Appendix IV. Risks Associated with Conventional Uranium Milling Operations

Introduction

Although uranium mill tailings are considered byproduct materials under the AEA and not TENORM, EPA's Science Advisory Board (SAB) recommended that EPA present information on uranium mill operations, as well as *in situ* leaching (ISL) mining operations, to provide a more complete picture of uranium production. While this report focuses on the impacts associated with conventional surface and underground uranium mines, it provides limited background materials, in this and other appendices, on risks associated with uranium milling and ISL operations and wastes generated by those processes, even though they may not be considered TENORM by virtue of their regulation by the NRC and its Agreement States under the Atomic Energy Act and its amendments.

The NRC stated its intent in July 2007 (NRC 2007b) to develop a Generic Environmental Impact Statement (GEIS) on uranium milling which would provide more detailed information and may include more recent information on the impacts of uranium milling. The reader is referred to that document when made available to the public in the future for additional background information and associated risk assessment.

This appendix summarizes information on environmental and health aspects of uranium mill operations. The primary sources used for this review are "*Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining. Volume 1: Mining and Reclamation Background"* by U.S. EPA (2006), *"Final Generic Environmental Impact Statement on Uranium Milling Volume 1 and 2"* by U.S. NRC (1980), "*Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192) Volume 1"* by U.S. EPA (1983), and "*Uranium Mining and Milling Wastes - An Introduction*," by Peter Diehl of the WISE Uranium Project (2004)**.**

Background

Uranium milling is the process of converting raw ore as it arrives from mining operations into a product known as uranium yellowcake. The raw uranium ore and resultant yellowcake are shown in Figure AVI-1, and a generalized schematic of a typical milling process is shown in Figure AVI-2.

The first steps in the milling process involve crushing and grinding the ore in order to obtain smaller, uniform particle sizes throughout. Often, water is added during this stage to control dust, or lixiviant may also be added to facilitate the extraction process. Screens separate fine particles, which continue to the next stage in the milling process, from coarse particles, which are recirculated in the milling circuit. Dust that is not sufficiently suppressed by the addition of water/lixiviant is generally collected by air pollution control mechanisms, which return the fugitive particles to the milling process.

Once the ore is ground into uniform small particles, the processed ore moves to the leaching stage. In the most common leaching method, known as "acid leaching", uranium is removed from the processed ore with sulfuric acid. Sodium chlorate is also added as an oxidizing agent to improve the solubility of the uranium. An alternative approach is alkaline leaching, which is preferable when the raw ore contains a significant portion of limestone (greater than 12%), because the acid leaching process then requires uneconomically large amounts of acid to be effective. Alkaline leaching, however, requires much finer grinding of the ore in comparison to acid leaching. Both methods of leaching have similar environmental and health impacts; however, the waste produced from acid leaching is generally more mobile and will be used as the bounding scenario in this treatment (U.S. EPA 1983).

