Occupational Health Clinics for Ontario Workers Inc.
Centres de santé des travailleurs (ses) de l'Ontario Inc.

Northern Region - Sudbury Clinic
84 Cedar Street, 2nd Floor
Sudbury, ON, P3E 1A5
Tel: (705) 523-2330
Fax: (705) 523-2606
1-877-817-0336
sudbury@ohcow.on.ca

Radiation (Radon) in Ontario Uranium Mines
WSIB Policy, Exposure Data and Risk of Lung Cancer

Last updated: October 1, 2019

Prepared by:

Paul Sampara, BSc., DOHS, MEng, ROH
Occupational Hygiene Consultant
OHCOW

Medical review by:

Dr. L. Christine Oliver, MD, MPH, MS, FACPM
Medical Consultant
OHCOW

Occupational hygiene review by:

Martin Albinger,
Occupational Hygiene Consultant
OHCOW

Editorial Review by:

Janice Martell,
Occupational Health Coordinator
OHCOW

Table of Contents

Executive Summary

- Uranium mining began in Ontario in the mid-1950s and cases of lung cancer among uranium miners began to be reported in the early 1970s.
- Beginning in the late 1960s and early 1970s some early epidemiological evidence suggested that uranium miners had an increased risk of lung cancer from exposure to radon.
- The first WCB/WSIB policy for lung cancer among uranium miners was the "Guidelines for Adjudication" published in 1976 that was based on studies of Colorado uranium miners since at this time no studies had been done on Ontario uranium miners.
- The first large scale epidemiological study of Ontario uranium miners published in 1983 reported a nearly 2-fold statistically significant increased mortality for lung cancer.
- In 1989 the Industrial Disease Standards Panel (IDSP) published a report that included findings, recommendations and proposed eligibility criteria for acceptance of claims for lung cancer from uranium miners. These were largely based on the Report of the Special Panel commissioned by the IDSP to reanalyze the 1983 study and on the findings of the 1988 Biological Effect of Ionizing Radiation (BEIR) IV Report.
- Based on information from the 1983 study and the 1989 IDSP report, substantive changes were made to the previous policy and Policy 16-02-04 was published by the WCB in 1999. This was meant to be an interim policy until further analysis of the Ontario mining industry was completed. There was considerable uncertainty and disagreement on how the exposure and epidemiological data was being translated into compensation policy. However, this policy has remained unchanged since 1999 except for a change in policy number in 2004 to Policy 23-02-03 which is still the current policy.
- Historical radon exposure information and how the radon exposure data was used to estimate lung cancer risks is provided in some of the studies and reports that formed the basis for the WSIB policy.
- Information on radon exposures for individual Ontario miners is provided in the Mining Master File (MMF) records and the National Dose Registry (NDR), with the NDR usually providing more complete information. Company mining records are another source for radon exposures in specific mines and for specific uranium miners; however, this information is usually only available to the WSIB. There is also limited published information on the historical exposures in Ontario uranium mines.
- The 2015 Occupational Cancer Research Centre (OCRC) update of the Ontario Uranium Mining Cohort included a detailed analysis of the sources of uncertainty related to radon exposure assessment. The OCRC report estimated that the total uncertainty in radon measurements made from 1958 to 1967 ranged from 53% to 66% and measurements made from 1968 to 1996 had a total uncertainty ranging from 31% to 38%.

- A greater understanding of the risk of lung cancer from exposure to radon over the years has resulted in a progressive reduction of the Ontario Ministry of Labour (MOL) occupational exposure limit (OEL) from 12 WLM/year in 1967 to the current MOL OEL of 1 WLM/year. When compared to the current OEL of 1 WLM, many historical exposures were many times greater and would be deemed unacceptable for present-day Ontario miners.
- Significant epidemiological evidence on lung cancer risk for uranium miners has been published in the intervening 20 years since the policy was last updated. This includes the 2015 OCRC update of the Ontario Uranium Mining Cohort that added an additional 21 years of follow up to the earlier 1983 Muller report, three additional BEIR Reports and updates of several large European uranium mining cohorts.
- The OCRC 2015 update of the Ontario Uranium Mining Cohort:
    a. Confirmed that underground uranium miners have an increased risk of lung cancer. An increasing risk of lung cancer was observed with cumulative radon exposures, particularly for exposures greater than 50 WLM. The excess relative risk per 100 WLM was 0.66 for lung cancer mortality and 0.64 for lung cancer incidence.
    b. Confirmed a strong positive exposure-response relationship between exposure to radon and lung cancer incidence and mortality among miners with > 50 and > 20 working level months (WLM) of cumulative radon exposure respectively. This was consistent with the exposure-response relationship observed in recent updates of large cohorts of French and German uranium miners and in 3 independent large-scale analyses of the uranium miners. These findings reinforce the linear, no threshold model proposed by the BEIR Committee. In addition, this model predicts that the exposure to the smallest radiation dose from radon would still have the potential to cause a small increase in the risk of lung cancer in humans.
    c. Concluded that lung cancer incidence was modified by time since first exposure, time since last exposure and exposure rate[A] and lung cancer mortality was modified by attained age, time since first exposure, time since last exposure, age at first exposure and dose rate[B]. Other exposures that may affect lung cancer incidence and mortality among uranium miners include cigarette smoking, respirable crystalline silica (RCS), diesel exhaust (DE), other types of mining (i.e. gold, nickel, copper) and arsenic exposure in gold mines.
    d. Confirmed earlier findings that Ontario uranium miners who also had gold mining experience had a 20% statistically significant increased risk of lung cancer incidence and mortality compared to those with no gold mining experience.

[A] ***Exposure rate = WLM per year***
[B] ***Dose rate = duration of exposure within cumulative dose categories***

- A 2019 analysis of a joint Czech, French and Canadian uranium miners observed a statistically significant increased risk of lung cancer mortality with cumulative radon exposures > 20 WLM which is consistent with the results of the OCRC 2015 update of the Ontario uranium mining cohort.
- Many epidemiological studies over the past 30 years have observed a greater than additive but less than multiplicative interactive effect of radon and cigarette smoke on risk for lung cancer. Studies of Ontario uranium or gold miners concluded that smoking alone could not account for the observed increased risk of lung cancer.
- Findings from a recent study of a large cohort of German uranium miners showed that the combined exposure to radon and silica may have a greater risk of lung cancer than exposure to either radon or silica alone.
- Two recent papers evaluated the combined effect of exposures to radon and DE. A 2017 paper suggested that the risk of lung cancer from historical DE exposures may be a more significant contributor to the risk of lung cancer than radon exposure for the Ontario and other uranium mining cohorts considered by the BEIR committees. A 2018 paper reanalyzed the lung cancer mortality reported in the Diesel Exhaust Miners Study (DEMS) and concluded taking radon exposures into account resulted in substantially weaker associations between cumulative and average DE exposures and lung cancer mortality.
- Gold mining in Ontario has been a major source of arsenic exposure. A 1993 update of the Ontario Uranium Mining Cohort concluded that uranium miners who also mined gold had an increased risk of lung cancer mortality that was associated with exposure to arsenic. For uranium miners with radon exposures < 40 WLM, the rate of lung cancer increased in a linear fashion; however, for uranium miners who also mined gold, and were exposed to radon > 40 WLM, lung cancer mortality was observed to increase at a faster rate as exposures to arsenic increased.
- It may be concluded that the current radiation exposure indices in the WSIB Policy 23-02-03 "Lung Cancer Among Workers in the Uranium Mining Industry" are based on outdated epidemiological information resulting in inconsistent interpretation and application of the policy for compensating lung cancer claims for Ontario uranium miners.

Introduction

The purpose of this document is to summarize the development of the current WSIB Policy 23-02-03 "Lung Cancer Among Workers in the Uranium Mining Industry"[1]. This document also summarizes the epidemiological studies on the risk of lung cancer from radon exposure in Ontario uranium mines and describes how exposure to radon was determined for the studies that provided the basis for the WSIB policy. This historical exposure data is useful for estimating Ontario uranium miners' exposures for compensation purposes.

This document begins with a chronology of the WSIB uranium mining guidelines and policies. This is followed by a summary of two major reports that influenced the development of the policy; the 1989 Industrial Disease Standards Panel (IDSP) Report and the 1988 Biological Effects of Ionizing Radiation (BEIR) Report IV. A discussion of the historical radon exposure data for Ontario uranium miners is provided followed by a summary of the epidemiological studies on the risk of lung cancer associated with radon exposure in Ontario uranium mines.

Chronology of the WSIB Uranium Mining Policy and significant reports and studies that influenced its development

The following is a brief chronology of the present WSIB Policy 23-02-03 "Lung Cancer Among Workers in the Uranium Mining Industry" and the significant reports and studies that influenced its development. WCB/WSIB guidelines or policies are in bold italics and a more detailed summary is provided in Table 1.

1974 A pilot mortality study "Causes of death in Ontario uranium miners" carried out by the Ministry of Labour reported a greater than 3-fold statistically significant increased risk of lung cancer among 8,649 uranium miners [SMR=3.13 (2.75-4.26)].[2] This led to the establishment of the Ontario Uranium Mining Cohort that has continued to be follow-up to the present.

January 1976 Up to this time, the WCB (Workmens Compensation Board) [C] had accepted 15 lung cancer claims from uranium miners in Elliot Lake (12 claims) and the Bancroft area (3 claims) where uranium mining had started in the mid 1950s.

April 1976 ***an internal guideline was developed by the WCB based on the 1974 Muller pilot study[2] findings and studies of Colorado uranium miners (no large-scale epidemiological studies had been made of Ontario uranium miners).***

June 30, 1976 Report of the Royal Commission on the Health and Safety of Workers in Mines (Ham Commission).[3] This report included an assessment of the exposure of uranium miners to radiation and made recommendations for improvements in monitoring exposures, exposure limits, ventilation and other exposure control measures. It is generally recognized that

[C] *The Workers Compensation Board (WCB) was renamed the Workplace Safety and Insurance Board in 1998* this report raised awareness of the occupational health hazards of working in Ontario mines and was instrumental in the reduction of radiation and silica exposures for miners.

August 1979 *WCB Board of Directors (BoD) approved a revised guideline outlining eight factors that would be considered for lung cancer claims with a latency period of at least 10 years.*

1983 Muller et al report; "**Study of mortality of Ontario miners 1955-1977, Part I"[4]** This study of nearly 16,000 miners in the Ontario Uranium Mining Cohort that were followed from 1955 to 1977, reported a nearly 2-fold statistically significant increased risk of lung cancer among Ontario uranium miners [SMR=1.81 (1.50-2.14)].

February 1986 The WCB requested the Industrial Disease Standards Panel (IDSP) to review the 1979 guideline and make recommendations for any changes

1988 Biological Effects of Ionizing Radiation (BEIR) IV Report "Health Effects of Radon and other Internally Deposited Alpha Emitters"[5] [D] published by the National Research Council in the US reviewed the epidemiological evidence for lung cancer in uranium miners in 4 cohorts of uranium miners including the Ontario Uranium Mining Cohort.

1988 "Report of the Special Panel on the Ontario Uranium Mining Industry". This report was requested by the IDSP and was attached as Appendix B to the 1989 IDSP report. This was a re-analysis of the Muller 1983 report by McMaster University researchers.

1989 "Factors modifying lung cancer risk in Ontario uranium miners, 1955-1981" paper by Muller et al. This study extended the follow-up period of the 1983 study by four years (1955-1981) and found a statistically significant increased risk of lung cancer among nearly 15,000 uranium miners [SMR=1.70 (1.46-1.97)].[6]

February 1989 IDSP "Report to the Workers' Compensation Board on the Ontario Uranium Mining Industry".[7E] The IDSP report made recommendations and outlined eligibility rules for the adjudication of claims from Ontario uranium miners. Three members of the IDSP dissented and provide alternative criteria for adjudicating WCB claims from uranium miners.

[D] The Committee on the Biological Effects of Ionizing Radiation (BEIR) is a committee of the National Research Council in the USA that publishes a series of reports informing the US government on the effects of ionizing radiation. The main focus of BIER is to analyze the available epidemiological and scientific literature on ionizing radiation and potential risks and health effects on the general population. The general approach has been to use data from more highly exposed occupational exposure such as underground mining and extrapolate to the lower doses that would be experienced by the general population (residential radon exposures). The BEIR IV Report published in 1988 included analysis of 4 principal studies of radon-exposed miners; Ontario uranium miners, Saskatchewan uranium miners, Colorado Plateau uranium miners and Swedish metal miners – and risk models for lung cancer were developed.

[E] *The Industrial Disease Standards Panel (IDSP) that transitioned into the Occupational Disease Panel (ODP) was created in 1986 under the Workers' Compensation Act of Ontario. The IDSP/ODP was created to be independent of the WCB with the authority to collect expert evidence on specific occupational diseases and to provide an open forum for the development of adjudicative guidelines. The ODP was disbanded in 1998. Between 1986 and 1998 the IDSP/ODP published 20 reports and numerous other publications on issues relating to workplace/occupational diseases and their compensation.*

November 1989 ***WCB BoD rescinded the April 1976 internal guidelines and published WCB Policy 04-04-10 "Lung Cancer and Radon Progeny Exposure" that incorporated the August 1979 guidelines.***

1993 "Mortality from Lung Cancer in Uranium Miners" paper by Kusiak et al.[8] This analysis of the Ontario Uranium Mining Cohort found a greater than 2-fold statistically significant increased risk of lung cancer associated with exposure to radon [SMR=2.25 (1.91-2.64)].

June 1999 ***WSIB Policy 16-02-04 "Lung Cancer Among Workers in the Uranium Mining Industry" was published on June 15, 1999 [BoD Minute #5(e) January 28, 1999, pg. 6133] and replaced the previous Policy 04-04-10****. Substantive changes to the previous policy were based primarily on information from the 1983 and 1989 Muller studies [4,6], the 1988 BEIR IV report[5] and recommendations in the 1989 IDSP report[7] (that included the findings of the 1988 Special Panel report) and the 1993 paper by Kusiak et al[8].* ***This was intended to be an interim policy until further analysis of Ontario miners was completed.***

October 12, 2004 Policy 23-02-03 Lung Cancer Among Workers in the Uranium Mining Industry replaced the June 1999 WSIB Policy 16-02-04 – only change was to the policy number as a result of overall OPM (Operational Policy Manual) changes.

The October 12, 2004 Policy 23-02-03 "Lung Cancer Among Workers in the Uranium Mining Industry" is reproduced in Appendix 1.

