Technical and Regulatory Support to Develop a Rulemaking to Potentially Modify the NESHAP Subpart W Standard for Radon Emissions from Operating Uranium Mills (40 CFR 61.250)

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
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ACRONYMS AND ABBREVIATIONS

ACE	Army Corps of Engineers
AEA	Atomic Energy Act
AIRDOS	AIR DOSe
ALARA	as low as reasonably achievable
AMC	American Mining Congress
ANPR	Advance Notice of Proposed Rulemaking
$BaCl_2$	barium chloride
BEIR	Biological Effects of Ionizing Radiation
BID	background information document
CAA	Clean Air Act
CAP88	Clean Air Act Assessment-1988
CFR	*Code of Federal Regulations*
CHP	certified health physicist
Ci/yr	curies per year
cm	centimeter
cm/sec	centimeter per second
cm^2/sec	square centimeter per second
CPI	consumer price index
CPP	Central Processing Plant
DARTAB	Dose And Risk TABulation
DOE	Department of Energy
EDF	Environmental Defense Fund
EIA	Energy Information Administration
EIS	environmental impact statement
EPA	Environmental Protection Agency
E-PERM	Electric Passive Environmental Radon Monitor
FGR	Federal Guidance Report
FR	*Federal Register*
ft	feet
g/cc	gram per cubic centimeter
G&A	general and administrative

GACT	generally available control technology
GCL	geosynthetic clay liner
GHG	Greenhouse Gas
gpm	gallons per minute
gpm/ft^2	gallons per minute per square foot
H_2SO_4	sulfuric acid
HAP	hazardous air pollutant
HDPE	high-density polyethylene
HRTM	Human Respiratory Tract Model
ICRP	International Commission on Radiological Protection
in/yr	inches per year
ISL	in-situ leach
ISR	in-situ recovery
km	kilometer
L	liter
LAACC	large-area activated charcoal collector
lb	pound
LCF	latent cancer fatalities
L/d	liters per day
LLDPE	linear low-density polyethylene
LoC	line of credit
m^2	square meters
m^3/hr	cubic meters per hour
m/sec	meters per second
MACT	maximum achievable control technology
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
mi	mile
MIR	maximum individual risk
mph	miles per hour
mrem	millirem
mSv	millisievert
N.C.	not calculated
NESHAP	National Emission Standard for Hazardous Air Pollutants

N.G.	not given
NMA	National Mining Association
NRC	Nuclear Regulatory Commission
NRDC	Natural Resources Defense Council
O&M	operation and maintenance
ORISE	Oak Ridge Institute for Science and Education
pCi	picocurie
pCi/(ft^2-sec)	picocurie per square foot per second
pCi/g	picocurie per gram
pCi/L	picocurie per liter
pCi/(m^2-sec)	picocurie per square meter per second
PIPS	passive implanted planar silicon
POO	Plan of Operation
PVC	polyvinyl chloride
R&D	research and development
Ra	radium
RADRISK	RADiation RISK
RCRA	Resource Conservation and Recovery Act
rem	roentgen equivalent in man
RMEI	reasonably maximally exposed individual
Rn	radon
RSO	radiation safety officer
SC	Sierra Club
SF	square foot
tpd	tons per day
U	uranium
U_3O_8	triuranium octoxide
UMTRCA	Uranium Mill Tailings Remedial Control Act
WCS	Waste Control Specialists, LLC
WL	working level
WLM	working level month
ZnS(Ag)	silver doped zinc sulfide

1.0 EXECUTIVE SUMMARY

The purpose of this report is to present the reader with an understanding of the facilities being regulated under this National Emission Standard for Hazardous Air Pollutant (NESHAP). The report also presents the technical bases that the Environmental Protection Agency (EPA or the Agency) has used for evaluating the risks from existing facilities and for determining that the prescribed work practice standards represent generally available control technology (GACT), as required by section 112(d) of the 1990 amendments to the Clean Air Act (CAA).

The Agency is also defining the scope of its review of the Subpart W NESHAP to include the waste impoundments at in-situ leach (ISL) uranium recovery facilities and heap leach recovery operations, since all post-1989 impoundments, which potentially contain uranium byproducts, are considered to be under the NESHAP. The Agency has defined the scope of the review to include regulation of the heap leach pile, as it believes the pile contains byproduct material during operations.

1.1 Introduction, History, and Basis

After a brief introduction, this report describes the events that led the Agency to promulgate a NESHAP for radon emissions from operating uranium mill tailings on December 15, 1989, in Section 40 of the *Code of Federal Regulations* (40 CFR) Part 61, Subpart W. The 1977 amendments to the CAA include the requirement that the Administrator of EPA determines whether radionuclides should be regulated under the act. In December 1979, the Agency published its determination in the *Federal Register* (FR) that radionuclides constitute a hazardous air pollutant (HAP) within the meaning of section 112(a)(1). In 1979, the Agency also developed a background information document (BID) to characterize “source categories” of facilities that emit radionuclides into ambient air, and in 1983, EPA proposed radionuclide NESHAPs for four source categories based on the results reported in a new BID. On September 24, 1986, the Agency issued a final NESHAP for operating uranium mill tailings, establishing an emission standard of 20 picocuries per square meter per second (pCi/(m^2-sec)) for radon (Rn)-222 and a work practice standard requiring that new tailings be disposed of in small impoundments or by continuous disposal. Between 1984 and 1986, the Environmental Defense Fund (EDF), the Natural Resources Defense Council (NRDC), the Sierra Club (SC), and the American Mining Congress (AMC) filed various court petitions seeking modifications to the NESHAPs.

In a separate decision, the U.S. District Court for the District of Columbia outlined a two-step decision process that it would find acceptable, first establishing a standard based solely on an acceptable level of risk, and then considering additional factors, such as costs to establish the “ample margin of safety.”

Section 112(q)(1) of the 1990 CAA Amendments requires that certain emission standards shall be reviewed, and if appropriate, revised to comply with the requirements of section 112(d). Subpart W is under review/revision in response to that requirement. Section 112(d) of the 1990 CAA Amendments lays out requirements for promulgating technology-based emissions standards for new and existing sources. In accordance with section 112(d), the Administrator has elected to promulgate standards that provide for the use of GACT or management practices to regulate radon emissions from uranium recovery facility tailings impoundments noted in Subpart W.

1.2 The Uranium Extraction Industry Today

From 1960 to the mid-1980s, there was considerable uranium production in the states of Colorado, Nebraska, New Mexico, South Dakota, Texas, Utah, Wyoming, and Washington. In the early years, the uranium recovery industry consisted of mines (open pit and underground) that were associated with conventional uranium milling operations. Because of overproduction, the price of uranium rapidly declined in the 1980s. The declining uranium market could not support the existing number of uranium recovery operations, and many of the uranium recovery facilities in the United States were closed, decommissioned, and reclaimed. In the mid- to late 1980s, several uranium recovery projects employing the solution, or ISL, mining process came on line. However, because of a need for clean energy, a need to develop domestic sources of energy, and other reasons, current forecasts predict growth in the U.S. uranium recovery industry over the next decade and continuing into the future.

Conventional uranium mining and milling facilities are one of two types of uranium recovery facilities that currently possess state or federal licenses to operate. Representative of the extent of the conventional uranium milling operations that currently exist and are licensed in the United States are the mills at Sweetwater, Wyoming; Shootaring Canyon, Utah; and White Mesa, Utah. Only the White Mesa mill is currently in operation. A conventional mill at Piñon Ridge, Colorado, is currently in the planning and licensing stage. Additionally, a total of six potentially new conventional mill facilities are being discussed in New Mexico, Wyoming, Utah, and Arizona.

The radon data for the conventional mill tailings impoundments indicate that the radon exhalation rates from the surfaces are generally within the Subpart W standard of 20 pCi/(m^2-sec), but occasionally the standard may be exceeded. When that occurs, the tailings are usually covered with more soil, and the radon flux is reduced.

Solution, or ISL, mining is defined as the leaching or recovery of uranium from the host rock by chemicals, followed by recovery of uranium at the surface. ISL mining was first conducted in Wyoming in 1963. The research and development projects and associated pilot projects in the 1980s demonstrated solution mining to be a viable uranium recovery technique. Ten ISL facilities are currently operating (see Table 8, page 33), and about 23 other facilities are restarting, expanding, or planning for new operations.

Uranium is leached into solution through the injection into the ore body of a lixiviant. A lixiviant is a chemical solution used to selectively extract (or leach) uranium from ore bodies where they are normally found underground. The injection of a lixiviant essentially reverses the geochemical reactions that are associated with the uranium deposit. The lixiviant ensures that the dissolved uranium, as well as other metals, remains in solution while it is collected from the mining zone by recovery wells.

During typical solution mining, a portion of the lixiviant is bled off in order to control the pressure gradient within the wellfield. The liquid bled from the lixiviant is sent to an evaporation pond, or impoundment. Since radium (Ra)-226 is present in the liquid bled from the lixiviant, radon will be generated in and released from the ISL's evaporation/holding ponds/ impoundments. The amount of radon released from these evaporation/holding ponds has been estimated and found to be small. (See Section 3.3.1.)

Heap leaching is a process by which chemicals are used to extract the economic element (for the purposes of Subpart W, uranium) from the ore. A large area of land is leveled with a small gradient, and a liner and collection system are installed. Ore is extracted from a nearby surface or underground mine and placed in heaps atop the liner. A leaching agent (usually an acid) will then be sprayed on the ore. As the leaching agent percolates through the heap, the uranium is mobilized and enters the solution. The solution will flow to the bottom of the pile and then along the gradient into collecting pools, from which it will be pumped to an onsite processing plant. In the past, a few commercial heap leach facilities operated but none is now operating. Planning and engineering have been undertaken for two heap leach facilities, one in Wyoming and the other in New Mexico.

A brief review of Method 115, "Monitoring for Radon-222 Emissions" (40 CFR 61, Appendix B) (SC&A 2008), demonstrated that its use can still be considered current for monitoring radon flux from conventional uranium tailings impoundments. It is not an option for measuring radon emissions from evaporation or holding ponds because there is no solid surface on which to place the monitors.

1.3 Current Understanding of Radon Risk

A description of how the understanding of the risk presented by radon and its progeny has evolved since the 1989 BID was published examines three parameters: (1) the radon progeny equilibrium fraction, (2) the epidemiological risk coefficients, and (3) the dosimetric risk coefficients. Additionally, SC&A (2011) used the computer code CAP88 version 3.0 (Clean Air Act Assessment Package-1988) to analyze the radon risk from eight operating uranium recovery sites, plus two generic sites.

The lifetime (i.e., 70-year) maximum individual risk (MIR)[1] calculated using data from eight actual uranium recovery sites was determined to be between 2.45×10^{-5} to 2.59×10^{-4}. The low end of the range is lower than the 3×10^{-5} lifetime MIR reported in the 1989 rulemaking for existing impoundments, while the high end of the range is slightly higher than the 1.6×10^{-4} lifetime MIR reported in the 1989 rulemaking for new impoundments. (SC&A 2011)

To protect public health, EPA strives to provide the maximum feasible protection by limiting radon exposure to a lifetime MIR of approximately 1 in 10 thousand (i.e., 10^{-4}). Although the calculated high end of the lifetime MIR range is above 10^{-4}, there are several mitigating factors. First, the highest MIR was calculated for a hypothetical mill at an eastern generic site. If an actual mill were to be located at the Eastern Generic site, it would be required to reduce its radon

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[1] In this BID all risks are presented as mortality risks. If it is desired to estimate the morbidity risk, simply multiply the mortality risk by 1.39.

emissions as part of its licensing commitments. Also, the assumptions that radon releases occur continuously for 70 years and that the same reasonably maximally exposed individual (RMEI) is exposed to those releases for the entire 70 years are very conservative.

Likewise, the risk assessment estimated that the risk to the population from all eight real uranium sites is between 0.0005 and 0.0009 fatal cancers per year, or approximately one case every 1,080 to 1,865 years to the 1.8 million persons living within 80 kilometers (km) of the sites. For the 1989 rulemaking, the estimated annual fatal cancer incidence to the 2 million people living within 80 km (50 miles) was 0.0043, which was less than one case every 200 years, for existing impoundments and 0.014, or approximately one case every 70 years, for new impoundments.

1.4 Evaluation of Subpart W Requirements

EPA has determined that radon releases from uranium recovery facilities are HAPs, as defined by the CAA. Furthermore, no radionuclide (including radon) releases have met the CAA's definition of major sources, and thus radon releases from uranium recovery facilities are classified as area sources. (See Section 5.3.) Under section 112(d) of the CAA, the EPA Administrator may elect to promulgate standards or requirements applicable to area sources that provide for the use of GACTs or management practices to reduce emissions of HAPs. For the four source categories of radon releases from uranium recovery facilities, the Administrator has elected to promulgate GACTs as follows:

Conventional Impoundments – Constructed on or before December 15, 1989

GACT The flux standard of 20 pCi/(m^2-sec) contained in the current 40 CFR 61.252(a) will no longer be required; require that these conventional impoundments be operated to meet one of two work practices: phased disposal and continuous disposal, contained in the current 40 CFR 61.252(b).

Conventional Impoundments – Constructed after December 15, 1989

GACT Retain the standard that conventional impoundments be designed, constructed, and operated to meet one of two work practices: phased disposal and continuous disposal, contained in the current 40 CFR 61.252(b).

Nonconventional Impoundments – Where uranium byproduct material (i.e., tailings) are contained in ponds and covered by liquids

GACT Retain the design and construction requirements of 40 CFR 192.32(a)(1), with no size/area restrictions, and require that during the active life of the pond, at least 1 meter of liquid be maintained in the pond.

Heap Leach Piles

GACT Retain the design and construction requirements of 40 CFR 192.32(a)(1), and require that the moisture content of the operating heap be maintained at or greater than 30 percent.

Additionally, the analyses provided in this BID support the following findings:

- Subpart W continues to be the appropriate regulatory tool to implement the Administrator's duty under the CAA for operating uranium mill tailings.
- By requiring that conventional impoundments be designed, constructed, and operated to meet one of two 40 CFR 61.252(b) work practices (i.e., phased disposal and continuous disposal), adoption of an emission limit (e.g., 20 pCi/(m^2-sec)) is not necessary to protect public health.
- The requirement that conventional impoundments use either phased or continuous disposal technologies is appropriate to ensure that public health is protected with an ample margin of safety, and is consistent with section 112(d) of the 1990 CAA Amendments that require standards based on GACT.
- The standard should be clarified to ensure that all owners and operators of uranium recovery facilities (conventional mills, ISL, and heap leach) are aware that all of the structures/facilities they employ to manage uranium byproduct material (i.e., tailings) are regulated under Subpart W.

1.5 Economic Impacts

The economic impact analysis to support any potential revision of the Subpart W NESHAP is presented in four distinct areas:

(1) A review and summary of the original 1989 economic assessment and supporting documents are provided.

(2) The baseline economic costs for development of new conventional mills, ISL facilities, and heap leach facilities are developed and presented.

(3) The anticipated costs to the industries versus the environmental and public health benefits to be derived from each of the four proposed GACTs are discussed.

(4) Finally, information is provided on the economic impacts to disadvantaged and tribal populations and on environmental justice.

The baseline costs were estimated using recently published cost data for actual uranium recovery facilities. For conventional mills, data from the proposed new mill at the Piñon Ridge project in Colorado were used. Data from two proposed new ISL facilities were used; the first was the Centennial Uranium project in Colorado and the second was the Dewey-Burdock project in South Dakota. The Centennial project is expected to have a 14 to 15-year production period, which is a long duration for an ISL facility, while the Dewey-Burdock project is expected to have a shorter production period of about 9 years, which is more representative of ISL facilities. For the heap leach facility, data from the Sheep Mountain project in Wyoming were used. Table 1 summarizes the unit cost (dollars per pound) estimates for all four uranium recovery facilities. As shown, on a unit cost basis, heap leach facilities are projected to be the least expensive, and the two ISL facilities the most expensive.

Table 1: U_3O_8 Market Value and Cost to Produce (Nondiscounted)

Average U_3O_8 Price ($/lb)	$65.00	
Average U_3O_8 Cost ($/lb)	w/ LoC	w/o LoC
Conventional	$51.56	$47.24
ISL (Long)	$53.89	$51.81
ISL (Short)	$52.49	$51.46
Heap Leach	$46.08	$42.87

Because the four proposed GACTs are not expected to change the manner in which any of the uranium recovery facilities are designed, built, or operated, no additional economic benefits or costs are associated with the proposed Subpart W revisions.

At 10 of the 15 existing or proposed uranium recovery sites analyzed, the percentage of Native Americans in the population exceeds the national norm, while at nine sites, the percentage of Native Americans in the population exceeds the regional norm. At 11 of the 15 sites, the percentage of the population that is white exceeds both the national and regional norms. Finally, the percentage of the population at all uranium recovery sites that is either African-American or Other is less than the national norm, while the percentage of African-Americans and Others is less than the regional norm at all but one site. The analysis found that uranium recovery facilities are located in areas that are very poor (i.e., ranked in the lowest 0.6% in the country) to areas that are more economically advantaged (i.e., ranked in the 91.2 percentile). Six of the 15 sites are located in areas that have per capita nonfarm wealth that is above the United States' 50th percentile. On the other hand, five sites are located in areas where the per capita nonfarm wealth is below the country's 10th percentile.

2.0 INTRODUCTION, HISTORY, AND BASIS

On December 15, 1989, EPA promulgated a NESHAP for radon emissions from operating uranium mill tailings (40 CFR 61, Subpart W). Section 112(q) of the CAA, as amended, requires EPA to review, and if appropriate, revise or update the Subpart W standard on a timely basis (within 10 years of passage of the CAA Amendments of 1990). Soon after the original promulgation of the standard, the uranium industry in the United States declined dramatically. However, recent developments in the market for uranium have led to some companies expressing their intention to pursue licensing of new facilities, and therefore, EPA is reviewing the necessity and adequacy of the Subpart W regulations before these proposed facilities become operational.

Two separate standards are defined in Subpart W. The first states that existing sources (facilities constructed before December 15, 1989) must ensure that emissions to the ambient air from an existing uranium mill tailings pile shall not exceed 20 pCi/(m^2-sec) or 1.9 picocuries per square foot per second (pCi/(ft^2-sec)) of Rn-222. To demonstrate compliance with this emission standard, facilities are required to monitor emissions in accordance with Method 115 of 40 CFR 61, Appendix B, and file an annual report with EPA showing the results of the compliance monitoring. The second Subpart W standard prescribes that for new sources (facilities constructed on or after December 15, 1989), no new tailings impoundment can be built unless it is designed, constructed, and operated to meet one of the two following work 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 U.S. Nuclear Regulatory Commission (NRC). 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 of with no more than 10 acres uncovered at any time and operated in accordance with 40 CFR 192.32(a) as determined by the NRC.

The work practice standard also applies to operations at existing sources, once their existing impoundments can no longer accept additional tailings.

The facilities covered by Subpart W are uranium recovery facilities, also licensed and regulated by the NRC or its Agreement States. The NRC becomes involved in uranium recovery operations once the ore is processed and chemically altered. This occurs either in a uranium mill (the next step from a conventional mine) or during ISL or heap leach. For this reason, the NRC regulates ISL facilities, as well as uranium mills and the disposal of liquid and solid wastes from uranium recovery operations (including mill tailings), but does not regulate the conventional uranium mining process. The NRC regulations for the protection of the public and workers from exposure to radioactive materials are found in 10 CFR 20, while specific requirements for the design and operation of uranium mills and disposition of tailings are found in 10 CFR 40, Appendix A.

2.1 Document Contents and Structure

This report is divided into six sections. The first two sections are the Executive Summary and this introduction, which includes discussions of the history of the development of Subpart W (Section 2.2) and the basis for the 1989 risk assessments (Section 2.3). Four technical sections, the contents of which are summarized below, follow this introductory section.

2.1.1 The Uranium Extraction Industry Today

After a brief history of the uranium market, Section 3.0 identifies both the uranium recovery facilities that are licensed today and those that have been proposed to be built in the future.

For currently existing impoundments, Section 3.0 presents the following information:

- Data on the configuration of current impoundments.
- Results of compliance monitoring.

Section 3.0 also presents a description of the Method 115 radon monitoring method.

2.1.2 Current Understanding of Radon Risk

Section 4.0 presents a qualitative analysis of the changes that have occurred in the understanding of the risks associated with Rn-222 releases from impoundments. Emphasis is on the changes to the predicted radon progeny equilibrium fractions and the epidemiological and dosimetric lifetime fatal cancer risk per working level (WL). Section 4.0 also discusses how the current analytical computer model, CAP88 Version 3.0, evolved from and differs from the models used for the 1989 risk assessment (i.e., AIRDOS-EPA, RADRISK, and DARTAB). Finally, Section 4.4 presents dose and risk estimates for several current uranium recovery facilities.

2.1.3 Evaluation of Subpart W

The evaluation of Subpart W requirements required the analyses of some key issues to determine if the current technology has advanced since the 1989 promulgation of the rule. The key issues include: existing and proposed uranium recovery facilities, Resource Conservation and Recovery Act (RCRA) comparison, regulatory history, tailings impoundment technologies, radon measurement methods, and risk assessment. Section 5.0 discusses these key issues, in order to determine whether the requirements of Subpart W are necessary and sufficient.

Based on the evaluation of the key issues and in keeping with section 112(d) of the CAA, Section 5.0 also presents GACT radon emission control standards for three categories of uranium recovery facilities:

(1) Conventional impoundments.

(2) Nonconventional impoundments, where uranium byproduct material (i.e., tailings) is contained in ponds and covered by liquids.

(3) Heap leach piles.

In addition to the key issues, several issues that need clarification in order to be more fully understood are presented and described. The issues in need of clarification include extending monitoring requirements, defining when the closure period for an operating facility begins, interpretation of the term “standby,” the role of weather events, and monitoring reporting requirements.

2.1.4 Economic Impact Analysis

Section 6.0 of the document reviews and reassesses all the additional economic impacts that may occur due to the extension and revision of the Subpart W NESHAP and specifically addresses the following:

- A review and summary of the original 1989 economic assessment and supporting documents are provided.

- The baseline economic costs for the development of new conventional mills and ISL and heap leach facilities are developed and presented.

- The anticipated costs to industries versus environmental and public health benefits to be derived from each of the four proposed GACTs are discussed.

- Finally, information is provided relating to economic impacts on disadvantaged populations and tribal populations and to environmental justice.

2.2 History of the Development of the Subpart W NESHAP

The following subsections present a brief history of the development of environmental radiation protection standards by EPA, with particular emphasis on the development of radionuclide NESHAPs.

Table 2 presents a partial time line sequence of EPA's radiation standards with emphasis on the NESHAPs, including Subpart W.

Table 2: Partial Timeline of EPA's Radiation Standards

January 13, 1977	EPA publishes 40 CFR 190 – Environmental Protection Standards for Nuclear Power Operations.
August 1979	EPA publishes first BID, *Radiological Impacts Caused by Emission of Radionuclides into Air in the United States*, EPA 520/7-79-006.
December 27, 1979	EPA determines radionuclides constitute a HAP – (section 112(a)(1) amendments to the CAA.
January 5, 1983	EPA under UMTRCA promulgates, 40 CFR 192, Subpart B "Standards for Cleanup of Land and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites," that for inactive tailings or after closure of active tailings, the radon flux should not exceed an average release rate of 20 pCi/(m^2-sec).
March 1983	EPA publishes draft report, *Background Information Document Proposed Standards for Radionuclides*, EPA 520/1-83-001, and proposes radionuclide NESHAPs for: 1. DOE and Non-NRC-Licensed Federal Facilities. 2. NRC-Licensed Facilities. 3. Elemental Phosphorus Plants. 4. Underground Uranium Mines.
September 30, 1983	EPA issues standards under UMTRCA (40 CFR 192, Subparts D and E) for the management of tailings at locations licensed by the NRC or the States under Title II of the UMTRCA. These standards do not specifically limit Rn-222 emissions until after closure of a facility; however, they require ALARA procedures for Rn-222 control.
February 17, 1984	SC sues EPA (District Court for Northern California) and demands EPA promulgate final NESHAP rules for radionuclides or find that they do not constitute a HAP (i.e., "de-list"" the pollutant). In August 1984, the court grants the SC motion and orders EPA to take final actions on radionuclides by October 23, 1984.
October 22, 1984	EPA issues *Final Background Information Document Proposed Standards for Radionuclides*, EPA 520/1-84-022-1and -2.
October 23, 1984	EPA withdraws the proposed NESHAPs for elemental phosphorus plants, DOE facilities, and NRC-licensed facilities.

Table 2: Partial Timeline of EPA's Radiation Standards

December 1984	District Court finds EPA in contempt. EPA and SC submit motion to court with schedule (August 5, 1985). Court orders EPA to issue final standards for Rn-222 emissions from licensed uranium mills and mill tailings impoundments by May 1, 1986 (later moved to August 15, 1986).
February 6, 1985, to September 24, 1986	EPA promulgates NESHAPs for: 1. DOE Facilities (February 1985). 2. NRC-Licensed Facilities and Non-DOE Federal Facilities (February 1985). 3. Elemental Phosphorus Plants (February 1985). 4. On April 17, 1985, Rn-222 emissions from underground uranium mines added. 5. On September 24, 1986, Rn-222 from licensed uranium mill tailings added – 20 pCi/(m^2-sec) and the work practice standard for small impoundments or continuous disposal.
November 1986	AMC and EDF file petitions challenging the NESHAPs for operating uranium mills.
July 28, 1987	The Court of Appeals for the District of Columbia remanded to EPA the NESHAP for vinyl chloride (see text). Given the decision, EPA petitioned the court for a voluntary remand of standards and asked that the pending litigation on all issues relating to its radionuclide NESHAPs be placed in abeyance during the rulemaking. EPA also agreed to reexamine all issues raised by parties to the litigation. The court granted EPA's petition on December 8, 1987.
September 14, 1989	EPA promulgates NESHAPs for benzene, etc. Importantly, EPA establishes the "fuzzy bright line." That is, EPA's approach to residual risk under section 112 (as advanced in the Hazardous Organic NESHAPs and approved by the District of Columbia Circuit in *NRDC v. EPA*) as essentially establishing a "fuzzy bright line" with respect to carcinogens, whereby EPA must eliminate risks above one hundred in one million (1 in 10,000) , does not have to address risks below one in one million (1 in 1,000,000), and has discretion to set a residual risk standard somewhere in between (Jackson 2009). In a second step, EPA can consider whether providing the public with "an ample margin of safety" requires risks to be reduced further than this "safe" level, based on EPA's consideration of health information and other factors such as cost, economic impact, and technological feasibility (Jackson 2009).
September 1989	EPA publishes the NESHAPs for radionuclides. The agency prepared an EIS in support of the rulemaking. The EIS consisted of three volumes: Volume I, *Risk Assessment Methodology*; Volume II, *Risk Assessments*; and Volume III, *Economic Assessment.*
December 15, 1989	EPA promulgates NESHAPs for: • Subpart B: National Emission Standards for Radon Emissions from Underground Uranium Mines. • Subpart H: Emissions of Radionuclides Other than Radon from DOE Facilities. • Subpart I: National Emissions of Radionuclides Other than Radon from DOE Facilities by NRC and Federal Facilities Not Covered by Subpart H. • Subpart K: Radionuclide Emissions from Elemental Phosphorus Plants. • Subpart Q: Radon Emissions from DOE Facilities. • Subpart R: Radon Emissions from Phosphogypsum Stacks. • Subpart T: Radon Emissions from the Disposal of Uranium Mill Tailings. (rescinded effective June 29, 1994; published in the FR July 15, 1994). • Subpart W: Radon Emissions from Operating Uranium Mill Tailings Piles.
November 15, 1990	President signs the CAA Amendments of 1990. Part of the act requires that some regulations passed before 1990 be reviewed and, if appropriate, revised within 10 years of the date of enactment of the CAA Amendments of 1990. The amendments also instituted a technology-based framework for HAPs. Sources that are defined as large emitters are to employ MACT, while sources that emit lesser quantities may be controlled using GACT.

2.2.1 The 1977 Amendments to the Clean Air Act

On January 13, 1977 (FR 1977), EPA established environmental protection standards for nuclear power operations pursuant to its authority under the Atomic Energy Act (AEA). The standards in 40 CFR 190, which covered all licensed facilities that are part of the uranium fuel cycle, established an annual limit on exposure to members of the public. The NRC or its Agreement States, which licenses these facilities, has the responsibility for the enforcement of the Part 190 standards. Additionally, the NRC imposes the requirement that licensees keep all exposures "as low as reasonably achievable" (ALARA). The Part 190 standards exempted Rn-222 from the annual limit because of the uncertainties associated with the risk of inhaled radon.

After the promulgation of 40 CFR 190, the 1977 amendments to the CAA were passed. These amendments included the requirement that the Administrator of EPA determine whether radionuclides should be regulated under the CAA.

In December 1979, the Agency published its determination in the *Federal Register* (FR 1979) that radionuclides constitute a HAP within the meaning of section 112(a)(1). As stated in the FR, radionuclides are known to cause cancer and genetic defects and to contribute to air pollution that may be anticipated to result in an increase in mortalities or an increase in serious, irreversible, or incapacitating reversible illnesses. The Agency further determined that the risks posed by emissions of radionuclides into the ambient air warranted regulation and listed radionuclides as a HAP under section 112.

Section 112(b)(1)(B) of the CAA requires the Administrator to establish NESHAPs at a "level which (in the judgment of the Administrator) provides an ample margin of safety to protect the public health" or find that they are not hazardous and delist them.

2.2.2 Regulatory Activities between 1979 and 1987

To support the development of radionuclide NESHAPs, the Agency developed a BID to characterize "source categories" of facilities that emit radionuclides into ambient air (EPA 1979). For each source category, EPA developed information needed to characterize the exposure of the public. This included characterization of the facilities in the source category (numbers, locations, proximity of nearby individuals); radiological source terms (curies/year (Ci/yr)) by radionuclide, solubility class, and particle size; release point data (stack height, volumetric flow, area size); and effluent controls (type, efficiency). Doses to nearby individuals and regional populations caused by releases from either actual or model facilities were estimated using computer codes (see Section 2.3).

In 1983, EPA proposed radionuclide NESHAPs for four source categories based on the results reported in a new BID (EPA 1983). These four source categories were the Department of Energy (DOE) and non-NRC-licensed federal facilities, NRC-licensed facilities, elemental phosphorus plants, and underground uranium mines. For all other source categories considered in the BID (i.e., coal-fired boilers, the phosphate industry and other extraction industries, uranium fuel-cycle facilities, uranium mill tailings, high-level waste disposal, and low-energy accelerators), the Agency found that NESHAPs were not necessary. In reaching this conclusion, the Agency found that either the levels of radionuclide emissions did not cause a significant dose to nearby individuals or the regional populations, the additional effluent controls were not cost effective, or the existing regulations under other authorities were sufficient to keep emissions at an acceptable level.

During the public comment period on the proposed NESHAPs, the Agency completed its rulemaking efforts under the Uranium Mill Tailings Remedial Control Act (UMTRCA) to establish standards (40 CFR 192) for the disposal of uranium mill tailings. With respect to the emission of Rn-222, the UMTRCA standards established a design standard calling for an Rn-222 flux rate of no more than 20 pCi/(m^2-sec).

In February 1984, the SC sued EPA in the U.S. District Court for Northern California (*Sierra Club v. Ruckelshaus*, No. 84-0656) (EPA 1989), demanding that the Agency promulgate final NESHAPs or delist radionuclides as a HAP. The court sided with the plaintiffs and ordered EPA to promulgate final regulations. In October 1984, EPA withdrew the proposed NESHAPs for elemental phosphorus plants, DOE facilities, and NRC-licensed facilities, finding that existing control practices protected the public health with an ample margin of safety (FR 1984). EPA also withdrew the NESHAP for underground uranium mines, but stated its intention to promulgate a different standard and published an Advance Notice of Proposed Rulemaking (ANPR) to solicit additional information on control methods. It also published an ANPR for licensed uranium mills. Finally, the FR notice affirmed the decision not to regulate the other source categories identified in the proposed rule, with the exception that EPA was doing further studies of phosphogypsum stacks to see if a standard was needed.

In December 1984, the U.S. District Court for Northern California found EPA's action of withdrawing the NESHAPs to be in contempt of the court's order. Given the ruling, the Agency issued the final BID (EPA 1984) and promulgated final standards for elemental phosphorus plants, DOE facilities, and NRC-licensed facilities in February 1985 (FR 1985a), and a work practice standard for underground uranium mines in April of the same year (FR 1985b).

The EDF, the NRDC, and the SC filed court petitions seeking review of the October 1984 final decision not to regulate the source categories identified above, the February 1985 NESHAPs, and the April 1985 NESHAP. The AMC also filed a petition seeking judicial review of the NESHAP for underground uranium mines.

On September 24, 1986, the Agency issued a final NESHAP for operating uranium mill tailings (FR September 24, 1986), which established an emission standard of 20 pCi/(m^2-sec) for Rn-222 and a work practice standard requiring that new tailings be disposed of in small impoundments or by continuous disposal. One justifications for the work practices was that, while large impoundments did not pose an unacceptable risk during active operations, the cyclical nature of the uranium milling industry could lead to prolonged periods of plant standby and the risk that the tailings impoundments could experience significant drying, with a resulting increase in Rn-222 emissions. Furthermore, the Agency believed that the two acceptable work practices actually saved the industry from the significant costs of constructing and closing large impoundments before they were completely filled. With the promulgation of the NESHAP for operating uranium mill tailings, three EPA regulations covered the releases of radionuclides into the air during operations and tailings disposal at uranium mills: 40 CFR 190; 40 CFR 192; and 40 CFR 61, Subpart W.

In November 1986, the AMC and the EDF filed petitions challenging the NESHAP for operating uranium mill tailings.

2.2.3 Regulatory Activities between 1987 and 1989

While the petitions filed by the EDF, NRDC, SC, and AMC were still before the courts, the U.S. District Court for the District of Columbia, in *NRDC v. EPA* (FR 1989b), found that the Administrator had impermissibly considered costs and technological feasibility in promulgating the NESHAP for vinyl chloride. The court outlined a two-step decision process that it would find acceptable, first establishing a standard based solely on an acceptable level of risk and then considering additional factors, such as costs, to establish the "ample margin of safety." Given the court's decision, the Agency reviewed how it had conducted all of its NESHAP rulemakings and requested that the court grant it a voluntary remand for its radionuclide NESHAPs. As part of an agreement with the court and the NRDC, the Agency agreed to reconsider all issues that were currently being litigated, and it agreed that it would explicitly consider the need for a NESHAP for two additional source categories: radon from phosphogypsum stacks and radon from DOE facilities. The subsequent reconsideration became known as the radionuclide NESHAPs reconsideration rulemaking.

2.2.4 1989 Radionuclide NESHAPs Reconsideration Rulemaking

In the radionuclide NESHAPs reconsideration rulemaking, the Administrator relied on a "bright line" approach for determining whether a source category required a NESHAP. This meant that no NESHAP was required if all individuals exposed to the radionuclide emissions from the facilities in the source category were at a lifetime cancer risk of less than 1 in 1,000,000, and less than 1 fatal cancer per year was estimated to be incurred in the population. For source categories that did not meet this "bright line" exclusion, the Agency adopted a two-step, multi-factor approach to setting the emission standards.

The first step established a presumptively acceptable emissions level corresponding to an MIR of about 1 in 10,000 lifetime cancer risk, with the vast majority of exposed individuals at a lifetime risk lower than 1 in 1,000,000, and with less than 1 total fatal cancer per year in the exposed population. If the baseline emissions from a source category met these criteria, they were presumed adequately safe. If they did not meet these criteria, then the Administrator was compelled by his nondiscretionary duty to determine an emission limit that would correspond to risks that were adequately safe.

After baseline emissions were determined to be adequately safe or an adequately safe alternative limit defined, the analysis moved to the second step, where reduced risks for alternative emission limits were evaluated, along with the technological feasibility and costs estimated to be associated with reaching lower levels. In the two-step approach, the Administrator retained the discretion to decide whether the NESHAP should be set at these lower limits.

2.2.5 1990 Amendments to the Clean Air Act

NESHAP Subpart W is under consideration for revision because section 112(q)(1) requires that certain emission standards in effect before the date of enactment of the 1990 CAA Amendments shall be reviewed and, if appropriate, revised to comply with the requirements of section 112(d). As stated previously, soon after the original promulgation of the standard, the uranium industry in the United States declined dramatically, negating the need to perform the Subpart W review. However, as discussed in Section 3.1, recent developments in the market for uranium have led to forecasts of growth in the uranium market over the next decade and continuing for the foreseeable future. Therefore, EPA is reviewing the necessity and adequacy of the Subpart W regulations at this time, before facilities developed in response to those forecasts become operational.

Section 112(d) of the 1990 CAA Amendments lays out requirements for promulgating technology-based emissions standards for new and existing sources. Section 112(c) lists radionuclides, including radon, as an HAP, while section 112(a) defines two types of HAP sources: major sources and area sources. Depending on whether the source is a major or area source, section 112(d) prescribes standards for the regulation of emissions of HAPs.

The regulation of HAPs at major sources is dictated by the use of maximum achievable control technology (MACT). Section 112(d) defines MACT as the maximum degree of reduction in HAP emissions that the Administrator determines is achievable, considering the cost of achieving the reduction and any non-air-quality health and environmental impacts and energy requirements. With respect to area sources, section 112(d)(5) states that, in lieu of promulgating an MACT standard, the Administrator may elect to promulgate standards that provide for the use of GACT or management practices to reduce HAP emissions.

EPA has determined that radon emissions from uranium recovery facility tailings impoundments are an area source and that GACT applies (see Section 5.3). The Senate report on the legislation (U.S. Senate 1989) contains additional information on GACT and describes GACT as:

> *…methods, practices and techniques which are commercially available and appropriate for application by the sources in the category considering economic impacts and the technical capabilities of the forms to operate and maintain the emissions control systems.*

Determining what constitutes a GACT involves considering the control technologies and management practices that are generally available to the area sources in the source category. It is also necessary to consider the standards applicable to major sources in the same industrial sector to determine if the control technologies and management practices are transferable and generally available to area sources. In appropriate circumstances, technologies and practices at area and major sources in similar categories are considered to determine whether such technologies and practices could be generally available for the area source category at issue. Finally, as noted above, in determining GACTs for a particular area source category, the costs and economic impacts of available control technologies and management practices on that category are considered.

2.3 Basis for the Subpart W 1989 Risk Assessment and Results

In the 1989 NESHAP for operating uranium mill tailings, exposures and risks were estimated using a combination of actual site data for existing impoundments and model or representative facilities for future impoundments and computer models. The 1989 risk assessment reflected the estimated risks to the regional (0-80 km [0-50 mile]) populations associated with the 11 conventional mills that were operating or in standby[2] at that time. Mathematical models were developed to simulate the transport of radon released from the mill tailings impoundments and the exposures and risks to individuals and populations living near the mills. Those models were programmed into three computer programs for the 1989 risk assessment: AIRDOS-EPA, RADRISK, and DARTAB. The paragraphs that follow briefly discuss each of these computer programs.

AIRDOS-EPA was used to calculate radionuclide concentrations in the air, rates of deposition on the ground, concentrations on the ground, and the amounts of radionuclides taken into the body via the inhalation of air and ingestion of meat, milk, and vegetables. A Gaussian plume model was used to predict the atmospheric dispersion of radionuclides released from multiple stacks or area sources. The amounts of radionuclides that are inhaled were calculated from the predicted air concentrations and a user-specified breathing rate. The amounts of radionuclides in the meat, milk, and vegetables that people ingest were calculated by coupling the atmospheric transport models with models that predict the concentration in the terrestrial food chain.

RADRISK computed dose rates to organs resulting from a given quantity of radionuclide that is ingested or inhaled. Those dose rates were then used to calculate the risk of fatal cancers in an exposed cohort of 100,000 persons. All persons in the cohort were assumed to be born at the same time and to be at risk of dying from competing causes (including natural background radiation). RADRISK tabulated estimates of potential health risk due to exposure to a known quantity of approximately 500 different radionuclides and stored these estimates until needed. These risks were summarized in terms of the probability of premature death for a member of the cohort due to a given quantity of each radionuclide that is ingested or inhaled.

DARTAB provided estimates of the impact of radionuclide emissions from a specific facility by combining the information on the amounts of radionuclides that were ingested or inhaled (as provided by AIRDOS-EPA) with dosimetric and health effects data for a given quantity of each radionuclide (as provided by RADRISK). The DARTAB code calculated dose and risk for individuals at user-selected locations and for the population within an 80-km radius of the source. Radiation doses and risks could be broken down by radionuclide, exposure pathway, and organ.

Of the 11 conventional mills that were operating or in standby at that time, seven had unlined impoundments (the impoundments were clay lined, but not equipped with synthetic liners), while five had impoundments with synthetic liners. As the NESHAP revoked the exemption to the liner requirement of 40 CFR 192.32(a), the mills with unlined impoundments had to close the

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[2] "Standby" means the period of time when a facility may not be accepting new tailings but has not yet entered closure operations.

impoundments and move towards final reclamation and long-term stabilization of the tailings impoundments.

2.3.1 Existing Impoundments

The NESHAP for operating uranium mill tailings addressed both existing and future tailings impoundments. For the existing impoundments, the radon emissions and estimated risks were developed using site-specific data for each of the 11 mills that were operating or in standby at the time the assessment was made. These data included the average Ra-226 content of the tailings, the overall dimensions and areas of the impoundments (developed from licensing data and aerial photographs), areas of dry (unsaturated) tailings, the existing populations within 5 km of the centers of the impoundments (identified by field enumeration), 5–80 km populations derived from U.S. Census tract data, meteorological data (joint frequency distributions) from nearby weather stations, mixing heights, and annual precipitation rates.