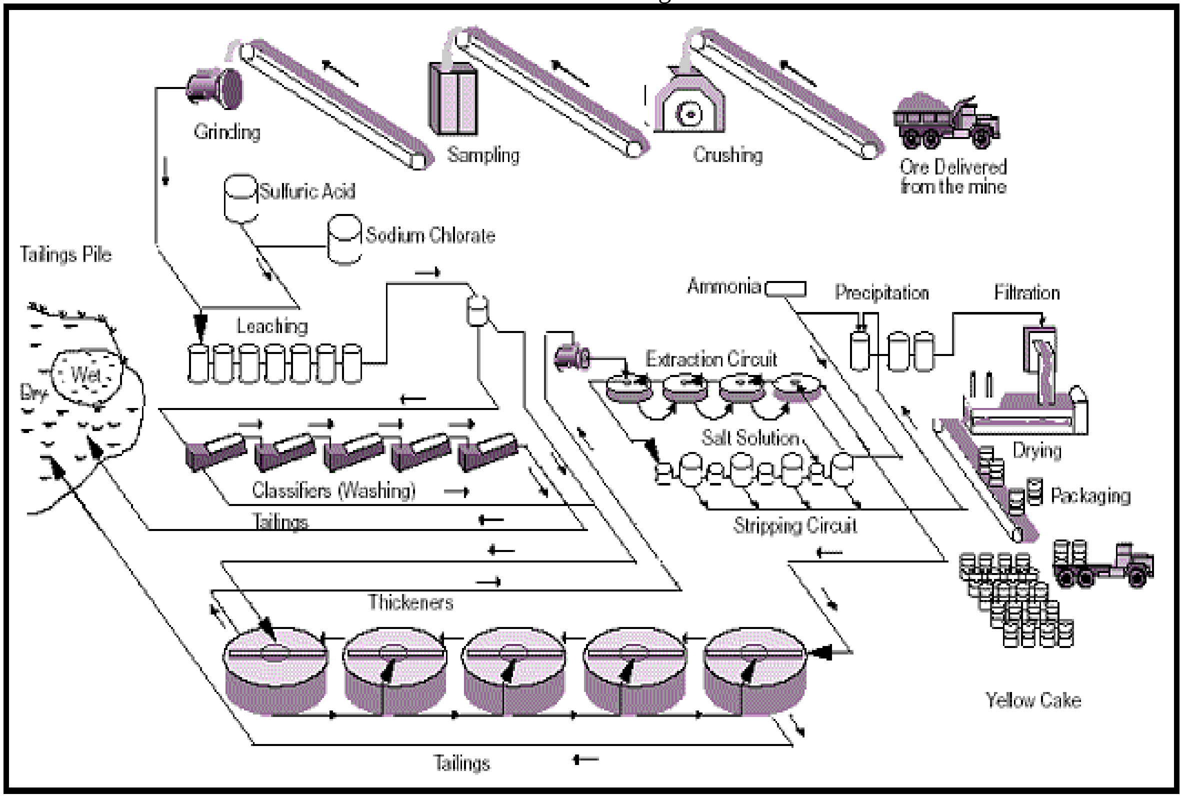
Figure AIV-1. Raw Uranium Ore and Yellowcake Product

This figure shows the incoming raw uranium ore as it enters the uranium milling process (left), as well as the final product of uranium yellowcake (right)

Source: http://www.eoearth.org/upload/thumb/c/c1/Uranium_ore_square.jpg (left)
http://www.eia.doe.gov/kids/energy_fungames/energyslang/images/yellowcake1.jpg (right)

Figure AIV-2. Generalized Uranium Mill Physical Layout

This figure shows how a uranium mill is physically set up to crush raw ore into particles amenable to chemical treatments for extracting uranium.



Source: http://www.eia.doe.gov/cneaf/nuclear/page/uran_enrich_fuel/uraniummill.html

After the leaching stage, the pregnant lixiviant generally contains about 50-60% solids. These solids, called "tailings," are filtered out and sent to on-site tailings piles or impoundments in the form of sands and slimes. Once most of the solids have been removed, the filtered lixiviant is transferred to an extraction circuit where the desired uranium is stripped from the pregnant lixiviant, followed by a precipitation and drying process, which produces the desired yellowcake product.

Potential Environmental and Health Issues from Mill Tailings

The wastes produced during the milling process and stored in tailings impoundments are the principal source of milling-related health and environmental hazards. Typical properties of these mill tailings are shown in Table AIV-1. During the milling process, nearly 90% of the uranium contained in the ore is removed, and so the primary radiological concern is the remaining progeny associated with uranium such as thorium, radium, radon, and lead. The actual activity of these uranium progeny can vary depending on the specific methods employed,; however, as much as 50-86% of the original activity of the ore is retained in the mill tailings (U.S. EPA 2006). Hazardous stable elements are also extracted from the ore and transferred to the tailings piles, including arsenic, copper, selenium, vanadium, molybdenum, and other trace heavy metals.

