Final Report

Review of Existing and Proposed Tailings Impoundment Technologies

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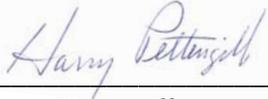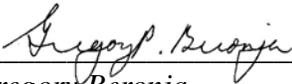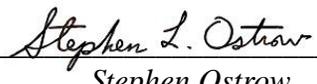
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1.0   HISTORICAL CONVENTIONAL TAILINGS IMPOUNDMENTS

Although the recovery of uranium dates back to at least the 16th century, large-scale operations did not commence prior to the 1940s. As there was initially little appreciation of the radiological or chemical hazards associated with the uranium tailings, early disposal practices followed those used in other metal extractions processes. The tailings were often disposed of in the least costly, most expeditious manner. Specific practices included returning the tailings to a mined out pit, placing them on open ground adjacent to the mill, depositing them in natural depressions, depositing them in a valley behind a dam or dyke, or placing them in man-made impoundments known as ring dykes or turkey nest dams (IAEA 2004). Specific examples of such early practices include the following:

- Grand Junction, Colorado, where tailings were deposited adjacent to the mill on open land bordering the mill or deposited in shallow depressions behind levees bordering a river

- Uravan, Colorado, where tailings were deposited on an open bench on a canyon wall with nothing to prevent their movement to the canyon and river below

- Grants, New Mexico, where a massive ring dyke embankment was created using the course fraction of the tailings sands

Disposal of the tailings in water (either deep lake or river), which has occurred in other countries, has not been practiced in the United States.

By the 1970s, the serious public health and ecological damage arising from the past disposal of tailings led to the passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA). Pursuant to the regulations promulgated under UMTRCA (40 CFR 192), the Department of Energy (DOE) at Title I sites and NRC licensees at Title II sites have almost completed the restoration and stabilization of current tailings impoundments. For the most part, these reclamation activities have entailed retrieval of wind-blown tailings from adjacent land and properties, stabilization of the piles in place under thick earthen covers with gravel caps, and riprap shoulders to minimize erosion. In extreme cases, the tailings have been physically removed to a new location to minimize their vulnerability to flooding or intrusion.

Impoundments at the few mills that remain operational and all future tailings impoundments must be built and operated to comply with the regulatory requirements of both the EPA and the NRC (or an NRC Agreement State).

2.0 PROFILE OF THE EXISTING INDUSTRY

At the time the NESHAP for Operating Uranium Mill Tailings Impoundments was promulgated (40 CFR 61, Subpart W, December 15, 1989 [FR 1989]), there were 11 conventional mills that were operating or on standby status. Of these mills, seven had unlined impoundments, while four had impoundments with synthetic liners. As the NESHAP revoked the exemption to the liner requirement of 40 CFR 192.32(a), the mills with unlined impoundments had to close them and move towards final reclamation and stabilization. Given the economics of uranium recovery throughout the ensuing years, all seven of the mills with unlined impoundments and one of the mills with a lined impoundment decided to dismantle the mills and move to final decommissioning and license termination. As a result, as of June 2008, the conventional uranium milling industry in the United States is comprised of only three facilities:

- The Sweetwater mill, with a capacity of 2,700 tonnes/day, owned by Kennecott Uranium Company

- The White Mesa mill, with a capacity of 1,100 tonnes/day, owned by UMETCO

- The Canon City mill, with a capacity of 1,800 tonnes/day, owned by the Cotter Corporation

The Sweetwater mill is located approximately 40 mills northwest of Rawlings, Wyoming; the White Mesa mill is near Blanding, Utah; and the Canon City mill is near Canon City, Colorado. All three mills employ acid-leaching to extract uranium from the ground ore and dispose of the tailings in synthetically lined, partially below grade impoundments with earthen dams. Of the three, only the Canon City mill is believed to be currently processing ore; Sweetwater and White Mesa are being maintained in standby mode.

Only limited new data have been developed on the current status of the impoundments. Based on the data developed during the 1989 NESHAPs rulemaking (EPA 1989), the impoundments are as shown in Table 1.

Table 1. Tailings Impoundments at Conventional Uranium Mills

Mill	Total Acres	Ponded	Wet	Dry	Radium Content (pCi/g)
Sweetwater	37	30	0	2	280
White Mesa	130	55	70	5	961
Canon City	130	128	2	0	400

The impoundments at the Sweetwater and Canon City mills are both single-cell impoundments. The White Mesa mill has a four-cell impoundment. Based on information reported in a 1st Quarter 2005 Inspection Report (UDRC 2005), one cell holds processing liquids, two cells hold tailings, and the fourth cell, previously used to hold liquid wastes, has a torn liner. The liner and waste materials in cell four are being removed to cell two for disposal. The first of the two cells that holds tailings is filled and covered with random fill to control radon. The second of the two cells has an earthen cover over about 40% of the surface, with tailings and ponded areas covering the rest.

