USING MACHINE LEARNING AND NATURAL LANGUAGE PROCESSING TO ENHANCE URANIUM MINING AND MILLING SAFEGAURDS

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Abstract

The recently-developed IAEA Content Reification Engine (ICORE) is used to examine open source reporting and utilise machine learning algorithms to help identify indications of undeclared nuclear fuel cycle activities. At present, when observing mining and milling processes, ICORE does not have a discrete discriminator between uranium mining and other mining processes, apart from the obvious terms 'uranium' or 'nuclear'. Therefore, in an Australian Safeguards Support Programme project, machine learning will be used to evolve safeguards technologies within the uranium mining and milling fields. This will be through the identification of unique discrete terms that differentiate uranium processes from other mining processes. The intent is to support ICORE through natural language processing rules for mining and milling in support of detecting undeclared nuclear activities.

Advanced analytics through machine learning can support current safeguards mechanisms by improving automation and thus increasing the size of the dataset analysed. However, this analysis is dependent on the quality of the training data sets developed to support the machine in its learning. Therefore, a thorough understanding of the language used in the mining sector for uranium mining and milling processes and discriminating this language from the processing of other minerals is required, in order to have the detail to build a natural language processing algorithm.

Australia has approximately one third of the world's recoverable uranium resources and also has a responsible mining sector. Therefore, in bringing together Australian academia, the mining industry, the Australian Safeguards and Non-Proliferation Office (ASNO) and the IAEA, an interrogation of literature, open source documentation and industry engagement can assist in building a solid natural language processing data set to employ within ICORE and support the enhancement of IAEA tools, to strengthen safeguards and maintain the peaceful uses of nuclear technologies.

1. INTRODUCTION

Nuclear safeguards ensure that States utilise nuclear materials for peaceful purposes. [1] Therefore, safeguards techniques are required to constantly evolve in order to best utilise available technologies in order to prevent the misuse or malicious use of nuclear materials. As the fourth industrial revolution emerges, the rise of artificial intelligence and machine learning [2] is an opportunity to enhance safeguards techniques. Machine learning is an application of data science that allows large volumes of data to be analysed and used quickly, however the machine's ability to analyse data is only as good as the data set used to build and train their machine on. The IAEA Content Reification Engine (ICORE) is a key machine used by IAEA's to assist in technical nuclear safeguards activities. ICORE has the ability to discriminate key terms linked to nuclear processing throughout the nuclear fuel cycle. However, difficulties arise with the front end (uranium mining and milling) and weapons conversion stages of the fuel cycle, largely due to overlap in terminology with non-nuclear analogous processes. [3] The paper is concerned with the front end of the nuclear fuel cycle and will address the issue of identifying key discrete terms (besides obvious terms like uranium, nuclear or yellowcake) that differentiate uranium mining and milling from other mining and milling activities in order to enhance ICORE and its ability to improve the technical safeguards program and identify undeclared uranium mining activities.

2. MACHINE LEARNING AND NATURAL LANGUAGE PROCESSING

As a subset of artificial intelligence, machine learning is based on a computer's ability to evolve its analysis of the data, from the data. The computer (or machine) learns from its previous decisions and analysis and adapts its algorithms to increase the reliability of future decisions or results. [4] Machine learning is based on complex mathematical algorithms and models to distil data and produce a repeatable pattern to shape and inform decisions. In order to do this, a machine learning model requires three key inputs. Firstly, it requires a prepared and comprehensive data set to train and test the machine on. Secondly, it requires an appropriate mathematical algorithm to base its analysis on, the choice of algorithm is dependent on the type of data that will be analysed. Finally, it requires the ability to be iterative in order to 'learn' and evolve from its decisions and analysis. [5]

ICORE has been developed to trawl open source documentation via the internet in order to identify unreported nuclear activities. This means the input data is text based. Therefore, Natural Language Processing (NLP) is the most suitable machine learning algorithm to be used in a nuclear safeguards machine. NLP can be described simply as teaching a machine how to read a string of naturally occurring text. While it is not an evolved version of artificial intelligence where the machine can understand the text, NLP allows a machine to 'read' the text and apply a mathematical model to that text to determine an outcome. [6] In the case of supporting the identification of uranium mining/milling activities, the outcome the machine is required to reach is identifying whether the activity involves or does not involve uranium. This therefore requires a training and testing dataset built off understanding the common and discrete terms used in mining and milling of uranium and non-uranium minerals.