Table AIV-1: Typical Properties of Uranium Mill Tailings

This table displays the chemical and radiological properties of the three classifications of uranium mill tailings (sand, slime, and liquid). Table was adapted from U.S. NRC 1980 and found in U.S. EPA 2006

Tailings Component	Particle Size (µm)	Chemical Composition	Radioactivity Characteristics
Sands	75 to 500	SiO_2 with <1 wt% complex silicates of Al, Fe, Mg, Ca, Na, K, Se, Mn, Ni, Mo, Zn, U, and V; also metallic oxides	0.004 to 0.01 wt % U_3O_8[a] Acid Leaching: 26-100 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Slimes	45 to 75	Small amounts of SiO_2, but mostly very complex clay-like silicates of Na, Ca, Mn, Mg, Al, and Fe; also metallic oxides	U_3O_8 and ^{226}Ra are almost twice the concentration present in the sands Acid leaching:[b] 150 to 400 pCi ^{226}Ra/g; 70 to 600 pCi ^{230}Th/g
Liquids	[c]	Acid leaching: pH 1.2 to 2.0; Na^+,NH_4^+, SO_4^2, Cl, and PO_4^3; dissolved solids up to 1 wt % Alkaline leaching: pH 10 to 10.5; CO_3^2 and HCO_3; dissolved solids 10 wt %	Acid leaching: 0.001 to 0.01% U; 20 to 7,500 pCi ^{226}Ra/L; 2,000 to 22,000 pCi; ^{230}Th/L Alkaline leaching: 200 pCi ^{226}Ra/L; essentially no ^{230}Th (insoluble)

[a] U_3O_8 content is higher for acid leaching than for alkaline leaching

[b] Separate analyses of sands and slimes from alkaline leaching process are not available. However, total ^{226}Ra and ^{230}Th contents of up to 600 pCi/g (of each) have been reported for the combined sands and slimes.

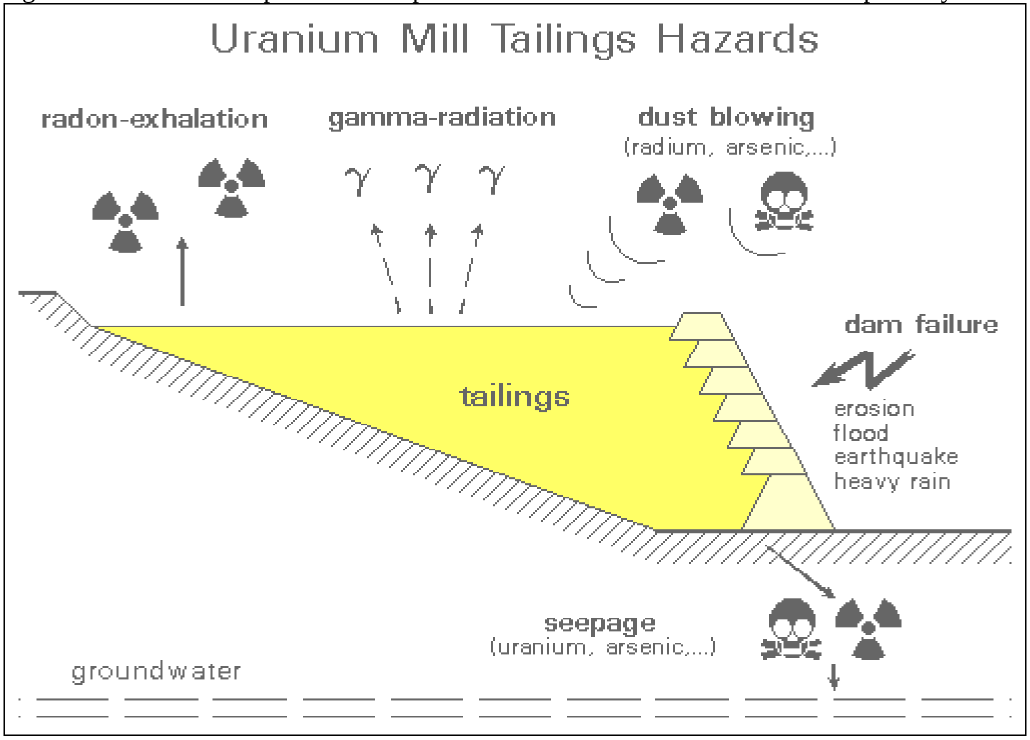
[c] Particle size does not apply. Up to 70 % vol. of the liquid may be recycled. Recycle potential is greater in the alkaline process.

