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A study of radon regulation and pathology as it relates to underground hardrock mining

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ABSTRACT: Radon progeny have been a health and safety concern for miners since the mining of radioactive minerals began. Through the "nuclear age", it has become better understood and the regulations have become more robust. Ventilation and control practices have improved, thus reducing miners' exposures. This paper provides an overview of radon in mining, the progress of the regulations, and discusses some of the uranium miner studies that contributed to the knowledge of the pathology of radon.

1 Introduction

Radon was first found as a cause of cancer in underground uranium miners in 1924. Since that time, many studies have been performed outlining the risks of radon to miners, and to the rest of the populace. The risks were well-documented, though in the early years of the "nuclear age," the federal government was reluctant to limit concentrations of radon in mine air. This, even though limits were set by various governing bodies in uranium processing facilities, mills, and other nuclear facilities. In 1967, the Secretary of Labor finally limited radon concentrations in underground uranium mines, and the 1977 Mine Act set radon limits in all US underground hardrock mines.

The U.S. Surgeon General states that 20,000 Americans die from radon-related lung cancer every year. The increasing demand for uranium, restart of American uranium mines, and continued measurement of radon levels and worker exposure in iron, molybdenum, tin, and other underground mines keeps this an issue. [USSG, 2005]

Table 1: Radon and Radiation Unit Conversions

3.7×10^{10} Becquerel (Bq) 1 Bq = 1 disintegration per sec	1 Curie (Ci) 27 pCi
37 Bq/m^3 1 Working Level (WL)	1 pCi/l 100 pCi/l ^{222}Rn
1 Seivert (Sv) 1 mSv	100 Rem 100 mrem

1.1 Review of Ionizing Radiation

The four radiation types are alpha particles (α), beta particles (β), gamma radiation (γ), and x-rays.

Alpha particles consist of two protons and two neutrons, identical to a helium nucleus, and have a +2 charge. They do not travel far in air before picking up free electrons and turning into helium. Alpha particles cannot penetrate the skin, but are extremely damaging to organs when inhaled or ingested.

Beta particles are equivalent to electrons, but originate in the atomic nucleus. They have a -1 charge. They are not radioactive themselves, but their energy breaks chemical bonds and forms ions, and can harm living cells.

Gamma radiation consists of high energy electromagnetic waves emitted from the nucleus of unstable atoms. The gamma rays transfer energy to atomic particles, which can then interact with tissues to form ions. Because gamma radiation penetrates further than Alpha and Beta radiation, this damage occurs further into the body.

X-rays are another form of electromagnetic energy, with similar hazards as gamma rays. They originate in the electron fields of atoms, however.

It is worth noting that the average American receives approximately 300 mrem of radiation per year from various sources. These included natural background radiation, solar, radon, and manmade radiation like dental x-rays.

Table 2: Some Radiation Exposure Limits

	Occupational	Public/Non-Radworker
ICRP (UN) recommended	20 mSv (2 Rem) per year, averaged over 5 years	1 mSv (100 mrem) per year
MSHA	50 mSv (5 Rem) per year	
DOE	50 mSv (5 Rem) per year	10 mSv (1 Rem) per year

2 Historical Background

2.1 Radon – Pre-WWII

Radon and its daughter decay products were first recognized as a part of the uranium series of elements in 1904. However, as early as the 1400's underground uranium miners in Germany and Czechoslovakia died early in life of a mysterious disease. In 1879 this disease was identified as lung cancer. It wasn't until 1924 that measurements of mine air began for radon, and found a correlation between areas of high radon and areas of high cancer incidence in mines. In 1932 lung cancer was designated a compensable occupational disease in Germany and Czechoslovakia.

The first standard for radon was issued in the US in 1942 by a committee headed by Dr. Robley Evans. The standard (10-11 Curies per liter) was based on Dr. Evans' research on radium dial painters and radium therapy patients. [ACHRE, 1995]

2.2 Post-WWII in the U.S.

The Atomic Energy Act of 1946 made the U.S. Atomic Energy Commission the sole purchaser of uranium ore. The AEC publicly announced a guaranteed price for Uranium in 1948, and the rush to the Colorado Plateau was on. A survey of Colorado Plateau mines later in 1948 found high levels of radon in the uranium mines – 100 mrem per hour exposure. This report was leaked to the Denver Post in 1949.

It was recognized that exposures in American uranium mines were high, but in 1946 the mines were not as deep as those in Europe. Miners were transient, much like contract miners today, and they did not work long hours. The role of radioactive polonium, bismuth, and lead, the decay products of radon, was not understood. Calculation of the dose of radiation due to radon in European mines did not seem high enough to cause cancer.

Two university scientists, one from the AEC, found in 1951 that radioactive particles attached to dust and remained in the lungs. When the doses to European miners were recalculated, they increased 76 times – indicating the importance of radon daughters, and explaining the observed cancer rates.

