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Methods of exploitation of different types of uranium deposits

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FOREWORD

The choice and evaluation of mining and milling methods in terms of costs are complex processes that require the evaluation of abundant data and in depth analysis of multiple options before making a production decision. Modern operation must take into consideration the regulations of the country in which they operate, the future decommissioning costs of the operation and the medium and long term economics of the metal they sell when opening new mines or improving existing mines. The wrong appraisal of a deposit or the wrong choice of methods can incur costs that will make the deposits non-viable, and, at times, a liability for the public or the country. It is therefore necessary to have a maximum of information before assessing and choosing mining methods that best fit the characteristics of the planned mine. It is important to note that proper mining methods can improve both the capital and operating costs of an operation. Increasing the grade of ore through ore beneficiation prior to processing it through the mill will decrease the amount of ore being processed in the mill and thus decrease the consumption of expensive chemical reagents.

Deposits are mined using three broad types of mining methods: open pit, underground and in situ leaching. This publication addresses all aspects of mining and milling methods for several types of deposits and provides information to assist in the selection process of methods and also considers what actions must be taken into account for obtaining regulatory approvals for a project and for final decommissioning and reclamation of a project. The objective of this publication is to provide a process of selections of methods for mining engineers and managers involved in modernising ongoing operations or considering opening new operations. Several practical examples are given. These guidelines can be consulted and used in many countries involved in uranium mining and milling operations. The examples where costs are given can also be adjusted to specific economic conditions of various countries.

The authors are from four uranium producing countries. They bring diversified experience for all types of mining and milling operations from the opening of a mine to the decommissioning of the complete operation.

This technical publication is one of a series of IAEA publications covering all aspects of the uranium mining industry, from exploration to exploitation and decommissioning. Reports already published address topics such as feasibility study (Steps for Preparing Uranium Production Feasibility Studies: A Guidebook, IAEA-TECDOC-885, 1996), development of regulations (Guidebook on the Development of Regulations for Uranium Deposit Development and Production, IAEA-TECDOC-862, 1996), environmental impact assessment (Environmental Impact Assessment for Uranium Mine, Mill and In Situ Leach Projects, IAEA-TECDOC-979, 1997) closeout of uranium mines (Closeout of Uranium Mines and Mills: a Review of Current Practices, IAEA-TECDOC-939, 1997), planning for environmental restoration (Planning for Environmental Restoration of Uranium Mining and Milling Sites in Central and Eastern Europe, IAEA-TECDOC-982, 1997), strategies for environmental restoration (Factors for Formulating Strategies for Environmental Restoration, IAEA-TECDOC-1032, 1998).

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1. INTRODUCTION

Selection of a method for exploitation of uranium deposits is a similar process to that of any other metal, that of modeling the ore deposit and then examining alternatives for mining and treatment. However, the health and social issues associated with uranium compared to other minerals requires a greater focus on issues such as radiation exposure to workers and members of the public and to waste containment and final rehabilitation of any disturbed areas. It can be expected that work on these issues will consume a great amount of time and effort.

Knowledge of the deposit geometry is critical for decisions on underground or surface mining. For surface methods, the total amount of waste removed per tonne of ore is directly related to the shape of the deposit and similarly for deeper deposits or in areas of rugged terrain or where surface disturbance must be minimized an underground mining method can be selected which maximizes extraction efficiency.

In selecting a mining method it is necessary to make estimates of capital and operating costs of alternatives and to determine whether they offer an economic return. The study of these alternatives and of consideration of environmental, geographical, personnel and financial restrictions will have an impact on the selection.

At the grassroots exploration stage an initial conceptual study will be undertaken when a deposit has been identified. This will entail an initial assessment of aspects such as ore reserve tonnage and grade, scale of operation which could be supported, mining methods, treatment options, infrastructure requirements and marketing of final product. The study would most likely be based on knowledge of similar projects with costs, etc. scaled in order of magnitude.

If the outcome of this initial study is seen as positive further geological evaluation of the resource would proceed together with preliminary mining and mineral processing studies. The results of this work would be further examined before making a decision to undertake a final feasibility study which would make detailed analysis of all aspects of the project and which would enable a final commitment to a commercial operation.

The decision to mine and treat a uranium orebody and the selection of methods to do so usually pivots on economics and environmental matters. If development, mine production and treatment costs per tonne of ore are greater for one method than another, the least expensive option will normally be chosen although it is necessary to also consider health, safety and environmental issues including final decommissioning in the final selection process. The cost figures given in this report are all in US dollars.

The material in this publication is intended to provide assistance in identifying alternatives and factors to be considered in making evaluations.

2. HISTORY OF URANIUM MINING

Uranium mining has a short history as the uranium element was not discovered until 1789 by the German chemist Martin Klaport.

For hundreds of years uranium was used as a colouring agent for ceramic glaze. The production of uranium came from Bohemia, Cornwall, Portugal and Colorado. With the discovery of radium by Marie Curie in 1898 and its implications for medicine uranium was mined for the recovery of radium and uranium was treated as a waste. Uranium production at this time came from the Colorado Plateau, the ex Belgian Congo and Bohemia.

Uranium entered a new era with the discovery of fission in 1939 leading to nuclear weapons and later to generation of electricity. In 1942 the first controlled nuclear chain reaction was achieved in Chicago and in 1945 the first nuclear explosion showed the enormous power potential of nuclear fission.

Civil nuclear programmes began with the resolution of the United Nations in 1954 to develop an agency, the IAEA, to manage development of programmes for the peaceful uses of nuclear technology.

With the emergence of electrical power plants fuelled by uranium, the metal became a commercial product.

The history of uranium mining can be divided into five main periods:

- 1795–1925: Uranium used for glass/ceramic
- 1905–1925: Radium as a by product of uranium as waste
- 1925–1945: Vanadium as a by product
- 1945–1967: Governmental use
- 1967–to date: Commercial.

Uranium mining started in Bohemia in the Joachimthal region during the 19th century as well as in Cornwall, Portugal and Colorado. At the beginning of the century other mines were developed in the former Belgian Congo, Canada, the USA and Bohemia. The main product was radium, not uranium. Uranium became an industrial product at the end of the World War II, during the Manhattan Project as substantial tonnage was necessary to build the Fermi reactor in Chicago.

After World War II uranium started to be used for the production of electricity. At this time uranium was mined in Australia, Canada, the former Soviet Union, the USA, the former German Democratic Republic, Czechoslovakia, South Africa, Gabon and France. Individual mine production was generally small by today's standards, most not exceeding 200 t U per year. Later, mining operations became larger in the eastern Europe, USA, Canada, and Australia with productions ranging from 1000 t U to 5000 t U per year. Ranger in Australia and Key Lake in Canada are such examples of large operations.

During the 1980s a drastic change appears in the uranium mining industry due to excess inventory, forcing the low grade and high cost mines to close. The USA and France were particularly affected by these changes. Political changes in the former Soviet Union also created dramatic changes as market economy rule starts to prevail closing uneconomic operations.

At the present time the mining operations are those that can support a weak market which means that only the mines with low operating cost are in operation. Uranium mining operations can be divided in two subgroups:

- the hard rock mining, open pit or underground with grade varying between 0.5% and 15% U_3O_8 where operating costs have been rationalised to innovative modern mining and milling techniques.
- the in situ leaching (ISL) operation that are able to mine very low grade ore.

The countries that have major mining operations are Australia, Canada, Niger, the Russian Federation, Uzbekistan and Kazakhstan.

3. CLASSIFICATION OF DEPOSITS

The classification of uranium, or any other mineral deposit, may be a controversial subject. Most classifications systems are designed to meet specific requirements. It is very difficult to produce a single system that satisfies mineral deposit specialists, exploration geologists, resource analysts and miners. From the point of view of a purist, a desirable classification is based on genetic considerations. However, such a classification is not easily developed as the genesis of some uranium deposits is still controversial. With this consideration in mind, in early 1989 the International Atomic Energy Agency prepared a uranium deposit classification used in the joint OECD/NEA–IAEA biennial report: “Uranium Resources, Production and Demand”, also known as the “Red Book”.

The outline of the classification is given below. Each deposit class, and corresponding sub-class, is defined and illustrated with type.

UNCONFORMITY-RELATED	Proterozoic unconformity-related	Clay-bound Proterozoic
		Strata-bound Proterozoic
		Fracture-bound Proterozoic
	Phanerozoic unconformity-related	
SANDSTONE	Roll-type	Detrital carbon
		Extrinsic sulphide
	Tabular	Extrinsic carbon
		Vanadium–uranium
	Basal-channel	
	Precambrian sandstone	
QUARTZ-PEBBLE		
VEINS	Spatially related to granite	Intragranitic veins
		Perigranitic veins
	In metamorphic or sedimentary rocks	
BRECCIA COMPLEX		
INTRUSIVE	Alaskite	
	Granite, monozite	
	Peralkaline syenite	
	Carbonatite	
	Pegmatite	
PHOSPHORITE		
COLLAPSE BRECCIA PIPE		
VOLCANIC		
SURFICIAL	Duricrust	
	Peat and bog	
	Karst cavern	
	Surficial pedogenic and structure fill	
METASOMATITE		
METAMORPHITE		
LIGNITE		
BLACK SHALE		
OTHERS		

3.1. DEFINITION AND EXAMPLES

3.1.1. Unconformity-related

Definition: Unconformity-related deposits are spatially associated with unconformities which separate the basement, commonly metamorphic rocks, from overlying clastic sedimentary rocks. The deposits are either of Proterozoic or Phanerozoic age.

3.1.1.1. Proterozoic unconformity-related

Definition: The deposits occur in Proterozoic sediments above the unconformity (clay-bound) and/or in Proterozoic metamorphic rocks below the unconformity (strata-bound or fracture bound), adjacent to highs of the Archean basement.

Type Examples: Athabasca Basin, Saskatchewan, Canada
Pine Creek Geosyncline, Northern Territory, Australia

Clay-bound proterozoic unconformity:

Definition: The clay-bound deposits are concentration of pitchblende and some coffinite that occur in clay-altered sandstone immediately above the unconformity. Mineralization commonly extends into the altered basement rocks. The orebodies contain polymetallic mineral assemblages (U, Ni, Co, As, Cu, Ag, Au) commonly accompanied by bitumen.

Type Examples: Cigar Lake, Saskatchewan, Canada
Key Lake, Saskatchewan, Canada
Cluff Lake “D”, Saskatchewan, Canada

Strata-bound proterozoic unconformity:

Definition: The strata-bound deposits occur below the unconformity in a sequence containing metamorphosed pelitic, carbonate and carbonaceous rocks. The principal ore mineral is pitchblende. Some deposits (e.g. Jabiluka II) contain significant amounts of gold.

Type Examples: Jabiluka II, Northern Territory, Australia

Fracture-bound proterozoic unconformity:

Definition: The fracture-bound deposits occur below the unconformity in variable altered metamorphic rocks and contain pitchblende as the principal ore mineral.

Type Examples: Rabbit Lake, Saskatchewan, Canada
Nabarlek, Northern Territory, Australia

3.1.1.2. Phanerozoic unconformity-related

Definition: The Phanerozoic deposits are concentrations of pitchblende and coffinite in altered granite below the unconformity and/or in clastic sediment above the unconformity.

Type Examples: Bertholène, France
Brousse Broquies (Le Rouble) France

3.1.2. Sandstone

Definition: Sandstone uranium deposits occur in carbon and/or pyrite-bearing fluvial (less commonly marine), arkosic sandstones that contain, are interbedded with, and are bounded by less permeable horizons. Primary minerals are predominantly coffinite and pitchblende.

3.1.2.1. Roll-type

Definition: Roll-type deposits are arcuate zones of uranium matrix-impregnation that crosscut sandstone bedding. The zones extend from overlying to underlying less permeable horizons and are convex down-hydrological gradient. Perpendicular to hydrological gradient they are elongated and sinuous. The zones are one to several metres wide, have sharp contacts with hematite- and/or limonite-bearing sandstone on the upgradient side (except in rereduced deposits) and diffuse contacts with carbon- and/or pyrite-bearing sandstone on the down-gradient side.

Detrital carbon:

Definition: Deposits are in contact with detrital, carbon-bearing (generally plant debris) sandstone on their down-gradient sides. Some deposits have tabular roll-front limbs (generally less than 1 metre thick and up to hundreds of metres in horizontal dimensions) against overlying and/or underlying carbon-bearing, fine-grained sediments (e.g. the Crooks Gap and Beverley deposits).

Type Examples:
Shirley Basin, Wyoming, USA
Crooks Gap, Wyoming, USA

Extrinsic sulphide:

Definition: Deposits are near faults and are in contact with Pyrite- and/or marcasite-bearing sandstone on their down-gradient sides. Detrital carbonaceous matter is virtually absent from these sandstones and detrital magnetite and ilmenite are replaced by sulphide. Sandstone on the upgradient sides of deposits is hematite- and/or limonite-bearing, except where it is pyrite-bearing (rereduced) due to reintroduction of sulphur.

Type Examples:
Benavides Deposit, Texas, USA
Lamprecht Deposit, Texas, USA
Crow Butte Deposit, Nebraska, USA

3.1.2.2. Tabular

Definition: Uranium occurs generally as tabular zones of uranium matrix-impregnations that crosscut sandstone bedding. The zones are one to several metres thick and are bounded on all sides by pyrite-bearing sandstone. The zones are irregular in shape and may be bounded by less permeable sedimentary horizons.

Extrinsic carbon:

Definition: Uranium occurs as isolated and stacked tabular zones of carbon–uranium impregnations in sandstone (one to tens of metres in thickness and tens to thousands of metres in horizontal dimensions). Host sandstones are within an extensive fluvial-lacustrine sedimentary sequence. The carbon with which the uranium is associated was introduced into the sandstone from adjacent siltstones during compaction. In the Ambrosia Lake District some primary carbon–uranium mineralization is redistributed into roll-type and, where near faults, disseminations in vertical (“stack”) deposits.

Type Example: Grants Uranium Region, New Mexico, USA

Vanadium–uranium:

Definition: Uranium occurs in irregular tabular zones of vanadium–uranium matrix impregnations, one to several metres thick and tens to thousands of meters in horizontal dimensions.

Type Examples: Uravan Mineral Belt, Colorado–Utah, USA
Henry Basin, Utah, USA

Basal channel:

Definition: Uranium concentrations occur in, on and/or adjacent to detrital plant debris within fluvial sandstone. Deposits are generally a metre or more thick and a few tens of a few hundred metres in horizontal dimensions.

Deposits may occur in:

(a) distinct narrow channels (hundreds of metres) or
(b) extensive blanket sands (thousands of metres) formed in braided fluvial systems that either unconformably overly or are eroded into underlying sedimentary or crystalline rocks.

Type Examples: White Canyon District, Utah, USA
Akouta, Niger
Nigyo-Toge, Japan

3.1.2.3. Precambrian sandstone

Definition: Uranium occurs in sandstones containing redistributed marine carbonaceous matter. Economically important deposits are in rocks of Lower Proterozoic age.

Type Examples: Oklo, Gabon
Mounana, Gabon

3.1.3. Quartz-pebble conglomerate

Definition: Quartz-pebble conglomerate uranium deposits are of Upper Archean to Lower Proterozoic age and consist of detrital ore minerals of uranium and other metals which may be modified diagenetically. The conglomerates are pyritiferous and are interbedded within siliciclastic sequences containing layers of quartzite and argillite. There are two kinds of mineralized conglomerates. At Blind River, uranium and rare earth elements occur in several beds at the base of the stratigraphic sequence above the unconformity. In the Witwatersrand, uranium occurs in multiple beds dispersed through a thick stratigraphic sequence and is recovered as a by-product of gold production.

Type Examples: Blind River — Elliot Lake, Ontario, Canada
Witwatersrand, South Africa

3.1.4. Veins

Definition: Vein deposits consist of uranium lenses or sheets in joints, fractures, breccias or stockworks. Uranium, generally occurring as pitchblende and/or coffinite, is commonly accompanied by gangue and alteration minerals. Size of veins may vary and their configurations may be complex.

(In this classification some uranium-bearing veins are included with other deposit types, e.g. veins and stockworks in volcanic rock are classified under volcanic deposits).

3.1.4.1. Spatially related to granite

Definition: Vein uranium deposits spatially related to granite occur within (intragranitic) and around (perigranitic) leucogranitic intrusions.

Intragranitic veins:

Definition: Pitchblende and coffinite occur:

(a) in simple veins or stockworks located within broader, linear fracture systems, and

(b) in episyenites, generally in voids formed by the removal of quartz. In Margnac and several other deposits both types are present.

Type Examples: Fanay, Haute Vienne, France
Margnac, Haute Vienne, France

Perigranitic veins:

Definition: Pitchblende and coffinite are irregularly distributed as disseminations and in veins, veinlets or stockworked within sedimentary rocks adjacent to granite plutons. Veins may be monometallic (pitchblende and gangue minerals) and/or polymetallic (U, Co, Ni, As and Ag minerals) with vertical extent up to 2000 metres.

Type Examples: Pribram, Czech Republic
Jachymov-Au area, Czech Republic and Germany

3.1.4.2. In metamorphic or sedimentary rocks

Definition: Uraninite, pitchblende or coffinite occur in fissures, fractures and joints (often associated with lineaments or large tensional structures) which transect metamorphic or sedimentary rocks. The deposits are either monometallic (e.g. Beaverlodge and Rozna) or polymetallic (e.g. Shinkolobwe). At Schwartzwalder the uranium is associated with iron formation.

Type Examples: Beaverlodge, Saskatchewan, Canada
Rozna, Czech Republic
Shinkolobwe, Shaba, Zaire
Schwartzwalder, Colorado, USA

3.1.5. Breccia complex

Definition: Breccia complex uranium deposits occur within complexity intermixed breccias composed dominantly of hematite or granite clasts. Other rock types include massive and fragmented mafic and felsic intrusives, and tuffaceous volcanic sediments. The breccia complex is surrounded by relatively unbrecciated granite. Mineralization occurs predominantly within the matrix of hematite-rich breccias. The Olympic Dam breccia complex is at least 20 km in area and 1 km in vertical extent.

Type Example: Olympic Dam, South Australia, Australia

3.1.6. Intrusive

Definition: Deposits in intrusive or anatectic rocks consist of disseminated primary, non-refractory uranium minerals. Deposits are generally low grade (20–200 ppm).

3.1.6.1. Alaskite

Definition: Dissemination uranium occurs in medium to very coarse graines alaskite bodies that are discordant to concordant with surrounding folded and highly metamorphosed and magmatized sedimentary rocks. The alaskite bodies range in size from small lenses and dykes to stocks and domes several hundred metres across. No alteration is associated with the uranium mineralization.

Type Example: Rössing, Namibia

3.1.6.2. Granite, monozite

Definition: Very low-grade uranium disseminations occur in copper porphyry deposits in quartz monazite stocks. Uranium is recovered only as a by-product of copper heap leaching.

Type Example: Bingham Canyon, Utah, USA

3.1.6.3. Peralkaline syenite

Definition: Low-grade uranium disseminations occur in peralkaline syenites.

Type Example: Kvanefjeld, Greenland

3.1.6.4. Carbonatite

Definition: Disseminated uranothorianite occurs in carbonatite and phosphorite. Uranium is recovered as a by-product from copper production.

Type Example: Phalaborwa, South Africa

3.1.6.5. Pegmatite

Definition: Uraninite and other uranium–thorium minerals occur in zoned granitic and syenitic pegmatites in sedimentary and igneous rocks, metamorphosed to amphibolite facies. Deformation and metasomatism commonly follow metamorphism. Hematite is a characteristic alteration product.

Type Example: Bancroft area, Ontario, Canada

3.1.7. Phosphorite

Definition: Uranium occurs in fine-grained apatite in phosphorite horizons within interbedded marine muds, shales, carbonates and sandstones. Deposits include primary bedded (Phosphoria Formation, Utah–Idaho) and sedimentologically reworked (Florida) phosphorite.

Type Examples: Florida, USA
Utah–Idaho, USA

3.1.8. Collapse breccia pipe

Definition: Deposits are in circular, vertical (up to 1000 metres in vertical extent) pipes filled with down-dropped coarse and fine fragments stopped from the overlying sediments. Mineralized pipes range from 30 to 200 metres in diameter. Uranium occurs as pitchblende with sulphides and carbon in permeable breccia matrix and in the arcuate fracture zones enclosing the pipe. Mineralization in the pipes is adjacent to permeable sandstones, haemititic siltstone and shale surrounding the pipes.

Type Examples: Orphan mine, Arizona, USA
Easy 1, Arizona, USA

3.1.9. Volcanic

Definition: Volcanic deposits are stratabound (disseminations and impregnations in permeable flows, flow breccias, tuffs, tuffites and other strata), structure-bound (disseminations and vein fillings in faults, fracture zones, diatremes and at boundaries or intrusive bodies) and combinations of both. Uranium may be accompanied by molybdenum, copper, selenium, fluorine and other elements. (In this classification uranium in veins or stockworks in volcanic rocks is classified as volcanic deposits and not vein deposits).

Type Examples: Michelin, Labrador, Canada
Rexspar, British Columbia, Canada
Ben Lomond, Queensland, Australia

3.1.10. Surficial

Definition: Surficial uranium mineralization occurs as recent near-surface concentrations:

(a) stratabound in dominantly unconsolidated surficial sediments proximal to uraniferous source rocks or

(b) structure-bound uraniferous within source rocks.

Uranium occurs almost exclusively as uranyl minerals or adsorbed on other materials.

Type Example: Lake Raeside, Australia

3.1.10.1. Duricrust

Definition: Uranium occurs in duricrust in shallow sediments within fluvial and eolian channel sands and playas. The duricrust is calcrete, silcrete and gypcrete that cemented or replaced the sediments at the groundwater table. There is insignificant organic matter. These deposits are restricted to areas with arid and semi-arid climates.

Type Example: Yeelirrie, Western Australia, Australia

3.1.10.2. Peat and bog

Definition: Uranium is in plant debris and clay-rich sediments in shallow depressions. These deposits are restricted to areas with humid climates.

Type Example: Flodell Crek, Washington, USA

3.1.10.3. Karst cavern

Definition: Uranium occurs as fine powdery coatings on fractures, solution voids, limestone blocks, calcite crystals, chert nodules and as disseminations in the matrix of the cavern fill.

Type Example: Pryor Mountains, Montana, USA

3.1.10.4. Surficial pedogenic and structure fill

Definition: Uranium occurs as near-surface mineralization in:

(a) pedogenic formations (laterite, ferricrete, calcrete, silcrete, gycrete, etc.);

(b) in structures.

Type Example: Summerland area, British Columbia, Canada

3.1.11. Metasomatite

Definition: Uranium occurs in alkali silicate metasomatites (albitites, aegirinites and alkali-amphibole rocks), commonly intruded by microcline granite. The uranium minerals (uraninite, nenadkevite and brannerite) are unevenly distributed in the metasomatites. At Zheltye Vody the metasomatites occur at the boundary between ferruginous metasediments and other metamorphic rocks which are intruded by microcline granite.

Type Example: Zheltye Vody, Krivoy Rog, Ukraine

3.1.12. Metamorphic

Definition: Stratabound, disseminated uranium occurs in metasediments and/or metavolcanics, generally without direct evidence of post metamorphic mineralization.

Type Example: Forstau, Austria

3.1.13. Lignite

Definition: Irregular concentrations of uranium occur in lignite and in clay and/or sandstone immediately adjacent to lignite.

Type Example: North Dakota and South Dakota, USA

3.1.14. Black shale

Definition: Uranium (generally 10–400 ppm) and associated metals, such as Mo, V and Cu, occur in carbonaceous marine shales.

Type Example: Kolm/Alum Shale, Sweden

3.2. THE EXPLOITABLE DEPOSITS

At the present time and because of the low selling price of uranium only two broad types of deposits are being exploited. They are the unconformity type of deposits where capital and operating costs may be high on a dollar per tonne basis but very low on a dollar per pound basis because of the high grade of the ore. The other type is the sandstone type when in situ leaching (ISL) methods can be applied, resulting in minimal infrastructure and low capital and operating costs.

Constant improvement and advance in technologies at the level of the mines and mills will likely allow other types of deposits to be economical. An increase in the selling price of uranium due to higher demands will also allow other types of deposits to be exploited.

4. PARAMETERS TO BE CONSIDERED WHEN ASSESSING A URANIUM ORE RESOURCE

Modeling of a uranium resource is the first and most important step in selecting a mining method that will optimize exploitation of a mineralized deposit. The term resource as used in this discussion is defined as any anomalous higher concentration of uranium. Mining methods considered are underground, open pit and in situ leaching (ISL).

The parameters used in modeling the resource will provide the physical data pertaining to the uranium occurrence and host rocks necessary to select a mining method as well as associated costs. Whether or not the resource can be exploited for a profit will not be determined in this phase of evaluation. It should be noted which ever mining method is selected, it must always provide for the health and safety of workers under the ALARA (as low as reasonably achievable) principle.

The following list includes parameters that must be considered when modeling a resource:

- location
- shape
- size
- depth
- orientation
- geotectonics
- mineralogy
- hydrology
- boundary conditions.

4.1. LOCATION

The physical location and the land status or ownership of the resource is of primary importance in selecting a mining method. The physiography of the land, populated areas and regulatory constraints may dictate how the resource must be exploited even though all three mining methods could be utilized. Resources discovered beneath bodies of surface water (lakes or rivers) or in aquifers may only be mined by underground methods or in situ leaching eliminating the open pit method, except in special cases. This may also be true in populated areas where access to the resource is only possible by in situ leaching or possibly underground methods. Environmental, governmental and mining regulations and moratoriums may have the most influence on determining the method used to mine a resource. For example, regulations may prohibit major surface disturbance or surface stockpiling which would eliminate underground or open pit mining methods to exploit the resource leaving in situ leaching as the only viable mining method. For the above reasons, it is extremely important to know and understand the physiography of the land and the regulations pertaining to the area under which the resource has been located.

4.2. SHAPE

The shape of the resource is determined by various geological and or geophysical techniques including surface sampling, surface drill hole data (core, cuttings, electric and gamma logs) and radiometric surveys will certainly aid in determining the optimum mining method. The shape of the resource varies from long, narrow, continuous or discontinuous sinuous trends, to layer types of occurrences, to thick (ranging in excess of 30 metres) massive deposits. By itself, the shape of the resource may be exploited by all three mining methods. However, the optimum method can only be determined upon completion of the model.

4.3. SIZE

The quantity and quality of the resource must be determined to be able to select the most efficient and economic mining method. Sufficient geologic data must be gathered to permit accurate calculations of the volume, tonnage and grade of the resource. The data required to make these calculations will come from surface drilling (core and down hole electric and gamma logs) for deeper mineral occurrences; and radiometric surveys and pit sampling for near surface anomalies.

