CIM Uranium Leading Practice Guidelines

Prepared by the CIM Mineral Resources & Mineral Reserves Committee

DRAFT

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1. INTRODUCTION

1.1. Abbreviations, Terms, and Definitions

Abbreviation/Term	Definition
BP	Best practice
Aquifer	An underground formation of permeable rock, rock fractures or unconsolidated materials that contains water
Aquitard	A bed of low permeability along an aquifer
CIM	Canadian Institute of Mining, Metallurgy and Petroleum
CPS	Counts per second
Decay product	Element that results from the radioactive decay of a parent element
Disequilibrium	An imbalance between the true uranium content in a given volume of mineralized rock versus that measured by radioactivity emitted by it.
ESG	Environmental, social and governance
eU_3O_8 or eU	Equivalent $\%U_3O_8$ or %U content derived from radiometric measurement
GT	Average grade x thickness of a mineralized interval
IAEA	International Atomic Energy Agency
ISR	In situ recovery (formerly referred to as in situ leach (ISL))
K	Hydraulic conductivity. A measure of how easily a fluid can pass through porous materials, soil or rock. It is dependent on intrinsic permeability of the porous material, the degree of saturation and on the density and viscosity of the fluid.
k	Intrinsic permeability. A quantitative property of porous material characterizing its ability to transmit a fluid under a potential gradient.
K-factor	Tool-specific factor obtained from a calibration facility used to convert measured gamma counts per second to equivalent grade uranium (eU or eU_3O_8)
Lixiviant	A liquid medium used in hydrometallurgy to extract elements from its ore. In ISR, is comprised of a complexing agent and in most cases, an oxidant.
L/S	Liquid to solid ratio of amount of solution required to reach the target extraction of a commodity in a given mass
MRMR	Mineral Resources and Mineral Reserves
NEA	Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD)
NI 43-101	National Instrument 43-101 *Standards of Disclosure for Mineral Projects*
PFN	Prompt fission neutron method of uranium measurement
PV	Pore Volume. A measure of the fluid content within a given volume of saturated sandstone.
Red Book	Bi-annual publication by NEA and IAEA of uranium resources, production, and demand
Redox zone	Zone where oxidation and reduction chemical reactions are occurring
REF	Radioactive equilibrium factor. The ratio between chemical U_3O_8 or U versus radiometric U_3O_8 or U. Sometimes referred to as disequilibrium factor (DEF).
RPEEE	Reasonable prospects of eventual economic extraction
Static water table	Water level under normal, undisturbed, no-pumping conditions
Transmissivity	The rate at which groundwater flows horizontally through an aquifer
Vadose zone	Undersaturated portion of the subsurface that lies above the groundwater table
Well pattern	In situ recovery term alluding to number and orientation of injection wells

	which introduce lixiviant and recovery wells which extract the loaded solution
QA	Quality assurance
QC	Quality control
Yellowcake	Uranium concentrate end-product obtained from processing

1.2. Review of Best Practice Guidelines

On January 9, 2018, the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Council formed the CIM Mineral Resources and Mineral Reserves Committee (CIM MRMR Committee), which is a combination of the previous Standing Committee on Reserve Definitions and the Best Practices Committee. As part of its mandate, the CIM MRMR Committee's is to update guidelines for use by Industry including the Uranium Practice Guidelines.

The 2022 CIM Uranium Practice Guidelines were adopted by CIM Council on **month/year/date** and supersedes the 2003 version.

The main principles and guidelines relating to preparation of Mineral Resource and Mineral Reserve (MRMR) estimates are provided in the CIM Estimation of Mineral Resources and Mineral Reserves Best Practices Guidelines (MRMR BP Guidelines, as updated from time to time). The MRMR BP Guidelines provide information pertaining to metalliferous and other deposits and many sections are readily applicable to the preparation of MRMR estimates for uranium deposits. However, additional guidance is appropriate for uranium deposits due to the radioactive nature of uranium, and its amenability, in some cases, to in situ recovery (ISR) mining methods.

1.3. General Considerations

1.3.1. Radioactive Nature of Uranium

Uranium is a radioactive element that naturally decays via a decay series ending as stable Pb-206 and Pb-207. Natural radioactive decay occurs when an unstable (radioactive parent) isotope transforms to another isotope by emitting an alpha or a beta particle. The decay of some isotopes is also accompanied by the emission of excess energy in the form of gamma radiation. Uranium, and its associated decay products' radioactive properties can be assessed by data collection techniques involving measurement of gamma radiation. This process can be used during exploration in the determination of an equivalent grade during MRMR estimation, as well as for grade control and ore sorting to provide cost-effective timely measurements and beneficiation during mining. However, this characteristic, its chemical properties and potential related health effects, imposes additional environmental, health and safety challenges at all stages of uranium projects: exploration, evaluation, mining, processing and post-mining remediation (OECD, 2014).

1.3.2. Market Considerations

The Practitioner preparing uranium MRMR estimates should be aware that the uranium concentrates market has several attributes that set it apart from other metals. Uranium concentrate is not traded in significant quantities on a commodity exchange and is characterized by a high degree of producer concentration. Producers consist of both commercial and state-owned entities (World Nuclear Association, 2022) with sales being principally based on bilaterally negotiated long-term contracts covering nuclear power plant requirements. In addition, the spot market serves a small portion of discretionary demand, which in recent years has seen increased interest from financial funds. Entrants into the market (as a producer) are often faced with high environmental, social and governance (ESG) related requirements and challenges. These factors can impose limits or constraints on achievable market volumes and introduce significant regulatory permitting hurdles leading to lengthy development timelines.

Market considerations for Mineral Resource estimation are generally less comprehensive and include only those items that are relevant to the "Reasonable Prospects for Eventual Economic Extraction (RPEEE)" requirement for a Mineral Resource as defined in the CIM Definition Standards. A discussion regarding those considerations that can satisfy the RPEEE requirement of a Mineral Resource is presented in Pressacco, Evans, and Postle (2023). For both Mineral Resources and Mineral Reserves, project production rates and realized commodity price assumptions should align with what the market can reasonably bear (for additional guidance, see the CIM Guidance on Commodity Pricing and Other Issues related to Mineral Resource and Mineral Reserve Estimation and Reporting, as amended from time to time).