The five on-site environmental pathways through which these tailings impoundments pose a risk are represented schematically in Figure AVI-3. In addition to the on-site scenarios, tailings have also been taken off-site and used as an inexpensive building material by some local populations. Each of these hazard pathways is listed below and the associated risks are discussed later.

(i) The release of gaseous radon-222 to the atmosphere and subsequent inhalation
(ii) Possible dust loading of contaminants from the impoundment due to natural wind conditions
(iii) The localized effect of direct external gamma radiation exposure from the tailings impoundment
(iv) Ground seepage and subsequent contamination of local aquifers, which has the potential to affect the water supply
(v) Dam failure due to erosion or natural disasters (flood, earthquake, etc.)
(vi) Improper use of tailings as a building material

All six of these hazard scenarios can apply to the general public and, with the exception of building materials, to the plant workers themselves. In addition, plant workers have added risks associated with accidents that may occur within the mill. The additional issues associated with workers are discussed in a separate section.

Figure AIV-3: On-Site Accident and Risk Scenarios Associated with Uranium Mill Tailings
This Figure shows a visual depiction of the possible environmental and health related pathways of concern



Source: http://www.wise-uranium.org/uwai.html

(i) Gaseous Radon-222 Inhalation

Radon-222 is an inert radioactive gas that can readily diffuse to the surface of a tailings impoundment where it would be released to the atmosphere. The main hazard of radon inhalation is the damage to the lung from four of its shorter-lived decay products (Po-218, Pb-214, Bi-214, and Po-214). Of particular concern are the two isotopes of polonium (Po-218 and Po-214), because they produce alpha particles, which are approximately 20 times more destructive than gamma or beta radiation. Because radon-222 has a half-life of approximately 3.8 days, it has the opportunity travel a significant distance in the atmosphere before decaying. U.S. EPA (1983) states that the health of populations living at a distance greater than 80 km from a tailings pile might be affected. The radon concentration at the edge of a typical tailings pile is approximately 4 pCi/l (WISE 2004). Using the methodology outlined in Chapter 1 of this report, a year-long exposure under these conditions would correspond to a lifetime risk of lung cancer of 1.1×10^{-2}.

(ii) Inhalation of Particles from Dust Loading

Dust loading occurs when wind blows over a dried portion of the tailings and dust containing hazardous contaminants is suspended in the air. Dust loading typically becomes a hazard in the post-operational phase of a uranium mill, as the tailings pile begins to dry, and may be exacerbated by any de-watering treatment that is performed to minimize ground seepage [see section (iv)]. The hazards associated with dust loading are dependent on the weather conditions and the amount of dried material that is available for suspension. It has been estimated that a person would have to inhale 2 grams of uranium mill tailings in a year to reach the annual dose limit for the general public (100 mrem). Assuming a continuous exposure and a breathing rate of 0.9 m^3/hr, this would correspond to a dust loading of 0.24 mg/m^3 (WISE 2004).

(iii) Direct Gamma Exposure

Uranium mill tailings pose an external exposure hazard from radioactivity that is present in the waste. Although milling operations generally remove about 90% of the uranium from the ore, the remaining waste can contain up to 86% of the original radioactivity which is mostly composed of uranium decay products such as radium and thorium. Worst-case external exposures have been estimated to be 0.41 mrem/h, if the subject were standing directly on top of the tailings; for a continuous yearly exposure, this yields a dose of 3.6 rem.