TABLE 1 Chronology of WSIB Guidelines and Policies for Lung Cancer Claims from Ontario Uranium Miners and other Workers	
Date and Title	**Basis of the guideline or policy and criteria for adjudicating lung cancer claims from uranium mines**
April 13, 1976 **Internal Guideline** **"Lung Cancer- Uranium Miners - Guidelines for Adjudication"**	The recommendations in the guideline were based on an April 28, 1975 memo from Dr. C. Stewart (WCB Chest Disease Consultant) in which he reviewed the approach to these claims since 1968 and recommended acceptance criteria based on the work of Dr. J. Muller of the Ontario Department of Health who had used findings from studies of uranium miners in Colorado that he thought could be applied to Ontario uranium miners The following recommendations were included in the guideline: • the miner worked at least 5 years underground prior to 1968[F] and the cancer is of the oat cell type • the miner worked more than 10 years underground prior to 1968 and the cancer is primarily in the lung • the accumulated radiation exposure is 120 working level months (WLM)[G] or more • claims which do not meet the above guidelines shall be individually judged on their own merits and consideration is given where it seems reasonably evident that the cancer resulted from uranium mining exposure prior to 1968 • borderline cases are to be considered on their own merits having regard for the accumulated radiation exposure and the benefit of reasonable doubt applies • the employee's work underground commenced after 1968 the case will be dealt with individually and consideration given where the radiation exposure records make it reasonably evident that the cancer resulted from uranium mining exposure
November 1989 **Policy 04-04-10 Lung Cancer - Radon and Radon Progeny Exposure** **(BoD Minute #14 August 14, 1979, pg. 4806)** **1976 Guideline rescinded**	Substantive changes from the 1976 guidelines included: • reference to WLM levels was removed as are result of more recent studies that found 120 WLM of exposure no longer represented a threshold above which one can expect an increased risk of lung cancer and below which one would not see an increased risk; Atomic Energy Control Board (AECB) was also of the opinion that use of cumulative WLM should be discouraged as it no longer indicates a threshold factor, and may give rise to misinterpretation and a false sense of security • latency period changed to at least 10 years without specifying which type of lung cancer (i.e. oat cell) • more general list of factors should be considered in lung cancer claims from uranium miners where the latency period was for at least 10 years: 1. duration of exposure 2. exposure density 3. smoking history 4. geographical location of exposure 5. age when lung cancer first appears 6. year of entry into mining 7. age at start of exposure *8.* previous underground exposure in non-uranium mining

[F] Prior to 1968 no individual exposure records were kept.
[G] A Working Level (WL) is a measure of the concentration of potential alpha particles per litre of air generated by radon gas or radon daughters. 1 WL = 130,000 or 1.3×10^5 mega electron volt (MeV) of alpha energy per litre of air. A Working Level Month (WLM) = 1 WL of exposure for 170 hrs.

TABLE 1 (cont'd) Chronology of WSIB Guidelines and Policies for Lung Cancer Claims from Ontario Uranium Miners and other Workers

Date and Title	**Basis of the guideline or policy and criteria for adjudicating lung cancer claims from uranium mines**
June 15, 1999 **Policy 16-02-04[H] "Lung Cancer Among Workers in the Uranium Mining Industry"** **BoD Minute #5(e) January 28, 1999, pg. 6133]** **replaced previous Policy 04-04-10**	Substantive changes from previous policy were based on more recent epidemiological evidence available in the 10 years since Policy 04-04-10 was published. This included the findings and recommendations of the 1989 IDSP (Industrial Disease Standards Panel) Report on the Ontario Uranium Mining Industry (IDSP report #6)[1]. The IDSP recommendations were based on the 1988 Report of the Special Panel on the Ontario Uranium Mining Industry that was a re-analysis of the 1983 Muller report prepared for the Ontario Ministry of Labour, and the Ontario Workers' Compensation Board[7] and the 1988 Biological Effects of Ionizing Radiation (BEIR) IV Report "Health Effects of Radon and other Internally Deposited Alpha Emitters"[5] [I]. Substantive changes to the policy included: ○ reverting back to using WLM as criteria for cumulative exposure to radiation in uranium mines based on BEIR IV and IDSP report ○ introducing age at diagnosis and cumulative exposure (WLM) criteria to estimate risk of lung cancer. (BEIR IV report was considered as the most reliable source of information since it included Ontario mining data, which made up half the person-years, but also included data from three other large cohorts) ○ although not explicitly stated in the policy, the latency was effectively reduced from 10 years in the previous policy (04-04-10) to 5 years based on the BEIR IV criteria The revised policy 16-02-04 included the following guidelines for entitlement: Among those who have sustained occupational radiation exposure in Ontario mines, the following can provide persuasive evidence that the worker's cancer of the trachea, bronchus or lung (ISCD9 162; ISCD10 C33, C34)[J] is work-related • a radiation index[K] of at least 33 for workers diagnosed with these cancers before 55 years of age • a radiation index of at least 40 for workers diagnosed with these cancers between 55 and 64 years of age • a radiation index of at least 100 for workers diagnosed with these cancers at 65 years of age or older. **This was intended to be an interim policy until further analysis of Ontario miners was completed (e.g. additional analysis by the IDSP).**
October 12, 2004 **Policy 23-02-03 Lung Cancer Among Workers in the Uranium Mining Industry** **(BoD Minute #8, June 10, 2004, pg. 6622)** **replaced** **Policy 16-02-04**	only change was the policy number as result of overall OPM (Operational Policy Manual) changes **Therefore, this policy is the same as the one published in 1999 and has not been updated since then.**

[H] The revised policy also addressed two other issues: it clarified that uranium mill workers would also be included in the policy, not just underground miners (mill workers included in 'dusty mining jobs" code 11 listed in "Lung Cancer – Gold Miners" Policy 04-04-08) and took into account uranium mining industry workers who also worked in gold mines and were exposed to radiation.

[I] Committee on the Biological Effects of Ionizing Radiation (BEIR); a committee of the National Research Council of the USA which publishes a series of reports informing the US government on the effects of ionizing radiation. The main focus of BIER is to analyze the available epidemiological and scientific literature on ionizing radiation and potential risks and health effects on the general population. The general approach has been to use data from more highly exposed occupational exposure such as underground mining and extrapolate to the lower doses that would be experienced by the general population. The BEIR IV Report published in 1988 included analysis of 4 principal studies of radon exposed miners – Ontario uranium miners, Saskatchewan uranium miners, Colorado Plateau uranium miners and Swedish metal miners – and risk models for lung cancer were developed.

*[J] *International Statistical Classification of Diseases (Ninth and Tenth Revisions).*
[K] The radiation index is a time-weighted index of the worker's occupational radiation exposure measured in cumulative Working Level Months (WLM). In calculating the radiation index, all WLM sustained 5-14 years before diagnosis of the cancer and half of WLM sustained 15 or more years before the diagnosis of the cancer are cumulated. All WLM exposures sustained in Ontario employment exposures, be it in uranium mines and mills or in gold mines, are included in the calculation of the radiation index. A worker's non-smoking status can provide evidence of work-relatedness in the weighing of evidence on the individual merits and justice of the case.

Further Discussion of the current WSIB Policy 23-02-03 Lung Cancer Among Workers in the Uranium Mining Industry

As discussed previously, the current WSIB Policy is based on the findings of the 1989 BEIR IV Report[5]; however, a more recent (1999) BEIR VI report[9] was available at the time this policy was published. The BEIR VI report[9] proposed new, more complex risk assessment models describing lung cancer risk based on additional data from 7 mining cohorts from around the world in addition to the original 4 cohorts considered in BEIR IV Report. However, WSIB concluded that since the findings of the BEIR VI report generally agreed with the earlier model, the BEIR IV report would be used as the basis for the revised policy.

As stated earlier, Policy 16-02-04 was an interim policy pending additional analysis. At that time, a preliminary analysis by the WSIB showed that the pattern of lung cancer risk in Ontario miners was like the pattern in the BEIR IV report. This finding is not surprising since the Ontario mining data made up about half of the person-years in the BEIR IV report.

In 1992, the IDSP notified the WCB that they were going to reconsider the entire issue of lung cancer in uranium mining in the broader context of hard-rock mining. In 1994, the IDSP released the "Report to the Workers' Compensation Board on Lung Cancer in the Hard Rock Mining Industry" (IDSP Report #12)[10] and in 1996, the IDSP released an addendum to this report (IDSP Report #12A)[11].

BoD Minute #5(e) January 28, 1999, pg. 6133 that formed the basis for Policy 16-02-04 stated: *"A formal Board final response on the IDSP's Report on uranium mining will be published after the Board has received the new IDSP report".* Also, *"After the Board receives final reports from the Ontario Miners Study, the policy may be modified. In addition, the work of the IDSP, and subsequent comments on the IDSP report, may also indicate the need to revise this interim policy"*[L]

[L] *It appears that a follow-up report was not provided by IDSP so there has not been a final response to date from the WSIB or any further revision of the policy.*

Summary of the IDSP (Industrial Disease Standards Panel) "Report to the Workers' Compensation Board on the Ontario Uranium Mining Industry"[1]

On February 17, 1986 WCB requested the Industrial Disease Standards Panel (IDSP) to review the existing guidelines[M] for adjudicating cases of lung cancer attributable to radon. This was essentially the same as Policy 04-04-10 "Lung Cancer Radon & Radon Progeny Exposure" published November 1989 as approved by the BoD Minute #14, August 14, 1979, pg. 4806.

The IDSP commissioned a Special Panel chaired by Dr. Harry Shannon of McMaster University, to conduct an epidemiological review of the entire Ontario mining industry beginning with gold mining.

The Special Panel began its investigations into the uranium mining industry after the completion of the Panel's gold mining report ("Report on the Ontario Gold Mining Industry", IDSP Report #1, April 1987[12]). The "Report of the Special Panel on the Ontario Uranium Mining Industry" was the basis for the April 1, 1989 IDSP Report #6 "Report to the Workers' Compensation Board on the Ontario Uranium Mining Industry"[7] (the full Report of the Special Panel was appended to the IDSP Report #6).

After considering the findings of the Report of the Special Panel (RSP), the IDSP Report presented two findings, two eligibility rules and one recommendation to the WSIB. An alternative eligibility rule was proposed by three members of the Panel in a "Statement of Dissent" (dated February 22, 1989).

Findings

> ***Finding 1***: *The Panel confirms the existence of a significant excess of mortality from cancer of the trachea, bronchus and lung among Ontario uranium miners in the dusty uranium jobs that are defined by WCB Occupation codes 11-16, 21,22,25,26 and 97.*
>
> ***Finding 2***: *At this time, the Panel does not find a probable connection between any other cancers and occupational groups within the Ontario uranium mining industry.*

Eligibility Rules

> The two eligibility rules recommended by IDSP informed the rules or eligibility criteria in the WSIB Policy. The eligibility rules and the rationale used by IDSP are summarized in Table 2.

[M] *"Guideline for Adjudication Lung Cancer – Radon and Radon Daughters" approved by the BoD August 2, 1979 – in Appendix A of IDSP report #6 (reference #7)*

Table 2 Eligibility Rules Recommended in the IDSP Report #6 and the Rationale for these Rules	
Eligibility Rule	**Rationale**
<u>Eligibility Rule #1</u>*: That claims arising from cancers of the trachea, bronchus and lung among Ontario uranium miners in dusty occupations (WCB Occupation codes 11-16, 21,22,25,26,97) and meeting the following criteria be compensated:* *1. Proof of work in a dusty Ontario uranium mine;* *2. Medical evidence of a primary cancer of the trachea, bronchus or lung;* *3. Latency period of at least 10 years (between first employment in a "dusty" occupation in a uranium mine and the diagnosis of a primary lung cancer);* *4. Sufficient occupational exposure defined as a cumulative exposure to radon and its progeny of at least 40 WLM.*	The Report of the Special Panel (RSP) estimated relative and attributable risk of lung cancer for the cohort of uranium-only miners (Table 22 in the RSP) and uranium miners who also had gold mining experience (Table 23 in the RSP). The RSP reported relative risks of 1.76 per WLM for uranium-only miners and 1.63 per WLM for uranium and gold miners. The Panel concluded that to reach a doubling of risk (RR=2.0), would require on average 57 WLM of exposure for uranium-only miners and 61 WLM for uranium and gold miners. Given the uncertainties of the exposure measurements, the Panel decided that the difference between the relative risks for these two cohorts was so small as not to merit making a distinction between the two groups of miners. Therefore, uranium miners would be considered as any miner employed in a dusty uranium mining job as defined by the WSIB Dusty Mining Occupation Codes (11-16, 21,22,25,26,97). The IDSP Report stated that the recommendation for a cumulative exposure of 40 WLM would provide for some allowance for uncertainty in an individual miner's exposure to radon.

Table 2 Summary of the Rationale for the Eligibility Rules recommended by IDSP (cont'd)	
Eligibility Rule	**Rationale**
<u>Eligibility Rule #2</u>*: That claims arising from cancers of the trachea, bronchus and lung among Ontario uranium miners in dusty occupations (WCB Occupation codes 11-16, 21,22,25,26 and 97) and meeting criteria 1, 2, and 3 in eligibility rule 1 above be compensated if they meet <u>one</u> of the following criteria:* *1. Total WLM exposure in the time period 10 to 14 years (i.e. a 5-year period) prior to diagnosis of the primary cancer is at least 20 WLM;* *2. Total WLM exposure in the time period 10 to 14 years (i.e. a 5-year period) prior to diagnosis of the primary cancer plus 0.5 (or 50%) of the WLM exposure in the time period 15 or more years prior to the diagnosis of the primary cancer is at least 20 WLM.*	Given the magnitude of uncertainty in individual WLM estimates from 1955 to the time of the report (1989), the Panel decided to recommend a second eligibility rule to compensate any miner whose cumulative exposure fell between 20 and 40 WLMs and who fulfilled one of the two listed criteria. The Panel noted that the second criterion of Eligibility Rule 2 was less stringent than the first criterion. Both are based on the RSP's modeling of lung cancer risks (Tables 24, 25, 28 and 29 in the RSP). From their analysis, the RSP concluded that the most important period for determining the risk of lung cancer was 10 to 14 years prior to diagnosis. The second criterion recognized that the next most important period was ≥ 15 years prior to diagnosis and that this contribution was about 50% of the importance of the 10-14-year period. The RSP also found that the most immediate period of 5 to 9 years before diagnosis was not significant in the risk of lung cancer (hence the recommendation for a 10-year latency period). The Panel also observed that the rationale of the second criterion was similar to the risk modeling described in the BEIR IV Report.

When the Panel tested Eligibility Rule 2 against the lung cancer cases in both study cohorts (uranium miners with gold mining experience or uranium-only miners) in the RSP. For the uranium miners with gold mining experience they observed that 46 out of the 90 (only 51%) of the lung cancer cases would be compensated according to this rule. However, they also observed that an additional 16 of the 44 cases would be compensated according to the gold mining eligibility rules at that time. In total 62 of the 90 cases or 69% of the uranium miners with gold mining experience would be compensated under either the Eligibility Rule 2 in the proposed uranium mining policy or the gold mining policy.

For the “uranium-only” miners’ cohort, only 27 of the 66 or 41% of the lung cancer cases would be compensated under Eligibility Rule 2. Despite the low number of claims that would be accepted under these eligibility rules, the IDSP proceeded with their recommendations to the WSIB.

Case by Case Adjudication

Section 5.0 of the IDSP report “Case by Case Adjudication” expressed concern that there might still remain legitimate cases of lung cancer among either gold miners or uranium miners (with or without previous gold mining experience) and who fall short of the eligibility criteria outlined above. In the recommendation the Panel urged the Board to take into account other considerations beyond radiation exposure in uranium mines.

> ***Recommendation #1***: *In adjudicating any claim for compensation for the cancers of the trachea, bronchus and lung among Ontario gold or uranium miners, that the Board take full conscience of the following considerations:*
>
> 1. *The range of additional evidence identified by the panel in its criteria of case evaluation (Section 4.0, Report on the Ontario Gold Mining Industry, IDSP Report no. 1, April 1987)*
> 2. *The many inaccuracies whose presence is acknowledged in the available estimates of any individual uranium miner’s radiation exposures as a result of:*
>   - *the use of radiation readings based on area sampling rather than individual records;*
>   - *the absence of records on known exposures to other radiation types such as gamma and thorium;*
>   - *the fact that no records on radiation exposures in either surface or mill workers are kept;*
>   - *the fact of exposure to other unidentified carcinogenic substances for uranium miners with prior gold mining experience (in the Panel’s Gold Mining Report, possible carcinogens included radon, silica, and arsenic)*
> 3. *The provisions stipulated in Section 3 (4) of the Ontario Workers’ Compensation Act when weighting all of the above items of evidence.*

The IDSP Report #6 was published in the Ontario Gazette and the Board received three submissions from stakeholders that raised complex issues regarding the report. In order to clarify these issues, the Board convened a three-member panel of experts to provide advice on these issues. The Expert Panel provided some opinions on the IDSP report and recommended further analysis of the Ontario data. The Board published an interim response to the IDSP report in October 1990 (BoD Minute #6, October 5, 1990, pg. 5397)[N]. The Report of the Expert Panel appeared in the Appendix to the Board's interim response.