4.4. DEPTH

The depth of the resource will generally be determined from surface drill hole data (core and down hole electric logs). This information is usually the deciding factor in choosing the conventional mining method to be used either open pit or underground. Occasionally both methods should be employed based on the configuration and continuity of the resource extending from the surface to depths beyond open pit limits. For underground mining methods, the depth of the resource is used to determine shaft depths or decline length and subsequent construction costs, and the number of mining levels required to efficiently and economically expedite exploitation of the deposit.

4.5. ORIENTATION

The orientation or attitude of the resource can range from horizontal to vertical and will generally be determined from surface drill hole data. This is a dimensional feature that must be considered when selecting a mining method. For example, uranium mineralization occurring in sedimentary rocks generally follows the bedding which can be flat lying or follow the dip of a particular stratigraphic unit as opposed to breccia pipes which stand nearly vertical.

4.6. GEOTECTONICS

Geotectonic data is the basic information obtained from surface mapping and surface drill holes that defines structural features and host rock types associated with the resource. Based on this information a mining method can be chosen as well as making the initial selection of equipment that will support the mining method. Both production rates and manpower requirements can be established allowing for labor and equipment costs to be determined. In addition, the competency of the host rock can be determined thus allowing for selection of ground support materials and associated costs. This is a major step in the preparation of a mine feasibility study. The information gained from this parameter is important for evaluating in situ leaching (ISL) projects as well as selection of an optimum conventional mining method.

4.7. MINERALOGY

The mineralogy of the resource is very important, as it will determine to a large extent the method of extraction and recovery. Some minerals will be difficult to extract and recoveries will be poor. In some cases, minerals that are not amenable or cannot be mobilized by in situ leaching (ISL) techniques would eliminate this method of mining.

4.8. HYDROLOGY

The hydrologic conditions associated with the mineralization is one of the most important parameters to be established when modeling a resource. Dry conditions would certainly eliminate in situ leaching as mining method. In a wet environment, particularly in an aquifer, the determination of the host rock permeability and porosity is paramount. This data is used to determine production pumping rates (gpm or m^3/h) for in situ leaching as well as draw down information of underground and open pit mining. The number of de-watering wells, the number of pumps and sizing can be made with their respective costs. In some cases freezing techniques must be employed when other methods to control water are unmerited. Again the cost of this technique can be determined.

4.9. BOUNDARY CONDITIONS

Knowledge of the boundary conditions of the resource for underground mining is essential for detailed mine planning and ore reserve estimation. The geology of the resource (rock types and structure) is determined from detailed analysis of core and cuttings produced from surface drilling. Knowledge of the hanging and footwalls will aid in selecting the method of underground mining to be used, the mining equipment, and the type of ground support required to exploit the resource.

Usually the above parameters to model a resource will provide the necessary information to accurately select a method of exploitation and to establish estimated costs of the mining operation. Detailed evaluation and analysis of these parameters will also provide data for feasibility.

5. PROJECT IMPACT AND APPROVAL

Before actual development of any project can commence it is necessary to obtain regulatory approvals from various, government agencies, who will need to assess the environmental, safety, occupational health, social and economic impacts created by the project and the measures proposed to mitigate those during the project life and any rehabilitation measures following closure. In these respects uranium mining is much the same as any other mining project but it can be expected that there may be a closer focus on some of the issues compared with other minerals. This is because uranium minerals are always associated with more radioactive elements such as radium and radon in the ore. Therefore although uranium itself is not very radioactive, the ore which is mined, especially if it is high grade, needs to be handled with some care for occupational health and safety reasons. Strict health standards for exposure to radiation and radon gas are set by Authorities for workers and members of the public.

Radiation comes principally from radium in surrounding rock mass, exposure can be reduced by dust suppression, ventilation and shielding. Radon gas emanates from rock or from tailings as radium or thorium decays. It then decays itself to radon daughters which can be significantly radioactive. Radon occurs in most rocks and traces of it are in the air we breathe, however at high concentrations it is a health hazard. Waste water discharged from mining or processing can contain traces of radium and other metals which would be undesirable in downstream environments. This waste water must be confined and treated or evaporated in safe storage.

After the uranium is recovered by processing the remainder of the ore with virtually all the radioactive elements is discharged as tailings. The radiation levels and radon emission from tailings storage are potentially significant so methods for management during operations and after decommissioning are important.

The following gives a general outline of the issues which need to be considered and the stages in the approval process.

5.1. PROJECT PROPOSAL

Initially a project proposal is prepared for submission to interested parties, this would include:

— Project location:
where the proposed project is to be located, access roads, any nearby towns,any significant geographical features;

— Project scope:
broadly how mining and processing will be carried out and at what scale and to what schedule;

— Project description
general description of facilities
  · mining method — open pit or underground
  · in situ leaching
  · processing methods
  · form of final product
  · waste disposal methods — tailings, waste water, solid wastes
  · air and gaseous emissions
  · infrastructure — power, water supplies — roads and transport — accommodation
  · work force requirements

— Project history and ownership

— Order of magnitude costs and funding

— Project benefits, potential impacts — environmental and social.

The completed project proposal would be considered by government agencies and then depending on legislation the development or environmental protection agency would assess the project for what level of environmental impact assessment would be appropriate. In the case of uranium mining it is usual for this to include full assessment by government agencies as well as comment and input from members of the public. To accommodate these guidelines for an environmental impact study (EIS) on the project are prepared by the government agency, sometimes again with input from members of the public, and given to the project proponent for the study to be undertaken.

5.2. EIS GUIDELINES

The Guidelines would require that all potential impacts of the project be studied and methods of mitigation be proposed. These impacts would include:

— surface disturbance from access roads, open pits, overburden and waste piles, processing plants and support facilities such as equipment shops and offices

— airborne dust and emissions from road traffic, drilling, blasting, excavation and transport of ore and waste, and processing operations

— noise and vibrations from plant and equipment operation

— ischarges of contaminated mine water, disruption of groundwater aquifers, disturbances of streams, drainage, and wetlands, tailings and waste disposal.

— visual intrusions

— land use, cultural and historic site disturbance, socioeconomic factors, occupational health and safety.

5.3. EIS REPORT

The report should give priority to the major issues associated with the proposed project. Matters of minor concern should be dealt with only to the extent required to show that they have been considered. The EIS should be based on the results of studies and research carried out to an appropriate level such that all issues are adequately considered. The text of the EIS should be written in a clear, concise style easily understood by the general reader. Technical jargon should be avoided wherever possible. The documentation should include references to studies and a listing of individuals and organizations consulted. Maps, plans and illustrations should be used where necessary to clarify the text. As well as examining the impacts of those issues listed in the guidelines the EIS report will also make comment on alternatives to the project ranging from "no action" or not going ahead with all or parts of the project to alternatives of mining and processing methods and their associated costs and benefits and the degree of mitigation or final reclamation that will be required. The report will address how protection will be afforded to workers, members of the public and the general environment from the proposed activities. Standards will be stated for air quality, groundwater drawdowns, vibrations, noise, mine water discharge, waste disposal, radioactivity levels and worker and members of the public dosage. Monitoring and inspection schedules will be provided and comparisons drawn to country or international regulations which may apply.

5.4. EIS APPROVAL PROCESS

When the EIS is completed it will be submitted to the relevant agency for assessment, this process may also include comment and consideration of submissions from members of the public. It can be expected that the assessment period will include a period of 6 to 8 weeks for these submissions to be made and then a further similar period for the actual assessment. It is normal then for a report to be issued by the agency which will where necessary detail where further work may be required in supplementary studies. If after consideration of the EIS and any Supplementary reports the overall impacts of the project including reclamation and rehabilitation at completion are considered to be positive, it can be expected that approval to proceed with the project will be given.

6. MINING

6.1. BENEFITS GREATER THAN LIABILITIES

Uranium mining presents unique challenges to the Mining Engineer to assure the safe and economic exploitation of this important energy resource. Because the material is radioactive and will remain so in the long term particular care must be exercised in the extraction of uranium ore to protect the health and safety of the miners during operations and to also ensure that the worked out areas and mine waste do not effect the environment in the long term. It must be clearly demonstrated that the social and economic benefits gained from the project are significantly greater than the liabilities created from the hazards to worker and public health and from harm in the long term to the environment.

6.2. ALARA

Mining regulations in place to provide for conventional health and safety and for the protection of the environment are supplemented by a higher standard of protection for excavating radioactive ore. Further because it has generally been determined that there is some risk associated with even small doses of radioactive exposure the International Commission for Radiation Protection (ICRP) has established a convention which requires that radioactive doses be kept “as low as reasonably achievable” (the ALARA principle). Uranium mining companies must not only design facilities and work practices to maintain dose levels below maximum regulated exposure limits but must also provide additional protection to reduce exposure to the lowest level practicable taking into account social and economic considerations.

6.3. MINING METHODS

Primary mining methods are determined by the shape depth and grade of the uranium deposit in conjunction the composition, hydrogeology and geotechnical aspects of the surrounding country rock. The two conventional methods are open pit and underground. A third method is recovery by in situ leaching (ISL).

In the final analysis, the decision to mine an orebody using surface methods as opposed to underground usually pivots on economics. If development, extraction, and removal costs per tonne ore are greater for one method than the other, the least expensive technique will undoubtedly be chosen. No general optimum deposit depth exists for surface mining. The practical depth for a specific deposit is determined by the stripping ratio, ore value, working slope angle, deposit volume, extraction method, mine life, and reclamation requirements. In many instances, ore is extracted by surface methods down to an economically determined cutoff point, then underground techniques are initiated. The above guidelines are general, and since all orebodies are shaped differently, the evaluator must decide which model most closely resembles this situation, and which method or combination of methods, is most appropriate.

Generally, surface mining is more efficient than underground. First, more energy is required to extract and remove a tonne of ore from an underground working than from a surface mine. Increases in drilling and blasting requirements per tonne of ore, limits in the size of ore conveyance equipment, restrictions in haulage routes and speeds, and additional handling and rehandling of the ore all raise the total energy needs of underground mining. Increases in energy requirements escalate the production costs per tonne, which in turn dictate higher cutoff grades. Second, higher ore losses are incurred in underground mining as compared to surface methods. While open pit recovery can approach 95%, underground methods such as room and pillar often leave as much as 40% of the ore behind, which translates directly into lost revenue.

Deposit geometry is critical in the estimate of costs for both surface and underground mining. For surface methods, the total amount of waste removed per tonne of ore is directly related to the shape of the deposit, and its relation to the surface topography. However, factors such as weathering, fracturing, rock strength, and groundwater all influence the stability of the ore and waste. Working pit slope is a function of this stability, and directly affects the production cost per tonne and the economic depth of the pit.

Before deciding on a mining technique, all remaining available information should be examined. Environmental, geographical, personnel, and financial restrictions may influence mine design. Since most sections have factors for unusual situations, this information will also increase the exactness of the cost estimation process. Although the benefits are often economically intangible, a prudent engineer must certainly study the advantages of reducing the environmental impact.

6.3.1. Open pit (See Fig. 1)

Open pit mines are limited by the ore to waste stripping ratio which is directly related to the depth of the deposit. Conventional pit designs and equipment are applied however special monitoring requirements and equipment modifications are necessary because the product is radioactive.

High grade ore (+1% U_3O_8) usually necessitates shielding devices be incorporated in loading and hauling vehicles to protect the operators from excessive doses of gamma radiation. Likewise monitoring stations must be established within the pit and in the ore storage areas to determine ambient air quality with analysis for radon and long lived dusts associated with uranium ores.

Control of water from surface runoff and underground aquifers plays an essential role in an effective pit operation. This is particularly true with uranium mining as water removed requires expensive processing before the effluent can be discharged to the natural environment. Treatment facilities require significant capital expenditures. Pit designs often incorporate methods to divert or intercept water flows prior to entering the pit. A common control measure involves drilling wells around the circumference of the pit and removing the water prior to it coming in contact with the uranium mineralization. Sealing water bearing areas in the surrounding rocks with cement or chemical grouts is also an effective method of water control.

Open pit mining requires the development of extensive surface areas for storage of overburden and waste rock. Waste rock contaminated with low levels of radioactive materials must be stored in special lined areas to assure contaminated runoff is contained and treated.

6.3.2. Underground (See Fig. 2)

Conventional underground mining methods are applicable to uranium ores only to the extent that they can be modified to address the particular health and environmental concerns associated with excavating radioactive materials. Permitted dose exposures now limited in most jurisdictions to a maximum of twenty microsieverts per year eliminates mining practice which requires workers to be in an unshielded environment in the close confines of most underground excavations. Many design layouts now incorporate non-entry type methods with mining and hauling equipment being operated from areas remote from the orebody.

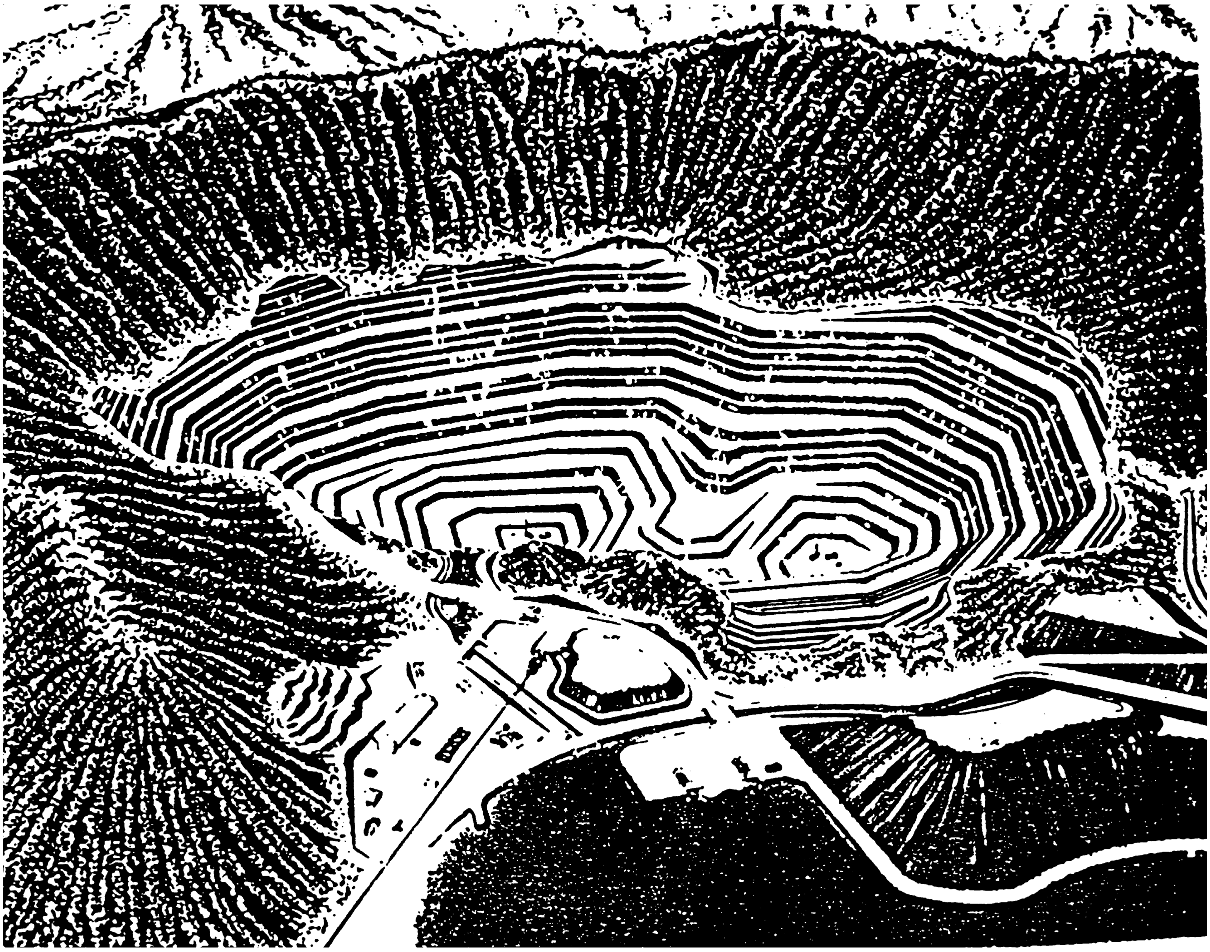


FIG. 1. Open pit mining.

Ventilation design for the control of radon gas and its radioactive daughter products is an essential component of an underground mine. Large quantities of fresh air are required to dilute and remove these contaminants. Radioactivity associated with the gas grows over time and it is therefore necessary that single pass fresh air be delivered to the work place and removed to exhaust quickly and continuously. The mine layout must include large delivery and exhaust tunnels with multiple outlets to surface.

Water inflows can present special problems in underground mines as it acts as a conduit for radon gas associated with radioactive minerals. Radon dissolved in water under pressure is freed when water passes into the underground works at atmospheric pressure. Radiation levels can become extremely high unless the water is confined in pipelines and pumped directly to surface. There are a number of examples of uranium orebodies where water present in large quantities causes the ore and surrounding rock to become unstable. Control measures include sealing with grout and in extreme conditions freezing the area surrounding and including the orebody. Practice in some sandstone deposits has incorporated the use of special drainage tunnels driven below and in advance of actual mining operations to dewater the deposit.

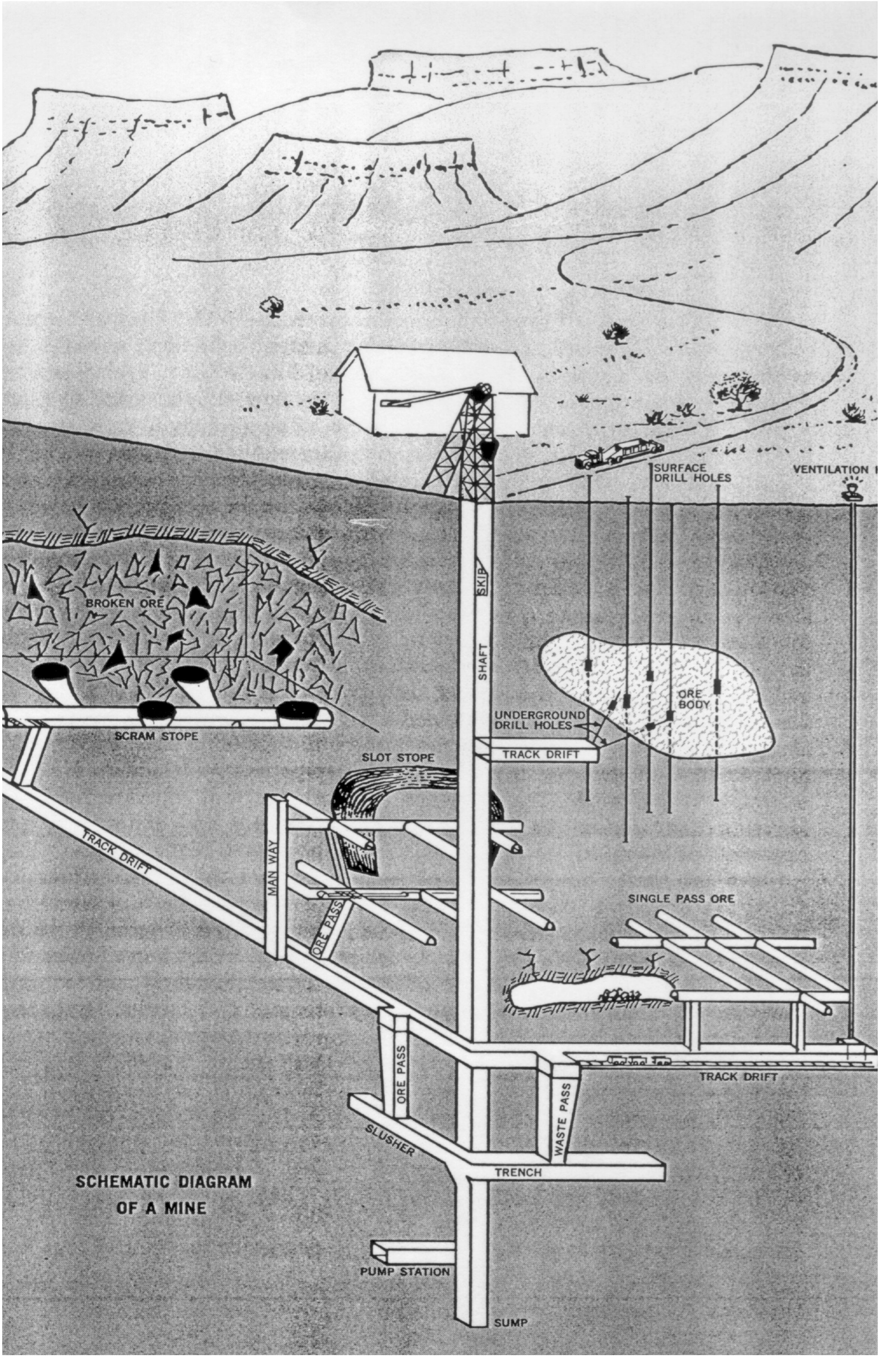


FIG. 2. *Underground mining.*

6.3.3. In situ leaching (ISL) (See Fig. 3)

In situ leaching (ISL) mining is a combined mining and extraction technology particularly suited to uranium ores hosted in pervious sandstone formations. Leaching solutions are circulated through the ore bearing formation by a system of patterned boreholes. Uranium minerals are dissolved and recovered for further processing.

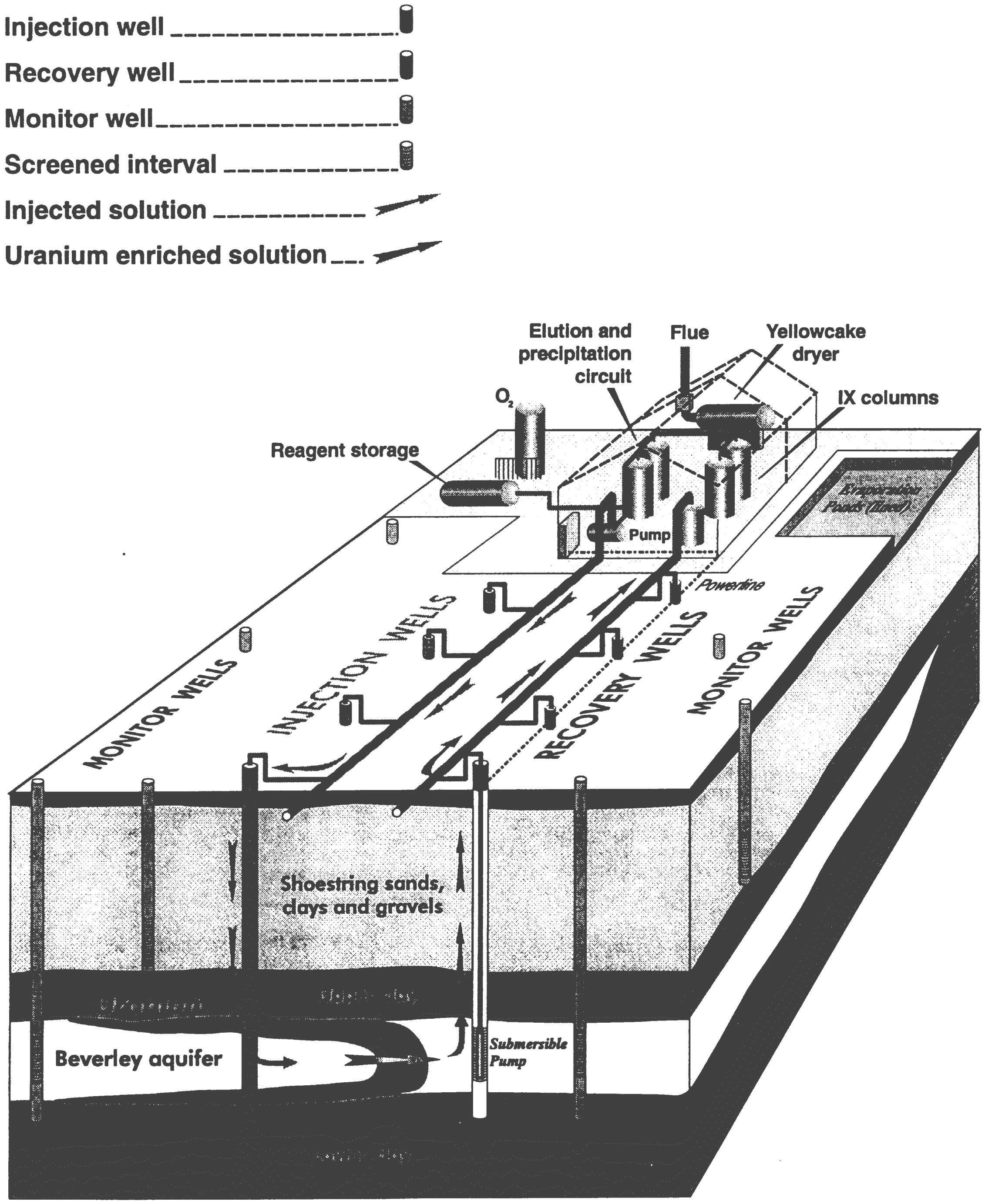


FIG.3. ISL mining.

The application of this method is limited to a bedded sandstone deposit with relatively high permeability sealed on the top and bottom with an impermeable layer such as a clay seam. Particular care must be exercised to ensure the leaching solutions are contained in the ore seams. An extensive array of monitor wells is required around the perimeter and above and below the deposit to identify any excursions. After the uranium is extracted it is normally necessary to restore the aquifer within the mined out deposit to its original condition. This process can take several years to accomplish and can represent a significant portion of the cost to extract the uranium product.

The advantage of this mining technique is the large reduction in exposure levels normally associated with uranium mining. The stringent exposure limits now proposed by uranium regulators both during operations and for decommissioning make ISL one of the few viable mining options to exploit low grade uranium deposits.

6.4. INFLUENCE ON MINING METHODS

6.4.1. Social and legal (regulatory)

Regulations for uranium mines and mills demand a higher standard of performance than the rules governing conventional mining and processing operations. Strict limitation on radiation exposures demand that mine design and method be formulated to ensure compliance is attained. One of the main documents for radiation protection is the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996). The political sensitivity of the nuclear industry also impacts directly on the scale and number of production facilities in certain jurisdictions.

Worker safety and health and long term environmental protection are key design parameters in uranium mining. The method chosen must guarantee that employees are protected not only from conventional hazards but also that individual radiation doses are strictly controlled. Exposure can be limited by shielding the workers by the installation of metal barriers on mining equipment such as drills, loaders and trucks. A common practice entails development of work stations in the footwall or hanging wall remote from the orebody.

Mine and process waste management facilities must be designed to protect the environment over the very long term. Regulations require that a programme of care and maintenance be established including monitoring to demonstrate compliance. The programme must be paid for by a fund which guarantees perpetual care.

6.4.2. Resource recovery

Uranium recovery from a given resource depends in large measure on the grade, position and size of the orebody. High grade deposits with well defined ore-waste contacts usually demand mining methods with very high extraction ratios. Mining lower grade material entails the use of economic cut-off grades which normally results in large portions of the resource being left behind.