In 1950-51 samples were taken in 48 Colorado Plateau uranium mines. The samples produced an average reading of 3100 pCi/l, over 300 times the established maximum concentration of 10 pCi/l that had been adopted by the National Bureau of Standards Committee on Radiation Protection.

The PHS (Public Health Service) noted in 1951 that data from German mines demonstrated that an average of 1500 pCi/l of radon coincided with a "definite pathology of 1% per year lung carcinoma attack rate and 50-70% of the workers' deaths from a primary cancer in the upper respiratory system."

In 1952, the PHS recommended a 100 picocurie per liter (pCi/l) concentration for RaA (Polonium-218) and RaC (Bismuth-214) as a working level for uranium mines. The PHS stated that this level resulted in approximately 25 – 575 rem (0.25 – 5.75 Sv) per year of alpha radiation exposure, which was under the 2000 rem (20 Sv) per year that PHS believed would definitely cause damage to lung tissue. [ACHRE] This was the first regulatory definition of a "Working Level" in the U.S., and seemed to conflict with the definitions set by 1955, 1956, and 1967 regulations.

Table 3: Uranium Decay Series

Isotope	Half-life
Uranium-238	4.5x109 years
Thorium-235	24.1 days
Protactinium-234	1.18 minutes
Uranium-234	250,000 years
Thorium-230	75,000 years
Radium-226	1,600 years
Radon-222	3.82 days
Polonium-218 (RaA)	3.1 minutes
Lead-214 (RaB)	26.8 minutes
Bismuth-214 (RaC1)	19.7 minutes
Polonium-214 (RaC2)	164 microseconds
Lead-210	22.3 years
Bismuth-210	5.01 days
Polonium-210	138 days
Lead-206	Stable

Table 4: Radon Decay Series

Isotope	Decay Mode	Half Life	MeV	Product of Decay
Rn 222	α	3.82 days	5.59	Po 218
Po 218	α 99.98 % β- 0.02 %	3.10 min	6.615 0.265	Pb 214 At 218
At 218	α 99.90 % β- 0.10 %	1.5 sec	6.874 2.883	Bi 214 Rn 218
Rn 218	α	35 msec	7.263	Po 214
Pb 214	β-	26.8 min	1.024	Bi 214
Bi 214	β- 99.98 % α 0.02 %	19.9 min	3.272 5.617	Po 214 Tl 210
Po 214	α	0.16 msec	7.883	Pb 210

2.3 The Push to Regulate

In 1955 the U.S. Bureau of Mines issued a bulletin discussing Kerr-McGee's uranium operations on the Colorado Plateau. This publication discussed ventilation techniques, the 1952 PHS study, a limit of 100 pCi/l radon gas per liter of air, and problems with radon in air and water.

Also in 1955, the State of Utah Industrial Commission issued a regulation limiting the radon concentration in mine air to "300 pCi/l of radon daughters in 1956." The State of Colorado issued a similar regulation, setting a standard of "100 pCi/l for each of the alpha decay products." [ACHRE, 1995]

It should be mentioned here that the sum of the energies of 100 pCi/l of each of the three progenies would result in 1 Working Level (WL). The energy from 973 pCi/l of RaA, or from 197 pCi/l of RaB, or from 268 pCi/l of RaC would also be equivalent to 1 WL. These conditions rarely, if ever, exist in the field, however.

Concentrations in mines are a mix of these progeny, with one study finding that an average concentration among mines of 224 pCi/l RaA, 102 pCi/l RaB, and 67 pCi/l RaC resulted in 1 WL. [Borak, 1982]

In 1958, Union Carbide adopted a 10 WL shutdown limit after performing extensive sampling in its mines. The company lowered this standard to 5 WL in 1962. The State of Colorado implemented a similar shutdown limit of 10 WL in 1961, and later lowered it to 3 WL in 1963. Presumably this was in addition to the 100 pCi/l per decay product standard that Colorado issued in 1955.

By 1967, Secretary of Labor Willard Wirtz had admitted that it was apparent to him that the Federal Radiation Council (FRC) would not agree on a recommendation for acceptable levels of radon in the uranium mines. Secretary Wirtz used the 1936 Walsh-Healy Act, which provided for the regulation of safety and health conditions under government contracts, as the basis for establishment of radon protection in the uranium mines.

Secretary Wirtz testified that the basis for his standard of 0.3 WL for uranium mines was the "...widely held view that this represents the maximum level of radioactive material to which a person can be exposed without creating some appreciable increased hazard of lung cancer." [ACHRE, 1995]

The Federal Mine Safety & Health Act of 1977 established the Mine Safety and Health Administration (MSHA), and with it federal governance, backed by the Code of Federal Regulations, of radon in all underground hard rock mines.