Customer specifications for uranium products are based on both physical properties and chemical characteristics for the mineral. Sample testing should include those tests that will provide the physical characteristics and chemical analyses that relate to the specifications of the end product. For example, natural uranium contains only 0.711% U-235, the "active" isotope in nuclear reactions, with the remainder largely being U-238 with minor U-234. Instances of deviations from the U-235 value of 0.711%, the result of natural fission reactions in high-grade deposits, are rare, but do occur. Deviations from isotopic and/or chemical specifications may be of concern to the industry because of radiological implications in fuel fabrication. It is advisable to conduct isotopic analysis for U-235 and U-234 in new districts or deposits, as warranted, since deviations may impact marketability.

1.3.3. In Situ Recovery Mining Method

With the in situ recovery mining method (ISR), sometimes referred to as in situ leaching, the host formation is selectively flooded with a water-based alkaline or acidic chemical solution that solubilizes the uranium in place with the loaded solution subsequently pumped to the surface for processing. Compared to other mining methods, ISR mining does not generate tailings or waste rock and generally results in low surface disturbance.

ISR of uranium now represents the majority of total world production and while it is typically applied to mineralization within sandstone-hosted roll-front type deposits, it is being explored as a potentially viable mining method for other types of uranium deposits.

Parameters pertinent to the ISR mining method are not necessarily applicable in the same fashion as for conventional mining methods (e.g., tonnage, minimum mining widths, cut-off grade, dilution and recovery) and consequently, a significant portion of this document is focused on guidance related to ISR-amenable deposits.

2. MINERAL RESOURCE ESTIMATION

2.1. Uranium Deposit Types

Uranium deposits occur in a broad range of geological environments globally. While other classifications are sometimes used, the IAEA geological classifications, as amended from time to time, are the most widely used. The most recent version was released in 2013 and has been adopted since 2014 in the biannual publications Red Book (International Atomic Energy Agency, 2020). This classification is also used in the IAEA's Geological Classification of Uranium Deposits and Description of Selected Examples publication (International Atomic Energy Agency, 2018). The classification groups uranium deposits into 15 major types based on their geological setting, with some categories having several sub-types. The 15 deposit types have fundamental characteristics and recognition criteria, and in that respect, while mainly named by host rock, the types are essentially empirical models, based on observable characteristics.

2.2. Disequilibrium

The presence of uranium is routinely detected and measured in field applications by monitoring and recording gamma radiation. However, uranium itself is not a significant gamma emitter; instead, gamma emission derives from some of the intermediate decay products of the U-238 isotope, primarily Bi-214 and Pb-214. This method of uranium measurement necessarily assumes that the parent U-238 and the gamma emitting decay products are in secular equilibrium. This means that decay has progressed sufficiently such that all the decay products are now disintegrating at the same rate as they are being produced, and that the ratio between the parent isotope and decay products remains stable. If this condition is not met, a state of disequilibrium is present, whereby there is an imbalance between the uranium content in a given volume of mineralized rock and that measured by the radioactivity emitted by it. For this reason, radiometric measurement of uranium by gamma radioactivity is considered an indirect, or equivalent, measure of uranium.

Since the gamma emitting decay products come late in the U-238 decay series, equilibrium may require from 0.5 to 1.7 million years to become established. Consequently, a state of disequilibrium may occur if the uranium deposition is geologically young and sufficient time has not yet elapsed for secular equilibrium to be established. In this case, a deficiency of decay products relative to uranium will cause an underestimation of uranium content if measured by radiometric methods. Since the establishment of equilibrium requires that all the constituents within the decay series remain in-place, disequilibrium also occurs when uranium or its decay products are completely or partially removed from the system. This situation may arise due to differential geochemical mobility between the parent uranium and its decay products. In the case where parent uranium has been removed, leaving the decay products in place, an overestimation of uranium content will occur if radiometric methods are utilized.

Under disequilibrium conditions, the measurement of uranium content by gamma radiometric methods may not be accurate, and the true content may be higher or lower than that determined by gamma radiometric methods. This is particularly common in sandstone-hosted uranium or other deposits which occur within a dynamic hydrological regime (such as within roll-front or similar type deposits), where the system had remained open since the deposition of uranium, precluding secular equilibrium from being established. Disequilibrium can also be significant at uranium deposits occurring within, or in proximity to, the vadose zone.

When present, the degree of disequilibrium is rarely uniform throughout the deposit. It may vary from place to place and can represent enrichment or depletion of uranium or its gamma-emitting decay products in different domains within the same deposit. Thus, it is critical that the potential presence of disequilibrium be thoroughly investigated, characterized, and incorporated into any MRMR estimation that relies on uranium content measured by radiometric means.

Disequilibrium is conventionally expressed as the term radioactive equilibrium factor (REF) (or disequilibrium factor (DEF)) which represents the ratio of true chemical uranium content to that measured by radiometric (gamma) methods (expressed as U_3O_8 or U (chemical)/eU_3O_8 or eU (radiometric). Thus, a REF value of 1.0 represents equilibrium, while a value >1.0 represents chemical enrichment compared to gamma measurements (also termed positive disequilibrium). In contrast, a REF value of <1.0 represents chemical depletion or negative disequilibrium. REF may be applied to an individual mineral sample point such as drill hole mineral intercept locally, or in some cases, if justified, to the entire deposit. Adjustment of the eU_3O_8 grade used for the MRMR estimates due to disequilibrium must be applied judiciously. If a singular REF value is applied to an entire uranium deposit it must be based on an adequate statistical population of sample points that fairly represents the various mineral domains.