3.0   ANTICIPATED CHANGES IN THE INDUSTRY PROFILE

The rapid increase in energy costs, increased concerns about global warming, and the tremendous world-wide surge in energy use have all led to considerable new interest in uranium recovery. At the spring 2008 joint National Mining Association/Nuclear Regulatory Commission (NMA/NRC) Uranium Recovery Workshop, the NRC identified 29 projects that have or are anticipated to file applications for new licenses, expansions of existing operations, or restarts of existing operations by the end of fiscal year 2011 (NMA/NRC 2008a). The vast majority of the new projects involve in-situ leach operations (discussed below), one is a new heap leach facility, and six are new conventional uranium mills. Of the six anticipated new mills, one is in Arizona, two are in Wyoming, and three are in New Mexico. Table 2 identifies each of these facilities.

Table 2. Anticipated New Conventional Uranium Milling Facilities

Owner	Site	State	Expected Filing Date
Strathmore Minerals Corp.	Rocha Honda	NM	April 2009
Uranerz Energy Corp	Mt. Taylor	NM	August 2009
Concentric	Yavapai County	AZ	November 2008
Neutron Energy	Marquez	NM	April 2010
Strathmore Minerals Corp.	Gas Hills	WY	February 2011
Wildhorse Energy	Sweetwater	WY	May 2011

It should be noted that the identified facilities are only those that the NRC is aware of. It is possible that additional facilities will be proposed in the Agreement States of Colorado, Utah, and/or Texas.

None of the conventional mills have filed anything more than a letter of intent at this time, so there is no information available on the types of tailings impoundments that they propose to utilize. In order to limit the potential radon that could be emitted from the tailings impoundments, Subpart W requires that the tailings be disposed of in a phased disposal system with disposal cells no larger than 40 acres, or by continuous disposal in which not more than 10 acres of undisposed tailings may accumulate at any time. Regardless of whether the new mills opt for phased- or continuous-disposal, they will all have to also demonstrate that their proposed tailings impoundment systems meet the design criteria given in Appendix A of 10 CFR 40. Criterion 3 of Appendix A identifies below-grade disposal, either in mines or excavated cells, as the "prime" candidate for tailings management. However, other methods may be approved if the applicant demonstrates that below-grade disposal is not feasible and that the proposed method will provide equivalent protection of persons and the environment. Additionally, every applicant will have to demonstrate that the proposed facility's operations will meet the NRC's ALARA (as low as reasonably achievable) requirement. The ALARA requirement almost certainly dooms any application that seeks to construct an above-grade impoundment with a ring dyke constructed with tailings sand. It also means that some method will have to be used at all facilities to minimize the potential for wind to disperse exposed tailings. The usual methods to minimize tailings dusting include using sprinklers to keep the tailings saturated, applying a sealant, or simply covering them with a clay or earthen cap.

4.0 COMPARISON OF URANIUM TAILINGS DISPOSAL TECHNOLOGY WITH THE REQUIREMENTS OF RCRA, SUBTITLE C

The comparison of tailings facilities at current or future uranium mills and the final reclaimed configuration with RCRA subtitle C surface impoundments and landfills is not directly comparable; however, there are many salient similarities in construction methods. There are significant similarities in the construction, even though the underlying "basis of design" of each is different.

The basis of the design of the reclaimed tailings area is to prevent the release of radioactive material into the atmosphere, primarily radon gas, and secondarily radioactive particulates. The prevention of radioactive material from leaching into the groundwater is also important via the Safe Drinking Water Act. Furthermore, all current and future uranium tailings impoundments are expected to be in arid to semi-arid areas in the western U.S., particularly in the states of Arizona, Utah, Colorado, New Mexico, Texas, Wyoming, Nebraska, and possibly Washington (the high desert area), with one possible exception in Virginia. Thus, on completion of the operating period, the reclamation of the tailings favors keeping water out of the tailings, i.e., total yearly evaporation is greater than total precipitation. This is in contrast to an RCRA subtitle C landfill cover with multiple layers of protection specifically designed to keep moisture away from the waste.

The cover or final cap on a tailings pile is designed to limit the radon flux from the surface to less than 20 pCi/m^2-sec. While this is called a "radon barrier," the nomenclature does not reflect the physics of the situation. Rather than a barrier, the cap is of sufficient thickness and density (actually tortuosity) that radon atoms diffusing from the surface of the tails (higher concentration) to the surface of the cap (lower concentration) must travel a long enough path that most will decay before reaching the surface. This is molecular diffusion through the soil. Obviously, soils such as clay or shale have much lesser porosity then sand or gravel and, therefore, require the radon atom to use more time to diffuse through the material to the surface. As the half-life of radon is 2.8 days, a few feet of clay or shale soil is sufficient to reduce the radon flux.

