White Paper

Low pH Uranium ISR: Historical Projects, Current Practices and Pathway to Future Use in Wyoming

A White Paper Prepared for:

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EXECUTIVE SUMMARY

This white paper examines *in-situ* recovery (ISR) of uranium and other minerals using low pH systems, summarizes the history and use of low pH ISR in the U.S. and internationally, evaluates low pH uranium ISR within Wyoming's regulatory program, and provides recommendations for its future use at a Wyoming ISR project, the Strata Energy, Inc. (Strata) Ross ISR Project.

New testing results on core samples from Strata's Ross ISR Project suggest the presence of uranium mineral(s) other than the more common forms of uraninite and coffinite. The Cretaceous age host formation at the Ross ISR Project is older than the Tertiary age host formations at other Powder River Basin uranium ISR mines. The unique uranium mineralization and host formation matrix combine to make ISR less efficient than with the alkaline leach methods used in other operating Wyoming uranium ISR mines. This has resulted in lower than anticipated uranium recovery rates.

Strata contracted low pH agitation leach studies on core samples from the Ross ISR Project. The results of these tests indicate that switching to a low pH lixiviant (using a dilute sulfuric or citric acid solution) may increase the recovery to 95 percent within 25 pore volumes, or more than twice the current recovery rate. Laboratory groundwater restoration tests indicate that there is a reasonable assurance that Strata will be able to meet target restoration values after mining with a low pH lixiviant.

Low pH ISR is a safe alternative to alkaline ISR and is used worldwide to recover 96 percent of all uranium produced by ISR methods. Low pH uranium ISR has occurred in Wyoming at research and development facilities and a commercial mine. Based on a review of current and historical projects, low pH lixiviants have technical and economic advantages over alkaline lixiviants in formations with relatively low carbonate content and amenable geology. These advantages include potential for higher recovery, shorter leaching duration, lower lixiviant and oxidant requirements, constituent-specific advantages during groundwater restoration, and a higher degree of natural attenuation than alkaline lixiviant. Two potential disadvantages include difficulty stabilizing pH levels following groundwater restoration and the potential for reduced injectivity in certain scenarios.

The Ross ISR Project is part of the larger Lance Uranium District, which has an estimated resource base of in-place uranium in excess of 50 million pounds. Application of low pH ISR has the potential to increase uranium recovery rates and associated benefits dramatically without compromising public health, worker safety, or the environment.

Section 1 of this white paper addresses the history and general benefits and risks of low pH ISR. Section 2 presents an overview of low pH ISR in Wyoming, Arizona, and internationally. Section 3 describes hydrogeologic, operational, and groundwater restoration considerations for the Ross ISR Project. Section 4 presents considerations for the Wyoming regulatory program, including identifying key aspects of the permit to mine and radioactive materials license that would need to be amended and technical issues that would need to be addressed. Section 5 includes a summary and recommendations.

1.0 BACKGROUND/INTRODUCTION

In-situ recovery (ISR), also known as *in-situ* leach (ISL), of uranium has been used in Wyoming as a uranium extraction method for more than five decades. The Wyoming Department of Environmental Quality-Land Quality Division (WDEQ-LQD), in coordination with the WDEQ-Water Quality Division (WQD), has been regulating ISR following passage of the Environmental Quality Act (Title 35, Chapter 11) in 1973 and through subsequently developed rules, regulations, and guidance. In excess of 47 million pounds of uranium oxide or yellowcake (U_3O_8) have been produced in Wyoming using ISR methods (Ur-Energy 2015; Gregory 2017). Today, all operating uranium mines in Wyoming use ISR methods. Given the relatively low environmental footprint compared to conventional mining, cost effectiveness, and general amenability of many Wyoming uranium deposits to ISR, it appears to be the method of choice for the foreseeable future. In fact, the chairman of the U.S. Nuclear Regulatory Commission (NRC), when voting to increase the license term from 10 to 20 years, recently stated that U.S. uranium recovery facilities “pose inherently low risk” (NRC 2017c). ISR uranium production accounts for almost 50 percent (nearly 80 million pounds per year of U_3O_8) of world production and will undoubtedly be a significant component of the world supply over the long term (International Atomic Energy Agency [IAEA] 2016, World Nuclear Association [WNA] 2017, Woods 2017).

Over the many decades of uranium ISR, a variety of chemical reagents (complexing agents and/or oxidants) have been used to dissolve and mobilize the uranium. These have included alkaline reagents (primarily carbon dioxide or bicarbonate), ammonia (generally in combination with bicarbonate or carbonate), low pH or acid reagents (sulfuric or nitric acid), and oxidants such as gaseous oxygen or hydrogen peroxide. Today, Wyoming ISR operations and other U.S. operations apply alkaline leach methods, typically using a combination of carbon dioxide or sodium bicarbonate along with gaseous oxygen to dissolve and mobilize the uranium. Low pH ISR reagents are used worldwide to recover a variety of minerals, including copper in Arizona and uranium in Australia, Kazakhstan, China, Uzbekistan, and the Russian Federation (IAEA 2016). Of the approximately 77 million pounds of uranium mined by ISR methods worldwide in 2015, 96 percent or 74 million pounds came from facilities using low pH lixiviants (WNA 2017). At this time, no Wyoming uranium ISR operations use low pH lixiviants, although there are no regulatory prohibitions on their use in Wyoming.

The Strata Energy, Inc. (Strata) Ross ISR Project is an operating Wyoming uranium ISR project in Crook County. Its two primary regulatory authorizations include WDEQ-LQD Permit to Mine No. 802 and NRC Source and Byproduct Materials License SUA-1601. These allow Strata to use alkaline reagents for extraction operations, specifically, native groundwater with an alkaline complexing agent (carbon dioxide and/or sodium bicarbonate) and an oxidant (gaseous oxygen and/or hydrogen peroxide). The permit and license authorize Strata to use sulfuric and/or hydrochloric acid for purposes other than for direct extraction of uranium. These purposes include breaking down uranium carbonate complexes within the precipitation circuit at the central processing plant and enhancing injection and recovery wells by dissolving calcite and eliminating bacteria. These acids are also approved to stimulate the deep disposal wells to sustain the wastewater injection rate. The health and safety aspects of the use and storage of concentrated sulfuric and/or hydrochloric acid at the Ross ISR Project are established by the permit and license (Strata 2011a).

Uranium recovery operations at the Ross ISR Project began in December 2015. As of October 2017, there are nine operating header houses in two mine units (Peninsula 2017d). As documented in NRC inspection reports, all operational aspects have been consistent with license requirements in terms of both environmental protection and worker health and safety (NRC 2016, 2017a, 2017b). However, despite extensive pre-startup laboratory leach testing and operational experimentation with well design, well reversals, and well workovers, the uranium recovery rate has been lower than anticipated. It is apparent that the deposit is not fully amenable to the approved alkaline and oxidant ISR reagents.

Strata is currently evaluating the use of low pH lixiviant in laboratory bench tests. The results suggest that the uranium recovery rate may be increased substantially using low pH lixiviant. With an estimated resource base of in-place uranium in excess of 50 million pounds (Strata 2017), utilization of a more appropriate chemical extraction system could lead to longer-term, economically competitive outcomes and other benefits such as increased royalties, tax revenues, and payroll. Application of low pH ISR methods has the potential to increase uranium recovery dramatically without compromising public health, worker safety, or the environment. Operations at the Ross ISR Project would continue to be required to maintain radiological exposures as low as reasonably achievable (ALARA), consistent with NRC regulations in 10 CFR Part 20. Environmental protection requirements, including groundwater target restoration values (TRVs), would remain unchanged and would continue to be enforced through permit and license conditions.

1.1 Purpose of This White Paper

This white paper examines ISR of uranium and other minerals using low pH systems, summarizes the history and use of low pH ISR in the U.S. and internationally, evaluates these reagents within Wyoming's regulatory program, and provides recommendations/paths forward for its future use at a Wyoming ISR project. The purposes of this white paper are to condense abundant publicly available information into a single document, provide specific technical evaluations of the environmental and human health aspects of low pH ISR, and, most importantly, provide a catalyst for engagement, input, and discussions with the regulatory community, area residents, general members of the public, and other stakeholders.

1.2 General Uranium ISR Description

Uranium ISR was developed independently in the U.S. and the former Soviet Union in the early 1960s (IAEA 2001). By the 1970s, uranium ISR mines had been constructed around the world. ISR targets uranium deposits hosted in permeable, water-saturated sandstone formations.

ISR is accomplished by injecting a solution (lixiviant), comprising native groundwater with reagents (alkaline, acid, and/or oxidants), into the host formation containing uranium mineralization. The lixiviant dissolves the uranium and forms a soluble complex with the dissolved uranium, which is pumped out of the formation through a recovery well. The recovered lixiviant is typically processed using ion exchange (IX) resin, which selectively removes the uranium complexes from the solution. The lixiviant is recharged with reagents and injected back into the formation so the process can repeat. There are three primary controls to prevent the spread of lixiviant outside of the mineralized horizon. These include natural geologic confining layers above and below the mineralized horizon, injecting less lixiviant than is withdrawn in order to maintain an inward groundwater flow direction into each wellfield, and implementing a monitor well network that surrounds each wellfield horizontally and vertically. Other than a potential change in an indicator parameter for excursion monitoring, which is addressed in Section 3.2, none of these controls is affected by the choice of lixiviant.