(iv) Groundwater Contamination

Groundwater contamination is so heavily dependent on site-specific parameters, such as the chemical characteristics of the waste products and soil, the location of neighboring aquifers, and the hydrology and geology of the site, that any general numerical risk assessment of groundwater contamination is of limited utility. Groundwater contamination can become a problem if liquid wastes from tailings impoundments seep into the ground and are transferred into shallow local aquifers. Mills employing acid leaching processes are of special concern, because this method renders the waste products more soluble than an alkaline leach process. The radiological contaminants would likely be pulled out of the seepage water into the immediate soil and so do not have the mobility to move offsite into neighboring aquifers. However, water-soluble non-radiological hazards may be problematic, including molybdenum, selenium, chlorine, sulfate, nitrate, arsenic, lead, and vanadium. An NRC report (1980) concluded that 95% of any possible groundwater contamination would occur while the site was in operation. Also, seepage should be expected unless the tailings pile was built on an artificial liner or impermeable natural clay formations. Besides lining tailings impoundments, milling waste is sometimes dewatered before disposal to reduce the risk of groundwater contamination. Dewatering, however, causes an increase in the rate of radon gas emissions (increase by a factor of 3.4 when comparing wet versus dry tailings) and also makes the pile more susceptible to wind-driven dust loading. An example of dewatering occurs at the White Mesa Mill, where the dry tailings are stored in an approved below-grade disposal cell. This disposal cell is covered with the excavated earth to mitigate the effects of radon emission and dust loading (Hochstein 2003).

Current controls exist as a result of the passage of UMTRCA to eliminate this hazard from existing and future licensed operations, as well as a certain number of previously closed and abandoned mills (see Volume I, Appendix VI for more background information). The EPA has been taking steps to work with the Navajo Nation to identify buildings constructed with uranium mine and mill wastes to assess their radiation risks, and conduct removal or other appropriate actions if necessary.

(v) Tailings Pile Dam Failure

The least predictable risk associated with conventional uranium milling operations is the failure of a tailings dam. A dam might fail because of poor design, natural erosion of the dam, or natural disasters such as flooding, heavy snow fall, tornados, or earthquakes. In the United States, notable dam failures include the 1977 spill in Grants, New Mexico (50,000 tons of sludge and several million liters of contaminated water), and the 1979 spill in Church Rock, New Mexico (1000 tons of sludge and 400 million liters of contaminated water). The second of these noted spill events, Church Rock, is the most notorious. It heavily contaminated the Rio Puerco river and shallow aquifers located near the river, which were used by the Navajo Nation as both an agricultural and domestic water source. As of 2003, the Navajo are still unable to use this water (Ali 2003).

(vi) Improper Use of Mill Tailings as a Building Material

As stated in Chapter 4 of the main report, the risk of radiological exposure to the general public is not only from the tailing piles themselves, but also the improper use of mill tailings as building materials. The sandy properties of mill tailings and their availability in certain economically depressed areas make their inclusion in concrete and use as a building material possible. This has occurred when tailings piles have been abandoned without having been properly closed, or when piles of tailings have fallen from trucks along rural highways. Though the problem has been documented in Grand Junction, Colorado (Elmer 2005), Monticello, Utah (EPA 1989), on the Navajo reservation in New Mexico, and elsewhere, its current pervasiveness remains unknown. Tables 4.1 and 4.2 of the main report present annual dose values based on a few sample activity concentrations within a Navajo hogan. See Chapter 4 of the main report for more in-depth discussion and analysis of the improper use of tailings.

Summary of Modeled Risks to the Public

In a study by the Nuclear Regulatory Commission, a generalized case was modeled in which it was assumed that a “low level” of environmental controls were in place. This report concluded that if the mills in place during the time of the study (by 1980 there were 16 mills producing approximately 43,900 megatons of ore annually) were in full operation through the year 2000, it would result in approximately 610 premature deaths in North America through the year 2100 and 6,000 premature deaths through the year 3000. This model was based on a low level of environmental control, and did not take into account mitigating factors, such as covering the tailings to reduce the atmospheric release of the radon. The estimated 15-year committed dose to the public is shown in Table AVI-3, at the end of the document, which also includes an estimate of the risk as a percentage of the risk from normal background radiation exposure. For example, an individual near by a cluster of mills would accrue a 15-year committed dose of 340 mrem to the lung (an effective dose equivalent[*] of 41 mrem), and would represent an increase of 38% above the normal risk from background exposure (U.S. NRC 1980).