The AIRDOS-EPA code was used to estimate airborne concentrations based on the calculated Rn-222 source term for each facility. Rn-222 source terms were estimated on the assumption that an Rn-222 flux of 1 pCi/(m^2-sec) results for each 1 picocurie per gram (pCi/g) of Ra-226 in the tailings and the areas of dried tailings at each site. The radon flux rate of 1 pCi/(m^2-sec) per pCi/g Ra-226 was derived based on theoretical radon diffusion equations and on the lack of available radon emissions measurements.

For each sector in the 0–80 km grid around each facility, the estimated Rn-222 airborne concentration was converted to cumulative working level months (WLMs), assuming a 0.50 equilibrium fraction between radon and its decay products, an average respiration rate appropriate for members of the general public, and the assumption of continuous exposure over a 70-year lifetime. Using a risk coefficient of 760 fatalities/10^6 WLM, lifetime risk, fatal cancers per year, and the risk distribution were calculated for the exposed population.

The baseline risk assessment for existing uranium tailings showed an MIR of 3×10^{-5} which was below the benchmark level of approximately 1×10^{-4} and is, therefore, presumptively safe. Additionally, the risk assessment calculated 0.0043 annual fatal cancers in the 2 million persons living within 80 km of the mills. The distribution of the cancer risk showed that 240 persons were at risks between 1×10^{-5} and 1×10^{-4}, and 60,000 were at risks between 1×10^{-6} and 1×10^{-5}. The remainder of the population of about 2 million was at a risk of less than 1×10^{-6}. Based on these findings, EPA concluded that baseline risks were acceptable.

The decision on an ample margin of safety considered all of the risk data presented above plus costs, scientific uncertainty, and the technical feasibility of control technology necessary to lower emissions from operating uranium mill tailings piles. As the risks from existing emissions were very low, EPA determined that an emission standard of 20 pCi/(m^2-sec), which represented current emissions, was all that was necessary to provide an ample margin of safety. The necessity for the standard was explained by the need to ensure that mills continued the current control practice of keeping tailings wet and/or covered. Finally, to ensure that ground water was not adversely affected by continued operation of existing piles that were not synthetically lined or clay lined, the NESHAP ended the exemption to the requirements of 40 CFR 192.32(a), which protects water supplies from contamination.

2.3.2 New Impoundments

The 1989 risk assessment for new mill tailings impoundments was based on a set of model mills, defined so that the impact of alternative disposal strategies could be evaluated. For the purpose of estimating the risks, the model mills were characterized to reflect operating mills, and the dispersion modeling and population exposures were based on the arid conditions and sparse population density that characterize existing impoundments in the southwestern states.

For new impoundments, a baseline consisting of one large impoundment (116 acres, which is 80% wet or ponded during its 15-year active life) was modeled (i.e., the continuation of the current practice). The baseline results indicated an MIR of 1.6×10^{-4}, a fatal cancer incidence of 0.014 per year, and only 20 persons at a risk greater than 1×10^{-4}. Given the numerous uncertainties in establishing the parameters for the risk assessment and in modeling actual emissions and exposures, the Administrator found that the baseline emissions for new tailings impoundments met the criteria for presumptively safe.

The decision on an ample margin of safety for new tailings considered two alternatives to the baseline of one large impoundment: phased disposal using a series of small impoundments and continuous disposal. The evaluation of these alternatives showed a modest reduction in the MIR and the number of fatal cancers per year, but a significant increase in the number of individuals at a lifetime risk of less than 1×10^{-6}. The costs estimated for the two alternatives showed that phased disposal would lead to an incremental cost of $6.3 million, while continuous disposal was believed to actually result in a modest cost saving of $1 million.

Given the large uncertainties associated with the risk and economic assessments performed for the new tailings impoundments, and considering the boom and bust cycles that the uranium industry has experienced, EPA determined that a work practice standard was necessary to prevent the risks from increasing if an impoundment were allowed to become dry. Finally, although continuous disposal showed slightly lower overall risks and costs than phased disposal, the Administrator recognized that it was not a proven technology for disposal of uranium mills tailings. Therefore, he determined that the work practice standard should allow for either phased disposal (limited to 40-acre impoundments, with a maximum of two impoundments open at any one time) or continuous disposal.

3.0 THE URANIUM EXTRACTION INDUSTRY TODAY: A SUMMARY OF THE EXISTING AND PLANNED URANIUM RECOVERY PROJECTS

Section 3.1 describes the historical uranium market in the United States. In the 1950s and 1960s, the market was dominated by the U.S. government’s need for uranium, after which the commercial nuclear power industry began to control the market. The next three sections describe the types of process facilities that were and continue to be used to recover uranium. Section 3.2 describes conventional mills and includes descriptions of several existing mines, while Section 3.3 describes ISL facilities. Heap leach facilities are described in Section 3.4. Finally, Section 3.5 discusses the applicability of the Subpart W recommended radon flux monitoring method.

3.1 The Uranium Market

The uranium recovery industry in the United States is primarily located in the arid southwest. From 1960 to the mid 1980s, there was considerable uranium production in the states of Colorado, Nebraska, New Mexico, South Dakota, Texas, Utah, Wyoming, and Washington. The majority of the uranium production at that time was associated with defense needs, while a lesser amount was associated with commercial power reactor needs. Without exception, the uranium recovery industry consisted of mines (open pit and underground) that were associated with conventional uranium milling operations. The conventional uranium mining/milling process is described in Section 3.2.

When the demand for uranium could not support the existing number of uranium recovery operations, there was a movement to decommission and reclaim much of the uranium recovery industry in the United States.

The UMTRCA Title I program established a joint federal/state-funded program for remedial action at abandoned mill tailings sites where tailings resulted largely from production of uranium for the weapons program. Now there is Federal ownership of the tailings disposal sites under general license from the Nuclear Regulatory Commission (NRC). Under Title I, the Department of Energy (DOE) is responsible for cleanup and remediation of these abandoned sites. The NRC is required to evaluate DOE's design and implementation and, after remediation, concur that the sites meet standards set by EPA.

The UMTRCA Title II program is directed toward uranium mill sites licensed by the NRC or Agreement States in or after 1978. Title II of the act provides –

- NRC authority to control radiological and nonradiological hazards.
- EPA authority to set generally applicable standards for both radiological and nonradiological hazards.
- Eventual state or federal ownership of the disposal sites, under general license from NRC.[3]

In the mid- to late 1980s, several commercial uranium recovery projects employing the solution, or ISL, mining process came on line. Section 3.3 describes the uranium ISL mining process. The uranium ISL projects and the data that they collected served as the industry standard. This industry saw an increase in activity as the conventional mine/milling operations were being shut down.

This shift in the method of uranium mining was associated with economic conditions that existed at the time. The price of uranium rapidly declined in the 1980s. The decline in price was associated with overproduction that took place during the earlier years. The peak in production was associated with Cold War production and associated contracts with DOE. However, as the

[3] http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/mill-tailings.html

Cold War came to an end, the need for uranium began to diminish. The amount of uranium that was needed for DOE projects was greatly diminished and, therefore, the price of uranium saw a decline. Figure 1 shows the spot prices for natural uranium. Note the price decline in the early 1980s.

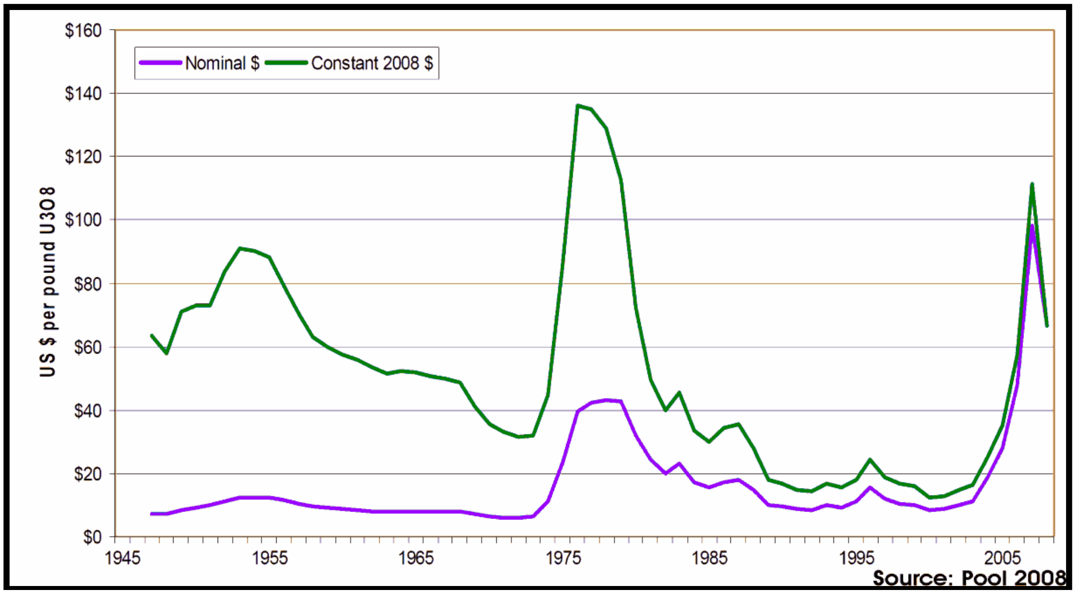
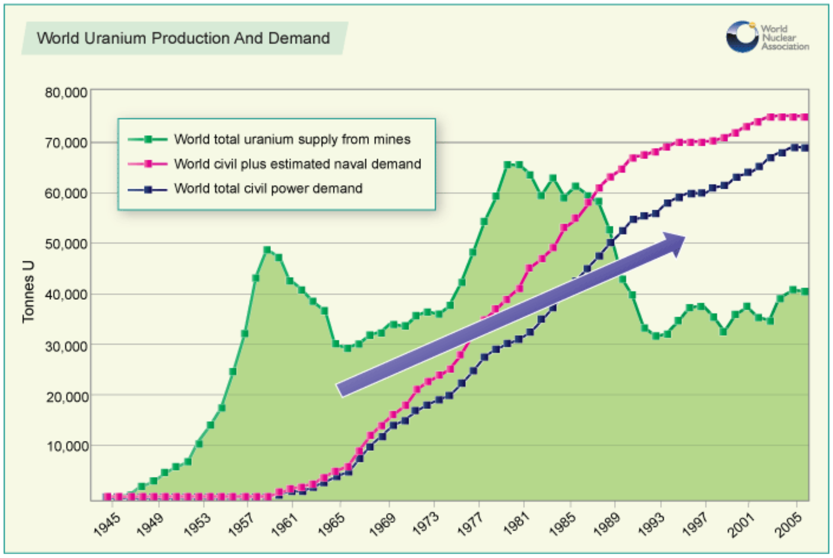


Figure 1: Historical Uranium Prices

Additionally, inexpensive uranium appeared on the worldwide market associated with the foreign supplies of low-grade and rather impure yellowcake. Only minimal purification and associated refinement was necessary to produce a yellowcake feedstock that could supply domestic and worldwide uranium needs from the low-grade foreign supply. Finally, the megatons to megawatts downblending program also supplied large supplies of uranium, both domestically and worldwide. Classical supply and demand economic principles established a market that had oversupply, constant demand and, therefore, a declining price. Consequently, the uranium industry in the United States saw a production decline. Although the number of uranium operations and production of domestic supply of uranium declined, several domestic uranium projects remained active, primarily supplying foreign uranium needs. These projects were generally located in the ISL mining production states of Nebraska, Texas, and Wyoming. This represented a significant shift in the method that was used to recover uranium, from conventional mines to ISL mines.

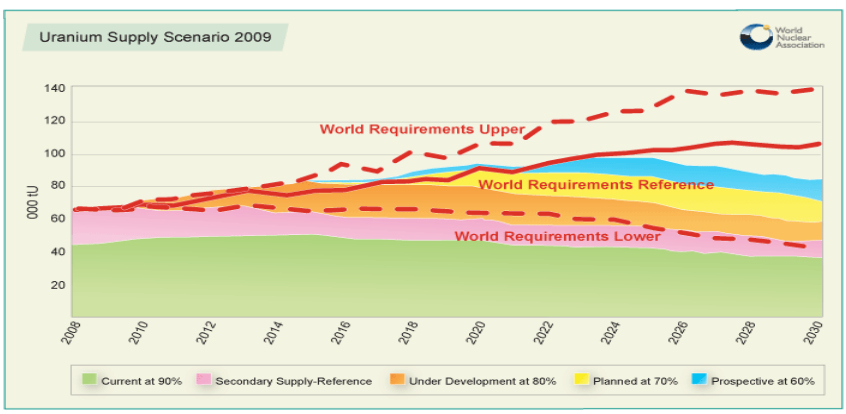
Numerous forecasts of worldwide uranium supply and demand exist. Perhaps one of the best graphical representations is from the World Nuclear Association. Figure 2 shows the actual uranium production rates from 1945 to 2005, as well as the demand trend that was established based on these production numbers. Figure 2 indicates that, from the 1960s to the present, the worldwide uranium demand has continued to increase even though the U.S. price for uranium has decreased.



Source: WNA 2010

Figure 2: Uranium Production and Demand from 1945 to 2005

Figure 3 shows the uranium supply scenario forecast by the World Nuclear Association. The three potential requirement curves shown are based on a variety of factors. The figure indicates that current production, as well as planned future worldwide production, may begin to fall short of demand in the next few years.



Source: WNA 2010

Figure 3: Uranium Supply Scenario from 2008 to 2030

In summary, all forecasts are for the uranium industry to show growth in the next decade and continuing for the foreseeable future. Drivers for this trend are a worldwide need for clean energy resources, the current trend to develop domestic sources of energy, and the investment of foreign capital in the United States, which is recognized as a politically and economically stable market in which to conduct business.

3.2 Conventional Uranium Mining and Milling Operations

Conventional uranium mining and milling facilities are one of two types of uranium recovery facilities that currently possess state or federal licenses to operate. There are currently no licensed heap leach facilities. Conventional uranium mining and milling operations are in the minority and are a carryover from the heavy production days of the 1970s and 1980s. Sweetwater Mill, Shootaring Canyon Mill, and White Mesa Mill represent the extent of the current conventional uranium milling operations that exist in the United States.

A conventional uranium mill is generally defined as a chemical plant that extracts uranium using the following process:

(1) Trucks deliver uranium ore to the mill, where it is crushed into smaller particles before the uranium is extracted (or leached). In most cases, sulfuric acid (H_2SO_4) is the leaching agent, but alkaline solutions can also be used to leach the uranium from the ore. In addition to extracting 90–95% of the uranium from the ore, the leaching agent also extracts several other "heavy metal" constituents, including molybdenum, vanadium, selenium, iron, lead, and arsenic.

(2) The mill then concentrates the extracted uranium to produce a material called "yellowcake" because of its yellowish color.

(3) Finally, the yellowcake is transported to a uranium conversion facility, where it is processed through the stages of the nuclear fuel cycle to produce fuel for use in nuclear power reactors.

Figure 4 shows a schematic of a typical conventional uranium mill.

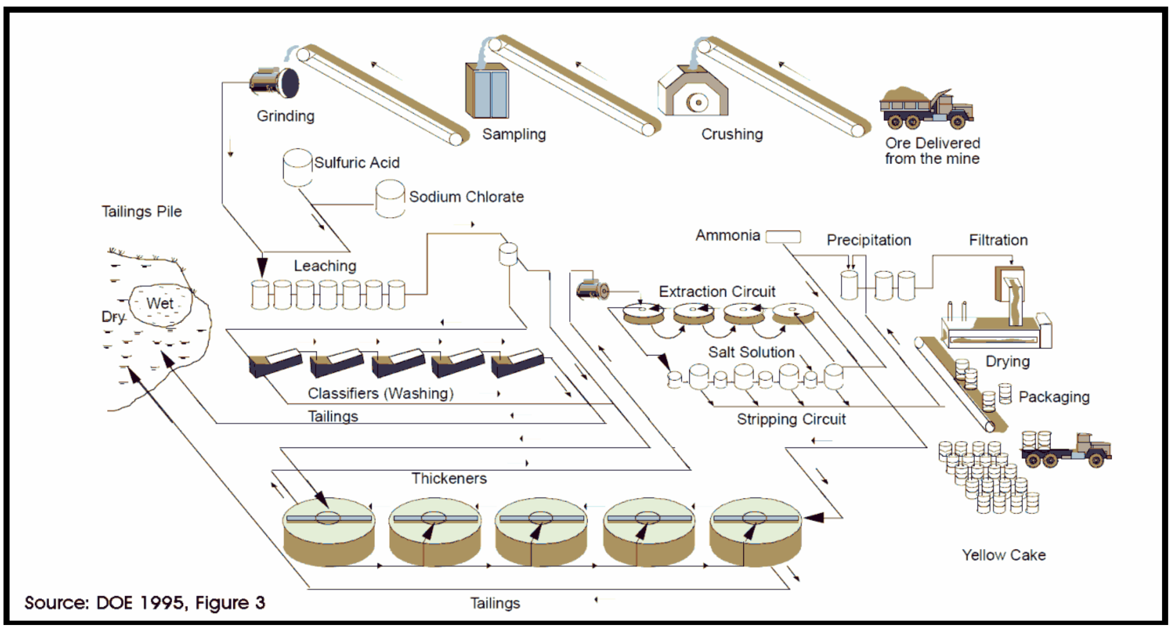


Figure 4: Typical Conventional Uranium Mill

Currently, there are three domestic licensed conventional uranium mining and milling facilities and a newly licensed facility that has yet to be constructed, as shown in Table 3.

Table 3: Conventional Uranium Mining and Milling Operations

Mill Name	Licensee	Location	Website
Sweetwater	Kennecott Uranium Co/Wyoming Coal Resource Co	Sweetwater County, Wyoming	None identified
Shootaring Canyon	Uranium One Americas	Garfield County, Utah	http://www.uranium1.com/indexu.php?section=home
White Mesa	EFR White Mesa LLC	San Juan County, Utah	http://www.energyfuels.com/white_mesa_mill/
Piñon Ridge	Energy Fuels Resources Corp.	Montrose County, Colorado	http://www.energyfuels.com/projects/pinon-ridge/index.html
Mill Name	**Regulatory Status**		**Capacity (tons/day)**
Sweetwater	Standby,* license expires November 2014		3,000
Shootaring Canyon	Standby,* license expires May 2012		750
White Mesa	Operating, license expires March 2015		2,000
Piñon Ridge	Development, license issued January 2011		500 (design)

* Standby means the period of time when a facility may not be accepting new tailings, but has not yet entered closure operations.

Instead of processing uranium ore, the conventional mills shown in Table 3 may process alternate feed stocks. These feed stocks are generally not typical ore, but rather materials that contain recoverable amounts of radionuclides, rare earths, and other strategic metals. These feed stocks are processed, the target materials are recovered, and the waste tailings are discharged to the tailings impoundment. The two facilities shown in Table 3 as being in standby (Sweetwater and Shootaring Canyon) have had their operating licenses converted into "possession only" licenses. Prior to recommencing operation, those facilities will be required to submit a license application to convert back to an operating license. EPA will review that portion of the license application associated with NESHAP to ensure that all Subpart W requirements are incorporated into the appropriate licensing documents and operating procedures.

As described in Section 3.1, the rapid rise in energy costs, increased concerns about global warming, and the tremendous worldwide surge in energy use have all led to renewed interest in uranium as an energy resource. At the spring 2010 joint National Mining Association (NMA)/NRC Uranium Recovery Workshop, the NRC identified numerous projects that have filed or are expected to file applications for new licenses, expansions of existing operations, or restarts of existing operations, including several proposals for conventional uranium recovery facilities. Contacts with the NRC and state regulatory agencies indicate that permitting and licensing actions are associated with the proposed conventional uranium milling and processing projects shown in Table 4. Although a significant uranium producer, at present, Texas has no interest in conventional uranium milling operations. The potential new mill at Piñon Ridge, Colorado, is not shown in Table 4, since its development is advanced and it has already been listed in Table 3.

Table 4: Proposed New Conventional Uranium Milling Facilities

Company	Site	(Estimated) Application Date	State
Uranium Energy Corp	Anderson Project	N.A.	AZ
Rio Grande Resources	Mt. Taylor	FY14	NM
Strathmore Minerals Corporation	Roca Honda	12-Sep	NM
Uranium Resources, Inc.	Juan Tafoya	FY 14	NM
Oregon Energy, LLC	Aurora Uranium Project	13-Dec	OR
Virginia Uranium	Coles Hills	N.A.	VA
Strathmore Minerals Corporation	Gas Hills	12-Sep	WY

N.A. = not available

No new construction has taken place on any milling facilities shown in Table 4; however, as with all industries, planning precedes construction. Considerable planning is underway for existing and new uranium recovery operations. As with facilities currently in standby, EPA will review the license application to ensure that all Subpart W requirements are incorporated into the appropriate licensing documents and operating procedures for these proposed new mills.

No specific information is available on the type of tailings management systems intended for the proposed new conventional mills. To limit radon that could be emitted from the tailings impoundments, Subpart W requires that the tailings be disposed of in a phased disposal system with disposal cells not larger than 40 acres, or by continuous disposal in which not more than 10 acres of exposed tailings may accumulate at any time. Regardless of the type of tailings management system the new milling operations select, they will all also have to demonstrate that their proposed tailings impoundment systems meet the requirements in 40 CFR 192.32(a)(1).

3.2.1 Sweetwater Mill, Kennecott Mining Company, Red Desert, Wyoming

The Sweetwater project is a conventional uranium recovery facility located about 42 mi northwest of Rawlins, Wyoming, in Sweetwater County. The site is very remote and located in the middle of the Red Desert. The approximately 1,432-acre site includes an ore pad, overburden pile, and the milling area (see Figure 5). The milling area consists of administrative buildings, the uranium mill building, a solvent extraction facility, and a maintenance shop. There is also a 60-acre tailings management area with a 37-acre tailings impoundment that contains approximately 2.5 million tons of tailings material. The Sweetwater impoundments are synthetically lined, as required in 40 CFR 192.32(a). The facility is in a standby status and has a possession only license administered by the NRC. The future plans associated with this facility are unknown, but the facility has been well maintained and is capable of processing uranium. The standby license for this facility is scheduled to expire in 2014. The licensee and/or regulator will decide whether to renew or to terminate this license.

Figure 5: Sweetwater – Aerial View

To demonstrate compliance with Subpart W, testing on the facility's tailings impoundment for radon emissions is conducted annually (KUC 2011). Table 5 shows the results of that testing. The lower flux readings measured in 2009 and 2010 are a direct result of the remediation work (regrading and lagoon construction in the tailings impoundment) performed in 2007 and 2008.

Table 5: Sweetwater Mill Radon Flux Testing Results

Test Date	Radon Flux (pCi/(m^2-sec))	Test Date	Radon Flux (pCi/(m^2-sec))
August 7, 1990	9.0	August 14, 2001	6.98
August 13, 1999	5.1	August 13, 2002	4.10
August 5, 1992	5.6	August 12, 2003	7.11
August 24, 1993	5.0	August 17, 2004	6.38
August 23, 1994	5.0	August 16, 2005	7.63
August 15, 1995	3.59	August 15, 2006	3.37
August 13, 1996	5.47	August 13, 2007	6.01
August 26, 1997	4.23	August 5, 2008	4.59
August 11, 1998	2.66	July 30, 2009	1.60
August 10, 1999	1.27	August 10, 2010	1.44
August 8, 2000	4.05		

Source: KUC 2011, p. 6

Summary of Results

Air monitoring data were reviewed for a 26-year period (1981 to 2007). Upwind Rn-222 measurements, as well as downwind Rn-222 values, were available. The average upwind radon value for the period of record was 3.14 picocuries per liter (pCi/L). The average downwind radon value for the same period was 2.60 pCi/L. These values indicate that there is no measurable contribution to the radon flux from the mill tailings that are currently in the lined impoundment. This monitoring program remains active at the facility.

Approximately 28.3 acres of tailings are dry with an earthen cover; the remainder of the tailings is continuously covered with water. The earthen cover is maintained as needed. One hundred radon flux measurements were taken on the exposed tailings, as required by Method 115 for compliance with Subpart W. The mean radon flux for the exposed beaches was 8.5 pCi/(m^2-sec). The radon flux for the entire tailings impoundment was calculated to be 6.01 pCi/(m^2-sec). The calculated radon flux from the entire tailings impoundment surface is approximately 30% of the 20.0 pCi/(m^2-sec) standard.

3.2.2 White Mesa Mill, Energy Fuels Corporation, Blanding, Utah

The White Mesa project is a conventional uranium recovery facility located about 6 mi south of Blanding, Utah, in San Juan County. The approximately 5,415-acre site includes an ore pad, overburden pile, and the milling area (see Figure 6). The mill area occupies approximately 50 acres and consists of administrative buildings, the uranium milling building, and ancillary facilities. The facility used a phased disposal impoundment system, and two of the 40-acre cells are open. The facility has operated intermittently in the past, and this type of operation continues on a limited basis. The amount of milling that takes place, as well as the amount of uranium that is being produced, is a small fraction of the milling capacity. The uranium recovery project has an active license administered by the Utah Department of Environmental Quality, Division of Radiation Control.

Figure 6: White Mesa – Aerial View

To demonstrate compliance with Subpart W, the radon flux from tailings surfaces is measured and reported to the State of Utah annually. As Table 6 shows, these data consistently demonstrate that the radon flux from the White Mesa Mill's tailings cells are below the criteria.

Table 6: White Mesa Mill's Annual Radon Flux Testing, Tailings Cells 2 & 3

Year	Radon Flux (pCi/(m^2-sec))	
	Cell 2	Cell 3
1997	12.1	16.8
1998	14.3	14.9
1999	13.3	12.2
2000	9.3	10.1
2001	19.4	10.7
2002	19.3	16.3
2003	14.9	13.6
2004	13.9	10.8
2005	7.1	6.2

Source: Denison 2007, p. 116

The Table 6 radon flux values for 2001 and 2002 were elevated when compared to the prior years. Denison believes that these radon fluxes were largely due to the drought conditions in those years, which reduced the moisture content in the interim cover placed over the inactive portions of tailings Cells 2 and 3. In addition, the beginning of the 2002 mill run, which resulted in increased activities on the tailings cells, may have contributed to these higher values. As a result of the higher radon fluxes during 2001 and 2002, additional interim cover was placed on the inactive portions of Cells 2 and 3. While this effort was successful, additional cover was applied again in 2005 to further reduce the radon flux (Denison 2007).

Summary of Results

Air monitoring data were reviewed for a 2-year period (2006 to 2008). The White Mesa site utilized the MILDOS code to calculate radon concentrations (ANL 1998), in the same calculation process that had been used since 1995. As a comparison, Denison Mines reactivated the six air monitoring stations that were used at the site. Data from these stations were collected for a 2-year period. The upwind and downwind measurements showed no definable trends. At times, the upwind concentrations were the higher values, while at other times, the downwind concentrations were the greatest. However, all values were within regulatory standards.

The tailings facilities at the White Mesa facility consist of the following impoundments/cells (Denison 2011):

- Cell 1, constructed with a 30-millimeter (mil) PVC earthen-covered liner, is used for the evaporation of process solution (Cell 1 was previously referred to as Cell 1-I, but is now referred to as Cell 1).

- Cell 2, constructed with a 30-mil PVC earthen-covered liner, is used for the storage of barren tailings sands. Cell 2 has 67 acres of surface area. Because 99% of the cell has a soil cover over the deposited tailings, only 0.7 acres of tailings are exposed as tailings beaches.

- Cell 3, constructed with a 30-mil PVC earthen-covered liner, is used for the storage of barren tailings sands and solutions. Cell 3 has 71 acres of surface area, and 54% of the cell has a soil cover over the deposited tailings. The remainder of the cell consists of tailings beaches (19%) and standing liquid (26%).

- Cell 4A, constructed with a geosynthetic clay liner, a 60-mil high-density polyethylene (HDPE) liner, a 300-mil HDPE Geonet drainage layer, a second 60-mil HDPE liner, and a slimes drain network over the entire cell bottom. This cell was placed into service in October 2008.

- Cell 4B, constructed with a geosynthetic clay liner, a 60-mil HDPE liner, a 300-mil HDPE Geonet drainage layer, a second 60-mil HDPE liner, and a slimes drain network over the entire cell bottom. This cell was placed into service in February 2011.

One hundred radon flux measurements were collected on the Cell 2 beach area, and an additional 100 measurements were taken on the soil-covered area in accordance with Method 115 for Subpart W analysis. The data were used to calculate the mean radon flux for the exposed beaches and the soil-covered area. The average radon flux for all of Cell 2 was calculated to be 13.5 pCi/(m^2-sec), or about 68% of the 20.0 pCi/(m^2-sec) standard.

At Cell 3, 100 radon flux measurements were collected from each of the soil cover and the beach areas, as required by Method 115. The data were used to calculate the mean radon flux for the exposed beaches and the soil-covered area. The radon flux from the standing liquid-covered area was assumed to be zero. The average radon flux for all of Cell 3 was calculated to be 8.9 pCi/(m^2-sec), or about 46% of the 20.0 pCi/(m^2-sec) standard.

3.2.3 Shootaring Canyon Mill, Uranium One Incorporated, Garfield County, Utah

The Shootaring Canyon project is a conventional uranium recovery facility located about 3 mi north of Ticaboo, Utah, in Garfield County. The approximately 1,900-acre site includes an ore pad, a small milling building, and a tailings management system that is partially constructed (see Figure 7). The mill circuit operated for a very short time and generated only enough tailings to cover 7 acres of the impoundment. Although the milling circuit has been dismantled and sold, the facility is in a standby status and has a possession only license administered by the Utah Department of Environmental Quality, Division of Radiation Control. The future plans for this uranium recovery operation are unknown. Current activities at this remote site consist of intermittent environmental monitoring by consultants to the parent company. The standby license for this facility is scheduled to expire in 2014. The licensee and/or the regulator will decide whether to renew or to terminate this license.

Figure 7: Shootaring Canyon – Aerial View

Summary of Results

Air monitoring data were reviewed for a 2-year period (2009 to 2010). Continuous air monitoring is not conducted at the site; rather, a 20- to 24-hour sampling event is required once per quarter as a condition of the license. The high-volume air sampler is located downwind of the tailings facility. Many sampling events during a 2-year period indicate that the downwind

Rn-222 concentrations are around 1% of the allowable effluent concentration limit. The two years of data reviewed indicated no trends.

The Shootaring Canyon facility operated for approximately 30 days. Tailings were deposited in a portion of the upper impoundment. A lower impoundment was designed but has not been built. Milling operations in 1982 produced 25,000 cubic yards of tailings, deposited in an area of 2,508 m^2 (0.62 acres). The tailings are dry except for moisture-associated occasional precipitation events; consequently, there are no beaches. The tailings have a soil cover that is maintained by the operating company. The impoundment at Shootaring Canyon is synthetically lined, as required in 40 CFR 192.32(a).

One hundred radon flux measurements were collected on the soil-covered tailings area in accordance with Method 115. The 2009 sampling results indicated that average flux from the covered tailings was 23.3 pCi/(m^2-sec), which exceeded the allowable 20 pCi/(m^2-sec) regulatory limit. In response to this result, the licensee notified the Utah Division of Radiation Control and placed additional soil cover on the tailings. The soil cover consisted of local borrow materials in the amount of 650 cubic yards. More sampling took place during the week of November 7, 2009. An additional 100 sample results were collected and showed that the average radon flux was reduced to 18.1 pCi/(m^2-sec). Sampling for 2010 took place in April. Again, 100 radon flux measurements were collected. The average radon flux revealed by this sampling was 11.9 pCi/(m^2-sec).

3.2.4 Piñon Ridge Mill, Bedrock, Colorado

The Piñon Ridge project is a permitted conventional uranium recovery facility in development. The permitted location is located about 7 mi east of Bedrock, Colorado, and 12 mi west of Naturita, Colorado, in Montrose County (see Figure 8). The approximately 1,000-acre site will include an administration building, a 17-acre mill site, a tailings management area with impoundments totaling approximately 90 acres, a 40-acre evaporation pond with proposed expansion of an additional 40-acre evaporation pond as needed, a 6-acre ore storage area, and numerous access roads. The design of the tailings management area is such that it can meet the work practice standard with a synthetically lined impoundment, a leak detection system, and a surface area that does not exceed 40 acres. The facility has not been constructed, but is fully licensed and administered by the Colorado Department of Public Health and Environment. Also, EPA has approved the facility's license to construct under NESHAP Subpart A of 40 CFR 61. Current activities at the site are maintenance of pre-operational environmental monitoring.

Figure 8: Piñon Ridge – Aerial View

3.2.5 Conventional Mill Tailings Impoundments and Radon Flux Values

In summary, the radon data for the active mill tailings impoundments indicate that the radon exhalation rates from the measured surfaces have exceeded the regulatory standard of 20 pCi/(m^2-sec) at times. Two instances exist in the records that were reviewed. One instance was in 2007, when a portion of the Cotter Corporation impoundment did not have sufficient soil cover. Monitoring results showed a flux rate of 23.4 pCi/(m^2-sec). The tailings surface was covered with a soil mixture, and the flux rate was reduced to 14.0 pCi/(m^2-sec). The second instance in which the regulatory standard was exceeded was recorded during the 2009 sampling event at Shootaring Canyon Mill. This sampling event indicated that average flux from the covered tailings was 23.3 pCi/(m^2-sec), caused by insufficient soil cover. Although covering tailings piles with various other materials (e.g., synthetics, asphalt, soil-cement mixtures) has been studied, covers made of earth or soil have been shown to be the most cost effective in reducing radon emissions (EPA 1989, NRC 2010). In both cases when monitoring indicated radon fluxes in excess of the standard, additional soil cover was added to the tailings, and the radon flux rates were reduced to below the regulatory standards.

Table 8 shows the average/calculated radon flux values, as reported by the uranium recovery operators.

Table 7: Mill Tailings Impoundments and Average/Calculated Radon Flux Values*

Facility	Radon Flux (pCi/(m^2-sec))		Calculated Tailings Impoundment Average Radon Flux (pCi/(m^2-sec))
	Soil-Covered Area	Tailings Beach	
Sweetwater Mill	No soil-covered area	8.5	6.01
White Mesa Mill, Cell 2	13.1	50.2	13.5
White Mesa Mill, Cell 3	13.9	6.7	8.9
Shootaring Canyon Mill	15 2-year average	Not applicable	15 2-year average
Piñon Ridge Mill	Not applicable	Not applicable	Not applicable

* The respective uranium recovery operators supplied all data and calculations.

3.3 In-Situ Leach Uranium Recovery (Solution Mining)

Solution, ISL or in-situ recovery (ISR), mining is defined as the leaching or recovery of uranium from the host rock (typically sandstone) by chemicals, followed by recovery of uranium at the surface (IAEA 2005). Leaching, or more correctly the remobilization of uranium into solution, is accomplished through the injection into the ore body of a lixiviant. The injection of a lixiviant essentially reverses the geochemical reactions associated with the uranium deposit. The lixiviant ensures that the dissolved uranium, as well as other metals, remains in solution while it is collected from the mining zone by recovery wells.

ISL mining was first conducted in Wyoming in 1963. The research and development projects and associated pilot projects of the 1980s demonstrated solution mining as a viable uranium recovery technique. Initial efforts at the solution mining process were often less than ideal:

- Lixiviant injection was difficult to control, primarily because of poor well installation.
- Laboratory-scale calculations did not always perform as suspected in geological formations.
- Recovery well spacing was poorly understood, causing mobilized solutions to migrate in unsuspected pathways.
- Restoration efforts were not always effective in re-establishing reducing conditions; therefore, some metals remained in solution and pre-mining ground water conditions were not always achievable.

Additional research and development work indicated that mining solutions could be controlled with careful well installation. The use of reducing agents during restoration greatly decreased the amount of metals that were in solution. As a result of these modifications in mining methods, solution mining of uranium became a viable method to recover some uranium deposits, many of which could not be economically mined by the open pit methods typically employed by the uranium industry. Additionally, the economics of solution mining were more favorable than conventional mining and milling. Because of these factors, solution mining and associated processing began to dominate the uranium recovery industry. Figure 10 shows a schematic of a typical ISL uranium recovery facility.

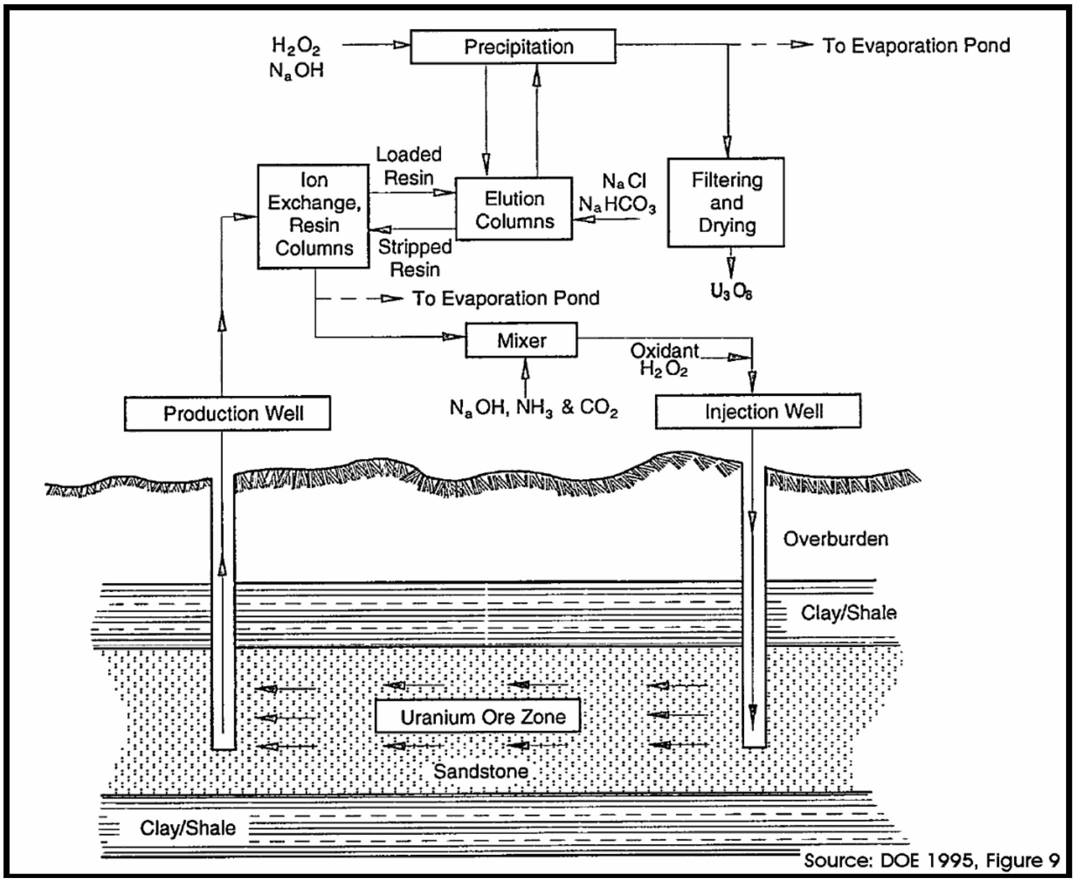


Figure 9: In-Situ Leach Uranium Recovery Flow Diagram

During typical solution mining, a portion of the lixiviant is bled off in order to control the pressure gradient within the wellfield. As Figure 10 shows, the liquid bled from the lixiviant is sent to an evaporation pond, or impoundment. The pond/impoundment may be used to dispose of the liquid via evaporation, or it may be used simply to hold the liquid until a sufficient amount has been accumulated so that other means may be used to dispose of it (e.g., land application or irrigation, deep well disposal). Since Ra-226 is present in the water bled from the lixiviant, radon will be generated in and released from the solution mining facility's evaporation/holding ponds or impoundments.

The 1989 NESHAP risk assessment (EPA 1989), although not conducted specifically for solution mining sites, is applicable to ponds/impoundments at solution mining facilities. All of the ponds at solution mining facilities are synthetically lined. Because of the presence of liners, none would be required to be closed. The solution mining industry is more transient in that the impoundment life is less than those at conventional uranium mining and milling sites. Typically, the impoundments are in the range of 1–4 acres and are built to state-of-the-art standards.

Two types of lixiviant solutions, loosely defined as acid or alkaline systems, can be used. In the United States, the geology and geochemistry of most uranium ore bodies favor the use of "alkaline" lixiviants or bicarbonate-carbonate lixiviant and oxygen. Other factors in the choice of the lixiviant are the uranium recovery efficiencies, operating costs, and the ability to achieve satisfactory ground water restoration. The acid systems once used in the United States are still used in Eastern Europe and Asia and were used recently in Australia on ore bodies in saline aquifers (IAEA 2005).

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

Four times a year, the Energy Information Administration (EIA) publishes data on the status of U.S. ISL facilities. EIA (2013) identified six ISL facilities that were recovering uranium and producing yellowcake in the 2nd quarter of 2013. Table 8 shows these facilities. These operations are located in NRC-regulated areas, as well as in Agreement States.