The lixiviant makeup for ISR is highly dependent on the local mineralogy, geology, hydrology, and type of mineralization. Alkaline-based lixiviants have been used extensively in the U.S., although several sites have operated research and development (R&D) or commercial uranium ISR facilities using low pH lixiviants. Low pH uranium ISR has been used and studied extensively around the world since the 1960s.

Low pH mining is of interest to Strata at the Ross ISR Project, where evidence suggests the presence of uranium mineral(s) other than the more common forms of uraninite and coffinite (Strata 2017). Low pH lixiviant has been demonstrated to be more effective at dissolving the uranium mineral(s) contained in this particular deposit. The simplified chemical reactions using sulfuric acid in the presence of oxygen are shown below (IAEA 2001). As described later, other reagents such as citric acid ($C_6H_8O_7$) can also be used.

$$UO_2^{2+}{}_{aq} + SO_4^{2-} \rightarrow UO_2SO_4$$

$$UO_2SO_4 + SO_4^{2-} \rightarrow [UO_2(SO_4)_2]^{2-}$$

1.3 Where Low pH ISR Is Employed

Low pH ISR of uranium and other minerals is used worldwide. Low pH uranium ISR mines are currently in production in Asia and Australia and have been operated historically in Wyoming and Europe. In the U.S., copper mines in Arizona use low pH ISR methods similar to uranium ISR.

Low pH uranium ISR was used commercially at the Pathfinder Mine in the Shirley Basin south of Casper, Wyoming during the 1960s (Ur-Energy 2015). It was also tested at two other Wyoming facilities: the Reno Creek R&D Project and the Nine Mile Lake R&D Project. Descriptions of these projects are provided in Section 2.

The Beverley, Four Mile, and Honeymoon projects are low pH uranium ISR projects in Australia that produced a combined 7,246 metric tons (16.0 million pounds) of U_3O_8 from 2007-2016 (WNA 2017). Australia's first uranium ISR facility, the Beverley Mine, operated from 2000 to 2014. The Four Mile Project is a satellite to Beverley. Production at the Four Mile Project began in 2014 and has averaged approximately 1,000 metric tons (2.2 million pounds) of U_3O_8 annually. Loaded IX resin is trucked from Four Mile to the Beverley processing plant for stripping, elution, precipitation and drying. The Honeymoon Mine operated from 2011 to 2013 but has been placed on care and maintenance due to low commodity prices and high operating costs.

Low pH uranium ISR using dilute sulfuric acid solution accounts for almost all of the uranium mined in Kazakhstan, the world's largest producer of uranium at 28,980 metric tons (63.9 million pounds) U_3O_8 in 2016 (WNA 2017). Low pH ISR is also used on a commercial scale in Uzbekistan, the Russian Federation, and China (IAEA 2016, Woods 2017). Historically, it was also used in Eastern European countries including Bulgaria, the former Czechoslovakia, and East Germany. Although low pH ISR is used around the world, this paper generally focuses on U.S. and Australian ISR projects due to the similarities in regulatory institutions, political structure, and social factors.

In addition to uranium, low pH mining solutions have also been used at U.S. copper mines. Earlier methods primarily relied on blasting or previous mining activities such as block caving to fragment or increase the permeability of the host rock prior to applying the leaching solution (Briggs 2015). These were associated with former underground or surface mines and are not analogous to uranium ISR. Since the mid-1970s, numerous copper mines have employed or have plans to employ low pH ISR without fragmentation prior to leaching. An example is the San Manuel Mine in Arizona, which recovered copper in the 1980s and 1990s using "well-to-well" (a wellfield with both injection and recovery wells) ISR methods that included a dilute sulfuric acid lixiviant and closely spaced injection and recovery wells (Briggs 2014).

1.4 General Benefits/Risks

Compared to alkaline lixiviants, low pH lixiviants have the potential to recover a higher percentage of uranium (including uranium that is resistant to other methods), require less lixiviant injection, require a shorter duration of ISR operations, result in lower radium levels, and result in a higher degree of natural attenuation during restoration (IAEA 1993, 2001).

Low pH lixiviants have technical and economic advantages over alkaline lixiviants in formations that are amenable to low pH solutions (especially those with low carbonate content). Low pH leaching has the potential to recover a higher percentage of uranium (70-90 percent versus 60-70 percent for alkaline leaching), uranium recovery requires fewer pore volumes (PVs) of lixiviant injection, it requires a shorter leaching duration, radium is less soluble in a sulfate medium than bicarbonate medium, it requires less oxidant, and the low pH lixiviant has a higher degree of natural attenuation during restoration (IAEA 2001). Low pH lixiviant is also effective at dissolving uranium that is resistant to other methods such as uranium contained or coated by other minerals (IAEA 1993). The relative disadvantages of low pH compared to alkaline lixiviants include higher chemical costs (especially in formations with carbonate content greater than 1.5-2 percent), risk of well screen and formation plugging due to gypsum precipitation and gas bubble formation, need to use corrosion-resistant materials and equipment, and the higher concentration of most dissolved constituents in the wellfield, which potentially present added challenges for groundwater restoration following mining (IAEA 1993, 2001).

2.0 LOW pH ISR PROJECT OVERVIEW

This section presents a brief history of low pH ISR in Wyoming, including commercial-scale and R&D projects that operated from the early 1960s through the early 1980s. Although the R&D projects demonstrated successful groundwater restoration in accordance with the standards of the day, these projects were generally characterized by broad variations in well construction techniques and operating parameters that often resulted in injectivity issues and poor uranium recovery. This was characteristic of R&D ISR projects during the development of ISR technology. This section also describes modern uranium ISR projects in Australia and Kazakhstan, which all use low pH lixiviants and where they have learned to overcome the early challenges of low pH ISR. Improvements after the initial R&D phase of low pH ISR have been made in well design, pumping arrangements, and lixiviant composition (Woods 2017). This section concludes with an overview of low pH copper ISR in Arizona, where state and federal permits have recently been granted for a project that is analogous to uranium ISR with respect to mining techniques, fluid control during mining, excursion monitoring, and groundwater restoration.

2.1 Pathfinder Mine

Project Summary

The Pathfinder Mine in the Shirley Basin of Carbon County, Wyoming was operated by Utah Construction and Mining Company (UCMC)/Pathfinder Mines Corporation (PMC). Three different mining techniques – underground (1960-1963), low pH ISR (1963-1970), and surface (1970-1992) – were used at the Pathfinder Mine. Underground mining had trouble resulting from unconsolidated ore sands and groundwater inflow. The geologic and hydrologic conditions that challenged underground mining were identified as positive qualities for ISR. Commercial low pH ISR began in 1963 and continued until

1970, when ISR operations were discontinued due to dewatering for open-pit mining (Ur-Energy 2015).

Geology/Hydrogeology Summary

The Shirley Basin is a small structural basin associated with the uplift of the Granite and Shirley mountains to the west and southwest and the Laramie Mountains to the east and northeast during the Laramide Orogeny. Post-Laramide Tertiary sediments were unconformably deposited on an eroded surface of mid-Cretaceous strata. In the Shirley Basin, the roll front uranium deposits are hosted by the Eocene-age Wind River Formation. The Wind River Formation is a fluvial depositional system that consists of sequences of medium to coarse-grained arkosic sandstones interbedded with claystones, clayey siltstones, and thin lignites. Uranium mineralogy was identified as uraninite and possibly coffinite (Ur-Energy 2015).

Operation Summary

ISR operations began at the Pathfinder Mine in 1963 using a low pH sulfuric acid-based lixiviant (IAEA 1993). Throughout 7 years of ISR, approximately 1.5 million pounds of U_3O_8 were recovered (Ur-Energy 2015). UCMC experimented extensively with lixiviant chemistry, wellfield design, and wellfield patterns in efforts to optimize uranium recovery (IAEA 1993). Environmental compliance during operations was consistent with the regulatory framework in place at the time.

Restoration Summary

Groundwater restoration at Pathfinder Mine is a unique case. ISR activities were halted due to widespread dewatering associated with the open-pit mine construction that began in the late 1960s. The surface mining progressed through and removed the former ISR production zone (Ur-Energy 2015). For these reasons, groundwater restoration following ISR was not a consideration at the Pathfinder Mine.

2.2 Reno Creek R&D Project

Project Summary

Rocky Mountain Energy Company (RMEC) operated the Reno Creek R&D Project in the Powder River Basin. R&D activities were conducted in two well patterns, Pattern I (1979) and Pattern II (1980-1981). The Pattern I test used a sulfuric acid-based lixiviant. Pattern II was a 6-spot pattern that tested an alkaline lixiviant (Staub et al. 1986).

Geology/Hydrogeology Summary

The Reno Creek R&D Project is located on the eastern flank of the Powder River Basin, with the uranium mineralization hosted in fluvial sands of the Eocene-age Wasatch Formation. The primary uranium minerals in the un-oxidized portion of the Reno Creek R&D Project are coffinite and uraninite (AUC 2016). The Wasatch Formation consists of approximately 1,600 feet of interbedded fluvial sandstones, siltstones, shales, claystones, and coals. The ore bearing sands range from 10 to 110 feet thick at a depth of 280 to 400 feet. The host sands have a high buffering capacity due to the presence of carbonate minerals found as scattered lenses throughout the area (AUC 2013).

Operation Summary

Pattern I was a 5-spot well pattern with injection wells about 40 feet from a centrally located production well. Throughout the test (February to November 1979), RMEC injected sulfuric acid, which was diluted in the lixiviant to a concentration of about 5 grams/liter (pH 1.8). Hydrogen peroxide was used as an oxidant (Staub et al. 1986).