3. URANIUM MINING AND MILLING METHODS

Uranium is mined in a very similar fashion to many other resources, including copper, gold and nickel. Uranium is also commonly co-mined in conjunction with other minerals and is found in the tailings of mined rare earths and phosphates. [7] In order to understand what terms are common and what are discrete, the four main mining methods for uranium were analysed and are briefly summarised here. They are in-situ leach (ISL), heap leach, open cut and underground mining. [8] Additionally, we reviewed the terminology surrounding exploration and identification of uranium ore deposits. Data gathered and analysed is from predominately Australian based mining companies and their open source materials. However, where Australian data was insufficient or where a technically interesting and different extraction technique was used, international mines were also analysed.

3.1. In-situ leach (ISL)

ISL is a technique where a liquid is circulated through an ore body to dissolve the desired mineral. This impregnated liquid is then brought to the surface where further processing extracts the target mineral. It is a process where there is minimal ground disturbance and is cost effective to extract low grade ore. [9] ISL is commonly used in the extraction of uranium and it is quite difficult to extract other minerals through this process. This is due to how ore bodies are formed. In the case of uranium, ore bodies are commonly found in a sandstone hosted deposit in a roll front therefore allowing for leach liquid to be exposed to enough of the ore. Other minerals that are typically extracted in similar fashion to uranium using ex-situ methods, for example copper minerals, form ore bodies differently and thus reduce the effectiveness of ISL for extraction. [10]

3.2. Heap leach

Similar to ISL, heap leach is a low-cost mining and processing technique that also utilises a fluid to extract the target mineral. However, heap leach does this through stacking ore on an impermeable pad. The 'heaped' ore is covered in the selected solvent, this can be acid or alkaline based dependant on the ore body. [11] The solvent seeps through the ore producing a pregnant solution which is collated in a pond for the target mineral to be extracted. Unlike ISL, heap leach does not require specific ore body formations and is therefore common in the mining of many minerals, used in conjunction with open cut or underground mining in order to extract the most from an ore body. [12]

3.3. Open cut mining

A physical technique for ore extraction where the deposit is located close to the surface. Open cut mining is often also referred to as open pit, open cast or strip mining. [13] It can use a combination of manual movement of surface layers and blasting techniques to reach the ore body. Open cut is used to extract many minerals including uranium and is often accompanied by heap leach or underground mining. [14]

3.4. Underground mining

When the target ore body is located at a significant distance below the ground, and open cut mining is unachievable, underground mining is used. There are many different ways the ore body is extracted including blasthole stoping, longwall mining, cut and fill mining as well as sub-level caving, just to name a few. The most common form of underground mining is room-and-pillar which, as the name suggests, utilises a number of pillars and extracts around them creating rooms. [15] While these are very common for the extraction of many minerals, uranium underground mining predominantly utilises two techniques, ground freezing and Jet Boring System (JBS).

Ground freezing is a technique not only used in uranium mining but is also commonly used in soil stabilisation in the construction industry. In uranium mining, it is used to isolate high-pressure water surrounding a uranium ore in a sandstone deposit. This forms a wall effect around the areas to be mined and therefore minimises the interference of water with the ore body. [16]

The JBS is designed by Canadian uranium mining company Cameco who needed a method to mine a technically difficult uranium ore body. The ore body is initially frozen using bulk ground freezing techniques, a hole is then drilled through the frozen ore body. A high-pressure water jet is fired into the ore body to cavity out the ore. The ore, in slurry form, is then stored and processed. [16]

3.5. Uranium ore deposits

Initial analysis focused the machine learning dataset on mining and milling activities of uranium only. However, in researching mining methods and techniques, it became apparent that there are discrete terms used in reference to uranium ore deposits and exploration. [17] These terms can provide discriminate terms for activities leading to the extraction and mining of uranium and in turn enhance the nuclear safeguards machine learning algorithm.

