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Radon and cancer mortality among underground uranium miners in the Příbram region of the Czech Republic

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Abstract

OBJECTIVES: This study aims to estimate the association between radon and cancers other than lung among a large contemporary cohort of uranium miners.

METHODS: Annual occupational radon exposure was estimated based on a worker's duration of underground mining in a year and estimates of potential alpha energy of radon progeny in their location of work. Cancer mortality over the period 1977–1992 was ascertained for a cohort of 16,434 underground uranium miners employed in the Czech Republic between 1946 and 1992. Poisson regression was used to estimate relationships between cumulative radiation exposure (in working level months, WLM) and site-specific cancer mortality.

RESULTS: Radon is positively associated with lung cancer mortality (Excess relative rate (ERR) per 100WLM = 0.2; 95%CI: 0.10, 0.37). The best fit of the dose-response relationship between radon and lung cancer mortality was linear and estimates of radon-lung cancer associations varied by windows of time-since-exposure. Positive associations between radon and several types of

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cancer other than lung cancer were identified, notably Chronic Lymphocytic Leukemia (CLL) (ERR/100WLM = 0.24; 95%CI ND, 5.10) and extrathoracic cancer (ERR/100WLM = 0.12; 95%CI: (ND, 0.69). We observed no associations between radon and stomach cancer, nor between radon an several hematopoietic cancer subtypes.

CONCLUSIONS: This study confirms the established radon-lung cancer association and suggests that radon may also be associated with other types of cancer mortality. Further investigations of extrathoracic and CLL cancer, with the aim of obtaining more precise estimates, are warranted to understand associations between radon and cancers other than lung.

INTRODUCTION

Positive associations between radon exposure and lung cancer have been reported in several studies.[1–3] Radon and its progeny is classified as a Group 1 carcinogen by the International Agency for Research on Cancer.[4] Several cohort studies of underground uranium miners have demonstrated the association between radon exposure and lung cancer, although magnitudes of associations vary somewhat between studies. Four North American cohorts,[5–10] a cohort of Czech miners in Western Bohemia,[11–13] a cohort of French uranium miners,[14–16] and a large cohort study of German uranium miners, similar in size to the pooled Committee on the Biological Effects of Ionizing Radiation (BEIR VI) analysis,[2,17,18] all found strong positive associations between radon and lung cancer.

While several studies of uranium miners have confirmed positive radon-lung cancer associations, more research is needed examining associations at lower levels, lower exposure rates, and under conditions that are representative of modern occupational radon exposures. Compared to many other uranium miner cohorts, the Příbram cohort has a lower average radon exposure and a higher proportion of workers with low cumulative exposures and low exposure rates. And, many Příbram miners were exposed to conditions representative of modern occupational conditions. The International Committee for Radiological Protection (ICRP) currently recommends an occupational exposure limit of 4 WLM per year averaged over 5 years [19], which is reflective of median exposures in the Příbram cohort. Příbram miners also have lower average exposures to other co-pollutants compared to some other uranium miner cohorts. Příbram miners were not occupationally exposed to diesel exhaust exposure and industrial hygiene surveys indicate low silica exposure in Příbram mines due to wet drilling practices (Appendix A) [20–22].

More research on radon-cancer associations other than lung is also needed. Epidemiological studies and dosimetric models suggest that radon progeny may be associated with cancer types other than lung.[2] Human and animal models have demonstrated that inhaled radon results in radon activity in blood, adipose tissue, and organs.[23–25] Radon gas is soluble in water, so inhaled radon progeny enters the bloodstream close to the airway and can cause leukemias through irradiation of T lymphocytes. Radon gas is also soluble in fat, so radon progeny reaches organs through proximity to adipose tissue. [25,26] Dosimetric models show that the liver, kidney, stomach and red bone marrow receive doses of radon progeny, although the doses are orders of magnitude smaller than doses received by respiratory tissues.[27] Prior uranium miner studies have examined solid cancer subtypes other than lung and reported excess mortality from leukemia among miners in a Czech cohort,[20] stomach cancer among German and US miners,[9,28,29] and kidney cancer among French miners.[30] While several uranium miner studies suggest exposure to radon progeny is associated with solid cancer subtypes other than lung, results are not consistent across studies, and several of the positive findings are based on standardized mortality ratios that use external comparison populations. Hematopoietic cancers have also been investigated in some uranium miner cohorts. Investigators studying red bone marrow doses among the German uranium cohort reported associations between high-LET radiation, mostly from radon gas, and myeloid leukemia.[31] In a case-cohort study of Příbram uranium miners, investigators reported positive associations between radon and both all leukemia combined and CLL.[20] Epidemiological studies of nuclear workers and mechanistic evidence suggest that radiation can increase CLL.[32–34]

When radon and its progeny are inhaled, the tissues of the extrathoracic respiratory system also receive radiation doses.[35] The association between cumulative radon exposure and rates of extrathoracic airway cancers has been characterized in only two groups of uranium miners. Recent studies of the Ontario and German uranium miners reported on the association between radon and extrathoracic cancer.[8,36] The German study found a positive association between radon and extrathoracic cancer mortality while the Ontario study found a negative association with extrathoracic cancer incidence and mortality, although both studies had low statistical precision.