The Pattern I test was discontinued due to low uranium recovery, reduced wellfield efficiency, and relatively high acid consumption caused by the buffering capacity of the host sands. Gypsum precipitation in the aquifer and scaling in the wells reduced wellfield efficiency and affected both mining and restoration of the Pattern I area (Staub et al. 1986). Formation plugging due to gypsum precipitation is attributed at least partially to the high carbonate content in the host sands. In contrast, the carbonate content of the host sands at the Ross ISR Project is low (Knode 2017). Gypsum is formed when low pH lixiviant reacts with carbonate to release calcium ions, which bond with the sulfate ions released through the dissolution of sulfate minerals and the decomposition of the sulfuric acid-based lixiviant.

Restoration Summary

Lixiviant injection in Pattern I was discontinued on November 12, 1979. The geochemical problems that affected uranium recovery – formation plugging and scaling in wells due to gypsum precipitation – also made groundwater restoration more difficult.

Initial restoration began with the injection of barren solution from the ion exchange columns. Approximately 0.7 PV, or approximately 968,000 gallons of fluid, were produced and approximately 389,000 gallons of fluid were injected in this phase of restoration. Groundwater sweep followed. From December 1979-March 1980, approximately 2.1 PVs (2.9 million gallons) of fluid were recovered without reinjection. The initial restoration and groundwater sweep increased the pH from 1.8 to about 5.0. Use of groundwater sweep as a stand-alone restoration method is not consistent with approved groundwater restoration methods at the Ross ISR Project (see Section 3.1).

RMEC installed a water treatment circuit in March 1980 to reduce the concentration of hydrogen ions further. RMEC stated that the hydrogen ions replaced the calcium in clays within the host sandstone and could not be removed by groundwater sweep (Staub et al. 1986). RMEC began injecting potassium salts to buffer the acid and increase the groundwater pH. RMEC later modified the treatment circuit to add calcium hydroxide ($Ca(OH)_2$) into the injection stream in an effort to increase the pH further. Approximately 1.8 PVs (2.4 million gallons) of groundwater were removed, of which, approximately 1.7 million gallons were treated and reinjected into the host sandstone. This phase of restoration lasted for approximately one year until March 1981. It was reported that the pH did not increase above about 5.0, and gypsum precipitation and well scaling hampered restoration efforts. In June 1981, WDEQ approved a period of stabilization monitoring without active restoration to observe the effect of natural geochemical processes on production aquifer water quality. By first quarter 1983, pH levels remained relatively low (slightly above 5.0), and the concentrations of uranium and other constituents remained above baseline levels (Staub et al. 1986). However, by March 1986, NRC acknowledged stabilization of the groundwater of Pattern 1 and signed off on the adequacy of groundwater restoration (AUC 2012).

2.3 Nine Mile Lake R&D Project

Project Summary

RMEC operated the Nine Mile Lake R&D Project north of Casper in Natrona County, Wyoming under a cooperative agreement with the U.S. Bureau of Mines (USBM) (Nigbor et al. 1982). Through laboratory agitation leach testing of core samples, it was determined that the host sands were amenable to low pH ISR using a sulfuric acid lixiviant with hydrogen peroxide oxidant. RMEC constructed four test patterns and a central processing plant (CPP) at the site. Field leach testing took place from November 1976 through November 1980, using low pH lixiviant in three patterns and alkaline lixiviant in the fourth. Groundwater restoration was conducted in all four R&D test patterns (Staub et al. 1986). The Nine Mile Lake R&D Project was the first restoration of a pilot-scale acid-leached ore body in the U.S. (Engelmann et al. 1982).

Geology/Hydrogeology Summary

The uranium host formation for the Nine Mile Lake R&D Project is the Teapot Sandstone, the uppermost member of the Cretaceous Mesaverde Formation (Nigbor et al. 1982). Uranium occurs in roll front-type deposits approximately 10 feet thick. The uranium mineralization was identified as primarily uraninite (UO_2) with minor amounts of coffinite. The Teapot Sandstone is medium to fine grained and fair to well sorted. It is made up of >90 percent quartz, <5 percent feldspar, and minor amounts of mica, glauconite, carbonaceous fragments, and clay minerals. Much of the feldspar has decomposed to kaolinite, which makes up approximately 2 to 5 percent of the sand. Montmorillonite is present in minor amounts, but it has been identified as having a low cation-exchange capacity. The carbonate content of the sand is very low, typically less than 0.1 percent.

At the site, the Teapot Sandstone dips to the east at 2 to 6 degrees, is approximately 500 feet deep, and is 50 to 80 feet thick (Nigbor et al. 1982). The Teapot Sandstone is locally divided into two sand units separated by a thin (2 to 4 feet) semipermeable layer of shale and lignite. Uranium mineralization is present in both the upper and lower sand units. The Teapot Sandstone is underlain by the Pumpkin Buttes Shale and overlain by the Lewis Shale.

Operation Summary

Low pH laboratory agitation leach tests on core samples of the ore from the site demonstrated 80 to 85 percent uranium recovery, which was comparable to tests using ammonium bicarbonate/carbonate and sodium bicarbonate/carbonate (Nigbor et al. 1982). A low pH (dilute sulfuric acid) lixiviant was selected for three of the four field leach patterns due to the low carbonate content of the host sand (<0.1 percent), to avoid the clay swelling potential of sodium bicarbonate/carbonate and to avoid restoration difficulties with ammonia.

RMEC installed and operated four well patterns. Injection and recovery wells consisted of 5-inch PVC well casing cemented in place and perforated with the USBM's water-jet perforator (Nigbor et al. 1982). A brief summary of the operation of four patterns follows, with emphasis placed on Pattern 2, which provided the best analogue for modern ISR operation and restoration techniques.

Pattern 1 was a 7-spot well pattern (six injection wells spaced 50 feet away from a central recovery well), with wells fully penetrating both sand units (Nigbor et al. 1982). The lixiviant averaged approximately 4 g/L of sulfuric acid (pH 1.7), 0.5 g/L of hydrogen peroxide, and 0.15 g/L of ferrous sulfate as an additional oxidant. Approximately 7 PVs of lixiviant were injected over a 10-month period in 1976-77 (Staub et al. 1986). Results of this first leaching test were described as "disappointing" and included problems with PVC well casing, pumps, gypsum buildup on injection wells, possible channeling, and poor injectivity (Nigbor et al. 1982).

Pattern 2 was a 5-spot well pattern with four injection wells spaced 34 to 57 feet from a central recovery well (Nigbor et al. 1982; Engelmann et al. 1982). Acid-resistant epoxy cement was used in the lower portion of the wells, with Portland cement used for the remainder. The wells were completed only in the mineralized portion of the lower sand unit, making this pattern the best analogue for modern ISR completions. During the leaching phase, the lixiviant solution strength was increased gradually to minimize clogging from reaction products. The sulfuric acid concentration was increased from 0.15 g/L to 5 g/L, resulting in a decrease in the pH of the injectate from 3.9 to 1.6. There was a delay of some 7 weeks before beginning hydrogen peroxide addition, after which the concentration was increased from about 80 to 1,000 mg/L. The uranium concentration in the production solution averaged 70 to 120 mg/L throughout most of the leaching phase. The concentrations of other constituents in the recovery solution at or near the end of leaching included a pH of about 2, vanadium of 700-800 mg/L, sulfate of 6,000-8,000 mg/L, calcium of 200-300 mg/L, and electrical conductivity of 10,000-15,000 µmhos/cm. Nigbor et al. reported relatively low concentrations of radium-226, arsenic, and selenium, which they noted may be an advantage of a sulfuric acid lixiviant compared to an alkaline lixiviant. Pattern 2 produced approximately 13 PVs of fluid over 9 months in 1977-78 (Staub et al. 1986). Injectivity was generally good, although limited occurrences of reduced injectivity due to gypsum precipitation were encountered. One possible explanation for this is the relatively low acid concentration (0.15 g/L initial concentration, which is 1/167th of the initial concentration used in the Strata leach tests discussed in Section 3.2). Using inadequate acid or gradually changing the pH during low pH ISR increases the gypsum precipitation potential. Adding acid at a higher initial concentration, such as used in Strata leach tests, rapidly reduces the pH and minimizes the risk of formation plugging due to gypsum precipitation. This is verified in Kazakhstan ISR operations (see Section 2.5), where low pH ISR has not resulted in irreversible well or formation plugging due to gypsum precipitation despite a relatively high carbonate content in the mineralized sandstones.

Pattern 3 was a modified 7-spot pattern completed in both the upper and lower mineralized sand units (Nigbor et al. 1982; Staub et al. 1986). It consisted of six injection wells spaced 60 feet from two central recovery wells. Each of the injection wells was completed across both sand units, whereas the recovery wells were completed in either the upper or lower sand unit. Pattern 3 was designed to test the possibility of mining both sand units simultaneously, but differing hydraulic properties resulted in an imbalance in injectivity between the two sands. It was operated over a 6-month period in 1979-80, during which 5.6 PVs were recovered. The lower sand was successfully leached, with an average uranium grade of 75 mg/L, but leaching in the upper sand was discontinued when an excursion was detected due to the flow imbalance. The lixiviant was composed of dilute sulfuric acid with either oxygen or hydrogen peroxide. In addition, peroxymonosulfuric acid (H_2SO_5; also known as Caro's acid), purported to act as a leaching agent and oxidant, was tested. Sporadic problems encountered at Pattern 3 were well plugging, frozen lines, equipment failures, and difficulties controlling lixiviant distribution between the two sand units (Staub et al. 1986).