3 Statutory Limits on Radon

3.1 Sampling

30 CFR 57.5037(a) requires all underground hardrock mines to take at least one radon sample in exhaust air to verify the absence of radon in the mine. This sampling must be performed by a “competent person.”

30 CFR 57.5037(a) also dictates sampling be performed based on Section 14.3 of ANSI Standard N13.8-1973 – "American National Standard Radiation Protection in Uranium Mines," which was approved on July 18, 1973. However, this standard has been withdrawn by the Health Physics Society, which oversees the N13 series of ANSI standards. [ANSI, 2006]

Where uranium is mined, 30 CFR 57.5037 requires bi-weekly sampling in active working areas when levels are between 0.1 and 0.3 WL. When levels are above 0.3 WL, sampling is required weekly. If levels are found to be less than 0.1 WL in exhaust air, at least one sample is required monthly.

30 CFR 57.5037 requires quarterly radon sampling in non-uranium hard rock mines in active working areas when levels are between 0.1 and 0.3 WL, and weekly sampling when radon levels are above 0.3 WL. If levels are found to be less than 0.1 WL in exhaust air, no further sampling is required. Regular work activities are not permitted in areas containing 1.0 WL or more.

3.2 Exposure Limits

The 30 CFR 57.5038 limits a miner’s annual exposure to 4 WLM (working level months). This corresponds to an average concentration of 0.333 WL, working 170 hours per month or 2,040 hours per year.

The maximum exposure allowed in active workings is 1.0 WL, as set by 30 CFR 57.5039. Inactive workings with concentrations above 1.0 WL are to be posted against entry by unauthorized personnel and required approved respirators for entry.

30 CFR 57.5042 revises the permissible exposure limits. “If levels of permissible exposures to concentrations of radon daughters different from those prescribed in 57.5038 are recommended by the Environmental Protection Agency and approved by the President, no employee shall be permitted to receive exposures in excess of those levels after the effective dates established by the Agency.” Presently, the EPA does not regulate radon exposure in underground mining. The EPA action level for airborne radon in homes is 4 pCi/l. [EPA, 1993]

The Ontario (Canada) Occupational Health and Safety Act – RRO 1990, Reg. 854, removes workers from an area in a uranium mine if concentrations exceed 0.33 WL. A written description of work practices and remediation plans is required when concentrations exceed 0.1 WL. These are more restrictive than U.S. MSHA regulations.

4 Exposure and Health Effects

4.1 BEIR Committee Reports

The National Research Council issued a number of studies known as the Biological Effects of Ionizing Radiation (BEIR). The fourth and six in the series of theses reports covered radon and its effects and are known, respectively, as BEIR IV and BEIR VI. These studies consolidated data on uranium miners from around the world, as well as other published research on radon and its effects. The purpose was to develop a risk model for radon in homes.

The reports drew on 11 studies of underground miners, totaling about 68,000 people. Data from these studies is summarized in Table 5 and Table 6. Of the 68,000 miners 2,700 had died of lung cancer as of the 1999 publishing of the BEIR VI report. BEIR VI derived a model for predicting risk of lung cancer from radon exposure. It is linear with respect to past exposure.

Equation 1:

$$ERR = \beta\left(w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+}\right)\phi_{age}\gamma_z$$

Where:

ERR = Excess Relative Risk

β = slope of the exposure-risk relationship

Table 5: Summary of Uranium Miner Pathology Studies. [BEIR VI]

Study	Number of workers	Number of person-years	Number of lung-cancers	Mean WLM[a]	Mean duration	Mean WL[a]	Weighted mean WL[b]
China	13,649	134,842	936	286	12.9	1.7	2.3
Czechoslovakia	4,320	102,650	701	196.8	6.7	2.8	4.2
Colorado[c]	3,347	79,556	334	578.6	3.9	11.7	17
Ontario	21,346	300,608	285	31	3	0.9	1.6
Newfoundland	1,751	33,795	112	388.4	4.8	4.9	12.2
Sweden	1,294	32,452	79	80.6	18.2	0.4	0.4
New Mexico	3,457	46,800	68	110.9	5.6	1.6	5.7
Beaverlodge	6,895	67,080	56	21.2	1.7	1.3	2.5
Port Radium	1,420	31,454	39	243	1.2	14.9	33.4
Radium Hill	1,457	24,138	31	7.6	1.1	0.7	1
France	1,769	39,172	45	59.4	7.2	0.8	2.6
Total[d]	60,606	888,906	2,674	164.4	5.7	2.9	10.8

a Weighted by person-years; includes 5-year lag interval.

b Weighted by WLM received at each exposure rate.

c Exposure limited to < 3,200 WLM.

d Totals adjusted for miners and lung-cancers that were included in both the Colorado and New Mexico Studies.

w = exposure during various windows (years), in WLM
θ = the relative effect of exposure of a time period
ϕ – accounts for declining risk with older age of first exposure
γ = average exposure

The reports' analysis found that 15,000 to 21,000 of the 157,000 lung-cancer deaths in the US each year are likely radon-related. However, due to various uncertainties, the number could be as low as 3,000 or as high as 33,000 per year. Most of the radon-related deaths occur among smokers, due to the synergistic effect between smoking and radon progeny. [BEIR VI]

The BEIR reports note that the majority of lives saved by reducing radon concentrations would be among smokers. They also note that most of the radon-related deaths would not have occurred if the victims had not smoked. A final conclusion is that lung cancer due to both factors is preventable and can be reduced.

