Uranium Study:
Air Quality Monitoring Report
Commonwealth of Virginia

Department of Environmental Quality
Department of Mines, Minerals and Energy

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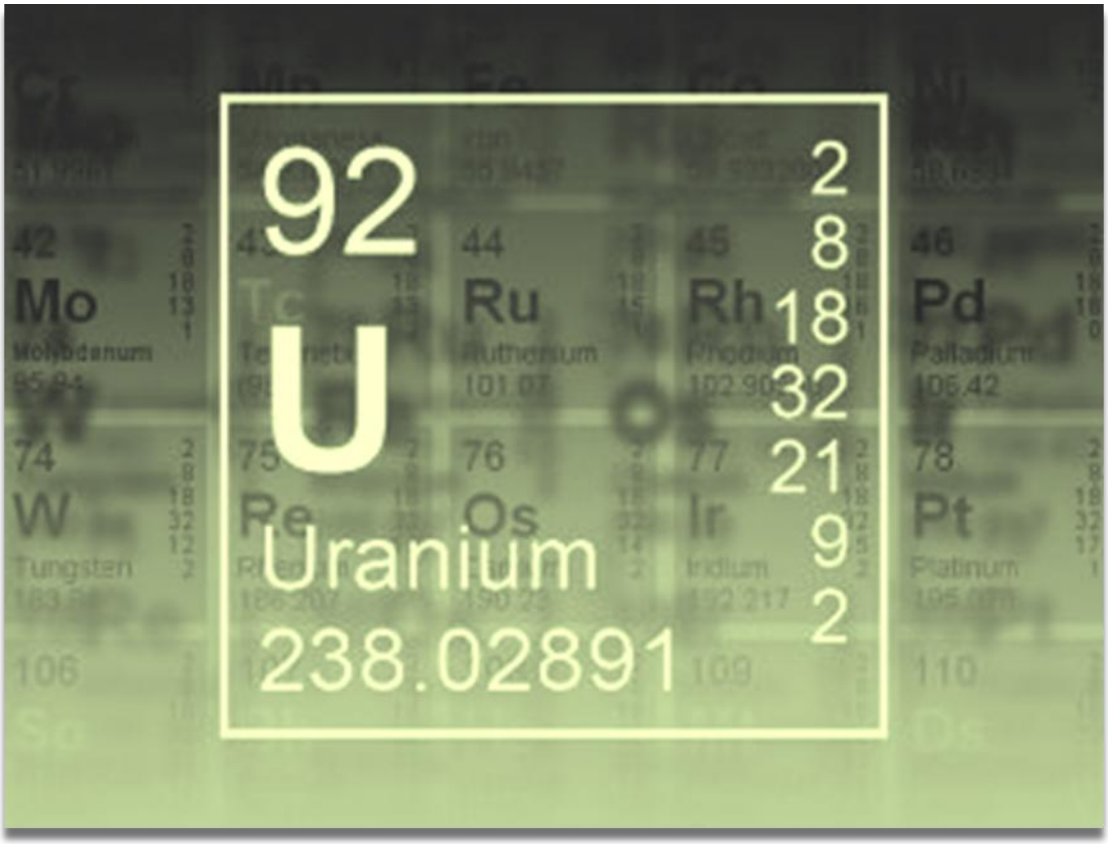

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Glossary

ACL	Alternative Concentration Limit
AQD	Air Quality Division
BACT	Best Available Control Technology
BMP	Best Management Practices
CCR	Colorado Code of Regulations
CDPHE	Colorado Department of Public Health and the Environment
CFR	Code of Federal Regulations
CHI	Cumulative Hydrologic Impact
COC	Constituents of Concern
COD	Chemical Oxygen Demand
CRS	Colorado Revised Statutes
CWA	Clean Water Act
DMME	Department of Mines, Minerals, and Energy
DMO	Designated Mining Operation
DOGAMI	Department of Geology and Mineral Industries
DOW	Division of Wildlife
DRMS	Colorado Division of Reclamation, Mining, and Safety
EA	Environmental Assessment
Eh	Oxidation/reduction potential
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EQA	Environmental Quality Act
FEM	Federal Equipment Methods
FRM	Federal Reference Methods
HAPs	Hazardous Air Pollutant
HUT	Hydrologic Unit Testing
IDEQ	Idaho Department of Environmental Quality
ISL	In Situ Leaching
ISR	In Situ Recovery
MCL	Maximum Contaminant Level
MLRA	Mined Land Reclamation Act
MOU	Memorandum of Understanding
NAAQS	National Ambient Air Quality Standards
NEPA	National Environmental Policy Act
NESHAP	National Emission Standards for Hazardous Air Pollutants
NPDES	National Pollutant Discharge Elimination System
NRC	Nuclear Regulatory Commission
NSPS	New Source Performance Standards
NSR	New Source Review
NUREG	Nuclear Regulatory Guide
PSD	Prevention of Significant Deterioration
OAR	Oregon Administrative Rule
ODOE	Oregon Department of Energy
ODEQ	Oregon Department of Environmental Quality

ORS	Oregon Revised Statute
OSM	Office of Surface Mining Reclamation and Enforcement
pCi/L	Picocuries per Liter
PHC	Probable Hydrologic Consequences
PMF	Permanent, Maintenance-Free (Diversion Design)
QA/QC	Quality Assurance and Quality Control
R&R	Rules and Regulations
RCRA	Resource Conservation and Recovery Act
RFP	Request for Proposal
RMEI	Reasonably Maximally Exposed Individual
SDWA	Safe Drinking Water Act
SIP	State's Implementation Plan
SLAMS	State and Local Air Monitoring Stations
SPCC	Spill Prevention, Control, and Countermeasure
SWPPP	Storm Water Pollution Prevention Plan
TDS	Total Dissolved Solids
UIC	Underground Injection Control
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act
USC	United States Code
USGS	United States Geological Survey
UWG	Uranium Working Group
VAC	Virginia Administrative Code
VDEQ	Virginia Department of Environmental Quality
WDEQ	Wyoming Division of Environmental Quality
WLQD	Land Quality Division
WPCF	Water Pollution Control Facility
WQD	Water Quality Division
WS	Wyoming Statute

1.0 Introduction

The Commonwealth of Virginia (Virginia), Department of Environmental Quality (VDEQ) has contracted with Wright Environmental Services, Inc. to provide Virginia's Uranium Working Group with information addressing air monitoring related to uranium mining and milling. The primary focus of this report is on monitoring radioparticulates and radon from uranium mining and milling projects, as these are programs that Virginia does not have in place and for which it does not have as much experience. This report emphasizes published material that provides a basis for consideration of systems, methods, techniques, and equipment should Virginia need to develop a regulatory structure for regulation of these activities. This report only briefly summarizes Environmental Protection Agency (EPA) programs under the Clean Air Act, which are already implemented by VDEQ/Air Quality Division (AQD) and for which they have extensive experience and expertise.

Air quality monitoring programs for uranium mines and mills are addressed by several Federal Programs administrated by the Nuclear Regulatory Commission (NRC) and EPA. In some cases, these agencies have delegated authority over these monitoring programs to state agencies. NRC air quality monitoring programs address uranium mills, while EPA air quality monitoring programs address uranium mines.

Air emissions from uranium processing, including uranium mills, heap leach facilities and in situ recovery (ISR) recovery facilities, are regulated by the NRC. The NRC regulatory program focuses on public health protection from radionuclides, primarily in the form of radioparticulates (airborne particles like fugitive dust containing radionuclides) as well as radon gas and its decay products, though direct gamma radiation is also monitored. NRC air monitoring programs do not address uranium mine air emissions, which are addressed by the EPA.

An exception to this jurisdictional division would be if a mine were processing mine wastes (e.g., removing uranium from mine dewatering effluent), and recovering significant quantities of source material (> 0.05% uranium), in which case that activity would be licensed by the NRC or Agreement State. In this case, NRC or the Agreement State would regulate radioactive air emissions from those licensed activities at the mine site.

Air emissions from uranium mines, whether underground, surface or in-situ, are regulated by the EPA. The Clean Air Act (CAA) gives EPA the authority to regulate emissions of both "conventional" (called "criteria") pollutants, like PM_{10} (particulate matter less than 10 microns) and hazardous pollutants, such as radon. Both of these air pollutants are emitted by uranium extraction and beneficiation activities. EPA authority under the CAA encompasses National Ambient Air Quality Standards (NAAQS), New Source Performance Standards (NSPS),

Prevention of Significant Deterioration (PSD), National Emission Standards for Hazardous Air Pollutants (NESHAP), and New Source Review (NSR).

There currently exists a disparity in state and federal programs regarding how air emissions from uranium mills, open pit uranium mines and underground uranium mines are monitored. While the NRC requires monitoring and modeling of public exposures to radioparticulates, radon and direct gamma radiation from uranium mills, states generally do not require monitoring or modeling of public exposures to radioparticulates from either open pit or underground uranium mines. Through 40 CFR Part 61, Subpart B (National Emission Standards for Radon Emissions From Underground Uranium Mines), EPA requires monitoring of radon emissions from underground mine vents and modeling of public exposure from these vents to ensure no public dose exceeds 10 mrem/yr from those emissions. However, EPA does not have specific regulations for radon emissions from open pit uranium mines.

This report addresses current air quality monitoring systems in Section 2, and the release of particulates from mining and milling activities in Section 3. Section 4 of this report discusses the adequacy of the existing National Emissions Standards for Hazardous Air Pollutants (NESHAP) while Section 5 addresses the emission of radon from mine and mill materials and Section 6 addresses the potential for radon release from liquid bodies such as mine dewatering activities and evaporation ponds. Taken together and in context with the other components of this Uranium Study, these topics will inform Virginia of appropriate air quality monitoring practices for uranium mines and mills.

1.1 Procurement Summary

On March 2, 2012, the Department of Environmental Quality issued the request for proposal (RFP) # 12-06-PJ (Uranium Study). The purpose of the procurement was to acquire contractor services to provide information and expert analysis of uranium mining and milling issues in Virginia relevant to the statutory jurisdictions of VDEQ and Virginia Department of Mines, Minerals and Energy (DMME). Sealed bids were submitted by April 3, 2012 and contract EP8811027 was awarded on May 21, 2012.

The Contract identifies two major work Tasks (A and B). Work Task A involves the development of an initial report based on 1) a review of studies related to uranium mining and milling in Virginia, 2) a comparison of other existing regulatory programs for uranium mining and milling and 3) a review of emerging standards from international organizations. This initial report is developed in response to Work Task A.

Work Task B involves providing ongoing technical advice and assistance to the Uranium Working Group (UWG). Work Task B will result in a series of interim reports, analyzing a

range of issues identified in the RFP, as well as other issues identified by the UWG, and will provide additional detail to the issues and recommendations addressed in this initial report.

1.2 Purpose and Objective

The purpose of this Air Quality Monitoring Report is to respond to Work Task B.2.c in Contract EP881027, which includes:

- Evaluation of air quality monitoring technologies
- Release of particulate matter from wind erosion of ore stockpiles, waste rock, mine tailings, processing facilities, and mine blasting
- Mobilization of contaminants
- Adequacy of the U.S. Environmental Protection Agency's National Emissions Standards for Hazardous Air Pollutants (NESHAP) for radon
- The emission of radon from waste rock piles, ore stockpiles and windblown particulates
- The potential for the release of radon from evaporation ponds and tailings impoundments
- The release of radon during dewatering activities

The objective of this report is to support the UWG in developing a policy analysis and regulatory framework for the Virginia General Assembly to consider as part of their decision making regarding the uranium mining moratorium.

2.0 Review of Current Air Quality Monitoring Systems

This section briefly describes the air monitoring programs administrated by EPA and NRC related to uranium mining and milling and discusses air quality monitoring equipment.
As stated previously, the NRC regulates air emissions from uranium mills (including heap leach facilities) and ISR uranium recovery facilities. The NRC does not regulate air emissions from uranium mines.

Air emissions from both mines and mills, including criteria and hazardous air pollutants as well as fugitive dust, are regulated by EPA and addressed by the Clean Air Act, Fugitive dust is measured by airborne particulates with diameters of 10 micrometers or less (PM_{10}) as well as finer particles with diameters of 2.5 micrometers or less ($PM_{2.5}$), which new studies suggest may cause serious adverse health effects if chronically inhaled. EPA also regulates radon emissions from uranium mill tailings and from underground mines through the regulations in 40 CFR Part 61, Subparts W and B, respectively. There are no radon-specific regulations for radon from open pit uranium mines.

2.1 EPA, NESHAPs and The Clean Air Act

EPA regulates a list of criteria pollutants, which include particulate matter (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ozone and lead under 40 CFR Part 50. Monitoring for criteria pollutants is regulated primarily through two programs: State and Local Air Monitoring Stations (SLAMS) and Prevention of Significant Deterioration (PSD) stations. EPA also regulates hazardous air pollutants (HAPs) under 40 CFR Part 63. EPA regulates radon emissions under 40 CFR Part 61.

Federal air quality regulations include both primary and secondary standards for ambient concentrations of criteria pollutants. Primary standards provide public health protection, including protecting the health of sensitive populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

PSD regulations stem from the Clean Air Act Amendments of 1977. PSD is designed to protect public health and welfare, and to preserve, protect, and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historic value. The goal of this program is to prevent significant deterioration of air quality in areas that meet the NAAQS. Areas in the U.S. have been classified in two categories for the purpose of this program. Class I areas include national wilderness areas, parks and memorial parks of a certain size, and international parks. In these areas, the maximum allowable increase of any criteria pollutant is significantly lower than

in Class II areas, which includes most of the country. The intent of PSD is to insure that economic growth will occur in a manner consistent with the preservation of existing clean air resources.

New Source Performance Standards (NSPS) regulations, authorized under Section 111 of the Clean Air Act, are found in 40 CFR Part 60. EPA has developed technology based performance standards which apply to specific categories of stationary sources. The NSPS apply to new, modified and reconstructed facilities in specific source categories referred to as "named sources." Uranium mining and milling operations do not qualify as named sources, although certain emitting units within these facilities may qualify (e.g., stationary internal combustion engines such as diesel generators).

40 CFR Part 51 specifies the process by which EPA can delegate certain federal air quality regulations to the states. Under specific delegation agreements, some states have EPA approval to enforce NAAQS, NSPS, National Emission Standards for Hazardous Air Pollutants (NESHAP) and NSR. Likewise, EPA can enforce certain state regulations that EPA approved under the state's implementation plan (SIP) to meet the NAAQS. With EPA approval, some states have enhanced portions of their regulatory programs beyond the minimum federal requirements. For example, Idaho Department of Environmental Quality (IDEQ) requires construction and Tier II operating permits for minor sources of criteria pollutant emissions (IDEQ, 2011), including hard-rock mining operations such as the Blackfoot Bridge phosphate mine. These permitting actions generally require air modeling. Wyoming Department of Environmental Quality (WDEQ) requires modeling for surface mine permitting, even though most of the mines are also minor sources (WDEQ/AQD, 2010). Wyoming enforces the use of Best Available Control Technology (BACT) for fugitive dust control at all surface mines. Wyoming also retained the annual average ambient PM10 standard of 50 $\mu g/m^3$ even though it was rescinded by EPA. Montana administers surface mine air quality permitting and regulation in a manner similar to Wyoming. Colorado Department of Public Health and Environment (CDPHE) required baseline air quality monitoring and modeling for the recently permitted Pinon Ridge uranium mine and mill, classified as a minor source (CDPHE, 2009). EPA retains air quality program authority in federal actions such as assessments under the National Environmental Policy Act (NEPA) for uranium mining and milling Environmental Impact Statements (EIS) and Environmental Assessments (EA). Uranium mining and milling operations proposed on federal lands are therefore subject to EPA review.

