Lithium-ion battery	200
Total cost	23700

Similar to the case of LIBS instrument, a rough estimate of the production cost of pXRF was done by adding up the acquisition costs of raw materials. Since the available information does not mention that additional instruments need to be placed during the construction process, this is not considered an expenditure. This results in a production cost of approximately A$24,000 for the pXRF.

The operating costs of pXRF were estimated through project reports. According to the Soil Geochemistry by pXRF at the Sonora Project, Mexico project report (Olympus IMS., n.d.), 4,000 samples per month can be measured using the pXRF in the field at a cost of US$12 (A$18) per sample, including labour, rental, sampling and processing. Further calculations on operating costs will be carried out once the lifetime of the pXRF tool has been determined.

In terms of maintenance costs, according to the information given by Bruker, the maintenance cost of the pXRF ranges from approximately A$10,500 - A$15,000 (USD 7,000 - 10,000). In this study, A$15,000 was taken as the cost of its repair and it was assumed that the instrument would require repair once during the life cycle of the pXRF.

Due to the small size of pXRF and the same laser inspection equipment as LIBS, this study adopted the same considerations as LIBS in estimating its end-of-life cost. As the pXRF instrument is considered a radiation source, scrapping the instrument must be done through the EPA. Therefore, the scrap costs of a pXRF instrument are considered the same as for the downhole LIBS tool, and require a declaration fee of A$450 and environmental management fee of A$960.

4.3 Comparative life cycle costs

Based on the above assumptions and data, this study can calculate the full life cycle cost of the LIBS sensor and the life cycle cost of the pXRF sensor from production to end-of-life. Due to the uncertainty of the assumptions, the calculation results are all taken as integers showing two significant figures. The specific calculation formula and process are shown below:

LIBS：

$$\text{Initial R\&D Cost} = \$3{,}000{,}000$$

$$\text{Production and Construction Cost} = \text{Raw Material Cost} + \text{Placement Cost} = \$120{,}000$$

$$\text{Operational and Maintenance Cost} = \text{Operational Cost} + \text{Maintenance Cost} = \$1{,}900{,}000$$

$$\text{Disposal Cost} = \$1{,}400$$

pXRF:

$$\text{Production and Construction Cost} = \text{Raw Material Cost} = \$24{,}000$$

$$\text{Operational and Maintenance Cost} = \text{Operational Cost} + \text{Maintenance Cost} = \$2{,}600{,}000$$

$$\text{Disposal Cost} = \$1{,}400$$

The life cycle cost of the downhole LIBS sensor has been estimated (Table 3). The total cost of the downhole LIBS tool is about A$5.1 million, and the total cost of the pXRF is about A$2.6 million. The greatest difference in cost between the two tools is in the O&M phase, where the cost of pXFR is approximately 36.8 per cent higher than the cost of the LIBS tool.

Table 3. LCC of the downhole LIBS sensor and pXRF

LCC Items/$	Downhole LIBS sensor	pXRF
Initial Research Cost	3000000	/
Production Cost	120000	24000
Operation and Maintain Costs	1900000	2600000
Disposal Costs	1400	1400
Total Cost	5021400	2625400

5 Discussion

5.1 Contribution analysis

Contribution analysis of the LCC models for the downhole LIBS and pXRF will…. What will it do? What insight will it give? Provide the reasoning for why you have done the analysis to provide context for the reader.

The total life cycle cost of the downhole LIBS downhole sensor is approximately $5.1 million. The cost of each stage is shown in 错误!未找到引用源。. In the whole development process, research and development costs accounts for 59.74% of the total cost, accounting for the largest proportion. Operation and maintenance cost accounted for the second largest portion of the total life cycle cost, accounting for 37.84%. As the downhole LIBS tool is a new technology, high R&D cost input is necessary and plays a vital role in the steady development of technology. Based on assumptions made in this study around disposal and scrapping of the downhole LIBS tool, the cost of production and disposal has little influence on the life cycle cost, especially the disposal cost. It is noted that the demolition, transportation and other costs in the scrap disposal stage cannot be estimated as the downhole LIBS sensor is not a large fixed asset and the disposal procedures in the scrapping stage are not expected to be complicated.