These risk estimates for fatal cancer have since been updated in U.S EPA (1983) and the results are shown in Table AVI-2. This study estimated the individual risk of cancer for a 15-year exposure to an individual at distances of 1,000-20,000 meters from the mill. The model also takes into account whether the mill was in an operational or post-operational phase. For each phase of operation, the individual 15-year risk is given as an average and a maximum value. The maximum value represents the individual who is downwind of the mill, while the average value represents the average of all wind directions (U.S. EPA 1983).

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[*] Effective dose equivalent based on the tissue weighting factors of ICRP-26

Table AIV-2: Results of the 1983 EPA Study[a] – Estimated 15-Year Risk of Fatal Cancer by Region and Phase of Operation

	Total Risk (Operational Phase)		Total Risk (Post-Operational Phase)	
Distance (meters)	**Average**	**Maximum**	**Average**	**Maximum**
1000	1.12E-03	1.97E-03	1.82E-03	3.18E-03
2000	3.39E-04	6.78E-04	5.51E-04	1.12E-03
3000	1.76E-04	3.60E-04	2.76E-04	5.72E-04
4000	1.17E-04	2.33E-04	1.89E-04	3.82E-04
5000	8.48E-05	1.74E-04	1.38E-04	2.76E-04
10000	3.18E-05	6.57E-05	5.09E-05	1.04E-04
20000	1.40E-05	2.76E-05	2.33E-05	4.45E-05

[a] Risk estimates are derived U.S. EPA 1983 Tables 6-1 and 6-2

Some studies of risks to human health from uranium mills have been conducted in the last several years (Boice et al 2007; Pinkerton et al 2004; Boice et al 2003). The authors reported no increases in mortality to some statistically significant increases in mortality for some diseases. However, all three studies share problems of limited size and control for confounding factors, such as lack of smoking data, specific exposure data, and population migration. Thus, the results of the studies are uninformative about the potential risks from uranium mills.

Additional Risks to Workers

Mill workers, beyond the six pathways described above, experience added risks associated with accidents inside the milling facility. The hazards due to chemical spills inside the plant exist, but may be minor relative to potential radiological accident scenarios.

At acid leaching mills, sulfuric acid is present. Though the acid is corrosive to the skin and eyes, the leaching process is carried out at atmospheric pressure, and the risk of workers coming into contact with a spray during a pipe failure is not plausible. If there were a fire coupled with the release of sulfuric acid, then the inhalation of acid aerosols and sulfur dioxide could result in severe irritation of the eyes, mucous membranes, and respiratory tract. In addition to sulfuric acid, ammonia is often added to help control the pH level during the uranium precipitation phase. It is likely that this ammonia would be under significant pressure, creating the risk of a spray, in the event of a pipe failure, that poses a risk to the skin and eyes of any nearby worker. The ammonia would also quickly evaporate, adding an inhalation hazard if the accident occurred in a poorly ventilated area.

The radiological hazards associated with milling work potentially involve the yellowcake product in a dangerous respirable form. The two most notable accident scenarios are a thickener tank failure where the yellowcake slurry is spilled to the floor and allowed to dry, or a yellowcake dryer accident. Inhalation of the yellowcake particulates is a significant inhalation hazard, because of the presence of U_3O_8 in the cake. The reader is referred to Appendix III: Risks Associated with *In Situ* Leaching [see section (ii) Radiological Hazards] for a more detailed description of operational accidents in the milling facility, specifically those involving yellowcake.