As briefly noted above, the typical RCRA subtitle C surface impoundment and landfill bottom liner systems have as a design basis the prevention of moisture from mixing with the waste and leaching hazardous material in the groundwater. The landfills are sited throughout the U.S. in areas where precipitation is likely to be greater than evaporation. Thus additional protection, such as double confinement with a leachate collection system in between, is the standard. The confinement layer is also a composite composed of clay and a High Density Polyethylene (HDPE) liner. This is the typical base layer of the landfill. The caps can be equally complex with topsoil often used as a drainage layer (to remove precipitation), and immediately below that is a liner which has been placed over compacted fill. Their primary function is not to delay the diffusion of gas coming from the waste, but to prevent moisture from getting in and contacting the waste.

The explicit similarities are more inherent to the technologies being applied. The use of synthetic liners, clay caps, and erosion barriers are common to both and are used to achieve the

regulatory goal of isolation of wastes contained therein from release to the environs (air and groundwater) over extended timeframes.

5.0 DISCUSSION OF CLIMATE AND IMPOUNDMENT SIZE ON RN-222 EMISSIONS

A number of factors influence the emission of Rn-222 from tailings impoundments, including the climate and the size of the impoundment. For a given concentration of radium in the tailings and a given grain size, the moisture content of the tailings will control the radon emanation rate; the higher the moisture content the lower the emanation rate. In the arid and semi-arid areas of the country where these impoundments are located or proposed, the annual evaporation rate is quite high. As a result, the exposed tailings (absent controls like sprinkling) dry rapidly. In its previous assessments, the EPA has explicitly taken the fact of rapid drying into account by using a Rn-222 flux rate of 1 pCi/m^2-s/pCi/g Ra-226 to estimate the Rn-222 source term from the dry areas of the impoundments (EPA 1984, EPA 1989). (Note: The estimated source terms from the ponded and saturated areas of the impoundments are zero, reflecting the complete attenuation of the Rn-222.)

Climate also effects the source term from the impoundments once they are filled. The emplacement of the thick earthen covers that are necessary to assure the long-term stability of the reclaimed impoundments cannot be initiated until the tailings have dried sufficiently to allow heavy earth-moving equipment to be operated on the surface. For impoundments in arid or semi-arid regions, the drying period will be shorter than in areas where annual evaporation does not exceed annual precipitation. In its 1989 evaluation of mills for the Subpart W rulemaking (EPA 1989), the EPA assumed that a 5-year drying period would be required. In practice, a number of facilities have been able to start cover operations earlier than that. For example, the White Mesa mill has a partial earthen cover on the disposal cell that is still open to accept additional tailings.

The size of the impoundment has a direct linear correlation with the Rn-222 source term. Again, assuming the same Ra-226 concentration and grain sizes in the tailings, a 100-acre dry impoundment will emit 10 times the radon of a 10-acre dry impoundment. This linear relationship between size and Rn-222 source term is one of the main reasons that the Subpart W NESHAP imposed size restrictions on all future impoundments (40 acres per cell if phased disposal is chosen and 10 acres undisposed if continuous disposal is chosen).

Using the sizes of the three existing conventional impoundments, and assuming identical grain sizes and a Ra-226 concentration of 400 pCi/g, the effect of impoundment size on Rn-222 emissions can be illustrated for the operational period, the drying period, and the reclamation period as shown in Table 3.

Table 3. Comparative Rn-222 Emissions over 70 Years
(Assuming 400 pCi/g Ra-226)

Mill	Total Acres	Ponded	Wet	Dry	Operating 15 yrs Ci	Drying 5 yrs Ci	Reclaimed 50 yrs Ci	Total 70 yrs Ci
Sweetwater	37	30	0	7	5.4E+3	9.4E+3	4.7E+3	2.0E+4
White Mesa	130	55	70	5	3.8E+3	3.2E+4	1.7E+4	5.0E+4
Canon City	130	128	2	0	0	3.2E+4	1.7E+4	5.0E+4

6.0   IN-SITU LEACH URANIUM RECOVERY FACILITIES

6.1   Scope and Background

Currently, in-situ leach (ISL) [also called in-situ recovery (ISR)] has become the predominant method for uranium recovery in the United States. Table 4 shows the ISL facilities that are currently in operation under NRC or State of Texas control. As was made clear at the 2008 National Mining Association/Nuclear Regulatory Commission's 2008 Workshop on Uranium Recovery, the number of ISL facilities is expected to increase substantially in the coming years. The National Mining Association estimated some 26 license/license amendment applications for uranium recovery facilities will be submitted by the end of 2009 (NMA/NRC 2008a). This may be an underestimate, as the NRC at the same conference indicated it anticipated some 29 applications for facility restarts, expansions, or new licenses for uranium recovery by the end of fiscal year 2011 (NMA/NRC 2008b). Of these applications, 23 are for ISL facilities (14 new, 7 expansions, 1 combined, and 1 restart). Table 5 shows the company, site, type of project, and anticipated application data for these projects. As with conventional mills, this list includes only facilities established or to be developed in non-Agreement States, e.g., Wyoming, and those agreement states that do not regulate uranium recovery, e.g., Nebraska. The list does not include ISL or conventional facilities in major uranium-producing Agreement States, such as Colorado, Utah, and Texas. There are at least three proposed facilities in Texas.