Statement of Dissent

Although they agreed with the two findings of the IDSP report, three members of the IDSP dissented with the other members on the two eligibility rules and the recommendation outlined above. The dissenting panel members submitted a separate letter to the WCB outlining their reasons for the dissent.

Although they agreed with the majority of the IDSP members that a probable connection between lung cancer and uranium mining and milling had been demonstrated, they recommended that WCB enter lung cancer due to uranium mining with or without prior gold mining experience into Schedule 3. The recommended alternative eligibility rule is included in IDSP Report #6:

> ***Alternate Eligibility Rule****: The Board should enter cancer of the lung into Schedule 3 of the Workers' Compensation Act, and that cancer of the lung be deemed to have been due to the nature of uranium mining, milling and surface work and uranium mining, milling and surface work with prior gold mining exposure, unless the contrary is proven.*

The letter of dissent raised concerns that the inaccuracies of the exposure measurements in the uranium mines had not been properly addressed by the exposure requirements of Eligibility Rule 1 & 2:

The dissenters raised the following issues:

- the RSP used average radon exposure levels (i.e. Standard Working Level Months) for the mines as an estimate of typical exposure whereas because of collective agreement restrictions on the ability to move from job to job some miners spent prolonged periods of time in higher radon exposures. They considered that Special Working Level Months exposure would be more accurate estimate for certain jobs with higher exposures to radon such as driller or slusherman.
- although surface and mill workers have been recognized as having radon exposure, the Mining Master File records zero exposure for these workers.
- requiring only exposure in dusty uranium mining in Eligibility Rules 1 and 2, meant that the period of actual radon exposure to other potential lung carcinogens like arsenic or silica for miners who also did gold mining, would not be considered.

Although the WCB did not accept the alternative eligibility rule proposed by the dissenting members of the ODSP, the revised policy 16-02-04 did take into account exposures in gold mining in addition to uranium mining

[N] *to date the full content of the Board's published interim response to the IDSP report in October 1990 (BoD Minute #6, October 5, 1990, pg. 5397) has not been obtained.*

Summary of the 1988 BEIR (Biological Effects of Ionizing Radiation) IV Report[O] "Health Effects of Radon and other Internally Deposited Alpha Emitters"[5]

- primary focus was on radon and radon daughters
- used actual data from four large cohorts of uranium miners – USA (Colorado Plateau), Czechoslovakia, Saskatchewan and Ontario – to develop a model to predict the probability of dying from lung cancer
- factors that were most important in determining the occupational contribution of lung cancer risk among uranium miners were: cumulative exposure to radon decay products measured in Working Level Months (WLM), age at death due to lung cancer and time of exposure relative to time of death
- analysis showed:
    - lung cancer risk for uranium miners could be described according to 3 groups of age at death; younger than 55, 55 to 64 and 65 and above
    - work-related lung cancer risks in uranium miners declined with age
    - taking the age group of 55 to 64 as the standard, for the same amount of exposure in WLM, the risk was 20% higher among those who died at 55 years of age or younger and 60% lower among those who died after age 65
    - lung cancer risk could be differentiated by two time periods: the risk of lung cancer from cumulative radiation exposure in WLM from 5 to 14 years before death was about 2-fold the risk for cumulative radiation exposure in WLM during the period of 15 years or more before death
    - there appeared to be a multiplicative effect between smoking and radiation exposure, but further studies were needed to clarify this association

---

O *The Committee on the Biological Effects of Ionizing Radiation (BEIR) is a committee of the National Research Council of the USA which publishes a series of reports informing the US government on the effects of ionizing radiation. The BEIR Committee has published the following reports to date:*

- *BEIR III 1980: "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation";*
- *BEIR IV 1988: "Health Effects of Radon and Other Internally Deposited Alpha-Emitters";*
- *BEIR V 1990: "Health Effects of Exposure to Low Levels of Ionizing Radiation";*
- *BEIR VI 1999: "The Health Effects of Exposure to Indoor Radon",*
- *BEIR VII, Phase 1 1998: "Health Risks from Exposure to Low Levels of Ionizing Radiation, Phase 1",*
- *BEIR VII, Phase 2 2006: "Health Risks from Exposure to Low Levels of Ionizing Radiation, Phase 2.*

Historical Radiation Exposure Data for Ontario Uranium Miners

Uranium mining began in Ontario in 1955 but exposures to radon in the mines were not measured until 1958 and by 1960, radon exposures were being measured by all Ontario uranium mines. Before 1958 the annual average radon levels were estimated based on the expert opinion of mining engineers. The exposure estimates took into account the amount of ore produced, ventilation practices and dust counts available for the specific mines. After 1958, measurement of radon was done by collecting stationary or area samples with no consistent schedule or extensive coverage throughout the mines. Area samples were typically taken in different areas of the mines including headings, stopes, raises and travelways. The percentage of time spent in work areas and travelways was used to estimate individual miners' exposures.

In 1968 the Atomic Energy Control Board (AECB) of Canada required periodic (preferably quarterly and at least annual) reporting of these area sampling results for each miner. This resulted in a more systematic estimation of the radon dose for individual miners. Area sampling became more extensive and consistent. In addition, more detailed work histories were collected for each individual miner that included better estimates of duration of task in specific locations of the mines. Mining companies used daily timecards and the most recent area measurements of radon in areas where the miners worked to calculate their daily exposures to radon. The daily exposures where then totaled to give the annual accumulated exposures that were reported to the AECB.

Sources for historical radon exposure data include:

- published reports or studies
- Mining Master File records
- National Dose Registry
- mining company records

Published Reports

There is little or no occupational exposures data in open peer-reviewed literature related to Ontario uranium mining. However, two reports are available that provide some useful information on historical exposures of uranium miners. The first is the Muller 1983 report[4] and the second is the more recent 2015 paper by Verma et al[13].

Muller 1983 Report[4]

One of the main published sources of historical radon exposures in Ontario uranium mines is the 1993 Muller report that summarized radon measurements[4]. This report also provides a detailed description of how radiation exposures were calculated for the early studies[4,6,8] of the Uranium Mining Cohort. This data was also used by the Special Panel in their re-analysis of the Muller 1983 report that was part of the 1989 IDSP Report[7].

For the period 1955 to 1977 the annual radon exposure for each uranium miner was calculated using the Working Level Table (WLT) (see Appendix 2). Radon levels were measured by taking stationary grab samples in different areas of the mines mainly for identifying areas of highest exposure that required ventilation or other control measures. Periodic reporting of these area sampling results for radon to the Atomic Energy Control Board (AECB) of Canada became a regulatory requirement in 1968. At this time regulatory requirements for increased ventilation in the mines was also introduced.

The Muller 1983 report stated that a group of mining engineers who were familiar with the Ontario uranium mines in the early years of their operation, observed that radon exposure in the earlier years was likely underestimated. It is generally recognized that most of the radon exposure (about 90%) came from broken ore rather than emitted from the undisturbed walls of the mines. The area sampling in the mines reported two types of exposure: Standard Working Level (Std. WL) and Special (or higher) Working Level (Spec. WL). Std. WL measurements were average radiation levels mainly in non-production areas of the mine such as travelways, whereas Spec. WL measurements were taken in the areas of highest likelihood of exposure such as drilling, slushing or mucking operations. Between the years 1958 to 1967, the total number of annual measurements for all mines ranged from 696 to 2,145 and the number of annual measurements for each mine ranged from 46 to 378 (Table IV-8 in BEIR IV).

The standard (or lower) WL values were the averages of the four quarterly averages or three 4-month averages for a particular year. To calculate the special (or upper) WL values, the average of the four highest quarterly measurements or the three highest 4-month measurements in headings, stopes and raises were multiplied by 0.8 and the average of the four highest quarterly or three highest 4-month measurements in travelways were multiplied by 0.2. These weighting factors were based on the assumption that miners typically spent 80% of their time working in stopes, drifts and raises (higher exposures) and 20% of their time in travelways (lower exposure).

The Std. WL and Spec. WL were used as the lower and upper bounds of the weighted concentration of radon in the mines respectively. The difference between the standard and special WL values varied with mine and year; for some mines these were equivalent and for other mines (and for some years for some mines) the special WL values were up to 4 times higher than the standard WL values.

The Working Level Table in the 1983 Muller et al report[4] also included Standard Working Level contractor values (shown in the table as Std. WL Cont.). These radiation exposure estimates would apply to contractors employed in such processes as shaft sinking and other non-production work. The Working Level Table from the 1983 Muller et al report is reproduced in Appendix 3.

A work history factor (WHF) was also derived that corrected for deviations from normal working hours in a mine. A WHF of 1 indicated normal working hours, a WHF greater than 1 took into account overtime work and a WHF less than 1 applied to work stoppages.

For the period 1955 to 1967 a miner's radon exposure in any given year was calculated by totaling the number months worked in each mine multiplied by the appropriate WHF and by the average WL measured in each mine. The calculation was done using both Std. WL and Spec. WL values to obtain the bounds for the radiation exposure. For 1968 and later the exposures were calculated by multiplying the number of hours the miner spent at each mine by the average concentration of radon for each mine and adding the WL hours over the calendar year. This was then converted into WLM by dividing WL hours by the number of hours worked per month.

For the period before 1954, which was generally recognized as the period of highest exposures to radon, estimates were based on extrapolation from measured values that were available after 1955. The Muller report observed that 22% of the total WLM accumulated by the cohort was based on this extrapolation; however, the maximum extrapolation period for any mine was 5 years.

The Report of the Special Panel (RSP) on the Ontario Uranium Mining Industry RSP, reanalyzed the data from the 1983 Muller report. The RSP analysis used only the Standard WLM values from the 1983 Muller report as these were the best estimate of actual exposure and the Special WLM values were more indicative of the upper limit of exposure.

1974 Ontario Ministry of Health Survey (Verma et al 2015 paper[13])

In 1974, the Occupational Health Protection Branch of the Ontario Ministry of Health conducted a comprehensive survey of dust, radiation, and diesel exhaust in two uranium mines (Rio Algom and Denison). The results of this survey report remained largely unknown and not easily accessible until a summary was published in the open literature by Verma et al in 2015[13]. Almost 1000 area and personal dust samples of various types were collected under normal working conditions. About 400 measurements of radon concentrations were also made, usually in the same vicinity of the dust sampling. Not all the dust and radon samples were included in this paper because some were duplicates, some were quality control samples and others were side by side samples collected at the same time as the mining company samples. A total of 756 dust samples and 293 radon samples were summarized. The table below was copied from the 2015 Verma et al paper[13].

Table 8: Summary of measurements within stated range of WL in various areas of the two mines

Rio Algom

Area type	N	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8
Production areas (stopes, raises)	68	21	22	9	6	3	4	2	1
Haulage	15	14	1	0	0	0	0	0	0
Fresh airways	5	5	0	0	0	0	0	0	0
Lunch rooms	8	7	0	0	0	0	0	1	0
Mill and crusher	23	23	0	0	0	0	0	0	0
Miscellaneous*	39	32	3	2	0	1	0	1	0

Denison

Area type	N	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.0	1-2	2-3	3-4	4-6	6-8	8-10
Production areas (headings, drifts, etc.)	38	0	11	10	6	3	6	1	0	0	1	0	0	0	0	0
Travel ways	5	1	1	2	0	0	0	0	0	0	1	0	0	0	0	0
Fresh airways	3	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Exhaust airways	3	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Refuge stations	12	6	0	2	0	0	1	0	1	0	1	1	0	0	0	0
Leaching	11	0	0	0	0	0	0	1	0	0	2	0	2	4	1	1
Miscellaneous*	27	14	4	1	2	2	0	0	2	0	2	0	0	0	0	0

*Miscellaneous includes conveyors, sumps, skip, bulkheads, workshops, grizzlies, U/G crusher, etc., WL: Working levels, N: Number of samples

The occupational exposure limit for radon exposure at the time of the 1974 Ministry of Health survey was 6 WLM/year. Any area with a radon concentration > 0.5 WL would be determined to be unacceptable for full-time occupancy since it would lead to the annual exposure of > 6 WLM (0.5 WL × 12 months = 6 WLM). As shown in the table below, 9 out of 135 of the Rio Algom measurements were found to have readings above 0.5 WL. In comparison, 30 out of 99 measurements at the Denison Mine were above 0.5 WL. Almost all underground mining areas would have been judged unacceptable if they were compared to the current occupational exposure limit of 1 WLM/year[14]. Areas having exposures > 0.084 WL would result in annual exposures > 1 WLM (0.084 x 12 = 1.01). At both mines, all above-ground measurements in mills and crusher areas were < 0.1 WL.

Mining Master File (MMF)

The Mining Master File (MMF) is the collected records (cards) for each miner that began in the early 1950s and continued to the mid-1980s. This was part of a record-keeping system for all Ontario miners that recorded employment history, dust exposure, and medical exam results (i.e. annual X-rays), primarily to monitor the incidence of silicosis. The Mining Master Record was a handwritten card that recorded the employment history, dust exposure, and medical exam results (i.e. annual X-rays) for each individual miner. These cards also recorded radiation exposures in WLM or Special WLM that was calculated by the mining companies.

National Dose Registry (NDR)

The National Dose Registry (NDR) that is presently maintained by Health Canada, contains the dose records of individuals who are monitored for occupational exposures to ionizing radiation. The NDR started collecting data in 1951 and in 1954 the annual radiation dose for uranium miners began to be recorded in the NDR.

The recent update of the Ontario uranium mining cohort by OCRC[15] used annual radiation doses from the NDR for the period 1954-2004 and from the MMF from 1954-1986. Where the radiation doses were provided from both sources, the NDR measurement was used as the best estimate of exposure since they considered the NDR data to be more complete.

Mining company records

As discussed above, mining companies were required to report the results of periodic sampling for radon to the Atomic Energy Control Board (AECB) of Canada beginning in 1968. Direct access to radon sampling data collected by mining companies is usually limited to requests from WSIB. The WSIB also routinely uses radon exposure data for individual miners from the NDR and MMF in the adjudication of claims from uranium miners.

Exposure Uncertainty

As with any exposure data, certain assumptions and inherent errors may affect accurate assessment of radon exposure.

The IDSP sought an expert opinion about the accuracy of the exposure measurements used in the 1983 Muller report and the RSP report from the Manger of the AECB Uranium Mining Division who concluded the following:

- prior to 1960, the uncertainty in WLM estimates is up to 1 order of magnitude (i.e. from 0.1 to 10 times the values shown (i.e. Table 1 of the 1983 Muller et al report[4])[P]
- from 1960 to about 1970, the WLM uncertainty is of the order of plus or minus 200%
- from 1970 on, the WLM uncertainty is of the order of plus or minus 100%
- from about 1978 onwards, the uncertainty is within plus or minus 50%

It is important to note that these uncertainty values are often quoted in WSIAT Decisions and because of the wide limits in the uncertainty of the radiation exposure, the appeals are often denied by using the low end of the uncertainty range rather than accepted by using the high end of the uncertainty range.

The 2015 OCRC update of the Ontario Uranium Mining Cohort also discussed in detail the sources of uncertainty related to radon exposure assessment[15]. The six major sources of uncertainty were:

1. natural variations in radon concentrations
2. estimation of working time
3. precision of the Kusnetz method for measuring radon
4. the accuracy of the Kusnetz correction/conversion factor
5. systematic errors/human errors
6. record keeping and data transcription

The uncertainty from each of these sources and the total uncertainty was assessed in the OCRC report and is summarized in Table 3. For full details please consult Appendix B of the OCRC report[15].