Dosimetric and epidemiological studies suggest radon exposure causes cancers other than lung. In this analysis we report on radon exposure-mortality analyses for lung cancer and other types of cancer among a cohort of workers from the Příbram region of the Czech Republic. Previously, two case cohort studies of cancer incidence have been conducted based on this cohort,[20,21] and standardized mortality and incidence ratios have been reported for the full cohort.[37] This is the first report of cancer mortality excess relative rates in the full cohort. This study adds to the understanding of cancer mortality by analyzing a large and historically significant uranium mining cohort routinely exposed levels of radon progeny reflective of modern occupational exposures, examining cancers other than lung, and extrathoracic cancers as a group.

METHODS

Study setting.

Příbram uranium mine operations occurred between 1946 and 1991, during which time over 46,000 workers were employed, producing over 98,500 metric tons of uranium.[22] Workers produced most of the country’s uranium through the collapse of the Soviet Union; and by the 1960s over 70% of all uranium production took place in Příbram (Appendix A).

Cohort definition.

The Příbram miner study is based on information collected from employment records for the Příbram Uranium Industry. Card records were kept for compensation purposes for each worker and subsequently computerized into an employment register containing 41,741 males and 6,106 females. Records included unique personal identification numbers, dates of birth, dates of employment, and location of employment within the mines (e.g., underground, surface, sorting ore).[20,21] Male employees who worked at least 12 months underground between 1949 and 1991, and were alive and residing in Czechoslovakia on January 1, 1977 are included in the follow-up cohort.[20,21]

Exposure assessment.

An annual estimate of exposure to radon progeny, expressed in Working Level Months (WLM), was assigned to each miner based on their duration of underground mining and estimates of potential alpha energy of radon progeny in their location of work. Duration of time spent underground was derived from the Czech Uranium Industry (UI) employment records. Annual radon exposure concentration estimates were based on measurements by the Czech UI using area monitors. Prior to 1968, potential alpha energy was estimated from >50,000 radon gas measurements throughout the mines.[20] Radon gas measurements were converted to working levels using an equilibrium factor based on mine ventilation practices (Appendix A). From 1968 onwards, direct measurements of the potential alpha energy of radon progeny were measured. Over 190,000 direct measurements were taken through the mines between 1968 and 1992.[20] Cumulative WLM of radon exposure was calculated for each miner by summing annual estimates for each year of exposure.

Other exposures.

Diesel fumes and dust are a concern among miners and may cause confounding of radon-cancer associations. Unlike many other mining operations, Příbram miners were not occupationally exposed to diesel exhaust because all vehicles in the Příbram mines were electric (Appendix A). Dust was measured in Příbram mines at least monthly and is described in detail in prior studies.[37] Average area measurements of airborne dust in Příbram were highest in the mid-1950s (but decreased in the 1970s with the introduction of a strong ventilation system. Heavy metals in dust sediments were measured in a pilot study and contained higher levels of lead and lower levels of arsenic compared to the other major Czech mine in the Jáchymov region (Appendix A). The mean concentration of free crystalline silica in the total dust in Příbram was estimated to be 15%, lower than many other hard-rock mines; dry drilling was not common in Czech mines which may have contributed to lower silica levels.

Outcome assessment.

Vital status for the period 1977–1992 was obtained for each worker from the Czech Central Register of Inhabitants using personal identification numbers listed on employment records. Person-time for workers who emigrated after the start of follow-up was censored at the date of emigration. For workers who died in the Příbram region (approximately 30% of all deaths), underlying cause of death was coded by a nosologist. For workers who died outside this region, underlying cause of death was obtained from district death registries, and if possible, hard copy death certificates were obtained. Additional sources of vital status follow up included pensions, UI death records, and medical documentation. Last date of follow-up, and vital status at end of follow-up were coded. Primary cause of death was coded to the International Classification of Diseases, 9th Edition (ICD-9).[20,21]

Outcomes in this analysis were chosen based on epidemiological and dosimetric studies of uranium miners and include lung, stomach, kidney, liver, extrathoracic and hematopoietic cancer subtypes. The category of extrathoracic cancers, defined as all respiratory tissues other than lung and bronchus, is grouped based on the ICRP dose calculations,[35] and includes the nasal passages, larynx, pharynx, oropharynx and mouth.

Statistical analyses.

Miners contributed person-time from the start of follow-up (1/1/1977) until the earliest of the date of death among deceased miners, date of migration out of the Czech Republic, or end of the study period (12/31/1992). Person-years and events were enumerated and analyzed using Poisson regression analyses with single units of person-time, without grouping.[38]

The relationship between cumulative radon exposure (in k categories) and cancer deaths of interest was modeled using the general model form $rate = \exp(\beta_0 + \sum_{i=1}^{k-1} \beta_i d_i + \sum_{j=k}^{p-1} \beta_j x_j)$. $\beta_1 - \beta_{k-1}$ represents the log relative rate (RR) of cancer mortality per category of lagged cumulative radon exposure in k groups (relative to the referent group). β_0 is the log rate of cancer among workers with the referent level of cumulative WLM, and β_j are parameters for effects of the p covariates x_j. Cumulative WLM was categorized as <25, 25 - <50, 50 - <150, and 150+ WLM for subtypes of interest except lung cancer. Due to the larger number of lung cancer deaths, lung cancer rates were modeled with more exposure categories (<15, 15-<25, 25-<50, 50-<75, 75-<100, 100-<150, 150-<200, 200-<250, 250+ WLM). A log-linear model was fit for continuous dose, $rate = \exp(\beta_0 + \beta_1 d + \sum_{j=2}^{p} \beta_j x_j)$ where β_1 represents the log RR of cancer mortality per unit of lagged cumulative radon exposure and β_j are parameters for effects of the covariates x_j. To account for an induction and latency times, 2-, 5- and 10-year lags were applied to cumulative radon exposures. Model fit and precision were used to determine final lag-time choice.