Pattern 4 was a 5-spot pattern that used a sodium carbonate/bicarbonate lixiviant along with carbon dioxide to maintain the pH at approximately 7.5 and two different oxidants (hydrogen peroxide and oxygen). The test results were reportedly "disappointing" (Staub et al. 1986). The fact that RMEC encountered problems with both low pH and alkaline lixiviants suggests that injectivity problems were more likely attributed to the lack of experience with uranium ISR than with specific issues caused by the lixiviant chemistry.

Restoration Summary

Groundwater restoration at the Nine Mile Lake R&D Project began after leaching operations ended within each pattern. Following is a summary of groundwater restoration efforts within Patterns 1, 2, and 3 (the three patterns leached with low pH lixiviant). Pattern 1 restoration began with approximately 12 PVs of groundwater sweep, during which groundwater was pumped intermittently from the pattern area and disposed of in an evaporation pond. After the groundwater sweep, water quality had been restored to near baseline levels except for calcium, sodium, sulfate, chloride, and magnesium. This was followed by about 2.5 years of inactivity, during which the TDS increased, primarily due to gypsum dissolution. A second phase of groundwater restoration followed. It involved treating about 2.5 PVs of groundwater using reverse osmosis (RO) and reinjecting the treated water (permeate) back into the pattern. The two restoration phases resulted in water quality improvements to near baseline levels followed by gradual deterioration and stabilization at higher TDS levels (Staub et al. 1986).

During the initial groundwater restoration phase in Pattern 2, 11.5 PVs were pumped from the wellfield and treated or disposed (Staub et al. 1986). The injection solution used for restoration consisted of about 75 percent native groundwater unaffected by leaching operations and 25 percent treated water from a water purification circuit that included neutralization, calcium precipitation, and RO (Engelmann et al. 1982). Sodium carbonate was briefly injected to raise the pH. This was discontinued after several days but followed by sodium hydroxide injection for more gradual pH increase.

Although nearly all major water quality parameters were restored to baseline levels during the initial period of restoration, subsequent monitoring indicated scattered areas of contaminated groundwater remaining in the aquifer. A second phase of groundwater restoration commenced. During that phase, 3.5 PVs were treated using a lime/barium chloride precipitation process and reinjected, and another 3.5 PVs of groundwater sweep was conducted, bringing the total restoration volume to 18 PVs. As of June 1984, all constituents except vanadium, radium-226, and TDS had been restored to near baseline levels (Staub et al. 1986).

Restoration in Pattern 3 involved pumping groundwater out of the wellfield, treating the water using RO, and reinjecting permeate along with native groundwater in the pattern. Restoration efforts included 6 PVs of groundwater and resulted in restoring water quality to baseline ranges or better except for uranium, vanadium, and radium-226 in some interior wells (Staub et al. 1986).

2.4 Australian ISR Projects

Project Summaries

Low pH ISR was first used commercially in Australia at the Beverley Mine owned by Heathgate Resources Pty Ltd (Heathgate) in South Australia (WNA 2017). Field leach testing began at the Beverley mine in 1998 and commercial operations in late 2000. When the main Beverley deposit became depleted, production moved to the nearby Beverley North and Four Mile satellite projects, also owned by Heathgate or a subsidiary. Loaded IX resin from the Beverley North and Four Mile satellites is trucked to the Beverley CPP for processing. Production at the Beverley wellfields was suspended in December 2013, and production at the Beverley North satellite was suspended in 2014.

Uranium One, under a joint venture with Mitsui, began low pH commercial ISR operations at the Honeymoon Mine in South Australia in 2011 (WNA 2017). After only about 2 years of operations, it was placed on care and maintenance in 2013 due to low uranium prices and high operating costs. The Honeymoon Mine was sold in 2015 to Boss Resources Lt. (Boss), who prepared a preliminary feasibility study in 2017 with the intent to resume production in 2019 (WNA 2017).

Geology/Hydrogeology Summaries

The uranium deposits at the Beverley, Beverley North, and Four Mile projects are paleochannel or alluvial fan deposits hosted in Tertiary age sandstone formations (WNA 2017). The hydrogeology in the vicinity of the Beverley Mine consists of three main aquifers: a surficial aquifer (Willawortina Formation), the production zone aquifer (Namba Formation), and an underlying aquifer (Great Artesian Basin) (Heathgate 2017). The water quality of the production zone aquifer is poor. Sulfate levels typically exceed the stock water guideline of 1,000 mg/L, and TDS ranges from about 3,000 mg/L in the north to 12,000 mg/L in the south (Heathgate 2017, WNA 2017). This poor water quality generally means that the groundwater is unsuitable for any use beyond industrial. Groundwater within the production zone aquifer is characterized as “semi-stagnant” (very slow lateral flow) (CSIRO 2004).

The uranium mineralization at the Honeymoon Mine is hosted within paleochannel deposits located in the Tertiary age Eyre Formation. The Yarramba paleochannel, which hosts the Honeymoon deposit, occurs at an average depth of 230 feet and includes approximately 180 feet of uncemented, poorly consolidated, interbedded sands and clays (Boss 2017). Similar to the Beverley deposits, the mineralized paleochannels of the Eyre Formation are low in carbonate content at Honeymoon (CSIRO 2004). The production aquifer is saline (typical TDS 20,000 mg/L) and unsuitable for any uses other than industrial.

Operation Summaries

Operations began at the Beverley mine in 2000 utilizing a low pH lixiviant, and in excess of 8,200 metric tons of U_3O_8 (18 million pounds) were produced over the life of the mine until 2014 (WNA 2017). The Four Mile satellite produced approximately 2,723 metric tons of U_3O_8 (6.0 million pounds) in its first three years of operations (2014-2016). Sulfuric acid was used in the Beverley project and satellite facilities to reduce the production zone pH to approximately 2.0 to 3.0 during mining, and hydrogen peroxide or oxygen were used as oxidants (WNA 2017).

The Honeymoon Mine produced approximately 312 metric tons of U_3O_8 (688,000 pounds) from 2011-2013 before being placed on care and maintenance (WNA 2017). The lixiviant includes sulfuric acid in a sufficient quantity to reduce the pH to approximately 2-2.5 and sodium chlorate ($NaClO_3$) as an oxidant (Boss 2017). Due to high sodium chloride levels in the production aquifer, which limit the effectiveness of ion exchange resins, the uranium is stripped from the recovered lixiviant using solvent extraction instead of the more traditional ion exchange (CSIRO 2004, Boss 2017). Solvent extraction is typically used in locations where the groundwater TDS levels are too high for ion exchange to operate efficiently.

Restoration Summaries

Restoration at the Beverley Mine and satellite projects begins with the decommissioning of wellfields through abandoning and capping wells, removing surface piping, and revegetating disturbed areas (WNA 2017). Upon closure of the mine facilities, the processing plant and associated facilities will be removed and the land will be returned to its pre-mine use. Since the production aquifer was not suitable for any uses other than industrial use prior to ISR and has no foreseeable use after uranium recovery is completed, the aquifer will be restored through monitored natural attenuation (MNA). Groundwater monitoring must be conducted for 7 years after mining to demonstrate that natural attenuation expectations are being met (CSIRO 2004).

> "Natural attenuation processes result in gradual changes in the pH and chemical compositions of mining-affected groundwaters towards natural background values. Natural attenuation is caused by hydrodynamic dispersion, mixing with other groundwaters and physical-chemical reactions between the fluids and aquifer minerals." (Commonwealth of Australia 2010)

Within 10 years of the cessation of mining, Heathgate is required to demonstrate, through monitoring, clear and unambiguous achievement of the closure outcomes (Heathgate 2017). Through natural attenuation alone, pH is expected to increase to its original level of 7 over time (WNA 2017).

The approved groundwater restoration method at the Beverley North satellite includes a staged enhanced natural attenuation (Heathgate 2016). The staged approach employs monitored enhanced natural attenuation, which provides a mechanism to determine if additional remediation is required in the future. The enhanced attenuation includes an active "groundwater flush" consisting of approximately 1 PV of groundwater sweep at the closure of each wellfield. Heathgate estimates that this will increase the pH from 1.7 to 2.0-2.2 and reduce the uranium concentration by a factor of 3. Monitoring and predictive model recalibration will occur as necessary based on the results of the flush and subsequent modeling. Heathgate has proposed a 5-year decommissioning period to be followed by an additional 2 years of groundwater sampling and other environmental monitoring. The total monitoring period will be reviewed with the regulatory authorities and may be extended.

The Honeymoon Mine will follow key rehabilitation strategies when the mine closes (Boss 2017). First, Boss will decommission and remove all mine facilities from the site. Then, soil surfaces will be stabilized, and disturbed areas will be revegetated. Finally, groundwater will be monitored to ensure the successful attenuation of impacted groundwater. MNA will be employed to ensure that contaminants associated with mining are removed or reduced in concentration below stock water limits within 1.2 miles of the lease boundary. Groundwater quality data collected from the monitoring network will be used to assess the fate of the mining fluids and validate predictive attenuation models for a duration of 3 to 5 years (Boss 2017).