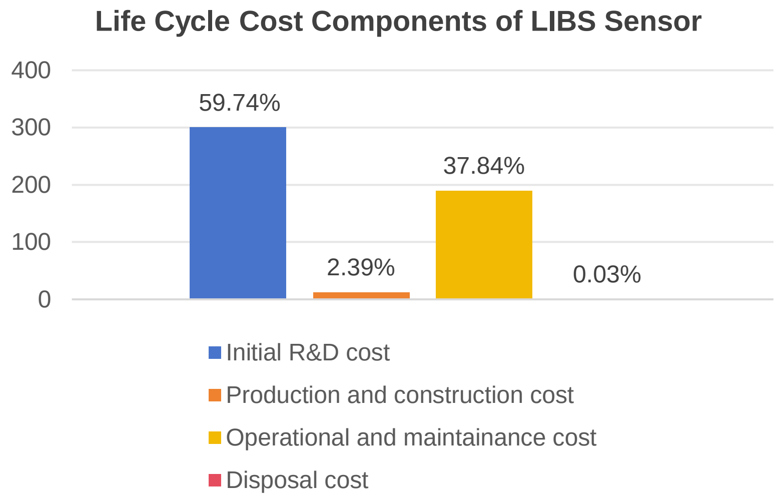

Figure 3. Comparison of LCC Components for the downhole LIBS tool.

The components of cost can be further explored by separating the whole life cycle into an initial phase (Fig. 4a) and an operation (until the end of the life cycle) phase (Fig. 4b). The initial phase shows that that R&D costs account for the largest proportion of cost.

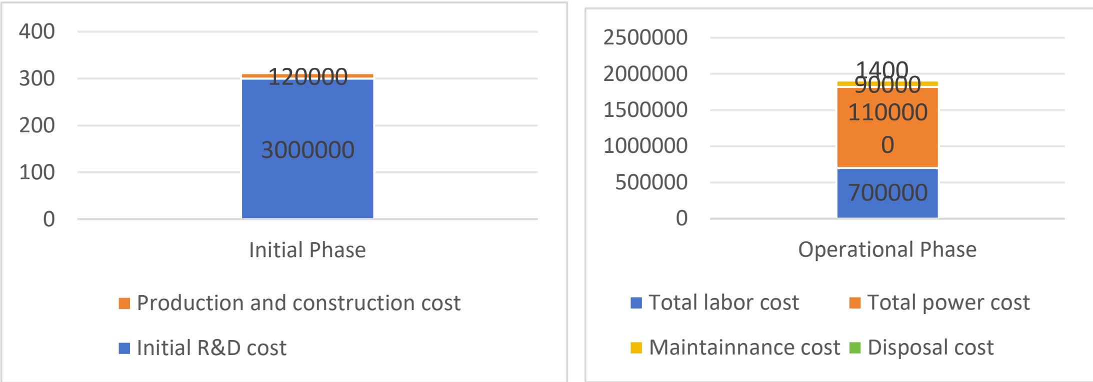

Figure 4a. Initial Phase Cost. Figure 4b. Operation Phase Cost

In the operational phase, energy and labor costs have the most significant impact (Fig. 4b). Although the power consumption of LIBS sensors is not large, it still accounts for a large proportion of operating costs because energy is a daily consumable, and its price is high and fluctuates over the long term. Therefore, the operation phase presents an opportunity to enhance the downhole LIBS tool's economy by further optimizing the structural expenditure of energy and labor force.

5.2 Sensitivity Analysis

Based on the above analysis, energy price is an important factor affecting the LCC. In practice, the price of diesel fuel may fluctuate over the life cycle of the tool. Therefore, we will examine the overall impact of diesel price fluctuations on LCC.