Table 4. Operating ISL Facilities

Company	Site	State
Cameco	Smith Ranch – Highland	WY
Cameco	Crow Butte	NE
Hydro Resources	Crown Point	NM
Hydro Resources	Church Rock	NM
Mestena	Alta Mesa 1,2,3	TX
Uranium Resources	Kingsville Dome 1,3	TX
Uranium Resources	Vaquez 1,2	TX

Table 5. Anticipated ISL Facilities

Owner	Site	Scope	State	Anticipated Application Date
Cogema	Christensen Ranch	Restart	WY	Rec'd April 2007
Cameco	North Trend	Expansion	NE	Rec'd June 2007
Cameco	Plant Upgrade	Expansion	NE	Rec'd October 2006
Lost Creek ISR	Lost Creek	New ISL	WY	Rec'd October 2007
Uranez Energy	Hank & Nichols	New ISL	WY	Rec'd December 2007
Uranium One	Moore Ranch	New ISL	WY	Rec'd October 2007
Uranium One	Jab & Antelope	New ISL	WY	July 2008
Cameco	Gas Hills	Expansion	WY	July 2008
Kennecott Uranium	Sweetwater	Expand Resin	WY	January 2009
Cameco	Three Crow	Expand ISL	NE	February 2008

Table 5. Anticipated ISL Facilities

Owner	Site	Scope	State	Anticipated Application Date
Lost Creek ISR	Lost Creek	Expand ISL	WY	October 2008
PowerTech Uranium	Dewey Burdock	New ISL	SD	October 2008
Cameco	Smith Ranch	Expand CPP	WY	May 2009
Cameco	North Butte	Expand ISL	WY	May 2009
Strathmore Minerals	Sky	New ISL	WY	April 2009
UR-Energy	Lost Soldier	NEW ISL	WY	January 2009
Uranez Energy	Collins Draw	New ISL	WY	July 2009
Uranium One	Ludeman	New ISL	WY	October 2008
Uranium One	Allemand-Ross	New ISL	WY	August 2009
Wildhorse Energy	West Alkali Creek	New ISL	WY	April 2009
Cameco	Ruby Ranch	New ISL	WY	October 2009
Strathmore Minerals	Reno Creek	New ISL	WY	December 2009
Wildhorse Energy	Sweetwater	New ISL	WY	May 2011

In-situ leach uranium mining is defined as the leaching or recovery of uranium from the host rock (typically sandstone) by chemicals, followed by recovery of uranium at the surface (IAEA 2005). Leaching, or more correctly the re-mobilization of uranium into solution, is accomplished through the injection into the ore body of a lixiviant. The injection of a lixiviant essentially reverses the geochemical reactions that deposited the uranium in the first place, and assures that the dissolved uranium remains in solution until it is pumped out of the ground and the uranium recovered. Two types of lixiviant systems can be used, loosely defined as acid or alkaline systems. In the U.S., the geology and geochemistry of the majority of the uranium ore bodies favor the use of an "alkaline" lixiviant or bicarbonate-carbonate lixiviant and oxygen. Other factors in the choice of the lixiviant are the uranium recovery efficiencies, low operating costs, and the ability to achieve satisfactory groundwater restoration. The acid systems once used in the United States are still used in Eastern Europe and Asia and recently in Australia on ore bodies in saline aquifers (IAEA 2005).

There are four major types of uranium deposits in the United States; strata bound, solution breccia pipes, vein, and phosphatic deposits (EPA 1995). Of these, in-situ leach is the uranium recovery technique used mostly on strata-bound ore deposits. Strata-bound ore deposits are ore deposits that are contained within a single layer of sedimentary rock. They account for more than 90% of the recoverable uranium and vanadium in the United States and are found in three major geographic areas—the Wyoming Basin (Wyoming and Nebraska), Colorado Plateau or Four Corners area (northwestern New Mexico, western Colorado, eastern Utah, and north eastern Arizona), and south Texas. A discussion of the origin of the uranium ore, including ore body formation and geochemistry, may be found in the reference, *Technical Resource Document Extraction and Beneficiation of Ores and Minerals - Volume 5 Uranium* (EPA 1995). Much of the recoverable uranium in these regions lends itself to in-situ leach or recovery, based on the physical and geochemical properties of their ore bodies.