EPA has authority to regulate radon gas emissions under 40 CFR Part 61 (NESHAP), though in some cases the EPA has delegated this authority to certain states (i.e., Utah). Virginia has not been delegated this authority. 40 Part 61 subpart A (General Provisions) lists the pollutants addressed by this regulation and includes radionuclides. Subpart B (National Emission Standards for Radon Emissions from Underground Uranium Mines) of 40 Part 61 addresses

radon-222 from underground uranium mines and limits doses to the public from radon-222 to no more than 10mrem/yr. Subpart W (National Emission Standards for Radon Emissions From Operating Mill Tailings) applies to radon from tailings and limits radon-222 flux to 20 pCi/m^2-sec from an existing tailings pile. Subpart T (National Emission Standards for Radon Emissions From the Disposal of Uranium Mill Tailings) applies only to uranium mill tailings "*…that are listed in, or designated by the Secretary of Energy under title I of the Uranium Mill Tailings Radiation Control Act of 1978,…*". Title I of Uranium Mill Tailings Radiation Control Act (UMTRCA) addresses mills and tailing from abandoned sites and under the ownership by the US Department of Energy, of which there are none in Virginia. This subpart explicitly excludes new mills and tailings sites, which are addressed under Title II of UMTRCA.

Currently, Part 61 does not address open-pit uranium mines. Only mill tailings are explicitly covered under NESHAP Subpart W. Subpart W also describes the only two approved tailings disposal design and practices:
"*(1) Phased disposal in lined tailings impoundments that are no more than 40 acres in area and meet the requirements of 40 CFR 192.32(a) as determined by the Nuclear Regulatory Commission. The owner or operator shall have no more than two impoundments, including existing impoundments, in operation at any one time.*

(2) Continuous disposal of tailings such that tailings are dewatered and immediately disposed with no more than 10 acres uncovered at any time and operated in accordance with §192.32(a) as determined by the Nuclear Regulatory Commission."

EPA is currently reviewing and developing revisions to the Part 61 requirements for uranium facilities. Draft rulemaking is planned for public comment in September of 2012.

It should be noted that EPA has issued NESHAP "construction approvals" under Subpart W to uranium facilities in Colorado and Wyoming that broadly interpret the definitions in the existing rule to include evaporation ponds and holding ponds. For example, the proposed Pinon Ridge uranium mill near Naturita Colorado has been issued NESHAP Construction Approval that states: "*The tailing cells and evaporation ponds at the Mill are regulated pursuant to 40 C.F.R. Part 61…The requirements of Subpart W specifically apply to the structures at the uranium recovery facility that are used to 'manage' or contain the uranium byproduct or tailings. At the Mill, these facilities are the tailings cell and evaporation ponds.*" Similarly, the Lost Creek ISR facility in Wyoming has been issued a NESHAP Construction Approval that states: "*The requirements of Subpart W specifically apply to the structures at the uranium recovery facility that are used to 'manage' or contain the uranium byproduct or tailings. At Lost Creek, these facilities are the holding ponds.*"

Prior to the early 2000's, EPA never required monitoring of process or evaporation pond radon emissions because it was generally understood that radon emissions from these types of facilities were very low (i.e., on the order of background levels) and that measurement of these emissions was problematic. Further, the NRC has strict radiation and radon exposure limits at the licensed boundary of a uranium recovery facility (10 CFR Part 20.1301 and 1302) that makes the minor radon emissions from the surface of liquid waste ponds in licensed areas restricted to public access essentially immaterial to ensuring public health. However, EPA has recently renewed its efforts to regulate sources other than conventional mill tailings and the draft rulemaking should indicate EPA's latest thinking on this subject. Any uranium mine or mill developed in Virginia would have to comply with the most current EPA standards for radon-222 emissions and monitoring, whether it was administered by EPA or if Virginia was delegated this authority. If Virginia wished to administrate standards more stringent than EPA's under 40 CFR Part 61 it would have to be delegated the authority for this program and undertake additional legislative rulemaking to adopt more stringent standards.

In 2009, EPA issued a rule requiring greenhouse gas reporting for certain industrial facilities (40 CFR Parts 86, 87, 89). In 2010, EPA initiated reporting requirements for greenhouse gas emissions from underground coal mines (40 CFR Part 98). Neither rule applies to uranium mining and milling facilities, unless those facilities include extremely large and stationary fossil fuel combustion sources.

2.2 NRC Requirements and Guidance

NRC air emissions requirements are identified in Criterion 6 and Criterion 8 of 10 CFR Part 40, Appendix A. In summary, these criteria generally state:

- Criterion 6
  - Byproduct material must be stabilized "*….in accordance with a design which provides reasonable assurance of control of radiological hazards to (i) be effective for 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years, and (ii) limit releases of radon-222 from uranium byproduct materials, and radon-220 from thorium byproduct materials, to the atmosphere so as not to exceed an average release rate of 20 picocuries per square meter per second (pCi/m^{2}s) to the extent practicable throughout the effective design life…*"
  - The licensee must test the final tailings radon barrier to ensure it is and can perform to this standard before placing the final erosion protection barrier.
- Criterion 8
  - Milling operations must be conducted so that all airborne effluent releases are reduced to levels as low as is reasonably achievable (ALARA), primarily by

means of emission controls through the use of institutional controls, "…*such as extending the site boundary and exclusion area, may be employed to ensure that offsite exposure limits are met, but only after all practicable measures have been taken to control emissions at the source*". Phased disposal and covering of the tailing should be considered as part of the effort to reduce particulate emissions to ALARA.

- "*The greatest potential sources of offsite radiation exposure (aside from radon exposure) are dusting from dry surfaces of the tailings disposal area not covered by tailings solution and emissions from yellowcake drying and packaging operations.*" However, the standard use of vacuum driers for production of yellow cake in modern uranium recovery facilities (mills and ISR facilities) as essentially eliminated radioparticulate emissions from driers.
- Dust control for ore pads and tailings not covered by "*…standing liquids must be wetted or chemically stabilized to prevent or minimize blowing and dusting to the maximum extent reasonably achievable.*" Exception to this requirement may be sought by a licensee if the tailings disposal design does not expose the tailings surface to the wind, though granting of this exception would be on a case by case basis.
- Additional requirements regarding monitoring of emissions control equipment are stated.

Monitoring requirements include both baseline (pre-operational) and operational uranium recovery phases. Monitoring for radionuclide air concentrations is described in Regulatory Guide 4.14 as follows:

"*Air particulate samples should be collected continuously at a minimum of three locations at or near the site boundary. If there are residences or occupiable structures within 10 kilometers of the site, a continuous outdoor air sample should be collected at or near the structure with the highest predicted airborne radionuclide concentration due to milling operations and at or near at least one structure in any area where predicted doses exceed 5 percent of the standards in 40 CFR Part 190. A continuous air sample should also be collected at a remote location that represents background conditions at the mill site; in general, a suitable location would be in the least prevalent wind direction from the site and unaffected by mining or other milling operations. Normally, filters for continuous ambient air samples are changed weekly or more often as required by dust loading.*"

Additional guidance is provided for determining the best locations for the air samplers:

"*The sampling locations should be determined according to the projected site and milling operation. Preoperational sampling locations should be the same as operational locations. The*

following factors should be considered in determining the sampling locations: (1) average meteorological conditions (wind speed, wind direction, atmospheric stability), (2) prevailing wind direction, (3) site boundaries nearest to mill, ore piles, and tailings piles, (4) direction of nearest occupiable structure ..., and (5) location of estimated maximum concentrations of radioactive materials. Samples should be collected continuously, or for at least one week per month, for analysis of radon-222. The sampling locations should be the same as those for the continuous air particulate samples."

NRC Regulatory Guide 4.14 also provides specific details regarding the radionuclides to be monitored, the lower limits of detection for analysis of each radionuclide and the frequency of monitoring.

Given the existing NRC and EPA guidance and anticipated regulatory guidance changes currently under development by NRC, the following sections focus on equipment and systems recommended for uranium mine or mill air quality monitoring. These recommendations are based on a combination of review of recent U.S. and international publications, standards and guidance, current and anticipated regulatory environment, and on our own collective experience.

The most complex situation, in terms of environmental air concentrations associated with uranium extraction operations, occurs when uranium mining, milling and tailings operations are essentially co-located (that is, when all occur within the same local area). Releases of radioactive and other hazardous materials from all three will essentially be additive and indistinguishable when monitored in the offsite environment: the radionuclides released are identical for all three facility types. Where facilities are co-located, monitoring should occur using a single system of monitoring equipment, to allow simple comparisons of all results.

Consequently, this report focuses on recommendations concerning the best systems and equipment to be used in the performance of such "integrated" monitoring (simultaneous monitoring of environmental concentrations of materials released from an area containing mine, mill and tailings facilities). Environmental monitoring systems developed for geographically independent facilities will differ only with respect to the number of air samplers installed around each perimeter. Consideration is also given to potential monitoring changes that may be recommended by regulatory authorities in the near future.

2.3 Current Air Quality Monitoring Systems

The following section summarizes the technical requirements for monitoring associated with uranium mining and milling projects, focusing on meteorological, particulate, radioparticulate and radon monitoring. Criteria and hazardous air pollutants must be characterized for air

permitting under the Clean Air Act but are not necessarily monitored, and may be rather conservatively modeled based on site operational sources. Table 2.1 summarizes the primary air emissions sources from typical uranium mines and mills.

Due to the prevalence of natural radon and the importance of understanding this particular constituent, a more in depth discussion of radon is in detail in Section 4.0 of this report.

2.3.1 Technical Requirements

Technical requirements for meteorological and air quality monitoring are developed by both EPA and NRC. A sound understanding of wind speed, direction, rainfall, evaporation parameters and other variables influencing atmospheric dispersion and deposition is necessary for acquiring an air quality permit for uranium mining and milling activities as well as for the development and operation of a uranium extraction facility's environmental monitoring and reporting system.

NRC Regulatory Guide 4.14 references a number of authorities, noted in this report's bibliography, regarding the specification of an adequate meteorological stations.
The reference "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (EPA, 2000) also provides guidance for the collection and processing of meteorological data for general use in air quality modeling applications. Information is provided concerning the *in situ* monitoring of primary meteorological variables for remote sensing of winds, temperature, and humidity, and for processing of derived meteorological variables such as stability, mixing height, and turbulence. The reference supports most categories of air quality models including: steady-state, non-steady-state, Gaussian, and non- Gaussian models, and notes that one of the most important aspects covered is the selection of a representative monitoring location, and discusses the general insufficiency of relying on airport data alone.

Additional reading is recommended by the EPA to provide detailed background: "Guideline on Air Quality Models" Appendix W to 40 CFR Part 5; "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV, Meteorological Measurements"; "On-site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources"; "Standard for Determining Meteorological Information at Nuclear Power Sites"; "Revision to the Guideline on Air Quality Models" Appendix W to 40 CFR Part 51.

To support modeling, uranium facilities should monitor horizontal wind speed and direction, standard deviation of horizontal wind speed, ambient temperature and temperature gradient, precipitation, relative humidity, and solar radiation. Some of these parameters contribute to the calculation of joint frequency distributions, which characterize wind patterns by wind speed

class, wind direction, and atmospheric stability class. Additional monitored parameters may include atmospheric pressure, evaporation, vertical wind speed, and cloud cover. Some of these parameters support more sophisticated modeling that incorporates atmospheric turbulence and site-specific mixing heights. An approved meteorological monitoring plan should guide the baseline monitoring program. This plan should address parameters to be monitored, data acquisition, validation and quality assurance, and reporting.

EPA requirements for meteorological monitoring are found in "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (EPA, 2000) and "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV, Meteorological Measurements" (EPA, 2008a).NRC requirements are found in NRC Regulatory Guide 3.63, "Onsite Meteorological Measurement Program for Uranium Recovery Facilities – Data Acquisition and Reporting" (NRC, 1988).

- Parameters needed – Both agencies recommend monitoring for hourly average wind speed, wind direction, vertical wind speed, sigma theta, temperature, temperature gradient, relative humidity, solar radiation and precipitation. NRC also recommends hourly evaporation measurements. EPA requires a minimum of 3 years of hourly meteorological data to support short-term impact analysis (averaging periods such as 24 hours). NRC requires a minimum of 1 year of hourly meteorological data, represented in the MILDOS model as an annual joint frequency or STAR distribution. MILDOS does not model hourly meteorology.
- Instrumentation precision/accuracy – EPA specifications for meteorological monitoring instruments tend to be slightly more restrictive than NRC specifications. NRC specifies a wind speed accuracy of 10% for speeds over 5 mph, whereas the corresponding EPA specification is 1%. Wind direction accuracy is ±5º for NRC and ±3º for EPA. Precipitation accuracy is 0.5% for EPA and 10% for NRC. Relative humidity specifications are similar. Unlike EPA, NRC Regulatory Guide 3.63 does not provide specifications for temperature measurements. Both agencies recommend a semi-annual calibration frequency for all instruments.
- NRC does not identify vertical wind speed as necessary primarily because the MILDOS radiation exposure assessment computer code, which uses the site meteorological data, is not designed to account for that parameter. NRC does suggest instrumentation at two elevations (e.g. 30 m and 10 m) to establish atmospheric stability classification (NRC Regulatory Guide 3.63). However, EPA does require assessment of vertical wind speeds.

In the years since the NRC Regulatory Guide 3.63 was published, developments in the fields of meteorological monitoring and the modeling of hazardous materials atmospheric transport, dispersion, deposition, uptake by and to humans, and the calculation of associated risk have changed significantly. For example, current environmental transport codes have capabilities that greatly exceed those of the MILDOS code now in use in the uranium regulatory context. Models

now may employ meteorological data from several sources, plus terrain data, to provide better pre-licensing estimates of environmental air particulate concentrations associated with releases from a proposed uranium extraction facility.

For example, the AERMOD atmospheric dispersion modeling system, developed by the American Meteorological Society and the EPA, handles flat or complex, rural or urban terrain and includes algorithms for building effects and plume penetration of inversions. AERMOD uses Gaussian dispersion for low-turbulence atmospheric conditions, and non-Gaussian dispersion for high turbulence. AERMOD employs a meteorological data preprocessor that accepts surface meteorological data, upper air soundings and data from on-site instruments. It uses a terrain preprocessor to enhance calculation of the behavior of near-surface plumes. In the long run, an eventual conversion of regulatory requirements from the currently accepted MILDOS atmospheric transport model to a more current model should lead to better prediction of a facility's impacts, especially in complex terrain. Selection of an alternative model is probably best handled at the NRC level, since it would involve changes affecting licensing over the entire U.S. It is possible that the NRC is considering such a change currently, while it revises Regulatory Guide 4.14.

Even given the current modeling systems in use for estimation of air concentrations associated with releases from a uranium extraction facility, the capabilities and thus specifications associated with current meteorological stations have changed drastically. Solar-powered systems are now the norm, as are instruments capable of providing far better low-wind-speed and dispersion data.

The following set of meteorological station specifications parallel those of recently installed systems at several new or pre-license, proposed facilities in the western U.S.

2.3.1.1 Meteorological Monitoring

Baseline meteorological monitoring for uranium mining and milling facilities serves two primary purposes: to support the locations of air quality samplers and to enable the modeling of atmospheric pollutant dispersion. Operational monitoring serves to verify proper sampler placement, interpret pollutant monitoring results and refine dispersion modeling exercises as the mining or milling operation advances. Key issues to be resolved for uranium facilities are the tower height, the meteorological parameters to monitor, instrument performance specifications and quality assurance procedures. For on-site baseline monitoring it is important to site meteorological monitoring stations at locations that represent as closely as possible the long-term meteorological characteristics of the area of interest. The monitoring instruments should be situated as close as possible and in the same meteorological regime as the emission sources for which monitoring is being conducted. Tower height is generally chosen to represent the plume

height of the principal source(s) for modeling purposes. For surface mining activities, near-ground-level sources generally dominate, whereas milling activities may include elevated sources such as stacks and vents. For a mine with milling facilities, wind monitors may therefore be positioned at multiple heights on the tower.

EPA provides guidance for locating meteorological monitoring stations and establishing the parameters to monitor in the "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (EPA, 2000). This reference also provides guidance for the collection and processing of meteorological data for general use in air quality modeling applications. Additional guidance related to instrument specifications and quality assurance is provided in the "Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements" (EPA, 2008a). NRC guidance for meteorological monitoring is provided in NRC Regulatory Guide 3.63 (NRC, 1988) and Regulatory Guide 4.14 references a number of authorities, noted in this report's bibliography, regarding the specification of an adequate meteorological stations.