[P] ***comment in parentheses added by P. Sampara***

Table 3 Sources and Magnitude of Uncertainty Associated with Estimating Exposure to Radon		
Source of Uncertainty	**Periods**	
	1958-1967	**1968-1996**
Natural Variations in Radon Concentrations	52-62%	30-36%
Estimation of Working Time	8%	4%
Precision of the Kusnetz Measurement Method*	3-23%	0.3-2.3%
Kusnetz correction/conversion factor**	3.5%	3.5%
Systematic Errors **Human Error when taking air samples**	5-10% 2-3%	5-10% 2-3%
Record Keeping and Transcription	1.5%	1.5%
Total Uncertainty	53.1-67.5%	30.9-37.8%

source: Appendix B: Sources of Uncertainty in reference 15

** the modified Kusnetz method was the most widely used method for measuring radon in Canadian uranium mines.[14] This method involved drawing a known volume of air through a filter for about 5 minutes. The radon daughters on the filter are then left to decay for 40 to 90 minutes and then the alpha particle activity on the filter is measured using an alpha particle counter. The radon concentration in working levels is then calculated with an equation.*

*** Kusnetz correction/conversion factor is part of the equation used to convert the alpha particle counts to radon concentration in working levels. see Appendix B in reference 15 for further details.*

The uncertainty estimates for the radon exposures calculated by the OCRC in Table 2 were considerably lower than those outlined in the 1989 IDSP Report #6[7] summarized on the previous page.

Radon Exposure Limits during Ontario's Uranium Mining Period

Regulation of radon exposure in Ontario uranium mines began in the early 1950s as a guideline recommended by the Atomic Energy Control Board (AECB) although it had no regulatory authority over Ontario mines. The AECB focused on the environmental effects of uranium mining and left the setting of occupational exposure limits (OELs) to the provincial jurisdictions. In 1967, the Ontario Department of Mines established a limit of 12 WLM as an annual OEL for uranium mines. The OEL was systematically reduced as new evidence of the hazards of radon became known. By 1976, the OEL was reduced to 4 WLM/year.

1967 to 1972	12 WLM/Year
1972 to 1974	8 WLM/Year
1974 to 1975	6 WLM/Year
1976 to 1996	4 WLM/Year

WLM/Year = Cumulative annual working level months exposure limit before being reassigned from underground mining

The Ontario Ministry of Labour presently has jurisdiction over health and safety in Ontario mines. Under the Occupational Health and Safety Act (R.R.O. 1990 Reg.854: Mines and Mining Plants)[14], mining employers are required to reduce radon to the lowest practical level and ensure that no worker is exposed to more than 1 WLM per year. The regulation also requires that if the concentration of radon exceeds 0.33 WL, the employer must remove all workers in addition to other measures.[Q]

[Q] ***Excerpt from R.R.O. 1990 Reg.854: Mines and Mining Plants (current version)***[14]

290. (1) Every employer shall ensure that the airborne concentration of radon progeny to which workers may be exposed in an underground mine is reduced to the lowest practical level in accordance with good industrial hygiene practice. O. Reg. 583/91, s. 8; O. Reg. 167/16, s. 17.

(2) An employer shall ensure that no worker who is continuously employed by the employer during a year inhales air which exposes the worker to more than one WLM. O. Reg. 583/91, s. 8.

291. If the concentration of radon progeny to which a worker may be exposed in an underground mine exceeds 0.33 WL, the employer,

(a) shall immediately remove all workers from the affected area of the mine;

(b) shall give written notice of the occurrence to the joint health and safety committee or health and safety representative, if any;

(c) shall implement the measures and procedures required by subsection 255 (1);

(d) shall provide the written instructions required by subsection 255 (3) to all workers assigned to do remedial work; and

(e) shall provide to workers doing remedial work and require the use of respiratory equipment appropriate to prevent or limit the workers' exposure to radon progeny. O. Reg. 583/91, s. 8; O. Reg. 272/97, s. 53; O. Reg. 167/16, s. 17.

Risk of Lung Cancer Associated with Ionizing Radiation Exposures in Ontario Mines

Uranium production from Ontario mines began in 1954 with about 500 development miners and increased rapidly from 1957 to 1960 when there were about 10,000 uranium miners. After the demand for uranium oxide ore from Ontario mines suddenly decreased in the early 1960s, the number of uranium miners also decreased rapidly to about 1,000 by the mid -1960s[3,16]. There was a brief resurgence of uranium mining in the Elliot lake region in the late 1970s because of power generation demands. However, by the 1990s only the Denison and Stanleigh uranium mines were in operation; and these mines ceased operation in 1992 and 1996, respectively.

Radon-222 is a radioactive gas released from the natural radioactive decay chain of uranium 238. Radon decays into a series of isotopes or radon decay products (RDP) through the emission of alpha particles. The half-life[R] of radon is 3.83 days (see Appendix 3). Lung cancer due to radon exposure is caused by the RDP which are suspended in air when radon gas is present, or when they attach to dust particles that are inhaled and deposited in the lungs[17,18]. Damage results when the inhaled RDP come into close proximity to lung tissue, particularly in the larger airways of the lung where these particles tend to settle out. Malignant change leading to cancer can occur if enough alpha radiation energy is released during a sensitive part of the lung cell life cycle, causing damage to cellular DNA.

Radon has been recognized as a hazard in mines for many years. The Committee on the Biological Effects of Ionizing Radiation (BEIR) that is part of the National Research Council (NRC) publishes periodic reports to advise the U.S. government on the relationship between exposure to ionizing radiation and human health. The BEIR Committee has published 7 reports to date and the most recent BEIR VII report addressed the health risks from exposure to low levels of ionizing radiation[19]. The BEIR IV report published in 1988 informed the development of the WSIB Policy on Lung Cancer in Uranium Miners[1].

In 2001, radon was classified by International Agency for Research on Cancer (IARC) as carcinogenic to humans (Group 1) because of the well-established link between radon exposure and lung cancer[20]. The 2012 IARC review of Group 1 carcinogens reaffirmed this classification[21]. Studies of uranium miners to date have demonstrated strong evidence for increased risk of lung cancer mortality compared to the general population, as well as strong exposure-response relationships between cumulative radon exposure and lung cancer mortality[8,22-27].

The most relevant studies for this summary are those of Ontario uranium miners. Radon was also present in Ontario gold mines, but to a much lesser extent than in uranium mines. The 1993 Kusiak et al study reported that the average cumulative exposure to radon in gold mines was 2 working level months (WLM), with 99% of the cumulative exposures being less than 22 WLM[8]. By comparison, the average

---

[R] *Half-life means the time it takes for the radioactivity to be reduced by half* cumulative exposure to radon in uranium mines was 30 WLM and 99% of the cumulative exposures were less than 255 WLM.

The earliest evidence of increased risk of lung cancer in Ontario uranium miners was provided in the Muller et al 1974 report[2] that found a greater than 3-fold statistically significant increased risk of lung cancer death among Ontario uranium miners (SMR = 3.13 95%CI 2.75-4.16).

This finding resulted in the creation of the Ontario Uranium Miners Cohort to better understand the health effects associated with uranium mining. This cohort includes about 30,000 uranium miners and continues as one of the largest cohorts of uranium miners in the world with high-quality exposure assessment. There have been several analyses and updates[3,4,6,8]of data collected from this cohort, with the most recent published in 2015[15] and 2016[28].

Table 4 summarizes the risk estimates for lung cancer mortality reported in the Ontario Uranium Mining Cohort studies to date. All of the analyses and updates found statistically significant overall rates of lung cancer mortality.

Table 4 Summary of Lung Cancer Mortality Reported in the Ontario Uranium Mining Cohort Studies

Study	Follow-up Period	Cohort size*	Lung Cancer SMR**	95% CI***
Muller et al 1974[2]	1955-1973	8,649	3.13	2.75-4.16
Ham, 1976[3]	1955-1974	~18,000	1.80	1.43-2.23
Muller et al 1983[4]	1955-1977	15,984	1.81	1.50-2.14
Muller et al 1989[6]	1955-1981	14,877	1.70	1.46-1.97
Kusiak et al 1993[8]	1955-1986	21,346	2.25	1.91-2.64
OCRC, 2015[15]	1954-2007	28,546	1.34	1.27-1.42

** Cohort sizes differ due to varying inclusion criteria and follow-up periods*
*** SMR = Standardized Mortality Ratio*
**** CI = Confidence Interval*

The updates of the Ontario Uranium Mining cohort published in 2015[15] and 2016[28] added 21 years of follow-up and examined lung cancer incidence as well as mortality. Presently, the Ontario Uranium Mining Cohort consists of 28,546 miners, with average age at entry of 28.8 years. Miners in the cohort had an average cumulative exposure to radon of 21.0 WLM (range 0 to 875.1) over an average of 5.3 years of total exposure (range 1 to 45 years). Based on these figures, the calculated average annual exposure to radon was 4 WLM (21 WLM ÷ 5.3 = 4.0 WLM/year). However, an individual miner's exposure to radon could vary widely as shown in the wide ranges of cumulative radon exposure and total years of exposure. For comparison, the current Ontario Ministry of Labour exposure limit for radon exposure in mines and mining plants is 1.0 WLM/year[14].

The overall lung cancer incidence over the period 1969 to 2005 for Ontario uranium miners, compared with the Canadian male population, was increased and statistically significant; SIR = 1.30 95% CI 1.23-1.37 (1291 cases). Lung cancer mortality over the period 1954 to 2007 was also significantly increased compared to Canadian males (SMR=1.34 95% CI 1.27-1.42 [1230 deaths]).

Exposure-Response

The latest BEIR VII report published in 2006 reaffirms the conclusions of the earlier BIER reports that, based on the available evidence from epidemiological studies and a comprehensive review of biological studies, a linear no-threshold model best describes the relationship between exposure to ionizing radiation and lung cancer[19]. According to this model, the risk of lung cancer increases as exposure to ionizing radiation (radon) increases. In addition, the BEIR committee has concluded that the risk continues in a linear fashion at lower doses without a threshold, so that even the smallest radiation dose has the potential to increase the risk of lung cancer in humans. The linear Excess Relative Risk (ERR) model proposed by BEIR based on the 11 uranium mining cohorts they considered, is as follows:

$$ERR_{radon} = \beta_{radon} \times w$$

where ERR_{radon} = Excess Relative Risk[S] of lung cancer from radon exposure,
β_{radon} = estimated cohort-specific exposure-response coefficient (ERR/WLM) and
w = cohort-specific cumulative radon exposure

The 2015 update of the Ontario Uranium Miners Cohort study[15] showed a positive exposure-response relationship between cumulative radon exposure and lung cancer incidence. There was a 28%, close-to-significant, increase in lung cancer incidence (RR=1.28 95% CI 0.96-1.70) at cumulative exposures of >30-50 WLM. There was a statistically significant nearly 2-fold increase in lung cancer incidence (RR=1.92 95% CI 1.45-2.54) at cumulative exposures from > 50 WLM to 100 WLM and a greater than 2-fold increase in the highest cumulative exposure category of > 100 WLM.

A positive exposure-response relationship was also observed between cumulative exposure to radon and lung cancer mortality. The statistically significant lung cancer mortality risk increased from 1.41 95% CI 1.03-1.94 for cumulative radon exposures of >20 to 30 WLM to a greater than 2-fold increased risk at cumulative exposures > 100 WLM (RR=2.33 95% CI 1.73-3.14). A statistically significant increase in lung cancer mortality was also observed at very low doses (>0 to 1 WLM) for miners exposed after 1970 (RR=1.43 95% CI 1.05-1.95). This finding indicates that the lung cancer mortality risk among miners exposed during the lowest exposure period (after 1970) was similar to the risk for the full cohort (RR= 1.34 95% CI 1.27-1.42). Lung cancer incidence and mortality by cumulative exposure to radon among Ontario uranium miners are summarized in Table 5.

[S]*Excess Relative Risk (ERR) corresponds to the percentage increase (or decrease if negative) of the health risk in one group compared to a reference group. Excess Relative Risk (ERR) = proportion of Relative Risk (RR) due solely to radiation exposure (ERR=RR-1) (reference: National Cancer Institute https://radiationcalculators.cancer.gov/irep/model)*

Table 5 Lung Cancer Incidence and Mortality by Cumulative Exposure to Radon Progeny in Working Level Months (WLM)* among Ontario Uranium Miners				
Lung Cancer Incidence			**Lung Cancer Mortality**	
Cumulative Exposure (WLM)**	**Mean Exposure (WLM)**	**Relative Risk (95% confidence limits) [number of cases]**	**Mean Exposure (WLM)**	**Relative Risk (95% confidence limits) [number of deaths]**
0	0	1 [70]	0	1 [60]
>0 to 1	0.35	1.10 (0.82-1.48) [119]	0.36	**1.43 (1.05-1.95) [125]**
>1 to 5	2.64	0.99 (0.75-1.32) [165]	2.66	1.22 (0.91-1.65) [162]
>5 to 10	7.22	0.86 (0.64-1.15) [124]	7.23	1.06 (0.77-1.44) [121]
>10-20	14.30	1.02 (0.77-1.34) [186]	14.30	1.24 (0.92-1.66) [179]
>20-30	24.40	1.21 (0.90-1.62) [119]	24.40	**1.41 (1.03-1.94) [111]**
>30-50	38.60	1.28 (0.96-1.70) [150]	38.60	**1.56 (1.15-2.12) [145]**
>50-100	70.00	**1.47 (1.11-1.95) [174]**	69.90	**1.81 (1.35-2.45) [163]**
>100	163.50	**1.92 (1.45-2.54) [174]**	162.7	**2.33 (1.73-3.14) [165]**

** WLM = Working Level Months; a working level (WL) is defined as 1.3 x 10^3 MeV of potential alpha energy per litre of air and 1 WLM corresponds to exposure to 1 WL for 1 month; i.e. 170 working hours.*
*** Cumulative exposures lagged by 5 years*
statistically significant risk estimates in bold
source: adapted from Table 3 in reference # 15

After applying the linear Excess Relative Risk (ERR) model proposed by BEIR, the OCRC Ontario Uranium Miners Cohort study[15] estimated an ERR/WLM[T] (β_{radon}) of 0.0064 for lung cancer incidence and 0.0066 for lung cancer mortality. As shown in figures 1 and 2, the exposure-response coefficients or ERR/WLM (β_{radon}) may be used to estimate the relative risk[U] for lung cancer incidence or mortality over the continuous range of radon exposures.

$$RR = \beta_{radon} \times w + 1$$

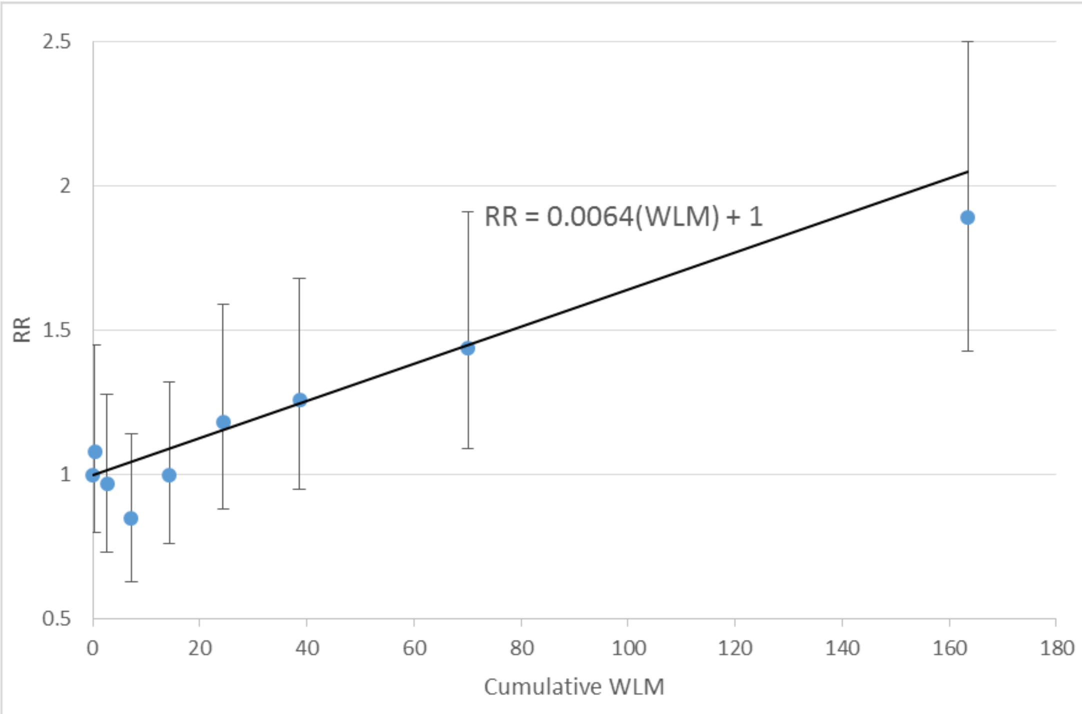
For lung cancer incidence, $RR = 0.0064 \times w + 1$

For lung cancer mortality, $RR = 0.0066 \times w + 1$

For example, for a cumulative radon exposure of 40 WLM[V], the relative risk (RR) for lung cancer incidence can be estimated as RR = 0.0064 x 40 WLM + 1 = 1.26; and the relative risk (RR) lung cancer mortality can be estimated as: RR = 0.0066 x 40 WLM + 1 = 1.26. This means that a cumulative radon exposure of 40 WLM would increase the lifetime risk of lung cancer incidence and mortality by about 26%.