Uranium content determined by down-hole gamma logs is an indirect, or equivalent assay expressed as eU_3O_8 or eU. Where employed, equivalent uranium determinations should be reported and appropriately identified in the database as discussed in Section 2.3 of this guideline. Disequilibrium conditions can be recognized by comparing an equivalent assay to a direct assay measurement of uranium content for the same sample. Direct assay methods include chemical analyses of core, muck, channel samples, etc., or down hole logging by direct measurement technology such as prompt fission neutron (PFN).

For the above reasons, Practitioners involved in uranium MRMR estimates should have a good understanding of the radioactive nature of uranium, thorium, and potassium minerals and their decay products. If relevant, the Practitioner should also be familiar with equipment and techniques used in acquiring radiometric and other geophysical data, and with methods for quality assurance (QA) and quality controls (QC) specifically applicable to uranium.

2.3. Data Collection and Databases

The type of uranium deposit under consideration can influence the selection of appropriate drilling equipment, sample collection and preparation protocols, analytical methods, and QA/QC programs undertaken during deposit exploration or delineation activities. For example, specialized drilling equipment may be required (e.g., triple-tube drill tools) in areas of poor ground conditions to ensure that the complete particle size fraction of the material of interest is recovered or that a representative volume of material is collected (e.g., to inform the gamma measurement to equivalent grade correlation curve). Such knowledge can also influence the selection of appropriate analytical methods or design of the accompanying QA/QC programs. Additional guidance on the creation and execution of mineral exploration and deposit delineation drilling programs is presented in the Mineral Exploration Best Practices Guidelines and MRMR BP Guidelines.

2.3.1. Drilling and Coring

Many uranium deposits are situated at depths that do not allow surface sampling. In such cases, assay data is generally obtained from core or by down hole radiometric logging but with proper precautions, assay and other data can be collected from mud-rotary or by percussion techniques, in which the host rock is disintegrated or pulverized. The latter types of drilling are most common in sandstone-hosted uranium deposits and are quick, productive, and relatively inexpensive. Samples of the drill cuttings from mud-rotary and percussion drill holes should be collected at regular depth intervals and described for characteristics such as lithology, alteration, and radioactivity. Chemical analysis of cuttings may be of limited value due to the large degree of disturbance of the samples and inaccurate depth control. Scintillometer measurements of drill core should be recorded routinely for a qualitative determination of grade and to define proper assay intervals, as well as for the shifting of core or probing data to ensure they represent the same depths. While scintillometer measurements are useful for rapid identification of those intervals of drill core containing elevated uranium concentrations, they should not be used as the basis for sample grades or for the estimation of Mineral Resources.

While data from non-core drill holes may populate a majority portion of a database; some coring is also required to collect relatively undisturbed samples for proper characterization of the deposit such as:

- Chemical analyses for uranium, and minor elements and constituents;
- eU_3O_8 (equivalent $\%U_3O_8$ derived from radiometric probing) determination and validation;
- REF determination;
- Metallurgical testing;
- Hydrogeological characteristics;
- Mineralogical investigations;
- Bulk density determination;
- Grain size analysis.

If geophysical logging is performed, comparison of chemical uranium analyses of core with the down-hole gamma logs requires precise depth correlations. The Practitioner should also be aware that the chemical analysis of the core material is a measure of uranium and other constituents within the actual core volume, while downhole logging through the core zone measures the characteristics of the rock material surrounding the core zone. In other words, downhole logging is not a direct measurement of the material within the core, and generally represents a larger 'sample' of rock material than the volume of the core itself. The amount of coring relative to non-core drilling should be sufficient to provide valid statistical analysis of the various characteristics relative to the deposit complexity.

2.3.2. Prompt Fission Neutron Logging

PFN probes use a pulsed neutron generator to emit very high-energy, fast neutrons that are thermalized (slowed down to thermal levels of energy), mostly via collisions with hydrogen nuclei (the process is thus dependent on the quantity of hydrogen present in water in the borehole, pore spaces and hydrogen-containing minerals in the rock). The thermalized neutrons can be captured by the U-235 isotope, triggering its decay, accompanied by the release of prompt fission neutrons with higher (epithermal) energy levels. The quantities of thermal and epithermal neutrons can be measured by the corresponding detectors in the probe. The ratio of prompt fission epithermal neutrons to thermal neutrons is proportional to the quantity of the U-235 isotope in the rock formation, and thus generates a direct measure of the U-235 content without the necessity to adjust for radioactive disequilibrium.

Some downhole logging assemblies for PFN probes use detectors for measuring epithermal neutrons only. The amount of thermal neutrons that is required to compute the uranium content is estimated based on the content of hydrogen nuclei that must be provided by other methods, such as measuring or estimating moisture and porosity in the rock, the hydrogen-containing mineral content and the known flux of high-energy fast neutrons from the neutron generator.

In addition to hydrogen nuclei affecting the rate at which high energy neutrons are thermalized, other nuclei can affect the neutrons in the terms of their thermalization or adsorption, such as neutron-adsorbing nuclei of chlorine or boron, among others. If applicable, the concentrations of these elements must be sufficiently characterized for the deposit.

PFN logging, as a direct measurement method, may offer some advantages over other direct methods reliant on core assays. These advantages include time and cost savings, as PFN logging does not necessitate core drilling, core logging, sampling, and assaying. PFN data are readily available for processing and interpretation immediately after downhole probing. In addition, the volumes of rock 'sampled' by PFN is up to a 0.5 metre radius around the drill hole, which is much greater in comparison to the typical volume of core samples with a diameter of several centimetres. Acquisition costs and maintenance of a PFN unit are, however, significantly higher, and probing speeds are lower relative to gamma logging. These considerations have limited the overall usage of PFN logging.

PFN logging is useful in uranium deposits where decay products are known or suspected to be in disequilibrium with uranium and where a disequilibrium factor has not been determined or sufficiently well characterized. In such cases, PFN logging may be preferred to chemical analysis from coring because it is quicker, and, depending on the program, may be less expensive overall.