4. DISCRETE TERMS IDENTIFIED

Analysis of the discrete terms common for all forms of uranium mining are centred on the mineral and the ore body itself. Terms including uranium, yellowcake, uranium ore concentrate, U_3O_8 and uranium oxide are common terms that are used across all forms of uranium mining. Other key indicators which are common to uranium mining and milling are based on radiation safety. This includes terms such as radium, radiation, radioactive waste, radiation safety and radiation protection. Also, it should be noted that detailed and descriptive mine site rehabilitation plans, that include radioactive waste management plans, are also linked solely to uranium mining activities.

Discrete terms common for all non-uranium mining activities are predominately due to the extraction of metals. Terms include gangue, calcium build up, electrowinning (EW), bacterial activity, electrolytes, smelter and refinery, as well as the name of the mineral or metal itself, and the associated carbonates or sulphides. The most commonly mined metals through leach, open cut or underground mining observed were copper, nickel, gold, cobalt, lead, silver and zinc.

Analysis for in-situ leach mining data indicates that ISL is very common for uranium ore extraction, and not for much else. Therefore, ISL more often leads to uranium mining activities than non-uranium mining activities. Sandstone hosted roll fronts was also identified as a common phrase linked to uranium ISL extraction specifically. Table 1 outlines the key source terms identified for ISL uranium and non-uranium mining.

TABLE 1. IN-SITU LEACH KEY WORDS IDENTIFIED

Uranium mining	Not uranium mining	Common to both
Uranium Ore Concentrate (UOC), U_3O_8	Gangue minerals	Wellfields
Sandstone hosted roll front	Copper minerals	Leach solution
Ion exchange resin	Ferric sulphate	In-situ leach (ISL), in-situ recovery (ISR), Solution mining
Uranium tenor	Excessive calcium build-up	Solvent extraction (SX)
Yellowcake	Gypsum and jarosite precipitation	Paleochannel
Low permeable sandstone uranium deposits	Gangue dissolution	Chemical oxidants (hydrogen peroxide)
	Gypsum inhibitors	Injection and extraction wells
	Undesirable cations	Carbonate based lixiviants

Analysis for heap leach mining identified many uranium and non-uranium mining activities. Uranium mining utilises both acid and alkaline processes, thus the solvent alone is not a suitable discrete term. Heap leach often produces oxides, sulphides and carbonates which is dependent on the solvent used in extraction. Therefore, key identifying words or phrases for heap leach mining are in relation to the target ore being extracted, in its associated chemical form. Uranyl, and uranyl peroxide were source terms identified with uranium heap leach extraction. Terms identified which linked to non-uranium mining activities relied on metallic reactions to the solvent used, examples were electrolytes, bacterial activity and electrowinning. A detailed list of heap leach terms is outlined in Table 2.

TABLE 2. HEAP LEACH KEY WORDS IDENTIFIED

Uranium mining	Not uranium mining	Common to both
Uranium Ore Concentrate (UOC), U_3O_8	Electro-Winning (EW)	Heap leach (HL)
Radium	Copper oxides, Copper cathodes, Copper sulphide Ore	Direct solvent extraction (DSX) or solvent extraction (SX)
Radon	Gangue metals	Agglomeration
Uranium oxides	Pyrite, Pyrrhotite	Sulphuric acid
Uranyl peroxide (UO_4 H_2O_2)	Nickel, Nickel sulphate, Nickel carbonate, Nickel cathode	Pregnant Liquid Solutions (PLS)
	Zinc	Lixiviant
	Gold	Leach pad
	Cobalt	Hydrogen peroxide
	Electrolytes	
	Fe/Al removal	
	Bacterial activity	

Open cut mining did not provide discrete source terms for uranium extraction in addition to uranium or yellowcake. Therefore, analysis for open cut mining is reliant on the source terms used to differential non-uranium mining. Discrete non-uranium mining terms centred on the extraction of metals using electrowinning, electro refined, floatation and cyanidation. Use of smelters was also linked to non-uranium mining. Table 3 provides the detailed list of terms found in open cut mining literature.