Linear excess relative rates (ERR) and 95% CIs were estimated by fitting a model for the association between continuous cumulative WLM and deaths by cancer types of interest. ERRs were obtained using a model form $rate = \exp(a_0 + \sum_{j=2}^{p} a_j x_j)(1 + a_1 d)$ where a_1 is the ERR per unit of lagged cumulative radon exposure d, and a_j are parameters for effects of the covariates x_j. Variation in the radon exposure-cancer mortality association with time-since-exposure was examined in analyses of lung cancer mortality; three windows of exposure (10–20 years, 20–30 years, and 30+ years) were modeled using a model form $rate = \exp(a_0 + \sum_{j=4}^{p+2} a_j x_j)(1 + \sum_{i=1}^{3} a_i d_i)$ where a_i represents ERRs per unit of lagged cumulative radon exposure in time windows d_i and a_j are parameters for effects of the covariates x_j.

Potential adjustment variables included age, year of follow-up, birth cohort groups (by decade of employment starting in 1890), duration of employment, and time since exposure. Model fit was assessed using Akaike information criterion (AIC). Due to the small number of measured potential confounders, the final adjustment set was mainly informed by a

Directed Acyclical Graph (DAG) with the aim of selecting the most parsimonious model. For most cancer outcomes, a model with log-age and birth cohort terms was the best fit; some cancer outcomes with few deaths had improved fit when excluding birth cohort terms or including interaction terms between birth cohort and age.

In sensitivity analyses of the lung cancer models, cumulative WLM was restricted to workers with <250 WLM to evaluate the impact of a small proportion of workers with very high exposure estimates. All statistical analyses were conducted using SAS statistical software (SAS 9.4; SAS Institute Cary, NC); PROC NLP and PROC NLMIXED with an iterative search were used to obtain profile likelihood CIs for RRs and ERRs, respectively. CIs were considered not determined (ND) if the lower CI was less than the negative inverse of highest cumulative exposure, −0.09.

RESULTS

16,434 male underground uranium miners met cohort inclusion criteria. They contributed 231,499 person-years during 16 years of follow-up. During follow up, 25.6% of workers died. Cause of death was available for 89.6% of deceased workers. Mean duration of employment was 7 years and mean cumulative radon exposure was 53 WLM. During follow-up, 1,416 malignant causes of death were identified (Table 1). This included 705 lung cancer deaths, 102 stomach cancer deaths, 59 extrathoracic cancer deaths and 58 hematopoietic cancer deaths (Table 2).

Figure 1 shows RRs and 95% CIs for the association between cumulative radon exposure under a five-year lagged exposure assumption and lung cancer mortality using log-linear RR models and linear ERR models. The highest RR was observed in the 200 to <250 WLM category (RR=1.88; 95%CI:1.23,2.87). A log-linear RR model with continuous exposure was best fit with a quadratic term for WLM (Table 2, RR at 100WLM=1.31; 95%CI:1.17,1.48). The linear model of ERR is also plotted in Figure 1. Lung cancer mortality increased with higher cumulative radon exposure (ERR/100WLM=0.22; 95%CI:0.10,0.37). Lung cancer results were not sensitive to exposure lag assumptions, such that 2, 5- and 10-year exposure lag assumptions yielded comparable estimates of association. Estimates with five-year lag assumptions were reported in order to be more directly comparable to estimates from other studies.

Lung cancer results by windows of time since exposure and restricted to cumulative radon exposure less than 250 WLM is shown in Table 3. Results were sensitive to restricting the model to workers with less than 250 cumulative WLM, which increased the ERR per 100 WLM to 0.32 (95%CI:0.11,0.53). Windows of exposure, where only exposures within specific time intervals are considered relevant,[39] showed substantial variations in rates across windows. In the 15 to 30-year window prior to case failure, the radon-lung cancer association was highest (ERR/100WLM=0.44;95%CI:0.21,0.67). In the 30+ year window prior to case failure, the radon-lung cancer association was lowest (ERR/100WLM=0.05; 95%CI:−0.11,0.20).

We examined cancer subtypes other than lung. Linear ERRs for other outcomes of interest are in Table 2. Positive but imprecise associations were observed between cumulative radon exposure and extrathoracic airway (ERR/100WLM=0.12; 95%CI ND,0.69), liver (ERR/100WLM=0.06; 95%CI:ND,0.58), kidney cancers (ERR/100WLM=0.01; 95%CI:−0.05,0.70), and chronic lymphocytic leukemia (CLL) (ERR/100WLM=0.24; 95%CI:ND,5.10). Log-linear RRs were similarly positive but imprecise for these subtypes. RRs for subtypes other than lung were assessed by categories of cumulative radon exposure (Appendix B Table 1). Although RRs are imprecise, there is suggestion of a linear dose response between for CLL and extrathoracic cancer mortality.

DISCUSSION

We identified strong associations between radon and lung cancer mortality, and suggestive associations between radon and cancer mortality other than lung, namely extrathoracic cancers and CLL. Liver cancer was also elevated but the magnitude of the association was lower compared to lung and extrathoracic caners or CLL. This study provides additional evidence regarding the positive exposure-response relationship between radon and lung cancer mortality. While the association between radon and lung cancer mortality has been observed in several other cohorts of uranium miners, estimates vary across studies as cohorts have different levels of radon exposure, rates of exposure, co-exposures, and smoking rates. This study provides lung cancer mortality estimates among a cohort of miners with low radon exposures and relatively few co-pollutants. Lung cancer mortality persisted throughout follow-up in this cohort despite having lower radon exposures than several other uranium miner studies.