High-grade deposits typically above 2% and up to 15% U_3O_8 as are found in northern Saskatchewan at depth employ expensive consolidation techniques such as freezing in order that portions of the ore can be excavated accurately to the waste contact and the cavities filled with concrete backfill to maintain the structural integrity of the surrounding rock. In open pits special measures are taken when mining in the ore horizon to separate ore and waste using breaking methods and loading equipment appropriate to the task.

Bulk mining methods are used in combination with ore sorting and/or beneficiation to recover uranium from low grade deposits. In situ leaching is also an economic alternative because of low capital and operating costs but extraction levels are normally below 80% of the total resource.

6.4.3. Reclamation and decommissioning

Decommissioning costs of uranium facilities can and usually do represent a significant percentage of the cost of production. Regulatory limits on radioactive contamination require that the site have contaminated material removed or covered, and plant and equipment cleaned, or demolished, with rubble removed to licensed containment areas. Similar stringent requirements pertain to mine waste and mill tailings.

ISL operations are generally much easier to decommission as the surface plant is small and there is only minor amounts waste products resulting from the process. Rehabilitation of aquifer surrounding the orebody does require time and money.

6.4.4. Fiscal

Some jurisdictions have in place royalty and tax regimes which encourage mining companies to extract the maximum amount of metal from a resource. Graduated profits royalty and penalty clauses in mining leases for low extraction levels are typical. The mining method would in certain circumstances be chosen to maximize overall recovery.

6.4.5. Beneficiation

6.4.5.1. Selective Mining

High grade uranium ores often occur in narrow seams and veins or in well defined pods. Excavating techniques utilizing small equipment are employed to first remove the ore with the subsequent removal of surrounding waste to allow access to more high-grade material. Particular care must be taken to protect the workers from receiving high radiation doses when handling the high-grade ore.

6.4.5.2. Sorting

Uranium ore because of its radioactivity and high specific gravity lends itself to several sorting techniques. Scanners are in general use in open pits to direct haulage trucks to dump their loads in high or low grade piles or if waste to special storage areas for material below ore grade but still contaminated with radioactive minerals. The same process is used in underground mines when the ore is hoisted in mine cars or in small skips, a practice common in FSU (former Soviet Union) countries.

6.4.6. Processing

Uranium tends to go into solution fairly readily under oxidizing conditions. This characteristic is utilized to extract the metal from low grade deposits when the ore is broken either in place in mining stops or in heaps stockpiled on surface.

In the latter case low grade ore, often the material remaining from car sorting is deposited on prepared pads. Oxidizing solutions, usually weak sulphuric acid, is sprinkled on the top of the pile and allowed to percolate through the dump. The uranium rich pregnant solution is then processed to obtain uranium yellow cake.

Stope leaching utilizes the space in underground excavations resulting from removal of higher grade ores. Low grade material, often in seams directly alongside or above existing openings, is blasted and left in place. Mine water is allowed to flood the piles. In some cases oxidizers must be added to the mine water solutions but in orebodies containing iron sulphides the sulphides will provide the necessary acid needed to dissolve the uranium metal. Mine water containing the uranium is collected and pumped to surface and treated in the processing plant to recover the uranium.

6.4.7. Mine life

Mine life is normally dependant on the size and accessibility of the orebody and the production rate chosen for the processing plant. In certain circumstances open pit deposits are mined out in their entirety prior to the start up of the processing plant. This is common practice when mill tailings are stored in the openings created by the excavation.

6.4.8. Location

Environmental effects from uranium mining particularly those associated with long lived radioactivity are subject to careful public scrutiny and regulation. Mining methods chosen must ensure that the worker, the public and the environment are protected over the long term. In general this requires that the workings be isolated from pathways through which the radioactive decay products can escape.

Aquifers must be isolated from open pit and underground workings by creating barriers of grout, freezing and hydraulic bypasses. Ore excavations must be backfilled or sealed to reduce the level of escaping radon gas.

6.4.9. Climate

Mining methods are impacted by local climate in a number of ways. Winter temperatures in the northern hemisphere require the use of equipment capable of being maintained and operated in severe cold. Underground operations need large heating plants to warm the large volumes of air necessary to ventilate the workings. In areas where energy supply is limited and expensive, mines operate during the summer months only.

Tropical climates with significant rainfall limit open pit operations during the rainy season and the water treatment plant must be sized to accommodate large effluent volumes. Where heap leach techniques are used it is often necessary to cease operations if process flows become too great due to rain dilution.

7. BENEFICIATION

In order to get precious metals and minerals: precious stones, gold, copper, tin, zinc, lead, etc. for making jewels, arms and useful tools, man began to mine thousands and thousands years ago. In the ancient times, as no chemical processes were known, miners found different means based on the physical characteristics of the ore, gangue and the host rock. Thus, they could obtain:

- gold, silver, precious stones
- high grade concentrates which could be easily treated by pyrometallurgy in simple and small furnaces and facilities.

In these conditions, throughout the mining history, mining and milling people found clever devices, sometimes very efficient, based on:

- the aspect of ore and waste,
- specific gravity,
- grain size.

Later, magnetism and more recently, flotation, radioactivity and colour were used to sort ore and waste and to upgrade the concentrates.

7.1. URANIUM PRODUCTION

7.1.1. Actual treatment of the uranium ore

We have seen in the prior paragraph, that miners, using specific equipment which recognizes the physical characteristics of the materials, could directly produce precious metals or high grade concentrates. In the uranium industry, it does not seem that beneficiation is currently used before chemical treatment. It is a paradox that in the gold mining business in South Africa radioactivity has been used successfully on a large scale to upgrade the mill feed. In these mines, uranium is associated with gold and is directly proportional. With these conditions, it is possible, using the radioactivity of the ore, to eliminate the lower uranium grade fraction which is also the lower gold grade fraction. The result represents substantial savings at the mill by not treating the fraction of the ore which has no economic value.

7.1.2. History of uranium ore treatment

Initially uranium was mined for making atomic bombs, towards the end of World War II and later during the Cold War. The cost of producing uranium was no issue, therefore beneficiation was not really considered. What was essential, was to produce uranium as rapidly as possible. As uranium is easy to leach, no time was spent for ore beneficiation and the yellow cake production was more a chemical process than a classic mineral process.

Another point is that the industry considered that uranium was a rare metal and should not be wasted. Therefore, a maximum recovery was preferred over the loss of metal through beneficiation. The discovery of large high grade deposits, and the consequence, drastic decrease of the selling price, led to some reassessments of beneficiation, but not to the extent possible.

As no beneficiation was done, and the selling price decreasing, mining was carried out more selectively at a higher cost per tonne. It is suggested that for a certain number of projects, beneficiation could allow mining with less selective and less costly methods, and eliminate the low value ore. The operating cost and also the capital cost could be lowered so that some non profitable projects could become economically feasible.

7.2. ORE SORTING PROCESSES

The uranium reserves are now, for their major part, located in huge high grade deposits (Canada, Australia). The genesis of these deposits lasted more than one billion years which explain the so important accumulation of metal and the high grade, up to 20% U_3O_8 with an average of 3 to 7%. Mining these deposits is not really an economical problem due to the grade which allows to use the more sophisticated methods like freezing for instance as we will see later on in one of the next paragraphs. For this type of deposits, ore sorting is useless. But it can prove greatly useful for mining lower grade deposits which otherwise would not be profitable.

7.2.1. Radiometric ore sorting (ROS)

Radiometric sorting has not been used in the uranium ore treatment as extensively as it could have been. Ore sorting equipments have been developed and used in gold mines. Only a very few number of uranium mines have used radiometric sorting for upgrading their mill feed. Lodève mine of COGEMA in the south of France is an example. Lodève ore contains a lot of carbonates and can only be economically treated by an alkaline process. Uranium is leached by sodium carbonate in autoclaves at high temperature and pressure. The treatment cost is high and it is paramount to remove the low grade fraction of the ore.

For radiometric sorting the ore must have the following characteristics:

- For economic reasons, only pebbles more than 30 mm can be treated.
- The ore must be hard to obtain a sufficient percentage of coarse material.
- The distribution of the uranium in the ore must be non-homogenous. It is easy to understand that if the ore is 100% homogenous, no sorting of any kind is possible.

After crushing to –150 mm, the plus 30 mm fraction is separated and passed over a belt conveyor. Commonly, the different granulometric fractions are: 30–60 mm, 60–100 mm, 100–150 mm. Pebbles of less than 30 mm are not amenable to ROS for economic reasons. Pebbles of more than 150 mm are too large compared to the uranium distribution.

Radiometric sorting equipment is composed of:

- belt conveyors which speed increases from one conveyor to the next in order to separate the pebbles,
- a radiometric scanner measuring the total radioactivity,
- a laser scanner measuring the horizontal surface of the stone,
- data from the scanners are sent to a computer which calculates the ratio radioactivity/surface of the pebbles and compares it to the preset cut off grade.

A compressed air jet, directed by the computer sorts the pebbles according to their ratio radioactivity/surface and separates the low grade fraction from the high grade one.

(For an example see Section 11.2.1).

The Indonesian Atomic Agency (BATAN) is currently studying an uranium deposit in N.W. Kalimantan with the assistance of IAEA experts. The deposit is a stockwork where uranium is concentrated in fine veinlets of uraninite. As the ore is very competent, it fits very well with radiometric sorting. According to the uranium distribution, it is possible to upgrade the run of mine ore. Average results on the total of the different granulometric fractions from 30 to 150 mm are as follows:

	Grade ppm U	Weight %	Uranium distribution %
Feed	2392	100	100
Rejected	85	52	1.9
Accepted	4889	48	98.1

Therefore, more than 50% of very low grade ore is eliminated, losing only 1.9% of the uranium content.

7.2.2. Magnetic sorting

Sometimes, uranium ores contain iron sulphides which can spoil the yellow cake. It is the case with pyrrhotite. As pyrrhotite is highly magnetic, it is easy to collect it with a low intensity magnetic separator in which the magnetic field is produced by ceramic magnets.

Magnetic separators, dry for grains and stones larger than 1 mm, wet for the finer fraction, are simple and cheap in capital cost and operating cost. According to the content of the magnetic iron sulphides, it can be interesting to eliminate them and get rid of the iron problem in the plant.

7.2.3. Gravimetric sorting

In many deposits, uranium is found in pitchblende, uraninite, with specific gravity much higher than the waste. There is a lot of gravimetric sorting equipment available in the industry but so far, most are really efficient only on particles larger than 1 mm. Since the grains of the uranium ore have a smaller size, these equipments like jigs, spirals, cones, are of no use except for high grade deposits where the uranium is concentrated in veins or lenses. But, in such a case, the grade is so high that upgrading is not a necessity.

New centrifugal equipment is now being marketed for recovery of fine grained gold. The pulp to be treated is fed into the centre axis of a vertical bowl turning at high speed. The pulp falls into the center of the bowl and then is forced along the walls of the bowl. The centrifugal acceleration causes the high specific gravity particles to be trapped in groves in the wall of the bowl. Water is injected under pressure through small holes from the bottom of the groves. Adjusting the pressure allows sorting of the material according to the specific gravity.

This centrifugal concentrator requires batch loading and can be automated and has low capital and operating costs. All solutions can be recycled.

7.2.4. Grain size classification

In sedimentary deposits the uranium is trapped in the fine clay of the unconsolidated sands. The grade is generally low: typically 0.1 to 0.2% U. Mining these deposits is not technically easy and not always economically feasible due to:

- the low grade,
- the poor geotechnical conditions of the ore and surrounding material,
- groundwater,
- clay.

In order to lower the treatment cost, it is possible to upgrade the mill feed by grain size classification due to the fact that the uranium is located in the fine clay and not in the sands. The ore is first cycloned in hydrocyclones which upgrade it by a significant factor of 2 to 3. When it is considered that the U grade of the tailings is too high, because of uranium being stuck on the surface of the sand grains, it is possible to improve recovery by attrition of the sand grains followed by cycloning.

Grain size classification is used to upgrade what would have been waste ore (0.12% U) of an open pit. Tests were run while crushing the low grade ore at –20 mm. The fraction above 20 mm graded only 0.075% U while the finer fraction graded 0.145% U and can be milled at a profit.

7.2.5. Flotation

Flotation is widely used in the mineral and mining industry to produce as pure as possible minerals and high grade concentrate of base metals when the size of the grains is not large enough to use simpler equipment.

Basically, the principle of flotation is, using specific reagents, to produce a consequent froth at the surface of the diluted ore pulp and maintain the valuable grains of ore (mainly sulphides) on the bubbles with specific reagents. The ore concentrate is regularly collected with rakes at the surface of the flotation cells. Flotation can be useful in the uranium ore treatment to eliminate undesirable gangue material contained in the ore.

7.2.6. Mechanized shedding

When size, colour, shape of the blocks of ore and waste are different, they can be easily detected, and a major part of the waste can be taken off. It is the case for coal the aspect of which is quite different from the shale and gritstone. It is also the case for specific minerals like quartz, feldspars, fine special clays for cosmetics production. It could also be the case for specific uranium ore but would require shielding equipment against gamma rays and ventilation for eliminating radon and dust.

8. ORE PROCESSING

The selection of an appropriate process flowsheet for treatment of the ore evolves from a comprehensive programme of ore sampling and testing. The work starts with early exploratory drill cores which provides the metallurgist with a preliminary understanding of the mineralogy of the deposit. The nature of the mineralogy can suggest possible process options for investigation in a bench scale test programme which can assess the amenability of the ore to conventional unit processes for ore preparation, separation and uranium recovery.

If the project looks likely to proceed larger ore parcels can be recovered and treated at pilot plant scale to determine the best treatment option.

8.1. MILL PROCESSING

The function of a uranium mill is to extract uranium oxide from uranium-bearing ores and concentrate it into a product called “yellow cake”. During the first stages of physical treatment the ore is weighed and sampled for moisture content. Accurate computation of the moisture content is important because the amount of ore fed to the mill is always calculated in dry tonne equivalents. Two different flow sheets are used for reducing the ore size to the suitable mesh for leaching. The first flow sheet consists of a primary and secondary crushing followed by a ball mill.

After weighing and sampling, the ore is fed to a crusher and reduced in size suitable for feeding to the milling circuit. In the milling circuit the ore is mixed with water and ground to a size suitable for leaching.

In the second flowsheet the ore is crushed and then milled in an autogenous or semi autogenous mill. According to the hardness of the ore a pebble mill may be required for further grinding of the ore.

As the ore leaves the mill, it is in the form of a slurry containing 70% solids and 30% water. Up to this point the ore has been physically treated, no chemicals have been added. In summary, the ore has been weighed, sampled for moisture, crushed, sampled for uranium content, blended, and ground. The ore is now ready for chemical treatment.

From the mill, the ore slurry is pumped to the leaching agitators which may be of atmospheric or pressure type. As the slurry enters the leaching circuit, sulfuric acid and an oxidant are added. Sometimes O_2 and heat are also added. Uranium and any other metals that are soluble in sulfuric acid are leached or dissolved. The oxidant speeds up the leaching process and improves recovery. During the leaching process the ore slurry is continuously mixed with the leaching and oxidizing agents for a residence time needed for optimum recovery of uranium. At the end of the leaching phase, the ore slurry is pumped to a circuit for liquid/solid separation and washing.

After washing the slurry is thickened and pumped to tailings storage facilities which may be mined out open pits, backfilled into underground mine openings or into specially designed dams.

Some ore types are not amenable to acid leaching due to their high carbonate content. In such cases an alkaline leach system is used.

As previously pointed out, the leaching process removes metals other than uranium from the host rock such as vanadium, molybdenum and iron. Therefore, it is necessary to extract the uranium from the leachate. This is accomplished by either "solvent extraction" or ion exchange. Before entering the extraction circuit, the solution is clarified or filtered to assure that no minute solid particles of slime are entrained. As the uranium solution enters one end of the extraction circuit, barren solvent solution is introduced at the other end. The two solutions advance counter current to each other through four stages of mixing and settling. The solvent extraction or liquid ion exchange process selectively removes the uranium from the acid water solution leaving the unwanted metals in solution. Concentration of uranium is accomplished by advancing solvent through the circuit at one-third the rate of acid water solution flow. This concentrates the uranium in the solvent three-fold. The barren acid water solution or "raffinate" free of uranium leaves the last stage of the extraction circuit and is pumped back to the washing circuit.

From the solvent extraction circuit, the uranium now concentrated in the solvent extraction, is pumped to the stripping circuit. Here the uranium is stripped from the solvent in a four stage mixer-settler circuit and again concentrated. The latter is accomplished by advancing one part of stripping solution through 10 parts of solvent solution. The acid strip solution leaving the circuit contains 30 times the concentration of uranium as compared to the acid water solution that was introduced into the solvent extraction circuit.

The ion exchange process operations uses organic compounds to perform solute concentration. Generally, fixed organic resins contained within a column are used to remove uraniferous compounds from the pregnant leach solution by exchange. After adsorption, the uraniferous compounds attached to the resins are released (eluted) by a stripping solution and sent to precipitation. Ion exchange is used by most if not all in situ operations and was employed by some conventional mills.

Resins are constructed with anionic or cationic functional groups (typically anionic for uranium compounds) that have an affinity for the target compound and specifically bind the compound to the resin. Resins are synthetic polymers in which hydrocarbon groups make up a three-dimensional network that hold stable, reactive functional groups (e.g. strong acid-SO_3H; weak acid-COOH; strong NR_3Cl; weak base-NH_2RCl). Resins containing acid groups are called cation exchangers while resins containing basic groups are termed anion exchangers. Chloride ions can exchange with the anionic component of all functional groups, thus providing an inexpensive stripping solution (i.e. any chloride salt solution) for any of the resins.

As the pregnant leach solution passes through the ion exchange resins, the uraniferous compounds bind to the resins. The barren leach solution is recycled back to the leaching circuit. As the resins' binding ports are filled by the uranyl ions, the uranyl ion concentration at the outlet of ion exchanger column increases. Once the uranyl ions at the outlet reach a predetermined concentration, the column is considered to be loaded and ready for elution. Typically, the pregnant leach stream is then directed to a fresh vessel of resins. A concentrated chloride salt solution is then directed through the loaded resins, eluting off the uraniferous complexes. The pregnant elute liquor can then be directed to the precipitation circuit. The pregnant elute solution may be acidified slightly to prevent the premature precipitation of uraniferous compounds.

Once the uraniferous ions have been concentrated by solvent extraction or ion exchange, they are precipitated out of solution to produce yellow cake. The precipitate is then washed, filtered, dried and drummed. The chloride stripping solution is recycled back to the stripping circuit. The type of ion concentration solution (e.g. acid or alkaline solution) governs the precipitation method employed. With acid pregnant stripping liquors or pregnant elute liquors, neutralization to a pH of 6.5 or 8 using ammonia hydroxide, sodium hydroxide or lime results in the precipitation of ammonium or sodium diuranate. Hydrogen peroxide may also be added to an acid pregnant stripping liquor or pregnant elute liquor to precipitate uranium peroxide. All forms of the uraniferous precipitate are known as yellow cake.

Alkaline pregnant stripping liquors or pregnant elute liquors typically contain uranyl carbonates. Prior to precipitation of the uranyl ions, the carbonate ions must be destroyed. An acid (usually hydrochloric acid) is added to the carbonate concentrate solution to break down the carbonates to carbon dioxide; the carbon dioxide is vented off. Once the carbonates have been destroyed, the acidified solution is neutralized with alkali or treated with hydrogen peroxide to precipitate the uraniferous compounds. Precipitation operations based on neutralization of acid solutions are favoured because of the higher purity of the yellow cake produced form an alkaline neutralization.

The yellow cake is separated from the precipitation solution by filtration. Thickeners may be used in conjunction with filtration units. The filtered yellow cake can then be dried and packaged for shipping. The supernatant generated from precipitation and dewatering circuits can be recycled to the respective solvent extraction or ion exchange stripping solution. A general schematic outlining mill processes is shown in Fig. 4.

8.2. HEAP LEACH PROCESSING

Uranium ores are mostly treated in mills. The ore is finely ground to a suitable size for obtaining the highest possible recovery. However, the refractory fraction of the uranium lost in the tailings can reach 5 to 10 % or more for medium grade ores.

Therefore with low grade ores the recovery is too low and does not pay for the mill treatment. Nevertheless uranium can be economically recovered using heap leach process. The recovery is lower than in a mill but the treatment cost is low enough to balance the low recovery.

Specific ores of medium grade with good porosity and permeability for instance can also be economically treated by heap leach process with the same recovery as in mill and at a lower cost. Where the new projects are being studied, it is recommended to consider the opportunity of the heap leach process in specific cases as a substitute for conventional milling.

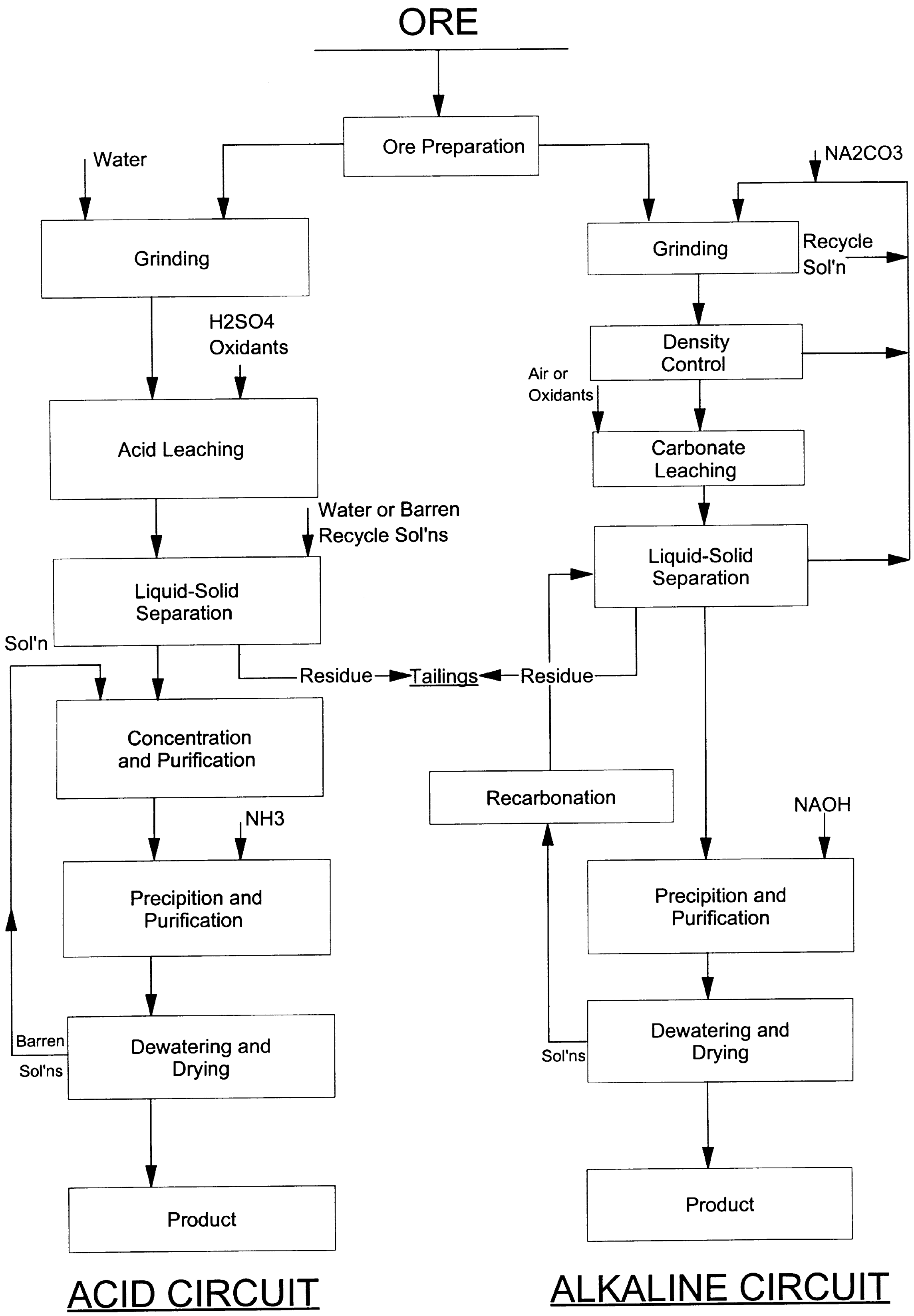


FIG. 4. Mill processing flowsheet.

8.2.1. Heap leaching pad construction

The ore is stockpiled on pads constructed to meet the following criteria:

- The floor of the pads must be impermeable, to prevent ground and water table contamination. The impermeable lining of the floor is covered with a layer of washed gravel to ensure a homogenous regular circulation of the leaching solution while protecting the lining.
- The pads are surrounded by lined ditches which collect the solution. Pads and ditches are built so that the solution can be recovered in a sump and pumped to the metal recovery unit (see Fig. 5).

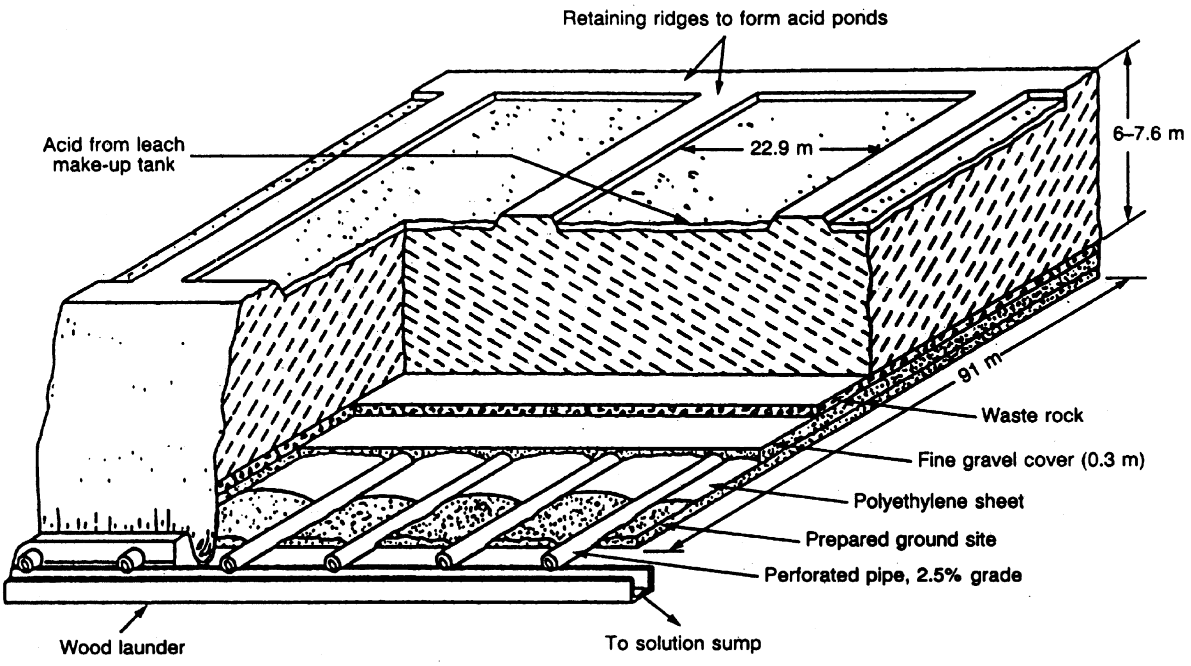


FIG. 5. Heap leaching pad construction.