2.3.3. High Resolution Spectral Gamma Ray Logging

High resolution spectral gamma technology in some implementations also performs down-hole uranium assaying, but focuses on the presence of protactinium-234, a decay product which occurs early in the decay series and is thus considered an indirect assay method. The short half-life of protactinium-234 (1.17 minutes) does not provide time for disequilibrium to develop between it and U-235. Therefore, the protactinium-234 concentration serves as a direct measure of U-235.

The gamma ray emission of protactinium-234 is much lower than emissions from other gamma emitters in the U-234 decay chain, such as bismuth-214 and lead-214, and comprises a small portion of total gamma radiation. To resolve the spectral lines of protactinium-234, a high-resolution spectral gamma probes use high purity germanium detectors that are required to be cooled to cryogenic temperatures. The application of this downhole logging technology is more recent than PFN or other variants of gamma ray logging, such as total count gamma or spectral gamma.

2.3.4. Gamma Ray Logging-Total Gamma

Although uranium grade data may be collected using chemical assays, PFN logging, or high-resolution spectral gamma logging ('primary data'), it can also be interpreted from radiometric logging information ('secondary data'). This differentiation of data types, where applicable, is important to communicate both in the recording of exploration data and in the preparation of MRMR estimates. Down-hole radiometric logging can play a significant role in estimation because it allows for use of fast, lower-cost methods, such as percussion or rotary drilling, and a reduction in the need for collection of assays from core. The method samples a larger volume of rock, as gamma radiation is obtained from a radius approximately 0.5 to 1 metre depending on local conditions. The continuous nature of the downhole radiometric logging data also provides a complete profile in situations where core recovery is poor or nonexistent. In sandstone-hosted uranium deposits radiometric (gamma) logging is commonly the main source of grade data.

Data typically recorded in the database with respect to the gamma logging tool parameters include:

- Radiometric tool identifiers;
- Probe diameter;
- Probe dead time;
- Calibration records (including method and date, determined K factors);
- Routine reference scan data (i.e., calibration test pits and/or source checks used in a similar fashion to laboratory certified reference materials). In the latter, dates and reading values are recorded to identify potential tool drift.

The guidelines for the collection of primary uranium grade data are similar to that of most other elements/commodities requiring chemical assay. However, the collection of secondary uranium grade data requires that additional data be captured to support the interpretation of grade through conversion of gamma measurements, often recorded as counts per second (CPS), to equivalent uranium grades (eU_3O_8 or eU).

The Practitioner should be aware that the drilling process can contaminate a portion of the drill hole when encountering a mineralized uranium intersection through smearing of cuttings or drilling fluid returns. Dissemination of radon in the hole and the mass effect of high-grade intersections may also inflate equivalent assay thicknesses (although the latter usually underestimates the grades obtained). These characteristics can result in the grade and thickness of an intersection being overstated during radiometric probing and results must be adjusted accordingly if they result in undue influence.

Radiometric logging of bore holes primarily measures gamma radiation due to their higher penetration properties when compared to alpha and beta particles. Probe measurements are sensitive to several factors including the presence of drill rods and/or casing in the hole, thickness and types of material in rods and casing, hole diameter, drilling medium (air or water/mud), logging speed, and probe characteristics (e.g., diameter, type, dead-time and measuring interval). The names, models and serial numbers of all equipment used, and the particulars of each drill hole, should be recorded on the drill hole logs. Periodically, each probe needs to be individually calibrated for K-factor adjustments. K-factors can be determined from specially designed calibration pits, reference sources or cored holes.

Drill holes are usually logged from the bottom up, after slowly lowering the probe to identify radioactive sections, to maintain optimum logging speed and to zero the depth measurements.

Considering these issues, data typically recorded in the database with respect to logging data and corrections used in the equivalent uranium grade calculation include:

- Logging speed;
- Material type and thickness of drill hole casing or drill rods;
- Presence, depths and composition of fluids in drill hole (typically water/mud or air);
- Depth interval adjustments;
- Probing date, identifier and type of probe;
- Raw counts per second (CPS);
- Electric potential / spontaneous potential (SP);
- Resistivity;
- Neutron density data;
- Core recovery;
- Factors typically applied for conversion to calculated eU_3O_8 including:
    - Logging tool parameters (K-factor, dead-time);
    - Drill hole diameter;
    - Fluids absorption coefficients;
    - Casing or drill rod absorption coefficients;
    - Presence of radon and adjustment made to CPS;
    - Disequilibrium factors (if applicable);
    - Analysis and characterization of other gamma emitters besides uranium including radium, thorium, and/or potassium contributors (through chemical analysis or spectral gamma-ray borehole logging).

When the precision of equivalent assay data has been demonstrated sufficiently with supporting QC, including core drilling and chemical assays, the eU_3O_8 data may be used with drill core chemical assay data in the database for use in MRMR estimation. The eU_3O_8 grades can be used for entire mineralized intervals in drill holes, or for intervals of poor core recovery where assays are less reliable (or non-existent) due to loss of material.

The Practitioner responsible for PFN, high-resolution spectral gamma ray or gamma ray logging data collection, processing, QAQC and interpretation should be sufficiently familiar with the underlying scientific principles used in the above-mentioned technologies and their specific requirements, potential caveats and limitations. Calibration procedures should be in place to ensure adequacy of the equipment performance, data collection, processing and interpretation, and ultimately, the accuracy of the uranium content measurements used in MRMR estimation. PFN-, high-resolution spectral gamma ray or gamma ray logging-derived grades should be compared against a statistically significant number of chemical assays to ensure their validity and reproducibility.

2.3.5. ISR-Data Collection

Besides the above gamma probing information, a significant amount of hydrogeological information must be collected. Laboratory testing of drill core can provide point measurements of porosity and permeability. Permeability is a measure of the material composing the aquifer to allow a fluid to flow through it and is commonly measured as intrinsic permeability (k). Intrinsic permeability is a property of the porous medium and can be applied to any fluid with the additional input of density and viscosity. More directly applicable to ISR is hydraulic conductivity (K), which depends on intrinsic permeability and other characteristics such as density and viscosity specific to aqueous fluids and the geological environment in which mineralization occurs. This can be derived from core analysis (or from pumping test results). The Practitioner should be comfortable that adequate testing has been performed to ensure that obtained results are representative of the mineralization-hosting aquifer. If permeability testing of core in the laboratory is conducted in terms of permeability to air (instead of water), the Practitioner should be aware that results could be significantly different in an ISR environment, particularly if swelling clays are present in the formation.