Similar to other studies of uranium miners, a positive exposure–response relationship was observed between cumulative radon exposure and lung cancer mortality. Characteristics of several recently updated cohorts and the BEIR VI report are shown in Table 4, which illustrates the variation in estimates between cohorts. The BEIR VI analysis includes 11 cohorts of several types of miners, with a total of 60,606 workers. BEIR VI reports a mean cumulative radon exposure of 164.4 WLM and a combined ERR/100WLM of 0.76.[2] Studies of the French, German, and Ontario uranium miners have been updated since the BEIR VI report. A study of 1,785 French uranium miners with a mean 71.3 cumulative WLM radon exposure reported an ERR/100WLM of 0.6 (95%CI:0.1,1.2).[15] In the study of 58,987 German uranium miners with a mean 5-year lagged exposure of 280 WLM among the exposed, an ERR/100 WLM of 0.19 (95% CI:0.17,0.22) was reported.[40] Among the Ontario miners, an ERR/ 100WLM of 0.66 (95%CI:0.44,0.87) was reported in the cohort of 28,546 workers with a mean 21 WLM lagged 5 years.[8] This study, the BEIR VI pooled analysis, and recent studies of the French, German and Ontario cohorts all support a positive association between radon exposure and lung cancer mortality.

While estimates in this study are consistent with those of other studies, estimates in this study may be lower because follow-up began long after the start of mining operations. This means lung cancer deaths prior to the start of follow up are unobserved for 30 years after the start of mining operations. This has several implications for the interpretation of results, particularly among the earliest birth cohorts. Workers who were employed at the start of mining operations had higher average radon exposures because they worked prior to the implementation of a strong ventilation system. The older workers who were alive at the start of follow-up survived the peak epidemic of lung cancer, which likely occurred prior to the start of follow up for these workers. Older workers also may have experienced more competing risks due to advanced age. Birth cohort and interactions between age and birth cohort were important adjustment variables in linear lung cancer models. This may reflect missed deaths in the early birth cohorts that occurred prior to the start of follow-up. Thus, cohort selection criteria and limited duration of follow up may have contributed to lower lung cancer mortality estimates than in other recent studies. Additionally, cause of death was missing for 10.4% of deceased workers, which reduces power and decreases sensitivity of the death certificates.

While overall ERRs were somewhat lower than in other uranium miner studies, estimates were higher when adjusted for time since exposure and when restricted to workers with less than 250 WLM. ERR estimates varied substantially by windows of exposure with the highest estimate when exposures in the 15 to 30-year window. Variation in risk with time since exposure has been observed in other uranium mining cohorts, including the West Bohemian Czech cohort, which reported substantial variations in estimates by time since exposure, with a decrease in ERR/WLM with increasing time since exposure.[41,42] We observed a higher ERR for lung cancer when we restricted the cohort to miners with lower cumulative exposures, which has also been observed in studies of sub cohorts of miners who worked in periods of lower exposures.[30,43]

Cancers other than lung have been investigated in several other uranium mining cohorts, as well as among Příbram miners. Two analyses of cancer incidence among the Příbram miners have been published to date.[20,21] One report examined incidence of leukemia, lymphoma, and multiple myeloma in a case-cohort study with a stratified random subcohort of 2,393 workers and 177 incident hematopoietic cancer cases, of which 53 were CLL cases. This study found an elevated rate of leukemia, including CLL. Authors reported an RR of 1.75 (95% CI:1.10,2.78) for all leukemia combined and an RR of 1.98 (95% CI:1.10,3.59) for CLL comparing high radon exposure (110 WLM) to low radon exposure (3 WLM). Suggestive associations of radon exposure with myeloid leukemia and Hodgkin lymphoma were also found.[20] The present study supports the CLL incidence findings from the incidence study of Příbram miners, although several differences exist. CLL has a high relative survival;[44] there are 42 fewer CLL fatalities than incident cases. Extended follow up will be important for understanding radon-CLL associations in this cohort because median age at diagnosis of CLL is 70 years, and average age at end of follow up among Příbram miners is 58.

Extrathoracic cancer is another area of concern since inhalation of radon and its progeny delivers radiation to the respiratory tract, and the German study of uranium miners suggests radon may be associated with extrathoracic cancer mortality.[35,36] Two other uranium miner cohorts have recently studied extrathoracic cancers as a group with conflicting results. A study of extrathoracic cancer among Ontario uranium miners found negative but imprecise associations with both incidence (ERR/100WLM =−0.29; 95%CI: −0.57,0.00) and mortality (ERR/100WLM=−0.17; 95%CI:−0.64,0.30).[8] Another recent study of extrathoracic cancer mortality among German uranium miners showed a small but imprecise increase (ERR/100WLM=0.04; 95%CI:−0.01, 0.08).[36] Another case-cohort study of Příbram miners found no association between radon exposure and the incidence of non-lung solid cancers except for malignant melanoma and gallbladder cancer, but examined extrathoracic cancers only by individual subtypes, reporting no statistically significant associations.[21] The present study also did not identify any statistically significant positive associations with non-lung solid cancers. However, there are several suggestive associations, particularly for the group of extrathoracic cancers. The combined study of extrathoracic cancer incidence in the case cohort study of Příbram miners will be an important direction for future research, as more incident cases and more detailed exposure estimates should improve the precision of estimates.