Table 8: Operating ISL Facilities

Plant Owner	Plant Name	County, State
Cameco	Crow Butte Operation	Dawes, Nebraska
Power Resources, Inc. dba Cameco Resources	Smith Ranch-Highland Operation	Converse, Wyoming
Uranium Energy Corp. dba South Texas Mining Venture	Hobson ISR Plant	Karnes, Texas
	La Palangana	Duval, Texas
Mestena Uranium LLC	Alta Mesa Project	Brooks, Texas
Uranium One USA, Inc.	Willow Creek Project (Christensen Ranch and Irigaray)	Campbell and Johnson, Wyoming

The two major geographical areas of ISL mining and processing have been Texas and Wyoming. These areas are well suited to this ISL mining technology, in that the geology associated with the mineralized zone is contained by layers of impervious strata. Texas is the major producer of uranium from ISL operations, followed by Wyoming. ISL operations in South Dakota and Nebraska recover lesser amounts of uranium.

For the 2nd quarter of 2013, EIA (2013) identified the ISL facilities shown in Table 9 as being developed, or partially or fully permitted and licensed, or under construction. As discussed, the economics of ISL uranium recovery are conducive to lower grade deposits or deeply buried deposits that could not be economically recovered with conventional open pit or underground mining actions.

As the data in Table 9 show, there is considerable interest in ISL mining operations in the U.S. uranium belt. Many of the existing ISL operations are planning for expansion by preparing the license applications and other permitting documents. It is apparent that most domestic uranium recovery will be associated with existing and new ISL operations.

Table 9: ISL Facilities That Are Restarting, Expanding, or Planning for New Operations

Plant Owner	Plant Name	County, State (existing and *planned* locations)	Status, 2nd Quarter 2013
Powertech Uranium Corp	Dewey Burdock Project	*Fall River and Custer, South Dakota*	Developing
Uranium One Americas, Inc.	Jab and Antelope	*Sweetwater, Wyoming*	Developing
Hydro Resources, Inc.	Church Rock	*McKinley, New Mexico*	Partially Permitted And Licensed
Hydro Resources, Inc.	Crownpoint	*McKinley, New Mexico*	Partially Permitted And Licensed
Strata Energy Inc	Ross	*Crook, Wyoming*	Partially Permitted And Licensed
Uranium Energy Corp.	Goliad ISR Uranium Project	*Goliad, Texas*	Permitted And Licensed
Uranium One Americas, Inc.	Moore Ranch	*Campbell, Wyoming*	Permitted And Licensed
Lost Creek ISR, LLC	Lost Creek Project	Sweetwater, Wyoming	Under Construction
Uranerz Energy Corporation	Nichols Ranch ISR Project	Johnson and Campbell, Wyoming	Under Construction

Table 10 shows the size of the surface impoundments at ISL facilities. It is noteworthy that the operation of these facilities does not require impoundments nearly as large as the impoundments used at conventional mills. The impoundments are utilized for the evaporative management of waste water. The impoundments are small because a minimal percentage of the process water needs to be over-recovered to maintain solution flow to the recovery wells. The solution mining industry has used deep well injection for most of the waste water. All signs indicate that this type of waste water disposal will continue in the future.

Table 10 shows that all of the solution mining sites reviewed are using the deep well injection method.

Table 10: ISL Evaporation Pond Data Compilation

Operation	Evaporation pond?	Date pond was constructed	Size of pond	Synthetic liner under pond?	Leak detection system?	Deep well injection?
Cameco, Smith Ranch	East and west ponds	1986	8.6 acres	Yes	Yes, ponds have had leaks	Yes, used for most waste water, started in 1999
Cameco, Crow Butte	3 commercial ponds and 2 R&D ponds	R&D ponds 1990	Pond 1, 2, 5 850×200 ft Pond 3, 4 700×250 ft	Yes	Yes	Yes, all bleed stream
Hydro Resources, Crown Point	Project is licensed with the NRC, but no construction has taken place (personal conversation with Uranium Resources personnel)					
Hydro Resources, Church Rock	Project is licensed with the NRC, but no construction has taken place (personal conversation with Uranium Resources personnel)					
Uranium Resources Inc., Kingsville Dome	Two 120×120 ft ponds	1990	120×120 ft	Yes	Yes	Yes, @ 200 gpm
Uranium Resources Inc., Vasquez	Two 150×150 ft ponds	1990	150×150 ft	Yes	Yes	Yes, @ 200 gpm
Uranium Resources Inc., Rosita	Two 120×120 ft ponds	1985	120×120 ft	Yes	Yes	Yes, @ 200 gpm
Mestena, Alta Mesa	Evaporation data not found					
STMV, La Palangana	Evaporation data not found					

3.3.1 Radon Emission from Evaporation and/or Holding Ponds

Unlike conventional mills, ISL facilities do not produce tailings or other solid waste products. However, they do generate significant amounts of liquid wastes during uranium extraction and aquifer restoration. During extraction, an extraction solution (lixiviant), composed of ground water enhanced by an oxidant and carbonate/bicarbonate, is injected through wells into the ore zone. This lixiviant moves through pores in the ore body and mobilizes the uranium. The resulting "pregnant" lixiviant is withdrawn by production wells and pumped to the processing plant, which recovers the uranium. To prevent leakage of the lixiviant outside the production zone, it is necessary to maintain a hydraulic cone of depression around the well field. This is accomplished by bleeding off a portion of the process flow. Other liquid waste streams are from sand filter backwash, resin transfer wash, and plant washdown. One method to dispose of these liquid wastes is to evaporate them from ponds. Deep well injection and land application (i.e., irrigation) are other methods for disposing of the liquid wastes. For these disposal methods, the waste liquid is collected in holding ponds until a quantity sufficient for disposal has been accumulated.

As defined by the AEA of 1954, as amended, byproduct material includes tailings or waste produced by the extraction or concentration of uranium from any ore processed primarily for its source material content (42 USC 2014(e)(2)). Clearly, waste water generated during solution mining is within this definition of byproduct material and is thus subject to the requirements of Subpart W.

The waste water contains significant amounts of radium, which will radiologically decay and generate radon gas. Radon diffuses much more slowly in water than it does in air. For example, the radon diffusion coefficient in water is about 10,000 times smaller than the coefficient in air (i.e., on the order of 10^{-5} square centimeters per second (cm^2/sec) for water and 10^{-1} cm^2/sec for air (Drago 1998, as reported in Brown 2010)). Thus, if the tailings piles are covered with water, then most of the radon would decay before it could diffuse its way through the water. However, since over time periods comparable to the half-life of radon, there is considerable water movement within a pond, advective as well as diffusive transport of radon from the pond water to the atmosphere must be considered. The water movement is partly caused by surface wind currents, thermal gradients, mechanical disturbance from the mill discharge pipe, and biological disturbances (animals, birds, etc.). Dye movement tests indicate that for shallow (less than 1 meter) pond water, advective velocities may exceed 1–2 millimeters per minute, resulting in virtually no radon containment by the surface water. If shallow water movement is sufficient to remove radon from the tailings-water interface and transport it to the atmosphere in a short time (several hours), the radon flux from the shallow tailings is nearly as great as that from similar bare saturated tailings; hence, no significant radon attenuation is gained by covering the tailings with water (Nielson and Rogers 1986). Consequently, in order for a pond covering a tailings pile to be effective at reducing the release of radon, the pond water must be greater than 1 meter in depth.

Additionally, if there is radium in the pond water, radon produced from that radium could escape into the atmosphere. A review of the various models used for estimating radon flux from the surface of water bodies indicates that the stagnant film model (also known as the two bottleneck model (Schwarzenbach et al. 2003)), coupled with a wind correction equation, can be used to estimate the radon flux based on the concentration of radium in the pond's water and the assumption that radon is in secular equilibrium with the radium. The radon flux from the surface of an evaporation pond, as a function of the wind speed (for winds less than 24 miles per hour (mph)), can be estimated using this model with the following equation:

$$J = \frac{1.48 \times 10^{-4}}{e^{-0.351V}} C_w \qquad (3\text{-}1)$$

Where	J	=	Radon flux	(pCi/(m^2-sec))
	C_w	=	Concentration of radium in the water	(pCi/L)
	V	=	Wind speed	(m/sec)

Implicit in this model is the fact that in pond water the radon diffusion coefficient is 10^{-5} cm^2/sec and that the thickness of the stagnant film layer can be estimated by an exponential relationship with wind speed (Schwarzenbach et al. 2003).

Baker and Cox (2010) measured the radium concentration in an evaporation pond at the Homestake Uranium Mill Site at 165 pCi/L. Assuming a direct conversion to Rn-222 (165 pCi/L), the flux is estimated from equation 3-1 at 1.65 pCi/(m^2-sec). This is comparable to measurements of the flux, which averaged 1.13 pCi/(m^2-sec). However, the Homestake measurement method did not allow the measurement of wind-generated radon fluxes, as the collar used to float the canister makes the wind speed zero above the area being measured. No data were found for measurements of the radon flux on evaporation ponds versus wind speed.

The model should not be used for wind speeds above 10 meters per second (m/sec) (24 mph). However, this is not expected to be a major limitation for estimating normal radon releases and impacts from operational evaporation ponds.

Using actual radium pond concentrations and wind speed data in equation 3-1, the radon pond flux was calculated from several existing ISL sites (SC&A 2010). Results showed that the radon flux ranged from 0.07 to 13.8 pCi/(m^2-sec). This indicates that the radon flux above some evaporation ponds can be significant (e.g., can exceed 20 pCi/(m^2-sec)). If such levels occur, there are methods for reducing the radium concentration in the ponds, the most straightforward being dilution. However, this solution is temporary, as evaporation will eventually increase the concentration. A second method is to use barium chloride ($BaCl_2$) to co-precipitate the radium to the bottom of the pond. The radon generated at the depths of the bottom sediments will decay before reaching the pond surface.

Again using actual ISL site data, the total annual radon release from the evaporation ponds was calculated and compared to the reported total radon release from three sites. The evaporation pond contribution to the site's total radon release was small (i.e., less than 1%).

Two additional sources of radon release were investigated: the discharge pipe and evaporation sprays. The discharge pipe is used to discharge bleed lixiviant to the evaporation pond. Radon releases occur when the bleed lixiviant exits the pipe and enters the pond. The investigation found that these radon releases are normally calculated using the methodology in NUREG-1569, Appendix D (NRC 2003); thus, this source is currently included in the total radon releases reported for an ISL site. For a "typical" ISL, with a purge water radon concentration of 3.2×10^5 pCi/L and a purge rate of 5.5×10^5 liters per day (L/d) or about 100 gallons per minute (gpm), NUREG-1569, Appendix D, calculated the radon released from the discharge pipe to be 64 Ci/yr.

Spray systems are sometimes used to enhance evaporation from the ponds. A model to calculate radon releases during spray operation was developed (SC&A 2010). Also, data from ISL ponds were used to estimate this source of radon release. The radon releases from spray operations were reported to range from <0.01 to <3 pCi/(m^2-sec) (SC&A 2010). Furthermore, operation of the sprays would reduce the radon concentration within the pond; therefore, the normal radon release would be depressed once the sprays are turned off (until the radon has had an opportunity to re-equilibrate with the radium). Hence, operation of spray systems to enhance evaporation is not expected to significantly increase the amount of radon released from the pond.

3.4 Heap Leaching

Heap leaching is a process by which chemicals are used to extract the uranium from the ore. A large area of land is leveled with a small gradient, layering it with HDPE or linear low-density polyethylene (LLDPE), sometimes with clay, silt or sand beneath the plastic liner. Ore is extracted from a nearby surface or an underground mine. The extracted ore will typically be run through a crusher and placed in heaps atop the plastic. A leaching agent (often H_2SO_4) will then be sprayed on the ore for 30–90 days. As the leaching agent percolates through the heap the uranium will break its bonds with the oxide rock and enter the solution. The solution will then flow along the gradient into collecting pools from which it will be pumped to an onsite processing plant.

In the past, there have been a few commercial heap leach facilities, but currently none are operating. However, this type of facility can be rapidly constructed and put into operation. Planning and engineering have begun for two heap leach facilities. At the spring 2010 joint NMA/NRC Uranium Recovery Workshop, the NRC identified two proposed heap leach projects, one in Wyoming and the other in New Mexico, as shown in Table 11. In addition to these two projects, Cotter has indicated to the Colorado Department of Public Health and Environment that it intends to retain the use of the secondary impoundment at its Cañon City site for heap leaching in the future (Hamrick 2011).

Table 11: Anticipated New Heap Leach Facilities

Owner	Site	State
Energy Fuels[4]	Sheep Mountain	Wyoming
Uranium Energy Corporation	Grants Ridge	New Mexico

Source: NMA 2010

[4] Energy Fuels acquired the Sheep Mountain Project through its acquisition of Titan Uranium Inc. in February 2012 (http://www.energyfuels.com/development_projects/sheep_mountain/, accessed 9/25/2013).

Higher uranium prices will likely lead to the processing of low-grade ore currently found in the uranium districts in Wyoming and New Mexico. Much of the low-grade ore currently exists in spoil piles that were not economical to truck to milling operations. Little processing equipment is necessary to bring heap leach operations on line. Additionally, minimal personnel are necessary to operate and monitor such an operation. However, the application of NESHAP Subpart W to heap leach facilities should be clarified (see Section 5.0). At a minimum, it is expected that these types of facilities will be limited in acreage according to the Subpart W standard and will be required to have synthetic liners with monitored leak detection systems.

Attempts have been made at heap-leaching low-grade uranium ore, generally by the following process:

(1) Small pieces of uncrushed ore are placed in a pile, or "heap", on an impervious pad of plastic, clay, or asphalt, to prevent uranium and other chemicals from migrating into the subsurface.

(2) An acidic solution is then sprayed onto the heap, which dissolves the uranium as it migrates through the ore.

(3) Perforated pipes under the heap collect the uranium-rich solution, and drain it to collection basins, from where it is piped to the processing plant.

(4) At the processing plant, uranium is concentrated, extracted, stripped, and dried to produce a material called "yellowcake."

(5) Finally, the yellowcake is packed in 55-gallon drums to be transported to a uranium conversion facility, where it is processed through the stages of the nuclear fuel cycle to produce fuel for use in nuclear power reactors.

Figure 10 shows a schematic of a typical heap-leaching uranium recovery facility.

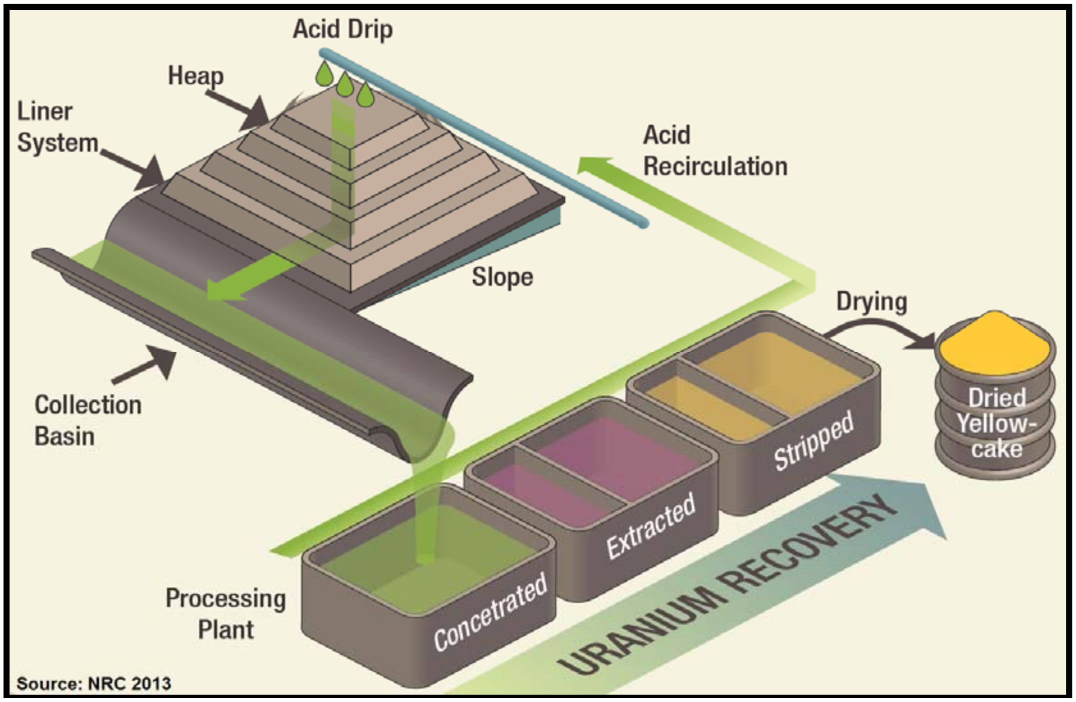


Figure 10: Typical Heap-Leaching Uranium Recovery Facility

Heap-leaching was not an industry trend; rather, it was an attempt to process overburden that contained a minimal concentration of uranium. Production records associated with this processing technique were not maintained, but certainly the technique represented less than 1% of the recovered uranium resources. Almost all of the conventional uranium recovery operations were stand-alone facilities that included the mining, milling, processing, drying, and containerization of the yellowcake product. The yellowcake product was then trucked to processing facilities that refined the raw materials into the desired product.

3.4.1 Sheep Mountain Mine, Energy Fuels, Fremont County, Wyoming

The Sheep Mountain mine, located at approximate 42º 24’ North and 107º 49’ West, has operated as a conventional underground mine on three separate occasions. Mining on the Sheep Mountain property started in 1956 and continued in several open pit and underground operations until 1982. The Sheep I shaft was sunk in 1974, followed by the Sheep II shaft in 1976. Production from the Sheep I shaft in 1982 was reported to be 312,701 tons at an average grade of 0.107% U_3O_8 (triuranium octoxide). In 1987, an additional 12,959 tons at 0.154% U_3O_8 were produced, followed by 23,000 tons at 0.216% U_3O_8 in 1988. The Sheep II shaft has had no production. The Congo Pit is essentially a single open pit which was being readied for development in the early 1980s, but plans were never realized because of the collapse of the uranium market. Feed from Sheep Mountain was processed at the Split Rock Mill, which was located north of Jeffrey City. Figure 11 shows the Sheep Mountain mine.

Figure 11: Sheep Mountain – Aerial View

Energy Fuels plans to develop the Sheep Mountain mine with both conventional underground and open pit mining, followed by heap leach extraction of the uranium with an ion-exchange recovery plant producing up to 1.5 million pounds of U_3O_8 per year. Energy Fuels' plans include the development of both the Sheep I and Sheep II underground mines, with access from twin declines. At its peak production, the underground mine will produce approximately 1.0 million pounds U_3O_8 per year. The Congo Pit will also be developed, producing an average of 500,000 pounds U_3O_8 per year. Recovery of the uranium will include heap leach pads using H_2SO_4 and a conventional recovery plant, through to yellowcake production on site. Assuming no re-use of heap pads, there will be 100 heap leaching cells, each with a capacity of 66,000 tons of material stacked to a height of 25 feet (ft) over an area of 40 ft by 100 ft. The mineral processing rate will be 500,000 tons per year or greater (Titan Uranium 2010).

Currently, the Wyoming Department of Environmental Quality has issued a fully bonded mining permit to Titan (now Energy Fuels). Energy Fuels is in the process of developing a source material license application for submittal to the NRC around mid-2011. The review and approval process is expected to take about 2 years (i.e., the NRC will complete it in mid-2013). Finally, the Plan of Operation (POO) is being developed and expected to be submitted to the U.S. Bureau of Land Management also around mid-2011. Submittal of the POO will trigger development of an environmental impact statement (EIS). This POO/EIS process is expected to be completed by the end of 2012 (Titan Uranium 2011).

3.5 Method 115 to Monitor Radon Emissions from Uranium Tailings

Subpart W (40 CFR 61.253) requires that compliance with the existing emission standards for uranium tailings be achieved through the use of Method 115, as prescribed in Appendix B to 40 CFR 61. Method 115 consists of numerous sections that discuss the monitoring methods that must be used in determining the Rn-222 emissions from underground uranium mines, uranium mill tailings piles, phosphogypsum stacks, and other piles of waste material that emits radon.

For uranium tailings piles, Method 115, Section 2.1.3, specifies the minimum number of flux measurements considered necessary to determine a representative mean radon flux value for each type of region on an operating pile:

- Water covered area—no measurements required as radon flux is assumed to be zero.
- Water saturated beaches—100 radon flux measurements.
- Loose and dry top surface—100 radon flux measurements.
- Sides—100 radon flux measurements, except where earthen material is used in dam construction.

The requirement of 300 measurements may result in more measurements then are necessary under the Subpart W design standards. For example, under design standard 40 CFR 61.252(b)(2) for continuous disposal, only 10 acres are uncovered at one time. The 300 flux measurements on a 10-acre area translate into one measurement every 1,500 ft^2, or one every 40 ft. At the time Method 115 was developed and amended to Appendix B (i.e., 1989), the uranium tailings areas were much larger than the Subpart W design standards presently allow. For example, DOE/EIA-0592 (1995) indicates that some mills had tailings areas of over 300 acres (although not necessarily in a single pile).

Method 115, Section 2.1.6, indicates that measuring "radon flux involves the adsorption of radon on activated charcoal in a large-area collector." Since 1989, there have been advances in methods of measuring radon flux. George (2007) is particularly relevant in terms of radon measuring devices:

> *In the last 20 years, new instruments and methods were developed to measure radon by using grab, integrating, and continuous modes of sampling. The most common are scintillation cell monitors, activated carbon collectors, electrets, ion chambers, alpha track detectors, pulse and current ionization chambers, and solid state alpha detectors.*

In George (2007) radon detection is divided into:

I. Passive integrating radon measurements

   (1) Activated carbon collectors of the open face or diffusion barrier type. Charcoal canisters often employ a gamma spectrometer to count the radon daughters as surrogates (bismuth-214, for example). Liquid scintillation vials also use alpha and beta counting. About 70% of radon measurements in the United States are canister type.

(2) Electret ion chambers are being used for 2–7 days duration to measure the voltage reduction (drop). The voltage drop on the electrets is proportional to the radon concentration. About 10%–15% of radon measurements use this methodology.

(3) Alpha track detectors are used for long-term measurements. Alphas from radon penetrate a plastic lattice, which is etched with acid, and the resulting tracks are counted. There is some use in the United States, but this is more popular in Europe.

II. Passive or active continuous radon measurements

(1) Scintillation cell monitors mostly include the flow-through type.

(2) Current and pulse ionization chambers (mostly passive).

(3) Solid state devices are either passive or active if they use a pump to move air through the sensitive volume of the monitor like the RAD 7, which uses a solid state alpha detector (passive implanted planar silicon (PIPS) detector).

Additionally, the Oak Ridge Institute for Science and Education (ORISE) compared various radon flux measurement techniques (ORISE 2011), including activated charcoal containers, the Electric Passive Environmental Radon Monitor (E-PERM) electret ion chamber, the AlphaGUARD specialized ionization chamber, semiconductor detectors to measure radon daughters, and ZnS(Ag) (silver doped zinc sulfide) scintillation detectors. ORISE stated that the last two techniques were not yet commercially available and that the AlphaGUARD detector was "expensive," and thus they are not currently candidates for radon flux monitoring of uranium tailings. Comparing the activated charcoal containers to the E-PERM, ORISE found that while both were easy to operate and relatively inexpensive, the E-PERM showed smaller variations in measurements, and the activated charcoal containers had higher post-processing costs. The only disadvantage of the E-PERM was that its Teflon disks must be replaced after each use. Based on this comparison, ORISE recommended that for a large number of measurements, such as those needed to comply with Subpart W, E-PERM flux monitors would be best.

This brief review of Method 115 demonstrates that its use can still be considered current for monitoring radon flux from uranium tailings. However, it is important to note that the specific design protocols were developed for use at larger tailings impoundments. Alternatively, many commercial enhancements to that design are widely available and in use today. Other forms of passive detectors, as well as active measurement detectors, are also acceptable alternatives to demonstrate conformance with the standard. In addition, the method as currently written has some elements and requirements that should be reviewed and possibly revised, particularly the location and the frequency of measurement. These would be better based on statistical considerations or some other technical basis. Additional discussion of the continued applicability of Method 115 appears in SC&A 2008, ORISE 2011, and George 2007.

4.0 CURRENT UNDERSTANDING OF RADON RISK

Subpart W regulates the emission of radon from operating uranium recovery facility tailings. To enhance the understanding of the need for Subpart W, this section presents a qualitative review and analysis of changes in the analysis of the risks and risk models associated with radon releases from uranium recovery tailings since the publication of the 1989 BID (EPA 1989). After presenting some brief radon basics, the analysis focuses on three areas that have evolved: radon progeny equilibrium fractions, empirical risk factors, and the development of dosimetric risk factors. Finally, Section 4.4 presents the results of a risk assessment performed using current methodology (i.e., CAP88, Version 3 (TEA 2007)), 2011 estimated population distributions, and historical radon release data. Section 4.4 also discusses and compares the current calculated risks to the 1989 risk assessment results, presented in Section 2.3.

4.1 Radon and Dose Definitions

Rn-222 is a noble gas produced by radioactive decay of Ra-226. As shown in Figure 12, one of the longer-lived daughters in the uranium (U)-238 decay series, Ra-226 is a waste product in uranium tailings and liquids from uranium recovery facilities. These include mills, evaporation and surge ponds, typically found in ISL facilities, and heap leach piles. Radium (and its daughter radon) is also part of the natural radiation environment and is ubiquitous in soils and ground water along with its parent uranium.

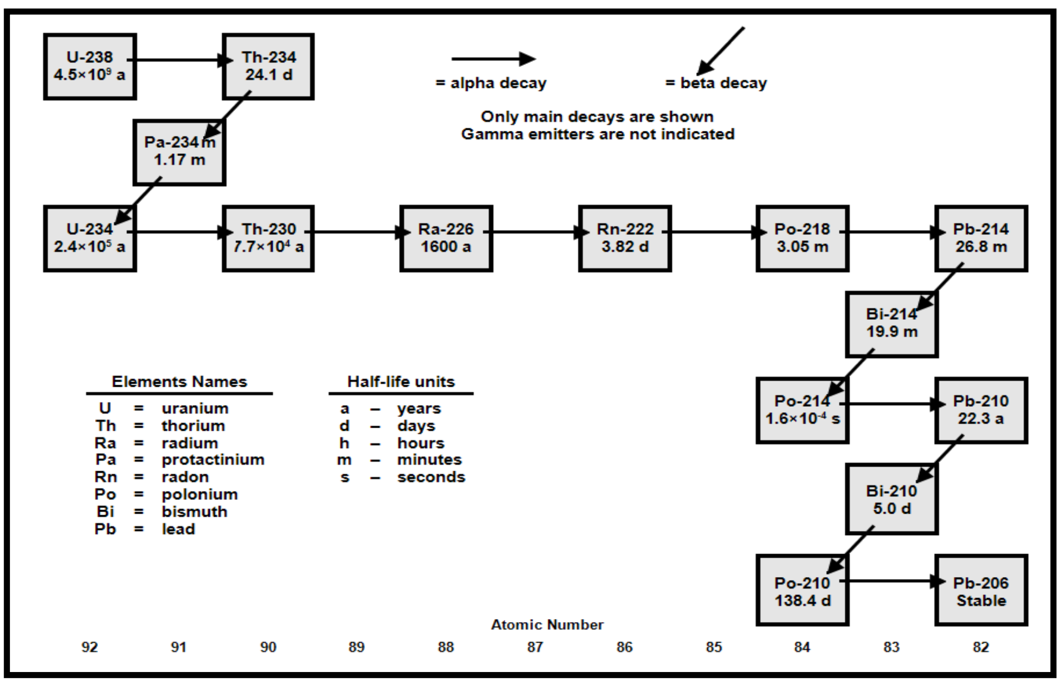


Figure 12: Uranium Decay Series

Radon, with a half-life of 3.8 days, decays into a series of short half-life daughter products or progeny. Being chemically inert, most inhaled radon is quickly exhaled. Radon progeny, however, are charged and electrostatically attach themselves to inhalable aerosol particulates, which are deposited in the lung or directly onto lung tissue. These progeny undergo decay, releasing alpha, beta, and gamma radiation that interacts directly with lung tissue. Of these interactions, alpha particles from polonium-218 and polonium-214 are the most biologically damaging. The resulting irritation of lung cell tissue particularly from these alpha particles enhances the risk of developing a lung cancer. Determining an estimate of the risk of developing a cancer is of primary importance to establishing the basis for any regulatory initiatives.

4.2 Radon Risk Factors

In 1988, the National Research Council's Committee on the Biological Effects of Ionizing Radiation (BEIR) presented a report on the health risks of radon (BEIR IV, NAS 1988). BEIR IV derived quantitative risk estimates for lung cancer from analyses of epidemiologic data from underground miners. The risk factor presented in BEIR IV for radon was 350 cancer deaths per million person-WLMs[5] of exposure.

The International Commission on Radiological Protection (ICRP), in its Publication 50 (ICRP 1987), addressed the question of lung cancer risk from indoor radon daughter exposures. The ICRP Task Group took a direction quite different from that of the BEIR Committee. The Task Group reviewed published data on three miner cohorts: U.S., Ontario, and Czech uranium miners. When the ICRP 50 relative risk model was run with the 1980 U.S. life table and vital statistics, the combined male and female reference risk was calculated in the 1989 BID to be 4.2×10^{-4} cancer deaths per WLM.

In the 1989 BID, EPA averaged the male and female BEIR IV and ICRP 50 risk coefficients and adjusted the coefficients for background, so that the risk of an excess lung cancer death for a combined population (men and women) was 3.6×10^{-4} WLM^{-1}, with a range from 1.4×10^{-4} to 7.2×10^{-4} WLM^{-1} (EPA 1989).

In addition to epidemiological radon risk coefficients, dosimetric models have been developed as a widely acceptable approach to determine the effects of exposures to radon progeny. One of the principal dosimetric models used to calculate doses to the lung following inhalation of radon and its daughters is the ICRP Human Respiratory Tract Model (HRTM), first introduced in ICRP Publication 66 (ICRP 1994). The ICRP used the HRTM to develop a compilation of effective dose coefficients for the inhalation of radionuclides, presented in Publication 72 (ICRP 1996).

Shortly after the publication of ICRP Publication 72, and using the information in that report, EPA developed Federal Guidance Report 13 (FGR 13) (EPA 1999)[6]. In addition to the risk factors given in FGR 13 itself, the FGR 13 CD Supplement (EPA 2002) provides dose factors, as well as risk factors, for various age groups. For this study, the dose and risk factors from the

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[5] Radon concentrations in air are commonly expressed in units of activity (e.g., picocuries (pCi) or becquerels) per unit volume (e.g., liters (L)); however, radon progeny concentrations are commonly expressed as working levels (WLs). In a closed volume, the concentration of short-lived radon progeny will increase until equilibrium is reached, under these conditions, each pCi/L of radon will give rise to (almost precisely) 0.01 WL, or 100 pCi/L = 1 WL (EPA 2003). Exposure to 1 WL for 1 month (i.e., 170 hours) is referred to as 1 working level month (WLM).

[6] Since FGR 13 was published, several organizations have produced updated radiation risk estimates. EPA 2011 reviewed the update risk estimates and concluded that the new mortality estimates do not differ greatly from those in FGR-13.

FGR 13 CD Supplement were used to calculate the dose and risk due to exposure to 1 WLM of radon and its progeny. The calculation assumed a radon airborne concentration of 100 pCi/L, a radon progeny equilibrium fraction of 0.4, a breathing rate of 0.9167 cubic meters per hour (m^3/hr), and an exposure duration of 170 hours.

The results of this calculation demonstrate that the FGR 13 based radon progeny lung dose conversion factor is between about 2.1 to 7.0 millisieverts (mSv)/WLM, depending on the age of the individual being exposed. The results also show that the lifetime fatality coefficient from lung exposure is between about 6×10^{-4} to 2.4×10^{-3} WLM^{-1}, depending on the exposed individual's age. This agrees well with the factor calculated from empirical data.

In conclusion, the radon progeny risk factor from FGR 13 of 6×10^{-4} WLM^{-1} used in this analysis falls within the risk factor range identified in the 1989 BID (i.e., 1.4×10^{-4} to 7.2×10^{-4} WLM^{-1}), and is about 67% larger than the 3.6×10^{-4} WLM^{-1} radon progeny risk factor used in the 1989 BID. Thus, the radon progeny risk factor used in this Subpart W analysis updates the risk factor used in the 1989 BID to reflect the current understanding of the radon risk, as expressed by the ICRP and in FGR 13.

4.3 Computer Models

Various computer models that could be used to calculate the doses and risks due to the operation of conventional and ISL uranium mines were compared. Seven computer programs were considered for use in the uranium tailings radon risk assessment: CAP88 Version 3.0, RESRAD-OFFSITE, MILDOS, GENII, MEPAS, AIRDOS, and AERMOD. A detailed selection process was used to select the program from the first five programs listed. AIRDOS was not included in the detailed selection process, since it is no longer an independent program, but has been incorporated into CAP88 Version 3.0. Because it calculates only atmospheric dispersion, but not radiological doses or risks, AERMOD was also not included. The five remaining programs received a score between 0 and 5 for each of the following 11 criteria: (1) Exposure Pathways Modeled, (2) Population Dose/Risk Capability, (3) Dose Factors Used, (4) Risk Factors Used, (5) Meteorological Data Processing, (6) Source Term Calculations, (7) Verification and Validation, (8) Ease of Use/User Friendly, (9) Documentation, (10) Sensitivity Analysis Capability, and (11) Probabilistic Analysis Capability. Also, each criterion had a weighting factor of between 1 and 2. The total weighted score was calculated for each code, and CAP88 was selected for use in this evaluation. A more complete discussion of the selection of the risk assessment computer code appears in SC&A 2010.

As described in Section 2.3, the 1989 BID used the computer codes AIRDOS-EPA, RADRISK, and DARTAB to calculate the risks due to radon releases from uranium tailings. Subsequent to the publication of the 1989 BID, CAP88 Version 3.0 was produced. CAP88 Version 3.0 was originally composed of the AIRDOS-EPA and DARTAB computer codes and the dose and risk factors from RADRISK (see Section 2.3). CAP88 Version 3.0 was first used for DOE facilities to calculate effective dose equivalents to members of the public to ensure compliance with the then-issued NESHAP Subpart H rules (TEA 2007). Currently, CAP88 Version 3.0 incorporates the dose and risk factors from FGR 13 for determining risks from radionuclides, including the radon decay daughters.

When calculating doses and risk from Rn-222, CAP88 Version 3.0 can be run in two different modes, either normally or in the "radon only" mode. When run in the normal mode, CAP88 Version 3.0 treats radon and its progeny as any other radionuclide and its progeny would be treated. That is, the radon is decayed as it travels from the release point to the dose receptor location, and the in-growth of the progeny is calculated. At the dose receptor location, doses are calculated assuming all the normal exposure pathways, including inhalation and air submersion, that are normally associated with radon doses, and also the exposure pathways from the longer lived radon progeny that deposit onto the ground, including ground shine and food ingestion. To perform these calculations, CAP88 Version 3.0 used the dose and risk factors from FGR 13.

In the "radon only" mode, CAP88 Version 3.0 calculates the risk from the radon WL concentration, but not the dose. The annual risk to an individual or population at a location is simply the WL concentration multiplied by a risk coefficient. The risk coefficient used by CAP88 Version 3.0 is 1.32 cancer fatalities per year per WL. Although this risk coefficient is not documented in any of the CAP88 Version 3.0 user manuals, so its origin is unknown, it can be derived from the CAP88 Version 3.0 output files. A risk coefficient of 1.32 WL-year^{-1} is equivalent to 2.56×10^{-2} cancer deaths per WLM, which is about two orders of magnitude larger than the risk coefficient discussed in Section 4.2. Thus, CAP88's "radon only" mode was not used to calculate the risk estimates that are summarized in the next section. Rather, the risk estimates are based on CAP88's atmospheric transport model (for radon decay and progeny buildup) and the radionuclide-specific risk factors from FGR 13.

4.4 Uranium Recovery Facility Radon Dose and Risk Estimates

To perform the CAP88 dose/risk analysis, three types of data were necessary: (1) the distribution of the population living within 80 km (50 mi) of each site, (2) the meteorological data at each site, particularly the wind speed, wind direction, and stability class, and (3) the amount of radon annually released from the site.

Dose/risk assessments were performed for the uranium recovery sites identified in Table 12, which include conventional uranium mills and ISL mines, plus two hypothetical generic sites developed to represent the western and eastern United States.

Table 12: Uranium Recovery Sites Analyzed

Mill / Mine	Type	State	Regulator	Latitude			Longitude		
				deg	min	sec	deg	min	sec
Crow Butte	In-Situ Leach	NE	NRC	42	38	41	-103	21	8
Western Generic	Conventional	NM	NRC	35	31	37	-107	52	52
Alta Mesa 1, 2, 3	In-Situ Leach	TX	State	26	53	59	-98	18	29
Kingsville Dome 1,3	In-Situ Leach	TX	State	27	24	54	-97	46	51
White Mesa Mill	Conventional	UT	State	37	34	26	-109	28	40
Eastern Generic	Conventional	VA	NRC	38	36	0	-78	1	11
Smith Ranch - Highland	In-Situ Leach	WY	NRC	43	3	12	-105	41	8
Christensen/Irigaray	In-Situ Leach	WY	NRC	43	48	15	-106	2	7
Sweetwater Mill	Conventional	WY	NRC	42	3	7	-107	54	41

Normally, the population doses and risks are calculated out to a distance of 80 km (50 mi) from the site. Therefore, it was necessary to know the population to a distance of 80 km from each site in each of the 16 compass directions. This information is not normally available from U.S. Census Bureau data. However, in 1973, EPA wrote a computer program, SECPOP (Sandia 2003), which would convert census block data into the desired 80-km population estimates for any specific latitude and longitude within the continental United States. The NRC adopted this program to perform siting reviews for license applications and has updated the program to use the 2000 census data. SC&A (2011) used the SECPOP program to estimate the population distribution around each site; that population was then modified to account for changes in the population from 2000 to 2010.

For those sites where site-specific meteorological data were identified, those site-specific data were used. For other sites, CAP88 Version 3.0 is provided with a weather library of meteorological data from over 350 National Weather Service stations. For sites without site-specific meteorological data, data from the National Weather Service station nearest the site were used.

Annual radon release estimates were determined for each site based on the available documentation for the site. For example, some sites reported their estimated radon release in their semiannual release reports, while other sites calculated their radon release as part of their license application or renewal application. Finally, for some sites, the annual radon release estimates were obtained from the NRC-produced, site-specific environmental assessment. If multiple documents provided radon release estimates for a particular site, the estimate from the most recent document was used. Consistent with the 1989 assessment, in order to bound the risks, radon releases were estimated from both process effluents and impoundments. Likewise, if both theoretical and actual radon release values were identified for a site, the actual radon release value was given preference.

Additional descriptions of each site's population, meteorology, and radon source term may be found in SC&A 2011. Doses and risks to the RMEI and to the population living within 80 km of the facility were calculated. The RMEI is someone who lives near the facility and is assumed to have living habits that would tend to maximize his/her radiation exposure. For example, the RMEI was assumed to eat all of his/her vegetables from a garden located nearest the facility, which is contaminated with radon progeny as a result of radon releases from the facility. On the other hand, population doses and risks are based on the number of individuals who live within 80 km of the facility. These people are also assumed to eat locally grown vegetables, but not necessarily from the garden located nearest the facility. The RMEI's dose and risk are included within the population dose and risk, since he/she lives within the 80-km radius.

Table 13 presents the RMEI and population doses and risks due to the maximum radon releases estimated for each uranium site.

Table 13: Calculated Maximum Total Annual RMEI, Population Dose and Risk

Uranium Site	Maximum Radon Release (Ci/yr)	Annual Dose		LCF(a, b) Risk (yr^{-1})	
		Population (person-rem)	RMEI (mrem)	Population	RMEI
Sweetwater	2,075	0.5	1.2	2.9E-06	6.0E-07
White Mesa	1,750	5.2	12.0	3.4E-05	6.4E-06
Smith Ranch - Highlands	36,500	3.7	1.5	2.3E-05	7.7E-07
Crow Butte	8,885	2.7	3.3	1.7E-05	1.7E-06
Christensen/Irigaray	1,600	3.8	1.9	2.4E-05	9.9E-07
Alta Mesa	740	21.6	11.5	1.3E-04	6.1E-06
Kingsville Dome	6,958	58.0	11.3	3.8E-04	6.1E-06
Eastern Generic	1,750	200.3	28.2	1.4E-03	1.6E-05
Western Generic	1,750	5.1	6.0	2.7E-04	7.7E-06

(a)Latent Cancer Fatalities
(b)In this table all risks are presented as LCF risks. If it is desired to estimate the morbidity risk, simply multiply the LCF risk by 1.39.

Table 14 presents the RMEI and population doses and risks due to the average radon releases estimated for each uranium site. The risks were based on average radon releases to make it easier to convert these annual risk values into lifetime risk values. This conversion is done by simply multiplying the Table 14 values by the number of years that the facility operates for the population risk, or by the length of time that the individual lives next to the facility for the RMEI risk.

Table 14: Calculated Average Total Annual RMEI, Population Dose and Risk

Uranium Site	Average Rado n Release (Ci/yr)	Annual Dose		LCF(a) Risk (yr^{-1})	
		Population (person-rem)	RMEI (mrem)	Populatio n	RMEI
Sweetwater	1,204	0.3	0.7	1.7E-06	3.5E-07
White Mesa	1,388	3.0	7.0	2.0E-05	3.7E-06
Smith Ranch - Highland s	21,100	2.2	0.9	1.3E-05	4.5E-07
Crow Butte	4,467	1.6	1.9	1.0E-05	1.0E-06
Christensen/Irigaray	1,040	2.2	1.1	1.4E-05	5.7E-07
Alta Mesa	472	12.5	6.7	7.6E-05	3.6E-06
Kingsville Dome	1,291	33.6	6.6	2.2E-04	3.5E-06
Eastern Generic	1,388	116.3	16.4	7.9E-04	9.2E-06
Western Generic	1,388	3.0	3.5	1.6E-04	4.4E-06

(a)Latent Cancer Fatalities

The dose and risk to an average member of the population within 0–80 km of each site may be calculated by dividing the population doses and risks from Table 13 and Table 14 by the population for each site. Table 15 shows the results of that calculation.