Additional data for uranium ISR-amenable deposits commonly collected for MRMR estimation purposes can include:

- Grade x thickness (GT) values per mineralized interval;
- Structural features (such as the stratigraphic dip, faults, unconformities);
- Textural features (including grain-size description and analysis);
- State of oxidation/reduction of the mineralization or hosting lithology;
- Lithostratigraphic and hydrogeological relationship between mineralization host and other aquifers;
- Roll-front zonation/domains;
- Pump test data to assess transmissivity, permeability and specific capacity, anticipated well flows, static water table;
- Clay content;
- Carbonate content;
- Organic carbon content;
- Sulfur content;
- Trace mineral content (including those with other gamma-emitting elements);
- Leachability of mineralization for anticipated recovery rate;
- Density of the rock formation hosting mineralization (including clays);
- Density of aquicludes that confine the host aquifer.

2.4. Quality Controls for Equivalent Assay Grade Determination

Equivalent uranium values may form much of the grade information in a MRMR estimate. For such data, the QC for radiometric data should be as rigorous as that for chemical assays from an analytical laboratory. Ensuring the reliability of radiometric data can be achieved through a rigorous, ongoing program of calibration and validation of individual assaying and logging tools.

In general, quality control programs for equivalent assay grade determinations include the following elements:

- Depth adjustment of geophysical logging (if applicable) or geochemistry data based on core recovery, to ensure that the two datasets represent the same depths;
- Representative and ongoing chemical assaying to monitor and ensure the continued validity of equivalent grades;
- Regular probe calibration and servicing being performed prior to initiation of the drill program, at regularly defined intervals and/or when readings fall outside established parameters. This may include double probing of drill holes against a reference probe and/or verification against test pits or assayed drill holes left open for calibration purposes (the latter two should be representative of expected grade ranges within the deposit). While probe results may not match precisely, they should maintain a similar ratio. In such cases, a factor can be established to correct for the ratio between the probes if necessary (similar to a K factor);
- Checks against sources of known activity levels performed immediately prior to probing as an additional quality check and to identify potential instrument drift over time. A secondary check can also be performed after probing to confirm the probe was functioning properly during use;
- Duplicate geophysical logging of drillholes, including:
  - Re-logging of holes with the same tool;
  - Re-logging of holes with a different tool and/or service provider.

In deriving chemical/radiometric correlation relationships where gamma logging results are compared to chemical analysis of core, care must be taken to ensure there is a high level of core recovery within the mineralized zone. Anything less than almost complete core recovery, particularly in the mineralized zone can lead to unreliable assay results. Ideally, care should be taken to ensure the core specimen includes the complete mineralized interval, as well as an interval of barren strata above and below the mineralized zone.

2.5. Geological and Mineralization Modelling

Preparation of geological, structural and mineralization models of uranium deposits apply many of the same principles and practices used in estimating metallic mineral deposits. These models should be prepared using sample data to estimate the volume and grade or material characteristics of the deposit under consideration. General guidance relating to preparation of these models is presented in the MRMR BP Guidelines. Additional modelling considerations or techniques, however, are often used for deposits planned to be mined using the ISR method.

2.5.1. ISR-Amenable Roll-Front Deposits

To date, virtually all commercial uranium ISR extraction has been performed in roll-front type deposits Roll-front deposits differ considerably from hard-rock uranium deposits and even from other sandstone-hosted uranium deposits. They present unique challenges in interpretation, modelling and MRMR estimation due to their complex geology and geometry. Likewise, ISR extraction demands some specific considerations that must be addressed in the development process. Proper evaluation of roll-fronts, particularly in relation to ISR, is very geology intensive and highly dependent on the Practitioner's interpretation and professional judgment and requires the Practitioner to have thorough understanding of the nature of roll-front deposits.

Mineralization geometry is typically complex and is closely aligned with the reduction-oxidation geochemical interface (or redox front) with the highest quality mineralization occurring immediately adjacent to the front in reduced ground. Mineralization continuity is typically very strongly parallel to the orientation of the redox front but can be vary considerably perpendicular to the redox front.

Roll-front deposits commonly consist of multiple stacked roll-fronts and where this occurs, individual roll-fronts are usually evaluated as independent units in terms of mapping, MRMR estimation and mining. Economic concentrations along the front may be sporadic (i.e., due to narrow widths of mineralization and/or lower grades or quality) and require extensive drilling to explore, delineate and properly evaluate.

It is common practice in MRMR estimates for roll-front type ISR projects to use GT techniques such as GT contouring or other methods for modelling mineralization. These methods are based on the product of the mineralization's average grade and true thickness and are applied to intercepts within the individual mineralized horizons. In these techniques, a minimum GT cut-off can be applied in much the same way that a grade cut-off is established for other uranium deposits and applied to drill-hole mineral intercepts for modelling purposes.

2.6. Mineral Resource Estimation

2.6.1. Mineral Resource Estimation

Multiple factors may be used in evaluating the grade, quality, or value of a uranium deposit during the Mineral Resource estimation process. For ISR roll-front type deposits, the previously discussed GT-type method results are accumulated to generate a value for individual horizons; while for very high-grade uranium deposits, such as those found in Canada's Athabasca Basin, the application of density weighting methods during the estimation process is sometimes performed to account for the very high density of pitchblende/uraninite minerals.

2.6.2. Mineral Resource Classification

The definition of Mineral Resources, and the categories Measured, Indicated, or Inferred confidence categories are provided in the CIM Definition Standards. The MRMR BP Guidelines provide guidance on classification methodologies that can be used.