In this cohort of miners exposed to relatively low radon levels and with less occupational co-pollutants compared other uranium mining cohorts, we see that the associations between radon and lung cancer persist. This study supports other findings that low-level, protracted radon exposure causes lung cancer. We also examined other cancer sites associated with radon inhalation in the epidemiologic and dosimetric literature and identified extrathoracic cancers and CLL as possible areas of concern. Extended follow-up of this cohort will improve the precision of these findings and allow for observation of cancers protracted induction and latency. This study illustrates the importance of the continuing to monitor both historical and contemporary populations of underground workers.

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APPENDIX A

This appendix contains an internal report drafted by researchers at the US National Institute of Environmental Science. It is an informative historical document describing the occupational hazards experienced by Czechoslovakian uranium miners. The report was completed circa 1995, and to the best of our knowledge, never submitted for journal peer review. Drs. Eva Hnizdo and Dale Sandler approved the inclusion of this document as an appendix to the main manuscript and edited the document for clarity. We include this document to provide researchers with valuable information about social and working conditions in the Příbram mines and other mines in the former Czechoslovakia. It should be considered a historical document rather than a peer-reviewed manuscript. We suggest the following citation for this appendix information:

Hnizdo E, Smetana J, Sandler DP, *et al.* Czechoslovakian uranium miners: description of working conditions and exposure levels. National Institute of Environmental Sciences, ca 1995. In Appendix A of Kelly-Reif K, Sandler DP, Shore D, *et al.* Radon and cancer mortality among underground uranium miners in the Příbram region of the Czech Republic.

Czechoslovakian uranium miners: description of working conditions and exposure levels

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Introduction

Epidemiologic studies of Czechoslovakian uranium miners in Western Bohemia (Jáchymov and Horní Slavkov) have shown that these miners have higher mortality from lung cancer for a given level of radon exposure than other cohorts of uranium miners (Ševc et al., 1988; Tomašek et al., 1993). The Czechoslovakian authors concluded that radon was the primary cause of excess lung cancer mortality among Czechoslovakian miners, while other researchers were concerned that additional occupational risk factors and smoking were the cause of excess lung cancer mortality (Ševc et al., 1984; Cohen, 1982). Although many papers have been published on the lung cancer risk in these miners, the working conditions and the measurements on which the exposure estimates were based have never been properly described (BEIR IV, 1988). Previous studies were limited by the lack of information relating to the uranium industry, which in general was regarded by the authorities as a secret state activity, and by the censoring of published information. After the collapse of the communist regime in 1989, extensive archives of documents including medical files, personal exposure records and other information became available to the larger scientific community.

The purpose of this paper is to provide a brief review of the documents and literature describing working conditions in the Czechoslovakian uranium mines, the development of radiation safety measures, and the measurements of radiation, dust and other potential exposures in the mines. We also present results from a pilot study that was designed to asses completeness and accuracy of the records on radiation, dust and smoking, and to assess the feasibility of further epidemiologic studies of the miners. Attention is paid primarily to the mining regions of Jáchymov and Příbram, as these regions employed a large proportion of the total number of the uranium miners, and also because the miners from these two regions have been the subject of published studies (Ševc et al., 1993).

Brief historical introduction

The development of uranium mines in Joachymsthal (Jáchymov) in the former Czechoslovakia was historically linked with the discovery of radium and radioactivity. Jáchymov's mining tradition dates to the 12th century and up to 1880 when silver, and in lesser amount cobalt, bismuth, arsenic and nickel, were mined there. Uranium ore mining started in 1880 to be initially used in the production of uranium colors, and from 1908 to 1938 in the production of radium. During this period, the uranium miners from Jáchymov became known for having high mortality from lung cancer (Pirchan et al., 1932). During World War II, Germans occupied the mines and continued the radium production.

During Cold War years, uranium became an important factor in the race for nuclear superiority between the former Soviet Union and the West. Immediately after the war, the Soviet Union staked a claim to the Czechoslovak uranium by the Red Army occupation of the mines in Jáchymov. In November 1945, the Czechoslovak government signed a secret treaty with the Soviet Union, which guaranteed to the Soviet Union a monopoly over the uranium wealth of Czechoslovakia (Kaplan et al., 1993). The subsequent communist takeover of Czechoslovakia in 1948 guaranteed to the Soviet Union total control over the uranium mining. At the time of signing of the treaty, the uranium deposits, estimated on the basis of the Jáchymov deposit, were thought to be small. In the end, the total uranium production from Jáchymov (6,065 tons), constituted only a small fraction of the total Czechoslovakian yield of uranium of 98,481 tons produced to 1990 (Pluskal, 1992). Extensive explorations from 1946 to 1967 found four other major regions (Horní Slavkov in 1946–48, Příbram in 1947–49, Dolní Rožínka in West Moravia in 1957, and Hamr in Northern Bohemia in 1960), and many minor deposits (CDU, 1984).

The Soviet takeover of the management of the mines from 1945 started a period of frenzied development, during which uranium production had priority over human lives, not to mention miners' health. Although the uranium production during the first ten years was relatively small (see Figure 1), its impact in terms of human suffering and the size of the population adversely affected was the greatest when compared to later periods (Kaplan et al., 1993).