2.5 Kazakhstan ISR Projects

Overview

Kazakhstan is the world's leading uranium producer with approximately 40 percent of world production and 12 percent of the world's uranium resources (WNA 2017). ISR of uranium in Kazakhstan commenced commercially in the late 1970s, with all production based on low pH (dilute sulfuric acid) leaching (IAEA 2016). All uranium development (exploration, production, or both) is done through the national operator of the uranium market, Kazatomprom. Kazatomprom wholly owns and operates five mines, and another 12 are operated through joint ventures with foreign equity holders (WNA 2017). The majority of the projects lie in two areas, the Chu-Sarysu and Syrdarya basins of south-central Kazakhstan (Boytsov 2014). Within the Chu-Sarysu basin lie some of the largest ISR projects in the world in terms of production capacity and resources. The mines of the Chu-Sarysu basin produced about 20,000 metric tons U_3O_8 (47 million pounds) in 2016 (WNA 2017).

Geology/Hydrogeology Summary

The primary host sediments in the uranium-rich Chu-Sarysu basin are Late Cretaceous and Paleogene horizons (Boystov 2014). Composed of fine- to medium-grained sandstones, they typically occur at depths of 100-300 meters (330–980 feet), although some are as deep as 800 meters (2,600 feet) (CSA 2013, WNA 2017). In addition to the mineralized sandstone intervals, the host formations also contain more coarse sediments (gravel and pebble beds) as well as compacted silts and clays. Carbonate concentrations within the host sediments are reported to be relatively high compared to Australian low pH ISR deposits (WNA 2017). One project reported carbonate concentrations of 0.5 to 1 percent (CSA 2013).

Operation Summary

Operations at uranium ISR mines in Kazakhstan typically follow a standard design used by Kazatomprom (CSA 2013). Solutions are pumped from the wells to the plant or ponds, then processed using ion exchange, denitrification, precipitation, and yellowcake drying. Irreversible well or formation plugging due to precipitation of gypsum are not known to be issues at these facilities. Gypsum precipitation is operationally controlled through the injection of hydrochloric or nitric acid or through mechanical well stimulation such as airlift pumping or pneumatic-impulse treatment (Gorbatenko 2013). The ISR process in Kazakhstan is generally similar to that used in Australia and the United States, except that more acid is generally used per pound of uranium produced in Kazakhstan compared with Australia due to higher carbonate content (WNA 2017).

Restoration Summary

Restoration and remediation information from ISR in Kazakhstan is limited, but remediation programs are required (IAEA 2016). The operators must pay particular attention to conservation of resources and the environment. Through the contracts issued by the government, operators are required to reclaim the disturbed area, pay fines for environmental contamination, submit a remediation program with estimated costs to remove facilities and equipment, and establish a remediation fund proportional to the total investment (exploration and operation). Groundwater restoration is achieved through MNA, with results from one site (Irkol) indicating complete restoration of four main parameters (pH, sulfate, nitrate, and uranium) within 12 years (Yazikov and Zabaznov 2000, Boytsov 2014). The effectiveness of MNA following low pH ISR demonstrates the low risk of off-site contaminant migration.

2.6 Low pH ISR of Copper in the United States

Project Summary

Historically, low pH leaching of copper ore has been done through a heap leach system or in mines where block caving has taken place (Briggs 2015). Although these methods utilize similar chemical reactions as well-to-well ISR, they do not provide a good analogue for uranium ISR.

In 1986, Magma Copper began a pilot low pH ISR program at the San Manuel mine in Arizona to determine the practicality of using this method for copper recovery from oxidized mineralization (Briggs 2014).

A production test facility for a low pH ISR copper project in Florence, Arizona has recently been permitted by the U.S. Environmental Protection Agency (EPA 2017) and the Arizona Department of Environmental Quality (ADEQ 2013). It is permitted to use well-to-well methods to recover copper from a shallow aquifer, much like an ISR uranium mine.

Operation Summary

Two types of ISR were used at the San Manuel Mine, well-to-well and well-to-underground (Briggs 2014). The well-to-well ISR, which is similar in design to a traditional uranium ISR mine, used closely spaced injection and recovery wells and was employed on open pit mining benches. The well-to-underground ISR was accomplished by trickling a low pH solution from a well through the caved zone in block caving mining and recovering the lixiviant from sumps and dams located on the lowest levels of the underground mine. In both methods of ISR, the lixiviant was recovered and processed at a solvent extraction plant. ISR recovery of copper at the San Manuel mine reached a high in 1990 and produced 12,500 tons in that year alone.

The recently permitted Florence production test facility will use a low pH lixiviant comprising 99.5 percent water mixed with 0.5 percent sulfuric acid

(ADEQ 2013). As with a uranium ISR facility, it is required to maintain an inward hydraulic gradient and monitor surrounding aquifers for potential water quality impacts. The estimated injection zone depth is 500 to 1,185 feet below ground surface.

Restoration Summary

The well-to-well ISR at the San Manuel Mine occurred on open pit mining benches, and many of the wells were mined through, negating any need for restoration (Briggs 2014). The underground mining operations were suspended in 2002 and following the salvaging of underground equipment the pumps were turned off and the underground workings were allowed to flood.

Groundwater restoration is required for the Florence production test facility after the mining phase is complete (ADEQ 2013). A process called “mine block rinsing,” which consists of injecting formation water with neutralization agents, is required until the pH is at least 5.0 and the sulfate concentration is less than 750 mg/L. This is followed by 1 year of stabilization monitoring within the production zone. At least 5 years of post-closure monitoring are required to ensure that compliance limits for arsenic and other constituents are not exceeded in downgradient compliance wells.

3.0 ROSS ISR PROJECT CONSIDERATIONS

3.1 Ross ISR Project History

Project Summary

The Ross ISR Project is an operating uranium ISR facility in Crook County, Wyoming. It is the first commercial ISR project within the Lance Uranium District, which was discovered in the early 1970s. An R&D uranium ISR project was operated within what is now the Ross ISR Project in 1978-79 by Nubeth, a joint venture between Nuclear Dynamics and Bethlehem Steel Corporation (Strata 2011b).

Peninsula Energy Ltd (Peninsula) acquired mineral holdings in the Lance Uranium District in 2007-08. Strata incorporated in 2009 as a wholly owned subsidiary of Peninsula and permitted and licensed the Ross ISR Project. Commercial uranium production began in December 2015.

Geology/Hydrogeology Summary

The uranium mineralization at the Ross ISR Project is located in sandstones of the Upper Fox Hills Formation and Lower Lance Formation. The production zone aquifer is saturated and confined above and below by low-permeability shales. Within the project area, the thickness of the production zone aquifer ranges from 100 to 180 feet, and the depth to the top of the aquifer ranges from 250 to 660 feet. Structural dips within the permit area are measured at 1 to 2 degrees west (Strata 2011b).

Uranium mineralization at the Ross ISR Project occurs in roll front and tabular ore deposits. The average dimensions of the mineral deposits are 115 feet wide, 8.9 feet thick and 2,000 to 3,000 feet long, with an average grade of 500 ppm as U_3O_8 (Strata 2011b). Evidence suggests the presence of uranium mineral(s) other than the more common uraninite and coffinite (Strata 2017). A petrographic analysis of a core sample collected in 1977 shows that it contains less than 1 percent carbonate (Strata 2011b). This is supported by additional core samples collected by Strata since 2010, in which carbonate concentrations in the mineralized sandstone range from 0.001 to 1 percent (Knode 2017). A carbonate value of less than 1.5 to 2 percent is considered appropriate for mining with a low pH lixiviant (IAEA 2001).

Regionally, the groundwater in the project area follows the formation dip and flows from the outcrops in the east towards the synclinal axis of the Powder River Basin in the west. Within each active mine unit, an inward groundwater flow direction is maintained by Strata's requirement to inject less water than is recovered from each mine unit. Based on the pre-operational water samples from 46 production or injection wells within the two operating mine units, the production zone aquifer has moderate TDS levels (1,200-2,500 mg/L), low calcium concentrations (2-9 mg/L) and moderate sodium (430-870 mg/L), bicarbonate (400-680 mg/L), and sulfate (400-1,320 mg/L) concentrations (Strata 2015, 2016b).

Operation Summary

Strata commenced uranium recovery operations at the Ross ISR Project in December 2015. As of October 2017, there are nine operating header houses in two mine units. Operations from the two mine units have produced over 200,000 pounds of U_3O_8 (Peninsula 2016a, 2016b, 2017a, 2017b, 2017c, 2017d). Through the 3rd quarter 2017, Strata has not detected any excursions in the perimeter, underlying, or overlying monitoring wells (NRC 2016, 2017a, 2017b).

Restoration Methods and Commitments

Following uranium recovery operations in each mine unit, Strata is required to restore the groundwater quality on a parameter-by-parameter basis. Specifically, Wyoming Statute 35-11-103(f)(iii) defines "groundwater restoration" as the "condition achieved when the quality of all groundwater affected by the injection of recovery fluids is returned to a quality of use equal to or better than, and consistent with the uses for which the water was suitable prior to the operation by employing the best practicable technology." In addition to the Wyoming requirement to restore groundwater to the prior class of use, Strata's NRC license requires the concentration of each constituent to be returned to its pre-operational baseline level or a maximum contaminant level (MCL), whichever is higher, or an alternate concentration limit, in accordance with 10 CFR Part 40, Appendix A, Criterion 5B(5). Prior to initiating operations within each mine unit, Strata establishes target restoration values (TRVs) for 35 to 40 constituents including major ions, metals, other trace elements, and radionuclides. TRVs are established as the pre-operational baseline level or TRV, whichever is higher (Strata 2011a).

> Following uranium ISR, groundwater would need to be "returned to a quality of use equal to or better than, and consistent with the uses for which the water was suitable prior to the operation" (W.S. 35-11-103(f)(iii)).