Given the wide range of uranium deposit types, the criteria applied during Mineral Resource classification can differ from other metallic mineral deposits. For example, the sampling points (i.e., drill holes) required for a uranium mineral deposit that exhibits strong geological and grade continuity (e.g., a bed of homogeneous uraniferous black shales) may be more widely spaced than they would be for a typical Proterozoic unconformity-related uranium deposit or a sandstone-hosted roll-front type deposit where either continuity and/or grade of the mineralization are generally much less uniform. Potential local scale REF variability should also be considered (e.g., this is often an issue in certain sandstone and surficial uranium deposits within dynamic hydraulic regimes).

Additional factors that must be considered where ISR mining is contemplated include but are not limited to, host lithology hydrological parameters accounting for variability in water table levels, aquifer permeability, leachability, the presence of reagent-consuming minerals and other geo-metallurgical considerations. From these criteria, the degree of unrecoverable in situ mineralization and an adequate level of confidence that ground water in proximity, both laterally and vertically, will not be contaminated by mining operations, can be obtained.

Mineralization within clay interbeds, fine-grained (such as silts or very fine-grained impermeable sands) or well-cemented lithologies that cannot be recovered by ISR due to the low permeability of the host should not be included in estimation. The impact of low permeability lithologies interbedded with a high permeability lithology such as coarse sands should also be considered given that the lixiviant flow paths will tend to preferentially follow the high permeability units and leaching from less permeable facies may be minimal. Uranium tends to form a tight bond with carbonaceous matter, which can negatively impact leaching. Mineralization associated with coal or lignite interbeds, or sands that contain a large quantity of fragmented carbonaceous detritus may be unrecoverable by ISR and similarly require omission from estimates.

2.6.3. Cut-Off Grade (or Value) Determination

Consideration of economic parameters contributing to development of a cut-off grade/quality (or value) can be an iterative process that is based on generally accepted industry practice and experience and the stage of the mineral property in the mining cycle. For ISR deposits, a minimum GT cut-off is generally considered the most practical measure of uranium content and quality and is an applicable gauge of the potential economic viability of mineralization (although grade and thickness minima are also commonly used in addition to GT).

One of the key inputs to preparation of MRMR estimates is the selection of an appropriate price or value for the products. In contrast to many metallic mineral products that are traded on open markets where the prices are readily available from several public domain sources, the price of uranium at any given time may not be known with accuracy since most of the uranium is sold under long-term, confidential contracts. A spot price, which generally represents the minimum prevailing market value and historically representing relatively small volumes, is readily available. Subscription-based market research and analysis companies such as UxC and TradeTech can also provide uranium price and other market-related information. Other sources, such as the "Red Book" (Nuclear Energy Agency, International Atomic Energy Agency, 2020) and various government agencies may provide indications of previous contract prices. Additional guidance in relation to the selection of appropriate product pricing can be found in the CIM Guidance on Commodity Pricing and Other Issues related to Mineral Resource and Mineral Reserve Estimation and Reporting, as amended from time to time).

It is the responsibility of the Practitioner to understand and justify the rationale for the selection of cut-offs for the subject deposit (detailed discussion of cut-off grades is found in Section 7.2 in the MRMR BP Guidelines and the references therein). In general, ISR deposits may be significantly less sensitive to grade than a deposit that is planned to be mined using conventional mining methods. This is related to the bulk mining nature of ISR and because the mineralization host does not need to be physically excavated and transported. The chemical extraction by solution mining is quite efficient in most cases, such that even low-grade mineralization can be extracted, provided it is efficiently and fully contacted by lixiviant. Consequently, cut-off grades for ISR deposits are generally much lower when compared to conventional mining scenarios.

3. MINERAL RESERVE ESTIMATION

3.1. Market and Uranium Price

Global uranium production comes from a small number of companies and there may be challenges to market entry by a new producer given that the spot market is relatively small, and the majority of uranium is sold on long-term contracts. The Practitioner should conduct sufficient investigations to ascertain whether a market exists for the forecasted production and that the intended product can reasonably be sold at the price used to estimate Mineral Reserves.

3.2. ESG Entry Challenges

The radioactive nature of uranium and its decay products often generates public concerns, leading to strict environmental, health and safety challenges. Stakeholder support may vary significantly depending on the jurisdiction. When reporting Mineral Reserves, the Practitioner should consider that development and mining of uranium are often tightly regulated activities that can lead to lengthy development timelines and in some cases, it may be unreasonable to assume that government approval will be given. In addition, conditions of approvals may add constraints on product sales and health, safety, and environmental controls, monitoring and reporting requirements.

3.3. ISR-Specific Considerations

Fundamental conditions that must be present for ISR are that the host formation has sufficient permeability, the deposit must be below the static groundwater table, and the geological environment of the deposit must be such that contamination of regional groundwater can be avoided or minimized through restoration activities to an acceptable level as defined by the local jurisdiction.

The Practitioner should discuss all known parameters that might affect exploitation of the deposit. Given the nature of uranium deposits targeted for ISR extraction, some factors may not necessarily apply, or may not be applied in the same manner as in conventional mining such as open pit and underground mining. Such factors include:

- Economic assessment methodologies (e.g., use of cut-offs based on pounds U_3O_8 (or kilograms U) within a given production well pattern);
- Hydrological characteristics (permeability and confinement of the mineralized horizon);
- Environmental considerations including ongoing monitoring of area aquifers and costs associated with monitoring wells to demonstrate effective containment of mining solutions;
- Leachability of the mineralized material;
- Recovery and dilution modifying factors.

3.3.1. Economic Assessments

As ISR development of resources advances toward production, a common economic evaluation methodology involves assessing the minimum required amount of recoverable uranium needed to justify the development of a production well pattern (i.e., an extraction well plus any injection wells which communicate with that extraction well). Tonnage does not play as significant a factor in economic evaluation as it does in conventional mining. This minimum resource requirement is often informally referred to as the pounds (or kilograms) per pattern cut-off. For producing wells, the expected minimum economical grade of loaded solution at the processing plant can be used.