4.2 Colorado Plateau Studies

Mining of uranium expanded rapidly on the Colorado Plateau – Colorado, Utah, Arizona, and New Mexico – in the late 1940's and continued until the 1970's, and the early 1990's in New Mexico. This group of miners had high exposures as many of the mines were small and unventilated, especially early on. Monitoring of mines for radon began in 1951.

Various studies of the Colorado Plateau uranium miners were undertaken in the 1960's, and some continue to this day. A group of 3,347 Colorado miners averaged 579 WLM (working level months) cumulative exposure – an average exposure of 11.7 WL. By 1990, 410 of these miners had died of lung cancer. In a normal group of miners this size, 75 lung cancer deaths would have been expected. One study group of New Mexico 3,457 uranium miners averaged 110 WLM cumulative exposure. A smaller group of 89 New Mexico miners averaged 761 WLM.

The Colorado study group had the highest average exposure of the various uranium miner studies. The group also had one of the highest lung cancer incidence rates – roughly 10%.

4.3 Other Miner Studies

The other nine cohorts had a variety of exposures. The most interesting, perhaps, was the Swedish cohort – iron miners working north of the Arctic Circle. This group had average exposure below 0.4 WL, but for an average of 18 years, an exposure rate of about 81 WLM. This cohort had a cancer mortality rate of 6%. A group of miners from Newfoundland also had a mortality rate of 6%, but with a much higher mean exposure – 4.9 WL and 388 WLM.

Three cohorts with mortality rates higher than 6% had average exposure rates over 195 WLM over a career.

The average exposure of 162 WLM over 5 years estimated for the pooled miner data would result in 1-5 alpha particles traversing each cell nucleus in bronchia over this time. An exposure of 5-20 WLM would result in an extremely low probability that any cell would be traversed by more that one alpha particle.

The eleven miner studies provide strong evidence that there is no material risk of cancers other than lung cancer from exposure to radon.

Table 6: Summary of Exposures below 0.5 WL in Uranium Miner Pathology Studies. [BEIR VI]

Study	Number of person-years	Number of lung-cancers	Mean WLM[a]	Mean duration	Mean WL[a]	Weighted mean WL[b]
China	1,106	9	35.6	9.6	0.31	0.38
Czechoslovakia	33	0	n/a	n/a	n/a	n/a
Colorado	291	0	n/a	n/a	n/a	n/a
Ontario	87,670	100	10.7	4.4	0.22	0.32
Newfoundland	7,362	8	8.4	4.1	0.16	0.28
Sweden	30,646	78	79.4	18.2	0.37	0.41
New Mexico	11,710	3	11.6	3.9	0.22	0.34
Beaverlodge	27,692	13	3.5	1.3	0.36	0.3
Port Radium	103	0	n/a	n/a	n/a	n/a
Radium Hill	8,781	16	7.9	1.7	0.39	0.41
France	23,720	24	25.2	7.6	0.25	0.36
Total[d]	198,720	251	21.1	6.3	0.27	0.39

[a] Weighted by person-years; includes 5-year lag interval.

[b] Weighted by WLM received at each exposure rate.

[c] There were no lung-cancers and very few person-years in the Czechoslovakia, Colorado, and Port Radium cohorts with average exposure rates < 0.5 WL, so means are not presented for these cohorts.

[d] Totals adjusted for miners and lung-cancers that were included in both the Colorado and New Mexico studies.

4.4 Recent Exposure Data

In countries where data were available, concentrations of radon daughters in underground mines are now typically less than 27-28 pCi/l. Modern uranium mines in Saskatchewan, Canada generally maintain concentrations below 0.10 WL in the working areas. Working areas in the Henderson molybdenum mine in Colorado have generally averaged 0.10 to 0.15 WL since 2000.

5 Summary and Conclusion

Radon has been a health and safety issue for miners since the mining of radioactive minerals began. The health risk is significant, according to many sources, and is well-studied. The underground mining of uranium and other radon-emitting ores continues today. This poses challenges for ventilation engineers, mine engineers, and industrial hygiene practitioners. Improvements to ventilation practices and regulations since the beginning of the "nuclear age" have reduced exposure and radon concentration in mines. The work to further improve our understanding and reduce exposures underground continues.

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