Other important physical or geologic properties also include the location of the ore body. Ore bodies amenable to ISL are usually within an aquifer (EPA 1995). The water quality within the aquifer can also vary, depending on the presence of and boundary between oxidizing and reducing groundwaters (EPA 1995). Additional factors important in the selection of the production method (lixiviant and well pattern) include chemical constituents, ore grade, permeability, and surrounding material. Ideally, the ore body should be confined by impermeable strata above and below the deposit. This assures better hydrogeologic control of the lixiviant and facilitates restoration of the groundwater following completion of the mining (IAEA 2005). These hydrogeologic controls include preventing contamination of adjacent aquifers by excursions (leaks of lixiviant and other material from the ore body area).

6.2   Uranium Recovery Process for ISL

The following discussions are taken in part from EPA 530-R-94-032 (EPA 1995) and NUREG/CR-6733 (NRC 2001). The operational steps for the recovery of uranium are straightforward and consist of the three primary operations of uranium mobilization, uranium processing, and aquifer restoration.

6.2.1   Uranium Mobilization

First, barren extraction solution (lixiviant) usually composed of groundwater enhanced by an oxidant and carbonate/bicarbonate is injected through wells into the ore zone. The lixiviant oxidizes and dissolves uranium. Carbon dioxide in the lixiviant reacts with water, forming carbonic acid, which complexes with the solubilized uraniferous ions forming uranyl carbonates keeping the uranium in solution. The resulting solution is referred to as "pregnant lixiviant." This process essentially reverses the geochemical reactions that initially caused deposition of the ore body particularly in "roll front" deposits. The solubilized uranyl carbonates and gangue minerals remain in solution as the pregnant lixiviant is pumped to the surface through production (recovery) wells. The pregnant lixiviant includes both radium and dissolved radon.

6.2.2   Wells

Three types of wells are used in the uranium recovery process; injection wells, recovery wells, and monitoring wells. The pattern of the injection and recovery wells is usually the 5-spot pattern or 7-spot pattern. In a 5-spot pattern, the injection well is in the center of a square with four recovery wells at the corners. The 7-spot pattern uses a hexagon for the recovery wells. The spacing between production and recovery wells can range from 20 to 200 feet. Pumping rates are also variable, and at one facility ranged from 2 gallons per minute (gpm) to 30 gpm for injection wells and 5 to 40 gpm for recovery wells.

6.2.3   Uranium Processing

The pregnant lixiviant is pumped from the production wellheads through sand filters to remove any large particulates and then pumped to the processing operations. Processing generally consists of three operations; ion exchange (IX), elution, and precipitation and drying. These are no different than that found in conventional mills, and indeed some ISL operations are co-located

with conventional mills or truck the pregnant lixiviant (liquor) to a conventional processing facility.

The pregnant lixiviant is either stored in a surge tank or sent directly to the IX resins. In the IX exchange resins, uranium is adsorbed onto the resin beads. The barren lixiviant is recharged and sent back to the production well fields. When the IX resins become saturated with uranium, they are taken offline and washed with a concentrated brine solution (the elution step). The uranium-rich solution, typically containing 8 to 20 grams/liter (g/l) uranium, is normally discharged to a holding tank. After a sufficient amount of pregnant eluant is obtained, it is moved to the precipitation and drying circuit.

In the precipitation and drying circuit, acid is added to the pregnant eluant to destroy the uranyl carbonated complex and is precipitated out with the addition of hydrogen peroxide. A base is added to neutralize any excess acid. The resultant slurry is sent to a thickener, where it is settled, filtered, and dewatered. The thickened slurry may be transported to a uranium processing plant to produce yellow cake (U_3O_8), or it may be dried and packaged (NRC 2001).

In terms of aquifer restoration, the objective is to provide extended flow through the mine field by injection, recovery, and bleed circuits, until it has been demonstrated that uranium is no longer being oxidized and released in the ore zone, and that confinement has stabilized within the aquifer.

6.3 Radon Source Terms

The above presents a capsule summary of the operations at an ISL facility. In this section, the potential radon source terms from these operations are identified and estimated.

6.3.1 Source Terms

The focus of this investigation is radon gas (radon-222, Rn-222), one of the principal contaminants in the uranium ore body and pregnant lixiviant. Radon in groundwater is well known from drinking water and home radon studies throughout the United States. These studies have found a range of radon concentrations from background to 10^5 to 10^6 pCi/l. While high, it is noted that the theoretical solubility limit for radon in liquid phase at atmospheric pressure is estimated to be about 3×10^{16} pCi/L [8.59×10^{-3} mol/L (NRC 2001)], considerably higher than what has been measured. Thus, concentrations of radon in water greater than that presented in the literature are possible.