To support modeling, uranium facilities should monitor wind speed and direction, vertical wind speed, standard deviation of horizontal wind speed, ambient temperature and temperature gradient, precipitation, relative humidity, and solar radiation. Some of these parameters contribute to the calculation of joint frequency distributions, which characterize wind patterns by wind speed class, wind direction, and atmospheric stability class. Additional monitored parameters may include atmospheric pressure, evaporation, and cloud cover. Some of these parameters support more sophisticated modeling that incorporates atmospheric turbulence and site-specific mixing heights. Most regulatory agencies require an approved meteorological monitoring plan prior to initiation of baseline monitoring. This plan should address the above issues, as well as data recording, acquisition, validation, and reporting.

Recommendation: require baseline and operational monitoring to support air sampler locations and, potentially, dispersion modeling.

2.3.1.2 Particulates

Ambient monitoring requirements are set forth in 40 CFR Part 58 Subpart C. For open-pit uranium mines, the dominant pollutant is particulate matter (PM_{10} and $PM_{2.5}$). 40 CFR Part 50 contains the applicable particulate standards. EPA and states with delegated authority administer particulate monitoring requirements through the SLAMS and PSD programs. 40 CFR Part 58, Appendix A outlines the major similarities and differences between these programs. Both programs require: (a) the development, documentation, and implementation of an approved quality system; (b) the assessment of data quality; (c) the use of federal reference, equivalent, or approved methods. The monitoring and quality assurance responsibilities for SLAMS rest with

the state or local agency, whereas for PSD they are assigned to the owner or operator seeking an air quality permit. The monitoring duration for SLAMS is indefinite, whereas for PSD the duration is usually 12 months for baseline monitoring (ongoing for operational monitoring). Whereas the reporting period for precision and accuracy data is on an annual or calendar quarter basis for SLAMS, it is on a continuing sampler quarter basis for PSD, since the monitoring might not commence at the beginning of a calendar quarter.

The principal source of particulate matter from uranium mines and mills is fugitive dust from unpaved roads, disturbed or open areas, blasting, storage piles, and crushing and screening operations, (see Table 2.1). Uranium facilities that monitor for air particulates may be subject to either the PSD or the SLAMS monitoring requirements, depending on the regulatory agency. The purpose of baseline monitoring is to determine the background air quality prior to being impacted by a proposed uranium facility. Operational monitoring measures facility impacts to demonstrate compliance (or noncompliance) with NAAQS. In special cases, monitoring with manual samplers may also provide a means to determine the mineral composition of dust particles through a variety of analytical techniques. Guidance for particulate monitoring is found in EPA's "Quality Assurance Handbook for Air Pollution Measurement Systems Volume II, Ambient Air Quality Monitoring Program," (EPA, 2008b). The QA Handbook covers project management, data acquisition, validation, reporting and usability, network design, sampling methods, sample handling, analytical methods, equipment calibration methods, and quality assurance.

Federal Reference Methods (FRM) and Federal Equivalent Methods (FEM) are detailed in 40 CFR Part 53. Manual air samplers, including high-volume and low-volume samplers, generally adhere to FRM requirements. Continuous, automated samplers such as certain Tapered Element Oscillating Microbalance (TEOM) and beta attenuation monitors (BAM) have obtained approval for FEM status. All of these technologies serve to monitor both PM_{10} and $PM_{2.5}$.

Requirements for particulate monitoring by federal reference methods are detailed in 40 CFR Part 50 Appendix J (PM_{10}) and Appendix L ($PM_{2.5}$). These methods address procedures for both ambient sample collection and gravimetric analysis. Methods for calculating ambient concentrations and determining NAAQS compliance are detailed in 40 CFR Part 50 Appendix K (PM_{10}) and Appendix N ($PM_{2.5}$). 40 CFR 50 Appendix O addresses the PM_{10}-$PM_{2.5}$ (PM-Coarse) reference method, although this program has not been implemented, does not currently have an ambient standard, and in any case exempts mining and agricultural operations. For FRM and FEM monitors used for NAAQS attainment or nonattainment determinations, quality assurance requirements of 40 CFR part 58 must be followed and are viewed by EPA as an indivisible element of a regulatory air quality monitoring program.

Siting of air particulate monitors is covered in 40 CFR Part 58 Appendix E. Monitor locations depend on monitoring objectives. Operational monitors are generally located in areas of anticipated maximum air quality impacts, normally directly downwind from the dominant emission source. For uranium facilities, the PSD program would typically require at least one upwind monitor and one downwind monitor. For manual samplers the monitoring network may include two collocated monitors for demonstrating instrument precision.

Uranium mines typically qualify as minor sources of criteria pollutants including particulate emissions (less than 250 tons per year of PM_{10}). The minor source designation relies on the exclusion of fugitive dust from the calculation of total PM_{10} emissions (40 CFR Part 52). Although no regulation under the CAA explicitly requires particulate monitoring for minor sources, some states either routinely require minor source monitoring, or, like Virginia, reserve discretionary authority to require it. States can also require opacity monitoring of particulate emission sources, from baghouses to truck dumps. Opacity monitoring is usually conducted according to EPA Method 9 or EPA Method 22.

Recommendation: Require baseline and operational monitoring to demonstrate compliance – especially given public concerns and the fact that air particulates can also host radionuclides.

2.3.1.3 Other Air Pollutants

HAPs and criteria pollutants other than particulate matter are not typically monitored at uranium mining and milling operations. Wyoming DEQ operates a network of NO_x monitors, some of which are located at surface coal mines, however, the state does not require the mines themselves to monitor for NO_x or other gaseous pollutants. Primary sources of NO_x emissions at surface mines are diesel powered equipment and blasting. HAP emissions from surface mines are generally negligible and rarely monitored. Emissions of Volatile Organic Compounds (VOCs) are also relatively small at surface and underground mines, although tailings ponds at uranium milling facilities can be significant sources of VOCs. The presence of both NO_x and VOCs in the atmosphere can lead to ozone formation. This is usually not a concern at mining and milling facilities. SO_2 and CO can be emitted at such facilities if they utilize diesel powered equipment, although the quantity of emissions is usually quite low. Emissions of lead are generally insignificant, although as a byproduct of radioactive decay, atmospheric lead can be present at uranium operations. Sampling for radioparticulates will detect the presence of lead.

2.3.1.4 Radioparticulates

Monitoring to determine the concentrations of specific radionuclides in air (particulates), as discussed in the NRC Regulatory Guide 4.14 (NRC, 1980), is performed by continuously

drawing air through a 47 mm diameter glass fiber filter, typically located at breathing zone height, open to the environment but protected from rainfall. Sufficient volume must be drawn to meet the Guide's Lower Limit of Detection for each nuclide (discussed later in this section). The filter is typically exchanged once per week, and the collection of filters from each sampling station is sent every three months to a laboratory certified to extract and analyze the total activity of each nuclide of interest. The lab divides that analysis result (e.g. uCi) by the total volume drawn through the monitor's filters during the quarter (mL), reporting air concentration in uCi/ml or similar units. Also reported are the results of the laboratory's quality assurance/quality control (QA/QC) program, using blanks and standards to qualify the extraction and analysis process results.

Blank filters may also be analyzed by the laboratory for contamination: 1) when a program is initiated, and 2) regularly thereafter. Significant uranium contamination in unused filters is uncommon but does occur occasionally.

The driver for NRC monitoring of uranium mill facilities has, since April 12, 1980, been Regulatory Guide 4.14. That guidance is currently being revised, according to recent discussions with NRC staff. The latest indication is that the revised version will be divided into three sections: conventional milling, heap leach milling and ISR. It is difficult to say how the atmospheric monitoring recommendations for each section of the new Guide may differ; drafts of the revision are not available for review as of August, 2012.

Early in the history of air monitoring for uranium mill sites and within the last 30 years, conventional air samplers were often operated using extended power cords or gasoline generators where reliable grid-based power was not economically or readily available. The problem of providing reliable power to the samplers, where power was not feasibly available, necessitated using short-period, repeated high-volume air sampling at the monitoring locations – a method that can provide adequate total air volume, but would not meet a Regulatory Guide specification for continuous environmental monitoring. "HiVol" sampling is useful in establishing a reasonable estimate of average concentration at a location, especially if sampling is performed often, and is randomized with respect to the time of sampling.

However, recent technological advances have allowed the application of reliable solar power to such sampling locations. For example, F&J Specialty Products has released a low-wattage air sampler capable of drawing 30 liters per minute (lpm), digitally controlled to automatically correct (within limits) for dust loading and other variables, capable of continuous operation for many months without repair, using brushless motors to avoid carbon dust release, with operational data collection capability (to SD card). This latter capability ensures that, in the event of off-normal operation or failure, a full record of total volume collected, time/date of failure, flow rate, voltage and other variables will be available.

Of these characteristics, the most important is the low-wattage pump. The F&J model DF-40L-8 draws 11 watts, immediately suggesting the development of a solar-powered continuous air particulate monitoring system. The F&J pump supports a flow rate adequate to meet NRC Regulatory Guide 4.14 requirements for the measurement of Th-230 (and the other uranium-chain nuclides of interest: natural uranium, Ra-226, Pb-210). Thirty lpm represents about 4 million liters per three-month quarter, more than sufficient for a qualified laboratory to meet the Guide's specified Th-230 lower limit of detection (10% of the 10CFR20 Table 2 [public] air concentration limit of 2e-14 uCi/ml). Detection limits for the other three nuclides are less restrictive, thus more easily met.

Although initial cost of such an air sampler system is higher than that of a line-powered unit, longevity has been very good, with moderate maintenance, and the ability to run indefinitely without external power, unattended except to change out the sampling filters weekly (per Regulatory Guide 4.14 recommendation), makes such units our recommended solution in most air sampling situations. A properly designed system is capable of running more than one sampler pump, supporting particle size segregation and sampling for non-radioactive hazardous constituents, as discussed in Section 3 of this report.

Given the availability of this pump, solar powered air sampler systems have been developed and are now in operation at many of the new and pre-license uranium ISR sites in the U.S., and at the proposed Sheep Mountain heap leach facility in Wyoming. Given a stable power supply (large, solar-specific deep-cycle battery, 100+-watt solar panel, charge controller with battery protection and thermal buffering capabilities, insulated enclosure) and 150-MPH wind-capable solar panel mounts, these units have proved capable of year-round operation in environments as inhospitable as the Red Desert in central Wyoming and the Gobi Desert in Asia. Figure 2.1 displays a solar-powered system of the type currently in use at uranium ISR sites in Wyoming.

Figure 2.1: A Current Solar-Powered Air Sampler System

(Sampler filter head is mounted directly under the solar panel)

In an environment where large grazing animals may occasionally interfere with the samplers, substantial fencing surrounds each unit.

Conventional milling and heap leach milling present similar potential for particulate (and radon) releases to the atmosphere. Conventional open pit uranium mines feeding either type of milling present similar particulate (and radon) release characteristics, given the nature of open pit mining (waste rock and ore extraction using heavy equipment and blasting, truck and/or conveyor transport of ore to the mill or heap facility). Note that heap leach solution recirculation, depending on process characteristics, may increase the concentration of Th-230 available for wind-driven release from the heap being leached, although systems to minimize particulate releases from the pile are being designed. Release of significant quantities of Th-230, a significant nuclide in terms of human health risk, will likely be controlled carefully in a heap leach system. No such Th-230 concentration mechanism is apparent in a conventional uranium mill system.

ISR mining presents far less potential for release of radioactive particulates to the atmospheric environment. In fact, all of the recent license applications and pre-license planning documents take advantage of a product (yellowcake) dryer system that involves a vacuum, recirculating particles, resulting in zero estimated routine particulate releases to the environment for an ISR facility. Nonetheless, the potential for accidental ISR facility release of dried yellowcake does exist. In addition, some particulate release potential may exist related to the dry edges of ISR overflow containment ponds. For such the revised air monitoring recommendations will likely remain similar for all convential, heap leach and ISR facility types.

Best practices for atmospheric monitoring of particulates are discussed in NRC Regulatory Guide 4:14:

"Uranium mill operators are required by Nuclear Regulatory Commission (NRC) regulations and license conditions to conduct radiological effluent and environmental monitoring programs. Regulations applicable to uranium milling are contained in 10 CFR Part 20, "Standards for Protection Against Radiation," and Part 40, "Domestic Licensing of Source Material." For example, § 40.65, "Effluent Monitoring Reporting Requirements," of 10 CFR Part 40 requires the submission to the Commission of semiannual reports containing information required to estimate doses to the public from effluent releases."

The Regulatory Guide also notes:

"Information on radiation doses and the radionuclides in a mill's effluents and environment both prior to and during operations is needed by the NRC staff:

- *To estimate maximum potential annual radiation doses to the public resulting from effluent releases.*
- *To ascertain whether the regulatory requirements of the NRC (including 10 CFR Part 20 dose limits, release limits, and the "as low as is reasonably achievable" requirement), mill license conditions, and the requirements of 40 CFR Part 190, "Environmental Radiation Protection Standards for Nuclear Power Operations," have been met.*
- *To evaluate the performance of effluent controls, including stabilization of active and inactive tailings piles.*
- *To evaluate the environmental impact of milling operations, both during operations and after decommissioning.*
- *To establish baseline data to aid in evaluation of decommissioning operations or decontamination following any unusual releases such as a tailings dam failure."*

The Regulatory Guide presents baseline and operational programs acceptable to the NRC staff for monitoring environmental releases of radioactive materials. These programs are not requirements, and alternatives may be proposed. Such alternatives, based on the very significant changes in available technology since publication of the Guide more than 30 years ago, have in fact been proposed by most recent license applicants and accepted by the NRC.

The Regulatory Guide's 1980 sampling program is divided into Preoperational and Operational monitoring sections, and covers areas including atmospheric particulate and radon monitoring, soil sampling, vegetation sampling, water sampling, etc. While there are significant differences between the two sections of the Regulatory Guide, current licensing experience and practices tend to blur the distinction for air monitoring, and the two regimes are not differentiated in this discussion.

2.3.1.5 Radon

Radon monitoring is also discussed in the context of the existing National Emissions Standards for Hazardous Air Pollutants (NESHAPs) regulations, presented in Section 4 of this report.

2.3.1.5.1 Background Information on Radon Gas and its Decay Progeny

The following material discusses radon gas and radon decay and is presented to assist a reader unfamiliar with this topic.

Radon is a naturally occurring odorless, colorless noble gas. It is produced from the radioactive decay of uranium and thorium and is ubiquitous in the environment. Radon is naturally present

in outdoor and indoor air in concentrations that depend on the underlying geology as well as lifestyle and construction characteristics of structure. Radon-222 (Rn-222) is the principal health concern for workers in the uranium recovery industry as well as members of the public living in the vicinity of such facilities. Radon-222 is the direct decay product of radium-226 (Ra-226). Radon-222, an inert gas with a half-life of 3.8 days, decays to polonium-218 (Po-218), lead-214 (Pb-214), bismuth-214 (Bi-214), and Po-214 termed the "short-lived radon progeny". The decay scheme for Rn-222 is shown in Figure 4.1. Polonium-218 and Po-214 are alpha emitters with half-lives of 3.0 minutes and 164 microseconds, respectively. Lead-214 and Bi-214 are beta emitters with half-lives of 26.8 minutes and 19.7 minutes respectively.

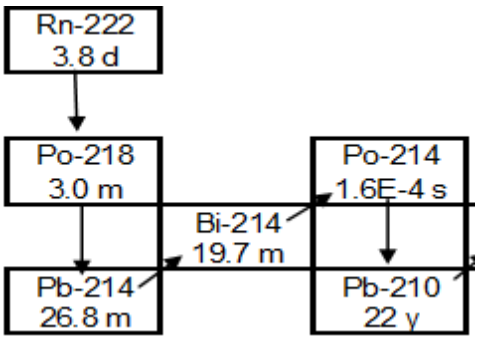

Figure 4.1: Radon-222 Decay Scheme

Two other naturally occurring radon isotopes (Rn-220, and Rn-219) are present in the environment but, in uranium recovery facilities, at concentrations much lower than Rn-222. Radon-220 is a decay product of natural thorium; Rn-219 is a decay product of U-235. For the purpose of this report, the term radon will be used to mean specifically Rn-222.

Radon diffuses from soil, ore, waste rock, and tailings into the air as an inert gas with no decay products present. The short-lived decay products build up as a function of time and eventually reach "equilibrium" with the radon. At equilibrium, the activity concentration of each of the short-lived decay products is equal to the activity concentration of the radon. The rate at which the decay products build in is governed by their half-lives. The concentration of radon progeny in air is a complex function of time.