According to the data shown in the AIP (Australian Institute of Petroleum, 2024), over the past five years, the average annual minimum price of diesel fuel has been approximately A$110/L, while the maximum price of diesel fuel has been approximately A$190/L. In this study, we use these two prices as the upper and lower bounds of the diesel fuel price for the LCC calculation of the LIBS instrument. We consider the impact on LCC for each A$20/L increase in diesel fuel price within this range(A$110/L-A$190/L).

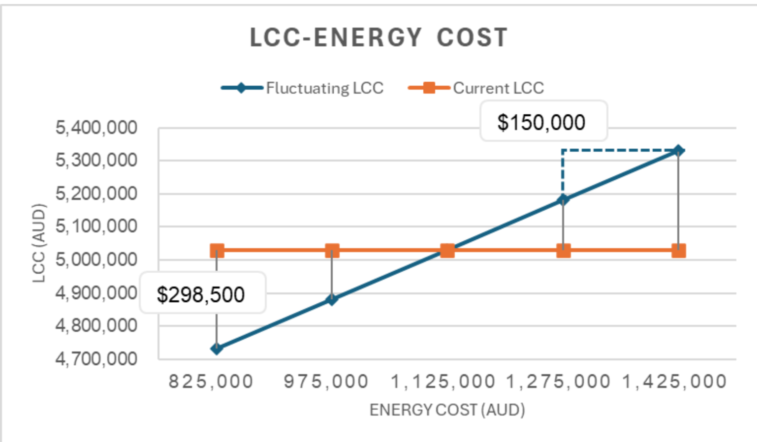

Figure 5. Sensitivity Analysis of Diesel Price

As shown in Figure , the LCC model is sensitive to changes in energy prices. Since market fluctuations determine the energy price that are out of the control of the company's operating activities, its fluctuations directly affect the life cycle cost of equipment. During diesel price fluctuations, the difference between the Fluctuating LCC and the Current LCC maximises to about A$300 thousand. When the annual average diesel price rises by A$20/L, the full life cycle cost increases by A$150 thousand.

Labor cost is another key factor in total life cycle costs. In practice, workers' hourly wages usually increase over time, but in the short term they do not change a lot. According to data shown by Trading Economics, the lowest average annual increase rate of hourly wages in Australian over the last 10 years was 1.3%, and the highest average annual increase was 4.3%. We use these two growth rates as the lower and upper bounds of the hourly wage growth rate respectively, with 1% intervals within this range, to calculate the impact on LCC when workers' hourly wages move upwards at different growth rates (Increasing rate=1.3%, 2.3%, 3.3%, 4.3%).

As shown in
Figure , in the growth rate fluctuation interval, for every 1% increase in the hourly wage growth rate, the LCC only increases by about $7,000. Thus, the LCC is less sensitive to changes in labour costs over the lifetime of the LIBS sensor, which is limited by the salary-fluctuation rate.

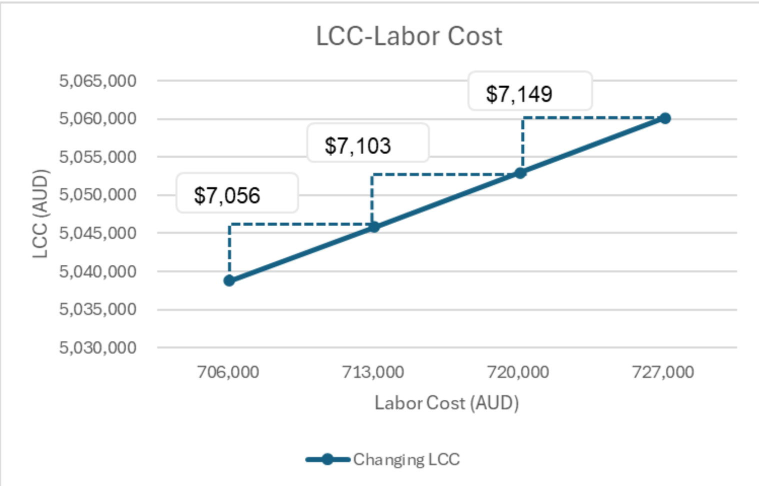

Figure 6. Sensitivity Analysis of Labor Cost fluctuations to LCC of the downhole LIBS tool.