8.2.2. Ore heaps building

As it is easy to understand an efficient leaching implies that the leaching solution can move easily in the totality of the heap and leach every ore pebble. For this reason the use of transportation equipment like loaders or trucks must be prohibited. If not they would compact the ore and the risk would be very high that the solution would flow rapidly through preferential channels without leaching the ore pebbles.

Therefore it is highly recommended to build the heaps using conveyor belts and stackers while adjusting continuously the ore chute height at its minimum value. This prevents compaction and breakage of the ore pebbles.

The granulometry of the pebbles depends on the characteristics of the ore. Low grade ore is crushed at a rather coarse size, normal grade ores at a finer size: — 10 to 20 mm. The fines less than 5 mm. are pelletized with a non acid consuming agglomerating agent.

The characteristics of the ore determines the size to which the ore must be crushed.

Low grade ore is crushed to a rather coarse size, average grade ores are crushed to a finer size of 10–70 mm. Fine of less than 5 mm are pelletized with a non-acid consuming agglomerating agent.

Small test heap leach piles are normally constructed to determine what is optimum sizing and leach durations.

8.2.3. Leaching process

In an countercurrent concentration process, an acid solution is sprinkled over the ore heaps. The pregnant solution recovered at the bottom of the last built heap is pumped to the metal recovery unit. Solution from pad no: N is recycled to pad no: N+1, first built heap no: 1 is the only heap watered with a new U barren solution.

8.2.4. Heap leach time

The heap leach process is achieved in several weeks which number depends on the characteristics of the ore. It normally does not exceed 2 months.

8.2.5. Ore removal

When the uranium recovery from pad no: 1 has become too low, the heap is watered with fresh water. When washed, the leached ore is removed and replaced by a new one and so on.

9. DECOMMISSIONING

9.1. DEFINITION

Decommissioning and site rehabilitation is the work required to return a uranium mine, mill or waste management facility to a condition which delivers a safe and sustainable environment that requires little or no human intervention over the long term. A decommissioning plan should be an integral part of the Environmental Impact Statement prepared to gain approval of the uranium mining project.

Decommissioning of a uranium project is site specific and will depend in large measure on the design of the mining operations, the process chosen and the geological environment in which it is situated. Regulations governing the requirements for an acceptable decommissioning plan may vary widely from jurisdiction to jurisdiction. Approaches common to all jurisdiction address the protection of the environment over the very long term. There is also a tendency to set lower limits on all levels of toxic substances over time.

Decommissioning costs are incurred at the end of the mine life and provision should be made to cover these costs. Common practice is to decommission as many facilities and areas during operation to reduce costs.

9.2. MINES

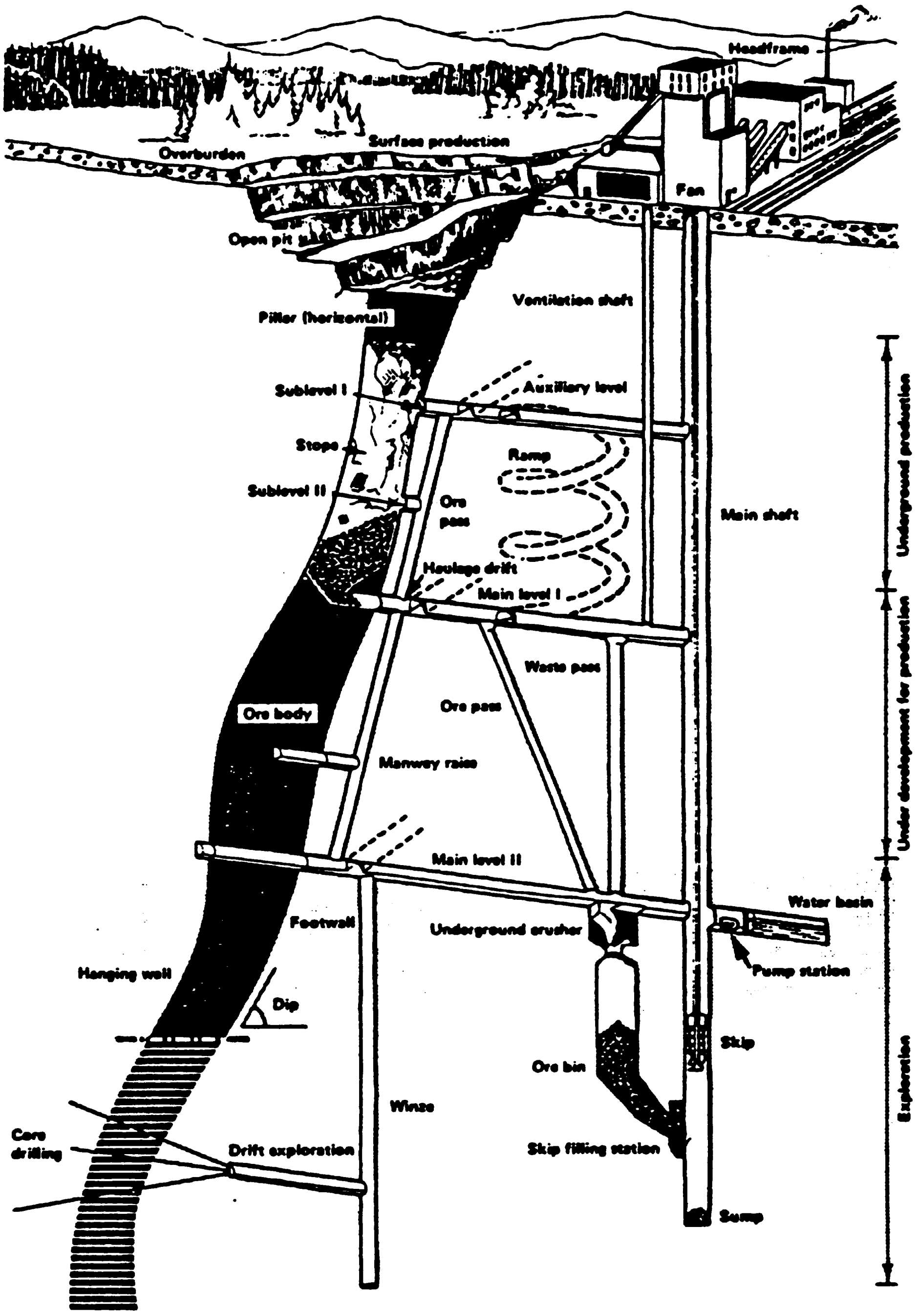
9.2.1. Open pit

Decommissioning open pits can take a number of forms. Most jurisdictions require that material such as waste rock removed to gain access to the uranium ore to be backfilled into the pit and steep side walls be given more modest slopes. In some cases where there is sufficient rainfall, the pits are allowed to flood.

Often, available pits are used to provide permanent storage for mill tailings. In these cases, abandonment will only be allowed after the tailings are suitably covered.

9.2.2. Underground excavation (See Fig. 6)

There are a number of issues which must be addressed when underground mines are abandoned. Complete and accurate maps of all underground openings are required for permanent government records. The regional stability of the mining operation must be known to determine if future subsidence will affect surface topography. Models of the hydrogeology of the deposit must be developed to determine if contaminated mine waters will reach the surface environment.



Courtesy, Atlas Copco Construction and Mining N.A.

FIG. 6. Underground excavation.

Underground workings, provided they can be properly isolated, are excellent repositories for contaminated surface debris resulting from demolition of uranium mills and contaminated soils. They also provide safe repositories for partial storage of mill tailings which may not be readily decommissioned in a surface tailings management facility.

All openings to underground workings must be either backfilled or have engineered permanent caps placed over the tops.

9.2.3. In situ leaching (ISL)

The major issue in decommissioning in situ leaching (ISL) operations is the restoration of the aquifer in which the uranium ore is situated. Permits of up to three or four years are sometimes required to restore water to an acceptable condition. It is important to note that in some jurisdictions it is necessary to not only restore to original condition but also improve water quality to drinking water standards. Other jurisdictions do not require any restoration if the water condition is naturally contaminated.

The surface expression of an ISL plant is not extensive and equipment can, in most case, be decontaminated and sold for other use when mining is completed.

9.3. MILLS AND PROCESSING PLANTS

Uranium plant buildings, because of their contamination with radioactive material, generally must be demolished. Salvaged equipment and construction material must be cleaned or covered or stored in underground mine excavations if available or transported and buried in mill tailings. Concrete must be rubblized and then covered with local drift material and revegetated.

Site cleanup standards vary depending on local regulations. In general, they vary on site specific bases and are determined on the basis of the expected usage on the property.

9.4. WASTE ROCK FROM MINING

Mine waste rock may contain acid producing minerals, have low levels of radioactivity (commonly called special waste) and be physically unstable. Decommissioning of the material requires containment, and to be covered to attenuate radon release, and to reduce or eliminate acid production from oxidation of sulfides.

Decommissioning methods include return to the source either to open pit or to underground excavations.

9.5. TAILINGS

Solid tailings from the milling operation are the insoluble leach residues with varying amounts of chemical precipitates produced in the hydrometallurgical process. Volumes are usually substantial and often contain metal sulphides which oxidize to form acid under certain conditions. The material also contains low levels of radioactive minerals which require special measures to mitigate the environmental effects.

The method of decommissioning is dependent on the method chosen for tailings containment. The end result must ensure that there is no escape of toxic chemicals or radioactivity to the environment.

Tailings stored on surface require a containment basin which is surrounded by low impermeable natural or man-made structures capable of ensuring that toxic elements cannot escape to the environment. Decommissioning of the tailings pit will include capping the entire surface with a suitable cover. Water cover has been proven to be effective in reducing radon release and gamma attenuation. It is also an effective barrier for sulphide oxidation. In dry climates, clay cover is used with a topping of rock or cobble for erosion protection.

Some jurisdictions now insist that the tailings be stored in underground excavations or in mined out open pits. Decommissioning requires that the mine opening be capped permanently and the material in open pits have a suitable cover placed after the operations are closed.

Tailings management facilities require monitoring and, in some cases, effluent treatment over the very long term. It is a normal requirement that a detailed programme be established and that monies be made available to fund this work. In most jurisdictions, the producer must provide bonds or letters of credit during operations and establish a fund on closure being the present value of a perpetual care and maintenance programme for the facility.

9.6. DECOMMISSIONING EXAMPLE OF SANDROCK MINE, ONTARIO, CANADA

The effort and expenditure to decommission a Uranium Mine and processing plant can and does represent a significant portion of the cost to produce uranium from the facility. This fact is recognized in a number of jurisdictions where regulation requires that financial sureties to cover decommissioning costs be provided when permission to construct a uranium mine is obtained. Most jurisdictions now require that existing mines have detailed closure plans in place with appropriate surety packages available on demand.

To illustrate the scope of work and the costs involved in a recent decommissioning project, the Stanrock Mine, an underground mine located in the Elliot Lake Mining Camp in Ontario, Canada has been chosen. It is important to note that as with all rehabilitation projects each uranium mine requires a site specific approach and the effort and costs incurred depend on location, climate, and regulatory framework.

9.6.1. History

The mine located 21 kilometers northeast of the city of Elliot Lake, is one of 11 mines developed in the area in the l950s. The property consisted of a mine, mill and tailings management area (TMA) situated on a rocky peninsula extending out into a large inland lake. The facility commenced production in March 1958 with a design capacity of 2995 tonnes of ore per day. The ore was extracted using variations of the room and pillar method and the mill used a conventional acid leach process. Tailings were discharged into a waste management area located in a rock basin and were contained in the basin by pervious dams constructed of spigoted tailings placed in four saddles in the surrounding basin walls. Mining ceased in 1964 with the TMA containing approximately 5.7 million tonnes of waste product, covering an area of 52 hectares. Operations remained suspended apart from some underground development work until 1991 when a decision to decommission the plant was taken.

9.6.2. Decommissioning studies

Detailed planning for the Stanrock Mine closure commenced in 1991. Comprehensive engineering studies were carried out first to characterize the site and then to determine a preferred closure option utilizing modeling techniques specifically developed to forecast the long term behavior of radioactive tailings in the Elliot Lake area.

Specific segments of the studies and the cost expressed in US $ are as follows.

9.6.2.1. Underground workings $33 000

(a) Long term stability of the openings
(b) Hydrogeology and water inflow modeling
(c) Permanent capping of all openings to surface

9.6.2.2. Plant and surface infrastructure $47 000

(a) Detailed contamination survey to identify hazardous substances both radioactive and other on the surface site.
(b) Identification of permanent disposal sites for contaminated debris from salvage demolition of the surface plant.

9.6.2.3. TMA Reclamation $167 000

(a) Surface hydrology study
(b) Subsurface hydrogeological study
(c) Detailed characterization of the tailings
(d) Analysis of the containment structure stability in situ and with relocation
(e) Tailings relocation options
(f) Tailings cover options

9.6.3. The environmental assessment review process

The Canadian Federal Government has in place a process which ensures that proposals which have been determined to have a significant environmental impact will be subject to a public environmental review panel. The panel issues guidelines to the proponent for the preparation of an EIS. The costs of these guidelines are $134 000.

9.6.3.1. Environmental impact statement

(a) Preparation of the EIS detailing the existing environment, decommissioning issues and alternatives, the proposed options and the long term environmental impact.
(b) Response to concerns and issues raised by the panel and public prior to panel public hearings.

9.6.3.2. Regulatory approval $67 000

(a) Amending the closure plan to address the panel and Government directives.
(b) Developing an environmental monitoring program for the long term acceptable to the regulating agencies.
(c) Obtaining a final decommissioning license for the Stanrock Mine.

9.6.4. Demolition, salvage and site cleanup

The plan envisaged salvaging all usable components from the hydrometallurgical plant and surface buildings and then complete demolition. Contaminated site areas were cleaned up with removal to underground or the TMA. All areas were vegetated.

9.6.4.1. Plant demolition $1 000 000

(a) Asset removal and sales
(b) Building demolition, scrap salvage and contaminated debris removal to underground storage.
(c) Foundation fill including till cover for revegetation.

9.6.4.2. Site cleanup	$134 000

(a) Removal of contaminated soil special waste products to the TMA (approx.10 000 cubic meters)
(b) Recontour the surface to natural surroundings and revegetate (approx 100 hectares).

9.6.5. Tailings reclamation (See Fig. 7)

Studies have shown that acid generation is the major environmental concern associated with Elliot Lake uranium tailings deposits.Stanrock tailings contain about 5% to 10% iron sulphide (pyrite). It has been demonstrated that the success of an approach to reduce the effects of radioactive elements can be evaluated by its ability to inhibit acid generation. The plan chosen for the Stanrock TMA allowed the tailings to remain in place with the construction of new low permeability perimeter dams to raise the water table in the tailings mass. Acid generating potential is greatly reduced and with interim treatment of surface run-off the TMA is expected to remain stable over the long term. The high water table, partial cover and revegetation will reduce radioactive emissions to acceptable levels.

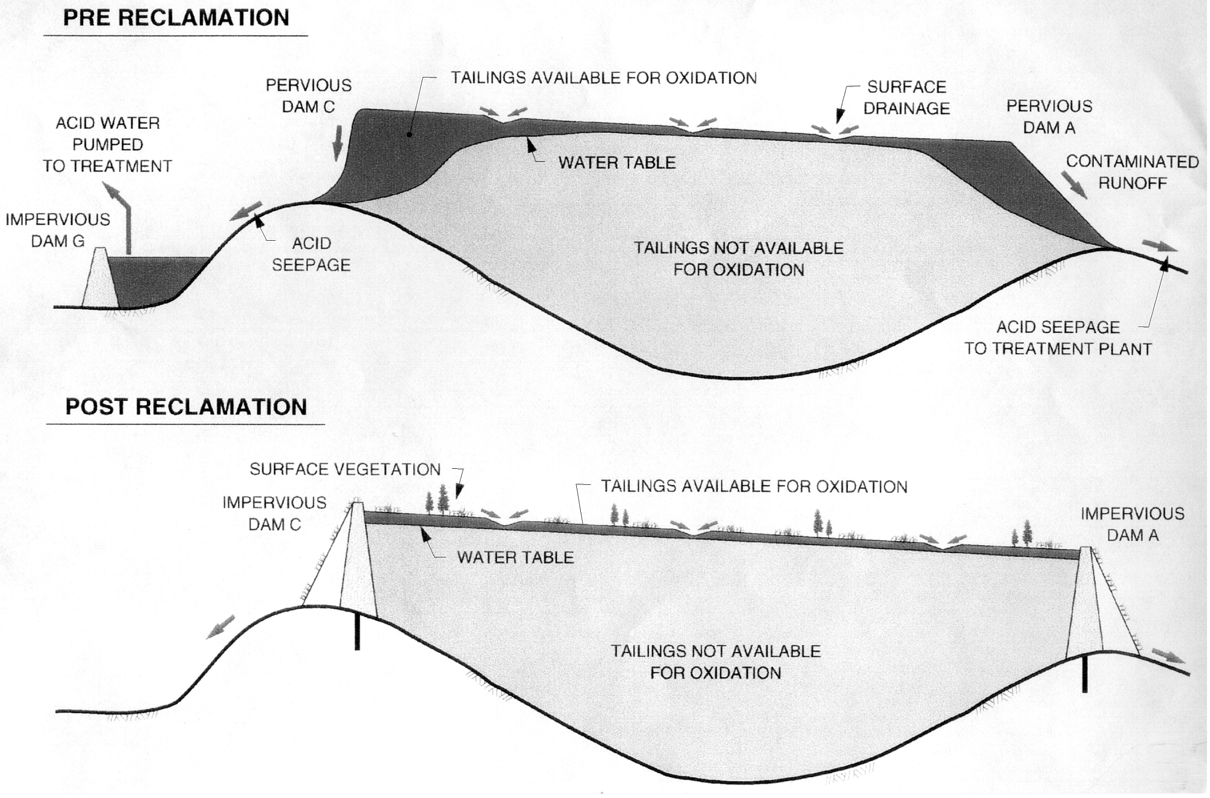


FIG. 7. Tailing management.

9.6.5.1. Dam construction	$ 4 690 000

(a) The ground surface within the foot prints of the new dams are prepared for construction. The bedrock foundations are grouted along the alignment of the glacial till core.
(b) The glacial till core is constructed along with an upstream shell (between the core and the tailings) of compacted tailings, and a downstream shell of crushed rock incorporating a sand filter and finger drain system.
(c) An emergency spillway constructed in bedrock is designed to prevent the loss of tailings due to water erosion in the TMA and to handle the maximum precipitation event.

9.6.5.2. Tailings surface rehabilitation $800 000

(a) Construction of surface drainage works (lined channels) to safely transport surface water from the TMA basin.
(b) Partially cover and revegetate the 52 hectare site.

9.6.5.3. Downstream treatment facility $600 000

(a) Construction of a lime and barium chloride treatment plant.
(b) Flow control ponds and measuring flumes.

9.6.6. Indirect costs

The rehabilitation process will be complete in 1998 some six years after project initiation.Costs due to the closure include the following items.

9.6.6.1. Environmental control $703 000 OR $117 000/year

(a) Chemical treatment of tailings effluent
(b) Monitoring and sample collection analysis.

9.6.6.2. Administration $402 000 OR $67 000/year

(a) Allocated costs from site operations.
(b) Allocated costs from Head Office.

9.6.7. Post-decommissioning environmental costs

Monitoring of the Stanrock TMA and the surrounding area will be required over the long term. The checking of the integrity of the structures and determination of environmental effects will be required long after the decommissioning project work is complete. The monitoring program include measurements of effluent, dam seepages groundwater, tailings pore water and surface water quality; air quality monitoring for dust; and radiation monitoring for gamma and radon. In addition it will be necessary to treat surface runoff for a period of time estimated at 25 years to neutralize residual acidity remaining in the TMA.

9.6.7.1. Annual monitoring cost

(a)	Facility care and maintenance	$27 000/year
(b)	Monitoring and assaying	$13 000/year

9.6.7.2. Annual treatment cost (25 years)

(a)	Treatment plant Op. & Mnt.	$10 000/year
(b)	Reagents	$20 000/year
(c)	Monitoring and assaying	$47 000/year

9.6.8. Summary and total reclamation costs

For the example given (the Stanrock Mine) it can be seen that the total cost to rehabilitate the site and ensure that the tailings remain in a benign state over the long term result in a substantial expenditure. In this case, total costs are in the order of $8 790 000 if annual indirect costs are included. This results in a unit cost of $1.53 per tonne of tailings. In addition, post decommissioning, annual costs are $117 000/year for the first 25 years and $40 000/year thereafter.

A report “Decommissioning of U.S. Uranium Production Facilities” DOE-EIA-0592 released in February 1995 contains many examples of similar rehabilitation. The Stanrock example falls in the mid-range on the basis of cost per tonne of tailings.

10. SPECIFIC ISSUES FOR HANDLING URANIUM ORE IN OPEN PITS

10.1. PIT MODELING AND DESIGN

Uranium orebodies located close enough to surface may be recovered by using open pit methods. Large earthmoving equipment is used to break the ore and strip waste material and load into trucks or conveyors for transport to the processing facility or waste rock stockpiles.

Pit slopes are designed based on parameters specific to each orebody including ground conditions, angles of rock structures, faults and joint planes, etc. A steeper slope will necessitate less waste removal (i.e. reduce the waste to ore ratio) and reduce the overall mining cost. There are available a number of commercial computer software programs which, if provided the correct input design parameters, will determine the optimum design for a given open pit resource.

There are, however, a number of specific issues for handling uranium ores from open pits which require careful consideration in the design of the mining operation.

10.1.1. Hydrogeology

Water flows into the pit during and after mining operations are important factors which influence the environmental effects and the ultimate mining costs associated with extracting the uranium ore. Prior to starting up the mine, it is necessary to determine accurately the various groundwater regimes both in the overburden, if such exists, as well as within the ore and surrounding cap and wall rocks.

The various parameters which must be determined in order that a hydrogeological model can be built include estimates of the structure, porosity and permeability of the ore and surrounding rocks, the presence of aquifers and their chemical constituents, the presence of faults or joint structures which act as conduits and the mineralogy of the uranium ore and its various other metalliferous components. The development of the model will require a series of bored holes with recovery of sufficient ore to determine strength, porosity, permeability and structure of the rock mass. Pump tests in bored holes in conjuncture with a number of suitably instrumented surrounding holes can accurately determine the amount and direction of waterflows. Chemical analysis of groundwater particularly from aquifers is also necessary.

The model which can be verified as the pit is developed will be used to design the capacity of the pit pumps, the capacity and components necessary to treat the pit effluent and in some cases prompt the installation of water interceptors, diversion walls to keep water from being contaminated from contact with the uranium ore.

10.1.2. Waste handling, special or contaminated waste

Open pit mining normally involves the handling of relatively large quantities of waste rock. There are special requirements needed when considering waste materials near uranium ores. Waste rock in close proximity to uranium orebodies often contain low levels of radioactive elements as well as metal sulphides associated with uranium deposits. When the waste rock is broken and removed to storage areas the contained metals and sulphides are exposed to weathering and in the case of sulphides, oxidation. The resulting effluent must be contained and or treated prior to it being allowed to enter the biosphere.

10.1.3. Ore handling

Special care must be exercised in the extraction of uranium ore particularly if it is high grade. Gamma logging of the holes drilled to blast the rock in the ore zones will give fairly accurate measurements of ore grade. Precautions which can be initiated include: the maintenance of cover rock to protect workers in the case of very high grades, special and monitoring procedures to limit exposure to high levels of radiation and the use of high efficiency equipment cleaning machines.

10.1.4. Equipment

Equipment normally used in open pit mining can be used with or without modification depending on the grade of ore being handled. Trucks hauling high grade ores are equipped with extra steel plate between the box and the cab to attenuate gamma radiation and maintain low exposure levels to the driver. In addition all equipment in use in the pit is normally equipped with high efficiency air conditioning units to reduce exposure to radioactive dusts.

Small bucket loaders or back hoes are used in cases where selective mining is employed to ensure high grade ore is not excessively diluted with waste rock. Subject equipment is used under careful geological supervision with technicians constantly monitoring ore content with the use of hand held gamma detectors.

10.1.5. Scanning

Materials removed from the pit are allocated to the various storage and disposal areas through the use of truck scanners which are calibrated to determine the approximate grade of the ore or special waste being transported. The scanner generally serves two purposes. The first is the separation of material sent to the ore stockpiles and the special waste disposal areas. The scanner also allocates ore within the stockpile area according to grade. This greatly assists the delivery to processing plant to obtain efficient extraction of uranium.

10.1.6. Decommissioning — tailings containment

Open pit excavations in a number of cases offer excellent repositories for mill tailings and radioactive residues from the uranium processing facility. The necessary attributes required for tailings pit disposal include a favorable hydrogeological regime, ore removal prior to mill startup and the necessary in pit development needed to handle tailings effluent during operations.

A detailed analysis of the possible contaminant pathways is through hydrogeological and geochemical modeling is a necessary precondition for this disposal system.

10.2. PIT PREPARATION

A number of facilities must be in place prior to actual pit excavation. These include water control and treatment facilities, the preparation of storage areas for ore, special waste and regular non-contaminated waste rock and over burden. In addition, surface infrastructure including employee change houses and equipment maintenance facilities designed to accommodate the pit equipment must be in place.

10.2.1. Water control

Water control can be accomplished by interception and or diversion. The purpose is to reduce the amount of water entering the pit excavation. Common practice is to drill a line or ring of interceptor wells into an aquifer or water conduit and remove the water by deepwell pumps before it can enter the excavation. The wells are spaced at intervals determined by the hydrogeological model. In some cases installation of a grout curtain will divert water away from the pit.

Water which does enter through the pit walls must be collected in sumps and then pumped to surface settling and holding ponds to allow pit effluent to settle out suspended solids. The water is then treated to remove contaminants prior to release to the environment. Pumps and lines must be sized to ensure adequate capacity to avoid flooding, particularly during rainy seasons or spring runoff.

10.2.2. Water treatment

Water in contact with uranium ore will become contaminated with uranium, radium and other radioactive materials. In addition, when uranium ores contain other metal sulphides, these tend to oxidize and metal ions go into solution adding further contaminates to the pit effluent.

The water pumped from the pit must be treated to remove all contaminants necessary to meet water quality objectives as promulgated by government regulations. These are normally very stringent and require sophisticated chemical processes to attain the desired purity. Water treatment costs represent a significant expense including a large capital charge for the facility as well as ongoing chemical, operating and maintenance costs. It is generally cost effective to reduce the quantity of water entering the pit to as low as possible.