Table 15: Dose and Risk to an Average Member of the Population

Uranium Site	Dose (mrem)		LCF[a] Risk (yr^{-1})	
	Average Release	Maximum Release	Average Release	Maximum Release
Sweetwater	0.03	0.05	1.6E-07	2.7E-07
White Mesa	0.15	0.25	9.6E-07	1.6E-06
Smith Ranch - Highlands	0.03	0.05	1.7E-07	2.9E-07
Crow Butte	0.05	0.08	3.1E-07	5.3E-07
Christensen/Irigaray	0.06	0.11	3.8E-07	6.6E-07
Alta Mesa	0.03	0.05	1.6E-07	2.7E-07
Kingsville Dome	0.07	0.13	4.8E-07	8.3E-07
Eastern Generic	0.05	0.09	3.7E-07	6.4E-07
Western Generic	0.04	0.07	2.2E-06	3.8E-06

[a]Latent Cancer Fatalities

As Table 15 shows, the annual latent cancer fatality (LCF) risk to an average member of the population surrounding a uranium site ranges from 1.6×10^{-7} to 1.6×10^{-6} for the seven actual sites, and from 3.7×10^{-7} to 3.8×10^{-6} for the two hypothetical generic sites.

The study estimated that the annual fatal cancer risk to the RMEI ranges from 3.5×10^{-7} to 6.4×10^{-6} for the seven actual sites, and from 4.4×10^{-6} to 1.6×10^{-5} for the two hypothetical generic sites. The highest annual individual risk occurred at the Eastern Generic site, which is not surprising considering that the nearest individual was assumed to reside only about 1 mi from the hypothetical site. It is likely that during the site selection process for an actual facility, a site this close to residences would be eliminated and/or the design of the facility would include features for reducing radon emissions in order to reduce the RMEI risk.

The lifetime risk would depend on how long an individual was exposed. For example, for the seven actual sites analyzed, assuming that the uranium mill operates for 10 years, then the lifetime fatal cancer risk to the RMEI would be 3.5×10^{-6} to 3.7×10^{-5}. Alternatively, if it is assumed that an individual was exposed for his/her entire lifetime (i.e., 70 years), then the lifetime fatal cancer risk to the RMEI would be 2.45×10^{-5} to 2.59×10^{-4}. For the two hypothetical generic sites, the lifetime fatal cancer risk to the RMEI would be 4.4×10^{-5} to 9.2×10^{-5} assuming 10 years of mill operation, or 3.1×10^{-5} to 6.44×10^{-5} assuming 70 years of mill operation. The lifetime risk calculation uses only the average radon release results, because while the maximum could occur for a single year, it is unlikely that the maximum would occur for 10 or 70 continuous years.

The study also estimated that the risk to the population from all seven real uranium sites is between 0.0005 and 0.0009 fatal cancers per year, or approximately one case every 1,080 to 1,865 years to the 1.8 million persons living within 80 km of the sites.

4.5 Summary of Radon Risk

This section described the evolution in the understanding of the risk presented by radon and its progeny since the 1989 BID was published. Additionally, the computer code CAP88 Version 3.0 was used to analyze the radon risk from seven operating uranium recovery sites and two generic sites.

The lifetime MIR calculated using data from seven actual uranium recovery sites was determined to be between 2.45×10^{-5} to 2.59×10^{-4}. The low end of the range is lower than the 3×10^{-5} lifetime MIR reported in the 1989 rulemaking for existing impoundments (see Section 2.3.1), while the high end of the range is slightly higher than the 1.6×10^{-4} lifetime MIR reported in the 1989 rulemaking for new impoundments (see Section 2.3.2).

In protecting public health, EPA strives to provide the maximum feasible protection by limiting radon exposure to approximately 1 in 10,000 (i.e., 10^{-4}) the lifetime MIR. Although the calculated high end of the lifetime MIR range is above 10^{-4}, the assumptions that radon releases occur continuously for 70 years and that the same RMEI is exposed to those releases for the entire 70 years are very conservative.

Similarly, the risk assessment estimated that the risk to the population from all seven real uranium sites is between 0.0005 and 0.0009 fatal cancers per year, or approximately one case every 1,080 to 1,865 years among the 1.8 million persons living within 80 km of the sites. For the 1989 rulemaking, the estimated annual fatal cancer incidence to the 2 million people living within 80 km of the sites was 0.0043, which was less than one case every 200 years for existing impoundments, and 0.014, or approximately one case every 70 years for new impoundments (see Sections 2.3.1 and 2.3.2).

5.0 EVALUATION OF SUBPART W REQUIREMENTS

The evaluation of Subpart W requirements required analyses of several items to determine if the current technology had advanced since the promulgation of the rule. These topics are listed below, along with the key issues addressed in this report to determine whether the requirements of Subpart W are necessary and sufficient.

5.1 Items Reviewed and Key Issues

Each of these items will be reviewed with reference to the relevant portions of this document:

(1) Review and compile a list of existing and proposed uranium recovery facilities and the containment technologies being used, as well as those proposed.

Key Issue – The standard should be clarified to ensure that all owners and operators of uranium recovery facilities (conventional mills, ISL, and heap leach) are aware that all of the structures and facilities they employ to manage uranium byproduct material (i.e., tailings) are regulated under Subpart W.

(2) Compare and contrast those technologies with the engineering requirements of hazardous waste impoundments regulated under RCRA Subtitle C disposal facilities, which are used as the design basis for existing uranium byproduct material (i.e., tailings) impoundments.

Key Issue – All new impoundments shall adopt the design and engineering standards referred to through 40 CFR 192.32(a)(1).

(3) Review the regulatory history.

Key Issue – NESHAP Subpart W continues to be the appropriate regulatory tool to implement the Administrator's duty under the CAA for operating uranium mill tailings.

(4) Tailings impoundment technologies.

Key Issue – The emission limit for impoundments that existed as of December 15, 1989, has been demonstrated to be both achievable and sufficient to limit risks to the levels that were found to protect public health with an ample margin of safety.

The requirement that impoundments opened after December 15, 1989, use either phased or continuous disposal technologies as appropriate to ensure that public health is protected with an ample margin of safety, which is consistent with section 112(d) of the 1990 Amendments of the CAA, which requires standards based on GACT.

(5) Radon measurement methods used to determine compliance with the existing standards.

Key issue – The approved method (Method 115, 40 CFR 61, Appendix B) of monitoring Rn-222 to demonstrate compliance with the emission limit for impoundments that existed as of December 15, 1989, is still valid.

(6) Compare the 1989 risk assessment with current risk assessment approaches.

Key Issue – Adoption of a lower emission limit is not necessary to protect public health, as the current limit has been shown to be protective of human health and the environment. Impact costs associated with the limit are considered to be acceptable.

5.1.1 Existing and Proposed Uranium Recovery Facilities

Sections 3.2, 3.3, and 3.4 describe the three types of uranium recovery facilities: conventional mills, ISL facilities, and heap leach facilities. Each facility type is briefly described below.

Conventional Mills

Section 3 of this report presents a review of the existing and proposed uranium recovery facilities. As indicated, there are five conventional mills at various stages of licensing, with various capacities to receive tailings. Of these five conventional mills, only White Mesa is operational. Some of these were constructed before December 15, 1989, and fall under the Subpart W monitoring requirement. Table 16 shows the current conventional mills with pre-December 15, 1989 conventional impoundments.

Table 16: Current Pre-December 15, 1989 Conventional Impoundments

Conventional Mill Name	Regulatory Status	Pre-December 15, 1989 Impoundments
Sweetwater	Standby,* license expires November 2014	37 acres not full
Shootaring Canyon	Standby,* license extension May 2013	Only 7 acres of impoundment filled
White Mesa	Active, license expires March 2015	Cell 2 closed, Cell 3 almost full

* Standby means the period of time when a facility may not be accepting new tailings, but has not yet entered closure operations.

The White Mesa Mill (see Section 3.2.2) has one pre-1989 cell (Cell 3) that is authorized to accept tailings and is still open. Cell 2 is closed. Both cells are monitored for radon flux. The average radon flux for Cell 2 was calculated at 13.5 pCi/(m^2-sec), while that at Cell 3 was 8.9 pCi/(m^2-sec). The mill also uses an impoundment constructed before 1989 as an evaporation pond.

The Sweetwater Mill (see Section 3.2.1) has a 60-acre tailings management area with a 37-acre tailings impoundment of which 28 acres are dry with an earthen cover. The remainder is covered by water. The radon flux from this impoundment is monitored yearly. The average flux (using Method 115) for the entire impoundment was 6.01 pCi/(m^2-sec), including the water-covered area, which had an assumed flux of zero.

The Shootaring Canyon Mill (see Section 3.2.3) had plans for an upper and lower impoundment, but only the upper impoundment was constructed. As the mill operated for approximately 30 days, only about 7 acres of tailings were deposited in the upper impoundment. These have a soil cover. The average radon flux from the covered tailings was measured using Method 115 at 11.9 pCi/(m^2-sec) in April 2010.

The Piñon Ridge Mill (see Section 3.2.4) is a permitted conventional uranium recovery facility in Montrose County, Colorado. The facility has not been constructed; however, there are current activities at the site, including a pre-operational environmental monitoring program.

In-Situ Recovery

As discussed in Section 3.3, ISL was first conducted in 1963 and soon expanded so that by the mid-1980s, a fair proportion of the recovered uranium was by ISL. Table 8shows the ISL facilities in the United States that are currently operational. As previously discussed, the economics of ISL uranium recovery are conducive to lower grade deposits or deeply buried deposits that could not be economically recovered with conventional open pit or underground mining. Thus, approximately 23 facilities are restarting, expanding, or planning for new operations (see Table 9).

Of particular importance to Subpart W are the impoundments that are an integral part of all ISL facilities. These impoundments are required to maintain the hydrostatic gradient toward the leach field to minimize excursions referred to as “flare,” a proportionality factor designed to estimate the amount of aquifer water outside of the pore volume that has been impacted by lixiviant flow during the extraction phase. While these impoundments typically do not reach the size and scale of conventional tailings piles, they are an integral component of ISL, contain various amounts of radium, and can function as sources of radon gas. Section 3.3.1 provides the mathematical framework for estimating the quantity of radon being emitted from an impoundment. The subsequent discussion of Subpart W, including a proposed standard for impoundments constructed after December 15, 1989, will further evaluate this radon flux.

Heap Leach Facilities

The few commercial heap leach facilities established in the 1980s have been shut down. Recently, however, two heap leach facilities have been proposed: one in Wyoming (Sheep Mountain – Energy Fuels) and one in New Mexico (Grants Ridge, Uranium Energy Corporation) (see Section 3.4). If the price of uranium increases, then recovery of uranium from heap-leaching low-grade ores will become economically attractive and will likely lead to additional facilities. The question to be addressed from the standpoint of Subpart W is the radon flux released from the active heap leach pile. Also, once the uranium is removed from the ore in the heap leach pile, the spent ore becomes a byproduct material much like the tailings, albeit not mobile. This spent ore contains radium that releases radon. As the heap leach pile is constructed to allow lixiviant to “trickle through” the pile, these same pathways could allow for radon release by diffusion out of the spent ore and then through the pile, which is addressed under Subpart W.

5.1.2 RCRA Comparison

Both alternative disposal methods presented in Subpart W (work practices) require that tailings impoundments constructed after December 15, 1989, meet the requirements of 40 CFR 192.32(a)(1). Tailings impoundments include surface impoundments, which are defined in 40 CFR 260.10:

> *Surface impoundment or impoundment means a facility or part of a facility which is a natural topographic depression, man-made excavation, or diked area formed primarily of earthen materials (although it may be lined with man-made materials), which is designed to hold an accumulation of liquid wastes or wastes containing free liquids, and which is not an injection well. Examples of surface impoundments are holding, storage, settling, and aeration pits, ponds, and lagoons.*

The above definition encompasses conventional tailings ponds, ISL ponds, and heap leach piles. The last is included as it is assumed that the heap leach pile will be diked or otherwise constructed so as not to lose pregnant liquor coming from the heap.

This being the case, 40 CFR 264.221(a) states that the impoundment shall be designed and constructed and installed to prevent any migration of wastes out of the impoundment to the adjacent subsurface soil or ground water or surface water at any time during the active life of the impoundment. Requirements of the liner system listed in 40 CFR 264.221(c) include:

(1)(i)(A) A top liner designed and constructed of materials (e.g., a geomembrane) to prevent the migration of hazardous constituents into such liner during the active life.

(1)(i)(B) A composite bottom liner, consisting of at least two components. The upper component must be designed and constructed of materials (e.g., a geomembrane) to prevent the migration of hazardous constituents into this component during the active life and post-closure care period. The lower component must be designed and constructed of materials to minimize the migration of hazardous constituents if a breach in the upper component were to occur. The lower component must be constructed of at least 3 ft (91 centimeters (cm)) of compacted soil material with a hydraulic conductivity of no more than $1{\times}10^{-7}$ centimeters per second (cm/sec).

The regulation also requires a leachate collection system:

(2) The *leachate collection and removal system* between the liners, and immediately above the bottom composite liner in the case of multiple leachate collection and removal systems, is also a *leak detection system.* This leak detection system must be capable of detecting, collecting, and removing leaks of hazardous constituents at the earliest practicable time through all areas of the top liner likely to be exposed to waste or leachate during the active life and post-closure care period.

Other requirements for the design and operation of impoundments, given in 40 CFR 264 Subpart K, include construction specifications, slope requirements, and sump and removal requirements. The above requirements are important to new uranium containment/impoundment systems because of the potential that water will be used to limit the radon flux from a containment/impoundment. Thus, it is also important to minimize the potential for ground water or surface water contamination. For conventional mill tailings impoundments, the work practices require a soil cover. With heap leach piles, the moisture in the heap would limit radon during operations, and after operations, a degree of moisture would be required to ensure that the radon diffusion coefficient is kept low (see Section 5.4).

5.1.3 Regulatory History

Section 2.0 reviewed the regulatory history of Subpart W. This review indicates that NESHAP Subpart W continues to be the appropriate regulatory tool to implement the Administrator's duty under the CAA. The following presents the use of GACT (see Section 5.3) in detail and describes its use in conventional and other than conventional uranium recovery.

5.1.4 Tailings Impoundment Technologies

Sections 2.3.1 and 2.3.2 discuss tailings impoundment technologies. The two primary changes to the technology as it was previously practiced were first that owners and/or operators of conventional mill tailings impoundments must meet the requirements of 40 CFR 192.32(a)(1) and second that they must adhere to one of the two work practices previously discussed (for impoundments constructed after December 15, 1989). Within these limits, tailings impoundment technologies have had no fundamental changes.

5.1.5 Radon Measurement Methods

As previously described, Subpart W defines two separate standards. The first states that existing sources (as of December 15, 1989) must ensure that emissions to the ambient air from an existing uranium mill tailings pile shall not exceed 20 pCi/(m^2-sec) of Rn-222. To demonstrate compliance with this emission standard, facilities are required to monitor emissions in accordance with Method 115 of 40 CFR 61, Appendix B, and file an annual report with EPA that shows the results of the compliance monitoring (see Section 3.5). As pointed out in Appendix B, the focus of the monitoring was on the beaches, tops, and sides of conventional piles. The radon flux from the water-covered portion of the tailings pile was assumed to be zero. Although regulated under Subpart W, it is unclear how to monitor the radon flux off the surface of evaporation ponds at conventional mills, ISLs, or heap leach facilities. Since these ponds are considerably smaller than tailings impoundments, the solution was to specify that as long as the water cover is 1 meter or more during the active life of the pond, no monitoring is necessary (see Section 3.3.1).

Section 3.3.1 also shows that, for evaporation ponds at ISL facilities, the radon flux from the surface is a function of the wind speed and the concentration of radium in the water. Estimates using actual ISL data showed the contribution to the sites' total radon release to be less than 1% of the total. In any case, the radon flux can also be reduced by co-precipitating the radium using barium chloride ($BaCl_2$) co-precipitation treatment to reduce the radium concentration.

For impoundments constructed on or after December 15, 1989, monitoring is not required. Rather, Subpart W requires that these impoundments comply with one of two work practice standards: the first practice limits the size of the impoundment to 40 acres or less, which limits the radon source, while the second practice of continuous disposal does not allow uncovered tailings to accumulate in large quantities, which also limits radon emissions.

For evaporation ponds or holding ponds as in the pre-December 15, 1989, case, a 1-meter cover of water should be sufficient to limit the radon flux to the atmosphere (see Section 3.3.1). Thus, the proposed GACT is that these impoundments meet the design and construction requirements of 40 CFR 192.32(a)(1), with no size or area restriction, and that during the active life of the pond at least 1 meter of liquid be maintained in the pond.

The last facility is the potential heap leach pile. Subpart W applies to the material in the pile as byproduct material is being generated. Considering a small section of the pile as the leach (acid or base) solubilizes the uranium, the material left is byproduct material. The result is a material similar to tailings and the heap is also wet. It is assumed that if the moisture content is greater than 30%, the heap is not dewatered. As long as the heap is not dewatered, the radon diffusion coefficient is such that minimal radon will escape the heap leach pile.

Heap Leach Radon Flux

A possible source of radon from a heap leach pile is from the surface of the pile. Assuming that the heap pile is more than 1 or 2 meters thick, the radon flux from this configuration can be estimated from the following formula (NRC 1984):

$$J = 10^4 R \rho E \sqrt{\lambda D_e} \qquad (5\text{-}1)$$

Where

J = radon flux (pCi/(m^2-sec))

10^4 = units conversion (cm^2/m^2)

R = specific activity of radium (pCi/g)

ρ = dry bulk density of material (1.8 g/cc)

E = emanation coefficient

λ = radon decay constant (2.11×10^{-6} sec^{-1})

D_e = radon diffusion coefficient (cm^2/sec)

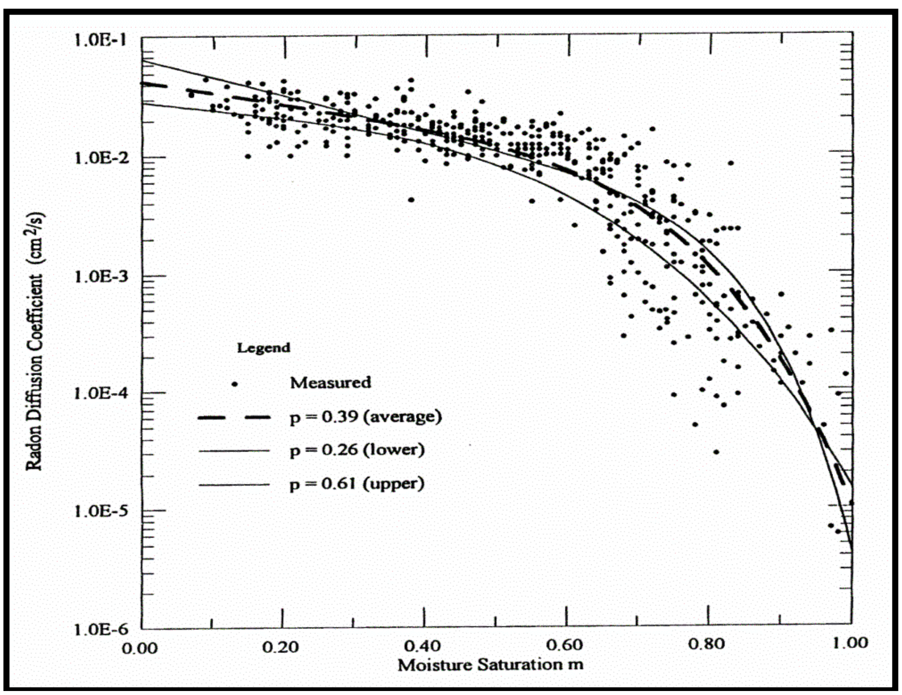
$$= D_0\, p \exp[-6\, m\, p - 6\, m^{14\, p}] \qquad (5\text{-}2)$$

D_0 = radon diffusion coefficient in air (0.11 cm^2/sec)

m = moisture saturation fraction

p = total porosity

The above empirical expression for the radon diffusion coefficient was developed by Rogers and Nielson (1991), based on 1,073 diffusion coefficient measurements on natural soils. Figure 13 shows that the diffusion coefficient calculated using the empirical expression agrees well with the measured data points over the whole range of moisture saturation at which diffusion coefficient measurements were made.



Source: Rogers and Nielson 1991, as reported in Li and Chen 1994

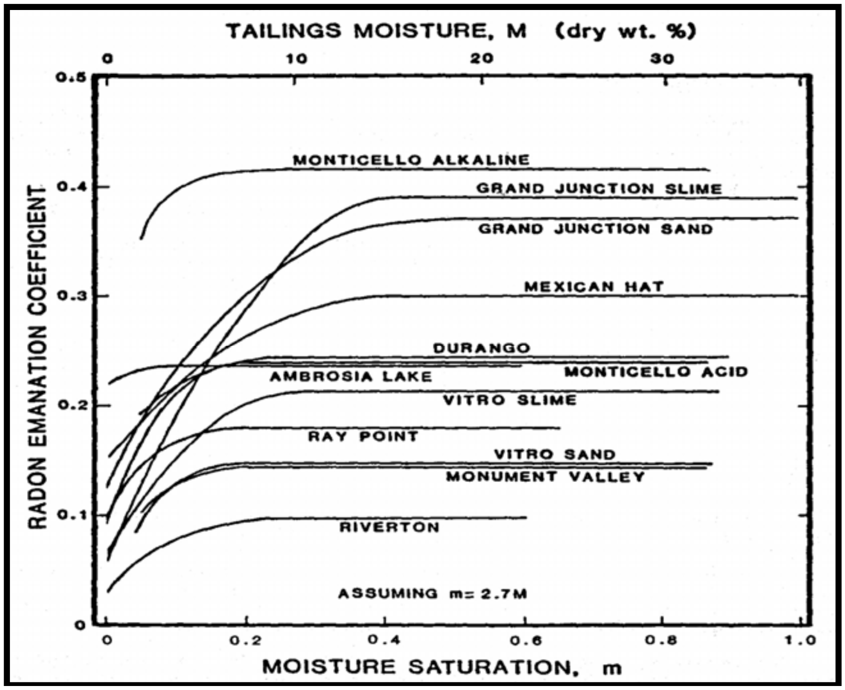
Figure 13: Diffusion Coefficient as a Function of Moisture Saturation

Figure 13 also demonstrates that as the moisture increases, the radon diffusion coefficient decreases significantly. This is because radon diffuses 10,000 times more slowly in water than it does in air (Drago 1998, as reported in Brown 2010). Therefore, adding moisture to the radium-containing material (whether it be a tailings pile or a heap pile) would decrease the diffusion coefficient, thereby increasing the time it takes for radon to diffuse out of the material and allowing more radon to decay before it can be released. As Figure 13 shows, the decrease in the radon diffusion coefficient can be significant, especially at high moisture levels.

However, in addition to the radon diffusion coefficient, the radon emanation coefficient is sensitive to the amount of moisture present. When a radium atom decays, one of three things can happen to the resulting radon atom: (1) it may travel a short distance and remain embedded in the same grain, (2) it can travel across a pore space and become embedded in an adjacent grain, or (3) it is released into a pore space. The fraction of radon atoms released into the pore space is termed the "radon emanation coefficient" (Schumann 1993). As soil moisture increases, it affects the emanation coefficient by surrounding the soil grains with a thin film of water, which slows radon atoms as they are ejected from the soil grain, increasing the likelihood that the radon atom will remain in the pore space. Research by Sun and Furbish (1995) describes this relationship between moisture saturation and the radon emanation rate:

> *The greater the moisture saturation is, the greater the possible radon emanation rate is. With moisture contents from 10% up to 30%, the recoil emanation rates quickly reach the emanation rate of the saturated condition. As the moisture reaches 30%, a universal thin film on the pore surface is formed. This thin film is sufficient to stop the recoil radon from embedding into another part of the pore wall.*

Figure 14 shows that the radon emanation coefficient can vary considerably for different tailings piles. Figure 14 also agrees with Sun and Furbish (1995) in that it shows that the emanation coefficient tends to level off when the moisture saturation level is above approximately 30%.



Source: NRC 1984

Figure 14: Emanation Coefficient as a Function of Moisture Content and Moisture Saturation

In conclusion, a moisture saturation level of up to about 30% tends to increase the radon emanation coefficient and decrease the radon diffusion coefficient, such that the amount of radon released from the pile could increase with increasing moisture. Above about 30% moisture saturation, the radon emanation coefficient is unchanged by increasing moisture, while the radon diffusion coefficient continues to decrease. Figure 15 shows the total effect of moisture on the radon flux. Equation 5-1 was used to develop Figure 15, along with the Rogers and Nielson (1991) empirical equation for the diffusion coefficient, an approximation of the Vitro Sand emanation coefficient from Figure 14, and a porosity of 0.39. Figure 15 does not show the radon flux values, since they would vary depending on the radium concentration and would not affect the shape of the curve.

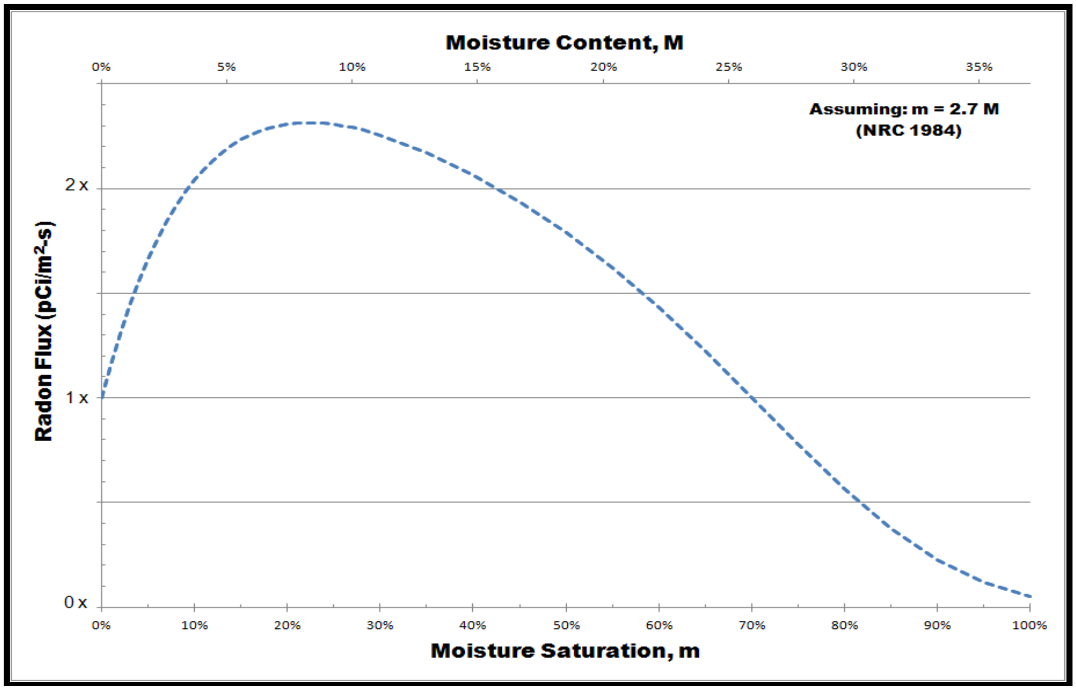


Figure 15: Radon Flux as a Function of Moisture Saturation and Moisture Content

Figure 15 shows that the radon flux starts low and increases as the moisture saturation increases due to the emanation coefficient. At between 20% and 30% moisture saturation, the flux reaches a peak that is about 2½ times the flux at zero moisture, after which the diffusion coefficient takes control and the flux decreases. Figure 15 is consistent with the results reported by Hosoda et al. (2007) in their study of the effect of moisture on the emanation of radon and thoron gases from weathered granite soil:

> *A sporadic increase in the radon and thoron exhalation rates was caused by the increase in the moisture content up to 8%* [27% moisture saturation]. *However, the exhalation rates showed a decreasing tendency with the increase in moisture content over 8%..., both measured and calculated radon exhalation rates had similar trends with an increase in the moisture content in the soil.*

The final point from Figure 15 is that the radon flux with a moisture content of 70% or greater is less than the flux at zero moisture, and that with a porosity of 0.39, 70% moisture saturation is equivalent to 27% moisture by weight. Thus, 30% moisture by weight would result in a radon flux significantly below the zero moisture flux.

5.1.6 Risk Assessment

Section 4.4 presents the results of a risk assessment performed for seven actual uranium recovery sites plus two generic uranium recovery sites. This risk assessment used the CAP88 Version 3.0 analytical computer model, which, as described in Section 4.0, evolved from and differs from the models used for the 1989 risk assessment (i.e., AIRDOS-EPA, RADRISK, and DARTAB). Additionally, this assessment used the latest radon dose and risk coefficients (i.e., millirem (mrem)/picocurie (pCi) and LCF/pCi) from FGR 13. Both the 1989 assessment and this assessment used site-specific meteorological data. This assessment used 2000 census data, updated to 2010, whereas the 1989 assessment used 1983 data. Finally, as stated above, this assessment used actual historical radon releases from the uranium recovery sites, whereas because of the lack of site-specific data, the 1989 assessment assumed a radon release rate based on 1 pCi/(m^2-sec) Rn-222 emitted per pCi/g Ra-226 during both the operating, standby, drying, and/or disposal phase, and either 20 pCi/(m^2-sec) or the design flux (if known) during the post-disposal phase.

Section 4.4 presents the doses and risks calculated by the current risk assessment, and Section 4.5summarizes them. Additional information on the current risk assessment appears in SC&A 2011.

5.2 Uranium Recovery Source Categories

The preceding items and key issues are the basis for categorizing the major uranium recovery methods that will lead to methods of reducing radon emissions. The next section, which addresses the GACT standard, further discusses the applicability of the control measures. The following source categories represent a logical breakdown of the current uranium recovery industry:

Conventional Impoundments – Conventional impoundments are engineered structures for storage and eventual permanent disposal of the fine-grained waste from mining and milling operations (i.e., tailings). All conventional uranium recovery mills have one or more conventional impoundments. Table 3 shows conventional uranium milling facilities that are either built or licensed. This category will also include future conventional milling facilities.

Nonconventional Impoundments – At nonconventional tailings impoundments, tailings (byproduct material) are contained in ponds and covered by liquids. These impoundments are normally called “evaporation ponds” or “holding ponds.” Nonetheless, they contain byproduct material and, as shown in Section 3.3.1, can generate radon gas. This category is usually associated with ISL facilities (i.e., process waste water resulting from ISL operations (see Section 3.3)), but can also be associated with conventional facilities or heap leach facilities. While these ponds do not meet the work practices for conventional mills, they still must meet the requirements of 40 CFR 192.32(a)(1).

Heap Leach Piles – While no heap leach facilities are currently operating in the United States, at least one potential operation is expected to go forward (see Section 3.4). Heap leach piles contain byproduct material, which is the residue of the operation. That is, as the lixiviant mobilizes the uranium, the remaining part of the ore becomes byproduct. As stated above, the design and operation of the heap leach is expected to follow the requirements of 40 CFR 192.32(a)(1).

5.3 The GACT Standard

Section 112(d) of the CAA requires EPA to establish NESHAPs for both major and area sources of HAPs that are listed for regulation under CAA section 112(c). Section 112(c) lists radionuclides, including radon, as a HAP, while section 112(a) defines two types of HAP sources: major sources and area sources. Depending on whether the source is a major or area source, section 112(d) prescribes standards for regulation of emissions of HAP. A "major source," other than for radionuclides, is defined as any stationary source or group of stationary sources located within a contiguous area and under common control that emits or has the potential to emit, in the aggregate, 10 tons per year or more of any HAP. For radionuclides, major source shall have the meaning specified by the Administrator by rule. An area source is a stationary source that is not a major source.

The regulation of HAPs at major sources is dictated by the use of MACT. Section 112(d) defines MACT as the maximum degree of reduction in HAP emissions that the Administrator determines is achievable, considering the cost of achieving the reduction and any non-air-quality health and environmental impacts and energy requirements. With respect to area sources, section 112(d)(5) states that, in lieu of promulgating a MACT standard, the Administrator may elect to promulgate standards that provide for the use of GACT or management practices to reduce HAP emissions.

In 2000, EPA provided guidance to clarify how to apply the major source threshold for HAPs as defined in section 112(b) of the CAA Amendments of 1990. The guidance stated how to apply the major source threshold specifically for radionuclides:

> *There have been some questions about determining the major source threshold for sources of radionuclides. Section 112(a)(1) allows the Administrator to establish different criteria for determining what constitutes a major source of radionuclides since radionuclides emissions are not measured in units of tons. This, however, would not preclude a known radionuclide emitter that is collocated with other HAP-emitting activities at a plant site from being considered a major source due to the more common, weight-based threshold. The July 16, 1992, source category list notice did not include any sources of radionuclides because no source met the weight-based major source threshold, and the Agency had not defined different criteria. At the current time, there remain no listed major source categories of radionuclide emissions.* [EPA 2000b]

Based on this guidance, radon emissions from uranium recovery facility tailings impoundments are not a major source, and therefore, they are area sources for which the GACT standard is applicable. Unlike MACT, the meaning of GACT, or what is "generally available" is not defined in the act. However, section 112(d)(5) of the CAA Amendments for 1990 authorizes EPA to:

> *Promulgate standards or requirements applicable to [area] sources…which provide for the use of generally available control technologies or management practices by such sources to reduce emissions of hazardous air pollutants.*

The Senate report on the legislation (U.S. Senate 1989) provides additional information on GACT and describes it as:

> *…methods, practices and techniques which are commercially available and appropriate for application by the sources in the category considering economic*

impacts and the technical capabilities of the forms to operate and maintain the emissions control systems.

Determining what constitutes GACT involves considering the control technologies and management practices that are generally available to the area sources in the source category. Also considered are the standards applicable to major sources in the same industrial sector to determine if the control technologies and management practices are transferable and generally available to area sources. In appropriate circumstances, technologies and practices at area and major sources in similar categories are also reviewed to determine whether such technologies and practices can be considered generally available for the area source category at issue. Finally, as noted above, in determining GACT for a particular area source category, the costs and economic impacts of available control technologies and management practices on that category are considered.

Thus, as presented above, "Promulgate standards or requirements … " does not limit EPA to strict "standard setting" in order to provide for the use of GACT. Rather, it allows EPA to promulgate at least two types of rules: rules that set emission levels based on specific controls or management practices (this is analogous to the MACT standard setting), and rules that establish permitting or other regulatory processes that result in the identification and application of GACT standards.

5.4 Uranium Recovery Categories and GACT

For conventional impoundments, the 1989 promulgation of Subpart W contained two work practice standards, phased disposal and continuous disposal (see Section 2.0, page 7). The work practice standards limit the size and number of the impoundments at a uranium recovery facility in order to limit radon emissions. The standards cannot be applied to a single pile that is larger than 40 acres (for phased disposal) or 10 uncovered acres (for continuous disposal). This approach was taken in recognition that the radon emissions from these impoundments could be greater if the piles were left dry and uncovered. The 1989 Subpart W also included the requirements in 40 CFR 192.32(a), which include design and construction requirements for the impoundments as well as requirements for preventing and mitigating ground water contamination.

As discussed earlier, it is no longer believed that a distinction needs to be made for conventional impoundments based on the date when they were design and/or constructed. The existing impoundments at both the Shootaring Canyon (Section 3.2.3) and Sweetwater (Section 3.2.1) facilities can meet the work practice standards in the current Subpart W regulation. Impoundments at both these facilities have an area of less than 40 acres and are synthetically lined as required in 40 CFR 192.32(a). Also, the existing Cell 3 at the White Mesa mill will be closed in 2012 and replaced with impoundments that meet the phased disposal work practice standard (Section 3.2.2). Therefore, there is no reason not to apply the work practice standards required for impoundments designed or constructed after December 15, 1989, to these older impoundments. By incorporating these impoundments under the work practice standards, the requirement of radon flux testing is no longer needed and will be eliminated.

For the proposed GACT, the requirements of 40 CFR 192.32(a) as they pertain to the Subpart W standards were evaluated. Liner requirements in use for the permitting of hazardous waste land disposal units under RCRA are contained in 40 CFR 264.221. Since 40 CFR 192.32(a)(1) references 40 CFR 264.221, it is the only requirement necessary for Subpart W, as the RCRA requirements are effective methods of containing tailings and protecting ground water while also limiting radon emissions. The regulation in 40 CFR 264.221 contains safeguards to allow for the placement of tailings and also provides for an early warning system in the event of a leak in the liner system. Therefore, the proposed GACT for conventional impoundments retains the two work practice standards and the requirements of 40 CFR 192.32(a)(1), because they have proven to be effective methods for limiting radon emissions while also protecting ground water. The NRC considers the requirements of 40 CFR 192.32(a) in its review during the licensing process.

For nonconventional impoundments, where tailings (byproduct material) are contained in ponds and covered by liquids, a new GACT is proposed. These facilities, called "evaporation ponds" or "holding ponds," also must meet the requirements of 40 CFR 192.32(a)(1). Specifically, these are the design and operating requirements for the impoundments. Because of the general experience that a depth of greater than 1 meter of liquid essentially reduces the radon flux of ponds to negligible levels, no monitoring is required for this type of impoundment. Given these factors, the following GACT is proposed:

> Nonconventional impoundments meet the design and construction requirements of 40 CFR 192.32(a)(1), with no size/area restriction, and during the active life of the pond, at least 1 meter of liquid be maintained in the pond.

For the last category, heap leach piles, an approach similar to that for nonconventional impoundments is proposed. As previously noted, these facilities contain byproduct material, which is the residue of the operation. That is, as the lixiviant mobilizes the uranium, the remaining part of the ore becomes byproduct material, which is regulated under Subpart W. As for nonconventional impoundments, the design and operation of the heap leach pile is expected to follow the requirements of 40 CFR 192.32(a)(1). This also will prevent the loss of pregnant liquor (lixiviant with dissolved uranium) from spillage or leakage.

The byproduct material that makes up the volume of the spent heap leach pile is typically wet. As Figure 15 shows, as material goes from dry to wet the radon flux first increases before it decreases (the reasons for this are discussed in Section 5.1.5). While it is impossible to maintain a completely wet state, it is possible to maintain a sufficient percentage of moisture content to meet a goal that the radon flux in the wetted material is below what the flux would be if the material was dry. This percentage is related to the state or material being "dewatered." By way of definition, 40 CFR 61.251(c) states:

> Dewatered *means to remove the water from recently produced tailings by mechanical or evaporative methods such that the water content of the tailings does not exceed 30 percent by weight.*

Thus, the proposed GACT for heap leach piles is that, in addition to meeting 40 CFR 192.32(a)(1), operating heap leach piles must maintain a moisture content greater than

30% (equivalent to about 70% to 80% moisture saturation, as described in Section 5.1.5). This would, as indicated, ensure that the radon flux from the surface of the pile is quite low, i.e., at or below what the flux would be if the material in the pile was dry.

Since the purpose of this GACT is to control the radon emissions, it may not be critical to maintain the 30% moisture content in the lower levels/lifts of the pile. The reason for this is two-fold; first, radon generated in the lower levels would have to travel further in the pile before it would escape to the atmosphere, thereby giving it more time to decay within the pile, and second, radon from the lower layers will be slowed due to the 30% moisture content in the upper levels. Additionally, if inter-lift liners are provided when the pile is composed of multiple lifts, the inter-lift liner would act as a barrier to radon from the lower lifts, and thus mitigate the need for those lower lifts to maintain the 30% moisture content. On the other hand, because radon emission do not stop when active uranium leaching has ceased, it will be necessary to continue wetting the pile to maintain the 30% moisture content until a final reclamation cover (including a radon barrier layer) has been constructed over the pile.

5.5 Other Issues

During the review of Subpart W, several additional issues were identified. These are identified and discussed in this section.

5.5.1 Extending Monitoring Requirements

In reviewing Subpart W, EPA examined whether radon monitoring should be extended to all impoundments constructed and operated since 1989 so that the monitoring requirement would apply to all impoundments containing uranium byproduct material (i.e., tailings). EPA also reviewed how this requirement would apply to facilities where Method 115 is not applicable, such as at impoundments totally covered by liquids. As the rule currently exists, only pre-1989 conventional tailings impoundments are required to monitor for radon emissions, the requirement being an average flux rate of not more than 20 pCi/(m^2-sec). This is because, at the time of promulgation of the 1989 rule, EPA stated that the proposed work practice standards would be effective in reducing radon emissions from operating impoundments. Since the work practice standards could not be applied to pre-1989 facilities, and since EPA determined that it is not feasible to prescribe an emissions standard for radon emissions from a tailings impoundment (54 FR 9644 (FR 1989a)), the improved work practice standards would limit radon emissions by limiting the amount of tailings exposed.

Thus, it is not necessary to require radon monitoring at facilities constructed after the current Subpart W was promulgated (i.e., December 15, 1989). With respect to tailings and the amount of water used to cover them, the work practice standards (now proposed as GACTs) are also protective in preventing excess radon emissions. Further, for nonconventional impoundments, where there is no applicable radon monitoring method, the standing liquid requirement will effectively prevent all radon emissions from holding or evaporation ponds.