5.3 Comparative analysis of LIBS's and pXRF's LCC

Based on the existing assumptions and calculations, we can roughly estimate the cost of pXRF in the production phase, operation phase and disposal phase of its life cycle. Therefore, a rough comparison of the cost of LIBS and pXRF from production to end-of-life stage is presented here based on the available results.

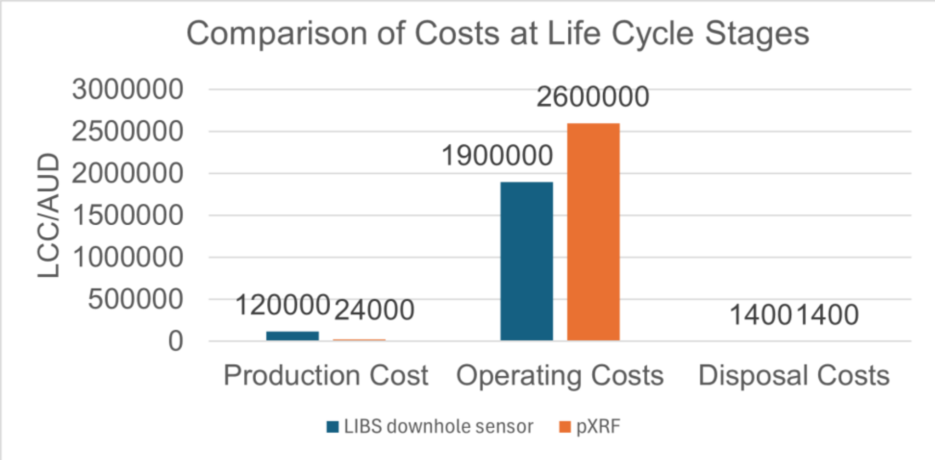

Figure 7. Comparison of LIBS's and pXRF's LCC.

Based on the estimated data, Figure 9 shows that the LIBS detector costs more than the pXRF during the production and construction phase. However, during the operation and maintenance phase, the pXRF costs $2,600,000, which is higher than the $2,000,000 projected for the LIBS.

The operating costs of LIBS and pXRF are the highest at this phase. During this phase, LIBS and pXRF will perform detection tasks. When performing lithogeochemistry analyses of rocks, there are many key elements that are lighter than magnesium, such as Na, which is considered to be a pathfinder element when exploring for carbonate rocks (Balaram &Sawant, 2022), and lithium, which is currently being used in a large number of new energy applications. However, according to Declercg et al. (2019) and Bastos et al. (2012), the identification of light elements can be quite challenging when using XRF due to their absorption of fluorescent X-rays. Lithium and beryllium cannot be determined pXRF because the fluorescent X-ray energy levels of the lighter elements are low enough that they cannot reach the detector without being absorbed. Even if they escape the sample, some of them cannot penetrate the air between the sample and the instrument to reach the detector (Balaram &Sawant, 2022).

The LIBS tool can detect elements lighter than magnesium. In addition to this LIBS can also detect the presence of halogens. Halogens are a group of target elements in exploration and remediation because they form strong complexes with metals, they tend to be mobile, and they are associated with mineralised fluids, and LIBS is one of the few technologies that can detect all the halogens (Kyser et al., 2015).

Thus, comparatively, LIBS can perform well in identifying light elements, making it more economical in terms of estimated costs, with lower costs during the operation and maintenance phase and better quality of data identification.

5.4 Methods of costs reduction

Based on the results, we can see that the three costs that contribute most to the LCC of a LIBS detector are the initial R&D cost, the energy cost and the labour cost (Fig. 4a and Fig. 4b).

The study found that there is a significant positive correlation between mining companies' spending on R&D activities and the companies' profitability and revenue growth. This suggests that companies that invest more in R&D tend to see better financial performance, and that high R&D investment can make a company more competitive in the long run (Wijayakusuma, 2022). Therefore, improvements in equipment economics cannot be achieved by cutting R&D costs. Current R&D investments can be maintained and continued investment can be made annually over the life cycle.