To estimate the quantity of radon released during the operation of an ISL, the methodology presented in Appendix D of NUREG-1569 was used (NRC 2003). The authors of this document estimated not only radon, but also releases of radium-226 (Ra-226) and some of its daughter products, and uranium-238 (U-238). They considered effluent from the following:

    (1) The drilling operation at new well fields
    (2) Uranium extraction operations at production well fields
    (3) Drying and packaging of yellowcake

    (4)   Restoration operations of old well fields
    (5)   Land application areas (broadcast of holding pond water)
    (6)   Decommissioning of well fields and evaporation ponds

Of all these, the third is not relevant for radon. To provide some quantitative framework for a discussion of the radon released from ISL, the following was taken from Appendix D and modified to focus only on the radon issue. The parameters were also taken from the same reference.

New Well Fields

New well fields are commonly investigated and established using conventional rotary drill rigs. Investigation drill holes assist in mapping the ore body and determining the establishment of the injection and production wells. Because all exploration drill holes are sealed with bentonite to maintain aquifer isolations, no radiological particulates are expected to be released from this operation. The only source of radioactivity is the radon (Rn-222) from the radium in the drill cuttings, which are temporarily stored in a mud pit. During storage, Rn-222 is generated from the decay of Ra-226 and released to the atmosphere. The amount of Rn-222 available for release on a yearly basis as a result of Ra-226 decay from stored cuttings can be estimated from the classic radon release equation:

$$Rn_{nw} = 10^{-12} \, E \, L \, [Ra] \, T \, M \, N \qquad\qquad \text{(equation 1)}$$

where:

Rn_{nw}	=	Rn-222 release rate from the new well field (Ci/yr)
10^{-12}	=	unit conversion factor (Ci/pCi)
E	=	emanating power or coefficient (dimensionless)
L	=	Rn-222 decay constant (0.181/d) (ln2 ÷ half-life of Rn-222)
[Ra]	=	Ra-226 concentration in the ore zone (pCi/g)
T	=	storage time in mud pit (days)
M	=	average mass of material in mud pit
N	=	number of mud pits generated per year

Production Well Fields

No particulates are released from the production well field, because its process streams from production and injection wells to IX columns are all in a closed-loop circuit. The primary radioactive emission from the process streams is Rn-222. During the process, radon released from the ore body is readily removed by the lixiviant (process water) moving through the well field by injection and production wells. The 3.8 day half-life of Rn-222 allows it to circulate along with the process water in the well field over a long period of time before it decays (NRC 2001). Not all the Rn-222 is dissolved in the process water. The portion or fraction that remains is trapped in the ore zone. Also, a portion of the water in the ore zone is periodically purged (called the bleed) to maintain a cone of depression around the well field to prevent leakage of the mining solution outside the production zone (minimize excursions).

The radon source term in the production ore can be estimated from the following:

$$S = 10^6 \, L \, E[Ra] \, A \, D \, P \qquad \text{(equation 2)}$$

where:

10^6 = unit conversion (cm^3/m^3)
E = Active ore zone emanating power (fraction of radon released)
[Ra] = Ra-226 concentration in the ore zone (pCi/g)
A = active area of the ore zone m^3
D = average thickness of the ore Zone (m)
P = bulk density of the ore material (g/cm^3)

In the IX circuit, the water discharge from resin unloading, Fi can be calculated from the following:

$$Fi = Ni \, Vi \, Pi$$

where:

Vi = Volume content of the IX column (L)
Ni = number of IX column unloading per day
Pi = porosity of the resin material

Under steady state conditions, the Rn-222 concentration in the process water C_{Rn} can be calculated from the following:

$$C_{Rn} = \frac{Sf}{((L+v)V + Fp + Fi)} \qquad \text{(equation 3)}$$

where:

f = fraction of radon source carried by circulation water (dimensionless)
v = rate of radon venting from piping and values during circulation (1/d)
V = volume of water in circulation (L)
Fp = "purge" rate of treated water (L/d)
Fi = water discharge rate from resin unloading of IX columns (L/d)

When pressure is reduced during purging or when water is aerated during irrigation, radon is released to the atmosphere. The amount of Rn-222 available for release from the "purge" is dependent on the water volume purge rate, Fp, and on the Rn-222 concentration in the purged water C_{Rn}. Assuming conservatively that all available Rn-222 in the purge water is released, the annual Rn-222 emission is as follows:

$$Rn_w = 3.65 \times 10^{-10} \, C_{Rn} \, Fp \qquad \text{(equation 4)}$$

where:

3.65×10^{-10} = unit conversion factor (Ci/pCi) (d/yr)
Rn_w = Rn-222 release rate from purge water (Ci/yr)

The annual Rn-222 release from occasional venting from wellheads and leaking transport piping can be calculated from the following:

$$Rn_v = 3.65 \times 10^{-10} \, v \, C_{Rn} \, V \qquad \text{(equation 5)}$$

where Rn_v is the annual Rn-222 Release from Venting (Ci/yr).