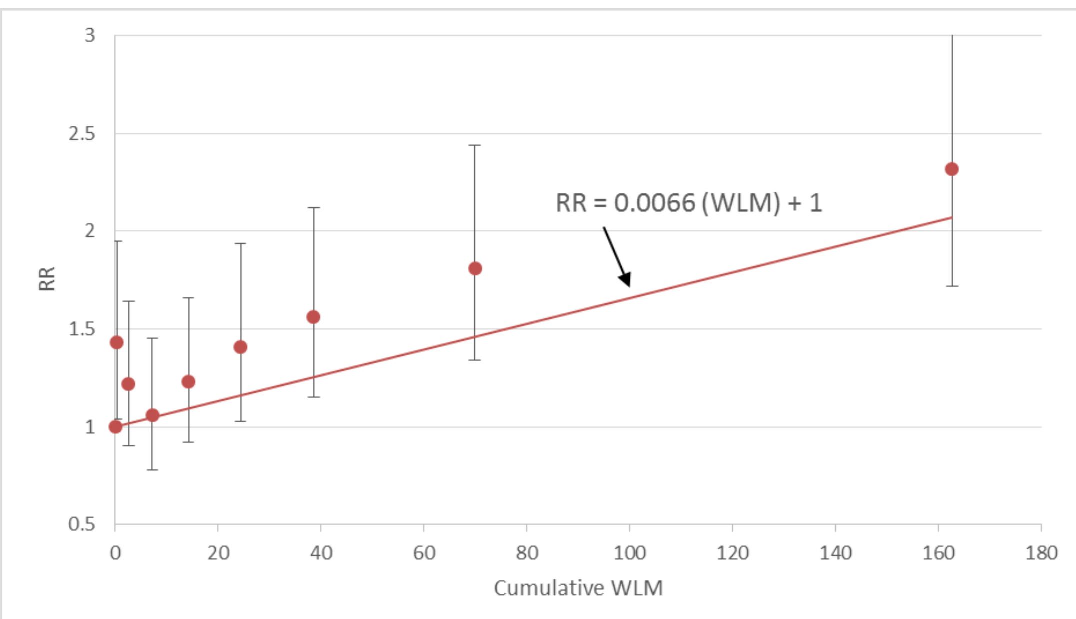
[T] *Excess Relative Risk per Working Level Month (ERR/WLM) is also referred to as β_{radon} or the exposure response coefficient from which Relative Risk can be calculated: (RR = β_{radon} x cumulative radon exposure in WLM + 1)*
[U] *Relative Risk (RR) = ratio of the total risk from exposure divided by risk due to background alone*
[V] *a cumulative exposure of 40 WLM would be equivalent to a 40-year work history as a uranium miner exposed at the current MOL exposure limit of 1 WLM/year*

Figure 1 Relative Risk (RR) and Excess Relative Risk per WLM (ERR/WLM) for lung cancer incidence associated with cumulative exposure to radon with a five-year lag[W] applied



source: reference #15

Figure 2 Relative Risk (RR) and Excess Relative Risk per WLM (ERR/WLM) for lung cancer mortality associated with cumulative exposure to radon with a five-year lag applied



source: reference #15

[W] Five-year lag = exposures prior to 5 years before diagnosis are not included

The finding of a strong linear exposure-response relationship between radon and risk of lung cancer from the recent update of the Ontario Uranium Miners Cohort (Figures 1 and 2) is consistent with the BIER linear no-threshold model. These findings are also consistent with those reported recent updates of large cohort mortality studies of French[29] and German[30] uranium miners exposed to low levels of radon.

The 2018 update by Rage et al[29] of an extended cohort of 5400 French uranium miners that were followed up from 1946 to 2007, had an average of 13.0 years of exposure to an average radon cumulative dose of 35.1 WLM. A statistically significant excess of lung cancer deaths was observed (SMR=1.32 95% CI 1.14-1.51), and the ERR (β_{radon}) for lung cancer mortality was calculated as 0.73/100 WLM (0.0073/WLM).

The 2018 update of the German uranium mining cohort by Kreuzer[30] et al added another 10 years of follow-up (up to 2013) to the earlier 2010 analysis by Walsh et al[27]. When the simple, linear ERR model was applied to the full cohort, for miners with cumulative exposures of < 100 WLM, the ERR/WLM (β_{radon}) for lung cancer mortality was 0.006.

Table 6 shows that the risk estimates from the Ontario[8,15]and French[29] and German[30] cohorts of uranium miners are similar to those reported in three independent, large scale pooled analyses of uranium mining cohorts[5,31,32]

Table 6 Summary of Excess Relative Risk (ERR) per working level months (WLM) (ERR/WLM) for lung cancer mortality from published analyses of uranium mining cohorts

Reference	Number of cohorts	Number of miners	ERR/WLM (β_{radon})
Lubin et al (1994)[31]	11	60,570	0.0049
BEIR IV (1999)[5]	11	60,705	0.0059
UNSCEAR (2009)[32]	9	125,627	0.0059
Rage (2018)[29] (France)	1	5,400	0.0073
Kreuzer (2018)[30] (Germany)	1	58,974	0.0060
Kusiak (1993)[8] (Ontario)	1	21,346	0.0089
OCRC (2015)[15] (Ontario)	1	28,546	0.0066

The effects of low occupational exposures to radon and the factors that may confound and modify this risk are not well understood. A 2019 study by Lane et al[33], assessed the risk of lung cancer mortality at low radon exposures (< 100 WLM) in a joint cohort analysis of Czech, French and Canadian[X] uranium

[X] *The Canadian cohort was taken from the full cohort of underground miners and mill workers near the town of Eldorado in Northern Saskatchewan known as the Beaverlodge cohort.*

miners, employed in 1953 or later. The full cohorts of Czech, French and Canadian uranium miners were included among the 11 mining cohorts considered in the BEIR reports[5,9,19]. For the purpose of this analysis, the cohorts were restricted to time periods after radiation protection measures were introduced, especially mechanical ventilation systems and when radon progeny measurements were routinely made in work areas and/or of individuals, as part of regulatory requirements. These periods corresponded to lower radon exposures and lower radon exposure rates; 1953-1999 for the Czech cohort, 1956-1999 for the French cohort and 1965-1999 for the Canadian cohort.

The mean cumulative radon exposure was 45.1, 32.9 and 32.3 WLM for the Czech, French and Canadian cohorts respectively. The overall mean cumulative exposure for the joint cohort was 36.42 WLM and the excess relative risk per working level month (ERR/WLM) was 0.022 (95% CI 0.013-0.034) based on 408 lung cancer deaths. The relative risks of lung cancer mortality by categories of radon exposure for the joint cohort restricted to cumulative exposures <100WLM is summarized in Table 7.

Table 7 Relative risks of lung cancer mortality by categories of radon exposure for the joint cohort restricted to cumulative exposures <100WLM

Cumulative Radon Exposure (WLM)	Mean Cumulative exposure (WLM)	Relative Risk* (95% CI) [number of lung cancer deaths]
0.0	0.0	1.00 [32]
>0.0-2	1.5	0.83 (0.51-1.34) [39]
3-9	6.0	0.94 (0.60-1.50) [51]
10-19	14.6	1.41 (0.90-2.25) [48]
20-39	29.6	**1.62 (1.06-2.52) [63]**
40-59	49.5	**2.02 (1.31-3.18) [66]**
60-79	69.4	**2.39 (1.55-3.76) [64]**
80-100	88.7	**2.32 (1.45-3.76) [45]**

statistically significant risk estimates in bold

** p value for linear trend <0.001*

This analysis of the joint cohort of Czech, French and Canadian uranium miners found a statistically significant monotonic increase in the relative risk of lung cancer mortality with increasing cumulative radon exposure from 20 to 100 WLM. The finding of a statistically significant increased lung cancer mortality with cumulative radon exposures > 20 WLM is consistent with the results of the OCRC 2015 update of the Ontario uranium mining cohort[15,28]. Although the mortality rates were higher than the 2015 OCRC study[15] and the 2018 update of the large French cohort[29], this may reflect the greater uncertainty in estimates of early or extrapolated radon exposure in those studies which may have resulted in underestimating the radon risk. Sensitivity analyses found that the statistically significant linear relationship between radon exposure and lung cancer mortality persisted after controlling for tobacco smoking.

Modifying Factors

The 2015 OCRC update of the Ontario Uranium Miner Cohort Study[15] also examined the effect of potentially modifying factors on the association between radon exposure and lung cancer incidence and mortality. In brief, lung cancer mortality from radon exposure was modified by attained age, time since first exposure, time since last exposure, age at first exposure and dose rate[Y]. Lung cancer incidence was modified by time since first exposure, time since last exposure and exposure rate[Z]. A detailed discussion of these factors is beyond the scope of this summary and the 2015 OCRC study[15] and BEIR reports[5,9] should be consulted for further information.

Other exposures that may affect lung cancer incidence and mortality among uranium miners are discussed below and include: cigarette smoking, RCS, diesel exhaust (DE), other types of mining (i.e. gold, nickel, copper) and arsenic exposure in gold mines.

Cigarette Smoking

Cigarette smoking is the major cause of lung cancer; and smoking status can modify the effect of other lung carcinogens such as radon. The interactive effect may be additive, in which case the effect of smoking appears to add to the effect of another lung carcinogen. The interactive effect may also be synergistic: greater than additive (supra-additive) or multiplicative.

Many epidemiological studies over the past 30 years have observed a greater than additive but less than multiplicative interactive effect of radon and cigarette smoke on risk for lung cancer[5,33-37]. A limitation of the Ontario Uranium Mining Cohort studies to date has been the lack of adequate information on the smoking status of the uranium miners. However, the Muller et al[2,4,6] and Kusiak et al studies[8,56] of lung cancer among Ontario uranium or gold miners, observed that smoking rates were similar across different mining categories (uranium, gold, nickel) and they concluded that smoking alone could not account for the observed increased risk of lung cancer.

A 2018 update by Kreuzer et al[30] of the earlier studies[39,40] of a large German cohort of nearly 60,000 uranium miners found that adjusting for smoking had little effect on the risk estimates for lung cancer mortality. The effect modification of smoking was analyzed in the 1960+ sub-cohort as better smoking histories were available for miners who started working after 1960. Notably, miners in the intermediate cumulative exposure category (10 to 50 WLM) had an increased lung cancer mortality risk (RR=1.29 95% CI 1.01-1.56) when compared to the low exposure category of <10 WLM. The increase in risk was similar after adjusting for smoking (RR=1.23 95% CI 0.98-1.50) and reached close-to statistical significance. A nearly 2-fold statistically significant increased risk was observed for uranium miners in the high cumulative exposure category of 50 to 334 WLM; (RR = 1.99 95% CI 1.52-2.47). Adjusting for smoking had only a small effect on the risk of lung cancer; (RR = 1.85 95% CI 1.40-2.30) and the risk remained statistically significant.

[Y] *Dose rate = duration of exposure within cumulative dose categories*
[Z] *Exposure rate = WLM per year*

Separate adjustment for occupational exposure to other lung carcinogens, including RCS dust and external gamma radiation or long-lived radionuclides, also resulted in only minor changes in the radon-related risk estimates.

The findings of this German study provide additional evidence for increased risk of lung cancer at low radon exposures after controlling for potential confounders such as smoking and occupational exposure to other lung carcinogens. The authors noted that although the small number of deaths in the respective smoking categories reduced the statistical power, the findings are consistent with a greater than additive or multiplicative interaction between radon exposure and smoking.

As noted earlier, the 2019 analysis of a joint cohort of Czech, French and Canadian uranium miners found that the statistically significant linear relationship between radon exposure and lung cancer mortality persisted after controlling for tobacco smoking.[33]

Combined Exposure to Radon and Respirable Crystalline Silica (RCS)

There is also some evidence that combined occupational exposure to radon and RCS may be associated with greater lung cancer risk than exposure to either agent alone. The 2012 Sogl et al study[41] of German uranium miners was large enough to investigate the combined effect of RCS and radon on lung cancer risk in uranium miners and the findings are summarized in Table 8.

Table 8 Combined Effect of Combined Exposure to RCS and Radon on the Risk of Lung Cancer

RCS (mg/m^3-years)	Radon WLM Relative Risk RR (95% CI) [number of cases]		
	< 50	50-1000	> 1000
< 10	1.0 (reference) [609]	**1.52 (1.34-1.69) [585]**	1.95 (0.83-3.07) [12]
10-20	1.10 (0.79-1.41) [54]	**2.45 (2.17-2.73) [663]**	**3.11 (2.62-3.61) [219]**
20-30	1.33 (0.26-2.41) [6]	**3.11 (2.63-3.60) [238]**	**4.29 (3.64-4.74) [420]**
30+	0	**4.75 (3.25-6.25) [42]**	**4.56 (3.72-5.42) [147]**

statistically significant risk estimates in bold
source: adapted from information in Sogl et al 2012[41]

An increased risk of lung cancer was observed among radon-exposed workers with increased cumulative exposure to RCS and an increased risk among RCS-exposed workers with increasing exposure to radon There was also a statistically significant increase in lung cancer risk with combined exposure to radon > 50 WLM < 1000 WLM at all cumulative RCS exposure categories (middle column) when compared to the reference category (< 10 mg/m^3 - years RCS and < 50 WLM radon). Further analysis found that the combined effect of RCS and radon exposure together is more likely to be additive rather than multiplicative. However, the cumulative RCS and radon levels reported in the German study are somewhat higher than those experienced by Ontario uranium miners.

Combined Exposure to Radon and Diesel Exhaust (DE)

Two recent papers, by Cao et al 2017[42] and Chang et al 2018[43] evaluated the combined effect of exposure to radon and diesel exhaust (DE).

Diesel engine-powered equipment has been widely used in trucking, railroad and underground mining facilities. The use of diesel-powered vehicles for ore haulage in Ontario mines began in the 1960s[44]. DE is a complex mixture of gases and particulates generated by the combustion of diesel fuel[44-47]. The composition of DE depends on the type of diesel fuel, the type and age of the engine, tuning and maintenance, workload, and the exhaust treatment system. The gas compounds can include water vapour, carbon dioxide, carbon monoxide, nitrogen oxides, and volatile organic compounds, such as benzene and formaldehyde. The particulates consist of elemental and organic carbon, ash, sulfate, and metals. Polycyclic aromatic hydrocarbons (PAHs) and nitroarenes are present in the gas phase and are also adsorbed onto the surface of the elemental carbon particles. Almost all the particulates in DE are respirable (<10 micrometers in diameter), with the majority having diameters of less than 1.0 micrometers. The particulates can occur individually or can "clump" together into larger clusters called agglomerates.