5.4.1 Energy costs

Although the LIBS sensor has very low energy consumption requirements, it is impossible to avoid being affected by energy prices in terms of costs, as the machine requires energy in its daily operation. It may be possible to utilise more efficient methods of power generation to power the equipment to save on energy bills.

The current market has off-grid solar-diesel generators for sale. Solar panels collect solar energy during the day and convert it into electricity, which is stored in the battery bank for use at night or on cloudy days; when the solar power generation is insufficient or the battery is low, the diesel generator will automatically start to provide the required power and charge the battery. The system automatically switches between solar and diesel power generation according to load demand and power source to ensure continuous power supply. If replacing the traditional diesel generator with this type of generator is considerd, the energy expenses may be able to be saved.

In the case of Adelaide, for example, the number of sunny days per year is approximately 91 based on meteorological statistics from 1991-2024 (Current Results, 2024). According to our previous assumptions, the generator will need to supply power to the LIBS tool for its three-year lifecycle, i.e., 3*5*50=750 days. Assuming that the number of sunny days in each of the three years is 91, and that the solar-diesel generator can supply sufficient energy from solar power alone on sunny days, and that the diesel generator powers the generator for the rest of the time, the number of days that the diesel generator will need to power the generator is:

$$750 - 91 * 3 = 477(\text{days})$$

Keep using the average price of diesel in Australia over the last five years ($149.8), the energy costs of burning diesel would be:

$$477 * 10 * \$149.5 = A\$714{,}546,$$

which is about $710,000.

Thus, life cycle energy cost savings compared to conventional generators can be around:

$$1{,}100{,}000 - 710{,}000 = A\$390{,}000$$

5.4.2 Labor costs

In terms of labor costs, firstly, the price of labor in the market is relatively stable and its fluctuation has little impact on LCC, so it's not necessary to try to find cheaper labor. Secondly, it is not realistic to lower the salary of workers or reduce their working hours for actual operation. With the development of LIBS technology and the improvement of workers' proficiency, it may not be necessary to have two workers to operate the machine in the future. If only one worker were required for deployment of the LIBS instrument, the labor cost will be cut by 1/2, i.e. from A$700,000 to A$350,000, a saving of A$350,000.

In summary, adjusting energy and labor expenditures to the projected scenario would reduce LCC by A$740,000, as shown in Figure 8.

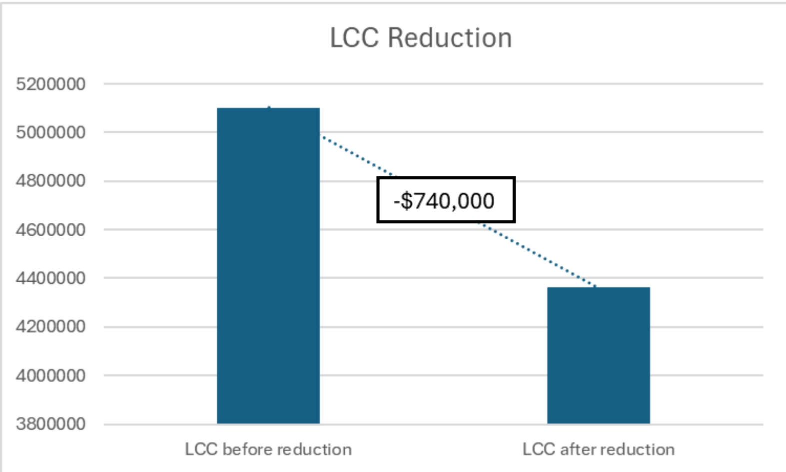

Figure 8. LCC Reduction based on assumed scenario.