A special unit was derived to express the exposure to radon progeny, recognizing that the particular exposure of concern in regard to human health is alpha radiation from the decay of Po-218 and Po-214. The concentration of radon progeny in air is expressed in working level (WL). The WL was defined at a conference in Salt Lake City in 1955 as a radon concentration of 10^{-10} curies of radon in equilibrium with its short-lived decay products per liter of air (100 pCi/l) (Holaday, 1969). The WL is a measure of the potential alpha energy in a liter of air. Potential alpha energy means the total alpha radiation energy that would be released when the radon progeny decay to stable Pb-206. The beta emitting radon progeny, Bi-214 and Pb-214 contribute

to the alpha energy since they decay to ^{214}Po. The WL is shown as a function of time in Figure 4.2.

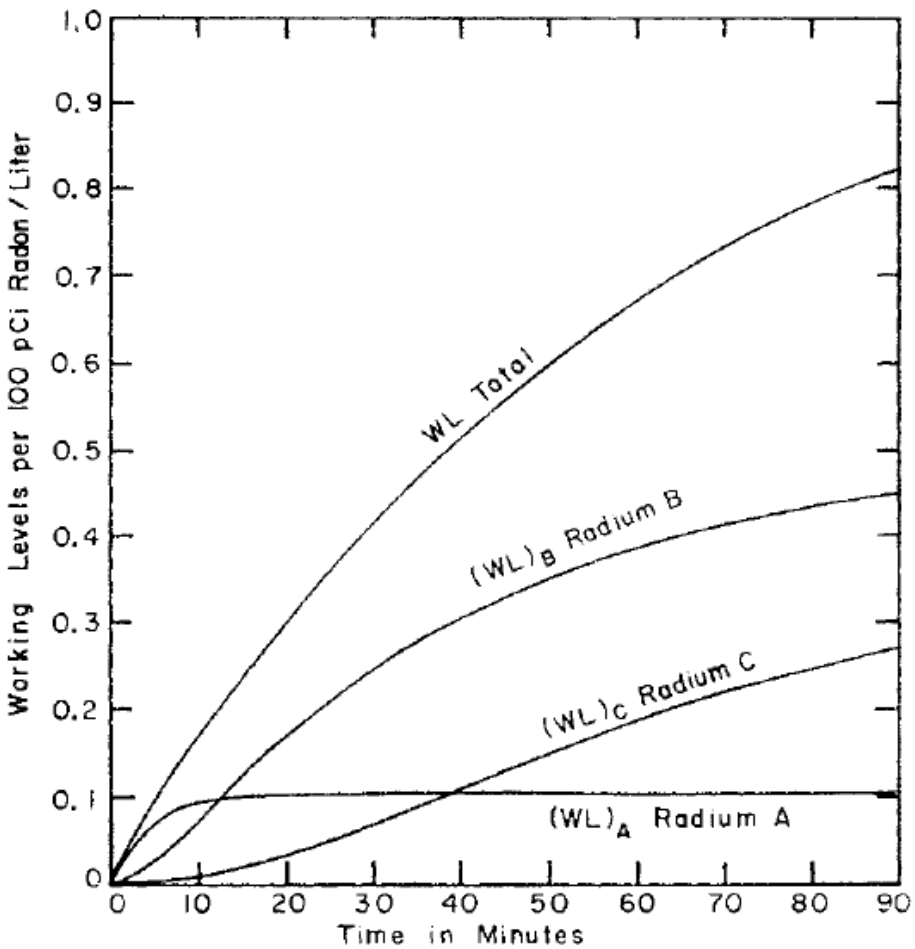

Figure 4.2: Working Level as a Function of Time Since Emanation (from Evans, 1969, Engineer's Guide to Radon)

Radon has been known to cause lung disease for more than five centuries. "Miner's disease" as it was called was identified as cancer in the late 1800s. The cause of the cancer was determined to be inhalation of radon decay products in the 1940s. The risk of adverse health effects from exposure to radon in air is a function of the amount of energy absorbed by tissue. The predominant adverse health effect due to radon is lung cancer. Exposure to radon progeny in air is expressed in units of "working level months" (WLM). One WL is the concentration of short-lived radon progeny in air that will result in the emission of 1.3 x 10^5 million electron volts (MeV) of energy per liter of air. One WLM is equivalent to exposure to 1.0 WL for 170 hours, originally, the average number of hours worked by a miner in one month. An exposure of 1.0 WLM would result in a Total Effective Dose Equivalent of 10 mSv (1.0 rem) (NCRP, 2009). The estimated lifetime risk from an exposure of 1.0 WLM is 5 x 10^{-4} (ICRP, 2010).

The WL was originally intended as an occupational standard, that is, a concentration of radon decay products in air to which a miner could be exposed without adverse health effects. That standard was later reduced by a factor of three to its current level or 4 WLM/year or 30 pCi/L Rn-222 in equilibrium with its short-lived progeny.

There are three common types of radon measurements applicable to uranium recovery facilities: radon gas concentration, radon decay product concentration, and radon flux concentration. Environmental radon gas concentrations are measured over a specified period of time, generally a calendar quarter, to determine the effluent from a particular facility; radon decay product concentrations (WL) are generally measured to evaluate the potential dose to workers from inhalation; radon flux is a measure of the amount of radon emanating from a particular source such as tailings.

At the time that Regulatory Guide 4.14 was developed, monitoring for radon in the open environment was a difficult process. For example, Eberline RGM-2 flow-through radon detectors that printed results to paper tape protected inside small metal housings were used on the U.S. Department of Energy's Uranium Mill Tailings Remedial Action program (UMTRA) implemented throughout the 1980's. The units were supplied with line power, limiting the locations at which they could be operated. The difficulties were significant enough that the Regulatory Guide acknowledged them, noting that "Samples should be collected continuously at the same locations, or for at least one week per month, for analysis of radon-222."

During that period, several other systems were under development, targeted on the measurement of average radon gas concentrations in air. Some, including the use of activated charcoal to capture radon for a few days then measuring gamma radiation from daughter decay after rough equilibration with radon in air had been established, are in use today to cost-effectively monitor short-term radon concentrations in buildings. These systems do not integrate radon concentrations over extended periods, and are not useful for long-term environmental monitoring.

A system that has gradually become accepted for long-term environmental monitoring, even with its shortcomings at very low radon concentrations, is the Landauer DRNM RadTrak track-etch method. The specification for this device allows reasonably reliable measurement of radon air concentrations over periods of several months at reported average air concentrations of 0.07 pCi/l, +/- 0.01 pCi/l. The system depends on damage done to CR-39 carbonate films by alpha particles, etched to make the damage tracks visible under microscope, counted and evaluated using known standard radon concentration exposures of other films. Although detector batch differences require careful QC work at very low concentrations, in the normal range encountered in the outdoor environment these detectors produce adequately reliable results, and have come to

be accepted by the NRC, as evidenced by the use of RadTrak data in successful uranium extraction facility license applications.

Therefore, the use of Landauer DRNM RadTrak Rn-222 detectors for measuring radon air concentrations is recommended. Additional measures include the use of thoron filters and careful QC involving the establishment of detector damage track inherent background by comparison to unexposed CR-39 films from the same production batch. Per NRC Regulatory Guide 4.14, these detectors are placed in the same locations (typically mounted on the protective fencing) as the air particulate samplers discussed above.

As of August, 2012, the NRC has stated that it is about to release proposed new radon and radon daughter monitoring requirements for uranium extraction facilities. It is not yet apparent how significant these changes will be in comparison to the environmental radon monitoring requirements of current Regulatory Guide 4.14, but indications at meetings and via phone calls with NRC staff indicate that the changes may be considerable. Radon-222 itself is not a significant hazard to humans, rather, the decay products of radon, themselves particles quickly attached to dust in the atmosphere, are responsible for almost all radiation dose delivered to the lung after inhalation. The new NRC guidance may require not only enhanced/increased monitoring for radon gas near a uranium extraction facility, but may also specify that the relative concentration of radon decay products (the equilibrium fraction) in the local environment be understood by a facility operator. This would not be a simple requirement, for several reasons:

- Radon daughter concentrations in the open environment tend to be very low and difficult to measure, especially if resulting from the decay of radon gas just released from a facility.
- Radon daughter concentrations from other sources, including simple natural regional radon background, will generally show much higher levels of equilibrium with their parent radon concentrations than will daughters from facility-released radon. Use of such measured values will overestimate, perhaps drastically, the dose and risk associated with radon released from the monitored facility.
- Radon and daughter monitoring at a much more extensive level than currently required will be a moderately expensive operation, with valid arguments to be made that little is gained in terms of monitoring for significant risk to members of the public. Our profession's ALARA (As Low As Reasonably Achievable) policy, recognized via NRC facility license incorporation, specifically discourages expensive requirements associated with insignificant dose reductions. This is based on the need to use dose reduction resources wisely. As the NRC moves forward in this area and a draft policy is released for review, regulatory authorities and uranium extraction companies will probably be monitoring its implications closely.

Virginia should consider closely tracking NRC's revision of their radon and radon daughter monitoring requirements for uranium extraction facilities.

2.3.2 Baseline and Background Determination

Preoperational atmospheric and air quality monitoring systems are (in current uranium mill and ISR license applications) designed to establish background environmental levels of pollutants potentially released during future operations. These include the radioparticulates (airborne particulates containing the uranium decay chain elements (Unat/Ra-226/Th-230/Pb-210/Po-210), radon gas and its decay products, and direct gamma radiation. Operational systems extend that baseline monitoring approach, to ensure that changes in atmospheric concentrations, during facility operation or post-closure, will be easily recognized and differentiated from background conditions. The purpose is to provide data that point toward facility modifications necessary to minimize environmental impact. Since uranium resource areas, prior to any facility-related disturbance, often exhibit background airborne radionuclide concentrations that are higher than U.S. average, current applicants recognize that detailed background studies are essential to ensure that pre-existing conditions are not later confused with environmental contamination resulting from their facility's operations.

2.3.2.1 Siting Long-Term Air Concentration Monitoring Locations

NRC guidance for siting meteorological systems is provided in Regulatory Guide 3.63 (NRC, 1988). NRC guidance for siting air quality monitoring equipment is provided in Regulatory Guide 4.14 (NRC, 1980). EPA Guidance for siting meteorological instrumentation is provided in "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (EPA, 2000). Criteria for selecting tower locations are similar between major sources requiring PSD permits, and minor sources such as surface mines. The principal variable is the recommended tower height, which should match the height of emission sources or plume release. EPA guidance for siting air quality monitoring instrumentation follows 40 CFR Part 58 Appendix E and is provided in "Quality Assurance Handbook for Air Pollution Measurement Systems Volume II, Ambient Air Quality Monitoring Program" (EPA, 2008b).

There is significant potential for error in the initial placement of the air particulate sampling locations unless meteorological data, including atmospheric stability data, happen to be available which are clearly representative of the proposed uranium extraction facility's meteorology. Because Regulatory Guide 4.14 states that these pre-licensing locations should become the final, operational monitoring locations, ideally to be used for many years without change, selection of incorrect locations, particularly the background location and the location of the structure with the highest predicted airborne radionuclide concentrations can be problematic. This problem can be

solved by locating initial air monitoring equipment based on best available information, then re-initiating some monitoring at better locations later if the site meteorological conditions significantly differ from those assumed during initial monitoring equipment siting.

Critical to this process is having a robust conceptual model of the proposed mine and/or mill before establishing the location of any monitoring equipment. At the earliest feasible time, soon after a proposed facility's features have been located and the site boundaries have been identified, a suitable meteorological stations (characteristics discussed later in this section) should be required at a location selected based on site topography and the best available wind speed and direction information. The meteorological data to be collected must be representative of conditions at the primary dust and radon release locations, must also be usable to model atmospheric dispersion of released materials out to at least 10 km from the site for radiological modeling and 50 km from the site for criteria pollutant modeling. The meteorological data must be helpful in the eventual selection of final environmental air monitoring locations using the appropriate guidance. A minimum of a year of data collection at the meteorological stations should be performed before final location of the air monitoring stations can be confidently established. Dispersion modeling requires a minimum of one year (preferable two or more) of meteorological data for radiological modeling and three years of data for criteria pollutant modeling.

Even with one or two years of onsite meteorological data collected, significant errors in the placement of air monitors are possible, since weather patterns at a site can vary over multi-year periods. A solution for this specific problem is to supplement the onsite meteorological data being collected, with information from nearby weather stations (airport data, for example). Graphical comparisons of wind speed, direction and direction prevalence among several different meteorological station data sets can lead to agreement between applicant and regulator that the developing onsite data are similar (or not) to decades of data from a nearby weather station. This reinforcement of the representativeness of the onsite meteorological data allows the information to be used with more confidence to select air monitor locations.

2.3.2.2 Use of a Dispersion Model to Select Monitoring Locations

The actual selection of locations is based on site and vicinity knowledge (nearest residents and nearest downwind residents), and the most likely facility (i.e., mine, mill, tailings) locations. An atmospheric dispersion code such as MILDOS, mentioned previously, is currently accepted by the NRC and Agreement States for location selection uses the best available meteorological data ("best" as determined above). The code can handle multiple release points and types (point vs. area sources, for example), and will identify the locations of the highest predicted radionuclide concentrations onsite and offsite. Note that the code's output is also useful to guide selection of the most appropriate background monitor spots.

MILDOS was developed decades ago specifically to support uranium extraction facility environmental assessment, and contains algorithms that predict not only air particulate and radon gas concentrations associated with multiple release locations (radon monitoring is discussed later in this section, but also the average radon daughter "equilibrium factors" on and offsite. This feature is particularly valuable as the NRC contemplates requiring pre-licensing estimation of radon daughter dose to individuals on and offsite, including individuals such as delivery personnel, truck drivers etc., who are present regularly onsite, for short periods.

2.3.2.3 Air Sampler Initial and Final Locations

Air samplers are typically installed well prior to availability of long-term data from the new, onsite meteorological stations. As noted, this may cause uncertainty about the suitability of the locations selected. Selection of initial monitoring locations based on available nearby meteorological station data will lead to reasonably accurate choices, especially for monitoring other than background and most highly exposed structure. In a lightly populated area, the selection of downwind occupiable structures may be very limited, leading to an obvious monitoring location. Choice of an upwind, background location may also be relatively easy, although it is useful to employ MILDOS runs at this time as well, using the best early meteorological data sets available (they must be complete, full-year data sets), to visualize predicted air particulate and radon/daughter concentrations during the monitor-locating process.

Installing and operating a full set of particulate monitors provides a license applicant with experience in the problems associated with continuous monitoring (power failures, weather problems including snow buildup, data loss, dust-related flow rate restriction, pump failures, calibration issues, etc.) When a year or two of onsite meteorological data have been collected and evaluated as discussed above, one or more of the air particulate monitors may have to be relocated based on better data used in new MILDOS runs. However, most of the monitors will likely have been placed in locations that remain satisfactory, and the licensing process is generally long enough to allow collection of at least a year's worth of data even for the relocated monitors. The experience gained during the first year of monitor operations will ensure competent development of monitoring data during the next years.

2.4 Specific Points for Consideration – Air Quality Monitoring

The following information relates to current uranium extraction facility licensing. The basis for these specifications remains the 1988 NRC Regulatory Guide 3.63, "Onsite Meteorological Measurement Program for Uranium Recovery Facilities – Data Acquisition and Reporting", but instrument specifications below are updated to current equivalent standards.

2.4.1 Siting

NRC Regulatory Guide 3.63 states:
"The location of the meteorological instruments should represent as closely as possible the long-term meteorological characteristics of the area for which the measurements are being made. Whenever possible, the base of the instrument tower or mast should be sited at approximately the same elevation as the facility operation. Ideally, the instruments should be located in an area where localized singular natural or man-made obstructions (e.g., trees, buildings) will have little or no influence on meteorological measurements. Measurements of wind speed, wind direction, and sigma theta if measured should be made at least 10 obstruction heights away from the nearest obstruction.

"To the extent practicable, these instruments should not be located in the prevailing downwind direction of an obstruction. At most facilities, the instruments could all be sited at one location. At some sites, instruments may need to be sited at more than one location if the meteorological conditions are not similar throughout the site vicinity."