10.2.3. Ore pads

Ore storage must be established on special pads which are lined with an impermeable blanket to ensure waste effluent can be collected and treated. The blankets are made of either a layer of clay or similar water-tight materials or with a synthetic blanket of material such as hypolon liner. The pads must be sized to hold the various grades of uranium ore and be capable in the case of an open pit which will be used for tailings containment, of storing the total ore reserve.

10.2.4. Special waste pads

These pads generally require the same construction materials as the ore pads and must be designed to ensure containment and eventual treatment of all runoff products. The pad must also incorporate materials and be designed such that the special waste can be covered and protected to ensure long term environmental acceptability. An alternative cost effective disposal method might be to return the special waste products to the pit from whence they came.

10.3. PIT OPERATION

Pit operations particular to uranium mining generally pertain to special requirements needed to protect workers and the environment from the hazards of radiation.

10.3.1. Mapping and sampling

An accurate record of the geological and hydrology is essential for the efficient and safe operation of the pit. As the pit is excavated, detailed mapping and water measurements are necessary to confirm the models generated for the pit design and the water balance.

Sampling, particularly via the use of down hole gamma logging of blast holes is important to locate the ore and in particular, high grade zones which require special handling techniques to protect workers. Accurate sampling is also necessary to ensure that excessive dilution from wall rock is not inadvertently sent to the ore stock pile. Similarly, small pods of high grade can be masked or covered with waste rock and can be diverted by the scanner to the special waste areas.

10.3.2. Water treatment

Water entering the pit from runoff and aquifers in the surrounding walls must be collected in sumps and then pumped to settling storage areas on surface. The water must be sampled on a regular basis to allow for efficient processing at the water treatment plant. It is especially important that the quantities entering and leaving the plant be closely monitored as excessive flows may surpass plant capacity, thus allowing contaminants to reach the environment. Any accedence of regulated levels will cause immediate shutdown of operations and lead to costly pollution penalties in most jurisdictions.

10.3.3. Special ore handling equipment

Mining equipment is normally equipped with extra shielding material to protect operators. In cases of extremely high grade ore, equipment which can be remotely controlled is used.

Maintenance plants require extensive cleaning facilities in order that production equipment can be thoroughly cleaned prior to repair work being carried out.

10.3.4. Material classification

The programme to distinguish between regular waste and special (contaminated with radioactive materials) waste is an essential part of the efficient operation of the mine. A general rule in North America is that material grading less than 0.03% U_3O_8 can be located in normal waste storage areas. Special waste containing uranium in the ranges from 0.1% to 0.03% is normally stored in special waste containment areas. Failure to maintain strict controls on the placement of these materials can lead to expensive relocation charges and or loss of uranium products.

10.3.5. Safety and health

Safety and health issues particular to the uranium mining industry are centered on maintaining exposure levels to radioactivity to levels below legislated limits and under the ALARA principle. Employee training plays a major role in an operational safety programme. The worker must be familiar with the hazards associated with working with radioactive materials and the methods and procedures used to reduce dose levels.

Accurate monitoring of radon, gamma and dust levels are essential components of the safety programme, as is the maintenance of clean equipment. Dust levels can be controlled by the use of water sprays.

10.3.5.1. Protective equipment

- self contained breathing apparatus
- powered respirators
- dust masks
- eye protection.

10.3.5.2. Laundry — change house

- separate clean and soiled units
- washing equipment for boots and outer apparel
- separate laundry facilities for cleaning overalls and work clothes.

10.3.5.3. Employee monitoring

- gamma badges
- pencil dosimeters
- personal dosimeter for radon daughters and radioactive dust
- measurement.

10.4. EXAMPLES

10.4.1. Open pit

There are a number of examples of high-grade uranium deposits located relatively close to surface such that ore can be mined by open pit methods. Known deposits are located in the province of Saskatchewan, Canada and in the Northern Territory, Australia. A typical example of such a deposit in Northern Saskatchewan illustrates the methods, plant, equipment and costs associated with mining with mining high-grade ore from an open pit.

10.4.1.1. Typical uranium deposit

The deposit is a zone of high grade mineralization emplaced primarily in sandstone at the unconformity with the underlying basement rocks at a depth of 120 metres. The mineralized zone contains a minable reserve of 20 000 tonnes of uranium (U) in 800 000 tonnes of ore. The open pit requires the removal of 20 000 000 cubic metres of waste rock to expose the ore. An additional 400 000 tones of special waste (material contaminated with low levels of radioactive minerals) will be produced as the ore is extracted.

A detailed hydro geological study has determined that a water pumping system capable of handling up to 15 000 cubic meters per day is required to control water inflow to the pit while the ore is being removed. A ring of water wells installed on the circumference of the pit is designed to remove uncontaminated water at the rate of 15 000 cubic meters per day. The in-pit pumping system is designed to handle up to 3000 cubic meters per day of contaminated water.

The deposit is located in a remote northern environment 600 kilometers from the nearest large community and is serviced by air and road transport and power is available at the site. The ore and waste are excavated with large open pit equipment over a period of five to six years.

10.4.1.2. Mine surface plant — capital cost

The plant service complex and infrastructure is designed to accommodate a mine life of five or six years. Buildings are prefabricated and equipment is installed with a view to ease of removal.

	Item	Cost US$
(1)	Shops and maintenance complex building sized to service 100 st trucks including enclosed wash/cleaning facility.	1 000 000
(2)	Office buildings/change room to accommodate 100 employees.	270 000
(3)	Area surface preparation — ore and special waste pads contour surface and install lined drainage ditches to ensure collection of contaminated run off. Prepare lined storage pads for up to 400 000 tones of ore and special waste.	1 000 000
(4)	Water treatment plant. Facility sized to treat up to 3 000 cubic meters per day of contaminated water with two stages of treatment and sand filtration	5 000 000
(5)	Surface infrastructure roads, power supply potable water and waste disposal	400 000
(6)	Indirects. engineering, construction management, camps and transportation costs during construction	1 330 000
	Total	9 000 000

10.4.1.3. Water management — capital cost

The system is designed to intercept the majority of the water before it is contaminated from the pit excavations. Uncontaminated groundwater is discharged directly into a receiving lake.

	Item	Cost US $
(1)	Well field system: A system of twenty wells is developed on the circumference of the pit such that 80% of the water inflow is captured prior to entering the pit.	2 345 000
(2)	Piping: Two kilometers of collection piping surrounds the pit and one kilometer of final discharge pipe is required. All pipe is insulated and heat traced to prevent freezing.	335 000
	Total	2 680 000

10.4.1.4. Open pit — mine operating costs

Mine operating costs include the direct cost of waste stripping and ore and special waste excavations. Indirect costs which are accumulated on an annual basis include various items such as engineering and administration, man transport and room and board, mining license fees, allocated Head Office costs and the cost to treat contaminated water from the pit.

Mining rate is at an initial rate of 5 000 000 cubic meters of waste per year reducing at the end of the second year to 3 300 000 cubic meters while ore and special waste are removed at the rate of 400 000 tonnes per year. Total excavation time is 5 years. Mining equipment includes a 12 cubic meter capacity hydraulic shovel, 100 trucks and necessary support and back-up loading equipment. The major mine equipment is leased and the leasing cost is included in the direct operating costs.

	Item	$/m^3	Cost $
(1)	Waste mining		
	Drill blast	0.84	
	Haulage	0.67	
	Maintenance	1.34	
		Total 2.85	
		Total cost 20 000 000 m^3	57 000 000
(2)	Ore special waste mining	$/t	
	Drill blast	1.34	
	Haulage	1.17	
	Maintenance	1.01	
		Total 3.52	
		Total cost 800 000 tonnes	2 816 000
(3)	Indirect costs	$/year	Cost $
	Water treatment	603 000	
	Allocated Site*		2 680 000
	Mine Admin. Engineering	1 206 000	
	Allocated H.O.**	1 005 000	
		Total 5 494 000	
		Total cost 5 years	27 470 000

* Allocated site includes transportation, room and board for 100 man campsite services including power and road and camp maintenance.

** Allocated H.O. includes management expense and site licensing fees.

10.4.1.5. Site reclamation

The site will be rehabilitated. Work includes removal of 400 000 tonnes of special waste to the pit bottom for permanent disposal. Removal and or demolition of all surface plant and the revegetation of all disturbed surfaces including the waste storage area.

	Item	Cost$
(1)	Remove 400 000 tonnes special waste	270 000
(2)	Remove/salvage/demolish plant	333 000
(3)	Vegetate — 500 hectares	467 000
	Total	1 070 000

10.4.1.6. Total costs

Total expenditures to mine the deposit (20 000 tonnes U) over a period of five years is shown on the table below.

	Item	Cost $
(1)	Surface plant capital	9 045 000
(2)	Water management capital	2 680 000
(3)	Waste mining operating	56 950 000
(4)	Ore and special waste mining operating	2 814 000
(5)	Indirect costs operating	27 470 000
(6)	Site reclamation operating	1 072 000
	Total	100 031 000

10.4.2. Under water

This method will be described according to the findings developed during the primary studies of a Tertiary deposit.

This type of sedimentary deposit where uranium is trapped in the fine clay fraction of consolidated clay sands is not easy to mine due to:

- the low grade
- poor ground conditions which do not allow use of any underground methods
- a large amount of groundwater radioactive enough to require a treatment before releasing into the environment
- clay which hinders the movement of trucks and other open pit mining equipment.

The stripping ratio is high (in the range of 8). Because of these specific conditions and the fact that the deposit which is located close to a main road and a railway could generate significant troubles due to ground surface movements resulting from dewatering, it was determined that a classical open pit operation was not feasible. A mining method was planned, requiring no dewatering and having a very low stripping cost per tonne.

It was considered achievable because the deposit presents some other favourable characteristics:

- the volume to mine is high (in the range of 120 million m^3 i.e. 6 to 10 million m^3 per year) allowing use of large drag lines which can strip under water at large capacity and very low cost
- the ore has an average thickness close to 8 m.

- the run of mine ore can be easily upgraded at low cost using grain classification by hydrocyclones
- the treatment cost per tonne is low because no crushing and no grinding are necessary. The acid consumption is low and leaching can be done at normal temperature without heating.

10.4.2.1. Stripping (See Fig. 8)

The plan developed was to strip with two drag lines, one on the surface stripping down to 10 m below the water level and the other mounted on a barge for stripping the remainder of the overburden. Stripping is stopped at the top of the subhorizontal mineralized zone. With new level control systems, stripping can be controlled with high accuracy. It will be shown later how it is possible to mine the mineralized zone with an appropriate selectivity.

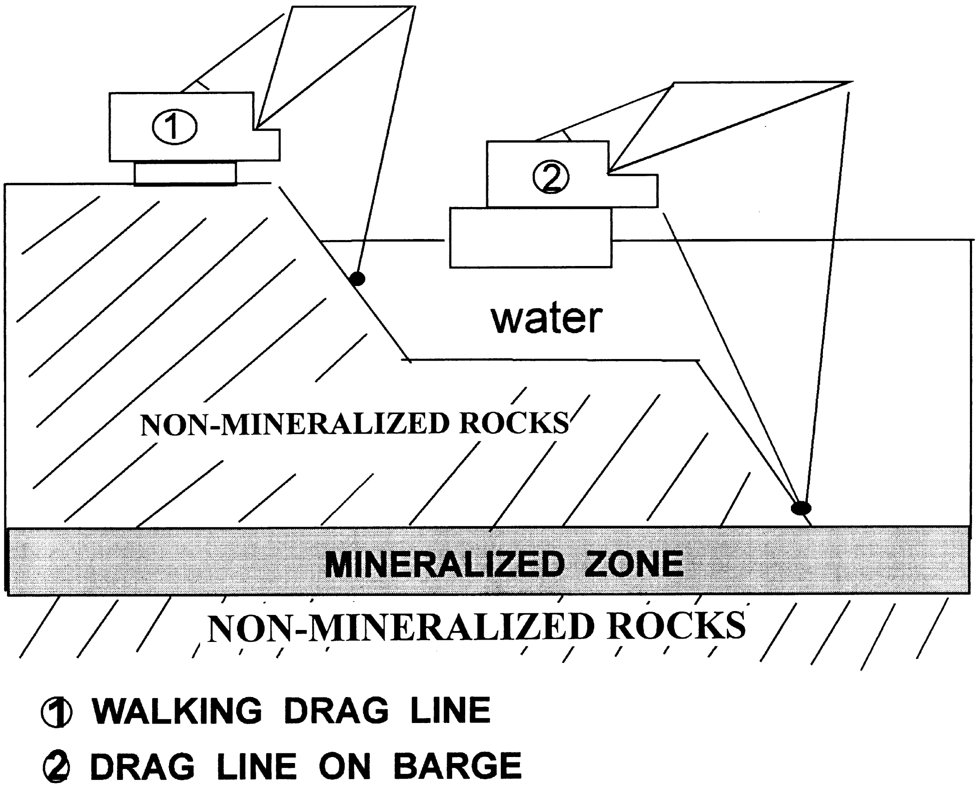


FIG. 8. Walking drag line.

The main characteristics of the drag lines are:

- operating weight: 1000 tonnes
- boom length: 79 m
- operating radius: 75 m
- max. hoisting distance: 45 m average necessary: 15 m
- bucket pay capacity: 36 m^3
- total electric power: 4000 kW average operating power: 750 kW.

The estimated costs per B.C.M. (bench cubic metre) are:

- operating: \$0.25 / BCM in place
- capital: \$0.25 / BCM in place.

10.4.2.2. Waste dumping

Because of the depth of the pit and the slope of the wastes, the boom of the drag line is not long enough to dump the bucket directly in the depleted zone behind the mined zone of the pit. The drag line will therefore dump the bucket into a large bin or skip placed on a barge. The bin or skip would transport the material via a cableway to the dump. The skip is used to maintain the integrity of the blocks. As the material is clayey and sticky, it is possible to maintain the shape and dimensions of the large blocks cut by the bucket of the drag line using a skip which capacity is higher than the bucket volume.

10.4.2.3. Ore mining (See Fig. 9)

The ore zone will be delineated in a tight grid in order to sort the low grade zones which will be left in place. As the minable ore is not homogenous, it is necessary to mine it selectively using an equipment with a slurry pump in combination with a cutting tool suspended from a small derrick which supports an open frame which has an enclosed section at the bottom allowing selection of blocks of 50 m^3. The pump and cutters work inside the open bin and deliver the pulp to the surface. The material mined in each block is stockpiled in a series of casings.

The material of each casing is sampled and roughly analysed in order to determine on which cyclone line it will be treated. Two or three different cyclones lines will be necessary.

Due to the upgrading of the ore by grain classification, and the use of drag lines equipment which allows stripping at a very low cost, this mining system means that it is possible to mine under water with no water treatment or release problem, and no ground surface disruption.

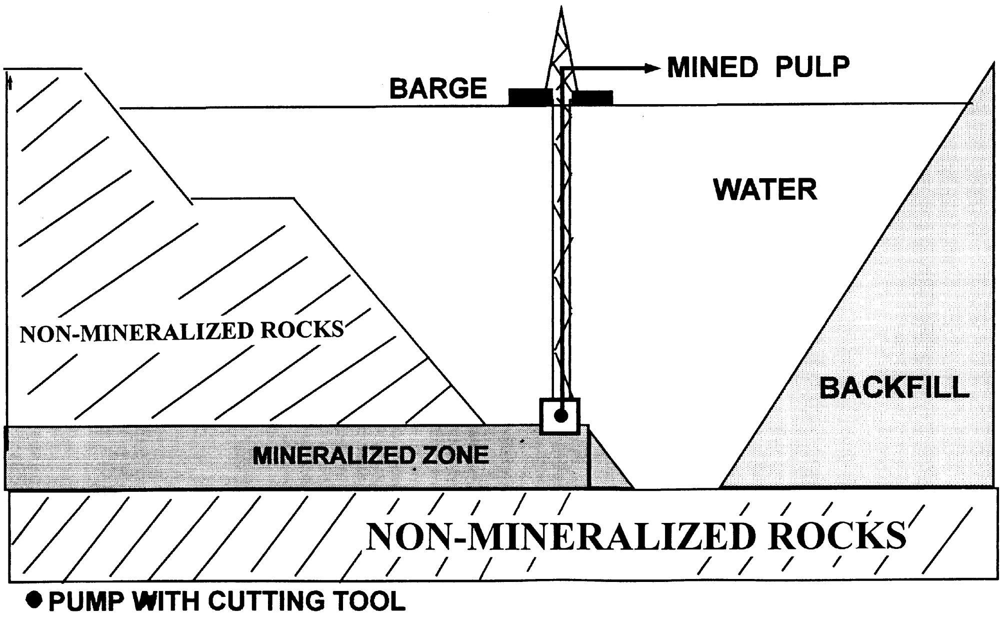


FIG. 9. Pump with cutting tool.

11. SPECIFIC ISSUES FOR HANDLING URANIUM ORE IN UNDERGROUND OPERATIONS

The initial step in planning an underground mine is to determine that the geological data pertaining to the mineralized deposit is sufficient, and the land status and permitting requirements are known. Geologic interpretation of surface drill hole data (core and cuttings analysis; electric and radiometric logs; hydrologic information; and calculation of the tonnage and grade of the deposit) form the basis for constructing an underground mine model and subsequent feasibility studies. Complete knowledge of the land and mineral ownership is imperative so that rights of egress and ingress are established as well as determining royalty schedules and other payments prior to mining. Permitting can be one of the most time consuming and costly aspects in planning a mine. Knowledge of the permitting organizations and regulatory agencies and their requirements will expedite the process. Requirements for permitting include mine life determinations, ore reserves calculations, surface disturbance plans, protection of surface and undergroundwater, production rates, and plans for mine closure and reclamation.

11.1. UNDERGROUND MINE MODELING AND DESIGN

The purpose of modeling an underground mine is to detail every activity required on surface and underground to accurately determine production rates, equipment and man power requirements, power and fuel usage and their respective costs. When completed the mine model will provide information for feasibility studies that will determine the ultimate mine plan and design. In all cases the mine plan must provide for the health and safety of workers under the ALARA principle. During this study standard manuals for operating procedures and drawings must be prepared.

11.1.1. Underground facilities

Based on detailed geologic data obtained from surface drill holes, cross-sections of the deposit are prepared depicting the thickness and grade of mineralization, structural features and host rock types. Also from this data the continuity of the mineralization is determined resulting in the calculation of ore reserves (volume, tonnes and grade) of the deposit. The major components that must be considered when modeling an underground mine are: shaft or adit; primary mining equipment; station area; primary haulage development; raise development; stope development; ore extraction; and ventilation.

11.1.1.1. Access to the reserve (shaft or adit)

At this point a key decision must be made concerning how the reserve will be accessed. Access to the reserve can be accomplished by either shaft or an adit or both.

11.1.1.2. Primary mining equipment

Once the decision is made on how to access the deposit from surface the next step is to select the primary mining equipment to move men, materials and muck in and out from the station areas. The type of equipment selected is generally dependent upon desired production rates and somewhat on ventilation requirements. It should be noted there is a wide selection of types and manufacturers of primary equipment.

11.1.1.3. Station area

The station area is the life line of each level of the mine. Proper design and modeling will not only minimize congestion of moving men and materials away from the shaft or adit but avoid costly delays of adding components once the mine is in production. Often the station area does not receive the attention it deserves in initial mine planning.

11.1.1.4. Primary haulage development

Primary development provides access from the shaft station area to the orebody. These drifts are driven either beneath or on the same level as the orebody and must be large enough to accommodate the equipment selected to tram the ore or waste as well as ventilation ducts, drainage ditches and utility lines (compressed air drill, water line and electrical cable). Long hole drilling from the haulage drifts provide more detailed knowledge of the orebody as well as drainage of the host rock. Rock conditions will dictate the type of ground support method to be employed. Core data can often supply sufficient information to determine types of ground control required and costs for purposes or modeling the mine. Common ground support methods are:

- steel and/or timber sets
- rock bolts or split sets with wire mesh
- cable bolts
- shotcrete
- in some circumstances freezing could be considered as a ground support method.

Haulage drifts must be constructed to last the life of the mine. Subsequent to ore extraction the haulage drifts are maintained to provide access to strategically placed ventilation holes, maintenance for either intake or exhaust air courses and for drainage of groundwater and/or leaching solutions.

11.1.1.5. Raises (manways and ore passes)

In underground mines in which the primary development (haulage drifts) are driven beneath or down dip of the orebody a series of raises are excavated to provide access from the haulage level to the ore level. These raises may be constructed by conventional drill-blast methods and supported, if necessary, with sets or bored either from underground or surface and supported with steel casing. The manways are planned large enough to accommodate a personnel and ventilation side and a material transfer side. Muck raises are usually single units and often not supported with sets or casing if ground conditions permit.

Construction of manways and muck raises is one of the more costly items in the mine therefore accurate planning of these items is very important when modeling a mine. Spacing of raises is dependent on the mining equipment selected and the continuity of the orebody. In a continuous orebody raises are generally driven every 30–40 metres to provide the greatest efficiency. Unit costs are usually expressed in dollars per meter ($/m).

11.1.1.6. Stope development (sub level ore development)

The type or method of developing the orebody is largely dependent on meeting radiation exposure regulations for workers. Where these regulations can be achieved using standard ventilation techniques, it is preferable to develop the orebody using the drill-blast-muck method with slushers and scrapers or load haul dump trackless equipment or a combination of both. Development drifts are driven through the orebody on a predetermined “street” pattern leaving pillars for ore extraction. Development drifts are often driven on 10 m centers where slushers are used and 15 m centers where trackless equipment is employed. Strict grade control practices are required in order to stay within — or metres ore boundaries and keep development costs as low as possible. Usually these development drifts are kept small (1.7 × 2.0 m) to speed up advancement and minimize the use of ground support materials. Upon completion of ore development, ventilation and access drifting are completed in preparation for final ore extraction.

In orebodies in which radiation exposures cannot be controlled by normal ventilation methods stope development techniques vary. In some cases the orebody can be developed as described above; however, both the workers and equipment must be shielded. In other situations the orebody is developed from footwall or boundary drifts utilizing remote controlled mining equipment such as continuous miners. Non-entry ore development may be selected by driving scram drifts or sub level drifts beneath the orebody which is then delineated by long hole drilling. Whatever stope development is selected the cost (cost/metre) must be determined for use in the mine model.

11.1.1.7. Ore extraction

Since stope extraction generates the highest production in the mine at the lowest cost great care must be taken when estimating ore tonnage for modeling purposes. Extraction rates are set based on the desired total mine ore production which then determines the number of extraction stops required and manpower. Production rates are commonly expressed in tonnes/manshift and costs in $/tonne.

There are many mining methods employed in stope extraction depending on the size, shape and ground conditions of the orebody. In some cases the final method selected for stope extraction cannot be determined until ore development is completed. Some of the mining methods used in stope extraction are:

- open stope
- room and pillar (See Fig. 10)
- slot stope
- scram stope
- top slice
- shrinkage mining (See Fig. 11)
- longhole mining (See Fig. 12)
- freeze and drill
- bottom slice
- non-entry vertical retreat
- undercut and fill
- blind boring from footwall or hanging wall drifts.

Equipment used in the ore extraction process varies with the method selected. Generally the ore is conventionally drilled and blasted and removed by slushers and scrapers or trackless equipment. Occasionally continuous miners or larger drilling technology is employed. Whichever method is used the safety and protection of the worker is paramount.

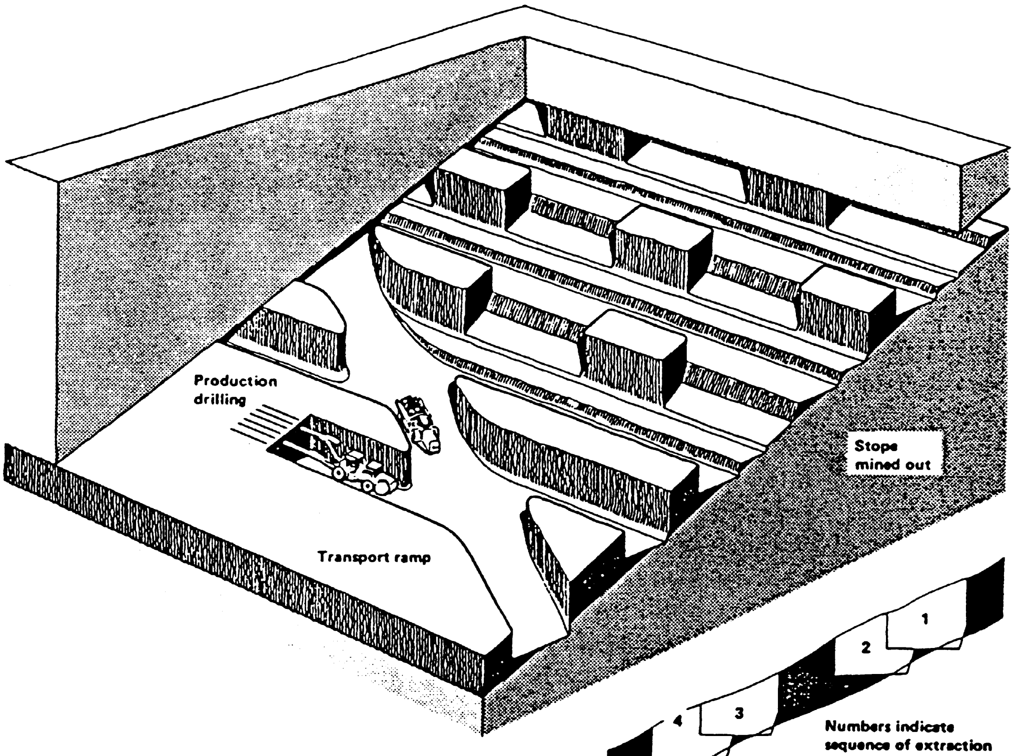


FIG. 10. Room and pillar mining.