TABLE 3. OPEN CUT MINING KEY WORDS IDENTIFIED

Uranium mining	Not uranium mining	Common to both
Uranium oxide	Gold, copper, lead, zinc, silver	Open pit(s)
U_3O_8	Electrowinning	Stripping
Yellowcake	Electro refined	Waste stripping
	Floatation concentrates/tailings	Waste rock/solid
		Waste
	Slurry	Open cut
	Cyanidation	Crushed ore
	Carbon in-leach circuit	Underground Mining
	Smelter	Furnace
		Hydraulic excavator
		Stope mining

While open cut mining did not provide many uranium mining specific discrete terms, underground mining provided many different terms and phrases to identify uranium mining. These terms were predominately due to the specialised uranium underground mining techniques as well as the requirements for underground radiation protection and safety. Non-uranium mining linked to metal processing through smelters and refineries. A detailed list of underground mining source terms is at table 4.

TABLE 4. UNDERGROUND MINING KEY WORDS IDENTIFIED

Uranium mining	Not uranium mining	Common to both
Surface freeze drilling	Copper, lead, zinc, gold, nickel, cobalt, lithium	Underground mines
Radiation protection	Smelter	Panel cave
Permeable Sandstone	Refinery	Raise-bored
Jet Boring System (JBS)		Cut and fill
Uranium oxide, U_3O_8, uranium		Long hole stoping
Freeze panels		Blasthole stoping
Uranium concentrate		

When analysing the discriminating terms for uranium ore deposits, there were a few key terms that were reoccurring, there are outlined in table 5. Pitchblende, which was the original name used for black uranium oxide minerals back in 1565, is still commonly referred to today for uranium ore deposits. [18] Uraninite was a reoccurring term only used within uranium ore deposits, while sandstone aquifer was very common for the geological conditions for a uranium deposit. [18]

TABLE 5. URANIUM ORE DEPOSIT KEY WORDS IDENTIFIED

Uranium deposits
Uraninite
Pitchblende
Sandstone aquifer

Therefore, in order to provide a thorough training and test data set for a machine learning NLP model, the following discrete terms would be linked to uranium, and non-uranium mining. It should be noted that these discrete terms do not include uranium or other mineral names specifically, however, the terms uranium, uranium oxide, U_3O_8 and yellowcake should also be included in the machine learning dataset.

TABLE 6. DISCRETE IDENTIFYING WORDS

Uranium mining	Non-uranium mining
Sandstone hosted roll front	Smelter
Low permeable sandstone deposit	Refinery
Radiation protection	Electrowinning
Radon	Electro refined
Jet Boring System (JBS)	Cyanidation
Ground freezing	Electrolytes
Uraninite	Bacterial activity
Radium	Cathode
Uranyl peroxide	Gangue metals
Pitchblende	Gypsum and jarosite
Sandstone aquifer	Calcium build up

5. CONCLUSION

In order to support ICORE and the IAEA's machine learning safeguards program, the discrete terms when identifying uranium mining and milling processes rely not just on uranium mining itself, but also on the mining and milling of other minerals in order to provide discrete terms. Words and phrases relating to the geology of uranium deposits also provides key discriminate terms that can aid ICORE's machine learning dataset. By including these key source terms in an NLP algorithm, undeclared uranium mining activities may be identified, thus strengthening nuclear safeguards. Further work should focus on feeding this initial dataset to a machine to train and test it in identifying documentation relating to uranium mining; this machine will learn and evolve as other source terms and patterns emerge which over time will produce a robust machine learning algorithm in support of safeguards activities.

ACKNOWLEDGEMENTS

The authors would like to acknowledge members of the Australasian Institute of Mining and Metallurgy (AusIMM) Uranium Conference 2018 and Australian Nuclear Science and Technology Organisation (ANSTO) Minerals, for providing expertise on uranium specific geological source terms and feedback on mining terminology. An initial discussion with the IAEA ICORE team ensured that this project started in the right direction and would be able to help inform their work in the future.

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