If a uranium mine site is located in the vicinity of a uranium mill site, an applicant should be required to either demonstrate that the mill meteorological data required by NRC or Agreement State is representative of the mine site conditions or establish additional meteorological monitoring to satisfy the agency issuing the air quality permit. Representativeness has been defined as *"the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application"* (Nappo et al, 1982)

EPA guidance states:
"As a general rule, meteorological sensors should be sited at a distance which is beyond the influence of obstructions such as buildings and trees; this distance depends upon the variable being measured as well as the type of obstruction. The other general rule is that the measurements should be representative of meteorological conditions in the area of interest; the latter depends on the application. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise the quality of the data. In addition to routine quality assurance activities (see Section 8); annual site inspections should be made to verify the siting and exposure of the sensors. Approval for a particular site selection should be obtained from the permit granting agency prior to any site preparation activities or installation of any equipment." (EPA, 2000).

Later in the same guidance, EPA states:

"A single well-located measurement site can be used to provide representative wind

measurements for non-coastal, flat terrain, rural situations. Wind instruments should be placed taking into account the purpose of the measurements. The instruments should be located over level, open terrain at a height of 10 m above the ground, and at a distance of at least ten times the height of any nearby obstruction. For elevated releases, additional measurements should be made at stack top or 100 m, whichever is lower. In cases with stack heights of 200 m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis." (EPA, 2000).

Based on the above and our experience, station locations should be selected considering the following parameters:

- Site operations
- Local topography
- Prevailing wind direction
- Proposed building(s) and activities
- Naturally occurring obstructions (trees, embankments)
- Additional site-specific factors, such as safe access
- Access to power supply
- Local approvals as needed

The meteorological station locations need to be representative of the proposed operations, and should meet the following objectives:

- Base of station should be at same elevation as the facility operation (when possible).
- The meteorological station should be located in the same wind regime as the emission sources, with wind monitors placed at anticipated emission release heights.
- Station should be located in open area free from obstructions and upwind from any nearby obstructions.
- Wind parameter measurements should be made at least 10 times the height differential of any obstructions (e.g., the stations need to be at least 300 ft. away from a 30 ft. building). Rough measurements should be made to verify that the tower will be a sufficient distance from obstructions and can be safely accessed for installation and servicing.
- If meteorological conditions vary over the site, more than one station may be required.
- Wind parameters should be measured at 30 m and 10 m above ground level with the sensors oriented into prevailing wind. Additionally, the sensors need to be two times the tower width away from tower.
- Alternatives to the 30 m tower height identified in NRC Regulatory Guide 3.63 should be allowable based on site specific and project specific conditions but robust justification for this deviation from guidance should be required from an applicant.

2.4.2 Air Particulate Monitoring

Most uranium mines and mills are generally not categorized as major sources of air emissions due to the scope and scale of their operations. As such, they typically are not required by EPA or the States delegated to regulate air emissions under the Clean Air Act to perform baseline or operational monitoring for dust particulates (e.g. PM_{10}, $PM_{2.5}$ and total particulates). Uranium mills are required to assess potential public radiological exposures and dose from operations for all appropriate pathways. To support these dose assessments, applicants and operators are required to perform baseline and operational monitoring for radioparticulates in air as well as monitoring for radon and direct gamma radiation at the licensed area boundaries. These actual measurements of airborne radioparticulates are used to support public dose modeling to demonstrate public exposures are below the levels identified in 10 CFR Part 20.

However, the public in Virginia have raised concerns about potential health impacts due to dust emissions from future uranium mine and mill operations. Therefore, the Commonwealth may wish to consider establishing more stringent requirements for monitoring of dust emissions from both uranium mines and mills and radioparticulate emissions form uranium mines, regardless of their status as minor or major sources under the Clean Air Act. Such monitoring would both allay public concerns regarding the potential for adverse effects on public and environmental health as well as provide the operators and Commonwealth agencies with valuable information on which to base operational changes, implementation of alternative best management practices for emissions controls and for implementing ALARA programs.

Environmental air particulate sampling should be performed using reliable power sources to ensure continuous monitoring. Where reliable line power is not available, solar-powered, stand-alone systems should be used. These systems have now been used for radioparticulate sampling to develop pre-licensing and licensed operational facility data sets, and thus have been accepted by the NRC for such use. They are designed to conform to the specifications identified NRC's Regulatory Guide 4.14 (NRC, 1980) and to allow determination of average air concentrations of the specified set of radionuclides at appropriate lower limits of detection, based on the NRC's air concentration limits for the general public (10 CFR Part 20, Appendix B). Properly designed systems can support additional sampler pumps to allow collection of air particulate concentration data as required for non-radioactive materials.

It is recommended that VDEQ consider requiring pre-construction, operational and reclamation monitoring of PM_{10} and $PM_{2.5}$ at uranium mining and milling operations. This source-specific air quality monitoring program would be in contrast to the ambient monitoring network already operated by VDEQ. The following issues should be considered:

- This would constitute a new regulation since federal rules require monitoring only for major emission sources, and uranium mining and milling facilities generally qualify as

minor sources. It may therefore need statutory authorization to implement minor source permitting and monitoring programs.

- The new regulation may enforce pre-construction monitoring as a prerequisite for a construction permit. Such monitoring should be conducted in accordance with 40 CFR 58 Appendix B, "Quality Assurance Requirements for Prevention of Significant Deterioration (PSD) Air Monitoring" (July 1, 2000). Since significant criteria pollutant emissions from uranium facilities will normally be limited to particulates (PM_{10} and $PM_{2.5}$), it is recommended that the monitoring requirement exclude other criteria pollutants.
- Post-construction monitoring should be considered as a condition of the construction permit, in order to establish the effect of particulate emissions on the air quality of nearby areas accessible to the public.
- If required, placement of particulate monitors should follow the guidelines referenced in 40 CFR Part 58 Appendix E. The number and placement of monitors should be sufficient to determine general background concentrations, to assess facility impacts at areas of maximum concentration or maximum potential public exposure, and to evaluate instrument precision.
- If implemented, the program should be administered through the existing VDEQ ambient air monitoring department. In Wyoming, the agency monitoring group oversees both State and Local Air Monitoring Stations (SLAMS) and PSD monitoring networks: "The Air Quality Division (AQD) Monitoring Section has the responsibility to protect, conserve, and enhance the quality of Wyoming's air resource. The Monitoring Section helps ensure the ambient air quality in the State of Wyoming is maintained in accordance with the National Ambient Air Quality Standards (NAAQS). To carry out this goal, AQD operates and maintains a network of ambient air quality monitors and requires industrial pollution sources to conduct source specific ambient air monitoring." (2010 Ambient Monitoring Network Assessment, Wyoming Department of Environmental Quality – Air Quality Division, April 28, 2011).
- Other states may provide precedent for establishing a source-specific minor source monitoring program. For example, Colorado routinely requires pre-construction and post-construction PM_{10} and $PM_{2.5}$ monitoring at surface mines and uranium facilities. Montana has a similar program. In Wyoming's air quality standards and regulations (WAQSR), Chapter 6, Section 2, is titled "Permit Requirements For Construction, Modification, And Operation." Requirements in this section apply to minor as well as major sources. Part (b)(i) states, "*The applicant shall conduct such continuous Ambient Air Quality monitoring analyses as may be determined by the Administrator to be necessary in order to assure that adequate data are available for purposes of establishing existing concentration levels of all affected pollutants. As a guideline, such data should be gathered continuously over a period of one calendar year preceding the date of application. Upon petition of the applicant, the Administrator will review the proposed*

monitoring programs and advise the applicant if such is approvable or modifications are required." While this regulation implies administrator discretion, permitting guidance effectively removes such discretion in the case of surface mines. Whether major or minor sources, all new and existing surface mines must adhere to the monitoring requirement unless sufficient ambient air quality data already exist in the vicinity of the mine. Since fugitive dust emissions tend to dominate, monitoring requirements at the mines are generally limited to $PM_{2.5}$ and PM_{10}.

- Several vendors offer reference method PM10 and PM2.5 samplers that will operate on solar power with battery backup. These are low-volume samplers (typically 16 liters per minute) intended for 24-hour sampling on either a 1-in-3 or 1-in-6 day schedule. The Commonwealth should consider establishing requirements for baseline and operational and reclamation construction monitoring of airborne radioparticulates (Unat/Ra-226/Th-230/Pb-210/Po-210), radon and direct gamma radiation monitoring for uranium mine permitting, as is required for uranium mill monitoring by NRC regulations and guidance. Such monitoring would provide a basis for predicting public exposures form mine operations as part of permitting and for assessing public and environmental health conditions outside the permit area.
- The Commonwealth should consider requirements for uranium mine applicants to submit predictive public dose and exposure models for planned mine operations using models such as MILDOSE, as is required for uranium mills. Such modeling would served to establish in advance of permit approval, during construction, mining and during reclamation, that mine emissions will be and remain protective and as low as reasonably achievable (ALARA).

2.4.3 Other Recommendations

NRC Guide 3.63 specifies the following maintenance, servicing, and data requirements for meteorological monitoring stations:

- Stations should be able to withstand severe weather and be protected against conditions such as blowing sand, lightening, and icing.
- Stations should be inspected a minimum of once every 15 days.
- Stations should be serviced at a frequency that ensures 90% annual data recovery and 75% annual joint data recovery of wind speed, wind direction, and atmospheric stability.
- The system should be calibrated at least once every 6 months (dusty environment should be calibrated more frequently i.e. quarterly).
- Extensive recordkeeping maintained for the duration of the uranium recovery operation.

Additional guidance related to instrument specifications, calibration and data quality assurance is provided in the "Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements" (EPA, 2008a).

- Recordkeeping should include the following information:
- Operating logs and results of reviews,
- Inspections, maintenance, calibrations, audits; a description of the types of observations
- Taken with the results and their acceptability; and actions taken in connection with any deficiencies noted. In addition, recordkeeping should identify who is responsible for data acquisition and data archiving.

2.4.3.1 Use of the Data in MILDOS Calculations

The MILDOS code, used to provide estimates of radionuclide air concentrations, requires an estimate of stability class, combined with wind direction and wind speed, organized into a stability class array. A variety of methods of stability class measurement may be used to run the MILDOS code. Based on EPA Meteorological Onsite guidance (EPA-454/R-99-005), the Turner Method is the best approach to determining stability class. However, this method requires cloud cover and ceiling height data, which can be difficult to interpret and process. The problem with obtaining cloud cover data has led to the development of other methods to estimate stability class. The solar radiation delta-T method, discussed in reference documents including the EPA report noted above, retains the basic structure of the Turner Method but does not require cloud cover and ceiling height data. Therefore the use of the solar radiation delta-T method, which includes the use of a solar radiation device and temperature probes at two different heights to calculate stability is recommended over the Turner method. The system below reflects this recommendation.

2.4.3.2 Equipment Specifications

Meteorological monitoring equipment specifications should meet both NRC requirements identified in NRC Regulatory Guide 3.63 (meteorological equipment) and NRC Regulatory Guide 4.14 (radioparticulates, radon, gamma radiation). In addition, meteorological equipment should conform to EPA guidelines (EPA, 2000). Meteorological equipment should be located, installed and maintained to satisfy the requirements of both regulatory agencies (EPA, 2008b) (NRC, 1988).

One objective of meteorological monitoring stations is to characterize atmospheric conditions at plume source and transport height so modeling of potential future exposures and impacts is representative of actual conditions. NRC guidance recommends a 30 m tower with instrumentation at both 30m and 10m. However, alternatives may be proposed (i.e., 10m and 2 m) based on site-specific emission source heights and configurations and site conditions. 30m towers are often required for uranium mills due to emission release heights from the plant or leach pad. 10m towers are typically used for uranium mines, but must be justified. Virginia should preserve flexibility in its statutes so that it may consider all applications against guidance and the site specific conditions in each application.

This system can be powered by A/C or a solar configuration. If solar power is chosen, additional solar panels and deep-cycle batteries will be required to power the 2-m and 10-m temperature aspirator fans. Monitoring communication system such as wired telephone; cellular wireless, satellite, or short range wireless (2.4 GHz) are recommended. This added capability will ensure that data loss situations are recognized and resolved quickly.

3.0 Release of Particulate Matter from Ore Stockpiles, Waste Rock, Mine Tailings, Processing Facilities and Mine Blasting; Mobilization of Contaminants

Sources of particulate emissions at uranium mining and milling facilities include stationary sources (having a stack or single point of release) and fugitive sources (mobile sources or emissions distributed over a large area). Examples are:

- Paved and unpaved roads
- Overburden, waste rock and ore excavation, loading and unloading
- Wind erosion on open or disturbed areas and storage piles
- Crushing, screening and material transfer operations
- Tailings cells, wastewater holding ponds and evaporation ponds
- Drilling operations
- Blasting operations
- Diesel and gasoline tanks and fuel dispensing systems
- Process tanks and vessels
- Dust filtration systems and process scrubbers
- Mobile equipment tailpipes (scrapers, dozers, graders, water trucks, excavators)
- Diesel powered generators, pumps, light plants, and portable welders
- Heap leach pads
- Boiler and yellowcake dryer stacks
- Mill vent stacks

In some cases, emissions can be measured directly (e.g., stack tests). In others, they can be calculated based on a mass balance. In most cases, however, each source's potential to emit (PTE) is calculated based on approved emission factors associated with the source types. Emission factors for surface mining activities appear in EPA's AP-42, Compilation of Air Pollutant Emission Factors. Chapter 11, Section 24 provides emission factors for crushing, grinding, and material transfer. Section 9 of Chapter 11 provides emission factors for blasting, topsoil operations, drilling, truck loading and unloading, storage pile wind erosion, and exposed area wind erosion. For wind erosion, AP-42 provides an alternative method to calculate emission factors based on the local wind speed distribution. Chapter 13, Section 2 provides emission factors for paved and unpaved roads.

Most of the AP-42 emission factors are stated as mass of emissions per unit of activity (hour, ton, cubic yard, acre, etc.). The mass may be given in terms of total particulate matter (PM), PM_{10} or in limited cases, $PM_{2.5}$. To develop a comprehensive emissions inventory, it is sometimes necessary to convert PM to an equivalent mass of PM_{10} or to convert PM_{10} to an equivalent mass of $PM_{2.5}$. Section 4 of AP-42 Chapter 13 provides typical ratios of $PM_{2.5}$ to PM_{10} for fugitive dust sources. $PM_{2.5}$/ PM_{10} ratios can also be obtained from a study performed by Midwest Research Institute (MRI, 2006).

EPA offers additional sources of emission factors and calculation methods through public domain software. Examples include Tanks 409, MOBILE6, NONROAD, and others. For sources regulated under NSPS or NESHAP, emission factors can be inferred from regulatory emission standards and, where applicable, maximum available control technology (MACT) limits. In addition, some states provide customized emission factors. Due to the extensive scale of surface mining in Wyoming, the Wyoming Department of Environmental Quality (WDEQ) has established a suite of approved emission factors for surface coal mining operations.

A primary sources of air contamination at uranium mine sites is fugitive dust emissions from mine pits and underground workings, overburden, mine rock dumps, ore, sub-ore, and haul roads. Tailings may also be a potential source of fugitive dust when particulates are transported by wind. Dust emissions vary depending upon moisture content, amount of fines, number and types of equipment operating, and climate. The movement of large haul trucks can be a source of dust at most uranium mines.

Methods to minimize fugitive dust emissions at uranium mines are similar to those implemented at coal and other hard-rock mining facilities. Control of fugitive dust from uranium mines is not specifically mandated by a federal regulation, since these sources are generally minor sources and are not listed under NSPS. However, most states require surface mines to control fugitive dust by implementing best management practices (BMP) or best available control technology (BACT). Some states such as Wyoming enforce mandatory or presumptive minor source BACT requirements. Wyoming also requires the submittal of a fugitive dust management plan with mining permit applications. Those states with administrative discretion may also routinely require BMP or BACT.