In the NRC report (U.S. NRC 1980), it was calculated that the committed annual dose to a worker at a conventional milling facility ranges from 2.0 rem to the bone up to 7.1 rem to the lung. These annual doses would result in an effective dose equivalent of 240 mrem to the bone marrow (red) and 60 mrem to the bone surface and lung. Any exposures accrued because of accidental exposure to yellowcake would be in addition to this. This information is summarized in Table AVI-3 found at the end of the document. A study by Pinkerton et al (2004) reported mixed results in a study of a cohort of uranium mill workers, but concluded that for several limiting factors, such as small cohort size, they could not make “firm conclusions about the relation of the observed excesses in mortality.”

Summary

The primary hazard associated with conventional uranium milling operations is the high level of radioactive contamination contained in the mill tailings (waste products). The decay progeny of uranium are the most significant of these radioactive contaminants, including radium and radon-222, which readily moves through the interstitial spaces of the tailing pile and is released to the atmosphere. Once inhaled, radon and its decay progeny can cause significant damage to the lung via alpha radiation. Other radiological hazards include direct gamma exposure from the tailings pile and the inhalation of any dust resuspended by wind. These hazards are typically mitigated through the use of a suitable cover over the tailing to reduce the radon released to the atmosphere and attenuate direct gamma exposure. A suitable cover can also eliminate the risks associated with the suspension of dust in the air.

Ground seepage of chemically hazardous constituents of tailings piles has been known historically to contaminate nearby aquifers. Modern milling facilities often employ a liner beneath tailings piles to prevent any ground seepage and subsequent groundwater contamination. The NRC concluded that 95% of the possible contamination would happen while the mill was operating, and that the threat was mainly from toxic elements such as arsenic, not the radioactive constituents of the pile.

As with any industrial facility, safe management practices are critical to the safe operation of uranium mills. Catastrophic accidents, such as a dam failure, have the potential to release large quantities of tailings, resulting in the contamination of local water supplies and the residential population. The improper use of mill tailings as a building material can also pose a severe radiological risk to private individuals, particularly in tribal communities. Accidents occurring within the milling facility could expose workers to chemical risks, and radiological risks from contact with or inhalation of uranium yellowcake.

Table AIV-3: Results of the 1980 NRC Model Uranium Mill Study – Committed Dose Values

From: U.S. NRC (1980)

Receptor	Dose Commitment[a] (mrem)			Risk from Mill as Percentage of Risk Due to Background (%) [b,c]
	Whole Body	**Bone**	**Lung**	
Nearby Individual[d]				
Annual 40 CFR 190 doses (excluding radon)				
1 mill	3	45	30	--
Mill cluster	4	51	36	--
Total Dose (including radon)				
1 mill	9.7	51	220	25
Mill Cluster	13	61	340	38
Average Individual[e]				
1 mill	0.061	0.50	1.6	0.19
Mill Cluster	0.66	5.8	16	1.9
Average Worker[f]				
Annual	450	2000	7100	800
Career[g]	2.1×10^4	9.3×10^4	3.3×10^5	800
Background	143	250	704	--

[a] All doses shown are total annual 15th-year dose commitments except where noted as being those covered by 40 CFR 190 limits.

[b] The range in risks due to uncertainties in health effects models extends from about one-half to two times the central value. This range does not include uncertainties in other areas (e.g. source term estimates and dose assessment models).

[c] Risk comparisons are presented for exposure received during entire mill life; that is, 15 years of exposure during operation of the mill, and 5 years of post-operation exposure while tailings are drying out, are considered. This value is greater than that from annual exposures presented because tailings dust releases increase in the period when tailings are drying.

[d] The "nearby individual" occupies a permanent residence at a reference location about 2 km downwind of the tailings pile.

[e] The "average individual" exposure is determined by dividing the total population exposure in the model region by its population total.

[f] The "average worker" exposure is determined by averaging exposures expected at the various locations in the typical mill.

[g] The career dose is based on a person who has worked 47 years in the milling industry (that is, from ages 18 to 65).

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