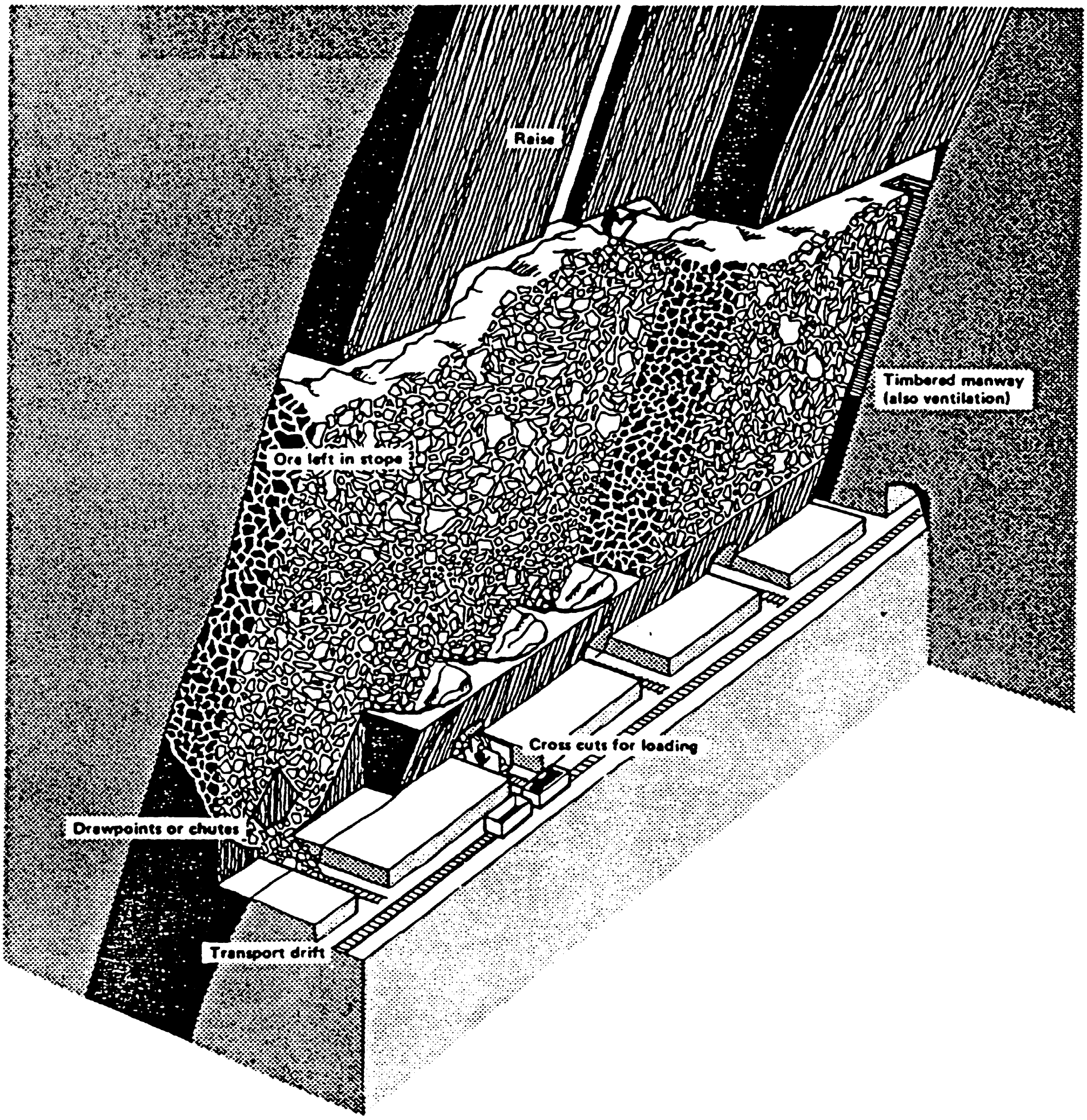


FIG. 11. Shrinkage mining.

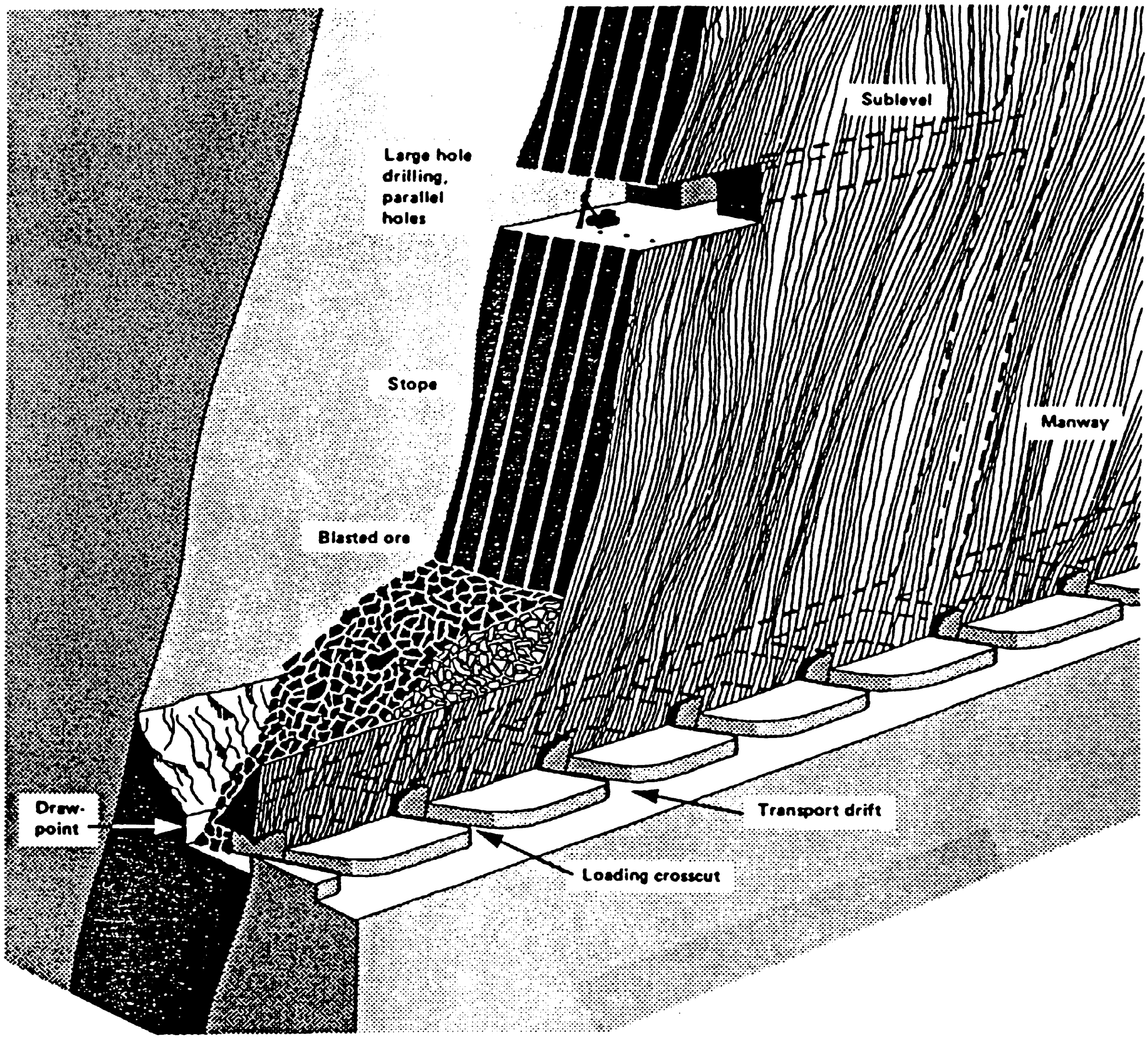


FIG. 12. Longhole mining.

11.1.1.8. Ventilation

In all underground mines and especially underground uranium mines, because of radon gas, proper ventilation is a necessity not only to meet regulatory requirements but also to practice the ALARA principle. Planning ventilation requirements is a major item in modeling an underground uranium mine. The amount of fresh air required (m^3/second) to operate can be determined subsequent to establishing the number of stops needed to meet set production rates; manpower requirements and; amount of diesel equipment to be employed. In general, 0.4 m^3/second is required for each worker and 0.2 m^3/second/KW for diesel equipment. Additional air may be required to maintain radiation levels to acceptable exposures. It is not uncommon for a mine producing 1500 to 3000 tonnes/day requiring 400 to 600 m^3/second. Mine ventilation is generally divided into primary and secondary systems.

Primary ventilating system

The primary ventilation system consists of locating and sinking or drilling large holes up to 7.0 m diameter from surface to specific targets underground. The holes are generally supported with steel circular casing and cemented in place to maintain the integrity of the hole and prevent commingling of groundwaters, Large centrifugal or axial vane electric fans (up to 1800 KW) are placed on top of the vent holes to provide adequate air flow through the primary development drifts in the mine. At times designated ventilation drifts are driven specially to direct air to predetermined locations in the mine. All ventilation holes are designated as "up cast" or "down cast" holes depending on the air requirements at any specific time. These fans may be reversed as required. Although all ventilation holes should be planned for costing purposes in the mine model, they probably will be constructed throughout the mine life as required. These ventilation holes also provide emergency secondary escape routes from the mine.

Secondary ventilation system

The secondary ventilation system takes the fresh air from the primary development or ventilation drifts and distributes it into the active stope development and extraction areas of the mine. This is usually accomplished with 5 to 60 KW electric centrifugal or axial vane and ventilation ducts or tubing. Each working area has its own intake or exhaust system sufficient to meet manpower, equipment and radon control demands. Some items used to control air flow and radon gas build up are as follows:

- air doors
- air curtains
- bulk heads
- balloons
- electro static precipitators

The cost of power, equipment, manpower and supplies can be estimated and included in the mine model.

11.1.1.9. Backfill

Backfilling is often employed as part of the mining method in the ore extraction phase. The cut and fill and bottom slice methods utilize backfill for ground support and a working base respectively. Open stops are generally backfilled to prevent weight transfer to adjacent ore extraction operations or to prevent subsidence. Prevention of subsidence by backfilling not only protects the surface but also eliminates commingling of groundwater from separate aquifers which is often protected by regulatory agencies.

The three methods generally used to place backfill are hydraulic, pneumatic and mechanical. The slurry for hydraulic fill is usually prepared in a surface plant and piped to the designated working area. The slurry is made up of sand grain size material with some slimes added to enhance transportation of the fill. The mixing unit varies from simple baffles to sophisticated mixing equipment and pumps in a series of tanks.

Both waste from the mine and surface materials are used as backfill material. In special situations cement or concrete is the backfill media. Hydraulic backfill may also be placed from small mixing plants underground which then pump the slurry to the desired working area through pipe lines. Proper stope drainage is required to prevent bulkhead failures.

Backfill placed pneumatically consists mainly of surface blow sand, sand deposits and classified soils readily available to the operation. The backfill material is screened at the surface plant and blown through pipe lines to the designated working area. Dust control is a major factor when using the pneumatic backfilling method.

Mine waste is generally used to backfill open stops mechanically. The backfill material is transported to the stope by rail cars or trucks and distributed in the opening by slusher and scrapers or by remote trackless equipment. Post extraction stope leaching may be successful where coarser low grade ore is used for backfill material.

Natural caving of mined stops is allowed where the coefficient of expansion of the falling host rock is known to fill the void before surface subsidence or commingling of groundwater can occur.

11.1.1.10. Manpower (staffing)

Manpower requirements both as to skills and numbers vary greatly with the size, extent and productivity of an underground mine.

11.1.1.11. Mine equipment

Like manpower, the type and amount of mine equipment required varies with host rock conditions, mining methods selected and desired production rates. Since there are many manufacturers of mining equipment selection must be based on availability, cost and performance. Most underground mining operations use conventional drill and blast techniques to break and remove rock, however, continuous cutting units have also been successfully employed.

11.1.1.12. Personal protective equipment

The underground uranium worker is not only subjected to the hazards inherent to any underground mine but in addition they are exposed to radiation. Personal protective equipment is required by all operators and regulatory agencies before an underground work can enter the mine.

11.1.1.13. Safety and health

Many countries throughout the world that produce uranium ore from underground mines are stringently monitored by regulations adopted by International agencies, Federal or National agencies, State or Provincial organizations and by the operating companies themselves. Uranium mining is the most heavily regulated and monitored of all industries pertaining to the safety and health of its workers. Constant improvements of working conditions underground are a never ending challenge for operators practicing the ALARA Principle. Many volumes of rules and regulations are available that have been written, and are constantly updated specifically for the purpose of improving the safety and health of underground uranium workers. These operating procedures are based on years of experience to determine the safest way to complete an assignment or job. Eliminating accidents and promoting a healthy working environment must be a prime objective of every operator.

11.1.1.14. Reclamation

Mine reclamation is generally defined as restoring the surface to equivalent or better condition than it was found. Viable eco-systems must be in place before the mining property is surrendered to its original owner as well as all regulatory concerns completed. In most cases mine reclamation can be completed in a relatively short period of time except for establishment of acceptable growth of vegetation. The cost of reclaiming a mine should be estimated and included in the mine model. The following items must be considered during mine reclamation:

- cap bulkhead or backfill all shafts, ventilation holes and other drill holes or other openings to the underground mine
- remove all equipment, structures, pipe lines and ponds
- cover and recontour all pads, waste piles and ponds
- seed the mine site and provide for desired vegetation cover.

11.1.1.15. Stope leaching

In most underground uranium mines, stope leaching operations occur either simultaneously with conventional mining or is a post mine activity depending on the mine's ability to handle leach solutions. Stope leaching is an inexpensive method of extracting uranium from loose muck or rubble left in stops, remnant pillars, ribs and low grade backfill material providing the uranium minerals are soluble to the mine water or lixiviant used. Mild alkaline and acidic lixivates as well as mine water is used as leachates. The leaching solutions are sprayed into the mined stops either from a series of holes drilled from surface or from drill holes or openings underground. Once the remaining material is saturated the solutions generally enter the mine dewatering system and are pumped to the surface ion exchange (IX) plants for processing; however, in some mines the resin columns which remove the uranium are located underground. In this situation the loaded resin must be removed from the columns and transported to surface for stripping, then returned underground. This is a more expensive and labor intense process. The lixiviants must be chosen with care not to react with host minerals to form toxic gases or insoluble uranium compounds.

11.1.2. Surface facilities

Detailed planning and design of surface facilities and estimating subsequent costs are a vital part of modeling an underground uranium mine. These facilities not only provide the infrastructure for the mine but also satisfy regulations concerning handling of mine production and mine water treatment.

11.2. EXAMPLES

11.2.1. Bulk mining method, sublevel stopping

A small deposit is being delineated in the Kalimantan province of Indonesia.

11.2.1.1. Description of the deposit

According to the results of a small scale mining test, it appears that the deposit could be considered as a stockwork. The interesting part of the stockwork is about 20 m. thick and 150 m long, dipping at 65°. The upper part of the deposit has been highly weathered and the uranium leached so that no open pit operation can be considered and underground mining methods must be utilized. The ground conditions are excellent. The waste as well as the ore are very hard. This allows large openings in the stops and infrastructures should not need support except bolts.

The uranium, in the form of uraninite, is concentrated in small fractures and thin veinlets of different directions. Due to the different directions and the great number of the fractures, the morphology of the deposit is not easy to determine.

The grade of the veinlets is high but as the veinlets are very thin, the dilution is high so that the grade of the bulk mined material of the stockwork is low. The ore contains carbonates, and therefore, the acid consumption and the cost of the ore chemical treatment would be high. In order to make the deposit economic, it requires a low cost beneficiation to reduce the carbonates and upgrade the run of mine ore.

By these means, it would be possible to bulk mine the stockwork with a high productivity and low cost method and feed a low capital cost small concentration plant with a high grade feed, the treatment of which can be achieved with lower acid consumption and lower operating cost.

11.2.1.2. Beneficiation

Physical sorting

The shape, colour and general aspect of the ore and the waste are quite different so that they can easily be separated by physical sorting. The major part of the waste can be eliminated so that after sorting, upgraded ore would be obtained at an average grade similar to the grade obtained with a costly selective mining method.

Radiometric sorting

The grade contrast between the ore and the waste is sharp. A test has been made on ore after physical sorting to a grade of 2400 ppm U.

Rejected material

Cut off ppm U	Weight %	U %	Average grade ppm U
50	34.3	0.3	19
500	51.9	1.9	88
1 000	60.0	4.2	167
2 000	74.5	13.0	417
3 000	80.6	19.0	564
4 000	84.5	24.6	696
5 000	87.8	30.6	837
10 000	93.8	47.4	1208

Accepted material

Cut off ppm U	Weight %	U %	Average grade ppm U
50	65.7	99.7	3 640
500	48.1	98.1	5 000
1 000	40.0	95.8	5 841
2 000	25.5	87.0	8 354
3 000	19.4	81.0	10 203
4 000	15.5	75.4	11 871
5 000	12.2	69.4	13 906
10 000	6.2	52.6	20 283

As the ore and waste are hard and rocky, radiometric ore sorting would give excellent results This was demonstrated in test work. The fraction more than 30 mm, which accounts for: 70 to 75% in weight of the total run of mine ore, is amenable to radiometric sorting. On this fraction, the uranium grade contrast between ore and waste is so high that it is possible to obtain excellent results with radiometric ore sorting.

Gravimetric sorting

It is possible to beneficiate the –30 mm fraction of the run of mine ore non amenable to radiometric sorting by means of a centrifugal concentrator. After grinding at less than 100 mesh, the concentrator recovers approximately 80% of the uranium. This represents an upgrading factor close to 10 and with little loss of valuable uranium.

According to the results of the radiometric sorting test, a 500 ppm cut-off allows to obtain a 98% uranium recovery in a 0.5% U grade concentrate. Sorting this concentrate a second time with a cut-off at 3000 ppm results in recovering two ore fractions:

- a 1% U grade fraction containing 81% of the total uranium in 19% of the total weight
- a 0.16% U grade fraction containing 17% of the total uranium in 29% of the total weight

The first fraction is sent directly to the treatment plant while the second fraction is ground and upgraded to more than 1% U grade in the centrifugal concentrator. According to the efficiency of the radiometric sorting and centrifugal concentrator, it is expected to obtain a total uranium recovery of about 90%.

11.2.1.3. Concentration plant

After beneficiation and because of the specific characteristics of the ore, a concentrate grading close to 1% U_3O_8 was obtained. The percentage of carbonates has decreased so that the acid consumption is lower. Therefore, the capital cost of the concentration plant is reduced and the same for the operating cost (low acid consumption). The deposit that was non economic could be considered to become profitable thanks to beneficiation allowing to mine the stockwork by a high productivity and low cost method. As a result of a high grade feed of the concentration plant the operating cost is reduced.

11.2.1.4. Bulk mining

The stockwork, roughly 20 m thick, 150 m long, dipping at 65°, has excellent ground conditions. The configuration of the stockwork does not allow any selective method. So, a bulk mining method must be utilized. Sublevel would be the best approach.

For this mining method, large diameter blasting holes are drilled at the highest diameter possible, with a specific electrohydraulic equipment from the upper level and lower level. As there is no groundwater problem, the cheapest explosive available could be used.

The configuration of the deposit calls for the use of trackless equipment. A decline will be used for hoisting the blasted material, moving the personnel as well as equipment and consumables. The ventilation circuit is designed so that the miners work in a fresh air environment. The fresh air enters the decline drilled in the foot wall of the stockwork and exits trough raises in the hanging wall and linked to a tunnel which portal is at the opposite side of the decline.

Physical sorting can make it possible in this example, due to beneficiation using specific characteristics of the ore and the waste, to eliminate a major portion of the waste, upgrade the ore, reduce acid consuming carbonates, thus producing a high grade concentrate which can be treated at low cost in a low capital cost small plant. It is only in these conditions that the stockwork deposit can become economically minable.

According to the results of the feasibility study, it can be assumed that the total mining and processing cost per run of mine ore tonne will be in the range of:

— $50 without beneficiation.
— $20 with beneficiation.

the total uranium recovery being the same in both cases, close to 85%.

The $30 difference is due to the low grade of the mill feed and consequently the high acid consumption when treating a non beneficiated ore.

According to that and assuming a maximum selling price of $20 per pound, beneficiation allows to mine profitably a low grade stockwork deposit of the KALIMANTAN type grading only 0.065% U_30_8 while the same kind of deposit could only be mined at an overage grade higher than 0.13% U_30_8.

11.2.2. Non-entry mining

11.2.2.1. Jet boring

Very large grade deposits have been recently discovered in northern Saskatchewan, Canada. These deposits are located at several hundreds of meters below the surface at the unconformity between Archean gneiss and sandstones. The deposits were formed by water circulation at the unconformity level diluting the uranium, precipitating it at the unconformity due to the pyrite and graphite contained in gneiss.

Abundant clay is present in the ore resulting in substantial geotechnical problems. The high grade and high radioactivity of the ore associated with enormous quantities of water under pressure created a big challenge to the miners.

One of these deposits is Cigar Lake located close to the Waterburry lake, at 450 m below the surface. The mining method successfully tested for this deposit in compliance with safety, radioactivity and environmental regulations is described below.

Mining constraints

Poor ground conditions call for a massive consolidation of the mineralized zone and its sandstones and clay environment. Due to the large amount of water under high pressure, the risk of flooding the mine is very high and the radioactivity does not allow miners to work in the ore. Only non-entry methods can be implemented.

Mining method (See Fig. 13)

For water control and ground consolidation: it appeared that freezing was the best solution to face the drastic water and ground constraints of the Cigar Lake deposit.

Freezing is realized with a refrigerated solution of calcium chloride circulating in double pipes located in holes drilled at a regular interval in the zone to be frozen. As the ground conditions of the gneiss are rather good, the freezing holes are drilled from galleries driven in the gneiss below the unconformity.

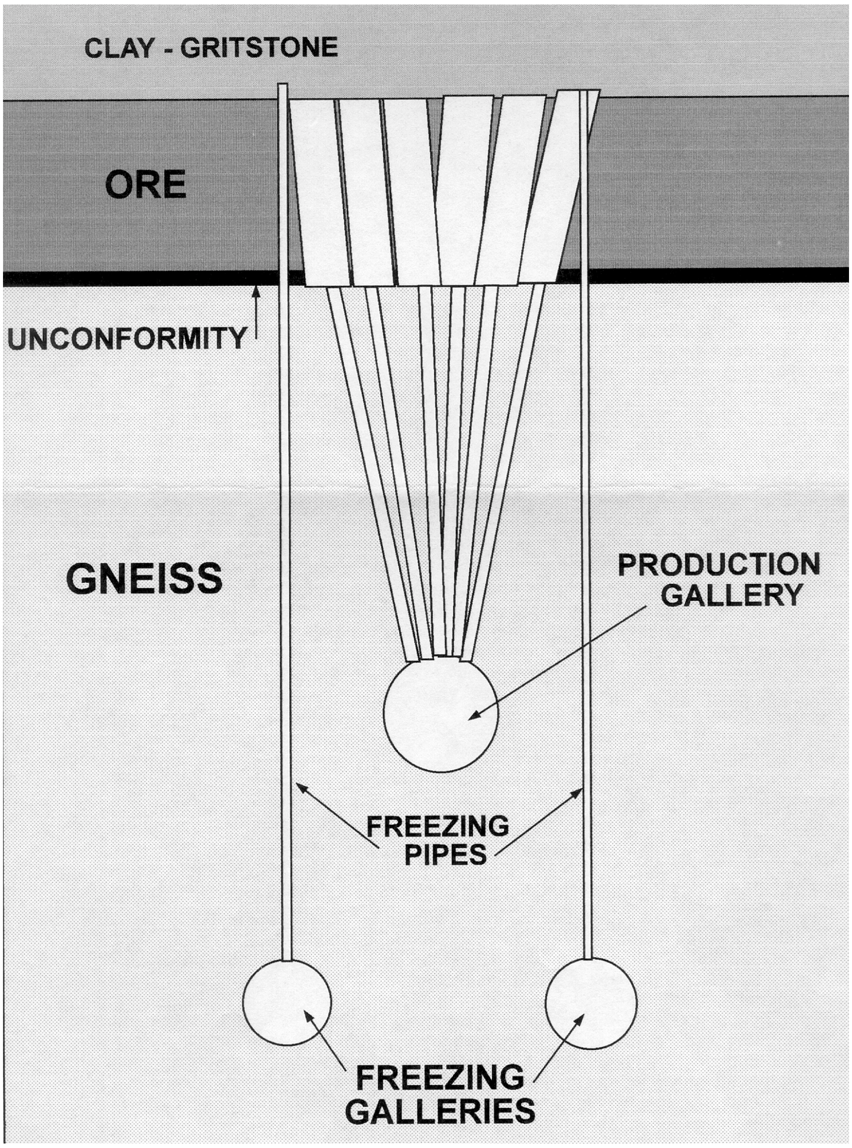


FIG. 13. Freezing.

Non-entry mining (See Fig. 14)

The mining method was designed by a German company: Klem, with the collaboration of Cogema and Cigar lake mining teams. Basically, the principle of the method is to desegregate the ore, moving downwards, by a water jet under an hydraulic pressure of 500 bars, from a rotating head equipped with 2 nozzles. The head and the rods which maintain and drive it are placed in a 280 mm hole drilled from a production gallery located in the gneiss above the freezing galleries. The ore pulp flows down in the space between the hole walls and the rods. It is collected at the bottom of the hole and from there, pumped to the underground station close to the shaft. It is ground there to the liberation size of the uranium, then directly pumped to the surface to the concentration plant.

Backfilling

As it is paramount to prevent any water movement in the ground, the holes are 100% backfilled with fine concrete under pressure. When a depleted zone has been backfilled, freezing is discontinued and the ground thaws slowly.

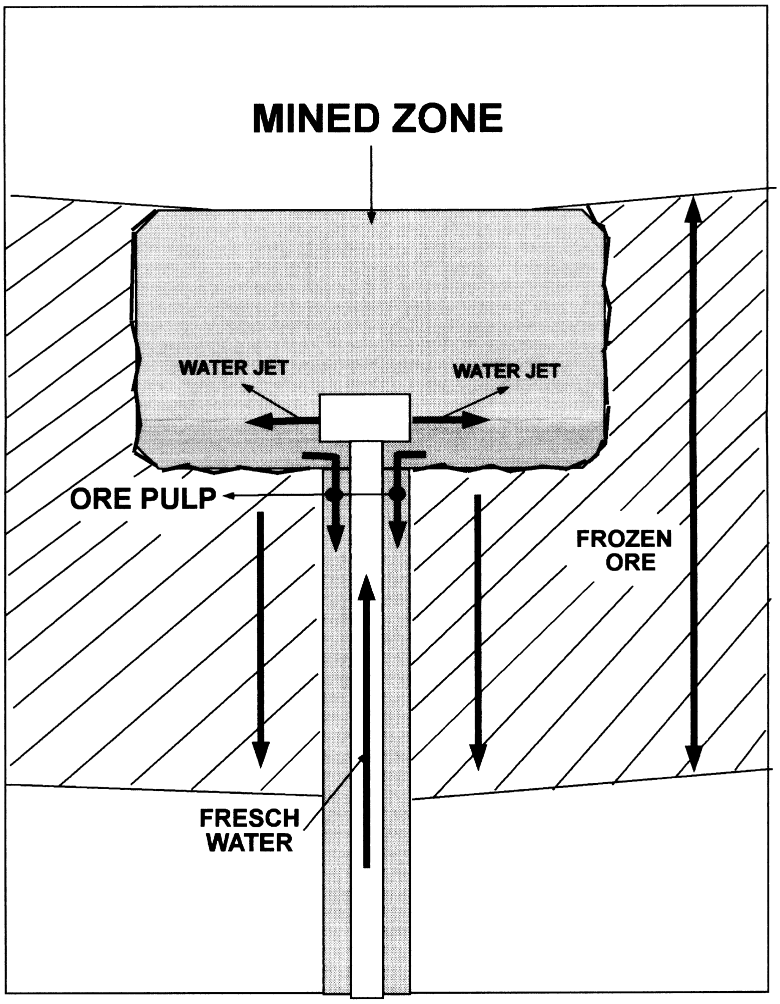


FIG. 14. Mining: Jet boring.