Potentially applicable fugitive dust control technologies for open-pit mines may include:

- Application of water or a chemical dust suppressant, including salts, surfactants and polymers on unpaved roads
- Enforcement of speed limits at the mine site
- Storage pile (overburden, waste rock, ore, tailings) dust control using water spray and/or wind screens, and covering with tarps
- Open area revegetation or temporary stabilization
- Covering ore haul trucks
- Dust filtration devices (dry baghouse or wet scrubber) on crushing, screening and conveyor transfer facilities
- Blasting restrictions (size or timing of blast, wind conditions, etc.)
- Conveyor shields and transfer point hoods with dust collection
- Truck dump hopper enclosures or stilling sheds with staging curtains
- Telescoping chutes for material loading and unloading
- Minimization of containment pond areas
- Final reclamation of disturbed lands

A detailed study and recommendations for surface mine dust control is presented in, “Dust Suppression on Wyoming's Coal Mine Haul Roads, Recommended Practices and Best Available

Control Measures - BACM," (Stevenson, 2004). Another useful source, available from the Center for Disease Control, is the "Handbook for Dust Control in Mining" (Kissel, 2003).

4.0 Adequacy of the EPA National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for Radon

The NESHAPs for radionuclides were promulgated in December, 1989 by the Environmental Protection Agency, Office of Radiation and Indoor Air. There are three sub-parts of concern for the uranium recovery industry: Subpart B, applicable to underground uranium mines, limits the allowable effective dose from inhalation of radon decay products by any member of the public to 10 mrem per year. Subpart T, applicable to UMTRCA Title 1 uranium mill sites, limits the radon flux from tailings piles that are no long operational to 20 picocuries per square meter per second (pCi/m^2-s). Subpart W applies to facilities licensed to manage uranium byproduct materials during and following processing of uranium ores, including associated tailings.

The EPA provided guidance on implementing the radionuclide NESHAPS in a document published in July 1991 (EPA, 1991).

Subpart B

Subpart B applies to underground uranium mines that will produce 100,000 tons or more of ore during their lifetime or will produce more than 10,000 tons of ore in a 12-month period. It limits the effective dose equivalent to any member of the public from inhalation of radon decay products to no more than 10 mrem per year. Subpart B requires the owners/operators of each mine to calculate the effective dose equivalent to any member of the public and report the information to the EPA annually. Subpart B would be applicable to underground uranium mines in Virginia.

Subpart T

Subpart T limits radon-222 emissions (radon flux) to the ambient air from mill tailings piles that are no longer operational to no more than 20 pCi/m^2-s. This standard is identical to the criteria in 40 CFR 192.32 and Subpart W to the NESHAPs. Subpart T applies to tailings disposal at non-operational mill tailings facilities, specifically Title 1 facilities under UMTRCA. Since there are no such facilities in Virginia at the current time, it does not apply. Subpart T was originally intended to be applicable to tailings disposal at all uranium mill sites, however in 1994 it was rescinded for operational facilities licensed under the NRC or an Agreement State as it was determined that the existing EPA and NRC regulations (40 CFR 192 and 10 CFR 40) would be protective. Under Subpart T, the EPA has the authority to reconsider rescission and reinstate Subpart T for non-operational uranium mill tailings disposal sites licensed by the NRC or an Agreement State if it determines that the NRC or Agreement State has failed to achieve compliance by the operator with applicable license requirements.

Subpart T is not applicable to Virginia.

Subpart W

Subpart W would apply to any uranium mill tailings generated in the state by a new facility. Subpart W limits Rn-222 emissions to the ambient air from an existing mill tailings pile to no more than 20 pCi/m^2-s and requires compliance with 40 CFR 192.32. It also prescribes conditions under which new tailings impoundments can be constructed and operated, including maximum size and number.

In 2007, two environmental groups, Colorado Citizens Against Toxic Waste, Inc. and Rocky Mountain Clean Air Action, sued the Environmental Protection Agency, alleging that EPA failed to review and, if appropriate, revise Subpart W, as required under the Clean Air Act. The suit was settled in 2008 resulting in an ongoing process to revise Subpart W.

As a result of the suit, the EPA established a workgroup on Subpart W comprised of scientists and engineers from various EPA offices. The function of the workgroup is to assure that appropriate options are considered and that actions are based on sound scientific, economic, policy and legal analysis. The issues raised by the public or industry at the time the workgroup was established include the following:

- Is 20 pCi/m^2-s still a protective number?
- Is the flux from in situ leach (ISL) evaporation ponds equal to zero? (ISLs were not intended to be regulated by Subpart W)
- Is there a need for regulatory guidance after the rule is published?
- Timeliness of radon flux reports
- Is there a need to measure radon progeny concentrations
- Is it appropriate to average areas of tailings piles with elevated radon flux with areas of low flux?

The EPA conducts quarterly conference calls with the stakeholders (regulators, environmental groups, industry, etc.). The minutes of those calls are posted on the EPA web site at http://www.epa.gov/rpdweb00/neshaps/subpartw/rulemaking-activity.html. The EPA website notes that it expects to make a decision with regard to the revised rule in September 2012. A final determination is expected in September 2013 after allowing for public comment and hearings as necessary. However, comments noted in the minutes of the quarterly conference call indicated that the revised rule was to be submitted to the Office of Management and Budget (OMB) on August 3rd for a 90-day review. That would perhaps put off the publication of the revised rule to early November, 2012.

Subpart W would be applicable to future uranium mills in Virginia.

4.1 Historic Technical Basis for the Radon Flux Limit

The EPA established environmental protection regulations for nuclear power operations, including the nuclear fuel cycle in 1977 (40 CFR Part 190). The regulations established annual limits of exposure but excluded radon from the standard based on the uncertainties associated with the risk of inhaled radon. In 1977, amendments to the Clean Air Act required that the EPA Administrator determine whether radionuclides should be regulated under the Act. The EPA determined that radionuclides constituted a hazardous air pollutant. As a consequence the Administrator was required to establish radionuclide NESHAPs. In 1983, the EPA proposed NESHAPs for NRC licensed facilities and underground uranium mines (Cohen, 2010).

During that time, the Agency also established standards for the disposal of uranium mill tailings under the UMTRCA (40 CFR Part 192). Part 192 established a design radon flux standard for disposal of uranium mill tailings of 20 pCi/m^2-s.

After a significant number of legal issues were resolved, in 1986 EPA issued a final NESHAP (Subpart W) for operating uranium mill tailings, establishing a radon flux standard of 20 pCi/m^2-s along with a work practice standard that required new tailings to be disposed of in small impoundments or by continuous disposal, i.e., phased disposal in lined tailings impoundments no more than 40 acres in area and no more than two such impoundments in operation at any time or continuous disposal of tailings such that tailings are dewatered and immediately disposed with no more than 10 acres uncovered at any time. Tailings disposal was required to be operated in accordance with 40 CFR Part 192.

4.2 Other Regulations Incorporating the 20 pCi/m^2-s Radon Flux Criterion

The 20 pCi/m^2-s flux limit is incorporated into 40 CFR Part 192.32, the regulations that are applicable to operating uranium mills. 40 CFR Part 192 was promulgated under UMTRCA. Subpart D includes the radon flux standard and tailings cover design requirements. Subpart W references 40 CFR Part 192.32 for design, construction, operation and monitoring of tailings impoundments. 40 CFR Part 192 is also in the process of revision. The reviews of Subpart W and 40 CFR Part 192 are being coordinated. The distinction between the two sets of EPA regulations is primarily that Subpart W was authorized under the Clean Air Act to specifically regulate radon emissions from uranium recovery facilities; whereas 40 CFR 192 was authorized under UMTRCA and authorizes the NRC to implement regulations written by EPA to provide for disposal, long-term stabilization and control of mill tailings. 10 CFR Part 40, Appendix A also includes the radon flux standard.

4.3 Potential Health Risks at the Existing Limit

The EPA commissioned a study of potential health risks to members of the public at the existing emanation limit of 20 pCi/m^2-s, in support of its effort to revise Subpart W (Cohen, 2011). The study evaluated potential radiation doses and risks from inhalation of radon progeny at eight existing facilities, three conventional mills and five in-situ facilities, as well as two generic conventional facilities representing eastern and western conditions. The hypothetical eastern generic facility was located in Culpepper County, Virginia. Three other facilities were considered for inclusion in the study but were deleted for various reasons. The sites analyzed are listed in Table 4.1.

The rationale for including in situ facilities in the dose/risk analysis is not clear since Subpart W applies specifically to tailings and the revision is focused on the radon flux standard. (The issue of radon flux from ISL facility evaporation ponds has been raised by members of the public and is addressed as described in Section 6 of this report.)

The annual doses to the reasonably maximally exposed individual (RMEI) and the population doses attributable to radon emissions from each facility were calculated using site-specific data on radon flux where it was available and assuming a flux of 20 pCi/m2-s for closed tailings facilities. The analysis also took into account radon emissions from other parts of the mill or ISR facilities. The doses were calculated using the CAP-88 computer program.

The computed calculations required three types of data:

- Distribution of the population living within 80 km of each site (as well as the location of the RMEI)
- Meteorological data for each site
- Annual radon release rates from each site

Population distributions were derived from 2000 census data adjusted for expected growth. Site-specific meteorological data were used where available; however, CAP-88 has an extensive library of meteorological data for various regions of the U. S. The annual radon release rates were derived from site-specific information provided by the mill operators or were gleaned from environmental reports submitted to the EPA or the NRC. The annual release rates for the two generic sites were assumed to be the same as the rate for the White Mesa Mill.

CAP-88 calculates the dose from all applicable pathways including: inhalation, air immersion, ingestion of vegetables, meat, and milk, and ground surface exposure. The code uses a Gaussian plume dispersion model to estimate radionuclide concentrations at receptor locations. The parameter values used in the analysis are very conservative in that they assume that only locally

grown food is consumed. (The Cohen report does not include doses by pathway so it is not possible to determine the impact of such conservative assumptions.)

Estimated average total annual RMEI and Population Doses and Risks are given in Table 4.2.

The analysis for the Eastern Generic Mill assumed a site north of the town of Culpeper and southwest of the town of Warrenton in an uninhabited area. The 2000 census data was adjusted by a factor of 1.4 to estimate the 2010 population distribution. Agricultural productivity factors, taken from the CAP-88 User's Manual were as follows: beef cattle density, 13.1 cattle/km^2; milk cattle density, 1.84 cow/km^2; Land cultivated for vegetable crops, 0.87%. Meteorology data were taken from the CAP-88-provided library for Gordonsville, VA. It was assumed that the radon release rate for the Eastern Generic Mill would be the same as for the White Mesa Mill, the only operating conventional uranium mill in the U. S. as of 2012. The calculated dose to the RMEI is significantly greater for the Eastern Generic Mill than for the other sites analyzed probably due to the much higher agricultural productivity factors.

The risk to outdoor mill workers from inhalation of radon progeny emanating from tailings covered under Subpart W would be negligible since the risk from radon is due to inhalation of radon decay products not the radon gas itself. Decay products would not be present at significant concentrations due to the short time between emanation of the gas and its arrival the receptor. The concentration of radon decay products is a function of the age of the air as described elsewhere in this report. The projected dose to a worker in the mill office from would be similar to the estimated dose to the RMEI for the Eastern Generic Mill, 16.4 mrem per year, adjusted by a factor of 3 to account for the difference in occupancy time, or approximately 5 mrem per year.

4.4 Legal Impetus for EPA Review of the Emission Limit

As noted above, two environmental organizations, Colorado Citizens Against Toxic Waste (CCAT) and Rocky Mountain Clean Air Action initiated legal action against the EPA for "Failure to Review National Emissions Standards for Radon Emissions from Operating Mill Tailings, 40 CFR Part 61, Subpart W" under Section 112(d) of the Clean Air Act as Amended in 1990 (CAAA) (Stills, 2007). That provision requires that any NESHAPs in effect prior to the enactment of the CAAA be reviewed and, if appropriate, be revised within 10 years of the enactment of the CAAA. The suit alleged that current standard allow unsafe and unhealthy levels of radon to be released into the air and that uranium mills can meet more stringent standards. The suit was filed on August 21, 2008.

A settlement agreement was reached with EPA in August 2009. The agreement requires the EPA to establish a web site that would:

- Provide internet access to background information compiled by EPA and would provide public access to all non-privileged records as soon as practicable
- Provide a current estimate of the timeframe for completing the Subpart W review
- Invite and encourage the public to provide comments

In addition, the settlement agreement requires the EPA to conduct a series of in-person meetings as well as quarterly conference calls to brief the public on the status of its review of Subpart W.

The review of Subpart W was initiated in 2009 with a team of fifteen scientists and engineers from various EPA offices. A consultant (Cohen and Associates) was hired to perform a risk assessment and to produce a document describing the history of Subpart W. The history document was posted on the web site in 2010. The risk assessment was finalized in November 2011 and posted on the web site in January 2012. As of July 5, 2012, the schedule for publishing the proposed revision of Subpart W in the Federal Register is likely to be early November as the proposed rule will be submitted to OMB in early August. This has been a long process with much input from the regulated community as well as other stakeholders. The potential impact to Virginia will not be known until the revised NESHAP Subpart W is finalized probably in the fall of 2013.

4.5 Other Approaches to Limiting Radon Emissions from Uranium Recovery Facilities

NESHAPs Subpart W addresses the most significant pathway for radon release at conventional uranium mills but, in its current form, does not address other sources of radon such as releases from ISL facilities. The primary approach to limiting radon emissions from tailings impoundments is limiting the exposed area and covering areas that are no longer operational. Subpart W imposes a two-year time constraint on disposal and compliance with the 20 pCi/m^2-s standard and limits the design and construction of new tailings impoundments to minimize radon emissions as follows:

- Phased disposal in lined tailings impoundments no more than 40 acres in area and meet the 40 CFR Part 192.32 requirements with no more than two impoundments operating at any one time
- Continuous disposal such that tailings are dewatered and immediately disposed with no more than 10 acres uncovered at any time

Current technology does not provide any new methods for limiting radon emissions from tailings other than limiting the area. Older tailings impoundments were maintained covered with water

to reduce radon emissions. Tailings areas covered with water were assumed to have radon flux levels that were negligible. That assumption has been questioned and is discussed further in Section 6. Cohen (2008a) reviewed existing and proposed tailings impoundment technologies but did not reference any methods for reducing radon emissions from surface tailings impoundments. 10 CFR Part 40 Appendix A notes that the "prime option" for disposal of tailings is placement below grade, either in mines or specially excavated pits. Below grade disposal in mines would reduce the radon flux at the surface but presents other potential problems. Below grade disposal in surface facilities may not be environmentally sound if a ground-water formation is relatively close to the surface or not well isolated.

4.6 Review and Evaluation of the Current NESHAP Approach and Weaknesses

The EPA is currently reviewing the current NESHAP approach and will revise its regulations, as necessary. The current NESHAP approach is to limit the allowable flux from tailings facilities by limiting the exposed area and requiring timely final disposal and covering of full or non-operational tailings impoundments. Issues raised concerning EPA NESHAP approach include the following:

- Adequacy of the risk basis for the flux standard
- Adequacy of the specified monitoring requirements including the method and frequency
- Adequacy of the reporting requirements particularly in regard to timeliness

At this time, the EPA NESHAPs do not address other sources of radon at conventional mills or ISL facilities. Radon releases from other sources at uranium mills are addressed by the 100 mrem per year 10 CFR Part 20 dose limit for members of the public, which does include radon decay products. The current review of Subpart W may address radon emissions from other sources at uranium mils such as ore stockpiles.

Radon emissions for open pit mines and waste rock piles are typically not addressed under CAA air permits. The EPA conducted risk assessments for active underground mines and surface uranium mines n 1989 in support of NESHAPs and found that the potential risks from radon progeny exposure from underground mines could be as high as 4E-3. As a consequence, Subpart B was promulgated. However, the risk of fatal cancer from inhalation of radon decay products at surface mines was estimated to be 5E-5 (EPA, 2007). The risk from radon at uranium mines is primarily due to indoor radon resulting from the use of building materials or fill with elevated Ra-226 concentrations.

4.6.1 Radon Monitoring

The radon flux monitoring procedure is prescribed by the regulations (Method 115). Method 115 was developed for phosphogypsum stacks. This method involves sealing a standard size canister (25 cm diameter) loaded with charcoal to the surface of the tailings. The canister is left in place for 24 hours then removed and the total activity of the radon in the charcoal determined by gamma spectroscopy. The radon flux is a function of the area of the canister, the total amount of Rn-222 adsorbed on the charcoal, and the duration of exposure. The Rn-222 activity must be corrected for the time between exposure and analysis. This is the accepted method for radon flux measurement; however, it is sensitive to weather conditions and temperature. Canisters may only be deployed when there has been no rain or snow for the previous 24 hours. This is generally not a problem in most arid climates but may be an issue in Virginia. If the seal between the canister and soil is incomplete or disrupted, the measurement may underestimate actual radon flux. Cohen (2008b) reviewed the methods of determining radon flux from tailings impoundments and concluded that Method 115 can still be considered current. However, the report also concludes that the number of radon flux measurements required should be determined based on statistics rather than requiring a specific number. The original requirements were based on much larger tailings impoundments than are allowed under Subpart W.