5.5.2 Clarification of the Term "Operation"

As currently written, 40 CFR 61.251(e) defines the operational period of a tailings impoundment. It states that "operation" means that an impoundment is being used for the continuing placement of new tailings or is in standby status for such placement [which means that as long as the facility has generated byproduct material at some point and placed it in an impoundment, it is subject to the requirements of Subpart W]. An impoundment is in operation from the day that tailings are first placed in the impoundment until the day that final closure begins.

There has been some confusion over this definition. For example, a uranium mill announced that it was closing a pre-December 15, 1989, impoundment. Before initiating closure, however, it stated that it would keep the impoundment open to dispose of material generated by other closure activities at the site that contained byproduct material (liners, deconstruction material, etc) but not "new tailings." The company argued that since it was not disposing of new tailings the impoundment was no longer subject to Subpart W. We disagree with this interpretation. While it may be true that the company was no longer disposing of new tailings in the impoundment, it has not begun closure activities; therefore, the impoundment is still open to disposal of byproduct material that emits radon and continues to be subject to all applicable Subpart W requirements.

To prevent future confusion, we are proposing to amend the definition of "operation" in the Subpart W definitions at 40 CFR 61.251 as follows:

> <u>Operation.</u> Operation means that an impoundment is being used for the continued placement of uranium byproduct material or tailings or is in standby status for such placement. An impoundment is in operation from the day that uranium byproduct materials or tailings are first placed in the impoundment until the day that final closure begins.

5.5.3 Clarification of the Term "Standby"

In the past, there has been confusion as to whether the requirements of Subpart W apply to a uranium recovery facility that is in "standby" mode. Although not formally defined in Subpart W, "standby" is commonly taken to be the period of time when a facility may not be accepting new tailings, but has not yet entered closure operations. This period usually takes place when the price of uranium is such that it may not be cost effective for the facility to continue operations, and yet the facility fully intends to operate once the price of uranium rises to a point where it is cost effective for the facility to re-establish operations. As shown in Table 3, the Sweetwater and Shootaring Canyon mills are currently in standby. While in standby, a uranium recovery facility can change its license from an operating license to a possession only license, thereby reducing its regulatory obligations (and costs).

The addition of the following definition of "closure" into the Subpart W definitions at 40 CFR 61.251 would eliminate confusion:

> <u>Standby</u>. Standby means the period of time that a facility may not be accepting new tailings, but has not yet entered closure operations.

5.5.4 The Role of Weather Events

In the past, uranium recovery facilities have been located in the western regions of the United States. In these western regions, the annual average precipitation (see Figure 16) falling on the impoundment is less than the annual average evaporation (see Figure 17) from the impoundment. Also, these facilities are located away from regions of the country where extreme rainfall events (e.g., hurricanes or flooding) could jeopardize the structural integrity of the impoundment, although there is a potential for these facilities to be affected by flash floods, tornadoes, etc. However, recent uranium exploration in the United States shows the potential to move eastward, into more climatologically temperate regions of the country. South central Virginia is now being considered for a conventional uranium mill (e.g., the Coles Hills, see Table 4). To determine whether additional measures would be needed for impoundments operating in areas where precipitation exceeds evaporation, a review of the existing requirements was necessary.

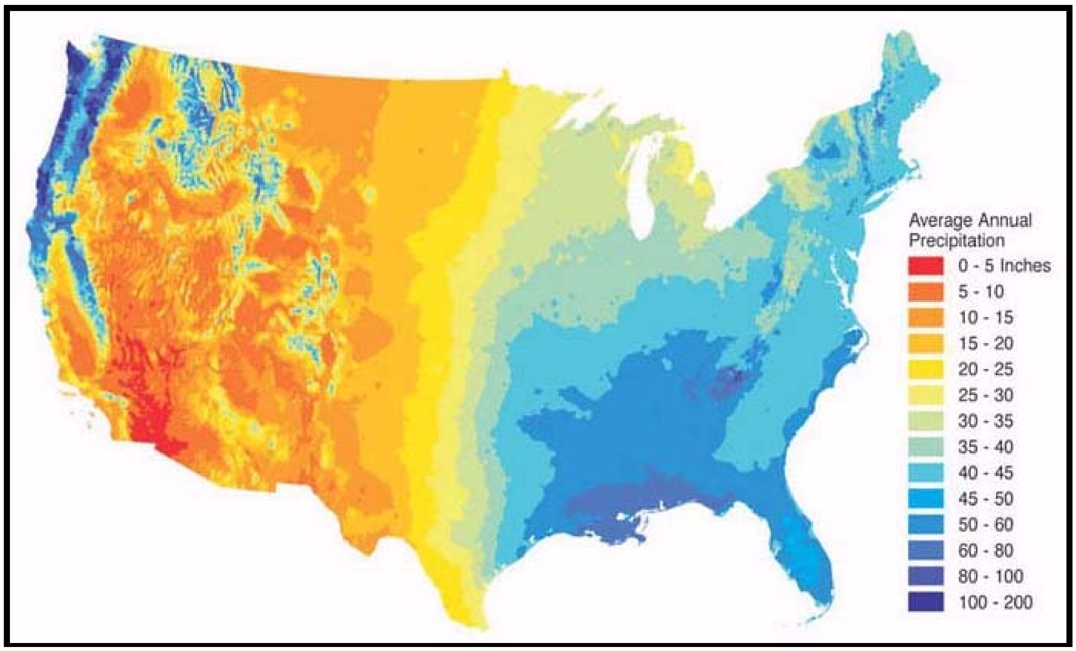


Figure 16: U.S. Average Annual Precipitation

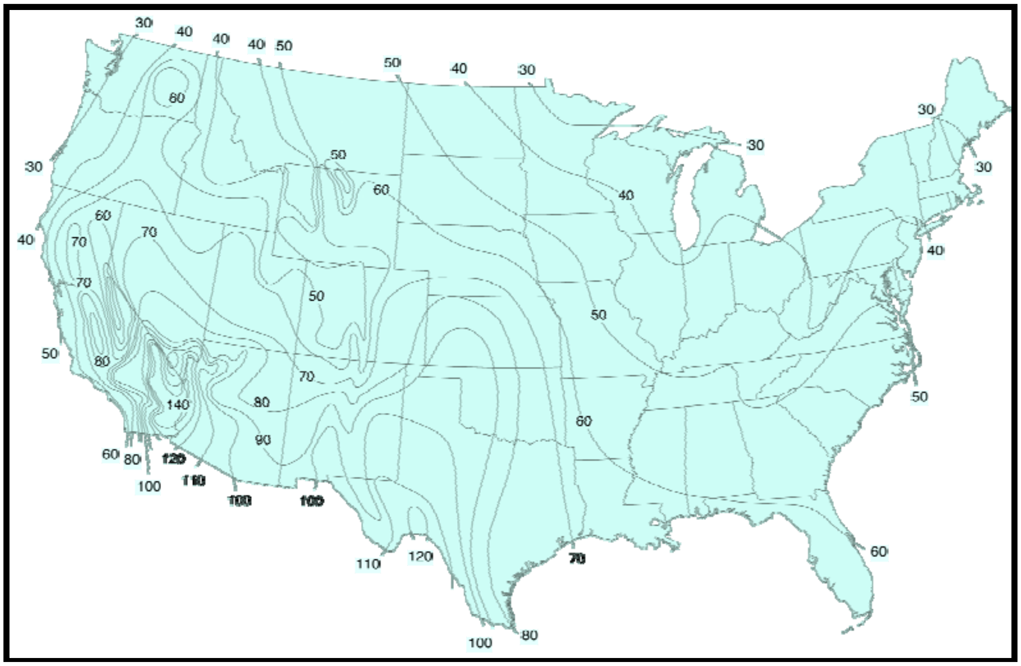


Figure 17: U.S. Mean Annual Evaporation

Subpart W requires owners and operators of uranium tailings impoundments to follow the requirements of 40 CFR 192.32(a). That particular regulation references the RCRA surface impoundment design and operations requirements of 40 CFR 264.221. At 40 CFR 264.221(g) and (h) are requirements that can be used to ensure proper operation of tailings impoundments. Section 264.221(g) states that impoundments must be designed, constructed, maintained, and operated to prevent overtopping resulting from normal or abnormal operations; overfilling; wind and rain action; rainfall; run-on; malfunctions of level controllers, alarms and other equipment; or human error. Section 264.221(h) states that impoundments must have dikes that are designed, constructed, and maintained with sufficient structural integrity to prevent massive dike failure. In ensuring structural integrity, it must not be presumed that the liner system will function without leakage during the active life of the unit.

Uranium recovery facilities are already operating under the requirements of 40 CFR 192.32(a)(1), including compliance with 40 CFR 264.221(g) and (h), which will provide protection against the weather events likely to occur in the eastern United States.

6.0 ECONOMIC IMPACTS ASSOCIATED WITH REVISION/MODIFICATION OF THE SUBPART W STANDARD

This section contains the following economic impact analyses necessary to support any potential revision of the Subpart W NESHAP:

- Section 6.1 provides a review and summary of the original 1989 economic assessment and supporting documents.

- The baseline economic costs for development of new conventional mills and ISL and heap leach facilities are developed and presented in Section 6.2.

- Section 6.3 presents the anticipated industry costs versus environmental and public health benefits to be derived from each of the four proposed GACT standards.

- Finally, Section 6.4 provides demographic data regarding the racial and socioeconomic composition of the populations surrounding uranium recovery facilities.

To assess the economic impacts of potential revisions to the Subpart W NESHAP, capital costs (including equipment costs), labor costs, taxes, etc., were obtained from actual recent cost estimates that have been prepared for companies planning to design, develop, construct, and operate uranium recovery facilities. For ISL facilities, two recent cost estimates were used as the basis for this analysis, while for conventional mills and heap leach facilities, a single cost estimate was used for each type of facility. Other necessary data, such as a discount rate, borrowing, and interest rates, were assumed, as described in Section 6.2.

Where feasible and appropriate, the economic models and recommendations from EPA's "Guidelines for Preparing Economic Analyses" (EPA 2010) were followed in assessing these economic impacts.

The cost and economic impact estimates described in Section 6.2 and 6.3 are based on industry data compiled in 2010-2011. Therefore, some of the analytical input values would differ somewhat if they were updated to reflect the latest information available. For example, the current long-term market price of uranium is approximately 17 percent lower than the $65 estimate that is used in the analysis (Cameco, 2013). The uranium mining industry is currently experiencing a volatile period resulting from the aftereffects of the Fukushima nuclear disaster. In particular, uranium demand has suffered from nearly all of Japan's workable reactors remaining offline since the March 2011 earthquake and tsunami triggered multiple meltdowns at the Fukushima Dai-ichi plant. Given the atypical post-Fukushima uranium market situation of the last couple of years and the prospects for a return to more normal market activity in the mid-term future,[7] we have decided not to update the analysis to incorporate the latest industry data. The results of the analyses described in this section are judged to be realistic estimates of the mid- to long-term impacts of the proposed Subpart W NESHAP.

6.1 1989 Economic Assessment

When Subpart W was promulgated in 1989, EPA performed both an analysis of the standard's benefits and cost and an evaluation of its economic impacts. Those analyses appear in the 1989 BID, Volume 3, Sections 4.4 and 4.5 (EPA 1989). This section briefly summarizes the Subpart W economic assessments performed in 1989.

[7]These prospects include: the conclusion of the U.S.-Russia program that annually removes 24 million pounds of ex-military highly enriched uranium from the market via down-blending for use as U.S. nuclear fuel; the 60 nuclear power plants that are currently under construction throughout the world; efforts to reduce climate change emissions; and expectations that Japan will slowly begin restarting its 50 nuclear plants.

In these 1989 assessments, EPA evaluated the benefits and costs associated with three separate decisions. The first decision concerned a limit on allowable radon emissions after closure. The options evaluated included reducing radon emissions from the 20 pCi/(m^2-sec) limit to 6 pCi/(m^2-sec) and 2 pCi/(m^2-sec).

The second decision that EPA investigated was the means by which the emissions from active mills could be reduced to the 20 pCi/(m^2-sec) limit while operations continue. Emissions could be reduced by applying earth and water covers to portions of the dry areas of the tailings piles, which could reduce average radon emissions for the entire site to the 20 pCi/(m^2-sec) limit.

While the first two decisions were focused on tailings piles that existed at the time the standard was promulgated, the third concerned future tailings impoundments. EPA evaluated alternative work practices for the control of radon emissions from operating mills in the future. Options investigated include the replacement of the traditional single-cell impoundment (i.e., the 1989 baseline) with phased disposal or continuous disposal impoundments.

6.1.1 Reducing Post-Closure Radon Emissions from 20 pCi/(m^2-sec)

The 1989 BID estimated the total annual tailings piles radon emissions for standards of 20, 6, and 2 pCi/(m^2-sec) and calculated the cancers that could result from those emissions. It found that over a 100-year analysis period, the 6 pCi/(m^2-sec) option could lower local and regional risks by 3.6 cancers, while the incremental benefit of lowering the allowable flux rate from 6 to 2 pCi/(m^2-sec) was estimated at 1.0 cancer.

The increased costs associated with reducing the allowable flux rate from 20 to 6 pCi/(m^2-sec) were estimated to be between $113 and $180 million (1988$) ($205 and $327 million (2011$)), while attainment of a 2 pCi/(m^2-sec) flux rate was estimated to result in added costs of $216 to $345 million (1988$) ($393 to $627 million (2011$)).

The 1989 BID does not make any statement regarding the monetized value of reduced cancer risks. Nor does it explicitly weigh the costs and benefits of the alternative standards. As the following excerpt from the preamble to the standard shows, for tailings piles at operating mills, EPA's decision was based on the very low risks associated with 20 pCi/(m^2-sec), rather than on a comparison of the benefits versus the costs of the alternative emission standards:

> *… the risks from current emissions are very low. A NESHAP requiring that emissions from operating mill tailings piles limit their emissions to no more than 20 pCi/(m^2-sec) represents current emissions. EPA has determined that the risks are low enough that it is unnecessary to reduce the already low risks from the tailings piles further.* [FR 1989a, page 51680]

While for tailings impoundments at inactive mills, the preamble presented a quantitative cost-benefit comparison as justification for maintaining the radon emission level at 20 pCi/(m^2-sec):

EPA examined these small reductions in incidence and maximum individual risk and the relatively large costs of achieving Alternative II [6 pCi/(m^2-s)]*, $158 million capital coat and $33 million in annualized costs and determined that Alternative I* [20 pCi/(m^2-s)] *protects public health with an ample margin of safety.* [FR 1989a, page 51682]

6.1.2 Reducing Radon Emissions During Operation of Existing Mills

The 1989 BID estimated the reduction in total risk that could be obtained by reducing radon emissions from active mills operating at that time to 20 pCi/(m^2-sec) through the application of an earthen cover and/or by keeping the tailings wet. The 1989 BID, Table 4-41, reported the risk reduction to be 0.17 fatal cancers for all active mills over their assumed 15-year operational life.

The 1989 BID, Table 4-42B, reported that the cost for providing the earthen covers and for keeping the tailings wet over the 15-year operating period was estimated to be $13.166 million (1988$) ($23.94 million in 2011$).

The 1989 BID does not make any statement regarding the monetized value of reduced cancer risks. Nor does it explicitly weigh the costs and benefits of the alternative standards. EPA nonetheless decided that without these standards the risks were too high, as the following segment from the preamble to the standard indicates:

… EPA recognizes that the risks from mill tailings piles can increase dramatically if they are allowed to dry and remain uncovered. An example of how high the risks can rise if the piles are dry and uncovered can be seen in the proposed rule, 54 FR 9645. That analysis assumed that the piles were dry and uncovered and the risks were as high as 3×10^{-2} with 1.6 fatal cancers per year. Therefore, EPA is promulgating a standard that will limit radon emissions to an average of 20 pCi/m^2-s. This rule will have the practical effect of requiring the mill operators to keep their piles wet or covered. … [FR 1989a, page 51680]

6.1.3 Promulgating a Work Practice Standard for Future Tailings Impoundments

Section 4.4.3.1 of the 1989 BID provides the following explanations of the phased and continuous disposal options:

Phased Disposal

The first alternative work practice which is evaluated for model new tailings impoundments is phased disposal. In phased or multiple cell disposal, the tailings impoundment area is partitioned into cells which are used independently of other cells. After a cell has been filled, it can be dewatered and covered, and another cell used. Tailings are pumped to one initial cell until it is full. Tailings are then pumped to a newly constructed second cell and the former cell is dewatered and then left to dry. After the first cell dries, it is covered with earth obtained from the construction of a third cell. This process is continued sequentially. This system *minimizes emissions at any given time since a cell can be covered after use without interfering with operations as opposed to the case of a single cell.*

Phased disposal is effective in reducing radon-222 emissions since tailings are initially covered with water and finally with earth. Only during a drying-out period of about 5 years for each cell are there any [significant] *radon-222 emissions from the relatively small area. During mill standby periods, a water cover could be maintained on the operational cell. For extended standby periods, the cell could be dewatered and a dirt cover applied.*

Continuous Disposal

The second alternative work practice, continuous disposal, is based on the fact that water can be removed from the tailings slurry prior to disposal. The relatively dry dewatered (25 to 30% moisture [by weight]*) tailings can then be dumped and covered with soil almost immediately. No extended drying phase is required, and therefore very little additional work would be required during final closure. Additionally, ground water problems are minimized.*

To implement a dewatering system would introduce complications in terms of planning, design, and modification of current designs. Acid-based leaching processes do not generally recycle water, and additional holding ponds with ancillary piping and pumping systems would be required to handle the liquid removed from the tailings. Using trucks or conveyor systems to transport the tailings to disposal areas might also be more costly than slurry pumping. Thus, although tailings are more easily managed after dewatering, this practice would have to be carefully considered on a site-specific basis.

Various filtering systems such as rotary vacuum and belt filters are available and could be adapted to a tailings dewatering system. Experimental studies would probably be required for a specific ore to determine the filter media and dewatering properties of the sand and slime fractions. Modifications to the typical mill ore grinding circuit may be required to allow efficient dewatering and to prevent filter plugging or blinding. Corrosion-resistant materials would be required in any tailings dewatering system due to the highly corrosive solutions which must be handled. ...

The committed fatal cancer risk[8] from the operation of model baseline (single-cell), phased disposal, and continuous disposal impoundments, as determined by the 1989 BID, is shown in Table 17. Table 17 shows the following:

[during] *the operational period the risk of cancer is reduced, relative to the single cell baseline, by 0.129 if phased disposal is adopted and by 0.195 if the continuous single cell method is used. The risk reduction associated with using the continuous single cell relative to the phased approach is 0.066. In the post-operational phase, phased disposal raises the risk by 0.012 relative to the*

[8] "Committed fatal cancer risk" is the likeliness that an individual will develop and die from cancer at some time in the future due to their current exposure to radiation. "Committed fatal cancer risk" is sometimes referred to as "latent cancer fatality risk."

baseline, while the continuous single cell approach lowers it by 0.017 relative to the baseline and by 0.028 relative to phased disposal. [EPA 1989, Section 4.4.3.3]

Table 17: Radon Risk Resulting from Alternative Work Practices (Committed Cancers)

	Baseline (Single Cell)	Phased Disposal	Continuous Disposal
Operational Period (0 to 20 years)	0.282	0.153	0.087
Post-Operations (21 to 100 years)	0.264	0.276	0.247
Total	0.546	0.429	0.334

Source: EPA 1989, Table 4-45

Concerning the cost to implement the work practices, the 1989 BID indicates the following:

> *the phased … disposal impoundment is the most expensive design ($54.02 million* [1988$]*), while the single cell … impoundment ($36.55 million* [1988$]*) is the least expensive. Costs for the continuous single cell design ($40.82 million* [1988$]*) are only slightly more than those of the single cell impoundment, although the uncertainties surrounding the technology used in this design are the largest*. [EPA 1989, Section 4.4.3.4]

The 1989 BID does not make any statement regarding the monetized value of reduced cancer risks. Nor does it explicitly weigh the costs and benefits of the alternative standards. However, as the following excerpt from the preamble to the standard shows, EPA was concerned about the uncertainty of the benefits and costs analysis that had been performed for this portion of the regulation. Ultimately, the Agency based its decision on the small cost to implement the work practices, rather than on weighing the benefits versus the costs:

> *The uncertainty arises because it assumes a steady state industry over time. If the uranium market once again booms there would be increased risks associated with Alternative I* [one large impoundment (i.e., baseline)]. *If the industry then experienced another economic downturn, the costs of Alternative I would increase because of the economic waste that occurs when a large impoundment is constructed and not filled. The risks can also increase if a company goes bankrupt and cannot afford the increased costs of closing a large impoundment and the pile sits uncovered emitting radon. The risks can also increase if many new piles are constructed, creating the potential for the population and individual risks to be higher than EPA has calculated.*
>
> *These uncertainties significantly affect the accuracy of the* [benefits and costs] *analysis and given the small cost of going to Alternatives II* [phased disposal] *and III* [continuous disposal]*, EPA has determined that in order to protect the public*

with an ample margin of safety, both now and in the future, new mill tailings impoundments must use phased or continuous disposal. [FR 1989a, page 51680]

6.1.4 Economic Impacts

To determine the economic impacts of the proposed Subpart W on the uranium production industry, the 1989 BID evaluated two extreme cases; in the first, it was assumed that "no portion of the cost of the regulation can be passed on to the purchaser of U_3O_8," and in the second, it was "assumed that the uranium production industry is able to recover the entire increase in the tailings disposal cost by charging higher U_3O_8 prices." These two cases provided the lower and upper bound, respectively, of the likely economic impacts of Subpart W on the uranium production industry.

As described in Section 3.1, from 1982 to 1986, the uranium production industry had been contracting and experiencing substantial losses because of excess production capacity. The 1989 Subpart W economic impact assessment concluded that if the industry had to absorb the costs of implementing the regulation, the present value cost at that time would be about five times the industry losses from 1982 to 1986, or equal to about 10% of the book value of industry assets at that time, or about 15% of industry's liabilities.

Alternatively, if the uranium production industry could pass on the Subpart W implementation costs to its electric power industry customers, who would likely pass on the costs to the electricity users, the 1989 economic impact assessment concluded:

> *The revenue earned by the* [electric power] *industry for generating 2.4 trillion kilowatt hours of electricity in 1986 was 121.40 billion dollars. The 1987 present value of the regulation (estimated to be $250 million) is less than 1 percent (.06%) of the U.S. total electric power revenue for the same year.* [EPA 1989, Section 4.5.1]

The 1989 BID drew no conclusions regarding what effects, if any, these impacts would have on the uranium production industry's financial health.

6.2 U_3O_8 Recovery Baseline Economics

This section presents the baseline economics for development of new conventional mills, ISL facilities, and heap leach facilities. EPA's economic assessment guidelines define the baseline economics as "a reference point that reflects the world without the proposed [or in the case of Subpart W, the modified] regulation. It is the starting point for conducting an economic analysis of potential benefits and costs of a proposed [or modified] regulation" (EPA 2010, Section 5).

The baseline costs were estimated using recently published cost data for actual uranium recovery facilities. For the conventional mill, data from the proposed new mill at the Piñon Ridge project in Colorado were used. For the ISL facility, data from two proposed new facilities were used: the first was the Centennial Uranium project in Colorado and the second was the Dewey-Burdock project in South Dakota. The Centennial project is expected to have a 14- to 15-year production period, which is a long duration for an ISL facility, while the Dewey-Burdock project is expected to have a shorter production period of about 9 years, which is more representative of ISL facilities. For the heap leach facility, data from the Sheep Mountain project in Wyoming were used. Sections 6.2.1 through 6.2.4 provide details of how the project-specific cost data were converted into base case economic data, and Section 6.2.5 presents a short sensitivity study for the conventional mill and heap leach cost estimates. Because two projects were analyzed, a sensitivity analysis of the ISL cost estimates was not performed.

Next it was necessary to estimate the annual amount of U_3O_8 that is currently used and how much would be required in the future. For these estimates, data from the Energy Information Administration (EIA) were used. Section 6.2.6 describes how the EIA data were coupled with specific cost data for the uranium recovery facilities to determine the cost and revenue estimates provided in Table 18.

Table 18: Uranium Recovery Baseline Economics (Nondiscounted)

Cost / Revenue	2009 ($1,000)		2035 Projections ($1,000)*			
	2009$	2011$	Reference Nuclear	Low Nuclear Production	High Nuclear Production	Ref Low Import
U_3O_8 Revenue	$347,000	$462,000	$502,000	$473,000	$605,000	$706,000
U_3O_8 Cost	$298,000	$372,000				
Conventional			$398,000	$375,000	$480,000	$560,000
In-Situ Leach			$396,000	$373,000	$477,000	$557,000
Heap Leach			$356,000	$335,000	$429,000	$501,000
Mixed Facilities			$392,000	$368,000	$472,000	$553,000

* See the discussion below and in Section 6.2.6 for a description of these cases.

Table 18 presents uranium production industry cost and revenue for six cases. The first two cases are based on the actual amount of U_3O_8 produced in the United States in 2009 (the last year for which data are available). The two 2009 cases differ in that the first is based on 2009 dollars, including the weighted-average price of $48.92 per pound for uranium of U.S. origin, while the second was based on assumptions used in this analysis (i.e., 2011 dollars and a U_3O_8 price of $65 per pound). The remaining four cases in Table 26 are all based on the assumptions used in this analysis, but differ in the amount of U_3O_8 assumed to be produced in the United States in 2035. The first through third 2035 cases are for the Reference, Low Nuclear Production, and High Nuclear Production projected 2035 nuclear power usage, as estimated by the EIA (see Section 6.2.6). It should be noted that most of the U_3O_8 used in the United States is from foreign suppliers. The fourth 2035 case (Ref Low Import) increases the percentage of U.S.-origin uranium to 20% for the reference nuclear power usage estimate.

For each of the four 2035 projection cases, four assumptions were made regarding the source of the U_3O_8: (1) all U_3O_8 is from conventional mills, (2) all U_3O_8 is from ISL (recovery) facilities, (3) all U_3O_8 is from heap leach facilities, and (4) the U_3O_8 is from a mixture of uranium recovery facilities (see Section 6.2.6, page 87, for a definition of the mixture). Table 19 shows that the type of uranium recovery facility assumed makes only about a 15% difference between the lowest cost (heap leach) and the largest cost (ISL) recovery type facility.

6.2.1 Conventional Mill Cost Estimate

The base case economic costs for development of a new conventional mill were developed using data from the proposed new mill at Piñon Ridge in Colorado (Edge 2009). Although cost estimates for other conventional mills were reviewed, e.g., Coles Hill (Lyntek 2010), Church Rock (BDC 2011), the Piñon Ridge cost estimate was selected for the base case because it is believed to be the furthest advanced. Specific cost data obtained from the Piñon Ridge project (i.e., Edge 2009, Tables 7.1-1 and 7.1-2) were for land acquisition and facility construction, operating and maintenance, decommissioning, and regulatory oversight. While the Piñon Ridge project supplied the mill design parameters and the overall magnitude of the cost, additional data on the breakdown of the capital and operating costs were taken from the Coles Hill uranium project located in Virginia (Lyntek 2010).

Assumptions used to develop the conventional mill base case cost estimate include:

- As per the Piñon Ridge project, the mill design processing capacity is1,000 tons per day (tpd), and the licensed operating processing rate is 500 tpd.

- The operating duration is 40 years, as per the Piñon Ridge project.

- Because they were more detailed, the Coles Hill cost data (Lyntek 2010) were used to generate a percentage breakdown of the Piñon Ridge cost estimates (Edge 2009). For example, the Piñon Ridge operating cost estimate was divided into labor, power and water, spare parts, office and lab supplies, yellowcake transportation, tailings operating, and general and administration (G&A) using Coles Hill percentages. Thus, the Coles Hill data affected the detailed breakdown of the cost estimate, but not its magnitude.

- Ore grades are 0.142% and 0.086% for underground and open-pit mined uranium, based on data from the EIA (EIA 2010, Table 2). The base case analysis did not use the Piñon Ridge project's average ore grade of 0.23%.

- The U_3O_8 recovery rate is 96% per the Piñon Ridge project.

- A line of credit (LoC) of $146 million has an annual interest rate of 4%, with a 20-year payback period.

- The price for U_3O_8 is $65 per pound (SRK Consulting 2010a, SRK Consulting 2010b, Berger 2009).

- Taxes, claims, and royalties total 11.5% of revenue.

- The discount rates are 3% and 7%, consistent with EPA's economic analysis guidelines (EPA 2010).

The Piñon Ridge project data do not include the costs to develop and/or operate a uranium mine. Rather, it is assumed that these costs are included in the cost of the uranium ore purchased for processing at the Piñon Ridge mill. Mine development and operating costs are included for the conventional mill based on an average of the open pit and underground mine costs developed for the heap leach facility (see Section 6.2.2).

Table 19 presents the cost estimates that were developed for the conventional uranium mill.

Table 19: Conventional Mill Cost Estimate

Component	Discount Rate		
	None	3%	7%
Resource mined (1,000 tons)	7,000	N.C.	N.C.
U_3O_8 Recovered (1,000 lb)	15,958	N.C.	N.C.
	Revenues/Costs ($1,000)		
Gross Revenue on U_3O_8	$1,037,299	$617,406	$369,925
Line of Credit (LoC)	$146,000	$154,891	$167,155
Mine Costs			
Development	$82,553	$49,136	$29,440
Operating	$261,195	$155,465	$93,148
Mill Costs			
Construction	$134,073	$139,870	$147,761
Mill Direct	$53,136	$55,434	$58,562
Mill Indirect	$9,547	$9,960	$10,522
Mill Contingency	$15,671	$16,348	$17,271
Tailings	$55,718	$58,128	$61,407
Operating and Maintenance	$124,397	$74,042	$44,363
Labor (All inclusive)	$59,267	$35,276	$21,136
Power & Water	$19,400	$11,547	$6,919
Spare Parts	$15,883	$9,454	$5,664
Office and Lab Supplies	$5,117	$3,045	$1,825
Yellowcake Transportation	$2,239	$1,332	$798
Tailings Operating	$22,492	$13,387	$8,021
G&A	$8,634	$5,139	$3,079
Taxes, Claims, and Royalties	$119,289	$71,002	$42,541
Regulatory Oversight	$11,800	$7,191	$4,541
Decommissioning/Closure	$12,000	$3,679	$801
Repay LoC, plus Finance Costs	$214,859	$169,561	$130,302
Total Cost	$968,801	$675,085	$495,978

The cash balance for the conventional mill (as well as the other uranium recovery facilities) is shown in Figure 18. Figure 18 shows that until production year 18, when the LoC has been paid off, the conventional mill is just breaking even.

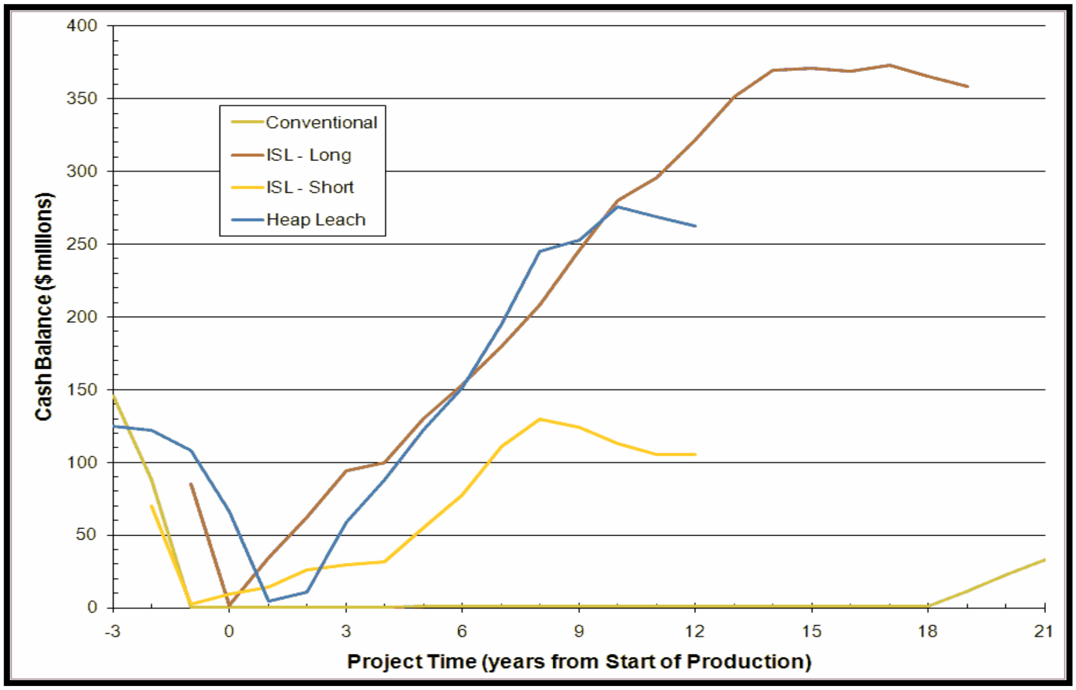


Figure 18: Estimated Cash Balance – Reference Cases

Figure 19 shows the assumed annual U_3O_8 production from the conventional mill (as well as the other uranium recovery facilities). Based on the assumptions used for the base case, the conventional mill produces the least amount of U_3O_8 annually.

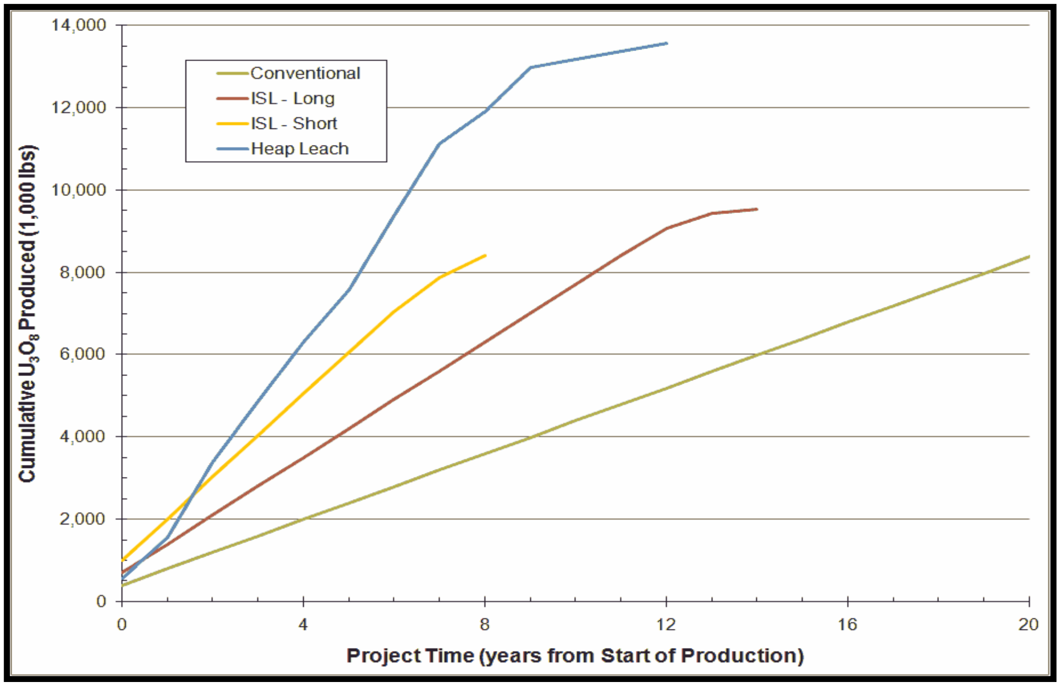


Figure 19: Cumulative U_3O_8 Projections – Reference Cases

6.2.2 Heap Leach Facility Cost Estimate

The base case economic costs for development of a new heap leach facility were developed using data from the proposed new facility at Sheep Mountain in Wyoming (BRS 2011). Specific assumptions used to develop the base case cost estimate for the heap leach facility include:

- The operating duration is 13 years, as per the Sheep Mountain project's uranium production schedule. The annual amount of ore processed averaged 491,758 tons, with maximum and minimum annual processing rates of 916,500 and 74,802 tons, respectively (BRS 2011, page 86).

- The U_3O_8 production rates were not adjusted to achieve equivalent production rates with the other types of facilities because to do so might affect the facility capital costs in a manner that would be inconsistent with the estimates provided for the Sheep Mountain project. If additional uranium ore production is to be modeled, a second (or more) and identical heap leach facility should be assumed, either concurrently or sequentially with the first facility.

- Consistent with the Sheep Mountain project cost assumptions, capital investment, totaling $14.177 million, was assumed during the operational period to add more heap leach pads and to replace underground mine equipment. Two additional heap pads were assumed, the first after approximately one-third of the ore is processed, and the second after two-thirds is processed.

- Ore grades were 0.142% and 0.086% for underground and open-pit mined uranium, based on data from the EIA (EIA 2010, Table 2). The Sheep Mountain project's ore grades averaged 0.132% for underground and 0.085% for open-pit produced uranium (BRS 2011, page 86).

- The U_3O_8 recovery rate varied between 89% and 92%, depending on the year of operation, as per the Sheep Mountain project (BRS 2011, page 86).

- The cost of open pit mining is $19.28 per ton of ore, while the cost of underground mining is $52.24 per ton, and the cost of heap leach processing is $13.51 per ton (BRS 2011, pages 87 and 88).

- The price for U_3O_8 is $65 per pound (SRK Consulting 2010a, SRK Consulting 2010b, Berger 2009).

- An LoC of $125 million has an annual interest rate of 4%, with a 15-year payback period.

- Taxes, claims, and royalties total 11.5% of revenue.

- The discount rates are 3% and 7%, consistent with EPA's economic analysis guidelines (EPA 2010).

Table 20 presents the cost estimates developed for the heap leach facility.

Table 20: Heap Leach Facility Cost Estimate

Component	Discount Rate		
	None	3%	7%
Resource mined (1,000 tons)			
Open Pit	2,895	N.C.	N.C.
Underground	3,498	N.C.	N.C.
U_3O_8 Recovered (1,000 lb)	13,558	N.C.	N.C.
	Revenues/Costs ($1,000)		
Gross Revenue on U_3O_8	$881,266	$764,878	$643,637
Line of Credit (LoC)	$125,000	$136,591	$153,130
Open Pit Mine			
Capital Costs	$14,590	$14,590	$14,590
Operating Costs	$55,817	$49,594	$42,879
Underground Mine			
Capital Costs	$60,803	$59,880	$58,997
Operating Costs	$182,723	$156,753	$130,078
Heap Pads/Processing Plant			
Capital Costs	$51,885	$50,788	$49,690
Operating Costs	$86,367	$74,973	$63,130

Table 20: Heap Leach Facility Cost Estimate

Component	Discount Rate		
	None	3%	7%
Shared Costs			
Predevelopment	$10,630	$11,149	$11,874
Reclamation Costs	$17,000	$14,755	$12,416
Taxes, claims, and royalties	$101,346	$87,961	$74,018
Repay LoC/Finance Costs	$168,640	$146,659	$125,441
Total Cost	$749,801	$667,102	$583,114

Figure 18 end of year cash balance for the heap leach facility (as well as for the other uranium recovery facilities). Figure 18 shows that by production year 4, the heap leach facility has a positive cash balance. Figure 19 shows the assumed annual U_3O_8 production from the heap leach facility (as well as from the other uranium recovery facilities). Based on the assumptions used for the base case, the heap leach facility consistently produces the largest quantity of U_3O_8 annually.

6.2.3 In-Situ Leach (Long) Facility Cost Estimate

The base case economic costs for development of a new ISL facility were estimated using data from the proposed new Centennial project in Weld County, Colorado (SRK Consulting 2010b). The Centennial project is expected to have a production period of 14–15 years, which is a long duration for an ISL facility. Annual cost estimates for the Centennial project are provided on pages 117 through 123 of SRK Consulting 2010b. SRK Consulting 2010b, Section 17.11, discusses the basis for the Centennial project cost estimate. Specific assumptions used to develop the ISL (Long) facility base case cost estimate for this analysis include:

- The operating duration is 15 years, as per the Centennial project's uranium production schedule (SRK Consulting 2010b, pages 117 and 120). The facility produces about 700,000 lb of U_3O_8 annually in the first 12 years, then reduces production until only 92,000 lb is produced in the last (15^{th}) year.

- The U_3O_8 production rates were not adjusted to achieve equivalent production rates with the other types of facilities because to do so might affect the ISL facility capital costs in a manner that would be inconsistent with the estimates provided for the Centennial project. If additional U_3O_8 production is to be modeled, a second (or more) and identical ISL (Long) facility should be assumed, either concurrently or sequentially with the first facility.

- Ground water restoration of a mining unit is assumed to begin as soon as practicable after mining in the unit is complete (SRK Consulting 2010b, pages 17–24). Funds for restoration are set aside beginning in the second production year and continuing until the end of the project (i.e., year 19 after the start of production).

- The price for U_3O_8 is $65 per pound (SRK Consulting 2010a, SRK Consulting 2010b, Berger 2009).

- An LoC of \$85 million has an annual interest rate of 4%, with a 10-year payback period.
- Taxes, claims, and royalties total 11.5% of revenue.
- The discount rates are 3% and 7%, consistent with EPA's economic analysis guidelines (EPA 2010).

Table 21 presents the cost estimates that were developed for the ISL (Long) facility.