Elemental carbon (EC), also referred to as respirable elemental carbon (REC), has been chosen by researchers as a surrogate or representative indicator of DE exposure since the early 1990s when it was found that most of the carcinogenic and mutagenic properties of DE were associated with the carbon particles[45-47].

Underground mining has been identified as an occupation with some of the highest exposures to DE (≥ 50 ug/m^3 measured as REC), mainly because of the enclosed nature of the workplace and their proximity to the diesel-powered vehicles and equipment[45,48]. Underground miners are typically exposed to DE concentration 10 or more times greater than surface mine workers.

No direct measurements of REC were made in Ontario uranium mines. In the 1970s, the MOL made indirect measurements of diesel exhaust by sampling for some of the gaseous by-products generated by diesel engines. Direct reading sampling (i.e. Dräger colorimetric tubes) was done for carbon monoxide, formaldehyde, and oxides of nitrogen in underground mining work areas[13]. Unburned carbon was also determined from some of the dust samples by ashing and reweighing.

The concentrations of DE in some workplaces, including mines have decreased in recent years largely because of stricter standards that required changes in diesel fuel composition (e.g. lower sulphur content) and more efficient exhaust treatment devices (e.g. filters or catalysts). The use of diesel-powered equipment and the resulting exposure to DE can be roughly divided into three periods[44].

1. Traditional diesel exhaust (TDE) refers to the period before 1988 when diesel exhaust was essentially unregulated.
2. Transitional diesel exhaust refers to the period between about 1988 and 2006 when there were progressively more stringent emission requirements.
3. New technology diesel exhaust (NTDE) refers to the period after 2006 when the most recent diesel emission standards were adopted.

The composition of NTDE is significantly different as it contains about 90% less particulates than TDE[45-46]. Since the carcinogenic properties of diesel exhaust appear to be associated with the particulates, it is thought that NTDE may be significantly less toxic than TDE. However, since the NTDE exposure period began in 2006/2007, there has been too short a time for epidemiological studies to observe the effect of exposures to lower concentrations of DE on long-latency diseases such as lung cancer. Present day cases of DE-exposure-related lung cancer are most likely to be associated with workplace exposures to TDE from more than 20 years ago.

As discussed earlier, radon risk models were developed by the BEIR committees of the US National Research Council. At the time of the 1999 BEIR VI report[9] DE exposure was identified by the BEIR committee as a suspected confounder to the estimates of risk from radon exposure. They concluded that DE appeared to be a weak carcinogen and probably not a necessary modifier to the risk of lung cancer from radon exposure. Later epidemiological studies found that occupational exposure to DE increased the risk of lung cancer in underground non-metal miners[49,50] and trucking industry workers[51-53].

In June 2012, IARC classified DE as carcinogenic to humans (Group 1) based on sufficient evidence that exposure is associated with an increased risk for lung cancer[45]. IARC found that the strongest evidence for an association between DE exposure and an increased risk of lung cancer was provided by two studies of a large cohort of US miners known as the Diesel Exhaust Mining Study (DEMS)[49,50] There was a statistically significant 2 to 3-fold increase in risk of lung cancer in the highest categories of cumulative exposure and average exposure to DE.

Cao et al 2017[42] is the first study that analyzed the possible confounding effect of exposure to DE on the risk of lung cancer associated with exposure to radon. The authors began by estimating the historical DE concentrations for the 11 mining cohorts used in the 1999 BEIR VI report[9] (and previous BEIR reports)[AA]. Although historical DE exposure data (i.e. concentrations of REC) were not available for the 11 uranium mining cohorts, ranges of REC exposures were calculated using the approach of Vermeulen et al 2010[54] that estimated the exposures in US non-metal mines for the DEMS studies[49,50]. According to Vermeulen et al, the REC concentration was essentially zero in the 1950s because diesel powered equipment was not widely used, and their use increased gradually during the late 1950s. It was estimated that the REC concentration was in the range of 20-60 ug/m^3

[AA] *BEIR reports[5,9,19,32] are used by the Environmental Protection Agency (EPA) in the US to estimate residential exposure to radon and risk of lung cancer. The residential radon risk estimates are extrapolated from the radon exposure and lung cancer risk in 11 international mining cohorts, including the Ontario uranium mining cohort.*

by 1960 and 110-350 ug/m^3 by 1970 which reflects the rapid growth in the use of diesel-powered equipment during the 1960s.

Using the REC concentration ranges estimates by Vermeulen et al 2010[54], Cao et al 2017[42] estimated the historical REC levels for the BEIR VI uranium mining cohorts. The cumulative exposure to DE was then estimated for the same period of the radon exposure and the relative risk (RR) was calculated for each BEIR VI uranium mining cohort using the concentration range estimates provided by Vermeulen et al 2010[54] and the exposure-response relationship derived by Vermeulen et al 2014[55] for the DEMS studies.

The cumulative DE exposure (i.e. dose) for the Ontario uranium mining cohort was estimated to have ranged from 190 ug/m^3-years to 598 ug/m^3-years during the period the cohort was exposed to radon (1963-1986). The corresponding relative risk of lung cancer from the estimated DE cumulative exposure (RR_{DE}) ranged from RR_{DE} = 1.20 (95% CI 1.11-1.31) to RR_{DE} = 1.80 (95% CI 1.39-2.32) and was statistically significant.

Cao et al 2017[42] used two models to assess the joint effect of radon and DE on the risk estimates for lung cancer: a multiplicative model that implies that the effect of radon depends on the effect of DE exposure ($RR_{radon, modified} = RR_{radon} \div RR_{DE}$) and an additive model that implies that the effect of radon exposure and DE exposure are considered to be independent ($RR_{radon modified} = RR_{radon} – RR_{DE}$).

Using these models, the estimated cumulative DE exposure ranges and estimated RR_{DE} were calculated using the Vermeulen et al approach[54,55]; the modified exposure-response coefficient for radon (ERR/WLM or $\beta_{radon modified}$) was then calculated for each of the BEIR VI uranium mining cohorts.

Cao et al 2017[42] observed that the modified β_{radon} was reduced in all 9 of the uranium mining cohorts. They concluded that the overall radon exposure-response coefficient (β_{radon}) may be overestimated by 9% to 26% after accounting for exposure to DE. The decline of the β_{radon} varied greatly across each cohort and decreased more with the modification by the multiplicative model (up to 26%) than by the additive model (up to 16%). Generally, the excess risk from radon exposure was reduced more in the mines that had longer duration of exposure and later first year of exposure to radon. This was attributed to the higher DE exposures in those mines estimated from historical data. The Ontario, Chinese, and French cohorts had the greatest decline in β_{radon} which coincided with these cohorts having the highest estimated cumulative exposure to DE. The estimated range of relative risk for lung cancer deaths from DE exposure for the Ontario cohort (RR_{DE} = 1.20 to 1.80) exceeded the relative risk for lung cancer from radon exposure (RR_{radon} = 1.28).[BB]. This finding suggests that historical DE exposure may be a larger contributor to the risk of lung cancer among Ontario uranium miners than exposure to radon.

[BB]*Using the approach outlined in Cao et al 2017, the RR_{radon} for the Ontario uranium mining cohort may be estimated from the ERR/WLM or β_{radon} value of 0.0089 per WLM and the mean radon exposure of 31 WLM:*
RR_{radon}= 0.0089 x 31 WLM + 1 = 1.28

Chang et al 2018[43], This study[CC] reanalyzed the lung cancer mortality reported in the DEMS studies[49,50] using alternative exposure estimates for DE and adjustment for radon exposure. The DE exposures (REC levels) were estimated from diesel engine horsepower data and mine air-ventilation rates rather than the approach used for the DEMS studies[54] that estimated REC levels from historical carbon dioxide (CO) measurements. The average radon exposure levels in the DEMS cohort were low; across all mine types in the complete cohort, the mean radon exposure was 0.008 WL, with mine-specific averages ranging from 0.008 to 0.017 WL[49]. Among ever-underground workers the mean radon exposure intensity was 0.011 WL, ranging from 0.008 to 0.017 WL. Both the original 2012 DEMS study[49] and the 2018 Chang study[43] detected a significant positive association only in the limestone mine and not in the other mines (potash, salt, trona). A nested case-control study based on the DEMS cohort by Silverman et al 2012[50] reported odds ratios of 1.08 (95% CI 0.63-1.84) for cumulative radon exposures ≥ 1.9 and <3.0 WLM and 1.32 (95% CI 0.76-2.29) for ≥ 3.0 WLM versus no exposure to radon.

Without controlling for radon exposure, several statistically significant positive exposure-response associations were found with cumulative REC and average REC intensity, based on both the DEMS REC data and the alternate REC data, among ever-underground workers, surface only workers, and all workers combined, but not among underground-only workers. Controlling for radon resulted in substantially weaker associations between cumulative DE exposure or average DE exposure intensity and lung cancer mortality among ever-underground, underground-only and all workers. Nearly all significant positive associations after control for radon were found only among ever-underground and all workers with cumulative DEMS REC exposure of < 1,280 ug/m^3-years.

The authors concluded that the findings of only positive associations with both REC (without radon adjustment) and the unexpected lack of association with REC among underground-only workers are not readily explained in the context of a positive exposure-response association between REC exposure and lung cancer mortality. The authors attributed the findings for the limestone mine to the high frequency of detectable radon, poor natural ventilation and a unique ore transport system that required high-horsepower diesel equipment. The higher average REC levels in the limestone mine as well as longer exposure due to earlier dieselization could have contributed to the positive associations with REC in that mine only.

Similarly, the weak associations between REC and lung cancer mortality among underground-only workers does not support a positive exposure-response relationship between REC and lung cancer as these workers would be the most heavily exposed to DE. It is also difficult to explain that after adjusting for radon, the only significant association between cumulative REC or average REC intensity was only found among those workers with cumulative REC of < 1,280 ug/m^3-years. Workers with cumulative REC >1,280 ug/m^3-years would have been the oldest and most highly-exposed workers in the cohort and would have been expected to have the highest risk of lung cancer. The observation of positive

---

[CC] *It is important to note that this study was sponsored by a coalition of trade organizations from the Truck and Engine Manufacturers Association*.

associations only after excluding those workers with the highest exposures does not fit with a monotonic exposure-response effect of DE. Chang et al 2018[43] concluded that the mutual confounding between REC and radon makes it difficult to disentangle associations of each exposure with lung cancer mortality.

Other Mining (Gold, Nickel, Copper)

Many of the uranium miners in the Ontario cohort also worked in gold, nickel and copper mines. The 1993 Kusiak et al update[8] of the Ontario Uranium Miners Cohort analyzed the combined effect of mining uranium, gold, nickel and copper in different time periods and these findings are summarized in Table 9.

Table 9 Lung Cancer Mortality in Uranium Miners: combined effect of mining uranium, gold and nickel and copper in different periods

Year miner first mined gold in Ontario	Never mined nickel and copper SMR (95% CI) [number of miners]	Ever mined nickel and copper in Ontario SMR (95% CI) [number of miners]	Total SMR (95% CI) [number of miners]
Never	**230 (1.64-3.09) [6730]**	151 (0.92-2.24) [3226]	**195 (1.49-2.48) [9956]**
≤ 1945	**270 (1.77-3.85) [306]**	**302 (1.85-4.42) [233]**	**238 (2.08-3.70) [539]**
≥ 1946	**177 (1.11-2.59) [1683]**	**287 (1.83-4.11) [1291]**	**221 (1.62-2.90) [2974]**
Total	**223 (1.79-2.72) [8719]**	**227 (1.75-2.86) [4750]**	**225 (1.91-2.62) [13469]**

Source Table 1 in reference 8 (confidence intervals calculated by PS); statistical significant results in bold

The increased mortality from lung cancer in uranium miners who also worked in nickel and copper mines (SMR=227) was similar to the risk for miners who did not work in nickel and copper mines (SMR=223). However, a larger excess of lung cancer deaths was observed in uranium miners who also worked in gold mines compared to uranium miners who never worked in gold mines (SMR=195).

The 2015 update by OCRC confirmed that uranium miners who also had gold mining experience had an increased risk of lung cancer incidence and mortality[15]. As shown in Table 10, when compared to uranium miners with no gold mining experience, those with gold mining experience had an approximately 20% increase in risk of lung cancer incidence (SIR 1.41 compared to 1.18) and mortality (SIR 1.42 compared to 1.25).

Table 10 Cancer Incidence and Mortality in Ontario Uranium Miners with and without Gold Mining Experience

	Incidence (1969-2005) Standardized Incidence Ratio SIR (95% confidence intervals)	Mortality (1954-2007) Standardized Mortality Ratio SMR (95% confidence intervals)
Uranium miners with gold mining experience	**1.41 (1.30-1.52)**	**1.42 (1.31-1.54)**
Uranium miners without gold mining experience	**1.18 (1.08-1.28)**	**1.25 (1.15-1.36)**

Source Tables 9 and 11, reference 15

Arsenic Exposure

Gold mining in Ontario has historically been a major source of exposure to arsenic and RCS[6,8,15,56]. Few measurements of airborne concentrations of arsenic in Ontario mines are available; however, the concentration of arsenic in the rocks from which the gold was mined is known. The concentration of arsenic in the rock found in Ontario gold mines ranges from less than 0.02% to over 1.0%. By comparison, the arsenic in the rocks in uranium mines is much lower and is in the range of 0.01% to 0.06%[8].

The 1991 Kusiak et al Ontario gold mining study[56] found that in gold miners who did not mine uranium, mortality from lung cancer was associated with exposure to RDP in gold mines and to arsenic before 1946 but not with exposure to arsenic after 1946. Analysis of the joint effect of exposure to RDP and arsenic showed that each exposure acted independently so that the risk to a gold miner exposed to both RDP and arsenic is the sum of the risk from each exposure.

In contrast, the 1993 update by Kusiak et al[8] of the Ontario Uranium Cohort concluded that mortality from lung cancer in Ontario uranium miners who also mined gold was associated with exposure to RDP and also exposure to arsenic before and after 1946. For uranium miners whose exposure to RDP (lagged 15 years) was < 40 WLM, the rate of lung cancer increased in a linear fashion which was similar to that found for gold miners who never mined uranium and were exposed to RDP < 40 WLM[56]. However, for uranium miners who also mined gold, and were exposed to RDP (lagged 15 years) > 40 WLM, the association between lung cancer mortality and exposure to arsenic was curvilinear. Lung cancer mortality was observed to increase at a faster rate as exposure to arsenic increased but at higher exposures to arsenic (~> 3.5 % As-year[DD]) the mortality rate levelled off or declined.

The 1993 Kusiak et al uranium mining study[8] suggested that that the timing of exposures to arsenic and radon is important in lung cancer mortality. Their analysis found that in Ontario uranium miners the increased risk of lung cancer death began about 20 years after exposure to arsenic and the risk from RDP exposure began about 5 years after exposure. They pointed out that the dose from radon is delivered to lung tissue within hours of inhalation, but inhaled arsenic may be retained in the lungs for several years, depending on its chemical and physical characteristics. However, it is difficult to measure the timing of the doses to the lung tissue for these exposures based only on the time of exposure in the mines.