Strata's approved groundwater restoration program stems from the successes and lessons learned from other ISR facilities in similar hydrogeologic settings. It includes up to four active groundwater restoration phases (Strata 2011a):

1. Groundwater sweep (targeted or selective);
2. Groundwater transfer;
3. Reverse osmosis treatment with permeate injection; and
4. Groundwater recirculation.

When groundwater has been restored to meet TRVs, Strata is required to conduct stability monitoring for at least 12 months to demonstrate that the restored production zone aquifer is chemically stable. The groundwater restoration and stability monitoring results are then submitted for regulatory approval prior to decommissioning each mine unit (Strata 2011a). Strata has not yet initiated groundwater restoration activities at the Ross ISR Project, since uranium recovery operations are ongoing in all active mine units.

3.2 Ross ISR Project Laboratory Testing Using Low pH Lixiviants

Objectives and Methodology

Strata contracted R and D Enterprises, Inc. (RDE) to conduct low pH agitation leach studies on core samples collected within the Ross ISR Project. The studies were conducted to evaluate how quickly the ore reacts to the leaching agents and the potential uranium resource recovery. The groundwater restoration potential was also evaluated using laboratory procedures that simulated the authorized groundwater restoration processes (internal Strata studies).

To evaluate how quickly the ore reacts and potential uranium recovery, core samples were tested under a staged, batch approach. A bottle roll leach test procedure based on processes currently used in Asia and Australia was used. Lixiviants were prepared using native groundwater from the production zone aquifer that was fortified with acid both with and without hydrogen peroxide as an oxidant. Most of the tests involved sulfuric or citric acid, but other low pH reagents were also tested, including acetic acid and phosphoric acid. One test also involved a sodium bicarbonate lixiviant fortified with hydrogen peroxide to compare low pH with alkaline leach test results on the same core sample.

The lixiviant was contacted with blended core in batches simulating 5 PVs of ISR. After a predetermined time, the liquid was separated from the core using a high-speed centrifuge, and the extracted solution was tested for uranium and other constituents. This process was repeated using fresh lixiviant until the desired number of PVs was tested. The recovered core was dried, ground and analyzed for uranium. This was used along with the analysis of the uranium concentration in each batch of extracted solution to estimate the overall percent recovery.

Multiple groundwater restoration simulations were also conducted using batch leach testing methods. The recovered core from the leaching bottle roll tests were used in the simulations along with production zone groundwater (to simulate groundwater sweep) and laboratory-synthesized RO permeate solutions. The groundwater restoration simulations involved 5 PVs of simulated groundwater sweep followed by 5 PVs of simulated RO permeate injection. This concluded with a simulated stabilization period.

Uranium Recovery Summary

The low pH agitation leach studies demonstrated much higher uranium recovery percentages and rates compared with alkaline leach tests and mine unit operations at the Ross ISR Project. Using sulfuric acid at an initial concentration of 25 g/L (1.4 percent by volume) for the first 5 PVs, decreasing to less than half this amount for the remainder of the tests, 95 percent of the uranium was recovered within 25 PVs. Peak recovery grades averaged nearly 1,000 mg/L, and average solution grades were approximately 300 mg/L. The uranium recovery percentage, recovery grade, and recovery rate were virtually indistinguishable in the tests using sulfuric acid with or without hydrogen peroxide.

The tests using citric acid with hydrogen peroxide performed very similarly to those using sulfuric acid. The uranium recovery rate was 95 percent within 25 PVs using citric acid along with an oxidant. The initial citric acid concentration was 50 g/L for the first 5 PVs, decreasing to less than half this amount for the remainder of the tests. The solution head grades were also very similar using citric acid with an oxidant compared with sulfuric acid.

Other low pH reagents that were tested achieved inferior results to sulfuric acid and citric acid with an oxidant. These included acetic acid (with and without oxidant), phosphoric acid (with and without oxidant), and citric acid without oxidant.

The laboratory leach studies demonstrate that the ore at the Ross ISR Project is much more amenable to low pH lixiviants than alkaline lixiviants. Laboratory leach studies using an alkaline lixiviant with oxidant only yielded about 35 percent uranium recovery within 25 PVs, which is confirmed by commercial operations averaging 40 percent recovery after 25 PVs (Peninsula 2017d). These comparisons demonstrate that more than twice as much uranium many be recoverable using low pH lixiviants. The fact that the recent alkaline leach studies yielded similar recovery rates to commercial operations after the same number of PVs of lixiviant injection supports the finding that the leach studies are representative of field conditions.

The laboratory leach studies are also useful in evaluating the effectiveness of the currently authorized excursion monitoring parameters. For the perimeter and overlying monitoring wells, these include electrical conductivity, total alkalinity, and chloride. Sulfate is used instead of chloride in the underlying monitoring interval due to the high natural chloride levels in that interval (Strata 2011a). The low pH laboratory leach studies show that conductivity will still be an effective indicator parameter. Similarly, the chloride concentration would increase within the production zone due to the ion exchange process regardless of whether a low pH or alkaline lixiviant is used. However, the alkalinity will be reduced within the production zone, which means that elevated alkalinity would no longer be an appropriate excursion indicator. Strata could consider modifying its permit and license to use sulfate in place of alkalinity or to use a lower control limit for alkalinity in place of the current upper control limit.

Restoration Summary

Laboratory groundwater restoration studies support the conclusion that the groundwater can be restored following low pH ISR using currently authorized methods. The results of the groundwater restoration studies using core samples previously leached with low pH lixiviants were compared with the TRVs for the first two mine units (internal Strata studies). The vast majority of the TRVs were achieved during simulated groundwater restoration (groundwater sweep followed by RO permeate injection). This included major ions, uranium, other trace elements, and radionuclides. For example, the uranium concentration was reduced by more than two orders of magnitude to levels well below the TRVs during simulated groundwater restoration following leaching with a sulfuric acid-based lixiviant.

The laboratory groundwater restoration studies suggest that it may take longer to achieve TRVs if citric acid is used instead of sulfuric acid in the low pH lixiviant. Although the pH rebounded more quickly during the citric acid groundwater restoration studies, the concentrations of some constituents remained above TRVs. On the other hand, the only constituent that consistently remained above TRVs in the dilute sulfuric acid groundwater restoration studies was iron. Iron is a non-hazardous constituent for which there is no health-based water quality limit. It is commonly found in Wyoming groundwater, and proven treatment methods are available to remove iron (e.g., adsorption on ion-selective media). Even if the TRV for iron or another constituent were not achieved during groundwater restoration, federal regulations in 10 CFR Part 40, Appendix A, Criteria 5B(5) and (6) would allow Strata to apply for an alternate concentration limit after demonstrating that the concentration is ALARA and that there is no risk to public health or the environment.

Although it is impossible to replicate long-term stability in laboratory tests, the same is true for the currently authorized alkaline lixiviant. Strata will be required by performance-based permit and license conditions to achieve groundwater stability regardless of the lixiviant used. The laboratory groundwater restoration studies conducted to date suggest that adequate demonstration of groundwater stability will depend on achieving and maintaining a consistent pH level in the restored aquifer. To reduce groundwater consumption, this may require the addition of a pH-buffering reagent such as sodium bicarbonate or sodium hydroxide during one or more groundwater restoration phases.

Conclusions

The laboratory testing using low pH lixiviants shows that the ore at the Ross ISR Project is much more amenable to low pH lixiviants than alkaline lixiviants. Uranium recovery was 95 percent within 25 PVs using groundwater fortified with sulfuric acid or citric acid with an oxidant. This is more than twice the uranium recovery observed within a similar number of PVs in alkaline leach tests and at the two operating mine units at the Ross ISR Project.

The optimal low pH lixiviant for the Ross ISR Project ore, based on leaching and groundwater restoration studies, is one comprising native groundwater fortified with sulfuric acid. The initial concentration of 25 g/L sulfuric acid represents approximately 1.4 percent concentrated acid by volume in the lixiviant. Therefore, about 98.6 percent of the lixiviant would be made up of groundwater. The acid concentration can be reduced after the initial leaching phase without raising the pH in the production zone.

The groundwater restoration tests showed that there is reasonable assurance that TRVs are achievable using currently authorized groundwater restoration methods following low pH ISR and that they will be achievable sooner if the lixiviant includes sulfuric acid instead of citric acid. Successful demonstration of stability following groundwater restoration will depend on achieving a relatively neutral and stable pH level. The TRVs would not need to be modified, since they are dependent on the pre-operational baseline groundwater quality rather than the lixiviant makeup.

4.0 CONSIDERATIONS FOR THE WYOMING REGULATORY PROGRAM

This section describes regulatory considerations for low pH uranium ISR in Wyoming. Although the State of Wyoming has authorized commercial and

R&D low pH ISR projects, there have not been any such authorizations within the past 30 years or more. During that time, there have been significant changes in the Wyoming regulatory program with more changes anticipated (especially Wyoming's application to NRC to become an Agreement State with respect to regulation of source material associated with uranium mining or milling and 11e.(2) byproduct material). Following is a description of Wyoming's uranium recovery regulatory program and an evaluation of specific elements of a uranium ISR permit to mine and license that would need to be modified to accommodate low pH uranium ISR.