The annual Rn-222 discharge from the unloading of the IX column content is as follows:

$$Rn_X = 3.65 \times 10^{-10} \, C_{Rn} \, Fi \qquad \text{(equation 6)}$$

where Rn_X is the annual Rn-222 release from unloading of IX column content (Ci/yr).

The total annual Rn-222 release from the production well field is the sum of the radon releases, $Rn_w + Rn_v + Rn_X$.

Restoration Well Field

The basic operation of the restoration well field is the same as that of the production well field. Groundwater in the ore body is restored to its pre-mining level by flushing with fresh or treated water injections (groundwater sweep). Again, the primary contaminant is the release of Rn-222 in the process water circulating within and discharged from the restoration operations. The annual Rn-222 releases from the restoration well field can therefore be calculated from equations 2 and 3.

6.3.2 *Example In-Situ Recovery Radon Source Calculation*

The following presents an estimation of the radon source term at a "typical" ISL operation. For brevity, only those facilities expected to release radon are considered and include the following:

- One well field under development
- Two production well fields
- One restoration well field
- Main processing facility
- A holding pond
- Two radium-settling ponds

A satellite facility and irrigation plot is not considered. It is noted that the irrigation plot is also a source of radon; however, the concentration of Ra-226 in the water is limited. The example provided in Appendix D (NRC 2003) results in a surface soil concentration of 1.3 pCi/g above background or total Ra-226 concentration of 2.3 pCi/g (background concentration of 1.0 pCi/g of Ra-226), which would give rise to radon flux of about 2.3 pCi/m2-sec.

Generic parameters applicable to the entire facility:

- Yellow cake production rate = 520 metric tons per years (MT/yr)
- Average ore activity of U-238 sand each progeny in secular equilibrium = 280 pCi/g
- Ore porosity = 0.28
- Ore density = 1.8 g/cm^3

Considering the different wells fields separately leads to the following:

<u>One Well Field Under Development</u>

- The parameters selected for this well field are:
- Number of new wells peak year = 600
- Each well "covers" a 10 m × 10 m area = 100 m^2
- Number of new wells per mud pit =12
- Number of mud pits =50
- 1.6×10^4 L/d
- Drill hole diameter = 8 in
- Average ore material per well = 2.9×10^5 g
- Total ore material in mud pit per year = 3.5×10^6 g
- Average storage time of ore grade waste in mud pits = 12 d
- Radon emanating power = 0.25

Using equation 1 (Rn$_{nw}$ = 10^{-12} E L [Ra] T M N) and substituting leads to the following:

$$Rn_{nw} = 0.027 \text{ Ci/yr}$$

The annual radon flux is estimated by dividing the total emission rate by the area under development:

$$60,000 \text{ m}^2 = 0.0143 \text{ pCi/m}^2\text{-sec}$$

<u>Two Production Well Fields</u>

The parameters selected for the hypothetical production well fields are as follows:

Operating Parameter	Well Field 1	Well Field 2
Operating days per year	365 d	365 d
Active ore body dimensions:		
Peak area per year to be mined	50,000m^2	55,000m^2
Ave thickness of ore body	3 m	5 m
Total flow volume in circulation	4.2×10^7 L	7.7×10^7 L
Facility (IX) parameters:		
Dimension/capacity of resin column	3,500 gal	3,500 gal
Resin porosity	0.4	0.4
Number loaded resin unloading per day	3	3

Operating Parameter	Well Field 1	Well Field 2
Water discharge rate from unloading:		
IX column	1.6×10^4 L/d	1.6×10^4 L/d
Total wastewater purge rate	5.5×10^5 L/d (100gpm)	5.5×10^5 L/d (100gpm)
Fraction radon in circulating water	0.8	0.8
Rate of radon venting during circulating	0.01/d	0.01/d

The radon concentration in the circulating water is calculated using equation 3:

$$C_{Rn} = \frac{Sf}{((L+v)V+Fp+Fl)}$$

Substituting both sets of parameters leads to the following:

For well field 1, $C_{Rn} = 3.2 \times 10^5$ pCi/L; for well field 2, $C_{Rn} = 3.3 \times 10^5$ pCi/L

Substituting these values in equations 4, 5 and 6 leads to the following radon emission estimates

Radon Emission Contributions	Well Field 1	Well Field 2
Rn_w –Release rate from "purge" (settling pond)	64 Ci/yr	66 Ci/yr
Rn_v-Release rate from gas venting and leakage during circulation	49 Ci/yr	93 Ci/yr
Rn_x-Release from IX unloading	1.9 Ci/yr	1.9 Ci/yr
Total release rate	115 Ci/yr	161 Ci/yr