Despite these difficulties, the authors concluded that the preferred equation that describes mortality from lung cancer in Ontario uranium miners that combines the exposure from radon and arsenic was:

$$O/E = 1.40 + 0.0096\,(WLM_{5\text{-}14} + 0.49\,WLM_{15+})\,(2.3\,A_1 + A_2 + 0.6\,A_3) + 0.077\,As\,WLM_{15+}\,e^{(-0.011\,As\,WLM_{15+})}$$

[DD] % As-year = percentage (%) of arsenic (As) in the rock x years of exposure

where:

O = number of observed number of lung cancer deaths,
E = number of expected number of lung cancer deaths,
WLM_5 = cumulative exposure to radon lagged 5 years
WLM_{15+} = cumulative exposure to radon lagged 15 years
$WLM_{5-14} = WLM_5 – WLM_{15+}$
As = index of exposure to arsenic lagged 20 years (calculated as % arsenic in rock x years of work underground)
A_1 = 1 when age is less than 55 years and 0 otherwise
A_2 = 1 when age is between 55 and 64 and 0 otherwise
A_3 = 1 when age is between 65 and 74 and 0 otherwise

The current WSIB Policy 23-02-03 “Lung Cancer Among Workers in the Uranium Industry”[57] does not include any consideration of arsenic exposure since it assumed that uranium mines had minimal arsenic exposures.

Appendix 1 WSIB Policy 23-02-03 "Lung Cancer Among Workers in the Uranium Mining Industry"

wsib ONTARIO

Operational Policy

Document Number 23-02-03

Section
Chronic Exposures

Subject
Lung Cancer Among Workers in the Uranium Mining Industry

Policy

Primary cancers of the trachea, bronchus and lung among workers previously employed in uranium mining in Ontario are recognized as occupational diseases under the *Workplace Safety and Insurance Act*. They are both characteristic of uranium mining and result from exposure to ionizing radiation relating to the uranium mining industry.

Guidelines

Among those who have sustained occupational radiation exposure in Ontario mines, the following can provide persuasive evidence that the worker's cancer of the trachea, bronchus or lung (ISCD9 162; ISCD10 C33, C34)* is work-related

- a radiation index of at least 33 for workers diagnosed with these cancers before 55 years of age
- a radiation index of at least 40 for workers diagnosed with these cancers between 55 and 64 years of age
- a radiation index of at least 100 for workers diagnosed with these cancers at 65 years of age or older.

**International Statistical Classification of Diseases (Ninth and Tenth Revisions).*

The radiation index is a time-weighted index of the worker's occupational radiation exposure measured in cumulative Working Level Months (WLM). In calculating the radiation index, all WLM sustained 5-14 years before diagnosis of the cancer and half of WLM sustained 15 or more years before the diagnosis of the cancer are cumulated. All WLM exposures sustained in Ontario employment exposures, be it in uranium mines and mills or in gold mines, are included in the calculation of the radiation index.

A worker's non-smoking status can provide evidence of work-relatedness in the weighing of evidence on the individual merits and justice of the case.

Application date

This policy applies to all claims with an accident date (the date of diagnosis) on or after 1947.

Document history

This document replaces 16-02-04.

Published: 12 October 2004

Application date: All accidents. The accident date for diseases is the earliest date of diagnosis or documented symptoms.

References

Legislative authority

Workplace Safety and Insurance Act, 1997, as amended
Sections 15(1) - (2)

Minute

Board of Directors
#8(XXXIV), June 10, 2004, Page 6622

Appendix 2 Working Level Table (reproduced from Muller 1983 report)

TABLE 1

ANNUAL RADON DAUGHTER CONCENTRATIONS IN MINES

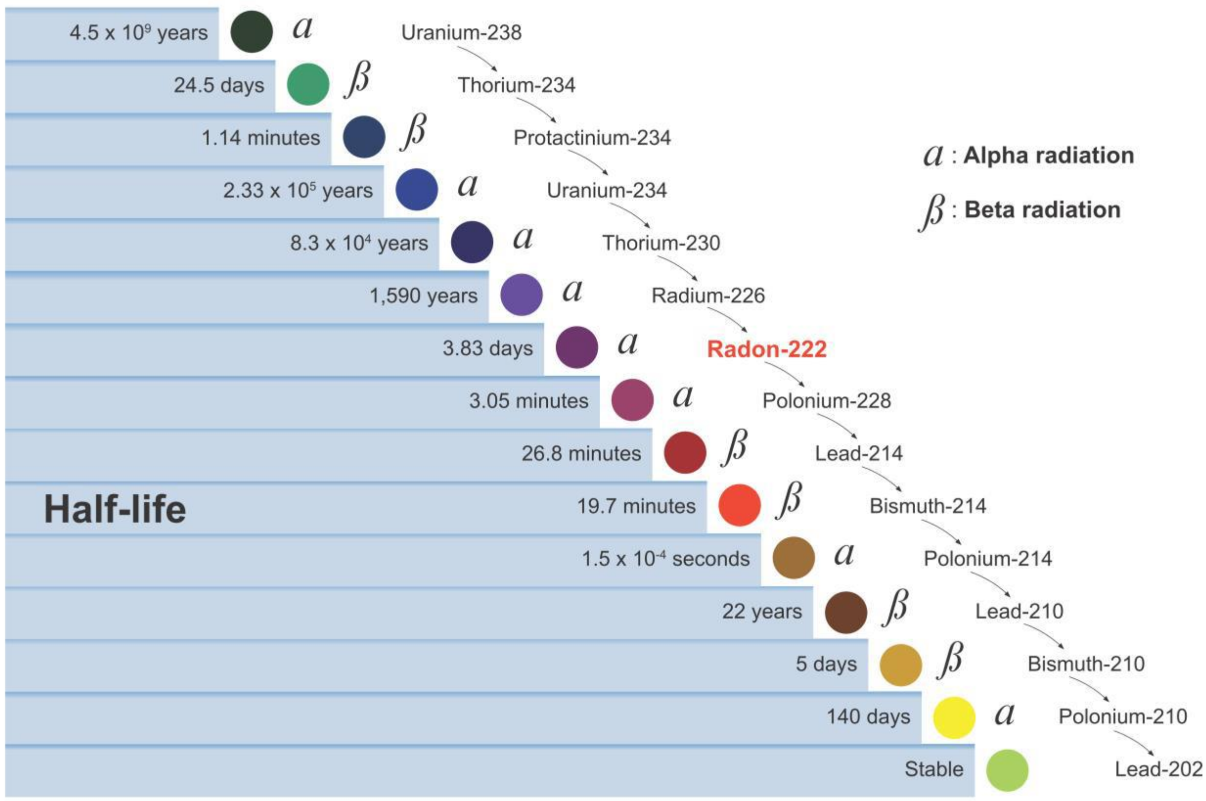
WORKING LEVEL TABLE

MINE NAME & CODE(S)		1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
Bancroft Area													
Canadian Dyno B-1	W.B.F.			1.10	1.10	1.10	1.10	1.10					
	Std.W.L.Mine			8.00	8.00	3.70	1.00	1.00					
	Std.W.L.Cont.			8.00	8.00	4.80	1.10	1.10					
	Spec.W.L.Mine			13.00	13.00	12.86	3.21	3.21					
Bicroft B-2	W.B.F.	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	
	Std.W.L.Mine	2.47	2.47	3.40	1.60	1.90	1.90	0.80	0.50	0.70	0.40	0.40	
	Std.W.L.Cont.	2.47	2.47	3.40	1.60	0.90	0.80	0.70	0.40	0.60	0.40	0.40	
	Spec.W.L.Mine	4.90	4.90	3.40	3.40	4.10	3.06	2.53	1.58	2.12	1.11	1.11	
Faraday (Madawaska) B-1	W.B.F.	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
	Std.W.L.Mine	2.79	2.79	7.00	6.00	4.40	3.60	2.00	1.40	1.30	0.50	0.40	0.40
	Std.W.L.Cont.	2.79	2.79	7.00	6.00	4.40	3.60	1.60	1.40	2.40	0.30	0.30	0.30
	Spec.W.L.Mine	4.18	4.18	16.00	16.00	16.38	13.77	5.79	5.30	3.29	1.80	1.27	1.27
Greyhawk B-4	W.B.F.				1.20	1.20	1.20	1.20					
	Std.W.L.Mine				3.16	3.16	2.41	2.41					
	Std.W.L.Cont.				2.20	2.20	2.80	2.80					
	Spec.W.L.Mine				5.65	5.65	3.98	3.98					
Bancroft Area B-5,B-6,B-7,B-8,B-9	W.B.F.	1.10	1.10	1.10	1.10	1.13	1.13	1.10	1.10	1.10	1.10	1.10	1.10
	Std.W.L.Mine	2.63	2.63	5.20	5.20	3.07	3.00	1.40	0.95	1.00	0.45	0.40	0.40
	Std.W.L.Cont.	2.63	2.63	5.20	5.20	3.08	3.08	1.15	0.90	1.50	0.35	0.30	0.30
	Spec.W.L.Mine	4.54	4.54	9.73	10.00	9.75	5.76	4.14	3.39	2.81	1.40	1.27	1.27
Elliot Lake Area													
Pronto %0	W.B.F.		1.00	1.00	1.29	1.07	0.96	0.96	0.96				
	Std.W.L.Mine		1.70	1.70	1.70	1.70	1.40	1.90	1.90				
	Std.W.L.Cont.		1.70	1.70	1.70	1.70	1.20	0.50	0.50				
	Spec.W.L.Mine		1.70	1.70	2.00	3.33	3.43	4.49	4.49				
Rio Algom - Quirke #1 %1	W.B.F.		1.00	1.00	1.08	1.07	0.98	0.97	0.97				
	Std.W.L.Mine		1.30	1.30	1.30	1.30	0.80	0.70	0.70				
	Std.W.L.Cont.		1.30	1.30	1.30	1.70	0.70	0.50	0.50				
	Spec.W.L.Mine		2.37	2.37	3.60	4.60	1.78	1.47	1.47				
Rio Algom - New Quirke %0	W.B.F.		1.00	1.00	1.08	1.07	0.98	0.97	0.97				
	Std.W.L.Mine		1.30	1.30	1.30	1.30	0.80	0.70	0.70				
	Std.W.L.Cont.		1.30	1.30	1.30	1.70	0.70	0.50	0.50				
	Spec.W.L.Mine		2.37	2.37	3.60	4.60	1.78	1.47	1.47				
Rio Algom - Unspecified %2	W.B.F.		1.00	1.00	1.09	1.07	0.96	0.96	0.95	0.91	0.92	0.90	0.89
	Std.W.L.Mine		1.30	1.30	1.30	1.30	1.05	0.75	0.60	0.50	0.30	0.40	0.50
	Std.W.L.Cont.		1.30	1.30	1.30	1.40	0.95	0.70	0.50	0.50	0.30	0.40	0.50
	Spec.W.L.Mine		2.07	2.07	3.15	4.09	2.93	2.02	2.06	2.18	1.11	1.09	1.15
Rio Algom - Nordic %4	W.B.F.		1.00	1.00	1.09	1.06	0.94	0.94	0.95	0.91	0.93	0.90	0.89
	Std.W.L.Mine		1.30	1.30	1.30	1.30	1.30	0.80	0.60	0.50	0.30	0.60	0.50
	Std.W.L.Cont.		1.30	1.30	1.30	1.50	1.20	0.90	0.50	0.50	0.30	0.40	0.50
	Spec.W.L.Mine		1.77	1.77	2.70	3.50	4.06	2.56	2.06	2.18	1.11	1.09	1.15
Can-Met %8	W.B.F.			1.26	1.26	0.62	1.09	1.02	1.02				
	Std.W.L.Mine			1.50	1.50	0.50	0.60	0.60	0.60				
	Std.W.L.Cont.			1.50	1.50	0.50	0.70	0.50	0.50				
	Spec.W.L.Mine			2.00	2.00	1.00	1.10	1.00	1.00				
Denison %3	W.B.F.			1.27	1.27	1.12	0.99	0.94	0.97	0.95	0.90	0.90	0.93
	Std.W.L.Mine			0.70	0.70	1.30	1.50	3.10	3.30	3.10	2.70	2.90	1.70
	Std.W.L.Cont.			0.70	0.70	1.20	1.30	1.20	3.40	3.10	2.60	3.10	1.00
	Spec.W.L.Mine			2.40	2.40	3.00	4.50	4.20	5.60	4.40	5.10	5.50	4.00
Stanleigh Uranium %5	W.B.F.			0.88	0.88	1.16	1.02	0.99	0.99				
	Std.W.L.Mine			0.50	0.50	0.30	0.50	0.80	0.80				
	Std.W.L.Cont.			0.50	0.50	0.30	0.50	1.00	1.00				
	Spec.W.L.Mine			0.58	0.58	0.64	1.17	1.35	1.35				
Milliken Lake %6	W.B.F.				1.04	1.04	0.95	0.95	0.95	0.91	0.93	1.00	1.00
	Std.W.L.Mine				0.70	0.70	0.70	0.80	0.60	0.60	0.60	0.60	3.10
	Std.W.L.Cont.				0.70	0.70	0.60	0.80	0.70	0.60	0.70	0.70	0.50
	Spec.W.L.Mine				1.39	1.39	1.54	1.89	1.59	1.65	1.41	1.23	10.86
Stanrock %7	W.B.F.			1.01	1.01	1.18	1.10	1.03	1.02	1.00	0.97	1.02	0.89
	Std.W.L.Mine			2.50	2.50	2.50	2.60	2.70	2.90	2.00	1.90	2.00	2.10
	Std.W.L.Cont.			2.50	2.50	2.50	0.10	0.30	0.20	2.70	1.00	1.90	0.50
	Spec.W.L.Mine			4.00	4.00	4.00	4.90	5.00	5.20	5.10	3.00	5.40	4.40
Northspan - Panel %4	W.B.F.			1.41	1.41	1.03	1.01	0.97	1.01	1.01			
	Std.W.L.Mine			1.30	1.30	0.00	1.10	0.90	1.30	1.10			
	Std.W.L.Cont.			1.30	1.30	1.00	1.30	1.00	1.30	1.10			
	Spec.W.L.Mine			1.30	1.30	1.19	2.29	1.50	1.60	1.60			
Northspan - Lake Nordic %5	W.B.F.			1.16	1.16	1.07	0.98	1.01	1.01				
	Std.W.L.Mine			1.00	1.00	0.00	1.00	0.70	0.70				
	Std.W.L.Cont.			1.00	1.00	0.00	1.00	0.20	0.20				
	Spec.W.L.Mine			1.00	1.00	1.70	1.00	1.71	1.71				
Northspan - Spanish Am. %6	W.B.F.				1.19	1.19	0.95	0.95					
	Std.W.L.Mine				0.40	0.40	0.30	0.30					
	Std.W.L.Cont.				0.50	0.50	0.30	0.30					
	Spec.W.L.Mine				1.43	1.43	0.30	0.30					
Northspan - Buckles %7	W.B.F.			1.20	1.20	1.19	1.19						
	Std.W.L.Mine			1.00	1.00	1.20	1.20						
	Std.W.L.Cont.			1.00	1.00	1.00	1.00						
	Spec.W.L.Mine			1.20	1.20	1.57	1.57						
Northspan - Unspecified %3	W.B.F.			1.29	1.29	1.14	0.98	0.99	1.01	1.01			
	Std.W.L.Mine			1.07	1.07	0.80	0.80	0.90	1.10	1.10			
	Std.W.L.Cont.			1.07	1.07	0.82	0.83	0.60	1.10	1.10			
	Spec.W.L.Mine			1.13	1.13	1.49	1.49	1.65	1.60	1.60			
Elliot Lake Area %9	W.B.F.		1.00	1.00	1.16	1.07	1.00	0.90	0.90	0.94	0.95	0.90	0.93
	Std.W.L.Mine		1.43	1.43	1.27	1.07	1.07	1.23	1.70	1.75	1.30	1.00	1.05
	Std.W.L.Cont.		1.43	1.43	1.27	1.12	0.79	0.70	1.10	1.73	1.35	1.53	0.83
	Spec.W.L.Mine		1.95	1.95	3.04	2.41	2.45	3.53	3.21	3.03	2.66	3.36	3.15