4.1 Wyoming's Uranium Regulatory Programs

Passage in 1973 of the Wyoming Environmental Quality Act, or "the Act" (Title 35, Chapter 11 of the Wyoming Statutes [W.S.]), by the Wyoming legislature initiated oversight of virtually all mining operations by the State and created the WDEQ (W.S. § 35-11-104). Statutory oversight relevant to uranium ISR can be found in W.S. §§ 35-11-103, 403-406, 410-412, 415-424, and 426-436. The Act authorized WDEQ to promulgate rules and regulations (R&R) in support of the Act. For ISR, these are found primarily in Noncoal R&R Chapter 11, with additional requirements in Noncoal R&R Chapters 2, 3, 7, and 8. Definitions applicable to the R&R are found in Noncoal R&R Chapter 1. WDEQ also has issued guidance documents relevant to ISR, especially Guideline No. 4, In Situ Mining (Noncoal). With over 40 years of oversight, WDEQ has accrued institutional wisdom through a long history regulating the uranium ISR industry. All Wyoming uranium ISR facilities are required to obtain a permit to mine from WDEQ-LQD, which is one of the two primary regulatory authorizations.

The second primary regulatory authorization required for a Wyoming uranium ISR facility is a radioactive materials license. Such licenses are currently issued by the NRC as source and byproduct materials licenses under the authority of the Atomic Energy Act of 1954, as amended. However, in February 2015, Wyoming submitted a letter of intent to the NRC to become an Agreement State with respect to regulation of radioactive materials found at uranium ISR facilities. Once approved, WDEQ-LQD, under a newly created Uranium Recovery Program (URP), will assume authority for radioactive materials licenses for uranium ISR facilities. Statutory authority will be found in W.S. 35-11-2001 *et seq*. At this time, the URP R&R are in draft form under review by NRC, having been approved by the Wyoming Environmental Quality Council (EQC) in August 2017. Wyoming anticipates receiving Agreement State authorization in late 2018 (WDEQ-LQD 2017). Therefore, this white paper is based on the URP rather than NRC reviewing a potential radioactive materials license amendment application to accommodate low pH uranium ISR. However, as an Agreement State, the Wyoming regulatory program will need to be at least as stringent as the NRC program with respect to regulation of radioactive materials. In light of this requirement, it is important to note that NRC regulations and guidance do not prohibit low pH ISR.

4.2 Permit and License Approvals Needed for Low pH Mining

The Pathfinder Mine operated the first low pH uranium ISR project in Wyoming prior to Wyoming's regulation of uranium mining. Subsequent to the passage of the Act, WDEQ-LQD issued permits to mine for two low pH uranium ISR R&D projects, the Reno Creek and Nine Mile Lake R&D projects. Today, the use of low pH lixiviant for uranium ISR similarly would require WDEQ-LQD authorization, either as a new permit to mine or through the significant or major revision (herein referred to as a major revision) process to an existing permit to mine. WDEQ-LQD Guideline 24 provides guidance for complex permitting actions, such as a change from alkaline to low pH lixiviant. It is anticipated that a change to low pH lixiviant for an existing ISR facility would require a major revision to the permit to mine under the criterion in Noncoal R&R Chapter 11, Section 19(b)(i):

> Any material or substantial alterations or additions to the facility which occurred after issuance of the permit or license…

The process for a major revision to a permit to mine, as outlined in Guideline 24, includes: 1) initial contact with the WDEQ-LQD permit coordinator, 2) a pre-application meeting to discuss the nature of the major revision and develop an action plan for developing a proposed permit action document, 3) development of the major revision application package, 4) one or more subsequent meetings with the permit coordinator and other appropriate staff as necessary to follow up on action plan outcomes, and 5) one or more draft review meetings for WDEQ-LQD staff to review draft documents prior to formally submitting the major revision package. The major revision application package would need to include an application form, any necessary baseline information to be added to the appropriate Appendix D documents, and Mine Plan and Reclamation Plan replacement pages to update currently approved pages in the permit to mine. A major revision would be subject to public notice and opportunity for public hearing in accordance with Noncoal R&R Chapter 7, Section 2.

The radioactive materials license for a new or existing uranium ISR facility would also need to accommodate the use of low pH lixiviant. Following NRC approval of Wyoming's Agreement State application, a new license or amendment would be accomplished through the URP within WDEQ-LQD. This white paper assumes that an existing license would be revised through the amendment process. Guideline 24 recommendations would also be utilized to amend a radioactive materials license. Similar to the major revision, the licensee would: 1) meet with the URP project manager (PM) and provide appropriate briefing materials, 2) prior to submitting the amendment package, the licensee and PM would meet to discuss the nature of the amendment and develop an action plan, 3) develop the amendment request package as draft, 4) review with the PM and other appropriate staff as necessary draft components of the amendment request, and 5) prepare and submit the amendment request package. Section 4.6 of this white paper describes the components of the amendment request package. Upon completing review of the license amendment application, including requests for additional information as warranted, the URP will provide notice to the public of an initial draft decision, where the license amendment application is approved, approved with conditions, or denied. This will be accompanied by a public comment period. A public hearing also may be held upon written request from an "aggrieved party," as defined in W.S. § 35-11-103(a)(vii). The final decision by the URP would be subject to review by the EQC and judicial review in accordance with Wyoming Law.

In summary, two separate regulatory actions would be necessary to use low pH lixiviant at an existing Wyoming ISR facility: 1) a major revision to the permit to mine and 2) an amendment to the radioactive materials license. It is not anticipated that any changes would be needed to Strata's Class I Underground Inspection Control (UIC) permit for wastewater disposal. Following approval of the Wyoming Agreement State program by NRC, the reviews would be done within WDEQ-LQD by two separate groups, and the public would be afforded two separate opportunities to comment and/or request a public hearing.

4.3 Mine and Reclamation Plan Revisions

The Mine Plan is the operating plan within the permit to mine. It establishes the extent to which the mining operation will disturb or change the lands to be affected by mining (W.S. § 35-11-406). The major revision to the Mine Plan would need to indicate how low pH lixiviant would be used for uranium ISR. Specific issues to address in the revised Mine Plan include: description of the mining chemistry; changes to wellfield operations; changes to the make-up of the lixiviant; changes to post-mining groundwater quality; prevention of well and formation plugging; compatibility with piping and equipment; compatibility with existing wastewater management facilities; suitability of deep disposal of wastewater; ability to re-mine areas previously mined with alkaline solutions; suitability of excursion detection parameters; changes to header house plumbing and piping; compatibility of instrumentation and control network; transportation, storage, and containment of the low pH reagent; changes to the effluent control systems; and any potential environmental impacts not previously addressed.

The Reclamation Plan is the portion of a permit to mine that describes how affected lands and aquifers will be restored to the proposed future uses (W.S. § 35-11-406). Revisions to the Reclamation Plan that would be necessary for low pH ISR include: groundwater restoration methods and timing; changes to the water balance during groundwater restoration and the number of PVs required to complete restoration; post-mining/pre-restoration groundwater quality; and changes to the method of estimating surety. Groundwater restoration methods and surety estimates would be the primary focus of changes to the Reclamation Plan. Although TRVs established for operating mine units and TRV calculation methods for future mine units would not change with the use of low pH lixiviant, the groundwater restoration methods and number of PVs needed to restore the groundwater to the TRVs may change.

4.4 Implications to Other Permit to Mine Sections

In addition to revising the Mine and Reclamation plans to accommodate low pH ISR, several baseline or Appendix D sections would also be revised. Appendix D5 establishes the geologic baseline for the project and would be updated through the major revision to include more measurements of the carbonate content of the host material as well as more recent analysis of the uranium minerals. Appendix D12 provides the Statement of Basis for the aquifer exemption and includes a wide range of information in support of that process. Some of the information is duplicated from the Mine Plan, including mineralogy, geochemistry, and groundwater monitoring for excursions. Appendix D12 would be updated through the major revision in order to be consistent with the Mine Plan.

4.5 Nexus for Other State or Federal Programs, Restoration and Surety Estimates

The major revision necessary for low pH ISR is primarily an update to the Mine and Reclamation plans. In addition, as previously discussed, Appendix D12 would also be updated. Since the major revision would not alter or increase the area of the exempted aquifer, changes to Appendix D12 would be limited to revising the uranium recovery description and any other areas needed to make Appendix D12 consistent with the revised Mine Plan. In this scenario, WDEQ-LQD would likely consult with WDEQ-WQD regarding the major revision to ensure compliance with WDEQ-WQD programs. If so, it would be helpful for WDEQ-WQD staff to participate in one or more pre-application meetings.

4.6 Radioactive Materials License Implications

Draft URP R&R Chapter 4 details the requirements for amending a license. The focus of the URP review would be the implications for worker health and safety, public health and safety, and the environment associated with using low pH reagents, including specific radiological hazards. Fundamental to the license amendment application would be the procedures to maintain exposure to radioactive materials and radiological releases ALARA. The license amendment package would need to include a description of the proposed license changes, an evaluation of potential environmental impacts, an evaluation of potential radiological and non-radiological impacts to public health and the environment, an updated financial assurance estimate, and a demonstration that decontamination, decommissioning, and groundwater restoration will be done in conformance with the requirements in 10 CFR Part 40, Appendix A. The license amendment package would need to include a Technical Report (TR) that would supplement or update the currently approved TR. It would describe changes in the uranium recovery and processing methodologies, changes to chemical storage and handling procedures, mitigation of any potential public health and environmental impacts from increased low pH reagent transportation, changes to waste disposal procedures, changes to the worker exposure monitoring programs, changes to groundwater restoration methods, changes to emergency response protocols, changes to approved effluent and environmental monitoring programs, and any other changes necessary to protect workers, public health and safety, and the environment.