Mining sequences

The different mining sequences are:

- drilling the freezing and production galleries in the gneiss
- freezing the ore and a suitable thickness of surrounding waste
- mining
- backfilling
- thawing.

Freezing and non-entry water jet boring allow to mine the Cigar Lake deposit, a high value uranium ore in specific drastic conditions. The method is highly safe and at the same time, favourable to the environment.

11.2.2.2. Non-entry Vertical Panel (NEVP)

The deposit (Midwest Lake, Saskatchewan, Canada) is situated approximately 190 metres below a small lake. The orebody has a relatively compact shape, measuring some 200 metres by 150 metres and varies from 2 metres to 20 metres in thickness. It is proposed to mine the orebody by underground methods, due to the location under the lake and the depth below surface.

The ore is mainly located at an unconformity between the overlying sandstone and basement gneiss. This contact is highly irregular and the ore zones are strongly faulted and jointed as well as containing up to 30 percent clay. These ground conditions as well as the expected high ore grades, limit the options for mining. The mining method proposed is Non-entry Vertical Panel (NEVP) for the high grade areas. The NEVP mining method is based on conventional blasthole stopping with all stopping operations remote from the orebody. This proven method addresses the potential problems with respect to ground conditions and radiation from high grade ore.

Access to the orebody, for development will be by an existing exploration shaft located on the west shore of the lake. Production access will be via a new shaft on the East shore. The production shaft will serve as the ventilation intake and be equipped to handle men and materials. Mine exhaust will be through the West shaft plus a parallel exhaust shaft. The orebody will be developed via three main levels: the drill level, located 5–10 metres above the orebody; the mucking level, located some 5–10 metres below the orebody and the drainage level, located below the mucking level. All development will be located in waste outside the main high grade ore reserve.

The program will take about 12–15 months to complete and will involve in excess of 8 000 metres of total development. This will complete all the development above and below the orebody. This is required to provide sufficient working panels for production mining. Included in the development are provisions for handling up to 3000 US gallons per minute of water inflow. Ongoing development will be limited to secondary panel development.

Production mining will commence with the development of a slot raise utilizing a raisebore drill. The stope will be drilled off with 100 mm diameter holes. Emulsion type explosives will be used to blast out a stope with dimensions suited to ore body configuration.

The broken ore will be mucked from the haulage drift with shielded equipment or by remote control and will be transferred by LHD units to haulage containers and transported to the shaft for hoisting to surface (See Figs 15, 16, 17).

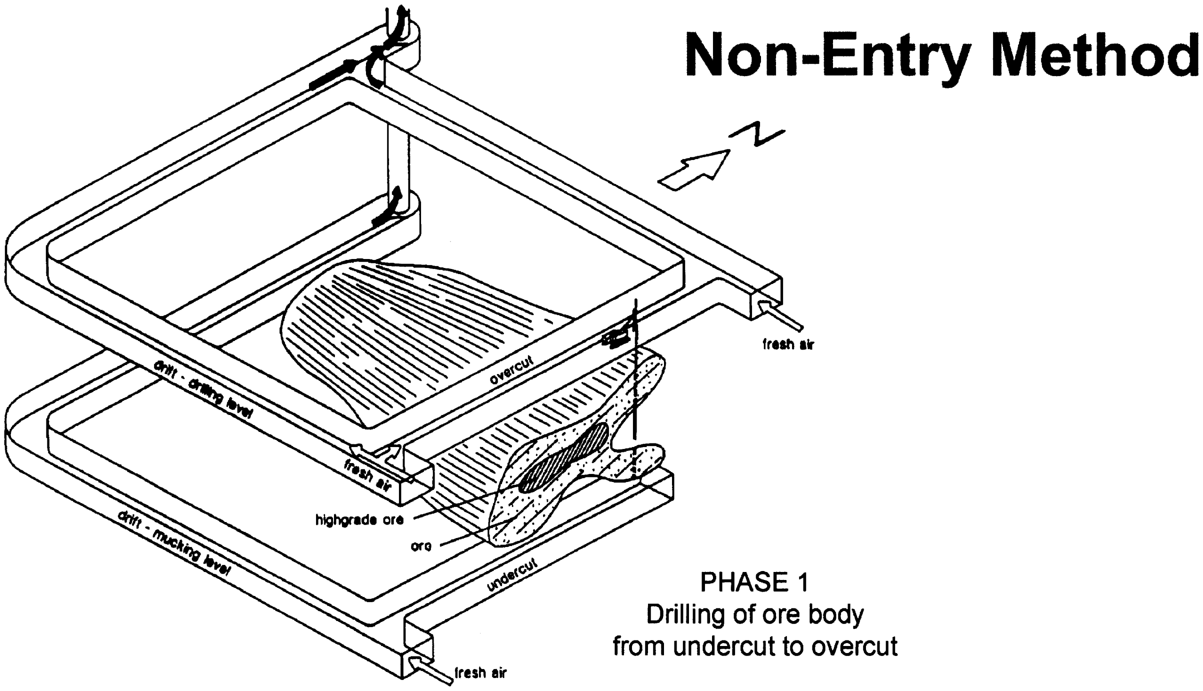


FIG. 15. Non-Entry method — Phase 1.

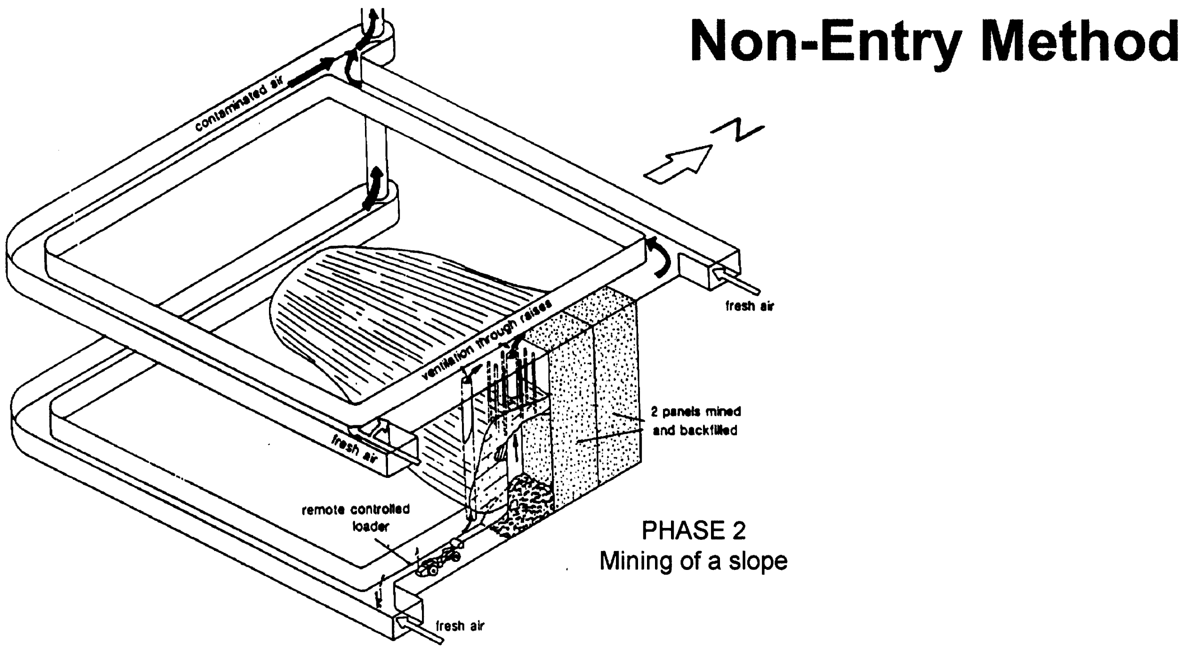


FIG. 16. Non-Entry method - Phase 2.

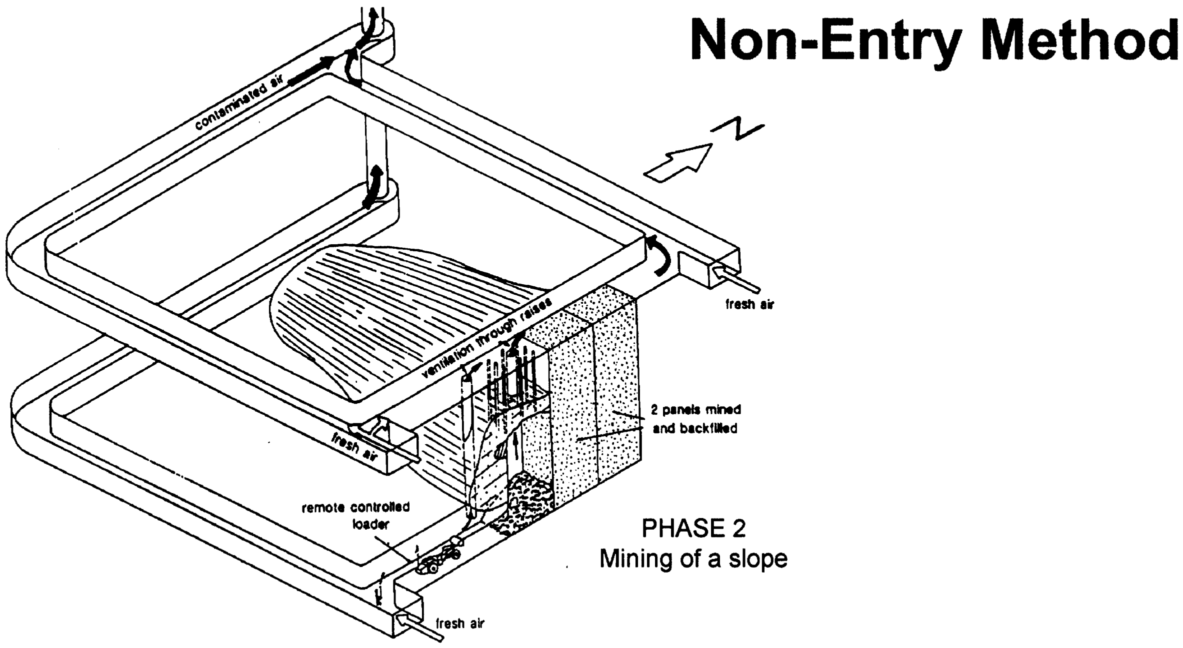


FIG. 17. Non-Entry method — Phase 3.

Following final stope cleanout, cemented rock fill will be used to fill the mined out opening as well as the drill drift above and the muck drift below the stopped out area. The fill will be allowed to set up for 28 days and the cycle will continue with the next panel stope.

The secondary stope, between two primary panels, will be mined as soon it can be scheduled. The process will be essentially the same as the primary stops with the addition of development the drill drift and haulage drift adjacent to the filled primary openings.

Mining costs are broken down into four main areas and are expressed in 1993 US dollars. Preproduction development includes all development required for mine access, mine infrastructure and high grade mining zone development. Mine capital involve costs associated with fixed and mobile equipment and include all mine related installations both surface and underground. Costs are included as well for services during development including power, propane and water treatment. Production operating costs include all mine related costs to deliver ore and waste to stockpile. A summary of development capital and production costs is as follows:

Mine Development	\$20 010 000
Mine Fixed Capital	\$10 350 000
Mine Mobile Equipment	\$ 4 140 000
Annual Mine Operating Cost	\$ 6 900 000

11.2.2.3. Vertical retreat/Long hole open stopping (See Figs 18 and 19)

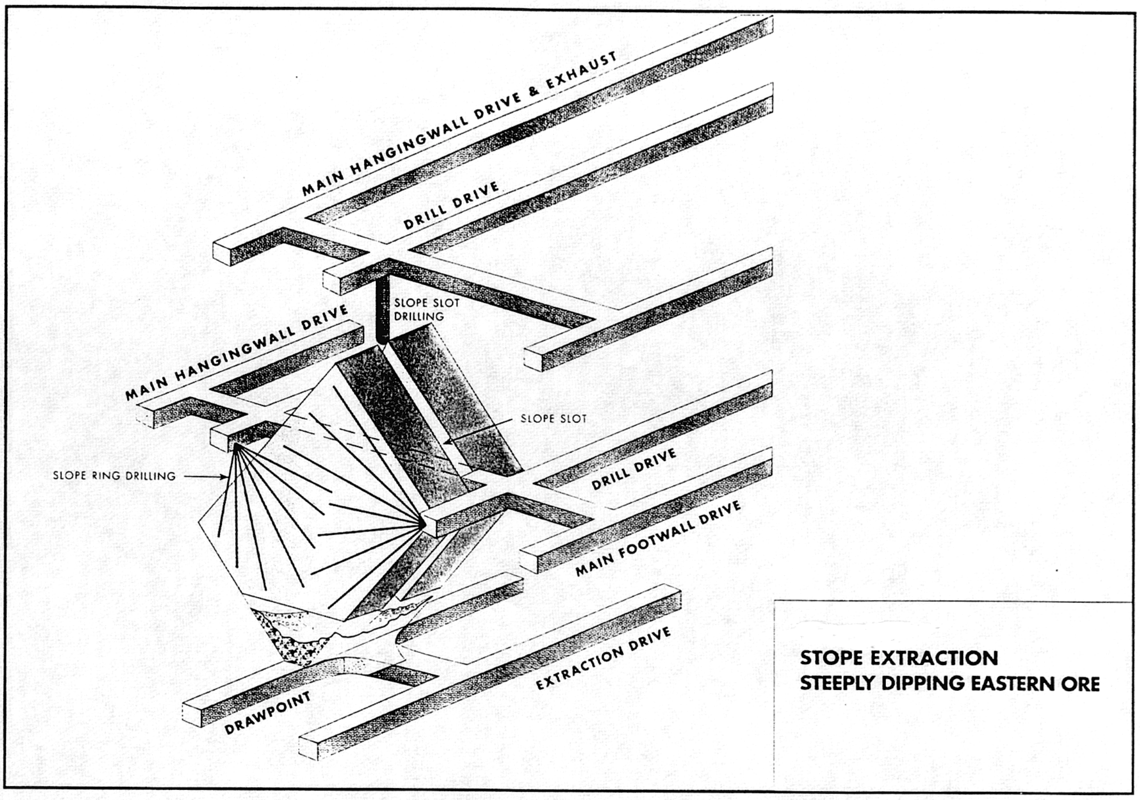
The mining method proposed to be used at Jabiluka in northern Australia is conventional long hole open stopping.

The ore body will be accessed from the surface by a 1 in 8 decline 5 m × 5.5 m. The stopping reserve extends approximately 800 m along strike and between 100 m and 400 m below the surface. Access to the stopping area will be in the footwall, stops will be 15m along strike and from 40 m to 80 m vertically with thickness across strike 30 m to 50 m depending on the ore body thickness. Cemented and uncemented rock backfill will be used after stope extraction.

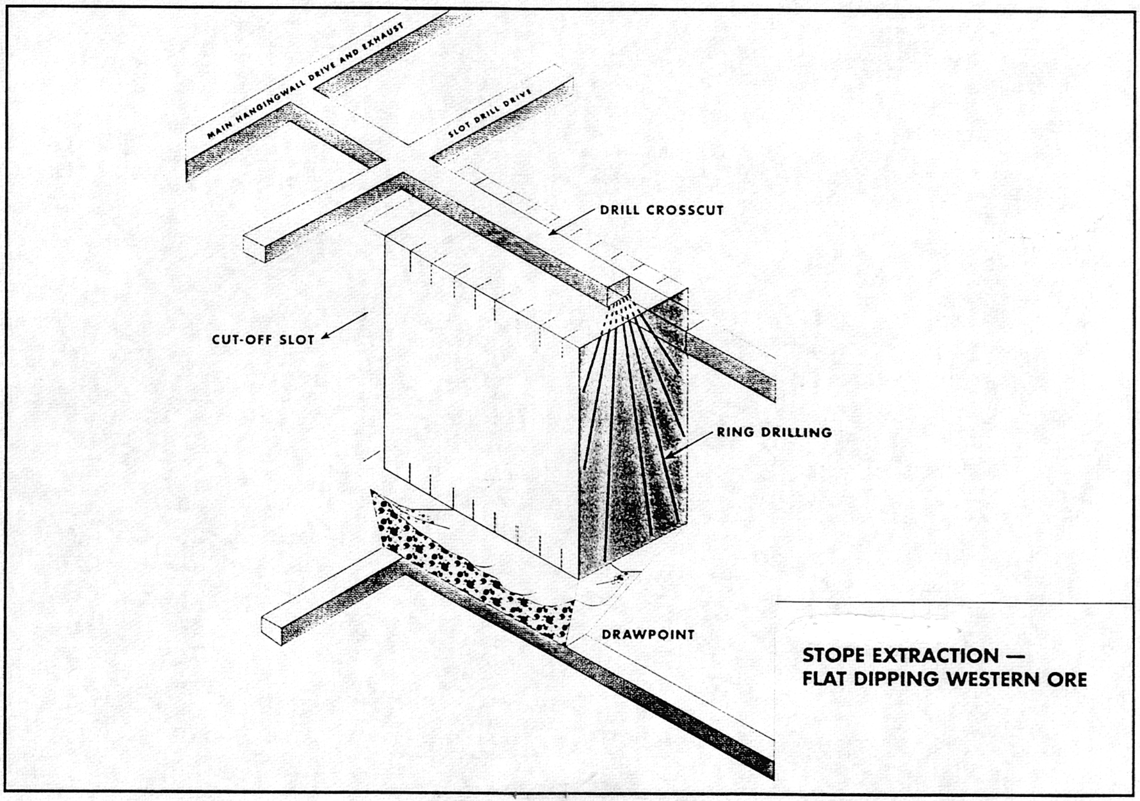
Stops will consist of a lower drawpoint and undercut level and one or two drill levels in waste depending on the ore geometry. Production drilling will be carried out with electrohydraulic machines drilling 89 mm to 115 mm diameter holes. Typical blast size will be about 30 000 tonnes of ore. Ore and waste will be loaded by 5 m^3 to 7 m^3 load/haul/dump units into 35 tonne trucks for hauling to the surface.

12. SPECIFIC ISSUES FOR HANDLING URANIUM ORE IN SITU LEACHING (ISL) OPERATIONS

In situ leaching (ISL) has emerged as one of the major mining methods for exploiting uranium ores along with open pit and underground methods. In many instances ISL is more economically attractive and environmentally preferred than the conventional methods. The initial step in planning an ISL operation is to determine the completeness of the geological data pertaining to the mineralized deposit and the land status and permitting requirements are known. Extensive laboratory and field tests must be conducted to demonstrate that the mineral deposit to be mined is amenable to in situ leaching. Successful application of the technology requires extensive knowledge of the stratigraphic, geochemical, hydrologic, and geologic nature of the deposits. Most of the information required to prepare the ISL mine model and subsequent feasibility studies will come from geological interpretation of surface drill hole data (core analysis, electric and radiometric logs, pump tests and calculations of the tonnes and grade of the deposit). Complete knowledge of the land and mineral ownership must be known so that rights of egress and ingress are established as well as determining royalty and other payments prior to mining. Permitting is the most time consuming and costly aspects of planning an ISL operation. Knowledge of the permitting organizations and regulatory agencies and their requirements will expedite the process. Requirements for permitting include mine life determination, wellfield patterns, production rates, ore reserve calculations, surface disturbance plans, protection of surface and undergroundwater, wellfield (aquifer) restoration plans, surface reclamation and plant decommissioning.



**STOPE EXTRACTION
STEEPLY DIPPING EASTERN ORE**



**STOPE EXTRACTION —
FLAT DIPPING WESTERN ORE**

FIG. 18. Stope extraction.

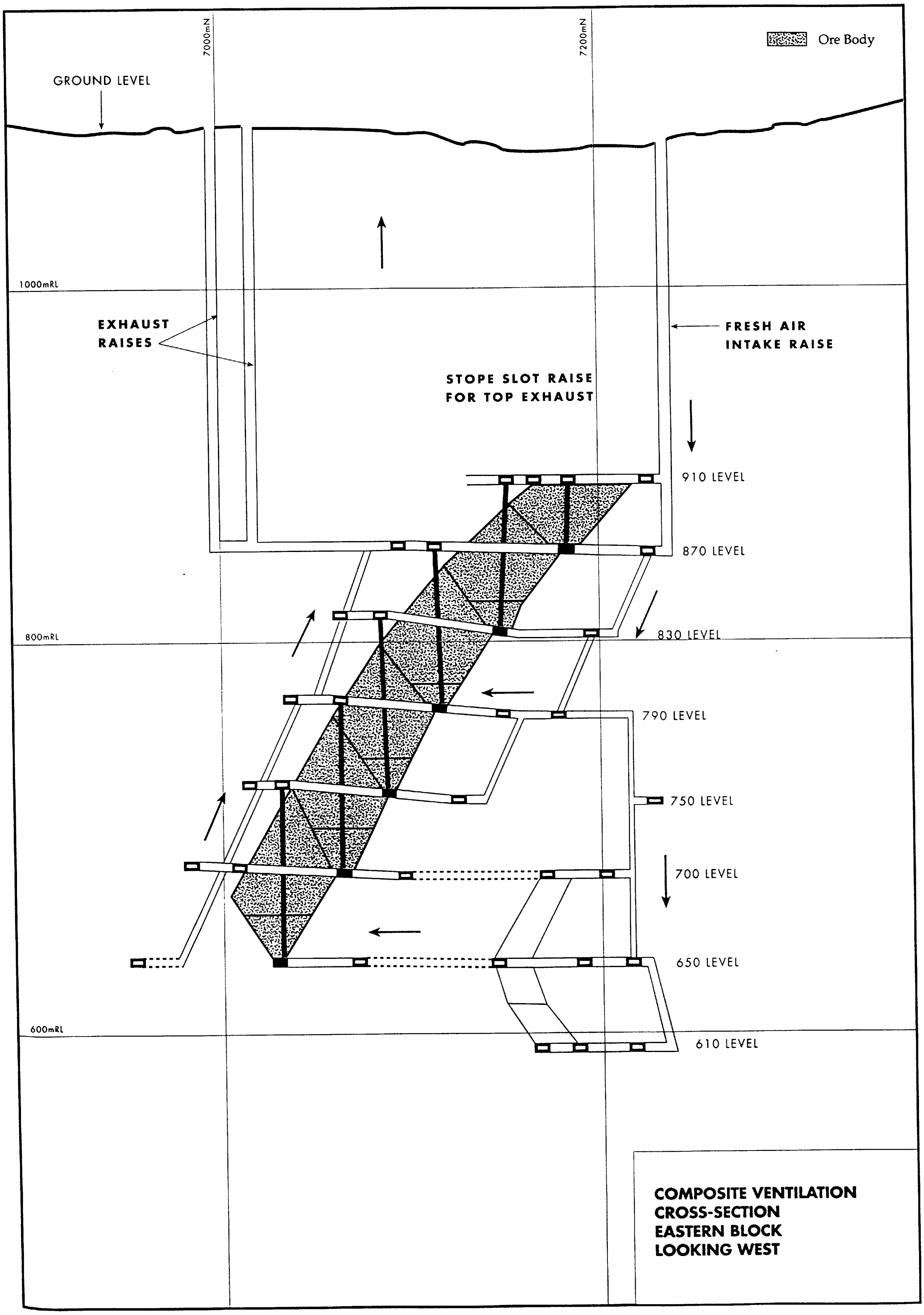


FIG. 19. Composite Ventilation.

12.1. ISL MINE MODELING AND DESIGN

The purpose of modeling an ISL mine is to detail every activity so that production rates, equipment and manpower requirements, power and fuel usage and their respective costs can be accurately determined. When completed, the mine model will provide information for feasibility studies that will determine the ultimate mine plan and design. In all cases the mine plan must provide for the health and safety of workers under the ALARA principle. During this phase of planning standard operating procedures and drawings must be prepared.

12.1.1. Surface drilling phase

The initial step in modeling an ISL mine subsequent to securing access to the mining property is to conduct an extensive surface drilling programme. The results of which will provide the following information:

(1) Delineation of the ore body (size, shape, thickness and depth)
(2) Ore reserve calculations
(3) Provide access to the host aquifer for pump testing to establish the hydrogeologic parameters
(4) Provide core from the ore zone
(5) Provide future wellfield drilling costs
(6) Collect water samples in the host and adjacent aquifers for base line water quality data
(7) Provide stratagraphic data.

Laboratory testing of the cores cut from the ore body will determine if the ore is amenable to ISL. Pump testing of the host and adjacent aquifers is necessary to demonstrate that the upper and lower confining units sufficiently restrict the vertical movement of water and determine the hydraulic conductivity (permeability) of the ore zone. The above information is necessary for both the operator and the regulatory agencies to determine if the project is to proceed with a pilot test mine.

12.1.2. Pilot test mine

The operation of a pilot test mine will provide the necessary economic and production data for the operator to model the project, generate detailed feasibility studies and provide sufficient data to satisfy regulatory agencies' requirements for future commercial licensing. The test mine will provide the following information:

(1) Selection and concentrations of the lixiviates (alkaline or acid base)
(2) Establish the amenability of the orebody to ISL mining
(3) Establish the technical and economic feasibility of successfully restoring the aquifer contaminated by mining
(4) Provide hydro-metallurgical information for economic analysis of ISL
(5) Satisfy regulatory agencies' requirements for commercial licensing
(6) Provide all the necessary economic and production data to construct a mine model required for the preparation of feasibility studies for commercial operation.

The major components for a pilot test mine are as follows:

(1) Permitting or licensing
(2) Wellfield
(3) Processing plant
(4) Restoration, reclamation, and decommissioning

12.1.2.1. Permitting or licensing

In most countries, agencies regulating ISL mining, as well as the public, require permitting or licensing for any mining activity including an ISL pilot test mine since both the surface and native aquifers containing the ore deposits will be disturbed. The permit or license application includes all of the geologic and hydrologic data, core analysis, results of pump tests, environmental base line data, and amenability tests. The application also requires the size and location of the test mine as well as detailed plans of operation, aquifer restoration, plant decommissioning and surface reclamation. Ownership of the surface and minerals including royalties or other payments are often required in the application.

12.1.2.2. Wellfield (See Figs 20, 21, 22)

The test wellfield usually contains several production patterns consisting of 5 or 6 five-spots which includes four injection wells and one projection well. The injection well pattern is usually square shaped with spacing between the wells dependent on the permeability of the ore zone. Variations of this pattern are often needed to conform to the ore occurrence. The production well is located in the center of the pattern. The methods used to complete these wells vary depending on the stratigraphy of the well location. In addition, monitor wells surround the wellfield and in the overlying and underlying aquifers. Prior to receiving approval from the regulatory agencies to operate the wellfield, all of the wells are sampled for water quality and hydrologic testing information. Subsequent to operating the wellfield, the monitor wells are sampled periodically to test for possible horizontal or vertical excursions of leaching solutions.