3.3.2. Hydrogeological Characteristics

Most uranium deposits targeted for ISR production occur within permeable sandstone hosts of fluvial origin. A thorough understanding of the hydrogeological characteristics and conditions of the host sand aquifer is required for ISR-amenable uranium deposits. Favorable hydrogeological conditions are as essential to ISR success as are adequate tonnage and grade estimates, and should be demonstrated with adequate testing (e.g., aquifer pumping tests to assess transmissivity, permeability, and specific capacity). The results of such tests are used to estimate the well flow rates and their sustainability over time (without excessively lowering the water level). In general, higher production well flow rates result in quicker, more efficient extraction, resulting in lower production costs.

Since ISR production depends on groundwater processes, the mineralization must be located below the static water table. When gaseous oxygen is used as the oxidant it is preferred that at least 15 metres equivalent of hydrostatic water pressure is present in the production zone to provide sufficient hydrostatic pressure to maintain oxygen in solution.

Field hydrogeological tests are important for assessing amenability of the host formation to the ISR mining method. A variety of aquifer tests exist ranging from single well swab to single well and multi-well aquifer pump tests. Testing typically involves recording water table drawdown in observation wells while pumping a well nearby at a certain rate. From the results, the aquifer transmissivity can be determined and used to provide well flow rates that can be expected during production. The Practitioner must be familiar with the methodologies and required data collection, processing and interpretations used in hydrogeological tests and validity of underlying assumptions.

The Practitioner should be familiar with the range of hydrogeological characteristics that are adequate for economic ISR production. Forecasting average production well-flow rates prior to ISR production start-up is critical for mine planning, design, and economic evaluation. The Practitioner should provide justification for the average well-flow rate employed in any economic assessment.

The ISR mining method requires that the regional hydrostratigraphy of the deposit area is thoroughly understood to establish the foundation for accurate correlation of mineralized horizons; and to identify and characterize the vertical confinement of the host aquifer by overlying and underlying aquitards. In general, confinement is considered a mandatory condition for vertical control of production fluids to prevent the loss of lixiviant or contamination of adjacent aquifers. Confinement can be characterized by aquifer pump-testing results, and by permeability testing of core samples from aquitards overlying or underlying the host aquifer.

3.3.3. Environmental Considerations

Solid and liquid wastes are generated during both ISR production and project decommissioning. Disposal protocols are generally based on radioactivity levels and vary between jurisdictions. In general, solid wastes are disposed of at licensed low-level waste disposal sites. ISR projects make use of deep disposal wells to dispose of excess wastewater recovered during ISR production, as well as any contaminated water produced during ground water restoration. These wells are typically drilled into deep, confined rock formations well below other aquifers.

The relationship of the target aquifer (for mining) to other parts of the same or other aquifers requiring protection, the ability to restore groundwater within the mining area to an acceptable quality level (original baseline or other) and all associated costs, must be considered during the reserve estimation process.

3.3.4. Leachability

The CIM Practice Guidelines for Mineral Processing (as amended from time to time) provide guidance readily applicable to the preparation of MRMR estimates for uranium deposits. However, given the amenability of some deposits of this metal to ISR mining methods and related challenges, additional guidelines are appropriate.

Like other metals, testing commonly involves agitation leach testing (or bottle-roll testing) where disaggregated material of known uranium content obtained from a composite core sample is mixed with various combinations of lixiviant chemical reagents. Each combination is then agitated by rolling in a cylinder. Samples are taken periodically and analyzed to determine the rate of uranium extraction. The results are recorded as percent recovery against either time or, preferably, against pore volumes (PV) or liquid-to-solid (L/S) ratio. A pore volume is a measure of the fluid content within a given volume of saturated sandstone. L/S is the ratio of the mass of the lixiviant to the dry mass of the mineralized sample. Both PV and L/S are directly related to porosity. It is standard to report test results against PVs or L/S because mining depletion during ISR production is commonly measured against the pore volume and L/S of lixiviant that have flowed through a particular well pattern.

These tests are performed to establish the amenability of the mineralization to in situ recovery, and to identify which combination and concentration of chemical ingredients is required for optimum uranium extraction. It is also used in the development of a recovery curve model which can be used as a guideline for life-of-mine planning and prediction of recovery well performance.

An alternative method to bottle-roll testing is column leach testing. The column test is similar in most respects to bottle-roll testing but is conducted on whole core or packed, disaggregated, mineralized material within a stationary column. While results are considered more reliable than bottle-roll tests, they are more expensive to obtain and take more time.

Care should be taken when gathering sample material for metallurgical testing to ensure the samples adequately represent in situ conditions. Exposure to oxygen should be avoided or minimized so as not to bias the leaching results. This can be accomplished during collection in the field by vacuum sealing the core or sealing the core in nitrogen.

The impact of interstitial clay mineralogy can be significant, given that some roll-front deposits include smectite (montmorillonite) content. The swelling nature of this clay can potentially severely damage the flow characteristics of the host formation under certain chemical conditions, with sodium-smectite being more problematic than calcium-smectite. Pore space can be severely diminished by either clay swelling or from fines migration caused by dispersal of particulates leading to eventual clogging. Once these conditions are established, it can be difficult, if not impossible, to reverse and restore permeability and flow rates. Bench tests should be conducted prior to production to test the sensitivity of the host formation to various combinations of lixiviant chemistry to ensure adequate characterization of these potential conditions, particularly when host sands approach or exceed 5% total clay content (VanHolland, 2017).

Carbonaceous material commonly occurs in roll-front host formations as small, carbonized plant fragments, carbonaceous detritus, or thin lignitic stringers. These can result in locally strong reducing environments. If present in significant amounts, carbonaceous material may increase oxygen consumption during production. Recovery is likely to be impacted if significant amounts of uranium mineralization are tied-up with carbonaceous material, because uranium tightly bonds with the carbonaceous content and consequently is much more difficult to extract. In general, carbonaceous contents ≥1–2% should be investigated and the impact quantified with appropriate metallurgical testing.