The Ross ISR Project has an NRC-approved restoration action plan (RAP), which is a stand-alone document that compiles relevant groundwater restoration methods, decommissioning requirements, and financial assurance cost estimates (Strata 2016a). This allows regulators and other stakeholders to access and review this information in one document rather than having to search through the various documents that contain the license commitments. The RAP and financial assurance estimate are updated annually and would be updated as necessary to accommodate low pH ISR.

Potential implications to worker health and safety, public health and safety, and the environment under the jurisdiction of the URP include changes in the radionuclide composition of the lixiviant and impacts from releases of low pH solutions. Alkaline lixiviants typically contain the solubilized uranium and radium complexed with carbonate. In a low pH lixiviant, other radionuclides in the uranium decay series are mobilized including thorium-230. For instance, the Nine Mile Lake pilot project reported that thorium increased more than radium (Nigbor et al. 1982). This aspect has implications for radiation safety since the Derived Air Concentration for thorium-230 is significantly lower than that for natural uranium and radium-226, potentially requiring more stringent control measures for airborne radioactive materials. On the other hand, radium-226 is less soluble in a sulfate medium than a bicarbonate medium. In any event, the application will need to discuss the implications of any changes in the radionuclide composition of the lixiviant on radiation safety measures. Releases of low pH lixiviant could affect soil pH and may require revisions to standard operating procedures for spills or leaks.

With regard to public health and safety, the transportation of low pH reagents would need to be addressed. For the Ross ISR Project, procedures are currently in place to transport and offload hydrochloric and sulfuric acid. Nevertheless, the additional low pH reagent shipments would need to be evaluated. Generally, a transition to low pH ISR would result in a decrease in the number of shipments of bicarbonate, oxygen, and carbon dioxide that would offset the traffic due to the increase in acid shipments. All shipments to and from the Ross ISR Project would continue to follow all applicable U.S. Department of Transportation rules and regulations.

5.0 SUMMARY AND RECOMMENDATIONS

5.1 Low pH ISR History and Precedent

Low pH uranium ISR is used throughout the world, with 96 percent (74 million pounds U_3O_8) of the 2015 uranium ISR production coming from low pH operations (WNA 2017). It accounts for almost all of the uranium mined in Kazakhstan, the world's largest uranium producer. It is also used in Australia, China, Uzbekistan, and the Russian Federation. Within the U.S., low pH ISR has been used historically for commercial and R&D uranium projects, and it continues to be authorized for Arizona copper mines. Although Wyoming has a history of low pH uranium ISR dating back to the 1960s, today all Wyoming uranium ISR projects use alkaline leach methods.

Based on a review of current and historical projects, low pH lixiviants have technical and economic advantages over alkaline lixiviants in formations with relatively low carbonate contents and amenable geology. These include the potential for higher uranium recovery (including the ability to dissolve uranium that is resistant to alkaline leaching), shorter leaching duration with less lixiviant, lower oxidant requirement, constituent-specific advantages during groundwater restoration (e.g., radium), and a higher degree of natural attenuation during restoration. Two potential disadvantages include the ability to achieve stable pH levels following groundwater restoration and the potential for reduced injectivity in certain formations.

5.2 Implications for the Ross ISR Project

The primary potential advantage in using low pH lixiviant at the Ross ISR Project is increased uranium recovery in a shorter time. Much of the uranium mineralization is occluded within the sandstone matrix and resistant to alkaline leach methods. Laboratory leaching studies indicate that the uranium recovery rate may more than double by switching from alkaline to low pH lixiviant. The most effective low pH lixiviant, based on uranium recovery and groundwater restoration laboratory testing, is native groundwater fortified with less than 2 percent (by volume) sulfuric acid. This will reduce the pH to within the range of 1.5-2 during uranium recovery.

In order for low pH ISR to be effective (i.e., to avoid excessive acid consumption and the potential for reduced injectivity), the carbonate content of the ore zone should be less than about 1.5-2 percent. Core sample analyses from the mineralized sandstones within the Ross ISR Project show that the carbonate content is consistently below 1 percent. Strata management has operational experience using low pH lixiviants in Australia and Kazakhstan—this experience would allow Strata to overcome the Wyoming R&D project injectivity issues, which were related to lack of operational experience, by using proven low pH ISR technology such as proper well construction techniques, rapid decrease in pH, and maintaining a stable pH throughout operations. Further, the ionic strength of the production aquifer groundwater is much lower than that in typical Australia projects where gypsum precipitation has been a concern. The typical TDS is 1,200-2,500 mg/L at Ross, compared with TDS levels of 3,000-20,000 mg/L at the Australian projects. Lower ionic strength results in reduced potential for precipitation of gypsum and other minerals.

Since low pH ISR would require less lixiviant and a shorter leaching duration, it would lessen the environmental impact of all project aspects that depend on the duration of ISR operations. These include water, energy, and chemical consumption; worker exposures; and traffic impacts.

Another potential advantage of low pH ISR is the ability to restore the production zone aquifer following uranium recovery. Leach studies support the conclusion that the groundwater can be restored following low pH ISR using currently authorized methods (primarily groundwater sweep and RO permeate injection). These leach studies demonstrate reduction in the concentration of uranium and other constituents at or below TRVs.

Although the ability to maintain stable levels of pH and pH-sensitive water quality parameters such as alkalinity has been identified as a potential disadvantage of low pH ISR, minimizing the potential for the long-term migration of constituents out of the production zone is an advantage of low pH lixiviants compared to alkaline lixiviants. There are at least three reasons for this. First, radium is less soluble in a sulfate medium than a bicarbonate medium. Second, little or no oxidant is required with low pH ISR, which reduces the potential dissolution and migration of selenium and other heavy metals. Third, carbonate forms more soluble complexes with uranium than sulfate, which means that the potential for uranium migration is greater in an alkaline environment than one that is higher in sulfate (EPA 1999). Side-by-side laboratory groundwater restoration studies following low pH versus alkaline leaching would be useful to identify which parameters are easier to restore following low pH ISR and which parameters may require special consideration. For example, the laboratory groundwater restoration studies conducted for the Ross ISR Project show that specific treatment may be needed to reduce the iron concentration following low pH ISR.

The fact that the Ross ISR Project already uses and is authorized to use sulfuric and/or hydrochloric acid for other purposes, including uranium processing, well maintenance activities, and deep disposal well stimulation, means that many of the standard operating procedures for safe transportation and use of low pH reagents are already in place. Nevertheless, Strata will perform an extensive evaluation of any potential impacts to worker safety, public health, and the environment before switching to a low pH lixiviant.

5.3 Recommendations

In order to conduct low pH uranium ISR at the Ross ISR Project, it will be necessary to submit a major revision to the permit to mine, issued by WDEQ-LQD. It will also be necessary to amend Strata's radioactive materials license.

The latter review would be performed by the URP within WDEQ-LQD. These permit and license amendments would be needed to ensure that proper procedures are in place to safely conduct low pH ISR, ensure exposure to radioactive materials and radiological releases remain ALARA, and provide reasonable assurance that groundwater TRVs will be met and stability will be achieved following groundwater restoration. No changes in the groundwater TRVs are anticipated, since they depend on the baseline groundwater quality rather than the lixiviant chemistry.

Low pH uranium ISR has been used historically in Wyoming, and there are no prohibitions on its use today. However, significant coordination between Strata, area residents, WDEQ-LQD, and other stakeholders will be needed, since low pH uranium ISR has not been used for many years.

This white paper is a starting point for stakeholder outreach that will continue throughout the permitting process. Strata intends to coordinate with stakeholders and continue to provide information to educate and address the public's questions and concerns about low pH uranium ISR.

Strata has begun the process of agency coordination with a presentation on the potential benefits of low pH ISR at the Ross ISR Project (Strata 2017). Beyond this white paper, Strata proposes collaborative development (with WDEQ-LQD) of support material for the license amendment and major revision. The collaboration would come through the process described in Guideline 24 and would result in a technical analysis to support the changes necessary to accommodate the use of low pH lixiviant. Table 1 provides some key technical issues for the two permitting actions and potential high-level conceptual resolutions to be more fully explored through the regulatory process.

Table 1. Summary of Potential Technical Issues and Conceptual Resolutions

Technical Issue	Potential Resolution
Water management infrastructure compatibility	Pond liner resistant to low pH; additional pre-treatment prior to deep injection
Well, piping, and process infrastructure compatibility	Minor changes necessary, although most of the currently installed piping and infrastructure is compatible with low pH reagents
Instrumentation and control network compatibility	Minor changes necessary, although most of the currently installed piping and infrastructure is compatible with low pH reagents
Occupational and public health implications	Additional control measures and standard operating procedures necessary
Acid transportation and storage	Described in approved permit and license; potential environmental and public health and safety impacts of increased acid transportation to be evaluated
Uranium recovery and processing implications	Address any changes if needed in the ion exchange or uranium processing circuits within the central processing plant
Injection well and formation injectivity	Plan for and manage the rate of pH decrease and methods to stabilize the pH during ISR; continued injection pressure monitoring/reporting
Ability to achieve groundwater TRVs and stability following low pH mining	Demonstrate through laboratory groundwater restoration studies (enhanced as needed to address agency concerns)
Adequacy of excursion detection parameters	Identify appropriate parameters with upper or lower concentration limits
Low pH ISR execution plan	Evaluate areas for initial commercial use of low pH lixiviant
Groundwater use and consumption	Evaluate potential impacts of any changes in proposed groundwater restoration methods or duration
Spill assessment and remediation	Revise spill assessment and remediation procedures
Updates to restoration action plan (RAP)	Amend RAP to address any changes in groundwater restoration methods and financial assurance estimate

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