The parameters selected for the hypothetical restoration well field are as follows:

Restoration Well Field
Expected restoration operation time = 7years
Operating days per year = 240 d
Area per year to be restored = 100,000 m^2
Average thickness of ore body = 5 m
Total flow volume in circulation = $100000 \times 5 \times 0.28 = 1.4 \times 10^8$ L
Total treated water purge rates = 1.1×10^6 L/d
Fraction of radon source carried by circulating water = 0.8
Rate of radon venting during circulation = 0.01/d

The radon concentration in the circulating water is as follows:

$$C_{Rn} = \frac{Sf}{((L+v)V+Fp+Fl)}$$

$$=3.3 \times 10^5 \text{ pCi/L}$$

The radon released rate from purge water into the settling pond is as follows:

$$Rn_w = 3.65 \times 10^{-10} \, C_{Rn} \, Fp = 87 \text{ Ci/yr}$$

The radon release rate form gas venting and leaking during circulation is as follows:

$$Rn_v = 3.65 \times 10^{-10} \, v \, C_{Rn} \, V = 197 \text{ Ci/yr}$$

The total radon released from the restoration field is 197 Ci/yr.

The radon flux from the irrigation plot is straightforward and was estimated as 1.3 pCi/m^2-sec, not much over background.

6.3.3 Decommissioning of Well Fields and Evaporation Ponds

Evaporation ponds are typically lined temporary ponds with areas of 3 to 5 acres (10,000 to 20,000 m^2). They are designed with sufficient freeboard to contain the waste water from the process and any natural precipitation. As they are wet, they do not represent a source term for either radon or radioactive particulates. Radon sources are also a function of the thickness of the soils generating the gas and containing the parent radium. The quantity of sediment (thickness) that eventually is deposited on the bottom of the pond is much less than that in tailings pond, and the generated radon is less and is covered by water. However, in many uranium production areas, the water balance favors evaporation. Should the ponds begin to dry out, they are sprayed to keep the surface wet, eliminating particulates and minimizing radon. On closure of the pond, the material is typically excavated and disposed of as by-product 11(e02) materials (NRC 2003).

Upon completion of groundwater restoration, the operator is required to decommission all well field piping and distribution systems, processing equipment, waste processing, and handling systems (including evaporation pond liners and resides) and to prepare it for appropriate disposal. Currently, under NRC guidelines, all residues and waste materials are treated as being uranium byproducts and disposed in licensed tailings impoundments. Radon emissions from well field piping and distribution networks and evaporation ponds have not been demonstrated to add significantly to the Rn-222 source term.

6.4   Discussion

As indicated in the prior calculations, the amount of radon released from the production well fields (115 Ci/yr and 161 Ci/yr) is greater than from the new production facility (0.027 Ci/yr) and comparable to that from the restoration well field (197 Ci/yr). The flux can be found by assuming the "foot print" of the area releasing radon is approximately equal to the area to be mined per year for the production well field and the area to be restored for the restoration well field. It is also assumed that the ponds in both cases have an area which is a few percent of the area to be mined or restored and can be ignored during the operational life of the facility. At the time of closure, waste from the evaporation ponds must be disposed of as if it were tailings waste. The NRC's preference is that it be disposed of at existing conventional tailings

impoundments, but where that is not feasible it may be disposed of on-site. The fluxes are just the total radon release per year divided by the area. They are presented in Table 6.

Table 6. Estimated Rn-222 Releases from an ISL Facility

Process Being Considered	Area (m$^{2)}$)	Annual Radon Release (Ci/yr)	Average Radon Flux pCi/m^2-sec
New Well Field	60000	0.027	0.0143
Production Well Field 1	50000	115	73
Production Well Field 2	55000	161	93
Restoration Well Field	100000	197	63

While these radon fluxes are three to four times greater than that allowed in conventional tailing facilities (20 pCi/m^2-sec), they are conservative. For the production well fields, they do not include the area of the ponds (purge water source term) or the area of the processing facility (IX unloading source term). Also, in the case of the restoration well field, they are transient releases and revert to background on completion of the restoration.

6.5   Next Step

The prior discussion indicates some emission of radon is estimated to be released from in-situ leach operations primarily during the operations period and during restoration. These releases could have an impact on the surrounding population. The estimated radon release is based on a number of parameters, many of which are assumed to be "best estimates" in and of themselves. As a start, it is suggested that a critical review of the parameters be undertaken to determine which are most susceptible to large variations and of these, which can be documented by actual or proposed but designed operations.

7.0   REFERENCES

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40 CFR 61, Title 40, *Part 61: National Emission Standards for Hazardous Air Pollutants, Subpart W: National Emissions Standards for Radon Emissions from Operating Mill Tailing*s.

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