Table 21: In-Situ Leach (Long) Facility Cost Estimate

Component	Discount Rate		
	None	3%	7%
U_3O_8 Recovered (1,000 lb)	9,522	N.C.	N.C.
	Revenues/Costs (\$1,000)		
Gross Revenue on U_3O_8	\$618,930	\$501,943	\$390,820
Line of Credit (LoC)	\$85,000	\$87,550	\$90,950
Operating Cost Summary			
Central Plant/Ponds	\$66,536	\$52,000	\$38,805
Satellite/Well Field	\$126,708	\$109,218	\$90,279
Restoration	\$11,257	\$8,353	\$5,844
Decommissioning	\$14,818	\$9,175	\$5,017
G&A Labor	\$16,379	\$12,849	\$9,732
Corporate Overhead	\$6,350	\$4,969	\$3,761
Contingency	\$48,410	\$39,313	\$30,687
Total Operating Costs	\$290,458	\$235,877	\$184,124
Capital Cost Summary			
CPP/General Facilities	\$55,097	\$54,027	\$52,739
Well Fields	\$14,209	\$13,868	\$13,450
G&A	\$13,605	\$13,428	\$13,212
Mine Closure	\$12,585	\$7,244	\$3,555
Miscellaneous	\$14,246	\$11,055	\$8,202
Contingency	\$21,948	\$19,924	\$18,232
Total Capital Costs	\$131,690	\$119,546	\$109,390
Severance, Royalty, Tax	\$71,177	\$57,723	\$44,944
Repay LoC/Finance Costs	\$104,797	\$92,076	\$78,758
Total Cost	\$598,122	\$505,223	\$417,216

Figure 18 shows the end of year cash balance for the ISL (Long) facility (as well as for the other uranium recovery facilities). Figure 18 shows that by the second year of production, the ISL (Long) facility has a positive cash balance. Figure 19 shows the assumed annual U_3O_8 production from the ISL (Long) facility (as well as from the other uranium recovery facilities). Based on the assumptions used for the base case, the ISL (Long) facility produces an annual amount of U_3O_8 that is midway between the amounts produced by the conventional mill and heap leach facility.

6.2.4 In-Situ Leach (Short) Facility Cost Estimate

The base case economic costs for development of a new ISL facility were estimated using data from the proposed new Dewey-Burdock project in South Dakota (SRK Consulting 2010a). The Dewey-Burdock project is expected to have a production period of about 9 years, which is representative for an ISL facility. SRK Consulting 2010a, pages 96 through 105, presents annual cost estimates for the Dewey-Burdock project, and Section 17.11 of that report discusses the basis for the Dewey-Burdock project cost estimate. Specific assumptions used to develop the ISL (Short) facility base case cost estimate for this analysis include:

- The operating duration is 9 years, as per the Dewey-Burdock project's uranium production schedule (SRK Consulting 2010a, pages 117 and 120). The facility produces about 1,010,000 lb of U_3O_8 annually in the first 6 years, then production declines until only 533,000 lb is produced in the last (9^{th}) year.

- The U_3O_8 production rates were not adjusted to achieve equivalent production rates with the other types of facilities because to do so might affect the ISL facility capital costs in a manner that would be inconsistent with the estimates provided for the Dewey-Burdock project. If additional U_3O_8 production is to be modeled, a second (or more) and identical ISL (Short) facility should be assumed, either concurrently or sequentially with the first facility.

- Ground water restoration of a mining unit is assumed to begin as soon as practicable after mining in the unit is complete (SRK Consulting 2010a, pages 17–18). Funds for restoration are set aside beginning in the first production year and continuing for 2 years after production ends (i.e., production year 11).

- The price for U_3O_8 is \$65 per pound (SRK Consulting 2010a, SRK Consulting 2010b, Berger 2009).

- An LoC of \$70 million has an annual interest rate of 4%, with a 5-year payback period.

- Taxes, claims, and royalties total 11.5% of revenue.

- The discount rates are 3% and 7%, consistent with EPA's economic analysis guidelines (EPA 2010).

Table 22 presents the cost estimates developed for the ISL (Short) facility.

Table 22: In-Situ Leach (Short) Facility Cost Estimate

Component	Discount Rate		
	None	3%	7%
U_3O_8 Recovered (1,000 lb)	8,408	N.C.	N.C.
	Revenues/Costs ($1,000)		
Gross Revenue on U_3O_8	$546,520	$491,065	$431,098
Line of Credit (LoC)	$70,000	$72,100	$74,900
Operating Cost Summary			
Central Plant/Ponds	$31,036	$27,485	$23,754
Satellite/Well Field	$130,056	$116,074	$100,788
Restoration	$6,159	$5,207	$4,234
Decommissioning	$11,614	$8,594	$5,835
G&A Labor	$9,750	$8,637	$7,500
Corporate Overhead	$3,900	$3,450	$2,994
Contingency	$38,503	$33,889	$29,021
Total Operating Costs	$208,558	$186,696	$162,811
Capital Cost Summary			
CPP/General Facilities	$49,338	$50,297	$51,598
Well Fields	$37,127	$36,951	$36,787
G&A	$2,507	$2,463	$2,414
Mine Closure	$22,460	$16,640	$11,314
Miscellaneous	$9,565	$8,253	$6,927
Contingency	$19,707	$19,593	$19,545
Total Capital Costs	$140,705	$134,197	$128,586
Severance, Royalty, Tax	$83,444	$74,899	$65,698
Repay LoC/Finance Costs	$78,619	$74,171	$68,984
Total Cost	$511,326	$469,963	$426,079

Figure 18 shows the end of year cash balance for the ISL (Short) facility (as well as for the other uranium recovery facilities). Figure 18 shows that in its first year of production, the ISL (Short) facility has a positive cash balance. Figure 19 shows the assumed annual U_3O_8 production from the ISL (Short) facility (as well as from the other uranium recovery facilities). Based on the assumptions used for the base case, the ISL (Short) facility produces an annual amount of U_3O_8 that is midway between the amounts produced by the ISL (Long) and heap leach facilities.

6.2.5 Cost Estimate Sensitivities

The uranium recovery facility base case cost estimates developed in Sections 6.2.1 through 6.2.4 were based on the specific assumptions presented in each section. One of the key parameters for the determination of the conventional mill and heap leach facility cost estimates is the assumed ore grade. Table 23 presents the average ore grades reported by the EIA for U.S.-origin uranium during 2009. These are the ore grades assumed for the conventional mill and heap leach facility cost estimates. As noted in Section 6.2.2, the ore grades assumed in the Sheep Mountain project cost estimate (BRS 2011) were very similar to the Table 23 values. However, as noted in Section 6.2.1, the Piñon Ridge project cost estimate used an ore grade of 0.23%, which is considerably higher than the Table 23 EIA values (Edge 2009).

Table 23: Uranium Ore Grade		
Mine Type	Ore Output (1,000 tons)	Ore Grade
Underground	76,000	0.142%
Open Pit	54,000	0.086%
In-Situ Leach	145,000	0.08%
Total	275,000	0.10%

Source: EIA 2011b

Table 24 summarizes the cost estimates for all four uranium recovery facilities developed in Sections 6.2.1 through 6.2.4. It includes the heap leach facility and conventional mill sensitivity cost estimates based on the alternate ore grade and ore processing assumptions just described.

Table 24: U_3O_8 Market Value and Cost to Produce (Nondiscounted)

Average U_3O_8 Price ($/lb)	$65.00	
Average U_3O_8 Cost ($/lb)	w/ LoC[1]	w/o LoC[2]
Conventional	$51.56	$47.24
ISL (Long)	$53.89	$51.81
ISL (Short)	$52.49	$51.46
Heap Leach	$46.08	$42.87
Conventional as Designed	$26.57	$25.45
Heap Leach w/ High Grade Ore	$22.13	$20.59

1 Total cost minus LoC revenue divided by the pounds of U_3O_8 produced
2 Total cost minus LoC revenue minus finance charge divided by the pounds of U_3O_8 produced.

The Piñon Ridge mill is being designed to process 1,000 tpd of uranium ore but, because of current market conditions, is currently being licensed to process only 500 tpd. The cost estimate in Section 6.2.1 is based on a conventional mill processing 500 tpd. As an alternative, the conventional mill cost estimate is recalculated using an ore grade of 0.23% and an ore processing rate of 1,000 tpd. These results have been included in Table 24.

So that the facilities maintain a positive cash flow, the analyses in Sections 6.2.1 through 6.2.4 assumed that each facility would be provided with an LoC to cover the construction and development costs. The amount of the LoC was determined by how much cash was necessary to maintain a positive cash balance. The interest on the LoC was assumed to be 4%, and the period to repay the LoC varied for each facility, depending on the amount of the LoC. The interest paid on the LoC is included in the facility cost estimates developed in Sections 6.2.1 through 6.2.4.

The right hand column of Table 24 shows what the facility-specific cost estimates would be without an LoC (and if the cash flow was allowed to be negative), or if the interest rate was 0%.

Figure 20 shows the effect of alternative assumptions on the cash balance.

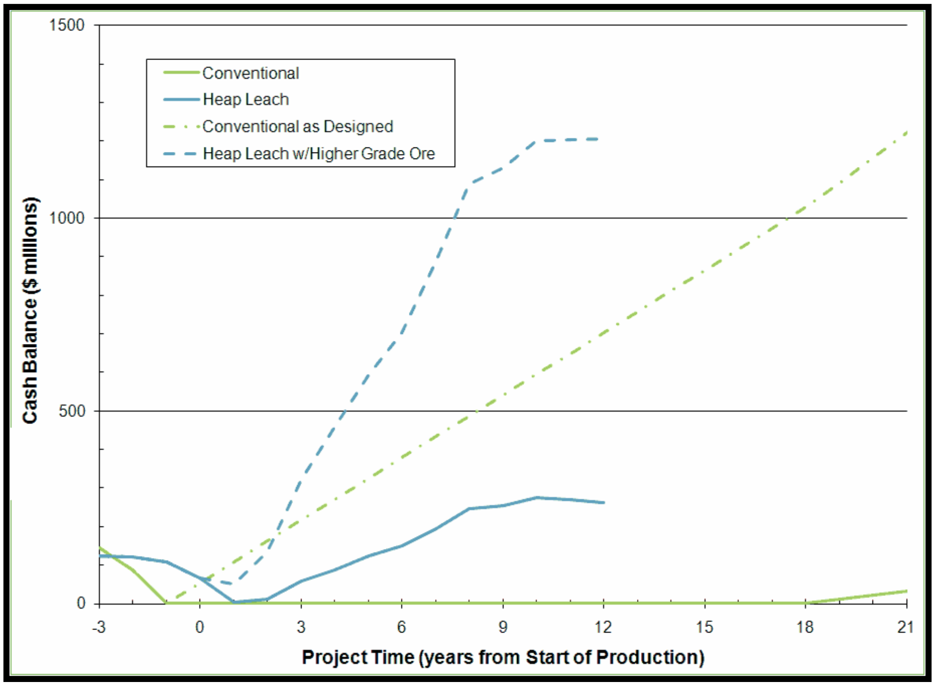


Figure 20: Estimated Cash Balance – Sensitivity Cases

Figure 21 shows the effect of the alternative assumptions on the U_3O_8 production. The obvious conclusion is that the higher the ore grade, the more U_3O_8 is produced, and therefore, the uranium recovery facility is more profitable.

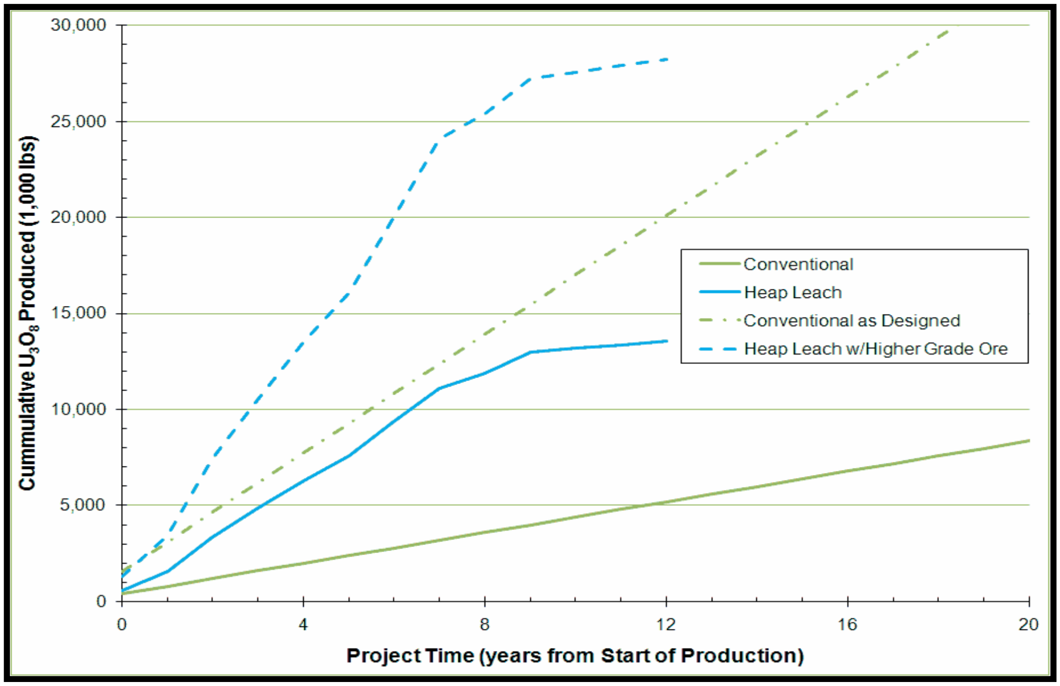


Figure 21: Cumulative U_3O_8 Projections – Sensitivity Cases

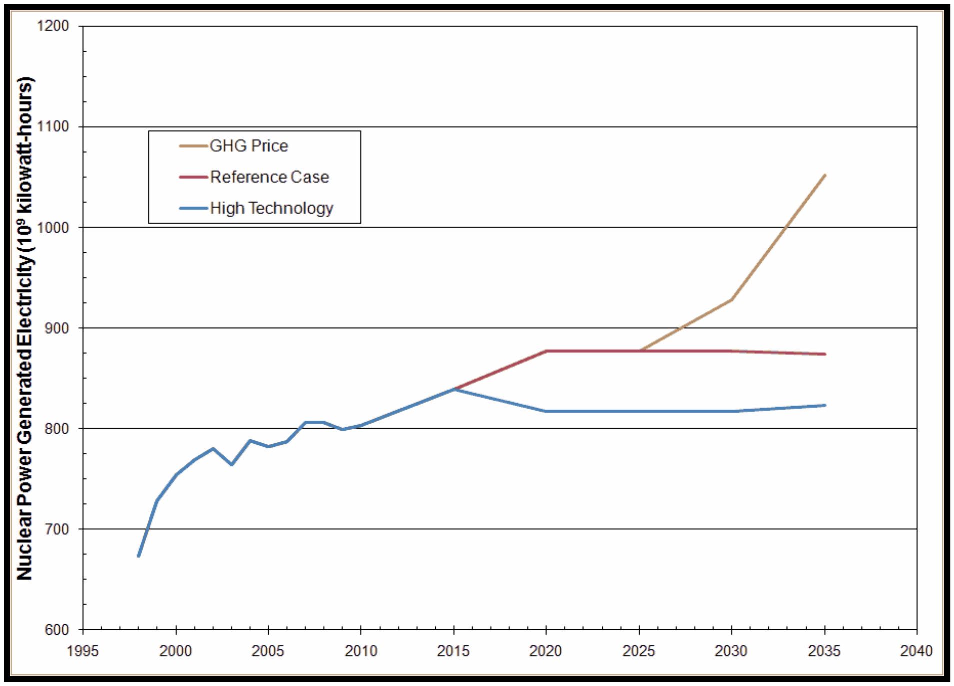
6.2.6 Annual Total U_3O_8 Cost Estimates

In Sections 6.2.1 through 6.2.4, base case cost estimates were developed for a conventional mill, a heap leach facility, and two ISL facilities. These individual uranium recovery facility cost estimates are used together with the actual 2009 (the last year for which data are available) and projected 2035 U.S.-origin uranium production.

For 2009, the EIA reports that 7,100 thousand pounds of U_3O_8 was produced in the United States (EIA 2011b). For this analysis, the total produced was divided between conventional mills and ISL facilities using the EIA-provided ore outputs, shown in Table 23, which resulted in 3,356,000 lb for conventional mills and 3,744,000 lb for ISL facilities. No heap leach facilities were operating in 2009, so the heap leach production is zero. The 2009 uranium recovery facility total cost and revenue estimates given in Table 18 (page 75) are based on these U_3O_8 production figures and the individual facility unit cost estimates given in Table 24.

These calculated 2009 economic data are based on 2011 dollars (e.g., \$65 per pound of U_3O_8). The 2009 calculated economic data are adjusted to 2009 dollars by assuming an average U_3O_8 price of \$48.92 lb^{-1} (EIA 2010) and adjusting the costs by the ratio of the 2009 energy consumer price index (CPI, 202.301) to the 2011 energy CPI (252.661) (BLS 2011, Table 25). Table 18 (page 75) also gives the 2009 economic data estimates based on 2009 dollars for uranium recovery facilities.

The next part of the analysis was to estimate the future value of the U.S. uranium recovery industry. To this end, it was necessary to estimate the future size of the nuclear power industry. The EIA (2011a) analyzed the U.S. energy outlook for 2011 and beyond, including the contribution from nuclear power. The EIA analyzed a reference case, plus 46 alternative cases, and determined the nuclear power contribution for each. The EIA reported that in 2010, nuclear power produced 803×10^9 kilowatt-hours of electricity and projected that for the reference case, nuclear power would produce 874×10^9 kilowatt-hours in 2035 (EIA 2011a). Of the 46 alternative cases, the Greenhouse Gas (GHG) Price Economywide and Integrated High Technology cases had the largest and smallest projected nuclear power contributions in 2035, respectively. The GHG Price Economywide case was projected to contribute $1{,}052 \times 10^9$ kilowatt-hours in 2035, while the Integrated High Technology case was projected to contribute 823×10^9 kilowatt-hours. Figure 22 shows and compares the EIA projections.



Source: EIA 2011a

Figure 22: Nuclear-Generated Electricity Projections

It is assumed that the 2035 to 2009 U_3O_8 requirements would have the same ratio as the 2035 to 2010 EIA (2011a) nuclear power estimates. Thus, for the EIA Reference Nuclear, Low Nuclear Production (Integrated High Technology), and High Nuclear Production (GHG Price Economywide) cases, the total U_3O_8 requirements in 2035 are estimated to be 7,728, 7,277, and 9,302 thousand pounds, respectively. Costs were estimated for four cases, with each case assuming a different type of uranium recovery facility responsible for producing the required U_3O_8. The cases are (1) only conventional mills, (2) only ISL facilities, (3) only heap leach facilities, and (4) a mixture of all three types of facilities.

To divide the total U_3O_8 requirement among the three types of uranium recovery facilities for Case 4, it is assumed that one reference heap leach facility would be operational, and that the remainder of the U_3O_8 would be divided between conventional mills and ISL facilities with the same ratio as in 2009. The total amount of U.S.-origin U_3O_8 for each of the 2035 projections is shown in Table 25 for Case 4. For the remaining three cases, the total 2035 projections given in Table 25 were assumed to be produced by the particular mine type associated with the case.

Table 25: Assumed Case 4 U_3O_8 Production Breakdown by Mine Type

Mine Type	U_3O_8 Produced (1,000 lb)				
	2009	2035 Projections			
		Reference Nuclear	Low Nuclear Production	High Nuclear Production	Ref Low Import
Conventional	3,356	3,159	2,947	3,903	4,642
In-Situ Leach	3,744	3,525	3,287	4,355	5,178
Heap Leach	—	1,043	1,043	1,043	1,043
Total	7,100	7,728	7,277	9,302	10,862

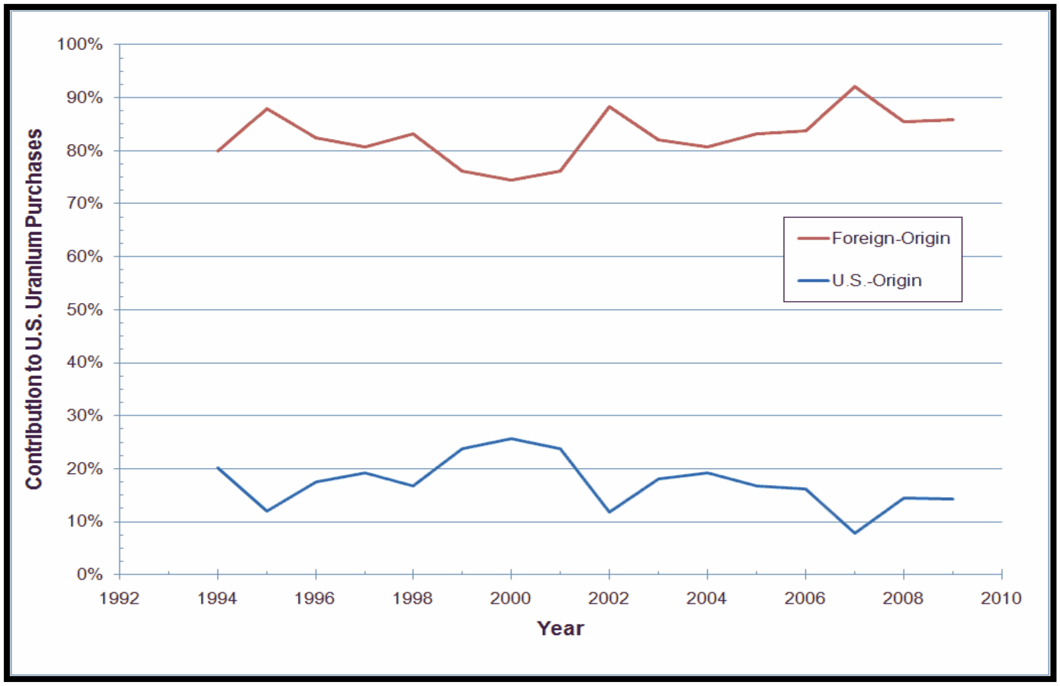
Source: EIA 2011b

The 2035 total cost and revenue estimates for uranium recovery facilities appear in Table 18 (page 75) and are based on the Table 25 U_3O_8 productions and the individual facility unit cost estimates given in Table 24. Refer to Section 6.2 for a discussion of the Table 18 total cost and revenue estimates. Table 26 gives a breakdown by facility type for Case 4, the mixed uranium recovery facility case.

Table 26: Case 4 (Mixed Uranium Recovery Facilities) Economic Projections (Nondiscounted)

Cost/Revenue	2035 Projections ($1,000)			
	Reference Nuclear	Low Nuclear Production	High Nuclear Production	Ref Low Import
U_3O_8 Revenue	$502,305	$472,994	$604,605	$706,057
Conventional	$205,407	$191,551	$253,767	$301,726
In-Situ Leach	$229,108	$213,653	$283,048	$336,541
Heap Leach	$67,790	$67,790	$67,790	$67,790
U_3O_8 Cost	$391,584	$368,411	$472,461	$552,668
Conventional	$162,932	$151,941	$201,292	$239,334
In-Situ Leach	$180,590	$168,409	$223,108	$265,273
Heap Leach	$48,062	$48,062	$48,062	$48,062

The EIA (2010, Table S1a) shows that most of the U_3O_8 purchased in the United States is of foreign origin (see Figure 23). In 2009, the 7,100 thousand pounds of U_3O_8 produced in the United States amounted to only 14.2% of the total amount of U_3O_8 purchased. Since the total cost and revenue estimates in Table 18 (page 75) are based on the 2009 U.S.-produced U_3O_8, then those estimates include the assumption that 85.8% of the U.S.-purchased U_3O_8 is of foreign origin. As Figure 23 shows, the amount of foreign origin U_3O_8 has fluctuated over time. If all of the U_3O_8 that is purchased in the United States were to be supplied domestically, then the total cost and revenue estimates shown in Table 18 would increase by a factor of 7 (i.e., 1/0.142 = 7). However, this is considered to be unrealistic and is unsupported by the data shown in Figure 23. As an alternative, the Ref Low Import case shown in Table 18 assumes that 20% of the 2035 EIA Reference case U_3O_8 needs would be met domestically.



Source: EIA 2010, Table S1a

Figure 23: U.S. and Foreign Contribution to U_3O_8 Purchases

6.3 Economic Assessment of Proposed GACT Standards

EPA is proposing to revise Subpart W by introducing three categories related to how uranium recovery facilities manage byproduct materials during and after the processing of uranium ore. are presented and described in Section 5.4 presents and describes the proposed GACTs for each category. This section presents the costs and benefits associated with the implementation of the various components of the GACTs. The first category is the standards for conventional mill tailings impoundments. The second category consists of requirements for nonconventional impoundments where uranium byproduct material (i.e., tailings) is contained in ponds and covered by liquids. Examples of this category are evaporation or holding ponds that exist at conventional mills and ISR and heap leach facilities. Requirements in this second category are that the nonconventional impoundments be provided with a double liner (Section 6.3.2) and that liquid at a depth of 1 meter be maintained in the impoundment (Section 6.3.3). The third category of revised Subpart W would require that heap leach piles be provided with a double liner (Section 6.3.4) and that the pile's moisture content be maintained above 30% by weight (Section 6.3.5). Additionally, the revised Subpart W would remove the requirement to monitor the radon flux at conventional facilities constructed on or prior to December 15, 1989 (Section 6.3.1).

6.3.1 Method 115, Radon Flux Monitoring

Existing Subpart W regulations require licensees to perform annual monitoring using Method 115 to demonstrate that the radon flux at conventional impoundments constructed before December 15, 1989, is below 20 pCi/(m^2-sec). The elimination of this monitoring requirement would result in cost savings for the three facilities to which this requirement still applies: Sweetwater, White Mesa, and Shootaring Canyon.[9]

Radon Flux Monitoring Unit Costs

Method 115 requires that multiple large-area activated charcoal collectors (LAACCs) be employed to make radon flux measurements. The first step in preparing this cost estimate was to develop the cost for making a single LAACC radon flux measurement. Unit cost data for performing LAACC radon flux measurements were obtained from three primary sources: the "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)" (EPA 2000a), KBC Engineers (KBC 2009), and Waste Control Specialists (WCS 2007). Weston Solutions provided fully loaded billing rates for radiation safety officers (RSOs) and certified health physicists (CHPs) (WS 2003).

MARSSIM (EPA 2000a)—MARSSIM is a multivolume document that presents methodologies for performing radiation surveys. Appendix H to MARSSIM describes field survey and laboratory analysis equipment, including the estimated cost per measurement. Included in Appendix H is the cost estimate for performing an LAACC measurement. The MARSSIM estimated cost range for LAACC radon flux measurements is $20 to $50 per measurement, including the cost of the canister. Since MARSSIM, Revision 1, was published in August 2000, it is assumed that this cost estimate is in 2000 dollars. MARSSIM does not estimate the cost for deploying the canisters or for final report preparation.

KBC Engineers (KBC 2009)—In November 2009, KBC Engineers prepared a revised "Surety Rebaselining Report" for the Kennecott Uranium Company's Sweetwater Uranium Project, which included an estimate for the cost of performing Method 115 radon flux monitoring. KBC based the canister testing cost of $50 per canister on past invoices received from Energy Laboratories, Inc. (a commercial analytical laboratory). In addition to the cost for the laboratory work, KBC included estimates for setting up and retrieving canisters in the field and for data analysis and report preparation. KBC estimated that a technician/engineer with a fully loaded billing rate of $100 per hour would require 40 hours to set up and retrieve 110 canisters, or $36.36 per canister. Also, KBC estimated that an engineer/scientist with a fully loaded billing rate of $105 per hour would require 20 hours for data analysis and report preparation for the 110 canisters, or $19.06 per canister. The KBC unit cost estimates are in 2009 dollars.

Waste Control Specialists (WCS 2007)—In its application to construct and operate a byproduct material disposal facility,[10] Waste Control Specialists, LLC (WCS) included a closure plan and corresponding cost estimate. As part of the final status survey, the radon flux through the disposal unit cap will be measured using LAACCs. WCS used the MARSSIM value as the cost for testing the canister. In addition, WCS included the cost of an RSO at $75 per hour to conduct the survey and prepare report and the cost of a CHP at $104 per hour to review the survey data. For the 100 canisters assumed, WCS assumed the RSO would require 40 hours for a cost of $30

[9] Cotter Corporation has indicated that the primary impoundments at its Cañon City site are no longer active, and thus, it has stopped performing Subpart W radon flux monitoring at that site (Thompson 2010).

[10] The WCS facility is not a conventional tailings facility or a uranium recovery facility. It was specially constructed to handle the K-65 residues that were stored at DOE's Fernald site.

per canister and the CHP would require 10 hours, or $10.40 per canister. The WCS unit costs are in 2004 dollars.

Weston Solutions (WS 2003)—Weston Solutions did not estimate the cost associated with Method 115 radon flux monitoring, but it did include the fully loaded hourly billing rates for radiation supervisors (equivalent to RSOs) and CHPs of $78 and $133, respectively. These billing rates are in 2003 dollars.

Unit Costs—Table 27 summarizes the data provided in the four source documents. The first step was to adjust all of the data to constant 2011 dollars. The CPI (DOL 2012) was used to make this adjustment. The right side of Table 27 shows the adjusted cost data.

Table 27: Data Used to Develop Method 115 Unit Costs

<table>
<tr><th colspan="6">Data as Provided</th><th colspan="3">Adjusted to November 2011 (CPI = 226.23)</th></tr>
<tr><th rowspan="2">Source</th><th rowspan="2">Date</th><th rowspan="2">CPI</th><th colspan="3">Cost per Canister</th><th colspan="3">Cost per Canister</th></tr>
<tr><th>Testing</th><th>Setup/ RSO</th><th>Analysis/ CHP</th><th>Testing</th><th>Setup/ RSO</th><th>Analysis/ CHP</th></tr>
<tr><td rowspan="2">EPA 2000a</td><td rowspan="2">Aug-00</td><td rowspan="2">172.8</td><td>$20.00</td><td>N.G.</td><td>N.G.</td><td>$26.18</td><td>N.G.</td><td>N.G.</td></tr>
<tr><td>$50.00</td><td>N.G.</td><td>N.G.</td><td>$65.46</td><td>N.G.</td><td>N.G.</td></tr>
<tr><td>WS 2003</td><td>Dec-03</td><td>184.3</td><td>N.G.</td><td>$31.20</td><td>$13.30</td><td>N.G.</td><td>$38.30</td><td>$16.33</td></tr>
<tr><td rowspan="2">WCS 2007</td><td rowspan="2">May-07</td><td rowspan="2">207.949</td><td>$25.00</td><td rowspan="2">$30.00</td><td rowspan="2">$10.40</td><td>$27.20</td><td rowspan="2">$32.64</td><td rowspan="2">$11.31</td></tr>
<tr><td>$50.00</td><td>$54.40</td></tr>
<tr><td>KBC 2009</td><td>Nov-09</td><td>216.33</td><td>$50.00</td><td>$36.36</td><td>$19.09</td><td>$52.29</td><td>$38.03</td><td>$19.96</td></tr>
</table>

N.G. = not given in the source document

Based on the data from Table 27, minimum, average, and maximum unit costs for performing Method 115 radon flux monitoring were estimated and are shown in Table 28.

Table 28: Method 115 Unit Costs

Type	LAACC Unit Cost ($/Canister)			
	Testing	Setup/RSO	Analysis/CHP	Total
Minimum	$26.18	$32.64	$11.31	$70.14
Average	$45.11	$36.32	$15.87	$97.29
Maximum	$65.46	$38.30	$19.96	$123.72

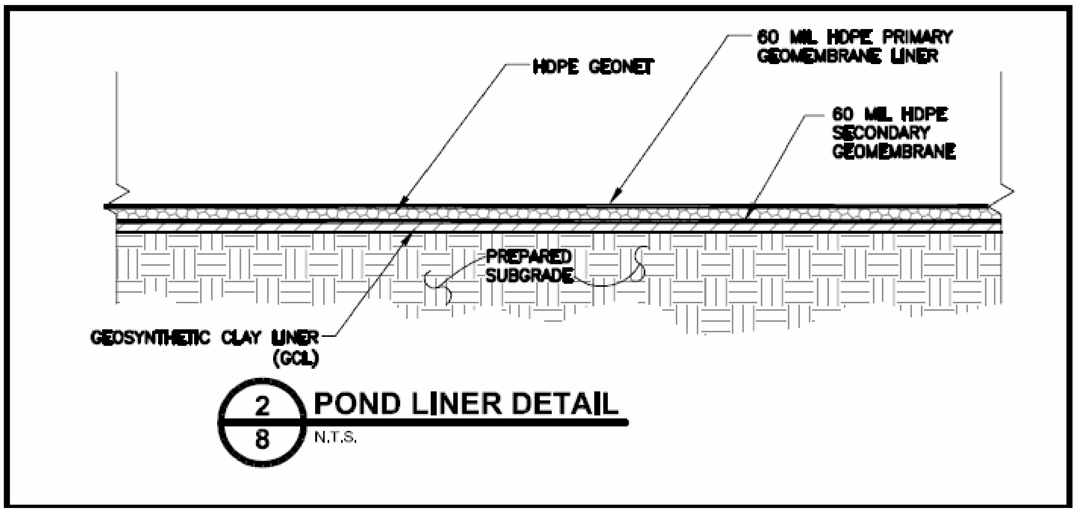
Total Annual Cost Savings (Benefit)

Method 115 requires 100 measurements per year as the minimum number of flux measurements considered necessary to determine a representative mean radon flux value. Additionally, if there are exposed beaches or soil-covered areas (as is likely at White Mesa), then an additional 100 measurements are necessary. Thus, for the three sites still required to perform Method 115 radon flux monitoring, the average annual cost to perform that monitoring (based on the Table 28 LAACC unit costs) is estimated to be about $9,730 per site per year for Shootaring and

Sweetwater, and $19,460 for White Mesa. For all three sites the total annual average cost is estimated to be $38,920 yr^{-1}, with a range from approximately $28,000 to $49,500 yr^{-1}.

6.3.2 Double Liners for Nonconventional Impoundments

Uranium byproduct materials are often stored in onsite impoundments at uranium recovery facilities, including in holding ponds and evaporation ponds. These ponds can be collectively referred to as nonconventional impoundments, to distinguish them from conventional tailings impoundments. This section provides an estimate of the cost to provide these nonconventional impoundments with a double liner, including a leak collection layer. Figure 24 shows a typical design of an impoundment double liner.



Source: Golder 2008, Drawing 8

Figure 24: Typical Double-Lined Impoundment with Leak Collection Layer

Double Liner Unit Costs

Unit costs, per square foot of liner, have been estimated for the three components of the double liner system: the geomembrane (HDPE) liner, the drainage (Geonet) layer, and the geosynthetic clay liner (GCL).

HDPE Unit Cost—The geomembrane (HDPE) liner installation unit cost estimates shown in Table 29 were obtained from the indicated documents and Internet sites. The Table 29 unit costs include all required labor, materials, and manufacturing quality assurance documentation costs (Cardinal 2000, VDEQ 2000). Where necessary, the unit costs were adjusted from the year they were estimated to year 2011 dollars using the CPI. The Table 29 geomembrane (HDPE) liner mean unit cost is $0.95 ft^{-2}, the median cost is $0.74 ft^{-2}, while the minimum and maximum costs are $0.45 and $2.35, respectively.

Table 29: Geomembrane (HDPE) Liner Unit Costs

Data Source	Unit Cost (ft^{-2})		Thickness - Area
	As Given	2011$	
Foldager 2003	$0.37	$0.45	Not Specified
Vector 2006	$0.45	$0.50	60 mil
Cardinal 2000	$0.39	$0.51	60 mil - 470,800 SF
Cardinal 2000	$0.40	$0.52	60 mil - 138,920 SF
Earth Tech 2002	$0.45	$0.57	60 mil
Cardinal 2000	$0.47	$0.61	60 mil - 118,800 SF
VDEQ 2000	$0.48	$0.63	60 mil
Duffy 2005	$0.60	$0.70	40 mil
Get-a-Quote	$0.70	$0.70	40 mil
Cardinal 2000	$0.54	$0.71	60 mil - 60,600 SF
MWH 2008	$0.70	$0.74	40 mil
Project Navigator 2007	$0.70	$0.76	60 mil
MWH 2008	$0.80	$0.84	80 mil
Get-a-Quote	$0.86	$0.86	60 mil
EPA 2004	$0.80	$0.96	60 mil
Get-a-Quote	$1.04	$1.04	80 mil
Free Construction	$1.05	$1.05	40 mil
Free Construction	$1.69	$1.69	60 mil
Foldager 2003	$1.40	$1.72	Not Specified
Free Construction	$2.00	$2.00	80 mil
Lyntek 2011	$2.35	$2.35	80 mil

Drainage Layer (Geonet) Unit Cost—Some of the documents reviewed included unit cost estimates for installation of the drainage (Geonet) layer, as shown in Table 30. As with the geomembrane (HDPE) liner unit costs, the drainage (Geonet) layer unit costs were adjusted from the year they were estimated to year 2011 dollars using the CPI. The Table 30 drainage layer (Geonet) mean unit cost is $0.64 ft^{-2}, the median cost is $0.57 ft^{-2}, while the minimum and maximum costs are $0.48 and $1.02, respectively.

Table 30: Drainage Layer (Geonet) Unit Costs

Data Source	Unit Cost (ft^{-2})	
	As Given	2011$
EPA 2004	$0.40	$0.48
Project Navigator 2007	$0.45	$0.49
Earth Tech 2002	$0.45	$0.57
MWH 2008	$0.60	$0.63
Duffy 2005	$0.88	$1.02

Geosynthetic Clay Liner (GCL) Unit Cost—Some of the documents reviewed also included unit cost estimates for installation of the GCL, as shown in Table 31. As for the geomembrane (HDPE) liner unit costs, the CPI was used to adjust the GCL unit costs from the year they were estimated to year 2011 dollars. The Table 31 GCL mean unit cost is \$0.69 ft^{-2}; the median cost is \$0.65 ft^{-2}; and the minimum and maximum costs are \$0.45 and \$1.12, respectively.

Table 31: Geosynthetic Clay Liner (GCL) Unit Costs

Data Source	Unit Cost (ft^{-2})	
	As Given	2011\$
Vector 2006	\$0.40	\$0.45
EPA 2004	\$0.40	\$0.48
Earth Tech 2002	\$0.52	\$0.65
Project Navigator 2007	\$0.70	\$0.76
Lyntex 2011	\$1.12	\$1.12

Some designs may choose to use a compacted clay layer beneath the double liner (e.g., Figure 26). However, Sandia (1998) has found that "[r]eplacing the 60 cm thick clay (amended soil) barrier layer with a GCL drastically reduced the cost and difficulty of construction." This savings was due to avoiding the expense of obtaining the bentonite clay and the difficulties of the clay being "sticky to spread and slippery to drive on," plus "compaction was extremely difficult to achieve." For these reasons, it is believed that GCL will be used in most future applications and is thus appropriate for this cost estimate.

Design and Engineering—The cost estimates include a 20% allowance for design and engineering for the mean and median estimates, and a 10% and 20% allowance for the minimum and maximum estimates, respectively. The design and engineering cost has been calculated by multiplying the capital and installation cost by the allowance factor.

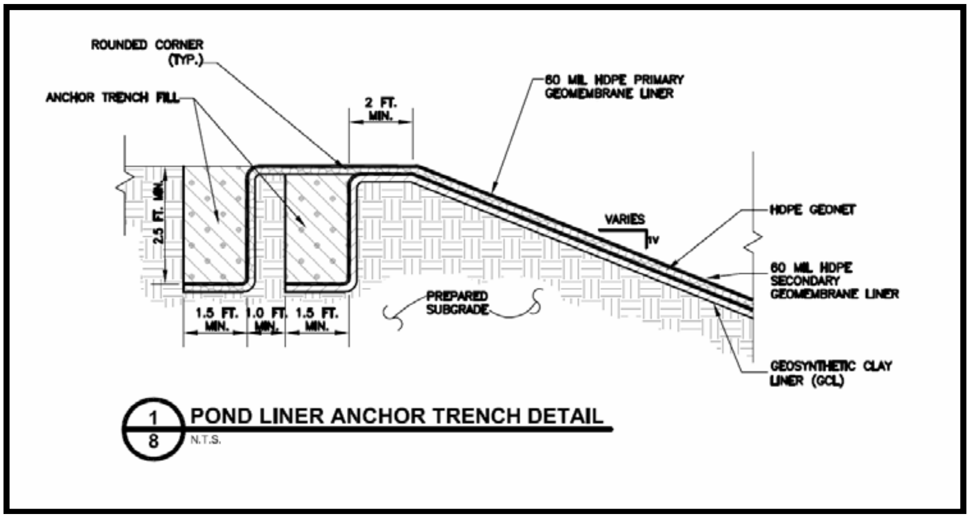
Contractor Oversight—The cost estimates include a 20% allowance for contractor oversight for the mean and median estimates, and a 15% and 25% allowance for the minimum and maximum estimates, respectively. The contractor oversight cost has been calculated by multiplying the capital and installation cost by the allowance factor.

Overhead and Profit—The cost estimates include a 20% allowance for overhead and profit for the mean and median estimates, and a 15% and 25% allowance for the minimum and maximum estimates, respectively. The overhead cost and profit has been calculated by multiplying the sum of the capital and installation, design and engineering, and contractor oversight costs by the allowance factor.

Contingency—The cost estimates include a contingency factor of 20% for the mean and median estimates, and 15% and 25% for the minimum and maximum estimates, respectively. The contingency has been calculated by multiplying the sum of all of the other costs by the contingency factor.

Double Liner Capital and Installation Cost

Impoundment Areas—Figure 25 shows that in order to anchor the upper liner and drainage layer (Geonet), an additional 8.5 ft of material is required on each side of the impoundment. Similarly, an additional 6 ft of material is required on each side of the impoundment to anchor the lower liner and the GCL.