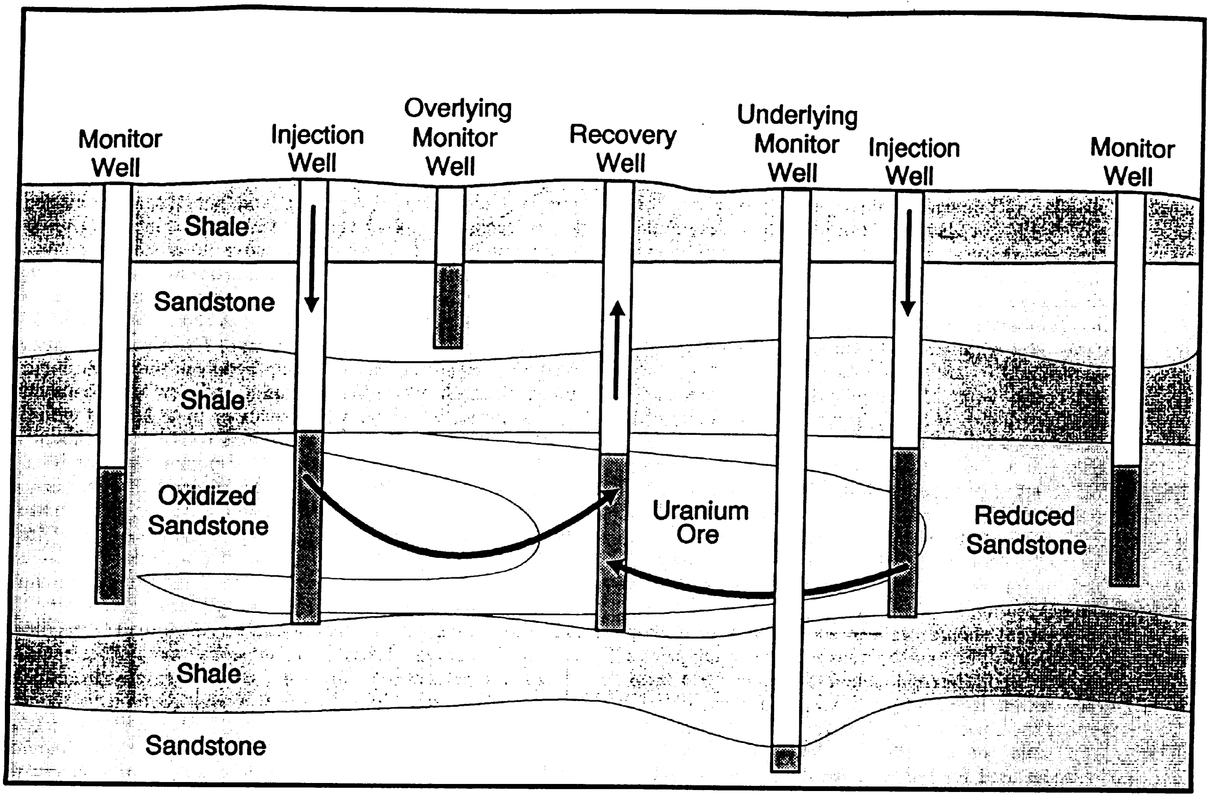


FIG. 20. Well field with overlying and underlying monitor wells.

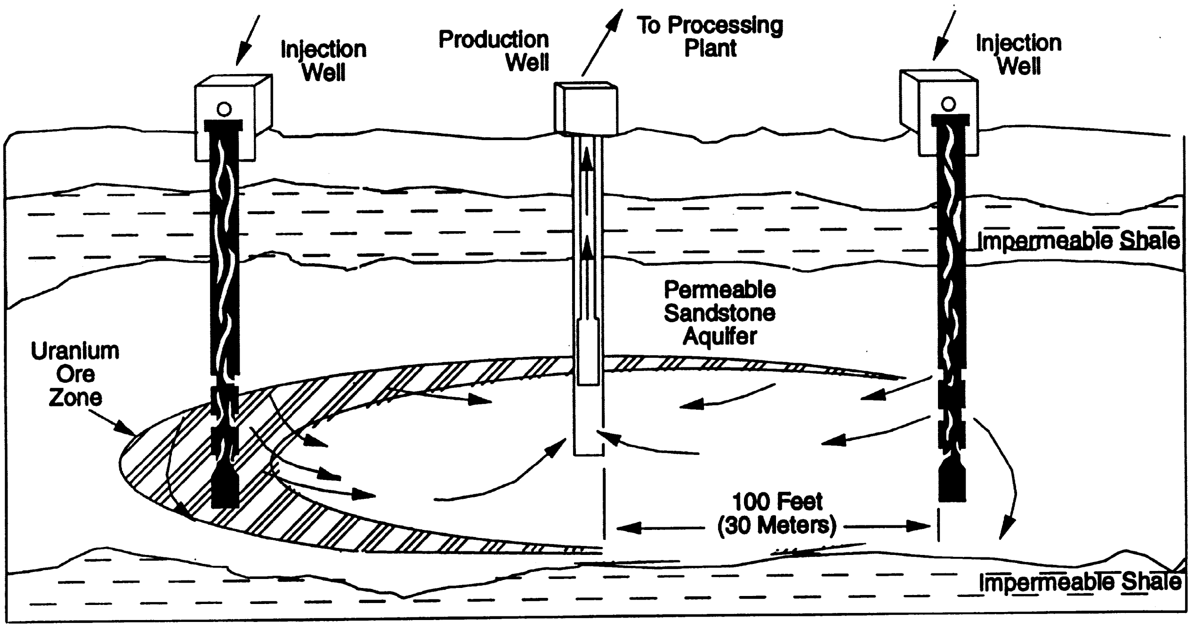


FIG. 21. Generalized cross section of a portion of a typical uranium in situ leaching wellfield.

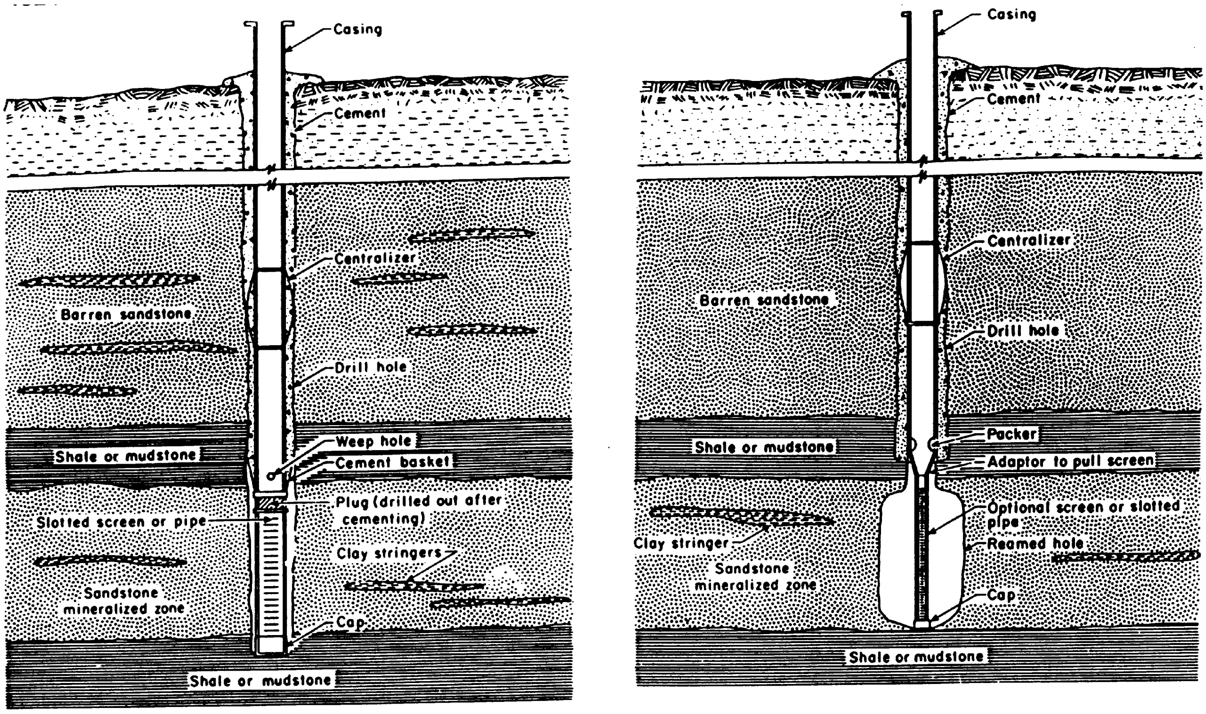


FIG. 22. Well completion.

All wells, including monitor wells, are piped into a header house where all injection and recovery well flow meters, pressure indicators, and flow controls as well as sample ports and mixers are located. Pregnant and barren lixiviates are pumped between the header house and processing plant through pipe lines. During the operation of the wellfield more water is recovered than is injected to maintain a localized depression in the natural hydrostatic pressure of the ore zone. This creates a pressure gradient which causes surrounding native groundwater to flow toward the recovery wells. Water levels in the surrounding monitor wells are measured periodically to evaluate the shape of this cone of depression. The influx of native water around the perimeter confines the lixiviate within the wellfield and, hence, within the uranium bearing sands. This system of over producing the wellfield is a key to controlling the lixiviate movement within the ore body and to protect the surrounding native groundwater.

The size and quality of equipment (pumps, flow meters, etc.) required to operate the test mine is dependent on the number of recovery and monitor wells, depth to the ore zone, and desired flow rates (production). There are many manufacturers available to supply the equipment necessary to operate an ISL mine.

12.1.2.3. Processing plant (See Fig. 23)

Uranium recovery from the pregnant lixiviate is usually accomplished with a small (capacity less than 55 m^3/h) ion exchange (IX) facility located at the wellfield site. The plant contains the following processing circuits:

(1) Resin loading
(2) Bleed treatment
(3) Resin elution
(4) Precipitation
(5) Product filtering, drying, and packaging

Resin loading

The resin loading circuit contains several pressurized vessels containing anionic ion exchange resin. The pregnant lixiviate enters the ion exchange (IX) facility where the uranium is chemically absorbed onto the resin. The barren lixiviate exiting the IX facility is recharged and pumped back to the wellfield for injection.

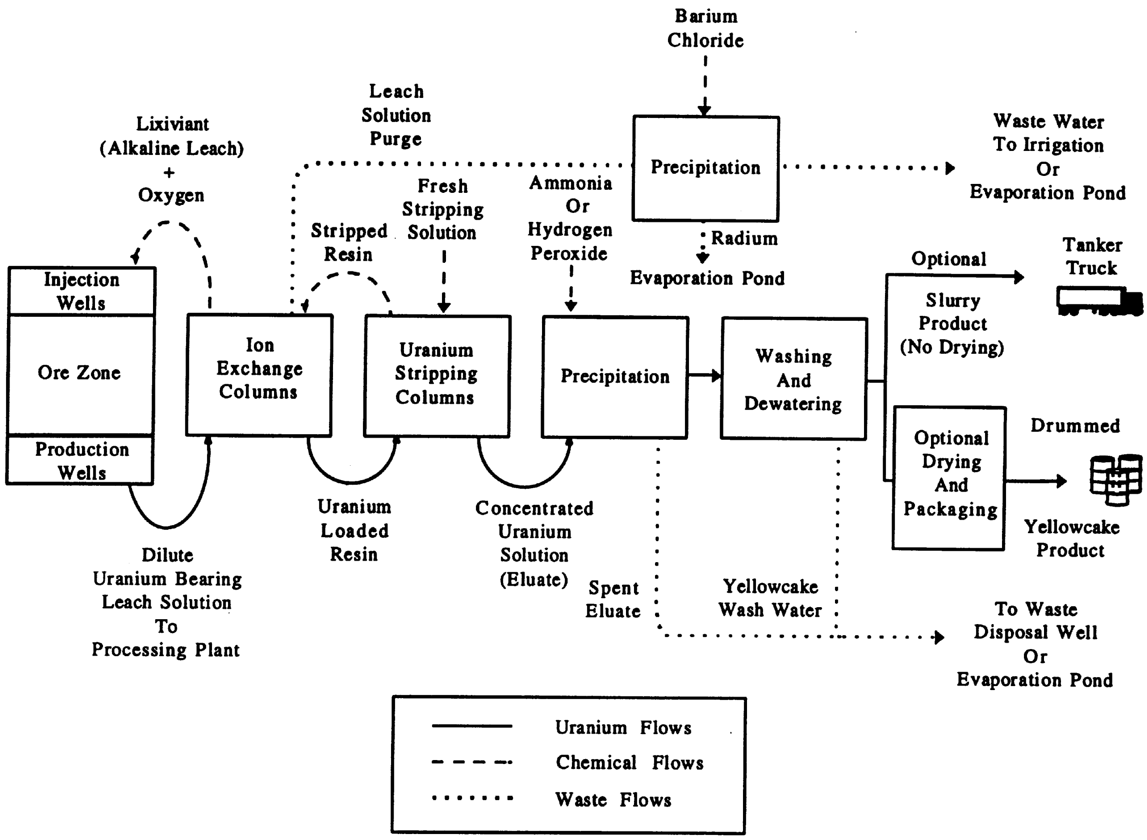


FIG. 23. Process flow diagram for a typical uranium in situ leaching mining facility.

Bleed treatment

To control the movement of the lixiviate within the ore zone, a fraction of the barren lixiviate is continuously removed. More fluid is produced than injected. This bleed or blow-down creates a cone of depression within the ore zone causing natural groundwater from the surrounding area to flow toward the ore zone. This negative pressure gradient holds or contains the lixiviate within the desired ore bearing region and prevents unwanted excursion of lixiviate away from the ore. The bleed fluid is treated in lined ponds for radium removal then evaporated or released for approved down hole disposal or irrigation.

Elution circuit

The loaded resin is transferred from the IX column to elution vessels for uranium recovery and resin regeneration. In the elution vessel, the resin is contacted with chemicals which produces a rich eluate and regenerates the resin. The eluted resin is rinsed with fresh water and returned to the IX vessel for reuse. The treated rich eluate contains sufficient uranium for economic precipitation.

Precipitation circuit

In the precipitation circuit, the rich eluate is again chemically treated to form an insoluble uranyl compound. The uranium precipitate (slurry) is allowed to settle in a thickener tank. The uranium depleted supernate solution is removed from the thickener tanks and pumped into a lined evaporated pond or an approved deep well for disposal.

Product filtering, drying and packaging

After precipitation, the settled yellowcake is washed, filtered, dried and packaged in a controlled area. Washing removes any remaining soluble contaminates. Filtering and dewatering is usually done in a filter press. The filter cake is then removed to yellowcake dryers, dried, packaged, and stored for future shipment to further processing facilities.

A stringent radiation safety and monitoring programme must be maintained through out the processing plant in order to meet the ALARA principle for workers and regulations adopted by various agencies. There are many manufacturers that make equipment for a processing plant described above.

12.1.2.4. Restoration, reclamation and decommissioning

An integral part of the pilot test mine is to prove to the operator and regulatory agencies that the mined aquifer can technically and economically be restored to premining conditions and use. Aquifer restoration has been successfully demonstrated using the following phases:

(1) Groundwater sweep
(2) Water treatment
(3) Reductant addition
(4) Aquifer recirculation.

The first phase is called groundwater sweep which involves pumping the wells and transferring the water to surface treatment ponds and released. There is no injection of fluids into the wellfield during this phase. This action draws the natural groundwater to the wellfield thus diluting and removing the leaching solutions.

The second phase uses water treatment to remove the contaminants from the water. The clean water from the water treatment plant is injected back into the wellfield being restored. The contaminated water is sent to the evaporation pond.

Phase three adds a reductant to the clean water being injected into the wellfield which will stop the chemical reactions taking place in the aquifer being restored.

The fourth phase is simply the circulation of the water through the ore body aquifer to make the quality of the groundwater homogenous.

Reclamation and decommissioning of a pilot test mine usually is required by regulatory agencies only if the project is not a candidate for commercial operating status. Following completion of aquifer restoration some operators extract core from the wellfield to determine the efficiency of the ISL operation.

Decommissioning includes removal of all pipe lines, dismantling of the header house and processing plant. Disposal of these items must be in accordance with regulations either through burial or transfer to other licensed disposal facilities.

Reclamation of the wellfield and processing plant sites includes plugging and capping of all wells and restoring the surface to its original use including recontouring and revegetation.

The results of the pilot test mine will determine the technical and economic viability of the project in terms of uranium extraction and aquifer restoration. It will also determine the success of the regulatory criteria for operating the test mine. Mine modeling and design can be completed as well as developing feasibility studies for future commercial ISL operations. The total time to license and operate a test mine could exceed three years.

12.2. MINE PREPARATION

There are several items that must be addressed when preparing an ISL mine for commercial operation. These are:

(1) Licensing
(2) Construction phase.

12.2.1. Licensing

Most countries require approval from regulatory agencies prior to operating a commercial ISL mine. Preparation of a commercial license application includes extensive information on geology, hydrology, vegetation, soils, wildlife and radiological conditions. Most of the information required by regulatory agencies for a commercial license application is obtained during the surface drilling programme and the operation of the pilot test mine. Information concerning the number of production units, production rates, plant size, method of waste disposal and aquifer restoration schedules must be included in the commercial license application. Approval of the commercial license by the regulatory agencies is required before the construction phase begins.

12.2.2. Construction phase

The construction phase of the commercial ISL mining facilities can be divided into three major components. The first component is the wellfield which consists of the injection and production (recovery) wells, monitor wells, downhole equipment and surface equipment. The second component is the processing plant which includes the building and the process equipment. The third component is the waste water disposal system.

12.2.2.1. Wellfield construction

The wellfield is designed to exploit all ore reserves included in the commercial licensed area and is often divided into mining units for scheduling development and for establishing baseline data, monitoring requirements and restoration criteria. Commonly wellfields will be developed based on five spot patterns consisting of four injection wells and one central production well. The patterns may be modified to fit the configuration of the ore body. All wells will be constructed to serve as either injection or recovery wells. This allows flow directions to easily be changed to optimize uranium recovery and groundwater restoration. The spacing of the injection wells is dependent on the hydrogeology of the production zone. Injection and recovery wells will be completed to isolate the ore bearing interval from all other aquifers. Production zone monitor wells will be located in a pattern around the mining unit. One overlying and one underlying monitor well will also be completed in the aquifers immediately above and below the production zone. There are several methods of completing a well to isolate the production zone. In many cases the well is cased and cemented. Regulatory agencies require that each well must successfully pass a mechanical integrity test before being activated.

Normally, a header or manifold house is constructed for each mining unit to monitor solutions via pipe lines from the wells and the processing plant. The header house includes flow meters, flow control valves and sample ports for each well piped to the house. The electrical on/off control for each well is also located in the house. The header houses are often skid mounted so that they can be easily moved to new mining units as old units are completed.

12.2.2.2. Processing plant

The processing plant complex plant usually includes the laboratory, maintenance shop, warehouse, staff offices and change rooms. The major components housed in the processing plant building include IX columns, elution tanks, precipitation and thickener tanks, filter press, chemical make up tanks and pumps. The number and size of these components is dependent on desired production rates for the project.

12.2.2.3. Waste water disposal system

The initial disposal of waste water in a commercial ISL operation is in evaporation ponds. The number and size of ponds is dependent on the production rate. These ponds are generally constructed with a double liner to provide a leak detection system. The sources of the waste water are the wellfield over production, the plant bleed and aquifer restoration effluent. The waste water either stays in the ponds and is evaporated, pumped to disposal wells or is used for irrigation depending on the regulatory license conditions.

12.3. MINE OPERATION

The wellfield in a commercial operation is divided into mining units each of which contains a sufficient number of patterns (five-spot) to initially meet planned production rates. As mining unit #l commences production, mining unit #2 would be installed followed by additional mining units as required to meet targeted flow rates. As the project expands it will be common to have several mining units in production and at the same time have a mining unit being installed and one or more being in the aquifer restoration phase. This procedure is necessary to provide the flexibility required to meet production goals. This sequence of mining will continue until the project is completed.

As each mining unit is installed, hydrogeological and baseline data is collected so that the aquifer and the surface can be returned to premining conditions following aquifer restoration and surface reclamation. In the producing mining unit, native groundwater is fortified with an acid or alkaline base lixiviate is pumped to injection wells and recovered from production wells. This process selectively removes uranium from the orebody. Since all wells are completed and tested in the same manner they can be interchanged from production to injection wells as necessary to maintain desired concentrations of uranium in the lixiviate. Constant monitoring of flow rates, well sampling and lixiviate concentration is essential to maintain a successful mining operation.

The pregnant lixiviate is pumped from the production or recovery wells to the header house then to the processing plant via pipe lines. The processing of the pregnant lixiviate, return of the barren lixiviate to the wellfield and the disposal of the waste water is the same as described in section 12.1.2. The components (number and size) of the commercial processing plant are upscaled to satisfy planned yellowcake output.

12.4. EXAMPLES

During the last decade numerous ISL mines throughout the world have been developed for commercial operations. ISL is now considered a major mining method which gives operators another viable option to exploit uranium reserves. Successful ISL mines are being operated using acid and alkaline base lixiviates to remove the uranium from the ore body. Examples of mines using acid and alkaline lixiviates are discussed below.

12.4.1. Alkaline leach

A large uranium ore body has been delineated in Western United States of America containing in excess of 35 million pounds U_30_8. The mineralization occurs in an arkosic sandstone aquifer at an average depth of 200 m. Laboratory analysis of core samples taken from the ore zone demonstrated that the ore body was an excellent candidate for ISL mining.

To further evaluate the potential of this ore body for ISL mining, a pilot test mine was permitted by regulatory agencies. The decision to operate a pilot test mine was to establish the amenability of the ore deposit to ISL mining and the technical and economic feasibility of restoring the aquifer to premine conditions. Development drilling consisted of injection wells, recovery wells and monitor wells placed along the periphery and above and below the ore zone. All the wells were sampled to provide background information and pump tests were conducted to establish flow data within the wellfield. The wellfield included several five-spot patterns with four injection wells arranged in a square with the recovery or extraction wells in the center. The spacing of the injection holes ranged from 78 to 40 m. All of the wells were connected to a header house by buried pipe lines. The header house contained flow meters, sample ports, chemical injection facility and well pressure gauges. Lixiviate chemistry was a bicarbonate leach with oxygen. Hydrogen peroxide was originally used as a down-hole oxygen source but later, gaseous oxygen was used as the oxidant. Calcite scaling was minimized by switching from sodium bicarbonate to carbon dioxide for lixiviate makeup. The carbon dioxide injection relies on cations all ready in the system as a carrier.

The pregnant lixiviate produced from the wellfield was pumped to the recovery plant in buried pipe lines. The recovery plant was a standard anionic resin ion exchange system. The average uranium concentration from the pilot mine was 70 mg/l over its life. Each recovery well produced between 1.5 and l/second. Following the production phase of the test mine, aquifer restoration was completed to the satisfaction of regulatory agencies using the groundwater sweep technique. The results of the test mine successfully produced the following information:

(1) Demonstrated than an environmentally sound mining methods can be conducted economically.
(2) The altered groundwater was restored to regulatory standards.
(3) Developed the technical and operational basis for a commercial ISL project.
(4) Demonstrated the technical and economical viability of aquifer restoration.
(5) The low cost lixiviate chemicals (oxygen and carbon dioxide) and open hole well completions were effective and applicable to commercial operations.
(6) Wellfield productivity in terms of recovery and average uranium concentrations were excellent.
(7) Conventional anionic exchange resins systems functioned well as did the hydrogen peroxide induced precipitation of yellowcake.

Based on the success of the pilot test mine, a commercial license application was submitted and approved by regulatory agencies. The ISL operation is designed to produce 750 t U annually. In order to meet the planned production rate, the wellfield area was divided into approximately 13 mining units for scheduling development and for establishing baseline data, monitoring requirements and restoration criteria. Two to three mining units may be in production at the same time with additional units in various states of development and restoration. The wellfield is developed on five-spot patterns with the injection hole varying from 75 m to 50 m apart depending on the characteristics of the ore body. All wells are constructed to serve either as injection or recovery wells which allows flow directions to easily be changed to optimize uranium recovery and groundwater restoration. The leaching solution (lixiviate) formed by adding gaseous carbon dioxide and oxygen to native groundwater is injected into the uranium ore bearing sandstone through a series of injection wells. The pregnant lixiviate flows to a recovery well where it is pumped to the surface by submersible pumps and transported to the surface recovery plant. At the plant the uranium is removed from the fluid by ion exchange (IX). The barren fluid is refortified with carbon dioxide and oxygen and reinjected into the wellfield. Commercially available anionic resin is used in the IX columns. The uranium is removed from the resin by conventional elution processing. The ion exchange resin, stripped of uranium, is reused. The eluted uranium is precipitated, washed, dried and packaged for shipment. The total cost to operate this ISL project ranges from 12 to 15 US dollars/lb. U_30_8. A generalized percentage breakdown of the major cost components follows:

Capital	17%
Operating	25%
Wellfield replacement	25%
Other	33%
Total	100%

12.4.2. Acid leach

Sulphuric acid is widely used as a lixiviant in Russia and former CIS countries for insitu leaching of uranium ores. An advantage of using strong acid solutions are high recovery of uranium from permeable sandstone ores over a relatively short period of time. Disadvantages include increased metal content of undergroundwaters and the requirement to use acid resistant materials and equipment to handle mining solutions. Acid lixiviant is practical only if the uranium deposit contains low levels of carbonates (generally CO_2 equivalent less than 2%).

12.4.2.1. Typical in situ acid leach mine

The mine is a well established insitu mining operation recovering uranium by acid leaching from an ore deposit an average depth of 500 meters. The reserves are in the order of 25 000 tonnes U at a grade of between .07 and .10% U in a sandstone rock.

The mine well field is laid out in five or seven spot pattern. The acid leaching solutions are pumped through stainless steel pipes to injector wells at 30 to 40 meter intervals from the recovery wells. Pressure at the top of the well is 3 atmospheres. Production wells deliver 10 cubic meters per day containing 100 to 120 milligrams U per litre. The average life of each well is three years to produce 20 tonnes U. Mine capacity is 500 to 600 tonnes/year from 100 production wells.

Restoration work is limited to surface cleanup and plugging the wells. The aquifer host rock has sufficient carbonates to eventually raise the lixiviant PH from 2.0 to 5.0. The well fields are closely monitored and there is no evidence of contaminant excursion. The processing plant takes the pregnant solution from the well fields and using a standard ion exchange system produces a 50% product as UO_2SO_4 which is further refined at an outside plant. The total cost including Administration, Amortisation and Royalty (A.A.R) to operate this project is in the order of 25.00/KgU. A generalized percentage breakdown of the major cost components.

(1)	Wellfield development	20%
(2)	Operating cost	35%
(3)	Admin, amortisation + royalty	33%
(4)	Refining to 98% U_30_8	12%

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