By the early 1960s, the pressure for high production eased. Relaxation of the political climate, and the realization that uranium miners had high mortality from lung cancer (Řeřicha et al., 1966), resulted in a gradual improvement in working conditions during the 1960s.

Up to 1955, most of the uranium produced in Czechoslovakia came from Jáchymov; thereafter, the Příbram mining region became increasingly more important. By 1960, the mines in Jáchymov were closing down and the administrative and medical centers for the uranium industry moved to the town of Příbram. Like Jáchymov, historically, Příbram is also a mining town, with a silver mining tradition dating to the 14th century. From 1949, uranium mines were developed there, but in a different locality than the old silver mines. It became clear from the start that the size of the uranium deposit merited a larger investment in modern technology, leading to higher production and better working conditions. Eventually, the Příbram deposit was the largest mined deposit in Czechoslovakia and produced 40–70% of the total uranium mined from 1955 to 1990. Although the mining methods used in Příbram were relatively safer and less labor intensive, the potential impact on health was nevertheless large because of the size of the uranium production. In the 1980s, approximately 40% of all incident occupational cancers in Czech Republic were attributed to employment in the Příbram mines (Pacina et al., 1989). Figure 1 shows the total yearly uranium production from 1946 to 1991 in Czechoslovakia.

The collapse of the communist block diminished the strategic importance of uranium production. The public awareness of the economic losses and of the environmental damages due to uranium mining led to the closure of most of the uranium mines in Czechoslovakia in 1991.

General working conditions and populations at risk

The high demand for uranium during the year 1946 resulted in a critical shortage of miners. As a temporary measure, about 5,000 German prisoners of war were transferred secretly from the Soviet Union to work in Jáchymov mines. They represented a large proportion of the underground workers during the years 1946–49. In 1949, according to an international treaty, these prisoners returned to Germany (Urych, 1965).

As a solution to the resulting labor shortage, the executive committee for the mines, which was dominated by Soviet personnel, decided to use convict labor, and requested 5,000 prisoners from the Czechoslovakian government. To that end, the penal system of the country was modified to permit arrests and a speedy processing of the requested number of men. The demand for prisoners increased yearly, reaching its peak in 1954 with a request for 17,000 men. The actual number of prisoners working in uranium mines was around 6,000 by the end of 1950, 9,500 in 1951, 14,000 in 1952, 16,000 in 1954, 11,000 in 1955 and 6,800 in 1956. Convicts, a large proportion of whom were labeled by the communist justice system the “enemies of the people”, were simply generated in accord with the demand for uranium production by the Ministry of Interior (Kaplan et al., 1993). It was not uncommon for a political prisoner to serve ten years in the uranium mines. During the first half of 1950s, prisoners constituted almost 50% of the underground workforce. In addition, a large number of volunteer workers, attracted by relatively high wages, circulated through the system. Only a small proportion of underground workers were experienced miners.

Working conditions in Jáchymov were harsh and dangerous. The employment of unskilled labor and the high intensity of work resulted in a deterioration of the technical aspects of mining and in a disregard of the basic safety rules. The occurrence of deadly accidents was high; many of these were caused by handling of explosives or from exposure to poisonous gases after blasting. Blasting was done in a haphazard way during shifts. Physical exertion was often extreme, as most of the work, including transport of ore, was done manually. Good quality ore was manually hammered out, sorted and loaded into wooden crates that weigh up to 160 kg when full. Hand-held pneumatic drills were used, and many miners suffered from vibration induced diseases. Wet drilling was prescribed, but the constant exposure to cold water resulted in traumatic vasoneuroses, consequently water was often switched off, which led to dustiness. Underground humidity, caused by abundant underground springs, was well over 80%. Other adverse factors, affecting most acutely the prisoners, included a constant shortage of food, inadequate clothing and housing, stress from harassment, and chronic lack of sleep resulting from night shifts, long outdoor assemblies under any weather, and a lack of privacy (Kaplan et al., 1993).

From the start, the working conditions and productivity in Příbram were better than in Jáchymov. The mines were newly developed and better designed in terms of ventilation and mechanized transport. The rapid expansion into depth resulted in overheating, and thus better ventilation and air cooling were introduced. Only hand-held pneumatic drills were used up to the end of 1960s, thereafter drills with support and pneumatic drilling carts were introduced. From the start, transport of the ore was done by electric locomotives. Surface jobs with radiation exposure included ore sorting and ore transport.

Instability of the working population in the uranium mines was high. In 1956, for example, there were 19,936 newcomers (surface and underground), 19,088 workers left and only 14,000 workers remained during the year (Kaplan et al., 1993). It is estimated that approximately 95,000 volunteer workers were employed in Jáchymov and Horní Slavkov (a smaller deposit next to Jáchymov) up to 1960, and about 50% of these were underground workers (Ševc et al., 1972). After the closure of the mines in Jáchymov in 1960, many miners transferred to other regions, especially to Příbram.

The total number of workers employed in Příbram from 1948 to 1992 was 46,948, of whom 40,956 were males and approximately 19,400 worked underground. Figure 2 shows the number of underground workers employed in the mines in Jáchymov and Příbram, by year, and illustrates in conjunction with Figure 1 the labor intensity in the Jáchymov mines.