Source: Golder 2008, Drawing 8

Figure 25: Typical Double Liner Anchor System

Section 6.2 describes base facilities for each type of uranium recovery facility: conventional, ISR, and heap leach. Since they are not given in Section 6.2, Table 32 shows the impoundment surface areas for each of the base facilities, plus the areas of the upper liner, drainage layer (Geonet), lower liner, and GCL. The liner areas include additional material in order to anchor the liner, plus an additional 10% to account for the sloping of the sides and waste.

Table 32: Nonconventional Impoundment Areas

Facility Type	Impoundment Type	Number	Area (acres)		
			Surface	Upper Liner & Geonet	Lower Liner & GCL
Conventional (Golder 2008)	Evaporation	10	4.13	4.94	4.82
	Total	10	41.30	49.39	48.22
ISR (Powertech 2009)	Water Storage	10	7.20	8.41	8.26
	Process Water	1	3.31	3.98	3.88
	Total	11	75.31	88.05	86.50
Heap (Titan 2011)	Raffinate	1	0.9	1.17	1.11
	Collection	1	1.5	1.88	1.81
	Evaporation	1	5.7	6.71	6.58
	Total	3	8.10	9.75	9.50

Impoundment Double Liner Cost—Based on the above estimated quantities of material and unit costs, Table 33 presents the median, minimum, and maximum capital costs for installing the double liner beneath the impoundments of each of the three types of uranium recovery facilities: conventional, ISR, and heap leach.

Table 33: Base Facility Nonconventional Impoundment Double Liner Capital and Installation Costs

Cost Type	Conventional	ISR	Heap
Mean	$13,800,000	$24,700,000	$2,700,000
Median	$11,500,000	$20,600,000	$2,300,000
Minimum	$6,500,000	$11,600,000	$1,300,000
Maximum	$32,900,000	$58,900,000	$6,500,000
Mean, w/o Upper Liner	$6,800,000	$12,100,000	$1,300,000

To demonstrate the individual component contribution to the total capital and installation cost, Table 34 presents the calculated mean capital cost breakdown by category.

Table 34: Mean Base Facility Nonconventional Impoundment Double Liner Capital and Installation Cost Breakdown

Liner Component	Unit Cost (ft^{-2})	Mean Impoundment Double Liner Capital and Installation Cost		
		Conventional	ISR	Heap
Upper Liner	$0.95	$2,040,654	$3,638,014	$402,799
Drainage (Geonet)	$0.64	$1,370,814	$2,443,844	$270,581
Lower Liner	$0.95	$1,992,191	$3,573,958	$392,414
GCL	$0.69	$1,455,818	$2,611,714	$286,761
Design & Engineering	20%	$1,371,895	$2,453,506	$270,511
Contractor Oversight	20%	$1,371,895	$2,453,506	$270,511
Overhead & Profit	20%	$1,920,654	$3,434,908	$378,715
Contingency	20%	$2,304,784	$4,121,890	$454,459
Total	—	$13,828,706	$24,731,338	$2,726,751

Table 33 includes capital and annual cost estimates for a mean, without upper liner case. This case was added because, even if not required to comply with 40 CFR 192.32(a)(1), the design of nonconventional impoundments at uranium recovery facilities would include at least a single liner. The reason is that the NRC, in 10 CFR 40, Appendix A, Criterion 5(A), requires that "… surface impoundments (…) must have a liner that is designed, constructed, and installed to prevent any migration of wastes out of the impoundment to the adjacent subsurface soil, ground water, or surface water … ." Thus, the Mean, w/o Upper Liner case estimates the cost to upgrade a single liner to a double liner system (i.e., the cost of the upper liner and the GCL have been removed).

Double Liner Total Annual Cost

Section 6.2.6 (Table 25) provided projections of the U_3O_8 requirements in the year 2035 for four different nuclear usage scenarios: Reference Nuclear – 7,728,000 lb; Low Nuclear Production – 7,277,000 lb; High Nuclear Production – 9,302,000 lb; and Reference Low Import – 10,862 lb.

Table 35 presents the calculated annualized cost for installation of a double liner in a nonconventional impoundment for the 2035 projected U_3O_8 productions. The annualized cost was calculated by first dividing the capital cost of the double liner by the total amount of U_3O_8 expected to be produced during the lifetime of each uranium recovery facility, and then multiplying by the projected amount of U_3O_8 produced annually. Table 35 presents four cases. In the first three cases, it was assumed that a single type of uranium recovery facility would produce all of the U_3O_8 required in 2035, while in the fourth case, it was assumed that a mixture of uranium recovery facilities would be operating in 2035. For the fourth case, Table 25 gives the contribution to the total U_3O_8 required in 2035 by each type of facility.

Table 35: Projected Nonconventional Impoundment Double Liner Annualized Capital and Installation Costs

Cost Type	Projected 2035 U_3O_8 Production	Annualized Capital and Installation Cost ($/yr)			
		Conventional	ISR	Heap	Mix
Mean	Reference Nuclear	$6,700,000	$22,700,000	$1,600,000	$14,800,000
Median	Reference Nuclear	$5,600,000	$18,900,000	$1,400,000	$12,400,000
Minimum	Low Nuclear Production	$2,900,000	$10,000,000	$700,000	$6,500,000
Maximum	Reference Low Import	$22,400,000	$76,100,000	$5,500,000	$49,300,000
Mean, w/o Upper Liner	Reference Nuclear	$3,300,000	$11,100,000	$800,000	$7,300,000

In addition to the annualized capital and installation costs, the total annual cost includes the costs associated with the operation and maintenance (O&M) of the double liner. For the double liner, O&M would consist of daily inspection of the liner and repair of the liner when rips or tears are observed above the water level or when water is detected in the leak detection layer. Since daily inspections of the nonconventional impoundments are part of the routine operation of the uranium recovery facility (Visus 2009), the only additional O&M cost associated with the double liner would be the repair costs. It was assumed that the annual O&M cost for the nonconventional impoundments would be 0.5% of the total capital cost for installing the liners (MWH 2008 and Poulson 2010). Using the Table 33 base facility cost estimates for installation of the double liner, Table 36 shows the calculated double liner O&M costs for each base facility.

Table 36: Base Facility Nonconventional Impoundment Double Liner Annual Operation and Maintenance Costs

Cost Type	O&M Allowance	Base Facility Annual O&M Cost ($/yr)		
		Conventional	ISR	Heap
Mean	0.5%	$68,000	$120,000	$13,000
Median	0.5%	$56,000	$100,000	$11,000
Minimum	0.25%	$16,000	$29,000	$3,200
Maximum	1.0%	$330,000	$590,000	$65,000
Mean, w/o Upper Liner	0.5%	$34,000	$61,000	$6,700

Table 37 shows annual O&M costs for the projected 2035 U_3O_8 productions. The Table 37 annual O&M costs were calculated by dividing the Table 36 costs by each base facility's annual U_3O_8 production and then multiplying by the projected 2035 U_3O_8 production.

Table 37: Projected Nonconventional Impoundment Double Liner Annual Operation and Maintenance Costs

Cost Type	Projected 2035 U_3O_8 Production	Annual Operation and Maintenance Cost ($/yr)			
		Conventional	ISR	Heap	Mix
Mean	Reference Nuclear	$1,300,000	$990,000	$50,000	$1,100,000
Median	Reference Nuclear	$1,100,000	$830,000	$39,000	$950,000
Minimum	Low Nuclear Production	$300,000	$230,000	$11,000	$250,000
Maximum	Reference Low Import	$9,000,000	$6,900,000	$330,000	$7,600,000
Mean, w/o Upper Liner	Reference Nuclear	$700,000	$500,000	$24,000	$560,000

The total annual cost for a double liner in a nonconventional impoundment is simply the sum of the annualized capital (Table 35) and installation cost plus the annual O&M cost (Table 37). Table 38 shows these total annual costs for the five cost types and four assumed uranium recovery facility cases.

Table 38: Projected Nonconventional Impoundment Double Liner Total Annual Costs

Cost Type	Projected 2035 U_3O_8 Production	Total Annual Cost ($/yr)			
		Conventional	ISR	Heap	Mix
Mean	Reference Nuclear	$8,000,000	$23,700,000	$1,700,000	$16,000,000
Median	Reference Nuclear	$6,700,000	$19,800,000	$1,400,000	$13,300,000
Minimum	Low Nuclear Production	$3,200,000	$10,200,000	$700,000	$6,800,000
Maximum	Reference Low Import	$31,400,000	$83,000,000	$5,800,000	$56,900,000
Mean, w/o Upper Liner	Reference Nuclear	$3,900,000	$11,700,000	$800,000	$7,800,000

Section 6.2, Table 18 (page 75), shows that the total estimated cost to produce all of the U_3O_8 projected for 2035 by the Reference Nuclear projection. Table 39 compares those total U_3O_8 production costs to the double liner total costs given in Table 38. As Table 39 shows, the cost to install a double liner is less than 6% of the total cost to produce U_3O_8, while the cost to upgrade from a single liner to a double liner is less than 3% of the total cost.

Table 39: Comparison of Double Liner to Total U_3O_8 Production Costs

Facility Type	2035 Projection Reference Nuclear Cost (million 2011$)			Liner Contribution	
	Total Annual (Table 18)	Double Liner (Table 38)	Single to Double (Table 38)	Double Liner	Single to Double
Conventional	$398	$8.0	$3.9	2.0%	1.0%
In-Situ Leach	$411	$23.7	$11.7	5.8%	2.8%
Heap Leach	$356	$1.7	$0.8	0.5%	0.2%
Mixed Facilities	$396	$16.0	$7.8	4.0%	2.0%

Finally, the conventional, ISR, and heap leach base uranium recovery facilities (see Section 6.2) include a double liner, with drainage layer (Geonet) collection system for their onsite impoundment designs. Thus, there is no additional cost for the Section 6.2 base uranium recovery facilities to meet the design and construction requirements at 40 CFR 192.32(a)(1) for onsite nonconventional impoundments.

Benefits from a Double Liner for a Nonconventional Impoundment

Including a double liner in the design of all onsite nonconventional impoundments that would contain uranium byproduct material would reduce the potential for ground water contamination. Although the amount of the potential reduction is not quantifiable, decision makers should consider this benefit because of the significance of ground water as a source of drinking water.

6.3.3 Maintaining 1 Meter of Water in Nonconventional Impoundments

As shown in Section 3.3.1, as long as a depth of approximately 1 meter of water is maintained in the pond, the effective radon emissions from the pond are so low that it is difficult to determine if there is any contribution above background radon values. This section estimates the cost to maintain 1 meter of water in the impoundment.

In order to maintain 1 meter, or any level, of water within a pond it is necessary to replace the water that is evaporated from the pond. If the evaporated water is not replaced by naturally occurring precipitation, then it would need to be replaced with makeup water supplied by the pond's operator. The replacement process is assumed to be required as part of the normal operation of the uranium recovery facility, which would occur regardless of the GACT. Thus, this cost estimate does not include process water replacement.

Unit Cost of Water

Three potential sources of pond makeup water were considered: municipal water suppliers, offsite non-drinking-water suppliers, and onsite water.

Municipal Water Supplier (Black & Veatch 2010)—In 2009/2010, a survey of the cost of water in the 50 largest U.S. cities was performed (Black & Veatch 2010). The survey compiled typical monthly bill data for three residential (3,750, 7,500, and 15,000 gallon/month), a commercial (100,000 gallon/month), and an industrial (10,000,000 gallon/month) water users. For this study, the commercial and industrial data were normalized to dollars per gallon, and the higher of the two values was used.

The survey found that the cost of water ranged from \$0.0012 gallon^{-1} in Sacramento, California, to \$0.0066 gallon^{-1} in Atlanta, Georgia, with a mean of \$0.0031 gallon^{-1} and a median of \$0.0030 gallon^{-1}. Looking at only those cities located within states potentially producing uranium (i.e., Arizona, Colorado, New Mexico, and Texas; the survey included no cities in Utah or Wyoming), the survey found that the cost of water ranged from \$0.0016 gallon^{-1} in Albuquerque, New Mexico, to \$0.0045 gallon^{-1} in Austin, Texas, with a mean and median of \$0.0031 gallon^{-1}.

Offsite Non-Drinking-Water Suppliers (DOA 2004)—The water supplied by municipal water suppliers has been treated and is suitable for human consumption. It is not necessary for impoundment evaporation makeup water to be drinking water grade. Therefore, using the data from the 50-city survey would likely overestimate the impoundment makeup water cost. Unfortunately, no data could be found as to the cost of non-drinking-water grade water for use as impoundment makeup water. However, another large scale use of non-drinking-water grade water is for crop irrigation, and the U.S. Department of Agriculture has compiled data on the cost of irrigation water for crops (DOA 2004).

For offsite sources of irrigation water, the Department of Agriculture states that the “31.6 million acre-feet of water received from off-farm water suppliers … cost irrigators $579 million, for an average cost of $18.29 per acre-foot of water …” (DOA 2004, page XXI), or $0.000056 gallon^{-1}.

Onsite Water (DOA 2004)—The Department of Agriculture identifies both wells (43.5 million acre-feet) and surface water (11.8 million acre-feet) as sources of onsite water. The cost for both sources is essentially the cost to pump the water from its source to where it is used. Unfortunately, the Department does not provide separate pumping costs for each onsite source, but instead states:

> *There were 497,443 irrigation pumps of all kinds used on 153,117 farms in 2003 irrigating 42.9 million acres of land. These pumps were powered by fuels and electricity costing irrigators a total of $1.55 billion or an average of $10,135 per farm. The principal energy source used was electricity, for which $953 million was spent to power 319,102 pumps that irrigated 24.1 million acres at an average cost of $39.50 per acre. Solar energy was reported as the source for pumping wells on 360 farms irrigating 16,430 acres.* [DOA 2004, page XXI]

From these data, it is possible to determine that the mean cost for pumping onsite water from both sources is $0.000086 gallon^{-1}. Also, on a per acre basis, the cost of using electricity to pump the water is slightly higher than the total average cost (i.e., $39.50 versus $36.13), and the use of solar energy to pump water is very rare (i.e., only about 0.03%).

Unit Costs—Table 40 shows the makeup water unit costs that have been estimated for this study. As described, the municipal water source costs are taken from Black & Veatch 2010, while the mean costs for offsite non-drinking and onsite water sources were taken from DOA 2004. All unit water costs were adjusted to 2011 dollars.

Although the Department of Agriculture did not present sufficient data to allow for the calculation of minimum, maximum, and median unit water costs, these costs were estimated by assuming that the cost of offsite non-drinking and onsite water sources have variation in costs similar to the variation in municipal supplier costs. Table 40 also shows these estimated makeup water unit costs.

Table 40: Makeup Water Unit Costs

Area	Source	Makeup Water Unit Costs (gallon^{-1})			
		Minimum	Mean	Median	Maximum
United States	Municipal Supplier	$0.0013	$0.0033	$0.0032	$0.0069
	Offsite Non-Drinking	$0.000027	$0.000069	$0.000067	$0.000144
	Onsite Source	$0.000041	$0.00011	$0.00010	$0.00022
Potential Uranium Producing States (AZ, CO, NM, TX)	Municipal Supplier	$0.0017	$0.0032	$0.0033	$0.0047
	Offsite Non-Drinking	$0.000035	$0.000068	$0.000068	$0.000099
	Onsite Source	$0.000054	$0.00010	$0.00010	$0.00015

Additionally, Edge (2009) presents the discounted cost of estimated consumptive water use for the Piñon Ridge conventional mill. With 3% and 7% discount rates, the 40-year cost of water was presented as $58,545 and $33,766, respectively, which translates into an annual cost of $2,533. Edge (2009, page 7-2) indicates that the Piñon Ridge mill is estimated to use 227 acre-feet of water per year. This gives a water unit cost of $0.000034, which is consistent with the Table 40 offsite non-drinking and onsite water sources unit costs.

Total Annual Cost to Maintain 1 Meter of Water

Required Water Makeup Rate (Net Evaporation Rate)—As stated above, in order to maintain the water level within a nonconventional impoundment, it is necessary to replace the water that is evaporated from the impoundment. Some (and in some places all) of the evaporated water will be made up by naturally occurring precipitation. Figure 17 shows the annual evaporation (inches per year (in/yr)) of the lower 48 states, while Figure 16 shows the annual precipitation (in/yr). To determine the annual required water makeup rate, the Figure 16 data is simply subtracted from the Figure 17 data. A positive result indicates that evaporation is greater than precipitation, and makeup water must be supplied, whereas a negative result indicates that precipitation is sufficient to maintain the impoundment's water level.

The U.S. Army Corps of Engineers (ACE) has published net lake evaporation rates for 152 sites located in the United States (ACE 1979, Exhibit I). The ACE found that the net evaporation ranged from -35.6 in/yr in North Head, Washington, to 96.5 in/yr in Yuma, Arizona, with a mean of 10.8 in/yr and a median of 0.9 in/yr. At 82 sites, the evaporation rate exceeds the precipitation rate, and makeup water would be required to maintain the impoundment's water level.

Looking at only those 22 sites located within states potentially producing uranium (i.e., Arizona, Colorado, New Mexico, Texas, Utah, and Wyoming), the ACE found that the net evaporation rate ranged from 6.1 in/yr in Houston, Texas, to 96.5 in/yr in Yuma, Arizona, with a mean of 45.7 in/yr and a median of 41.3 in/yr. The evaporation rate exceeded the precipitation rate at all 22 sites in the potentially uranium-producing states included in the ACE study.

Uranium Recovery Facility Pond Size—As described in Section 6.2, a base facility was assumed for each of the three types of uranium recovery facilities. Table 41 gives information for each base facility that is necessary to calculate the annual makeup water cost (i.e., the surface area of the onsite impoundments and the annul U_3O_8 production).

Table 41: Summary of Base Facility Characteristics

Parameter		Conventional	ISR	Heap
Impoundment Surface Area	(acres)	41.3	75.3	8.1
U_3O_8 Production	(lb/yr)	400,000	930,000	2,200,000

Total Annual Cost—The only cost associated with maintaining the water level within the impoundment is the cost of the water. It is assumed that existing piping will connect the nonconventional impoundment to the water source, and that the water level will be visually checked at least once per day (Visus 2009).

The makeup water unit cost data from Table 40, the net evaporation rates from above (page 102), and the impoundment areas from Table 41 are combined to calculate annual makeup water cost estimates provided in Table 42.

Table 42: Base Facility Annual Makeup Water Cost

Cost Type	Water Cost ($/gal)	Net Evaporation (in/yr)	Makeup Water Cost ($/yr)		
			Conventional	ISR	Heap
Mean	$0.00010	45.7	$5,313	$9,687	$1,042
Median	$0.00010	41.3	$4,840	$8,826	$949
Minimum	$0.000035	6.1	$240	$438	$47
Maximum	$0.00015	96.5	$16,337	$29,790	$3,204

The annual cost of makeup water from Table 42 was divided by the base facility U_3O_8 annual production rate from Table 41 to calculate the makeup water cost per pound of U_3O_8 produced, shown in Table 43.

Table 43: Base Facility Makeup Water Cost per Pound of U_3O_8

Cost Type	Makeup Water Cost ($/lb)		
	Conventional	ISR	Heap
Mean	$0.0133	$0.0104	$0.00047
Median	$0.0121	$0.0095	$0.00043
Minimum	$0.00060	$0.00047	$0.000021
Maximum	$0.041	$0.032	$0.0015

Section 6.2.6 (Table 25) provided projections of the U_3O_8 requirements in the year 2035 for four different nuclear usage scenarios: Reference Nuclear – 7,728,000 lb; Low Nuclear Production – 7,277,000 lb; High Nuclear Production – 9,302,000 lb; and Reference Low Import – 10,862 lb. Table 44 shows the makeup water costs which were calculated for the U_3O_8 production projected for 2035. The first three cost estimates assume that a single type of uranium recovery facility would be responsible for producing all of the projected U_3O_8, while the last estimates assume that a mix of uranium recovery type facilities is used, as described in Section 6.2.6.

Table 44: Projected Annual Makeup Water Cost

Cost Type	Projected 2035 U_3O_8 Production	Makeup Water Cost ($/yr)			
		Conventional	ISR	Heap	Mix
Mean	Reference Nuclear	$102,630	$80,489	$3,660	$88,979
Median	Reference Nuclear	$93,500	$73,329	$3,334	$81,063
Minimum	Low Nuclear Production	$4,366	$3,424	$156	$3,780
Maximum	Reference Low Import	$443,678	$347,963	$15,821	$381,053

Table 18 (page 75) shows the total estimated cost to produce all of the U_3O_8 projected for 2035 by the Reference Nuclear projections. Table 45 compares those total U_3O_8 production costs to the costs for maintaining 1 meter of water in the impoundments given in Table 44. As Table 45 shows, the cost to maintain 1 meter of water in the impoundments is much less than 1% of the total cost to produce U_3O_8 for all four cases analyzed.

Table 45: Comparison of Cost to Maintain 1 Meter of Water in the Impoundments to Total U_3O_8 Production Cost

Facility Type	2035 Projection Reference Nuclear Cost (million 2011$)		1 Meter Water Contribution
	Total Annual (Table 18)	1 Meter Water (Table 44)	
Conventional	$398	$0.103	0.026%
In-Situ Leach	$411	$0.080	0.019%
Heap Leach	$356	$0.004	0.001%
Mixed Facilities	$396	$0.089	0.022%

Total Annual Benefits from Maintaining 1 Meter of Water

By requiring a minimum of 1 meter of water in all nonconventional impoundments that contain uranium byproduct material, the release of radon from these impoundments would be reduced. Nielson and Rogers (1986) present the following equation for calculating the radon attenuation:

$$A = e^{\left(-\left[\frac{\lambda}{D}\right]^{0.5} d\right)} \tag{6-1}$$

Where: A = Radon attenuation factor (unitless)
λ = Radon-222 decay constant (sec^{-1})
= 2.1×10^{-6} sec^{-1}
D = Radon diffusion coefficient (cm^2/sec)
= 0.003 cm^2/sec in water
d = Depth of water (cm)
= 100 cm

Solving the above equation shows that 1 meter of water has a radon attenuation factor of about 0.07. To demonstrate the impact that a 1-meter water cover would have, the doses and risks reported in Section 4.4, Table 13 (page 49), have been recalculated. In this recalculation, it was assumed that an additional 1 meter of water covered all of the radon sources. Table 46 shows the results of this recalculation, in terms of the dose and risk reduction attributable to covering the source area with 1 meter of water. Table 46 shows both the original radon release (as reported in Table 13, page 49) and the radon release after the source area has been covered with 1 meter of water.

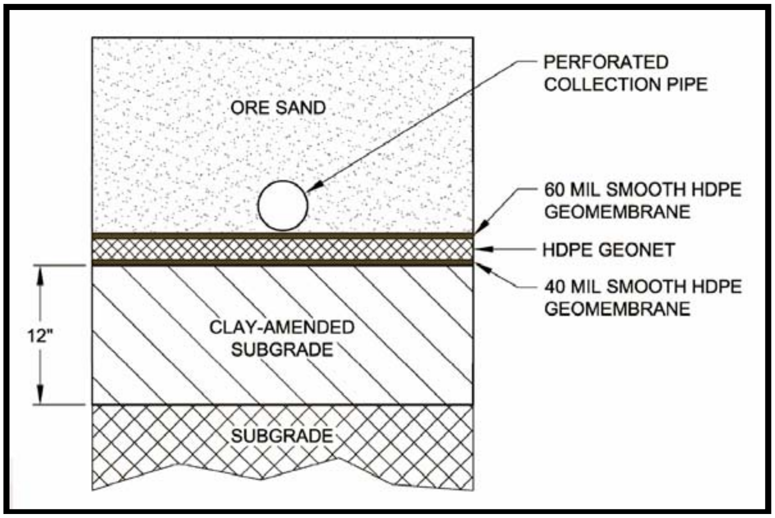
Table 46: Annual Dose and Risk Reduction from Maintaining 1 Meter of Water in the Impoundments

Uranium Site	Radon Release (Ci/yr)		Annual Dose Reduction		LCF(a) Risk Reduction (yr^{-1})	
	Table 13	1 Meter Water	Population (person-rem)	RMEI (mrem)	Population	RMEI
Sweetwater	2,075	147	0.5	1.1	2.7E-06	5.6E-07
White Mesa	1,750	124	4.8	11.1	3.2E-05	5.9E-06
Smith Ranch - Highlands	36,500	2,590	3.4	1.4	2.1E-05	7.2E-07
Crow Butte	8,885	630	2.5	3.1	1.6E-05	1.6E-06
Christensen/Irigaray	1,600	114	3.5	1.8	2.2E-05	9.2E-07
Alta Mesa	740	52	20.1	10.7	1.2E-04	5.7E-06
Kingsville Dome	6,958	494	53.9	10.5	3.5E-04	5.7E-06

* LCF = latent cancer fatalities

6.3.4 Liners for Heap Leach Piles

Designing and constructing heap leach piles to meet the requirements at 40 CFR 192.32(a)(1) would minimize the potential for leakage of uranium enriched lixiviant into the ground water. Specifically, this would require that a double liner, with drainage collection capabilities, be provided under heap piles. Figure 26 shows a typical design of a heap leach pile double liner. Although Figure 26 shows a clay-amended layer beneath the double liner, for the reasons given in Section 6.3.2, this cost estimate has assumed that a GCL would be used beneath the double liner, as shown in Figure 24.



Source: Titan 2011

Figure 26: Typical Heap Pile Liner

Double Liner Unit Costs

The unit costs for installing a double liner, with a leakage collection system, to a heap leach pile are assumed to be the same as the units costs developed in Section 6.3.2 for nonconventional impoundments.

The base heap leach facility utilizes a conveyor to deliver crushed material to the pile (Titan 2011). However, if material is delivered to the pile by truck, then the truck would put additional stress on the liner. Additional costs would be incurred to protect the liner from the additional stress. Because this analysis uses a range of liner unit costs, the additional costs for protecting the liner if truck loading is employed have been enveloped.

Total Cost of Heap Leach Pile Double Liner

Section 6.2.2 base heap leach facility (i.e., Sheep Mountain in Wyoming) includes two 80-acre heap piles. Using the same method described for the nonconventional impoundment (page 96), it was estimated that 90.3 acres of material would be required for the upper liner and drainage (Geonet) layer, and 89.6 acres of material for the lower liner and GCL. With these quantities of material and the unit costs from Section 6.3.2, Table 47 presents the median, minimum, and maximum capital and installation costs for installing the double liner beneath the two 80-acre heap piles.

Table 47: Heap Pile Double Liner Capital and Installation Costs

Cost Type	Capital and Installation Cost
Mean	$25,200,000
Median	$20,600,000
Minimum	$11,900,000
Maximum	$60,700,000
Mean, w/o Upper Liner	$12,900,000

Table 47 includes capital and annual cost estimates for a Mean, w/o Upper Liner case. This case was added because even if not required to meet the requirements at 40 CFR 192.32(a)(1), the design of the heap leach pile would include at least a single liner to collect the lixiviant flowing out of the heap. The reason is that since the lixiviant flowing out of the heap contains the uranium, it is in the licensee's economic interest to recover as much of it as possible, and since the rinsing liquid would be mixed with the lixiviant, it too would be recovered. Thus, the Mean, w/o Upper Liner case estimates the cost to upgrade a single liner to a double liner system (i.e., the cost of the upper liner and the GCL have been removed).

To demonstrate the individual component contribution to the total capital and installation cost, Table 48 presents a breakdown by component of the calculated mean capital and installation cost.

Table 48: Mean Heap Pile Double Liner Capital Cost Breakdown

Liner Component	Unit Cost (ft^{-2})	Mean Heap Pile Double Liner Capital Cost
Upper Liner	$0.95	$3,730,077
Drainage (Geonet)	$0.64	$2,505,687
Lower Liner	$0.95	$3,702,230
GCL	$0.66	$2,579,315
Design & Engineering	20%	$2,503,462
Contractor Oversight	20%	$2,503,462
Overhead & Profit	20%	$3,504,847
Contingency	20%	$4,205,816
Total	—	$25,234,896

Table 49 presents the heap pile double liner annual cost estimates. The total annual cost is the sum of the annualized capital and installation cost and the annual O&M cost. The annualized capital cost was calculated by first dividing the capital cost of the double liner by the total amount of U_3O_8 expected to be produced during the lifetime of the heap leach facility, and then multiplying by the amount of U_3O_8 produced annually. The U_3O_8 annual production was based on 2035 projections made in Section 6.2.6.

Table 49 presents two cases. In the first case, it was assumed that all of the U_3O_8 required in 2035 would be produced by heap leach facilities, while in the second case, it was assumed that heap leach facilities would be part of a mixture of uranium recovery facilities operating in 2035. For the second case, Table 25 gives the heap leach facility contribution to the total U_3O_8 required in 2035.

Table 49: Heap Pile Double Liner Annual Costs

Case	Cost Type	Annualized Capital Cost	Annual O&M Cost	Total Annual Cost
Heap Only	Mean	$15,100,000	$220,000	$15,300,000
	Median	$12,300,000	$180,000	$12,500,000
	Minimum	$6,700,000	$60,000	$6,800,000
	Maximum	$51,100,000	$1,340,000	$52,400,000
	Mean, w/o Upper Liner	$7,700,000	$110,000	$7,800,000
Mix	Mean	$340,000	$5,000	$350,000
	Median	$280,000	$4,000	$280,000
	Minimum	$160,000	$1,000	$160,000
	Maximum	$1,600,000	$43,000	$1,600,000
	Mean, w/o Upper Liner	$170,000	$3,000	$170,000

Table 18 (page 75) shows that the total estimated cost to produce all of the U_3O_8 projected for 2035 by the Reference Nuclear projection is $356 million. Thus, the cost for installing a double liner under the heap leach pile is about 4% of the total cost of heap leach U_3O_8 production (i.e., $15.3 million/$356 million), while the cost to change from a single liner to a double liner is about 2% of the total cost of heap leach U_3O_8 production (i.e., $7.8 million/$356 million).

Finally, the Section 6.2.2 base heap leach facility design includes a double liner, with drainage layer (Geonet) collection system, as shown in Figure 26. Thus, there is no additional cost for the Section 6.2.2 base heap leach facility to meet the design and construction requirements at 40 CFR 192.32(a)(1).

Benefits from a Double-Lined Heap Leach Pile

Including a double liner in the design of all heap leach piles would reduce the potential for ground water contamination. Although the amount of the potential reduction is not quantifiable, it is important for decision makers to consider this benefit because of the significance of ground water as a source of drinking water.

6.3.5 Maintaining Heap Leach Piles at 30% Moisture

As described in Section 5.4, the goal of this GACT is to maintain 30% moisture content in the heap leach pile so that the radon flux will be no larger than the flux from dry ore.

Simply adding water to the surface of the heap leach pile will replenish and maintain the moisture content in the surface layer. The moisture content in the remainder of the heap leach vertical profile will be a function of the ore materials ability to retain moisture. The field moisture capacity of any earthen material is a function of the grain size and the mineralogy of the materials. Accordingly, the 30% moisture content should be attained with all low grade ore materials, due to the presence of significant fine-grained materials. Furthermore, it may not be necessary to maintain the entire pile at 30% moisture content, but only the upper portion of the pile. The exact depth to which the 30% moisture content requirement would apply would be determined on a site by site basis. The cost to supply the water to replenish the pile's moisture content has been estimated below.

It is also recognized that imposing a 30% moisture content requirement on the pile might (and likely, would) require certain design changes to the pile. Principal concerns to be addressed during pile design are slope stability and the liquefaction potential. Regarding slope stability, many leach piles are provided with containment dikes which provide structural support to the pile. The 30% moisture content requirement will have little or no effect on the moisture associated with the containment dikes, and thus the dikes would continue to provide support. Additionally, the pile design may be altered to increase its stability. For example, lower slopes, higher confinement dikes, the construction of stair-step pad grade, or the installation of textured (as opposed to smooth) geomembrane liner in critical areas would enhance pile stability.

Regarding liquefaction potential, it has been estimated that liquefaction is unlikely if the degree of saturation in the pile is less than about 85% (Sassa 1985, as referred to in Smith 2002, Thiel and Smith 2004). Assuming a 2.7 ratio between moisture content and saturation (NRC 1984), the 30% moisture content require translates into 81% saturation, which is slightly below the level required for liquefaction. Needless to say, with the increase in the saturation that will result from the imposition of the 30% moisture content requirement, more attention will need to be paid to the pile design to minimize the liquefaction potential.

The costs associated with these design changes have not been included in the following cost estimate because any design change would depend very much on the site's characteristics, and in many cases the design change might be inexpensive to implement if it is identified during the design phase. For example, using a textured rather than smooth liner, constructing higher containment dikes, and using stair-step pad grade could all be incorporated into the pile's design at minimal, if any, additional cost.

Unit Water Cost

The unit costs for providing water to a heap leach pile are assumed to be the same as the unit costs developed in Section 6.3.3 (page 100) for providing water to nonconventional impoundments.

Cost of Soil Moisture Meters

Soil moisture sensors have been used for laboratory and outdoor testing purposes and for agricultural applications for over 50 years. They are mostly used to measure moisture in gardens and lawns to determine when it is appropriate to turn on irrigation systems. Soil moisture sensors can either be placed in the soil or held by hand.

For example, one system would bury soil moisture sensors to the desired depth in the heap. Then, a portable soil moisture meter would be connected by cable to each buried sensor one at a time, i.e., a single meter can read any number of sensors (Irrometer 2010). The portable soil moisture meter costs about $350, and each in-soil sensor about $35 or $45, depending on the length of the cable (either 5 or 10 ft) (Ben Meadows 2012).

Alternatively, with a handheld soil moisture meter, two rods (up to 8 inches long) that are attached to the meter are driven into the soil at the desired location, and a reading is taken. A handheld meter of this type costs about $1,065, and replacement rods about $58 for a pair (Spectrum 2011, Spectrum 2012).

Total Annual Cost to Maintain 30% Moisture in the Heap Leach Pile

The only cost associated with maintaining the moisture level within the pile is the cost of the water. It is assumed that existing piping (used to supply lixiviant to the pile during leaching) would be used to supply water necessary for maintaining the moisture level. Also, it is assumed that the in-soil method for moisture monitoring would be used, and that the above costs are insignificant. Finally, it is assumed that moisture readings would be performed during the daily inspections of the heap pile (Visus 2009), with no additional workhours.

The base heap leach facility includes a heap pile that will occupy up to 80 acres at a height of up to 50 ft. With an assumed porosity of 0.39 (see Section 5.1.5, page 56) and a moisture content of 30% by weight, the effective surface area of the liquid within the heap pile is 33.7 acres.

Table 50 presents the calculated cost for makeup water to maintain the moisture level in the heap pile, such that the moisture content is at 30% by weight, or greater. The unit costs for water and the net evaporation rates derived in Section 6.3.3 were used for this estimate.

Table 50: Heap Pile Annual Makeup Water Cost

Cost Type	Water Cost ($/gal)	Net Evaporation (in/yr)	Makeup Water Cost ($/yr)	Makeup Water Rate (gpm/ft^2)
Mean	$0.00010	45.7	$4,331	2.3E-05
Median	$0.00010	41.3	$3,946	2.1E-05
Minimum	$0.000035	6.1	$196	3.0E-06
Maximum	$0.00015	96.5	$13,318	4.8E-05

To place this amount of makeup water in perspective, during leaching and rinsing of the pile, liquid is dripped onto the pile at a rate of 0.005 gallons per minute per square foot (gpm/ft^2) (Titan 2011), or about 4,220 in/yr. This application rate is almost two orders of magnitude larger than the mean net evaporation rate, and is over a factor of 40 larger than the maximum net evaporation rate, shown in Table 50, and should be sufficient to maintain the moisture content within the pile

Section 6.2.6 and Table 25 (page 89) present projections of the U_3O_8 production for the year 2035. Table 51 presents the annual cost for makeup water to maintain the heap pile's moisture content. Table 51 presents two cases. In the first case, Heap Only, it was assumed that heap leach facilities would produce all of the U_3O_8 required in 2035, while in the second case, it was assumed that heap leach facilities would be part of a mixture of uranium recovery facilities operating in 2035. For the second case, Table 25 gives the heap leach facility contribution to the total U_3O_8 required in 2035.

Table 51: Projected Annual Heap Pile Makeup Water Cost

Cost Type	Projected 2035 U_3O_8 Production	Makeup Water Cost ($/yr)	
		Heap Only	Mix
Mean	Reference Nuclear	$15,000	$300
Median	Reference Nuclear	$14,000	$300
Minimum	Low Nuclear Production	$650	$20
Maximum	Reference Low Import	$66,000	$2,100

Table 18 (page 75) shows that the total estimated cost to produce all of the U_3O_8 projected for 2035 by the Reference Nuclear projection is $356 million. Thus, the cost for maintaining 30% moisture in the heap leach pile is well under 1% of the total cost of heap leach U_3O_8 production (i.e., $15,000/$356,000,000).

Total Annual Benefits from Maintaining 30% Moisture in the Heap Leach Pile

By requiring a minimum 30% by weight moisture content in the heap leach pile, the release of radon from these piles would be reduced by up to about a factor of 2½, as shown in Figure 15. From the base case production profile (BRS 2011, page 86), it can be determined that the heap pile ore has a mean U-238 concentration of 213 pCi/g, and a range of 135 to 321 pCi/g. Assuming the normalized radon flux from a heap pile with 30% moisture content is 1 pCi/(m^2-sec) per pCi/g Ra-226, and that the Ra-226 is in equilibrium with the U-238, then the mean annual radon release from the 80-acre heap pile would be 2,180 Ci/yr. A comparable annual radon release from a dryer heap pile could be as high as 5,450 Ci/yr. Table 52 shows a comparison of annual doses and risks using these heap pile annual radon releases and the release to dose/risk relationship for the Western Generic site from Table 13.

Table 52: Annual Dose and Risk Comparison for Maintaining 30% Moisture Content in the Heap Pile

Heap Pile Moisture Content (by Weight)	Radon Release (Ci/yr)	Annual Dose		LCF[a] Risk (yr^{-1})	
		Population (person-rem)	RMEI (mrem)	Population	RMEI
>30%	2,180	6.3	7.5	3.4E-04	9.6E-06
<30%	5,450	16	19	8.4E-04	2.4E-05

* LCF = latent cancer fatalities

Of course the exact reduction will depend upon the specific heap pile. For example, if a heap pile is operating at 20% moisture content without the GACT, then according to Figure 15, imposing the GACT would result in a radon flux reduction of about a factor of 1.6. Also, as Figure 14 shows, the response of the radon emanation coefficient to increasing moisture is very dependent on the material. This relationship between the emanation coefficient, moisture content, and material also influences the amount of reduction provided by the GACT.

6.3.6 Summary of Proposed GACT Standards Economic Assessment

Sections 6.3.2 through 6.3.5 presents the details of the economic assessment that was performed for implementing each of the four proposed GACT standards. **Table 53** presents a summary of the unit cost (per pound of U_3O_8) for implementing each GACT at each of the three types of uranium recovery facilities. In addition to presenting the GACT costs individually, **Table 53** presents the total unit cost to implement all relevant GACTs at each type of facility.

A reference facility for each type of uranium recovery facility is developed and described in Section 6.2, including the base cost estimate to construct and operate (without the GACTs) each of the three types of reference facilities. For comparison purposes, the unit cost (per pound of U_3O_8) of the three uranium recovery reference facilities is presented at the bottom of **Table 53**.

Table 53: Proposed GACT Standards Costs per Pound of U_3O_8

	Unit Cost ($/lb U_3O_8)		
	Conventional	**ISL**	**Heap Leach**
GACT – Double Liners for Nonconventional Impoundments	$1.04	$3.07	$0.22
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$0.013	$0.010	$0.0010
GACT – Liners for Heap Leach Piles	—	—	$2.01
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$0.0043
GACTs – Total for All Four	$1.05	$3.08	$2.24
Baseline Facility Costs (Section 6.2)	$51.56	$52.49	$46.08

Based on the **Table 53**, implementing all four GACTs would result in unit cost (per pound of U_3O_8) increases of about 2%, 6%, and 5% at conventional, ISL, and heap leach type uranium recovery facilities, respectively.

Included in the Section 6.2 descriptions is the operational duration and amount of uranium produced by each reference facility. This information from Section 6.2 has been used to calculate an annual U_3O_8 production rate for each type facility, which in turn has been coupled with the unit costs provided in **Table 53**, to generate the annual cost for implementing each GACT at each reference facility. These annual costs are presented in **Table 54**. Again for comparison the baseline cost (without the GACTs) is provided at the bottom of **Table 54** for each type facility.

Table 54: Proposed GACT Standards Reference Facility Annual Costs

	Reference Facility Annual Cost ($/yr)		
	Conventional	**ISL**	**Heap Leach**
GACT – Double Liners for Nonconventional Impoundments	$410,000	$2,900,000	$230,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$5,300	$9,700	$1,100
GACT – Liners for Heap Leach Piles	—	—	$2,100,000
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$4,500
GACTs – Total for All Four	$420,000	$2,900,000	$2,300,000
Baseline Facility Costs	$21,000,000	$49,000,000	$48,000,000

Based on EIA (EIA 2011a) nuclear power productions, Section 6.2.6 estimated the U.S. U_3O_8 productions until the year 2035. Using those EIA-based production estimates for 2011 and 2035 and the unit cost values from **Table 53**, **Table 55** presents the estimated national annual cost for implementing the proposed GACTs.