5.5 Comparison of research findings and discussion of commercialisation of tools

5.5.1 Comparison of findings with other fields of research

When looking at the life cycle costs of other sectors, such as new energy vehicles, roads and bridges, operation and maintenance costs are generally recognised as the largest portion of the cost of the vehicle. recognised the largest portion of the lifecycle costs (Kendall, et al., 2008; Kara, 2017; Babashamsi, et al., 2016). Whereas, in this study, R&D costs are found to be the highest portion of the lifecycle costs, while operation and maintenance costs are ranked second. This study suggests that the following reasons may have led to the emergence of such a discrepancy.

1. uncertainty in assumptions and estimates. Since portable LIBS instruments have not yet been formally introduced into the market, this study used certain assumptions and estimates for the calculation of costs during the operation phase. The assumptions and estimates are idealistic and may differ from the actual situation. A more detailed study needs to be carried out after the LIBS tool is formally put into practical use, and the calculation is based on the data obtained.

2. Real-time downhole LIBS detection tools are a new technology that requires high R&D investment to achieve innovation and results. As one of the important channels for generating new technologies, the intensity of R&D expenditures has been found to have a positive impact on the generation of new technologies (Lv, L., et al., 2020; Guo, B., et al, 2018). The real-time downhole analysis LIBS tool, as a new upcoming technology, must receive sufficient R&D funding during the initial investment phase to test the technology and ultimately translate the results so that it can actually be used in mining activities.

In summary, the uncertainty of assumptions and estimates and the necessity of new technologies requiring R&D funding are two reasons that may lead to the findings of this study being different from those of life cycle cost studies in other fields.

5.5.2 Discussion on the commercialisation of tools

The current tool is still at TRL 6 and is still three TRL stages away from true commercialisation, i.e., the technology is truly maturing and going through production and certification, leading to commercial deployment.

Based on current findings, LIBS does not need to cut R&D costs and should continue to invest in R&D. Such a move would be beneficial in helping LIBS tools to become more technically mature, reach a TRL 7 rating, and enter the real production phase.
Operating costs need to be considered and planned for financially before real commercial deployment can take place. Based on the results of this study, the use of

more energy-efficient new energy generating machines and the reduction of labour are the expected ways to reduce the cost of the operational phase. In the future, more factors may have to be taken into account in the actual commercial layout, such as the cost of transporting the tools and the cost of setting up the site. The LIBS tool will face more complex situations in the practical application of the LIBS tool, which will present both opportunities and challenges.

6 Conclusions

The life cycle cost analysis of the downhole LIBS sensor underscores the importance of operational and maintenance costs in determining its overall economic viability. Although the initial investment in research and development is significant, it is essential for advancing this innovative technology. To optimize the economic performance of the LIBS sensor, future efforts could focus on enhancing energy efficiency and refining labor management practices. By doing so, the operational costs can be significantly reduced, making LIBS a more competitive alternative to commonly used methods like pXRF. Looking forward, the continued evolution of LIBS technology promises not only to lower costs but also to expand its applicability, potentially revolutionizing the field of mineral exploration and resource management with more precise and timely data and achieve more effective commercialisation.

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Appendices

Appendix A. Components and costs of LIBS

Components	Cost
Laser	70000
Spectrometers	15000
Optical fiber	5000
Winch	20000
Placement cost	7500
Replacement Cost	5000

Appendix B. Sensitivity Analysis of LCC-Energy Cost

Sensitivity Analysis of LCC-Energy Cost					
Energy Cost/LCC	825000	975000	1125000	1275000	1425000
5029684	4731184	4881184	5031184	5181184	5331184
Current LCC	5029684	5029684	5029684	5029684	5029684

Appendix C. Sensitivity Analysis of LCC-Labor Cost

Sensitivity Analysis of LCC-Labor Cost				
Rounded Labor Cost	706000	713000	720000	727000
Labor Cost/LCC	706379	713435.2778	720538.1858	727687.5788
5029684	5038788	5045844	5052947	5060097

Appendix D. Operating cost of pXRF

Items	**Amount**
Samples/month	4000
Unit Cost	18
Total months/year	12
Life span	3
Total operating cost	2592000
Rounded taotal operating cost	2600000