Pyrite content should also be investigated since in sufficient concentrations, it can impact pH control and cause the buildup of sulfate in the lixiviant or potentially combine with calcium to precipitate gypsum. Pyrite can also cause buildup of iron-hydroxides, potentially clogging the formation, well screens, or piping. In general, pyrite concentrations ≥1% should be investigated and the impact quantified with appropriate metallurgical testing.

Sand formations that host uranium roll-front deposits are typically uncemented to very poorly cemented. Any cementation usually occurs in the form of interstitial calcium carbonate as calcite. Interstitial calcareous content of ≤2–3% is generally of little concern. However, if calcite is extensively present in greater percentages, its impact should be characterized with appropriate metallurgical testing. Dense calcite cemented nodules, concretions, and stringers can be common within the host sands and can be locally associated with mineralization. Recovery of such mineralization and its potential impact on lixiviant flow patterns, if significant enough, should be considered.

In addition to uranium, other metals are often concentrated to some degree within a roll-front deposit such as vanadium, selenium and molybdenum. Having geochemistry similar to uranium, they can also be mobilized and precipitated during the ISR extraction process and can become problematic as contaminants in the yellowcake product if they occur in significant amounts within the production lixiviant. In that case they may require a separate circuit in the processing plant for removal; or, if present in sufficient quantities, may be extracted as an economic by-product of uranium production.

3.3.5. Recovery and Dilution

In a conventional mining scenario, mining losses (sometimes expressed as mining recovery) are applied as part of the modifying factors to determine the grade and tonnes of material that will be sent to the processing plant. In the case of ISR, however, the leaching occurs in situ rather than at the processing plant and is sometimes considered as part of the overall metallurgical recovery.

Prior to production, adequate metallurgical testing results can be used to generate anticipated recoveries, but for existing operations, production performance should be monitored regularly and tracked both on a per pattern basis, and on a per wellfield basis. Depending on the leaching regime used, typical recoveries generally range from 60% to 90% of estimated resources within a wellfield pattern but this can vary considerably from pattern to pattern. For early-stage projects that lack appropriate testing, parameters from an operating mine with similar geological characteristics to the deposit under study may be considered but as a general guideline, recoveries are commonly in the order of 60–70% for alkaline leaching and 70–90% for acid leach systems, the former generally being required in deposits with high calcium content , typically from limestone or gypsum (World Nuclear Association, 2022).

Factors impacting recovery can include:

- Lixiviant type (e.g., acid or alkaline based);
- Inefficient mineralization- lixiviant contact related to;
    - Imperfect flow paths from injector to recovery;
    - Channeling of lixiviant within highly permeable stratigraphic intervals;
    - Balance of flows within production patterns are not maintained due to formation plugging by swelling clays or accumulation of particulates;
- Incomplete digestion of uranium, caused by a chemical imbalance in the lixiviant or the presence of other lixiviant consuming constituents;
- Mineralization-lixiviant contact outside of planned well patterns (excursions)

Since ISR does not involve physical removal of gangue material, the nature of dilution in an ISR environment is also considerably different when compared to a conventional mining scenario. The bulk mining nature of ISR often results in situations where injector or recovery wells are placed near or outside the boundaries of mineralization. This may result in the passage of chemical lixiviant through some barren host rock along its path from injectors to recovery wells, and some unwanted chemical consumption. Likewise, recovery wells located near or outside the boundaries of mineralization will take in some barren groundwater, thus diluting the production head grades. While these should have little impact on final recovery, there may be some influence on production costs. For these reasons, the Practitioner should consider the volume of the production zone relative to the Mineral Resource estimate when determining Mineral Reserves.

3.4. Radiometric Scanners

Radiometric scanners (often called truck or bucket scanners) can be used for grade measurements of material being handled by mining equipment (e.g., scoops, trucks). If effectively managed, such production data can be reconciled against, and used to validate an estimate. To ensure reliability, the scanners must be subjected to regular maintenance and monitored over time as there can be impacts from instrument drift or changes to the background environmental gamma readings (this latter is common in an active mining environment).

Scanner radiometric grades and QC should be done by checking the consistency of the scanner using a variety of methods. Development of a gamma scanner procedure addressing scanning time, location of material relative to scanner, and the size of the load being measured should be completed and adhered to. Other factors relevant to use of scanners may include:

- Checking consistency of sample masses, sample grain sizes, gamma and grade measurements with physical/chemical limits;

- Periodic scanner calibration with monitoring of calibrations over time;

- Ongoing validation through hand-held scanning and laboratory assays;

- Monitoring of scanner results over time to identify potential instrumentation drift;
- Monitoring of scanning area background readings;
- Duplicate gamma scanning records.

4. CONCLUSIONS

Uranium deposits occur in a broad range of geological environments and while most of the uranium produced is recovered as a primary product, it is also sometimes recovered as a by-product in other deposits. Almost all of the world's production is used to produce nuclear fuel for nuclear power reactors, but the metal also has military and other civilian sector applications.

While the MRMR BP Guidelines (as amended) provide guidance in relation to the preparation of MRMR estimates for metalliferous and other deposits, additional guidance is provided within this document due to the radioactive properties of uranium and its potential amenability to the ISR mining method.

The Practitioner reporting an estimate of a uranium deposit should provide a discussion on any database limitations and special economic or technical considerations. Any pertinent characteristics or conditions should be clearly stated (e.g., the use of radiometric-derived data, types of equipment employed, possible disequilibrium status, potential impact of radon or drill hole contamination etc.).

In the case of ISR estimates, it is good practice to discuss parameters that might affect exploitation of the deposit. It should provide a discussion on the supporting hydrological and geochemical data, the volume of material expected to be under leach conditions, the impact of dilutive material and the leaching performance (mining losses) expected during the in situ recovery process. In addition to uranium content, tonnage, and grade, the Practitioner should provide supporting information such as the deposit area, average thickness of mineralization and average GT. The average GT of a deposit can be the single-most revealing factor for estimating the quality of a roll-front uranium deposit.

For ISR-amenable deposits, it is not uncommon that the reference point at which Mineral Reserves are defined to be the portion of economic Mineral Resources under existing or planned wellfield patterns.

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