Other methods for radon flux measurement also involve accumulation of radon gas in a closed container. For one method, the radon decay product concentration is measured with an electret. However, these methods have not been widely used or tested in the field on uranium mill tailings impoundments. Regardless of the method used, baseline radon flux measurements are critically important.

Environmental radon gas concentrations are measured using alpha track detectors. These detectors are generally easy to deploy, inexpensive, and reliable. However, the sensitivity of the detectors may not be sufficient under the standard type of analysis to distinguish very low incremental concentrations above background. In general, the minimum detectable concentration for a quarterly measurement is approximately 0.3 pCi/L. If the detectors are deployed for six months instead of three months, the minimum detectable concentration is 0.2 pCi/L. The effluent limit for radon with decay products present is 0.1 pCi/L above background. Background levels can range from 0.3 to 0.7 pCi/L and vary significantly with seasons. The vendor can improve sensitivity of the detectors by counting tracks on a larger number of fields.

The 10 CFR 20, Appendix B effluent concentration limits may be adjusted to take into account the actual physical and chemical characteristics of the effluents including equilibrium status. The equilibrium status can be calculated based on distance between the source and receptor, average wind speed, and radon decay product build up factors from the literature. It is impractical to determine equilibrium factors directly since a measured equilibrium factor for

environmental radon gas would reflect the buildup of decay products in global radon rather than the equilibrium factor for radon attributable to a specific nearby source such as a tailings impoundment.

4.6.2 Scope of the NESHAP Requirements

NESHAPs Subparts T and W apply only to uranium mill tailings. It is possible that, based on the stakeholder input during the quarterly conference calls, the EPA will propose to cover other large area sources, such as ore storage areas and evaporation ponds at conventional mills, as well as evaporation ponds and well fields for in situ facilities in the NESHAPs.

4.6.3 Potential Impacts of Specific Revisions to NESHAPS Subpart W

The potential impacts of specific revisions to NESHAPs Subpart W are not known since there is no indication, as yet, from the EPA as to what form those revisions might take. Reducing the allowable radon flux by requiring cover or reducing the size of tailings impoundments could increase the costs of tailings management. Presumably the EPA will have performed a cost benefit analysis on any revisions they propose for Subpart W.

4.6.3.1 Subpart B – Underground Mines

Subpart B applies to effluent from underground mines, primarily due to ventilation. The standard is based on dose to a member of the public, 10 mrem per year, rather than a specific radon concentration.

When underground mines are operating they emit large amounts of radon into the atmosphere through their ventilations systems. Because of the risk of radon to miners, the mine atmosphere must be ventilated at a high rate, therefore increasing the potential exposure to members of the public. Subpart B requires the mine operator to use EPA approve monitoring methods as well as an approved computer code, COMPLY-R, or to use other pre-approved methods of determining dose.

Appendix B to 40 CFR Part 61.253 describes in detail the acceptable methods for measuring emissions from underground uranium mine vents as well as the required sampling frequency. Method 114 prescribes specific methods for determining Rn-222 concentration in air: continuous gas monitor, i.e., Lucas Cell (Method A-6) or alpha track detectors (Method A-7).

The dose limit of 10 mrem per year to any member of the public is 10 percent of the allowable dose to members of the public from licensed facilities and approximately 5 percent of the average U. S. dose from residential radon exposure. The potential increased risk of cancer at an annual dose of 10 mrem for a 30-year duration would be approximately 1.5 in 10,000. Given the fact that the allowable dose for members of the public from facilities licensed by the Nuclear Regulatory Commission or an Agreement State is 100 mrem per year, Subpart B should be considered to be adequately protective.

4.7 Specific Points for Consideration - NESHAP

Ensure that a representative of Virginia participate on the Subpart W revision quarterly conference calls, if the state is not already represented. The calls are most instructive. Mining regulations in Virginia should be augmented to require adequate radon monitoring around uranium mines.

5.0 The Emission of Radon from Uranium Extraction Residues

There has been increasing interest in the long-term release of radon from uranium mining and milling sites, focused on abandoned, operational and rehabilitated sites. Currently, an International Atomic Energy Agency (IAEA) committees is developing instrumentation to allow rapid and inexpensive surveys of the old sites.

The mining of uranium ore generally involves the removal of very large quantities of overburden rock, some of which contain concentrations of uranium too low for economic processing. This waste rock, broken into relatively small pieces during the mining process, presents an increased potential for the release of radon gas that would normally remain trapped. An evaluation of releases from waste rock, ore stockpiles and windblown mill tailings is appropriate, to understand the relative risk associated with these materials vs. the more obvious potential radon source, uranium mill tailings.

A great deal of the radon release rate information of interest in this context has been developed outside the U.S. Data are usually reported in the international SI units. Release rates useful to this discussion are:

- Rate of radon release per unit area, measured as the quantity of radon activity exiting a square meter area of waste rock (or other radon source material) per second, with units of, e.g., one $Bq/m^2/s$ (= 27 $pCi/m^2/s$)
- Total release rate of radon for a uranium facility area (for example, an ore pile), with units of, e.g., one GBq/d (= $27x10^9$ pCi/d)
- Radon release rate per ton of U^3O^8 produced by a facility, with units of, e.g., one GBq/t (= $27x10^9$ pCi/t)

As discussed in Section 2.3.1.5.1, radon is a chemically inert gas with a half-life of about 3.8 days produced via the decay of Ra–226. Immediately upon its creation, it is freed chemically from its rock matrix, and depending upon the characteristics of the rock can move into the open environment. Once there, it continues to decay, producing the alpha emitting decay products that are responsible for its health risk. Over a period of a few days, during ingrowth to near-equilibrium, the radioactivity associated with these decay products can approach the same air concentration as the decaying radon gas.

The key factor determining the environmental health risk associated with radon gas and its decay products, involves the likelihood that a specific radon gas molecule will exit its host rock before decaying back to a trapped solid particle. The rate of radon release into the rock's interstitial environment depends on a number of factors, including rock mineralogy and structure, distribution of the parent nuclide radium 226 (whether precursor radium is distributed on the

surface or within impermeable rock crystals), temperature, water content of the host rock, and other factors. The fraction released is called the emanation coefficient, it is generally between 0.2 and 0.5 (Flugge and Zimens, 1939). Near an uranium deposit or an extraction project, the concentrations of radon in air can be significantly higher than natural background, and can be responsible for a significant fraction of the environmental health risk associated with uranium extraction operations.

Most research and measurement work related to radon releases from uranium facilities has focused on uranium mill tailings. These finely divided residues of the milling process, from which uranium but not radium or other naturally occurring nuclides have been extracted, contain the majority of the radium residual from extraction operations, and thus the majority of the radon-producing potential of all residues.

Relatively little research has been done on the radon-related risk associated with the other residues of uranium extraction: ore piles ready for processing, ore with too little uranium content to be processed, waste rock with still lower but above-background uranium concentrations, and wind-blown tailings re-deposited by high winds and potentially producing large areas of radon-emitting material.

While a great deal of work was done during the UMTRA Project beginning in 1983 to clean up wind-blown tailings (members of our team were closely involved in that project from its inception), that work was directed by the gamma radiation signature of the material, and involved cleanup of thousands of acres. Radon release from wind-blown tailings, unprocessed ore and waste rock was largely treated as a nuisance, making sensitive measurements of soil radium concentrations more difficult at some sites. The result was a great deal of mill-tailings-associated radon data and model development during the 20-year period prior to and during the UMTRA Project, with very little useful radon measurement or theory development related to the other residuals. This is still the situation.

5.1 Compilation of Radon Release Data from Australian Uranium Extraction Residues

Some studies of the radon releases from uranium extraction residues have been performed, and a compilation of Australian studies (Mudd, 2007) is valuable in this context and should be reviewed in detail by interested parties. Of particular interest is the report's extensive reference list; 150+ publications covering the topic. The bottom line of Mudd's comprehensive study of some 11 Australian uranium mills and 31 mines, including review of a great deal of information from other countries, is that "The extensive Australian data compiled for radon exhalation and releases for the various components of uranium mining and milling *demonstrate wide variation*

and data quality, and show that *waste rock and low-grade ores can be significant sources of radon* (italics ours)." Mudd goes on to say, "Importantly, the evidence on the effectiveness of rehabilitation works in reducing radon exhalation and releases is not convincing, especially when comparing cumulative changes from pre-mining conditions." Mudd recommends further research to establish a reliable system for the prediction of radon release rates from ore, waste rock and other non-tailings sources (tailings are considered to be reasonably well understood).

Mudd presents a summary in the report's Table 15, "Predicted normalized radon exhalation and releases from Australian uranium for a standard reactor year (1 GWe year)", of interest in the context of our report. Table 15 indicates that the average contribution of waste rock to overall radon released (largely from tailings) at an Australian uranium extraction site is about 5% of the tailings total release. However, the range of contribution estimates extracted from this table is very large, from 1% to 70% (with 5% as the average). The uncertainty shown in Mudd's data-based table is the result of both true variations in radon release rates and of problems with the reviewed data sets, the latter often solved by necessarily making significant assumptions concerning key unreported variables. Elsewhere in the report Mudd notes that relatively little actual radon release or environmental concentration information has been developed for uranium production residues, other than tailings.

A report by a United Nations committee (UNSCEAR, 2000) concluded that radon releases from uranium mill tailings are the major factor in long-term public radiation exposure associated with the nuclear fuel cycle. That report estimated that between 16% and 75% of local and global fuel cycle exposures are related to radon. However, the UNSCEAR report considered radon releases from mill tailings only, and is not useful for the purposes of this section of our report except to establish context concerning the management of radon released from all extraction residues.

5.2 Other Compilations of Radon Release Data from Uranium Extraction Residues

Other data compilations and analyses have been performed to attempt to quantify releases from radium extraction residues to develop either remedial action approaches or pre-mining/milling control requirements.

In 1980, the US Nuclear Regulatory Commission, in its Final Generic Environmental Impact Statement on Uranium Milling (NRC, 1980) estimated radon source terms for a model uranium mill. Using assumptions based on a standard mill size, the NRC's analysis suggested that ore stockpiles and the crushing facilities would release about seven GBq per day of radon, the tailings pile would release about fifty GBq per day, and wind-dispersed ore and tailings perhaps five GBq per day.

In contrast, estimates developed for the Ranger project in Australia (Ranger Uranium Environmental Inquiry 1975-77) were very different, with very large associated ranges: 20-148 GBq/d radon to be released from the mill, 96 GBq/d from ore stockpiles, 20-281 GBq/d from the open pits, and 1.4-14 GBq/d from saturated or water-covered tailings. Note that even the range of all tailings release estimates (some were disregarded) presented to the Authority directing the Inquiry was enormous: from zero to 4440 GBq/d. Note also the range and size of the radon release estimates for the Ranger open pit mines.

5.3 Challenges to Predicting Radon Release from Uranium Extraction Residues

Multiple radon emission sources such as ore piles to be processed, low-concentration ores set aside unprocessed, waste rock, wind-blown tailings; all may be present at an extraction facility. Important radon release factors include depth to recoverable ore, soil and rock stabilities determining open pit sidewall slopes, variability in a deposit's uranium concentrations, operator treatment of developing waste rock and tailings emplacements, and others. Exposed volumes of materials with significant potential for radon release may change greatly over time depending on these factors, and may also vary greatly from one proposed facility to another.

Attempts to limit radon releases from open pits, extracted ore and waste rock piles have been notable in their general ineffectiveness. Radon gas moves quickly through broken rock and soil covers. Control requires a barrier effective against a nonreactive gas – thick clay, well-characterized and installed to detailed specifications, has been demonstrated to provide reliable control of radon, but other methods have not seen significant success in general. Interim control of developing ore and waste rock piles is especially difficult.

Important variables controlling radon release include rock type/porosity/fracture status, deliberate and weather-related moisture content (that greatly influence radon release potentials, in complex ways), open pit mine surface area and effective surface area (which may be much larger than simple pit geometry indicates), underground mine ventilation patterns and air release volumes, blasting or ripping methods influencing ore and waste rock micro-surface conditions, meteorological variations influencing radon and decay product concentrations (example: turbulent dispersion, vs. boundary layer concentration effects).

Even with a great deal of additional research the case-by-case nature of radon release from uranium extraction residuals is unlikely to lend itself to reliable advance modeling in general. Each unique facility will produce very significant quantities of radon during production; these quantities are unpredictable to a significant extent, based on review of the literature and

disagreement among the experts. The potential for continuing significant release following final closure of a facility is also high, given past experience with uranium production worldwide. However, computer modeling to define *upper limits* of release rates, quantities and environmental concentrations, based on available data, expert estimates and design aspects of specific facilities, seems feasible.

5.4 Specific Points for Consideration – Predicting Radon Release from Uranium Extraction Residues

Large prediction uncertainties in radon emissions, which may represent a significant fraction of a project's overall risk lead to regulatory challenges. The prediction uncertainties regarding releases from radon extraction residues, which represent a significant fraction of a project's overall risk, provide regulatory challenges. If Virginia's moratorium on uranium mining is reversed, and given that a resulting initial licensing proposal will probably involve co-location of a mine, mill and tailings facility within a small area, including all of the known likely residuals (ore, low-content ore, waste rock and dispersed tailings (the latter much less likely in Virginia's wetter environment than in the western U.S.), the regulatory structure should treat the facility as a single unit from the perspective of potential environmental impact. Pre-licensing modeling, development of a suitable environmental monitoring system (for all types of releases), license specifications, allowable environmental release and concentration limits, regulatory oversight and enforcement, and financial bonding and bond release stages, should all be under the overall control of a single Commonwealth Agency. Specific responsibilities would be assigned to other Agencies with direct expertise, but overall environmental protection should be the responsibility of a single enforcer. Without this decision, the current system in place elsewhere, including a variety of regulations, guidance, and enforcement, a system based on historical inertia rather than the need to understand the full impact of an operation, will continue as default.

Given the requirement that the potential licensee treat the facility as one releasing system, it is then possible to invoke adequate facility modeling, using the best available engineering and historical data, employing current, capable computer codes supported by sufficient meteorological data, utilizing radionuclide source term estimates that gradually become data-based as operations develop over time. The regulator can then understand the nature of, and require sufficiently conservative, radionuclide release controls in advance, to prevent significant environmental impact during the early, low-production stages of a licensed operation. An environmental monitoring system, developed to provide early warning of exceedances, can then be designed based on the best available modeling results.

Controls can be built into a radioactive materials license such that, in the event of environmental monitoring results in excess of prescribed values for defined periods, additional controls must be

developed by the licensee and implemented. Licensee response must then reduce environmental concentrations to these levels within a defined period of time. Shutdown enforcements with bond-linked payments to Virginia should be license-specified, allowing the Agency's timely hiring of an independent contractor action to resolve an issue if necessary.

A local community Stakeholder Permanent Oversight Committee can provide tight and immediate additional review of the licensee's environmental data, given sufficient support, access to unbiased expertise from Virginia or elsewhere, and funding for certified laboratory analysis of split samples. Key to this aspect of the overall system is a commitment from the primary regulatory Agency to swiftly respond, via an audit of the licensee, if the Oversight Committee formally notes a potential problem concerning the licensee's operations.

The licensee's data management system should be specified in advance, in the radioactive materials license, to allow real-time access by the regulating Agency, and the local Oversight Committee, to all environmental monitoring results. The system should provide immediate access as results are reported by onsite or by vendor laboratories without delays commonly associated with data QC review by a licensee (QC review can be performed concurrent with data inspection by the Agency and the Oversight Committee, with corrections made upon the discovery of errors). Such a system is now feasible using web-based data management, including automatic development of color graphics depicting lab QC results, trends, exceedances and notification of outliers. Recently such a system was installed at a large radioactive waste management facility in the U.S., jointly available to the regulatory Agency, members of the public, and maintained as the licensee's primary data analysis system (with full, independent backup and protection against hacker interference).