All volunteer employees of the uranium industry are recorded in employment registries, now archived in Příbram. Prisoners are not included; their work records are kept by the Ministry of Interior, and include information on length of imprisonment, labor camp where imprisoned and job held. The exception are prisoners employed in Příbram from 1968, who have the same personal dosimetric cards as other workers. The precise number of prisoners employed in the uranium mines is still not known. The prisoners' morbidity and mortality has never been studied.

Description of uranium deposits in Jáchymov and Příbram

The uranium deposit in Jáchymov, Western Bohemia, forms only a small part of a deposit that lies mainly in Germany. The length mined on the Czech side is about 15 km. The deposit consists of a system of veins up to 30 cm wide and 1 km long, formed by volcanic hydrothermal processes in the contact zone between a large volcanic granite and bordering sediments. Uranium ore in the veins was often found as a soft black substance containing lots of water. Other metals found in the mines are silver, bismuth, nickel, cobalt, arsenide, sulpha-arsenide and carbonates. The maximum depth of mining reached 600 m.

Příbram is situated in the Central Bohemia, 60 km south west of Prague. The length of the mined deposit reached 25 km. The deposit consists of veins formed by volcanic hydrothermal processes in the contact zone between the Central Bohemian volcanic granite and the bordering sediments deposited in the Příbram valley (anticline). The uranium veins have mostly vertical inclination (65–90 degree), and their usual thickness ranges from several cm to about 1 m, but in extreme cases can reach up to 12 m. The uranium ore in the veins was formed into irregular flat bodies, called “lenses”, with dimensions ranging from one to several hundred meters; these were “peeled off” the wall. The richest vein was mined to depth of 1450 m and the productivity in some places was up to 100 kg of uranium per m^2 (Pluskal, 1992). The lode rock consisted mainly of calcite and uranite; less frequent were galenite, uranium anthraxolite, pyrite and sphalerite. Other accompanying minerals include siderite, ankerite, hematite, goethite, pyrite, and small amounts of arsenide, allemontite and quartz (CDU, 1984).

The main method of mining was “cut-and-fill” stoping (from bottom), with the waste rock piled at the bottom of the stope. The mined blocks, about 50 × 50 minimum dimension, were separated by chutes used for ventilation and transport. The usual width of the stope ranged from one to two meters. It took about a year to complete one block and usually a crew worked one block from the start to the finish.

Development of radiation safety methods and legislation

By the 1920s, the radon exposure in the uranium mines was linked with the high mortality from lung cancer in the uranium miners (Löwy, 1929). First measurements of radon concentration in mines in Jáchymov were done in 1924 (Běhounek, 1927; 1970) and further measurements were made during the years 1928–34. The measured concentrations ranged from 300 to 9,100 pCi/liter (11,100–336,700 Bq/m^3), see Table 1. From 1931, mechanical ventilators were installed in areas with high radon concentration. In 1938, the so called “Karlovy Vary (Carlsbad) Act” set the limit of concentration for radon to 2 Mache units (about 730 pCi/liter= 27,000 Bq/m^3). It also prescribed use of artificial ventilation in workplaces where Rn concentration reached 3 Mache units (about 1,090 Pci/liter= 40,000 Bq/m^3). Table 1 indicates that the prescribed measures resulted in some improvement.

During the years 1948 to 1952, the radon concentrations were substantially higher than the limit set by the Karlovy Vary Act, and the pre-war levels. Table 1 shows the yearly average radon concentrations recorded in Jáchymov mines from 1924 to 1962. Tables 1 and 3 show that from 1948 to 1950 the concentration of Rn activity was high, on average 1,238 pCi/liter (45,806 Bq/m^3), with upper limit reaching 28,902 pCi/liter (1.07xlo6 Bq/m^3). In the stopes, the yearly averages during the years 1949–52 were 1928, 1103, 988 and 725 pCi/liter, respectively. Mainly natural ventilation was used up to 1955; only in 1955 did the ventilation system in some mines achieved required capacity. In addition, the mines in Jáchymov often connected to old gullies, which contaminated the workplaces with radon.

In Příbram mines, the radiation safety measures were more stringent then in Jáchymov. In the early 1950s, when the deposit was mined under the surface, mainly natural ventilation was used (Polášek et al., 1969). The average radon concentration was 1,058 pCi/l, but the number of exposed workers was small. With increasing depth of mining, the natural ventilation was supplemented with local electric blowers which helped to decrease the concentration of radon in the work areas. Tables 2a and 2b show the yearly averages for the mines in Příbram. The higher ventilation capacity was necessary also to keep the temperature low in deeper areas. Figure 3 shows the trends in radon exposure in mines in Příbram and Jáchymov in terms of working level unit (WL).

The radon concentration limit of 730 pCi/liter set in 1938 was valid until 1957. A new law issued in 1957 decreased the limit to 100 pCi/liter (3, 700 Bq/m^3). It also prescribed use of "a workplace hygienic card" for each uniquely identified workplace, where measurements of radon concentration, airflow, and total airborne dust concentration were to be recorded at least monthly. In 1961, the limit for radon concentration was changed to 30 pCi/liter (1, 110 Bq/m^3) for newly established mines only (Vancl, 1985). However, in the early 1960s, the existing ventilation system became obsolete for the expanding mining structure. To achieve the limit of 100 pCi/liter, more powerful suction ventilators and better systems of air distribution had to be built, and it took almost ten years to achieve the limit set in 1957, see Figure 3 and Table 2a.