MINE NAME & CODE(S)		1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Faraday (Madawaska) B-1	W.B.F.										1.00	1.00	1.00
	Std.W.L.Mine										0.07	0.07	0.15
	Std.W.L.Cont.										0.05	0.05	0.14
	Spec.W.L.Mine										0.07	0.07	0.15
Bancroft Area B-5,B-6,B-7,B-8,B-9	W.B.F.										1.00	1.00	1.00
	Std.W.L.Mine										0.07	0.07	0.15
	Std.W.L.Cont.										0.05	0.05	0.14
	Spec.W.L.Mine										0.07	0.07	0.15
Rio Algom - Quirke #1 %1	W.B.F.	0.97	0.97	0.86	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine	0.20	0.20	0.40	0.30	0.30	0.50	0.60	0.20	0.20	0.21	0.20	0.20
	Std.W.L.Cont.	0.30	0.30	0.40	0.22	0.17	0.39	0.40	0.15	0.16	0.11	0.18	0.17
	Spec.W.L.Mine	0.30	0.30	0.40	0.30	0.30	0.50	0.60	0.20	0.20	0.20	0.20	0.20
Rio Algom - New Quirke %0	W.B.F.	0.97	0.97	0.88	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine	0.20	0.20	0.30	0.25	0.25	0.30	0.40	0.30	0.30	0.20	0.20	0.20
	Std.W.L.Cont.	0.30	0.30	0.30	0.13	0.17	0.25	0.26	0.15	0.16	0.11	0.18	0.17
	Spec.W.L.Mine	0.30	0.30	0.20	0.25	0.25	0.30	0.40	0.20	0.20	0.30	0.30	0.30
Rio Algom - Unspecified %2	W.B.F.	1.00	0.95	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine	0.40	0.25	0.40	0.20	0.27	0.30	0.40	0.20	0.30	0.20	0.20	0.20
	Std.W.L.Cont.	0.40	0.40	0.30	0.22	0.15	0.25	0.26	0.15	0.16	0.11	0.18	0.17
	Spec.W.L.Mine	1.30	0.94	0.40	0.30	0.27	0.30	0.40	0.20	0.20	0.20	0.20	0.20
Rio Algom - Nordic %4	W.B.F.	1.00	0.97	0.92	1.00	1.00	1.00						
	Std.W.L.Mine	0.40	0.50	0.40	0.40	0.20	0.20						
	Std.W.L.Cont.	0.40	0.50	0.30	0.30	0.11	0.11						
	Spec.W.L.Mine	1.30	1.50	0.60	0.40	0.30	0.30						
Denison %3	W.B.F.	0.92	0.90	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine	1.20	1.20	1.10	0.70	0.70	0.60	0.40	0.40	0.40	0.60	0.30	0.70
	Std.W.L.Cont.	1.40	1.30	1.30	0.63	0.71	0.52	0.36	0.32	0.30	0.29	0.22	0.52
	Spec.W.L.Mine	3.00	2.40	1.10	0.70	0.70	0.60	0.40	0.40	0.40	0.40	0.30	0.70
Milliken Lake %6	W.B.F.	1.00											
	Std.W.L.Mine	3.10											
	Std.W.L.Cont.	0.50											
	Spec.W.L.Mine	10.86											
Stanrock %7	W.B.F.	0.90	0.90	0.92	0.92								
	Std.W.L.Mine	2.30	2.00	1.50	1.50								
	Std.W.L.Cont.	0.70	1.10	2.00	2.00								
	Spec.W.L.Mine	4.40	4.30	3.00	3.00								
Agnew Lake %8	W.B.F.								1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine								0.16	0.16	0.41	0.77	0.16
	Std.W.L.Cont.								0.15	0.15	0.39	0.11	0.14
	Spec.W.L.Mine								0.16	0.16	0.41	0.77	0.16
Elliot Lake Area %9	W.B.F.	0.94	0.94	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Std.W.L.Mine	1.30	0.90	0.76	0.40	0.30	0.40	0.40	0.30	0.25	0.36	0.42	0.35
	Std.W.L.Cont.	0.83	0.70	0.60	0.33	0.29	0.34	0.29	0.24	0.22	0.23	0.19	0.36
	Spec.W.L.Mine	3.97	3.15	1.32	0.60	0.50	0.60	0.60	0.30	0.35	0.36	0.42	0.75

N.B. To view the numbers more clearly, consult the original Muller 1983 report[4] and enlarge the view to the desired magnification

Appendix 3 Uranium 238 Decay Chain



source: reference 17

References

1. Lung Cancer Among Workers in the Uranium Mining Industry. Workplace Safety and Insurance Board (WSIB). Policy 23-02-03. October 12, 2004.
2. Muller J, Wheeler WC. Causes of death in Ontario uranium miners. Occupational Safety and Health. 1974;32(29):29-42.
3. Ham JM. Report of the Royal Commission on the Health and Safety of Workers in Mines. Toronto, ON: Ministry of the Attorney General, Province of Ontario; 1976.
4. Muller, J., et al Study of Mortality of Ontario Miners 1955-1977. Part I. Ontario Ministry of Labour, Ontario Workers' Compensation Board, Atomic Energy Control Board of Canada. 1983.
5. BEIR (Biological Effects of Ionizing Radiation) Report IV "Health Effects of Radon and other Internally Deposited Alpha Emitters", National Research Council, 1988
6. Muller J, Kusiak RA, Ritchie AC. Factors modifying lung cancer risk in Ontario uranium miners, 1955-1981. Toronto, ON: Ontario Ministry of Labour; Ontario Workers' Compensation Board; Atomic Energy Control Board of Canada, 1989.
7. Report to the Workers' Compensation Board on the Ontario Uranium Mining Industry. Industrial Disease Standards Panel (IDSP) Report No. 6., Toronto, Ontario February 1989.
8. Kusiak RA, Ritchie AC, Muller J, Springer J. Mortality from lung cancer in Ontario uranium miners. Br J Ind Med. 1993;50(10): 920-928.
9. National Research Council Committee on the Biological Effects of Ionizing Radiation. Health Effects of Exposure to Radon: BEIR VI Report. Washington (DC): National Academies Press (US); 1999.
10. Report to the Workers' Compensation Board on Lung Cancer in the Hard Rock Mining Industry. Industrial Disease Standards Panel (IDSP) Report No. 12., Toronto, Ontario March 1994.
11. Addendum to the Report to the Workers' Compensation Board on Lung Cancer in the Hard Rock Mining Industry. Industrial Disease Standards Panel (IDSP) Report No. 12A., Toronto, Ontario September 1996.
12. Report to the Workers' Compensation Board on Lung Cancer in the Ontario Gold Mining Industry. Industrial Disease Standards Panel (IDSP) Report No. 1., Toronto, Ontario April 1987.
13. Verma, D.K., et al. Dust, radiation and diesel exhaust exposures in Ontario uranium mines and mills. J Environ Occup Sci Vol 4, Issue 2, pg. 70-77.
14. R.R.O. 1990, Reg. 854: Mines and Mining Plants, under Occupational Health and Safety Act, R.S.O. 1990.O.1. Ontario Ministry of Labour. available from eLaws https://www.ontario.ca/laws/regulation/900854
15. Occupational Cancer Research Centre (OCRC) Ontario Uranium Miners Cohort Study Report. prepared for the Canadian Nuclear Safety Commission. February 2015. https://tspace.library.utoronto.ca/handle/1807/74748.
16. Runnalls OJC. Ontario's uranium mining industry: past, present, and future: a report prepared for the Ontario Ministry of Natural Resources. Toronto, Ontario, Canada: Ministry of Natural Resources; 1981.

17. Bissett RJ, McLaughlin JR. Radon. Chronic Dis Can. 2010;29 Suppl 1:38-50.
18. Radon and Health. Canadian Nuclear Safety Commission. Ottawa, ON: January 2012.
19. National Research Council Committee on the Biological Effects of Ionizing Radiation. Health Risks from Exposure to Low Levels of Ionizing Radiation. BEIR VII Report. Phase 2 Washington (DC): National Academies Press (US); 2006.
20. International Agency for Research on Cancer. IARC monograph summary, Volume 78 (2001).
21. International Agency for Research on Cancer. IARC monograph summary, Volume 100 Part D (2012)
22. Boice JD, Cohen SS, Mumma MT, et al. A cohort study of uranium millers and miners of Grants, New Mexico, 1979–2005. J Radiol Prot 2008;28:303–25.
23. Lane RSD, Frost SE, Howe GR, et al. Mortality (1950–1999) and cancer incidence (1969–1999) in the cohort of Eldorado uranium workers. Radiat Res 2010;174:773–85.
24. Rage E, Caër-Lorho S, Drubay D, et al. Mortality analyses in the updated French cohort of uranium miners (1946–2007). Int Arch Occup Environ Health 2015;88:717–30.
25. Schubauer-Berigan MK, Daniels RD, Pinkerton LE. Radon exposure and mortality among White and American Indian uranium miners: an update of the Colorado Plateau cohort. Am J Epidemiol 2009;169:718–30.
26. Tomasek L. Lung cancer mortality among Czech uranium miners—60 years since exposure. J Radiol Prot 2012;32:301–14.
27. Walsh L, Grosche B, Schnelzer M, et al. A review of the results from the German Wismut uranium miners cohort. Radiat Prot Dosimetry 2015;164:147–53.
28. Navaranjan, G,. Berriault, C., Minh Do,. Villeneuve, P.J., Demers P.A. Cancer incidence and mortality from exposure to radon progeny among Ontario uranium miners. Occup Environ Med 2016;0:1–8. doi:10.1136/oemed-2016-103836
29. Rage, E., et al Low radon exposure and mortality among Jouac uranium miners: an update of the French cohort (1946-2007). J Radiol Prot. Vol 38 no. 1, pg. 92-108, March 2018.
30. Kreuzer, M., Factors modifying the radon-related lung cancer risk at low exposures and exposure rates among German uranium miners. Radiation Research. Vol. 189, pg. 165-176, 2018.
31. Lubin JH, Liang Z, Hrubec Z, Pershagen G, Schoenberg JB, Blot WJ, et al. Radon exposure in residences and lung cancer among women: combined analysis of three studies. Cancer Causes Control. 1994;5(2):114-28.
32. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation-UNSCEAR 2006 Report to the General Assembly, with Scientific Annexes A and B. New York, N.Y.: United Nations Publications; 2009.
33. Lane SD et al Low radon exposures and lung cancer risk: joint analysis of the Czech, French and Beaverlodge cohorts of uranium miners. International Archives of Occupational and Environmental Health vol. 92, pg 747-762, 2019

34. Hunter, N., et al. Joint analysis of three European nested case-control studies of lung cancer among radon exposed miners: exposure restricted to below 300 WLM. Health Physics. vol. 104. pg. 282-292. 2013.
35. Bijwaard H, Dekkers F, van Dillen T. Modelling lung cancer due to radon and smoking in WISMUT miners: preliminary results. Radiat Prot Dosimetry. 2011;143(2-4):380-3.
36. Leuraud K, Schnelzer M, Tomasek L, Hunter N, Timarche M, Grosche B, et al. Radon, Smoking and Lung Cancer Risk: Results of a Joint Analysis of Three European Case-Control Studies Among Uranium Miners. Radiat Res. 2011;176(3):375-87.
37. Tomasek L. Lung cancer risk from occupational and environmental radon and role of smoking in two Czech nested case-control studies. Int J Environ Res Public Health. 2013;10(3):963-79.
38. Schnelzer M, Hammer GP, Kreuzer M, Tschense A, Grosche B. Accounting for smoking in the radon-related lung cancer risk among German uranium miners: results of a nested case-control study. Health Phys. 2010 2010/01//;98(1):20-8.
39. Walsh, L., et al. The influence of radon exposures on lung cancer mortality in German uranium miners, 1946-2033. Radiation Research. Vol. 173, pg. 79-90. 2010.
40. Kreuzer M., et al. Lung cancer risk at low radon exposure rates in German uranium miners. British Journal of Cancer. Vol. 113, pg. 1367-1369, 2015.
41. Sogl M, Taeger D, Pallapies D, Bruning T, Dufey F, Schnelzer M, Straif K, Walsh L, Kreuzer M. Quantitative relationship between silica exposure and lung cancer mortality in German uranium miners, 1946-2003. Br J Cancer 2012;107(7):1188-94.
42. Cao X, et al Radon-induced lung cancer deaths may be overestimated due to failure to account for confounding by exposure to diesel engine exhaust in BEIR VI miner studies. PLoS One 12(9) (http://doi.org/10.137/journal.pone.0184298). September 8, 2017.
43. Chang ET et al Reanalysis of Diesel Engine Exhaust in Miners Study Cohort Using Alternative Exposure Estimates and Radon Adjustment. Am J Epidemiol vol 187, no. 6, pg 1210-1219. April 3, 2018.
44. Kabir H, Bilgi C Ontario Gold Miners with Lung Cancer; Occupational Exposure Assessment in Establishing Work-relatedness. JOM, vol 35, no. 12, December 1993, pg. 1203-1207.
45. (IARC) International Agency for Research on Cancer. Diesel and Gasoline Engine Exhaust and Some Nitroarenes. IARC Monographs. Vol. Volume 105, 2013.
46. National Toxicology Program (NTP). Diesel Exhaust Particulates in 12th Report on Carcinogens. http://ntp.niehs.nih.gov/ntp/roc/twelfth/roc12.pdf
47. CAREX Canada Diesel Engine Exhaust - Substance Profile. http://www.carexcanada.ca/en/diesel_engine_exhaust/
48. Pronk A, Coble J, Stewart PA. Occupational exposure to diesel engine exhaust: a literature review. J Expo Sci Environ Epidemiol 2009;19(5):443-57.

49. Attfield MD, Schleiff PL, Lubin JH, Blair A, Stewart PA, Vermeulen R, Coble JB, Silverman DT. The Diesel Exhaust in Miners study: a cohort mortality study with emphasis on lung cancer. J Natl Cancer Inst 2012;104(11):869-83.
50. Silverman DT, Samanic CM, Lubin JH, Blair AE, Stewart PA, Vermeulen R, Coble JB, Rothman N, Schleiff PL, Travis WD, Ziegler RG, Wacholder S, Attfield MD. The Diesel Exhaust in Miners study: a nested case-control study of lung cancer and diesel exhaust. J Natl Cancer Inst 2012;104(11):855-68.
51. Garshick E, Laden F, Hart JE, Davis ME, Eisen EA, Smith TJ. Lung cancer and elemental carbon exposure in trucking industry workers. Environ Health Perspect 2012;120(9):1301-6.
52. Garshick E, Laden F, Hart JE, Rosner B, Davis ME, Eisen EA, Smith TJ. Lung cancer and vehicle exhaust in trucking industry workers. Environ Health Perspect 2008;116(10):1327-32.
53. Steenland K, Deddens J, Stayner L. Diesel exhaust and lung cancer in the trucking industry: exposure-response analyses and risk assessment. Am J Ind Med 1998;34(3):220-8.
54. Vermeulen R, et al, The Diesel Exhaust in Miners Study IV. Estimating historical exposures to diesel exhaust in underground non-metal mining facilities. Annals of Occupational Hygiene. 2010; 55(7):774-88. https://doi.org/10.1093/annhyg/meq025 PMID 20876235
55. Vermeulen R, Silverman DT, Garshick E, Vlaanderen J, Portengen L, Steenland K. Exposure-response estimates for diesel engine exhaust and lung cancer mortality based on data from three occupational cohorts. Environ Health Perspect 2014;122(2):172-177.
56. Kusiak, RA, Springer J, Ritchie AC, Muller J, Carcinoma of the lung in Ontario Gold Miners: possible aetiological factors. British Journal of Industrial Medicine, Vol 48, 1991 pg. 808-817.
57. Lung Cancer-Gold Miners. Workplace Safety and Insurance Board (WSIB). Policy 16-02-07. October 12, 2004.