The above recommendations will not provide a fail-safe system, but given expert review of preliminary license conditions, engineering information, modeling methods and results, monitoring system design, specifications concerning allowable environmental medial concentrations, remedial action time limits, plus incentives to a prospective operator to default to best practices (including proactive and continuous evaluation of monitoring data), it should prevent significant and extended exceedances of hazardous material concentrations in the environment. In particular, it would provide a rational way to deal with the potential for significant radon releases from uranium extraction residual materials.

6.0 Radon Release Potential from Evaporation Ponds, Dewatering Activity and Tailing Impoundments

The NESHAPs Subparts W and T address radon emanation from uranium mill tailings. Calculations of average radon flux from such facilities have, in the past, assumed that radon flux from tailings areas covered with water is negligible. However, concerns have been raised as to the accuracy of that assumption for conventional mill tailings and in regard to evaporation ponds at ISL facilities. In addition, active or spray evaporation of wastewater at uranium facilities has raised questions regarding radon release. The EPA requested information from uranium facilities regarding radon flux from water sources. Several facilities responded by conducting research in this regard including direct measurement of radon flux from tailings ponds and measurement of radon concentrations surrounding the ponds.

6.1 Solubility of Radon in Water

Radon is relatively soluble in water, depending on temperature. Radon atoms generated by the decay of Ra-226 in soil or tailings grains generally remains in the grain until it decays. However if the radon is generated near the surface of the grain it can recoil into the pore between grains. The emanation fraction, i.e., the fraction of the radon in the material that is released from typical soils or rock, varies from approximately 5% to 50% (NAS, 1999). Radon emanating from uranium mill tailings will be dissolved in the water in the pore spaces depending on the degree of saturation. At complete saturation, all of the available radon will move into the water phase (NAS, 1999).

The solubility of radon in air is described by the Oswald coefficient (K).

$K = C_w/C_a$

Where: C_w = radon concentration (by volume) in water

C_a = radon concentration in air

At 20 degrees Celsius, K is equal to approximately 0.25; at 40 degrees, 0.17 (Surbeck, 1996). Therefore, the concentration of radon in water under unsaturated conditions is proportional to the concentration in air in the pore spaces with the addition of radon that directly recoils from the soil to the water.

6.2 Radon Releases from Non-Mining/Milling Related Sources

The radon concentration in groundwater-derived public water supplies and water from private wells used for domestic or agricultural purposes is a function of the concentration of uranium in the host rock. Radon concentration data for public water supplies were collected in a database by EPA. High radon concentrations were found in public water supplies in the New England states, the Rocky Mountain region and some southern states including Virginia, North Carolina, South Carolina, and Georgia (NAS, 1999).

Radon is released into the air from water as it is used for domestic purposes. The transfer coefficient in homes varies depending on water usage, as well as size and ventilation rates for the home.

Estimates of release of radon gas from water under aerated conditions range from 50% for a single stage aeration unit (Robillard, 2005), 75.7 % for a spray aeration system (Rost, 1981, as cited by Brown, 2010) to 95% (Robillard, 2005) for a packed column system with an air blower. The EPA estimates that on average 70% of radon contained in household water is released into indoor air (EPA, 2012). It is therefore reasonable to assume that under turbulent conditions; approximately 70% of radon in water is released to the ambient air. The average ratio of Rn-222 in air in residences to Rn-222 in domestic water is estimated to be 1.2×10^{-4} (NAS, 1999).

A study in a fish hatchery in New York State found that groundwater with an elevated radon concentration resulted in elevated concentrations in the indoor areas of the facility (Kitto, 1995). However reducing the radon in water did not have a significant impact on the indoor radon concentration.

While no published studies of the impact of elevated radon concentrations in irrigation water could be found, it is likely that spray irrigation releases some radon to the environment. Tilling a typical 40-acre field to a depth of 0.15 meters could result in release of approximately 0.01 Ci of Rn-222. Spray irrigation with water at a Rn-222 concentration of 1000 pCi/L would add a total of 0.06 Ci per year to the environment. In both cases the amount of radon added to the global radon in outdoor air would be negligible.

Volume of soil = 40 acres x 4.05×10^{7} cm^2/acre x 15 cm = 2.43×10^{10} cm^3

Assume a soil density of 1.6 g/m^2, background Ra-226 activity concentration of 1.0 pCi/g and a Rn-226 emanation fraction of 0.3, the total amount of Rn-222 released would be as follows:

Rn-222 release = 2.43×10^{10} cm^3 x 1.6 g/cm^3 x 1.0 pCi/g x 0.3 = 1.2×10^{10} pCi = 0.012 Ci

Total Rn-222 released annually during spray irrigation at a rate of 0.5 m/y and a Rn-222 concentration in irrigation water of 1,000 pCi/L, the total Rn-222 release would be as follows:

Rn-222 release = $1x10^3$ pCi/L x 40 acres x 4.05 x 10^7 cm^2/m^2 x 50 cm/y x 10^{-3} L/cm^3 x 0.7 = 5.7 pCi/y = 0.057 Ci/y

6.3 Radon Releases from Saturated and Water Covered Tailings

Radon releases from water covered and saturated tailings have been assumed to be negligible since the diffusion coefficient of Rn-222 in water is very low, i.e., 10^{-5} cm2/s; however there are some studies that show that advective transport of radon may occur, reducing the effectiveness of water in reducing radon flux (Nielson, 1986). Nielson and his colleagues measured radon flux from a water column over tailings in the laboratory. They found a mean reduction in radon flux for saturated beach areas of approximately a factor of 10 and a reduction for the pond area by a factor of 20. No field measurements were observed that verify those laboratory results.

An Australian study of the effect of moisture on radon emanation from tailings found that the flux increased with moisture content from the absolutely dry state (0.2% moisture) to a moisture content of 2% (Strong, 1982). However the water saturated tailings had the lowest measured flux. The calculated flux from an infinitely thick pile was four times as great for moist tailings compared to dry tailings and a factor of 28 times lower for saturated tailings. This ratio for saturated tailings is consistent with the Neilson study.

6.4 Radon Releases from Evaporation Ponds

In contrast to tailings impoundments, the Rn-222 in evaporation pond water comes from Ra-226 in the water itself rather than the submerged Ra-226 bearing tailings. In response to public concerns that the Rn-222 flux from evaporation ponds at in situ facilities as well as conventional mills was not being taken into account in dose assessments, the EPA required that certain uranium recovery facilities measure flux from water covered surfaces. This presented a significant challenge since the standard flux measurement technique (Method 115), which uses charcoal to accumulate radon, would not be appropriate for use on water surfaces. However, methods to keep the charcoal canister dry while in place on water surfaces were devised and field tested on an evaporation pond at the Homestake Mining Company facility in New Mexico (Baker, 2010). A stagnant film model for transport of a gas across an air-water interface indicated that the Rn-222 flux in pCi/m^2-s would be equal to a factor of 0.01 times the Rn-222 concentration in the water in pCi/L (Schwarzenbach, 2002). Assuming the stagnant film model and a measured Ra-226 concentration in water of 165 pCi/L with Rn-222 in equilibrium with the Ra-226, the flux should be approximately 1.6 pCi/m^2-s. For the field test, the Method 115 flux

canister was mounted in a foam base that would float on the water surface. The mean measured flux for five canisters was 1.13 pCi/m^2-s, in reasonable agreement with the calculated value.

These data indicate that while the radon flux from saturated tailings beaches and submerged tailings is at least an order of magnitude lower than the flux from unsaturated tailings, these areas could contribute to the total flux from a tailings impoundment. It is important to note the results of the Nielson work with caution, since no publications reporting on tests replicating the work have been found in the literature.

Radon flux from evaporation ponds is not likely to contribute greatly to the overall radon release from a site; however, radon releases from active spray evaporation should be evaluated. As part of the EPA investigation, radon monitors were deployed at various heights and distances from the edge of an evaporation pond at an ISL facility in Wyoming. The measured radon concentrations were either less than or indistinguishable from background values indicating that the radon flux from the evaporation pond, if any, did not impact the ambient radon concentration even at the edge of the pond.

6.5 Specific Points for Consideration - Radon Releases from Wet Media

Based on the evaporation pond tests and the measured radon concentrations at the edge of the ponds, no additional monitoring is required for such facilities. Ambient radon concentration measurements will capture any impact of evaporation ponds. 40 CFR 61 Subparts T and W do not apply to evaporation ponds. Unless the revised EPA Subpart W adds such facilities, there is no need to measure flux. If Subpart W is revised to include a requirement for accounting for the flux from evaporation ponds, a provision should be added to the regulations to allow for calculating the flux rather that measuring it.

The potential flux from saturated tailings beaches should be measured or calculated and incorporated into the average flux for demonstrating compliance with Subpart W. Given the limited area for “new” tailings impoundments under Subpart W and the move towards dewatered “paste tailings”, there does not seem to be a need to measure or calculate the contribution from ponded water. The available data are not an adequate basis for requiring such measurements.

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Table 2.1 General Summary of Air Emission Sources and Types

		Emissions Type								
Sources Area	**Source**	**Fugitive Dust**	**VOC/SVOC**	**CO**	**NOx**	**SO_2**	**Ozone**	**Radio-Particulates**	**Radon**	**Gamma**
Underground Mine										
	Generators/Emergency Power	**X**	**X**	**X**	**X**	**X**				
	Mobile equipment	**X**	**X**	**X**	**X**	**X**				
	Vent Shafts	**X**						**X**	**X**	
	Mine Solids (ore, topsoil, overburden)	**X**						**X**	**X**	**X**
	Fuel storage		**X**							
	Roads (unpaved)	**X**						**X**		**X**
	Material loading and transfer points	**X**						**X**	**X**	**X**
	Crushing/screening	**X**						**X**	**X**	**X**
Surface Mine										
	Mobile equipment	**X**	**X**	**X**	**X**	**X**				
	Mine Solids (ore, topsoil, overburden)	**X**						**X**	**X**	**X**
	Fuel storage		**X**							
	Roads (unpaved)	**X**								
	Material loading and transfer points	**X**						**X**	**X**	**X**
	Crushing/screening	**X**						**X**	**X**	**X**

Table 2.1 General Summary of Air Emission Sources and Types (continued)

		Emissions Type								
Sources Area	**Source**	**Fugitive Dust**	**VOC/SVOC**	**CO**	**NOx**	**SO_2**	**Ozone**	**Radio-Particulates**	**Radon**	**Gamma**
Mills/ISR	Ore stockpiles	**X**						**X**	**X**	**X**
	Mill Vent Stacks	**X**						**X**	**X**	**X**
	Material loading and transfer points	**X**						**X**	**X**	**X**
	Tailings	**X**						**X**	**X**	**X**
	Heap Leach Pad	**X**						**X**	**X**	**X**
	Waste Storage Ponds/Evap Ponds	**X**						**X**	**X**	**X**
	Reagent Storage/Transfer	**X**						**X**	**X**	**X**
	Crushing/screening	**X**						**X**	**X**	**X**

Emissions Types:

1. Fugitive Dust (PM_{10}, $PM_{2.5}$, diesel particulates, metals on particulates [i.e., lead, arsenic, mercury, etc.])
2. Volatile organic carbon compounds (VOC)/ Semi-volatile organic carbon compounds (SVOC)
3. Carbon monoxide (CO)
4. Nitrogen Oxides (NOx)
5. Sulfur dioxide (SO_2)
6. Ozone
7. Radioparticulates (Typically Unat, Ra-226, Pb-210, Th-230)
8. Radon (Rn-222)
9. Gamma radiation

Table 2.2 Sample AERMOD Meteorological Instrument Specifications

Level	Instrumentation	Range	Accuracy
10 meters	Horizontal wind speed sensor	0 to 50 m/s	± 5%
	Horizontal wind direction sensor	0 to 360 degrees	± 3 degrees
	Temperature sensor (with fan-aspirated shield)	-30 to +50°C	± 0.5 ^{o}C (delta T: 0.1 ^{o}C)
	Relative Humidity sensor	0 to 100%	± 7% RH
	Solar radiation sensor	0 – 1,300 w/m^2	± 5%
30 meters	Horizontal wind speed sensor	0 to 50 m/s	± 5%
	Horizontal wind direction sensor	0 to 360 degrees	± 3 degrees
	Vertical wind speed sensor	0 to 50 m/s	± 5%
	Temperature sensor (with fan-aspirated shield)	-30 to +50°C	± 0.5 ^{o}C (delta T: 0.1 ^{o}C)
Enclosed Cabinet	Data acquisition and storage	0 to 500 millivolts with (a minimum) of 5 differential terminal inputs)	0.1% of FSR
Tower	30 meter tower	N/A	N/A
0.5 meters	Tipping bucket rain gauge	0.01 inch per tip	0.5%
Ground Level	Evaporation Pan and Gauge	0 to 2 inches	± 10%

Table 2.3 Summary of NRC Regulatory Guide 3.63 Specification

Parameter	Comment	Range	Accuracy	Threshold	Instrument Height
Wind Speed		0 to 50 mph	±0.5 mph up to 5 mph, 10% of reading above	1.0 mph	10 meters
Wind Direction		0 to 360º	±5º	1.0 mph	10 meters
Temperature	(consistent with state of the art)				
Temperature Difference	(consistent with state of the art)				
Precipitation			0.01in, ±10% @ 0.2 in or greater	0.01 inch	
Evaporation	(consistent with state of the art)				
Solar Rad.					
Relative Humidity		0 – 100% -40º to 60ºC	±3% RH 10% to 90%	--	2 meters
Data Logger	Maximum Sampling Interval	60 sec.	--	--	--
Calibration	Calibration Freq.	2/year	--	--	--

Table 4.1 Uranium Sites Analyzed for Radon Risk Assessment

Mill/Mine	Type	State	Regulator
Canon City Mill	Conventional	Colorado	Colorado
White Mesa Mill	Conventional	Utah	Utah
Sweetwater Mill	Conventional	Wyoming	NRC
Alta Mesa 1,2,3	In situ leach	Texas	Texas
Kingsville Dome 1,3	In situ leach	Texas	Texas
Smith Ranch-Highland	In situ leach	Wyoming	NRC
Crow Butte	In situ leach	Nebraska	NRC
Christensen/Irigaray	In situ leach	Wyoming	NRC
Western Generic Mill	Conventional	New Mexico	NRC
Eastern Generic Mill	Conventional	Virginia	For the purpose of the risk assessment, assumed to be NRC

Table 4.2: Calculated Average Total Annual RMEI, Population Dose and Risk

Uranium Site	Average Rn Release (Ci/y)	Annual Dose		Latent Cancer Fatalities per year of exposure	
		Population (person-rem*)	RMEI (mrem**)	Population	RMEI
Canon City Mill	146	28.6	6.0	1.8E-4	3.1E-6
White Mesa Mill	1,388	3.0	7.0	2.0E-5	3.7E-6
Sweetwater Mill	1,204	0.3	0.7	1.7E-6	3.5E-7
Alta Mesa 1,2,3	472	12.5	6.7	7.6E-5	3.E-6
Kingsville Dome 1,3	1,291	33.6	6.6	2.2E-4	3.5E-6
Smith Ranch-Highland	21,100	2.2	0.9	1.3E-5	4.5E-7
Crow Butte	4,467	1.6	1.9	1.0E-5	1.0E-6
Christensen/Irigaray	1,040	2.2	1.1	1.4E-5	5.7E-7
Western Generic Mill	1,388	3.0	3.5	1.6E-4	4.4E-6
Eastern Generic Mill (Culpepper County, Virginia)	1,388	116.3	16.4	7.9E-4	9.2E-6

*The Cohen document is confusing in regard to the dose units. In one table the population dose is given in person-rem; in the table from which this information was taken, the population dose is given in person-mrem. This appears to be a typographical error.
**The Cohen document also appears to have confused the RMEI dose units. The table from which this information was taken gives the RMEI dose in rem. That is not possible under these conditions so, as with the population dose unit, this was assumed to be a typographical error.

[The cancer risks for the RMEI were apparently calculated using a risk coefficient of approximately 5E-7 per mrem, a standard value for radiation risk. The risk coefficient used for the population risks appears to be different. The Cohen report did not describe in detail the risk calculation method. The risks may have been automatically calculated by the CAP-88 code.]