Table 55: Proposed GACT Standards National Annual Costs

	National Annual Cost ($1,000/yr)			
	2011 U_3O_8 Production			
	Conventional	**ISL**	**Heap Leach**	**Total**
GACT – Double Liners for Nonconventional Impoundments	$3,500	$12,000	$0	$15,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$45	$40	$0	$85
GACT – Liners for Heap Leach Piles	—	—	$0	$0
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$0	$0
GACTs – Total for All Four	$3,600	$12,000	$0	$15,000
Baseline Facility Costs	$180,000	$200,000	$0	$380,000
	2035 U_3O_8 Production			
	Conventional	**ISL**	**Heap Leach**	**Total**
GACT – Double Liners for Nonconventional Impoundments	$3,300	$11,000	$230	$14,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$42	$37	$1.1	$80
GACT – Liners for Heap Leach Piles	—	—	$2,100	$2,100
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$4.5	$4.5
GACTs – Total for All Four	$3,300	$11,000	$2,300	$17,000
Baseline Facility Costs	$160,000	$190,000	$48,000	$400,000

Since no facilities were operating, it was assumed that all 2011 U_3O_8 production was divided between conventional and ISL facilities with the 2009 ratio, as shown in Table 25 (i.e., 47.3% conventional and 52.7% ISL). As described in Section 6.2.6, for 2035 it was assumed that one heap leach facility would be operational, and that the remainder of the U_3O_8 production would be divided between conventional and ISL facilities with the 2009 ratio.

Of course, if the amount of U_3O_8 produced by each type facility changes the annual cost to implement the GACTs changes as well. For example if in 2035 all U_3O_8 is produced by ISL facilities, then the national annual cost to implement the GACTs would increase from $17 million (as shown in **Table 55**) to $24 million. Alternatively, if all 2035 U_3O_8 is produced by conventional facilities, then the national annual cost to implement the GACTs would decrease to $8.1 million. Because the baseline U_3O_8 production costs are fairly constant across all three types of uranium recovery facilities (see **Table 53** and Sections 6.2.1 through 6.2.4), the 2035 baseline U_3O_8 production national annual cost would remain fairly constant around $400 million, regardless of how the U_3O_8 is produced.

Table 56 presents the national cost for the implementation of the four proposed GACTs summed over the years 2011 to 2035. As with the **Table 55** annual national costs, the **Table 56** summed national costs are based on EIA (EIA 2011a) nuclear power productions, as described in Section 6.2.6.

Table 56: Proposed GACT Standards Summed National Costs

	National Cost, Summed from 2011 to 2035 ($1,000)			
	Non-Discounted			
	Conventional	ISL	Heap Leach	Total
GACT – Double Liners for Nonconventional Impoundments	$81,000	$270,000	$5,800	$350,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$1,000	$910	$27	$2,000
GACT – Liners for Heap Leach Piles	—	—	$52,000	$52,000
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$110	$110
GACTs – Total for All Four	$82,000	$270,000	$58,000	$410,000
Baseline Facility Costs	$4,000,000	$4,600,000	$1,200,000	$9,800,000
	Discounted @3%			
	Conventional	ISL	Heap Leach	Total
GACT – Double Liners for Nonconventional Impoundments	$58,000	$190,000	$4,100	$250,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$740	$650	$19	$1,400
GACT – Liners for Heap Leach Piles	—	—	$37,000	$37,000
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$80	$80
GACTs – Total for All Four	$59,000	$190,000	$41,000	$290,000
Baseline Facility Costs	$2,900,000	$3,300,000	$850,000	$7,000,000

Table 56: Proposed GACT Standards Summed National Costs

	National Cost, Summed from 2011 to 2035 ($1,000)			
	Discounted @ 7%			
	Conventional	**ISL**	**Heap Leach**	**Total**
GACT – Double Liners for Nonconventional Impoundments	$40,000	$130,000	$2,900	$170,000
GACT – Maintaining 1 Meter of Water in Nonconventional Impoundments	$510	$450	$13	$970
GACT – Liners for Heap Leach Piles	—	—	$26,000	$26,000
GACT – Maintaining Heap Leach Piles at 30% Moisture	—	—	$55	$55
GACTs – Total for All Four	$41,000	$130,000	$29,000	$200,000
Baseline Facility Costs	$2,000,000	$2,300,000	$590,000	$4,800,000

As with the **Table 55** annual national costs, if the amount of U_3O_8 assumed to be produced by each type facility changes the **Table 56** summed national costs to implement the GACTs changes as well. For example if all U_3O_8 is produced by ISL facilities, then the non-discounted summed national cost to implement the GACTs would increase from $410 million (as shown in **Table 56**) to $590 million. Alternatively, if all U_3O_8 is produced by conventional facilities, then the non-discounted summed national cost to implement the GACTs would decrease to $200 million. Similar to the baseline annual national costs, the baseline U_3O_8 production non-discounted summed national cost would remain around $9.8 billion, regardless of how the U_3O_8 is produced.

6.4 Environmental Justice

Concerning environmental justice, EPA's economic assessment guidelines state:

> *Distributional analyses address the impact of a regulation on various subpopulations. Minority, low-income and tribal populations may be of particular concern and are typically addressed in an environmental justice (EJ) analysis. Children and other groups may also be of concern and warrant special attention in a regulatory impact analysis.* [EPA 2010, Section 10]

6.4.1 Racial Profile for Uranium Recovery Facility Areas

This section presents information on the racial (e.g., tribal populations) and economic (e.g., low income) profiles of the areas surrounding existing and proposed uranium recovery facilities.

Table 57 presents the racial profiles in the immediate areas (i.e., counties) surrounding the existing and proposed uranium recovery facilities, while Table 58 presents the profiles in the surrounding regional area (i.e., states) and on a national basis. A comparison of Table 57 to Table 58 indicates whether the racial population profile surrounding the uranium recovery facilities conform to the national and/or regional norms.

Table 57: Racial Profile for Uranium Recovery Facility Counties

Existing/Proposed Facility	Facility Type	County, State	White	Black	Native American	Others
Juan Tafoya	Conventional	McKinley, NM	22.2%	0.4%	75.4%	2.0%
White Mesa Mill	Conventional	San Juan, UT	42.7%	0.1%	55.8%	1.3%
Grants Ridge	Heap Leach	Cibola, NM	56.2%	1.0%	40.9%	1.8%
Sheep Mountain	Heap Leach	Fremont, WY	78.3%	0.1%	19.8%	1.8%
Crow Butte	In-Situ Leach	Dawes, NE	94.5%	0.9%	3.0%	1.6%
Piñon Ridge	Conventional	Montrose, CO	96.6%	0.4%	1.4%	1.7%
Sweetwater Mill	Conventional	Sweetwater, WY	96.3%	0.8%	1.1%	1.9%
Christensen / Irigaray	In-Situ Leach	Campbell, WY	97.4%	0.2%	1.0%	1.4%
Smith Ranch - Highland	In-Situ Leach	Converse, WY	97.5%	0.1%	1.0%	1.4%
Shootaring Canyon	Conventional	Garfield, CO	97.2%	0.5%	0.8%	1.6%
Kingsville Dome	In-Situ Leach	Kleberg, TX	92.8%	3.9%	0.8%	2.6%
Goliad	In-Situ Leach	Goliad, TX	93.6%	5.0%	0.7%	0.7%
Palangana	In-Situ Leach	Duval, TX	98.3%	0.6%	0.7%	0.4%
Alta Mesa	In-Situ Leach	Brooks, TX	98.8%	0.4%	0.6%	0.3%

Source: http://www.census.gov/popest/counties/asrh/

Table 58: Regional and National Racial Profiles

State		White	Black	Native American	Others
New Mexico	NM	85.4%	2.1%	9.8%	2.7%
Wyoming	WY	95.1%	0.8%	2.3%	1.8%
Utah	UT	94.0%	0.9%	1.4%	3.7%
Colorado	CO	90.7%	4.0%	1.2%	4.1%
Nebraska	NE	92.7%	4.1%	0.9%	2.3%
Texas	TX	83.7%	11.8%	0.7%	3.9%
United States	US	81.1%	12.7%	0.9%	5.3%

Source: http://www.census.gov/popest/counties/asrh/

At 10 of the 15 sites, the percentage of Native Americans in the population exceeds the national norm, while at nine sites, the percentage of Native Americans in the population exceeds the regional norm. At 11 of the 15 sites, the percentage of the population that is White exceeds both the national and regional norms. Finally, the percentage of the population at all uranium recovery sites that is either Black or Other is less than the national norm, while the percentage of Blacks and Others is less than the regional norm at all but one site.

For all of the sites considered together, the data in Table 57 do not reveal a disproportionately high incidence of minority populations being located near uranium recovery facilities. However, certain individual sites may be located in areas with high minority populations. Those sites would need to be evaluated during their individual licensing processes.

6.4.2 Socioeconomic Data for Uranium Recovery Facility Areas

Table 59 shows the socioeconomic data for the immediate areas (i.e., counties) surrounding the existing and planned uranium recovery facilities. Specifically, the socioeconomic data shown in Table 59 is the fraction of land that is farmed, the value of that farmland, and the nonfarm per capita wealth. The percentages shown next to the value of that farmland and the nonfarm per capita wealth indicate where the site ranks when compared to all other counties in the United States.

Table 59: Socioeconomic Data for Uranium Recovery Facility Counties

Existing/Proposed Facility	Facility Type	County, State	Farm Land	Farm Value Per Hectare		Per Capita Nonfarm Wealth	
White Mesa Mill	Conventional	San Juan, UT	31.1%	$670	4.0%	$103,073	0.6%
Juan Tafoya	Conventional	McKinley, NM	90.9%	$185	0.0%	$115,603	1.9%
Alta Mesa	In-Situ Leach	Brooks, TX	72.8%	$1,423	13.2%	$117,693	2.2%
Grants Ridge	Heap Leach	Cibola, NM	58.2%	$378	0.7%	$118,862	2.4%
Palangana	In-Situ Leach	Duval, TX	74.1%	$1,792	17.5%	$132,493	6.9%
Crow Butte	In-Situ Leach	Dawes, NE	88.0%	$895	6.9%	$144,291	15.1%
Kingsville Dome	In-Situ Leach	Kleberg, TX	0.0%	$1,478	13.9%	$149,865	20.4%
Goliad	In-Situ Leach	Goliad, TX	92.6%	$2,244	22.0%	$162,584	35.4%
Piñon Ridge	Conventional	Montrose, CO	23.3%	$2,916	30.1%	$181,133	59.5%
Sheep Mountain	Heap Leach	Fremont, WY	42.6%	$768	5.3%	$186,775	65.4%
Shootaring Canyon	Conventional	Garfield, CO	21.4%	$3,195	34.3%	$200,316	76.7%
Smith Ranch - Highland	In-Situ Leach	Converse, WY	92.5%	$381	0.7%	$208,583	82.1%
Christensen/Irigaray	In-Situ Leach	Campbell, WY	97.3%	$437	1.1%	$225,858	89.3%
Sweetwater Mill	Conventional	Sweetwater, WY	22.2%	$242	0.1%	$232,504	91.2%

The discussion first focuses on the per capita nonfarm wealth. For comparison, the per capita nonfarm wealth in the United States ranges from $39,475 (Slope County, North Dakota) to $618,954 (New York County, New York). Table 59 shows that uranium recovery facilities are located in areas that are very poor (i.e., ranked in the lowest 0.6% in the country) to areas that are very well to do (i.e., ranked in the 91.2 percentile). Six of the 15 sites are located in areas that have per capita nonfarm wealth that is above the 50th percentile in the United States. On the other hand, five sites are located in areas in which the per capita nonfarm wealth is below the country's 10th percentile.

Table 59 shows that eight of the sites have more than 50% of their land devoted to farming. However, the Table 59 farm value data show that the farmland for all 15 sites is below the 35th percentile farmland value in the United States. This could indicate that the farmland is of poor quality, or simply that the land is located in an economically depressed area. For comparison, farmland in the United States ranges in value from $185 per hectare (McKinley County, New Mexico, which is the location of the proposed Juan Tafoya uranium recovery facility) to $244,521 per hectare (Richmond County, New York).

For all of the sites combined, the data provided in Table 59 do not reveal a disproportionately high incidence of low-income populations being located near uranium recovery facilities. However, certain individual sites may be located within areas of low-income population. Those sites would need to be evaluated during their individual licensing processes.

6.5 Regulatory Flexibility Act

The Regulatory Flexibility Act requires federal departments and agencies to evaluate if and/or how their regulations impact small business entities. Specifically, the agency must determine if a regulation is expected to have a significant economic impact on a substantial number of small entities. Small entities include small businesses, small organizations, and small governmental jurisdictions.

If a rulemaking is determined to have a significant economic impact on a substantial number of small entities, then the agency must conduct a formal regulatory flexibility analysis. However, if the agency determines that a rulemaking does not have a significant economic impact on a substantial number of small entities, then it makes a certification of that finding and presents the analyses that it made to arrive at that conclusion.

To evaluate the significance of the economic impacts of the proposed revisions to Subpart W, separate analyses were performed for each of the three proposed GACTs.

The GACT for uranium recovery facilities that use conventional milling techniques proposes that only phased disposal units or continuous disposal units be used to manage the tailings. For either option, the disposal unit must be lined and equipped with a leak detection system, designed in accordance with 40 CFR 192.32(a)(1) (see Section 5.4). If phased disposal is the option chosen, the rule limits the disposal unit to a maximum of 40 acres, with no more than two units open at any given time. If continuous disposal is chosen, no more than 10 acres may be open at any given time. Finally, the agency is proposing to eliminate the distinction made in the 1989 rule between impoundments constructed pre-1989 and post-1989, since all of the remaining pre-1989 impoundments comply with the proposed GACT. The elimination of this distinction also eliminates the requirement that pre-1989 disposal units be monitored annually to demonstrate that the average Rn-222 flux does not exceed 20 pCi/(m^2-sec).

The conventional milling GACT applies to three existing mills and one proposed mill that is in the process of being licensed. The four conventional mills are the White Mesa mill and the proposed Piñon Ridge mill owned by Energy Fuels; the Shootaring Canyon mill owned by Uranium One, Inc.; and the Sweetwater mill owned by Kennecott Uranium Co. . Of the three companies that own conventional mills, one, Energy Fuels, is classified as a small business, on the basis that they have fewer than 500 employees (EF 2012 states that Energy Fuels has 255 active employees in the U.S.).

Energy Fuels' White Mesa mill uses a phased disposal system that complies with the proposed GACT. When its existing open unit is full, it will be contoured and covered. Then, a new unit, constructed in accordance with the proposed GACT, will be opened to accept future tailings.

Energy Fuels is proposing a phased disposal system to manage its tailings; this system also complies with the proposed GACT.

Section 5.4 describes the proposed GACTs. Because both the White Mesa mill and the proposed Piñon Ridge mill are in compliance with the proposed GACT, it can be concluded that the rulemaking will not impose any new economic impacts on small business (i.e., Energy Fuels). For White Mesa, the proposed rule will actually result in a cost saving as Energy Fuels will no longer have to perform annual monitoring to determine the average radon flux from its impoundments.

The GACT for evaporation ponds at uranium recovery facilities requires that the evaporation ponds be constructed in accordance with design requirements in 40 CFR 192.32(a)(1) and that a minimum depth of 1 meter of liquid be maintained in the ponds during operation and standby. The key design requirements for the ponds are for a double liner with a leak detection system between the two liners.

In addition to the four conventional mills identified above, the GACT for evaporation ponds applies to ISL facilities and heap leach facilities. Currently, there are six operating ISLs (as shown in Table 8) and no operating heap leach facilities. The operating ISLs are Crow Butte and Smith Ranch owned by Cameco; Alta Mesa owned by Mestena Uranium, LLC; Willow Creek owned by Uranium One, Inc.; and Hobson and La Palangana owned by Uranium Energy Corp. Again, using the criterion of fewer than 500 employees, Mestena Uranium, LLC, and Uranium Energy Corp. are small businesses, while both Cameco and Uranium One, Inc., which is owned by Rosatom, are large businesses.

All of the evaporation ponds at the four conventional mills and the six ISLs were built in conformance with 40 CFR 192.32(a)(1). Therefore, the only economic impact is the cost of complying with the new requirement to maintain a minimum of 1 meter of water in the ponds during operation and standby.

In addition to the operating ISLs listed above, Table 9 shows that there are nine ISLs have been proposed for licensing. These are: Dewey Burdock owned by Powertech Uranium Corp.; Nichols Ranch owned by Uranerz Energy Corp.; 'Jab and Antelope' and Moore Ranch owned by Uranium One Americas, Inc., a subsidiary of Rosatom; Church Rock and Crownpoint owned by Hydro Resources, Inc. a subsidiary of Uranium Resources, Inc.; Ross owned by Strata Energy Inc., a subsidiary of Australian-based Peninsula Energy Limited; Goliad owned by Uranium Energy Corp.; and Lost Creek owned by Lost Creek ISR, LLC a subsidiary of Ur-Energy. All of these companies, except Rosatom, are small businesses.

According to the licensing documents submitted by the owners of the proposed ISLs, all will be constructed in conformance with 40 CFR 192.32(a)(1). Therefore, the only economic impact is the cost of complying with the new requirement to maintain a minimum of 1 meter of water in the ponds during operation and while in standby status.

The requirement to maintain a minimum of 1 meter of liquid in the ponds is estimated to cost up to $0.03 per pound of U_3O_8 produced. Considering that the current (i.e., January 30, 2012) price of U_3O_8 is \$52 per pound (UxC 2012), this cost does not pose a significant impact to any of these small entities.

The GACT for heap leach facilities applies the phased disposal option of the GACT for conventional mills to these facilities and adds the requirement that the heap leach pile be maintained at a minimum 30-percent moisture content by weight during operations. Although no heap leach facilities are currently licensed, the small business Energy Fuels is expected to submit a licensing application for the Sheep Mountain Project. From the preliminary documentation that has been presented (Titan 2011), the Energy Fuels facility will have an evaporation pond, a collection pond, and a raffinate pond. All three ponds will be double lined with leak detection. Based on the unit and facility cost comparisons presented in **Table 53** and **Table 54**, respectively, the implementation of the proposed GACTs at a heap leach facility (such as Sheep Mountain) would increase the U_3O_8 production cost by about 5%. Based on this small increase, the Sheep Mountain Project would: 1) remain competitive with U_3O_8 production cost for other types of facilities, and 2) continue to provide Energy Fuels with a profit. Energy Fuels is the only entity known to be preparing to submit a license application for a heap leach facility.

Of the 20 uranium recovery facilities identified above, 13 are owned by small businesses. As documented above in this report, those 13 facilities are either already in compliance with the proposed GACTs, with no additional impact, or compliance with the GACTs would not pose a significant impact to any of the small businesses (e.g., \$52.03 lb^{-1} versus \$52 lb^{-1}). Thus, after considering the economic impacts of this proposed rule on small entities, it is concluded that this action will not have a significant economic impact on a substantial number of small entities.

7.0 REFERENCES

10 CFR 20. Title 10 of the *Code of Federal Regulations*, Part 20, “Standards for Protection Against Radiation.”

10 CFR 40. Title 10 of the *Code of Federal Regulations*, Part 40, “Domestic Licensing of Source Material.”

40 CFR 61. Title 40 of the *Code of Federal Regulations*, Part 61, “National Emission Standards for Hazardous Air Pollutants,” Subpart W, “National Emission Standards for Radon Emissions from Operating Mill Tailings.”

40 CFR 190. Title 40 of the *Code of Federal Regulations*, Part 190, “Environmental Radiation Protection Standards for Nuclear Power Operations.”

40 CFR 192, Title 40 of the *Code of Federal Regulations*, Part 192, “Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings.”

40 CFR 264, Title 40, Part 264, “Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities.”

ACE (U.S. Army Corps of Engineers) 1979. "Feasibility Studies for Small Scale Hydropower Additions, A Guide Manual, Volume III, Hydrologic Studies," Hydrologic Engineering Center, July 1979.

ANL (Argonne National Laboratory) 1998. *MILDOSE-AREA User's Guide*, Environmental Assessment Division, Argonne National Laboratory, 1998.

Baker, K.R. and A.D. Cox, 2010. "Radon Flux from Evaporation Ponds," presented at the National Mining Association/Nuclear Regulatory Commission Uranium Recovery Workshop, May 26–27, 2010.

Ben Meadows 2012. "WATERMARK Soil Moisture Meter," http://www.benmeadows.com/WATERMARK-Soil-Moisture-Meter_31226679/, accessed 1/19/2012.

Berger (The Louis Berger Group) 2009. "Socioeconomics Baseline and Impact Analysis for the Proposed Piñon Ridge Uranium Mill, Montrose County, Colorado," prepared for Energy Fuels Resources Corporation, November 5, 2009.

BEIR (Biological Effects of Ionizing Radiation) 1988. BEIR IV Report*, Health Risks of Radon and Other Internally Deposited Alpha-Emitters: BEIR IV.* Committee on Biological Effects of Radiation, Board on Radiation Effects Research, Commission on Life Sciences, National Research Council, National Academy Press.

Black & Veatch 2010. "2009/2010 50 Largest Cities Water/Wastewater Rate Survey."

BLS (Bureau of Labor Statistics) 2011. "CPI Detailed Report (tables 1-29 only) August 2011," Department of Labor, http://www.bls.gov/cpi/tables.htm, accessed 9/16/2011.

Brown, Steven 2010. *Evaporation Pond Radon Flux Analysis, Piñon Ridge Mill Project, Montrose County, Colorado*. SENES Consultants Limited, prepared for Energy Fuels Resources Corporation, August 30, 2010.

BRS 2011. "Sheep Mountain Uranium Project, Fremont County, Wyoming, 43-101 Mineral Resource, Report Update," prepared for Titan Uranium, USA Inc., March 1, 2011.

BDC (Behre Dolbear & Company) 2011. "Scoping Study of the Strathmore Resources (US), LTD, Church Rock Deposit, McKinley County, New Mexico," April 4, 2011.

Cameco Corp. 2013. "Uranium Price, Long-term Uranium Price History," http://www.cameco.com/investors/markets/uranium_price/longterm_5yr_history/, accessed September 17, 2013.

Cardinal Engineering 2000. "Solid Waste Financial Assurance Program Report," prepared for Oklahoma Department of Environmental Quality, Waste Management Division, December 22, 2000.

Denison Mines (USA) Corp., 2007. "White Mesa Uranium Mill License Renewal Application, State of Utah Radioactive Materials License No. UT1900479, Volume 4 – Environmental Report," February 28, 2007.

Denison Mines (USA) Corp., 2011. "Reclamation Plan, White Mesa Mill, Blanding, Utah, Radioactive Materials License No. UT1900479," Revision 5.0, September 2011.

DOA (U.S. Department of Agriculture) 2004. "2002 Census of Agriculture, Farm and Ranch Irrigation Survey (2003), Volume 3, Special Studies, Part 1," November 2004.

DOE (U.S. Department of Energy) 1995. "Decommissioning of U.S. Uranium Production Facilities," Energy Information Administration, DOE/EIA-0592, February 1995.

DOL (U.S. Department of Labor) 2012. "Consumer Price Index," Bureau of Labor Statistics, ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt, January 19, 2012.

Drago, J.A. 1998. *Critical Assessment of Radon Removal Systems for Drinking Water Supplied,* Chapter 3, Table 3.2, American Water Works Association.

Duffy, Daniel P. 2005. "Landfill Economics Part III: Closing Up Shop," MSW Management, August 31, 2005.

Earth Tech, Inc. 2002. "Cost Estimates for Various Base Liner Systems and GIA," prepared for Bureau of Land, Illinois Environmental Protection Agency, December 3, 2002.

Edge Environmental, Inc., 2009. "Piñon Ridge Project Environmental Report, Montrose County, Colorado," November 2009.

EF (Energy Fuels) 2012. "2012 Annual Information Form," December 20, 2012.

EIA (U.S. Energy Information Administration) 2010. "U.S. Uranium Reserves Estimates," July 2010.

EIA (U.S. Energy Information Administration) 2011a. "Annual Energy Outlook 2011 with Projections to 2035," Department of Energy, DOE/EIA-0383(2011), April 2011.

EIA (U.S. Energy Information Administration) 2011b. "2009 Uranium Marketing Annual Report," August 18, 2011.

EIA (U.S. Energy Information Administration) 2013. "Domestic Uranium Production Report 2nd Quarter 2013," August, 2013.

EPA (Environmental Protection Agency) 1979. "Radiological Impacts Caused by Emission of Radionuclides into Air in the United States," EPA 520/7-79-006, Office of Radiation Programs, Environmental Protection Agency, August 1979.

EPA (Environmental Protection Agency) 1983. “Background Information Document Proposed Standards for Radionuclides,” Draft Report, EPA 520/1-83-001, Office of Radiation Programs, Environmental Protection Agency, March 1983.

EPA (Environmental Protection Agency) 1984. “Final Background Information Document Proposed Standards for Radionuclides,” EPA 520/1-84-022-1, Office of Radiation Programs, Environmental Protection Agency, October 1984.

EPA (Environmental Protection Agency) 1986. “Final Rule for Radon-222 Emissions From Licensed Uranium Mill Tailings Background Information Document,” EPA 520/1-86-009, Office of Radiation Programs, Environmental Protection Agency, August 1986.

EPA (Environmental Protection Agency) 1989. “Risk Assessment Methodology Environmental Impact Statement NESHAPS for Radionuclides Background Information Document,” Volumes 1–3, EPA 520/1-89-005, Office of Radiation Programs, Environmental Protection Agency, September 1989.

EPA (Environmental Protection Agency) 1995. “Technical Resource Document, Extraction and Beneficiation of Ores and Minerals,” Volume 5, “Uranium,” EPA 530-R-94-032, Office of Solid Waste, U.S. Environmental Protection Agency, January 1995.

EPA (Environmental Protection Agency) 1999. “Cancer Risk Coefficients for Environmental Exposure to Radionuclides,” EPA-402-R-99-001, Federal Guidance Report No. 13, prepared by K.F. Eckerman, et al., Oak Ridge National Laboratory, Oak Ridge, Tenn., for Office of Radiation Programs, U.S. Environmental Protection Agency.

EPA (U.S. Environmental Protection Agency) 2000a. “Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM),” EPA-402-R-97-016, Rev. 1; Nuclear Regulatory Commission, NUREG-1575, Rev.1; Department of Energy, DOE/EH-0624, Rev. 1; Department of Defense, August 2000.

EPA (Environmental Protection Agency) 2000b. “Guidance on the Major Source Determination for Certain Hazardous Air Pollutants,” John S. Seitz, Director, Office of Air Quality Planning and Standards (MD-10), August 14, 2000.

EPA (U.S. Environmental Protection Agency) 2002. “Federal Guidance Report 13, CD Supplement, Cancer Risk Coefficients for Environmental Exposure to Radionuclides,” EPA 402-C-99-001, Revision 1, April 2002.

EPA (Environmental Protection Agency) 2003. “EPA Assessment of Risks from Radon in Homes,” EPA 402-R-03-003, Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, June 2003.

EPA (U.S. Environmental Protection Agency) 2004. “Record of Decision, Spectron, Inc., Superfund Site, Operable Unit 1, Elkton, Cecil County, Maryland,” Region 3, September 2004.

EPA (Environmental Protection Agency) 2010. "Guidelines for Preparing Economic Analyses," EPA 240-R-10-001, December 2010.

EPA (Environmental Protection Agency), 2011. "Radiogenic Cancer Risk Models and Projections for the U.S. Population." EPA Report 402-R-11-001, Washington, DC: U.S. EPA. April 2011.

FR (*Federal Register*) 1977. EPA established environmental protection standards for nuclear power operations pursuant to its authority under the Atomic Energy Act (AEA), Volume 42, p. 2858, January 13, 1977.

FR (*Federal Register*) 1979. EPA determination that radionuclides constitute a hazardous air pollutant within the meaning of section 112(a)(1), Volume 44, p. 78738, December 27, 1979.

FR (*Federal Register*) 1984. EPA withdrew the proposed NESHAPs for Elemental Phosphorus Plants, DOE-Facilities, and NRC-Licensed Facilities. Volume 49, p. 43906. October 23, 1984.

FR (*Federal Register*) 1985a. EPA promulgated final standards for Elemental Phosphorus Plants, DOE-Facilities, and NRC-Licensed Facilities, Volume 50, p. 7280, February 8, 1985.

FR (*Federal Register*) 1985b. EPA established a work practice standard for Underground Uranium Mines, Volume 50, p. 15385, April 17, 1985.

FR (*Federal Register*) 1986. 40 CFR Part 61, National Emission Standardss for Hazardous Air Pollutants, Standards for Radon-222 Emissions from Licensed Uranium Mill Tailings; Final Rule, Volume 51, p. 34056, September 24, 1986.

FR (*Federal Register*) 1989a. National Emission Standards for Hazardous Air Pollutants; Regulation of Radionuclides; Proposed Rule and Notice of Public Hearing, Volume 54, pp. 9612–9668, March 7, 1989.

FR (*Federal Register*) 1989b. National Emission Standards for Hazardous Air Pollutants; Radionuclides, Volume 54, p. 51654, December 15, 1989.

FR (*Federal Register*) 1994. National Emission Standardss for Hazardous Air Pollutants; Final Rule, Volume 59, p. 36280, July 15, 1994.

Foldager, Robin A. 2003. "Economics of Desalination Concentrate Disposal Methods in Inland Regions: Deep-Well Injection, Evaporation Ponds, and Salinity Gradient Solar Ponds," New Mexico State University, Honors Program thesis, Fall 2003.

Free Construction Cost Data 2012, "Membrane lining systems," http://www.allcostdata.info/browse.html/022670010/Membrane-lining-systems, accessed 1/26/2012.

George, A.C., 2007. "World History of Radon Research and Measurement from the Early 1900s to Today," Natural Radiation Environment Conference VIII (NRE VIII) in Buzios, Brazil, Radon Bulletin of the CRCPD, reprinted in November 2007.

Get-a-Quote.net 2012, "CSI 02-545, Membrane Lining Systems," http://www.get-a-quote.net/QuoteEngine/costbook.asp?WCI=CostFrameSet&BookId=48, accessed 1/26/2012.

Golder Associates Inc. 2008, "Evaporation Pond Design Report, Piñon Ridge Project, Montrose County, Colorado," submitted to Energy Fuels Resources Corporation, October 2008.

Hamrick, John S. 2010. "Regulatory Status of the Cotter Corporation Primary Impoundment Located at the Cañon City Milling Facility," letter to the Director, U.S. Environmental Protection Agency, July 23, 2010.

Hamrick, John S. 2011. "Comprehensive Reclamation Plan and Strategy Summary," letter to Mr. Steve Tarlton, Manager, Radiation Management Unit, Hazardous Materials and Waste Management Division, Colorado Department of Public Health and Safety, June 17, 2011.

Hosoda, Masahiro, Michikuni Shimo, Masato Sugino, Masahide Furukawa, and Masahiro Fukushi 2007. "Effect of Soil Moisture Content on Radon and Thoron Exhalation," *Journal of Nuclear Science and Technology*, Vol. 44, No. 4, pp. 664–672, 2007.

IAEA (International Atomic Energy Agency) 2005. "Guidebook on Environmental Impact Assessment for In-Situ Leach Mining Projects," IAEA-TECDOC-1428, IAEA, May 2005.

ICRP (International Commission on Radiological Protection) 1987. *Lung Cancer Risk from Indoor Exposures to Radon Daughters,* Publication 50, Annals of the ICRP 17(1), Pergamon Press, Oxford.

ICRP (International Commission on Radiological Protection) 1994. *Human Respiratory Tract Model for Radiological Protections*, Publication 66, Annals of the ICRP Volume 24 (103), Elsevier.

ICRP (International Commission on Radiological Protection) 1996. *Age-dependent Doses to the Members of the Public from Intake of Radionuclides - Part 5 Compilation of Ingestion and Inhalation Coefficients*, Publication 72, Annals of the ICRP Volume 26 (1), Elsevier.

Irrometer Company, Inc. 2010. "WATERMARK Digital Meter," Catalog #30-KTCD-NL, May 2010.

Jackson, A., 2009. "EPA's Fuzzy Bright Line Approach to Residual Risk," *Ecology Law Quarterly*, Vol. 35:439, 2009.

KBC Engineers 2009. "2009 Surety Rebaselining Report, Response to the Request for Additional, Information (RAI) Dated October 16, 2009," prepared for Kennecott Uranium Company, October 21, 2009.

KUC (Kennecott Uranium Company) 2011. "Application for a Five (5) Year Postponement of the Initiation of the Requirements of Timeliness in Decommissioning Pursuant to 10 CFR 40.42(e) for the Sweetwater Uranium Project," June 1, 2011.

Li, Pamela Y. and P.K. Chen 1994. "Relationships of Radon Diffusion Coefficient with Saturated Hydraulic Conductivity, Fine Content and Moisture Saturation of Radon/Infiltration Barriers for the UMTRA Project," Morrison Knudsen Corporation, *Waste Management '94*, 27 Feb–3 Mar 1994.

Lyntek Inc. and BRS Engineering 2010. "Preliminary Economic Assessment on the Coles Hill Uranium Property," prepared for Virginia Uranium Inc. and Virginia Energy Resources Inc., December 2010.

Lyntek Inc. 2011. "Roca Honda Resources; Water Treatment Plant, 60% Design, Grants, New Mexico, Appendix E—Capital and Construction Costs," prepared for Roca Honda Resources, LLC, January 2011.

MWH (Montgomery Watson and Harza) Global, Inc. 2008. "Sierrita Mine Groundwater Treatment Alternative Evaluation," prepared for Bridgewater Group, Inc., Reference No. 1005720.011801, October 14, 2008.

NAS (National Academy of Sciences) 1988. *Health Risks of Radon and Other Internally Deposited Alpha-Emitters: BEIR IV*, 1988.

Nielson, K.K., and V.C. Rogers, 1986. "Surface Water Hydrology Considerations in Predicting Radon Releases from Water Covered Areas of Uranium Tailings Ponds," *Proc. 8th Annual Symposium on Geotechnical & Geohydrological Aspects of Waste Management*, Geotechnical Engineering Program, Colorado State University & A.A. Balkema, Fort Collins, Colorado, pp. 215–222, February 5–7, 1986.

NMA (National Mining Association) 2010. "Uranium Recovery Licensing Activities," presentation by Larry W. Camper (Director), Division of Waste Management and Environmental Protection, Nuclear Regulatory Commission, National Mining Association Uranium Recovery Workshop held in Denver, Colorado, May 26–27, 2010.

NRC (U.S. Nuclear Regulatory Commission) 1984. "Radon Attenuation Handbook for Uranium Mill Tailings Cover Design," V.C. Rogers, K.K. Nielson, Rogers and Associates Engineering Corporation, and D.R. Kalkwarf, Pacific Northwest Laboratory, NUREG/CR-3533, PNL-4878, RAE-18-5, April 1984.

NRC (U.S. Nuclear Regulatory Commission) 2003. "Standard Review Plan for In Situ Leach Uranium Extraction License Application – Final Report," NUREG-1569, June 2003.

NRC (U.S. Nuclear Regulatory Commission) 2010. "Workshop on Engineered Barrier Performance Related to Low-Level Radioactive Waste, Decommissioning, and Uranium Mill Tailings Facilities," ML101830458, August 3–5, 2010.

NRC (U.S. Nuclear Regulatory Commission) 2013. "2013–2014 Information Digest," NUREG-1350, Volume 25, ML13241A207, August 2013.

ORISE (Oak Ridge Institute for Science and Education) 2011. "Technical Bases and Guidance for Radon Flux Monitoring at Uranium Mill Tailing Sites," DCN 2042-TR-01-0, June 27, 2011.

Pool, Tom 2008. "U.S. Uranium and Nuclear Power Outlook: 2008 – 2030," International Nuclear, presented to National Research Council of the National Academies, November 18, 2008.

Poulson, Thomas K. 2010. "Central Arizona Salinity Study, Strategic Alternatives for Brine Management in the Valley of the Sun," January 2010.

Powertech (USA) Inc. 2009. "Dewey-Burdock Project, Application for NRC Uranium Recovery License, Fall River and Custer Counties, South Dakota, Technical Report," February 2009.

Project Navigator, Ltd. 2007. "Revised Feasibility Study, Ascon Landfill Site, Huntington Beach, California, Appendix R, Remedy Capital/O&M Costing," prepared for Ascon Landfill Site Responsible Parties, September 21, 2007.

Rogers, V.C. and K.K. Nielson 1991. "Correlations for Predicting Air Permeabilities and ^{222}Rn Diffusion Coefficients of Soils," *Health Physics*, Vol. 61, No. 2, August 1991.

Sandia National Laboratories 1998. "Construction Costs of Six Landfill Cover Designs," Stephen F. Dwyer, Environmental Restoration Technology Department, SAND98-1988, September 1998.

Sandia National Laboratories 2003. "SECPOP2000: Sector Population, Land Fraction, and Economic Estimation Program," prepared for U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Division of Risk Analysis and Applications, NUREG/CR-6525, Rev. 1, SAND2003-1684P, August 2003.

Sassa, K. 1985. The mechanism of debris flows. Proc. of the 11th Intl. Conf. on Soil Mech. and Foundation Engineering, San Francisco, V. 3, pp. 1173-1176.

SC&A (S. Cohen & Associates) 2008. "Report on the Review of Method 115 to Monitor Radon Emissions from Uranium Tailings," Contract Number EP-D-05-002, Work Assignment No. 4-11, Task 6, SC&A, Inc., Vienna, Virginia, September 25, 2008.

SC&A (S. Cohen and Associates) 2010. "Risk Assessment Revision for 40 CFR Part 61 Subpart W – Radon Emissions from Operating Mill Tailings, Task 5 – Radon Emission from

Evaporation Ponds," Contract Number EP-D-10-042, Work Assignment No. 1-04, Task 5, SC&A, Inc., Vienna, Virginia, November 2010.

SC&A (S. Cohen and Associates) 2011. "Risk Assessment Revision for 40 CFR Part 61 Subpart W – Radon Emissions from Operating Mill Tailings, Task 4 – Detailed Risk Estimates," Contract Number EP-D-10-042, Work Assignment No. 1-04, Task 4, SC&A, Inc., Vienna, Virginia, March 25, 2011.

Schumann, R.R., 1993. "The Radon Emanation Coefficient: An Important Tool for Geologic Radon Potential Estimations," *The 1993 International Radon Conference, September 20–22, 1993*, Denver, Colorado, preprints, pp. IV-40–IV-47.

Schwarzenbach, Rene, P. Philip, M. Gschwend, and Dieter M. Imboden, 2003. *Environmental Organic Chemistry*, 2nd edition, Chapter 19, Wiley-Interscience, Hoboken, New Jersey, IBSN-0-471-35750-2.

Smith, Mark E., 2002, "Liquefaction in Dump Leaching," Mining Magazine, July 2002.

Spectrum Technologies, Inc. 2011. "FieldScout TDR 300, Soil Moisture Meter, Product Manual," Item # 6430FS, December 2011.

Spectrum Technologies, Inc. 2012. "FieldScout TDR 300 Soil Moisture Meter with Case," http://www.specmeters.com/soil-and-water/soil-moisture/fieldscout-tdr-meters/tdr300/, accessed 1/19/2012.

SRK Consulting 2010a. "Powertech Uranium Corp., NI 43-101 Preliminary Assessment, Dewey-Burdock Project, Custer and Fall River Counties, South Dakota," July 6, 2010.

SRK Consulting 2010b. "NI 43-101 Preliminary Assessment, Powertech Uranium Corp., Centennial Uranium Project, Weld County, Colorado," August 13, 2010.

Sun, Hongbing, and David J. Furbish 1995. "Moisture Content Effect on Radon Emanation in Porous Media," *Journal of Contaminant Hydrology* 18 (19s 5) 239–255.

TEA (Trinity Engineering Associates) 2007. *CAP88-PC Version 3.0 User Guide*, prepared for U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, by Trinity Engineering Associates, Inc, December 2007.

Thiel, Richard, and Mark E. Smith, 2004, "State of the Practice Review of Heap Leach Pad Design Issues," Geotextiles and Geomembranes, 22(5): 555-568.

Titan Uranium 2011. "Sheep Mountain Uranium Project Crooks Gap, Wyoming," presentation to U.S. Nuclear Regulatory Commission, ML111740073, May 24, 2011.

U.S. Senate 1989. *1990 Amendments to the Clean Air Act*, Report No. 101-228, 101st Congress, 1st session, pp. 171–172, December 20, 1989.

UxC (The Ux Consulting Company) 2012. "UxC Nuclear Fuel Price Indicators," http://www.uxc.com/review/uxc_Prices.aspx, accessed 2/3/2012.

Vector Colorado, LLC 2006. "Rosemont Mine, Conceptual Heap Leach Pad Design Layout," prepared for Augusta Resource Corp., June 5, 2006.

VDEQ (Virginia Department of Environmental Quality) 2000. "Landfill Cost Estimate Form."

Visus Consulting Group, Inc. 2009. "Facility Operating Plan, Piñon Ridge Mill Facility, Montrose County, Colorado," prepared for Energy Fuels Resources Corporation, November 3, 2009.

Waste Control Specialists (WCS) 2007. "Byproduct Material Landfill License Application, Appendix 6.A: Closure Cost Assumptions and Calculations," Revision 16, May 18, 2007.

Weston Solutions (WS) 2003. "2003 Decommissioning Cost Estimate for the Boyertown, Pennsylvania Site," prepared for Cabot Supermetals, Inc., December 11, 2003.

WNA (World Nuclear Association) 2010. "Uranium Markets," http://world-nuclear.org/info/inf22.html, updated July 2010.