In 1965, the International Commission on Radiological Protection (ICRP) recommended a maximum admissible radon concentration of 0.3 working level (WL) (6.4 μJ/m^3) (1 WL=potential α-energy of radon progeny present in 1 liter of air that is equivalent to 1.3×10^5 MeV of energy) (ICRP, 1965). Consequently, a law introduced in 1966 in Czechoslovakia set the limit for individual exposure, in terms of time-weighted average early potential-alpha-energy concentration (PAEC), as 4.0×10^4 MeV/liter (0.31 WL). From 1967 to 1968, the measurements of PAEC gradually replaced those of Rn concentration.

Between 1966–67, personal "dosimetric cards" were introduced. These recorded monthly the number of shifts spent in a workplace, measurements of the PAEC and total airborne dust in that workplace, and the gamma-radiation exposure (measured by film badges in workers with high risk). Miners whose yearly average PAEC exceeded 0.31 WL were moved to a less exposed area or to the surface. However, the retrospective method of control of yearly exposure permitted a relatively large number of miners to exceed the yearly limit. In early 1970, a more powerful ventilation system was introduced, whose main principles were regular interchange of air inflow and outflow gullies, the use of more powerful air blowing ventilators, and the use of fresh air inflow into each workplace.

From 1975, exposure limits were set in terms of the inhaled PAEC per year, assuming inhalation of 9,600 liters of air per shift. The limit value was set to 9×10^{10} MeV (3.4 WL months (WLM) per year), and from 1981 to 8×10^{10} MeV (3.0 WLM per year). Personal exposure was assessed monthly, and miners who reached the scheduled cumulative limit were moved to a less exposed workplace. Thus from 1975, the exposure limits were generally not exceeded (Vancl, 1985).

The population exposed each year is shown in Figure 1. Between 1968 and 1975, all workers with more than ten years of underground exposure before 1968–75 were retired. The workers hired after 1968 were mostly young, in the 20–25 age category.

Estimation of radon exposure

In the late 1960s, the uranium industry used existing records of radon concentration to construct tables of yearly averages for each mine, and estimated radon exposure of individual miners by applying these to the number of shifts a person worked in each mine. Table 1 shows the yearly average concentrations of ^{222}Rn (measured in pCi/liter) for the mines in Jáchymov, and the total number of measurements on which the mine means were based. To verify the averages, we used all available archived measurements for Jáchymov and were able to calculate averages for years 1948–1952, see Table 3, and averages for years 1924–34, see Table 1. Generally, there is good agreement between the two tables. The lower value for 1948 can be explained by the fact that the preserved records were from winter months, when outside cold air increases the natural air circulation in mines.

Table 2a shows the yearly averages for the Příbram mines, in terms of Rn concentration up to 1968, and Table 2b shows the PAEC of radon progeny from 1969. The yearly averages have been calculated also for four main types of workplaces in each mine. Again, we used original laboratory records from 1957 to recalculate radon concentration for the largest and deepest mine that had the worst hygienic conditions (Bytiz). For years 1957–59, all existing records were used, and after 1959 sequential samples were drawn from existing records for each fifth year. Table 4 shows the averages and other calculated statistics, and the official mean values for the mine. The difference between our and the official mean for the year 1957, we believe, is due to an error in the original value. The differences after 1957 are probably caused by sampling errors. Records of actual measurements for period 1953–56 are missing.

Conversion of ^{222}Rn gas activity to potential energy

Prior to 1968, the measurements of radiation are in terms of 222Rn decay activity; from 1968 the PAEC was measured. Assuming certain equilibrium ratios between radon and individual decay products, it is possible to estimate the PAEC when Rn activity is known. The traditional unit of measurement of the PAEC is 1 WL (1 WL= 1.3×10^5 MeV/liter=2.08 μJ/m^3).

Potentially, the important elements of the uranium series are, in terms of biological damage, ^{222}Rn, RaA (^{218}Po), RaB (^{214}Pb), and RaC (^{214}Bi). Of the long-lived decay products, ^{210}Pb and ^{210}Po are important. The concentration of Rn and its progeny in the air depends mainly on the air exchange rate in the mines. In closed spaces with no air exchange, Rn and its progeny would reach, in an ideal state, a radioactive equilibrium, in which the ratio of Rn:RaA:RaB:RaC, characterized as Q_0:Q_1:Q_2:Q_3, is 1:1:1:1. With an increasing ventilation rate, the proportional representation of the decay products will decrease. The most probable ratio under the mining conditions in late 1970s was reported as 1:0.737:0.570:0.337 (Domanski et al., 1981). For Příbram, the average equilibrium ratio reported in 1967 was 1:0.39:0.25:0.19 (Čech, 1967). Another way to characterize the equilibrium in the mines is to use the so-called equilibrium factor, defined as F= 100(WL)/Rn, where Rn represents the concentration of ^{222}Rn in air in pCi/liter. The equilibrium factor can be estimated also from the following equation F= Σ (E_i/lambda$_i$) × Q_i/Q_0, where E_i is the alpha-particle energy n

MeV/l, and $lambda_i$ is the constant of decay. Substituting E_i and $lambda_i$ in the equation, we get $F = (0.10\ Q_1 + 0.52\ Q_2 + 0.38\ Q_3) / Q_0$.

Generally, the F ratio depends on the ventilation method used and on the rate of attachment of α-particles to the mine walls and dust particles. To convert the Rn concentration from pCi/l to WL, different mean equilibria are assumed according to the system of ventilation used, and the Rn concentration measured. Table 5 shows the equilibria used by the uranium industry to estimate miners' exposure (Ševc et al., 1972) and we used them to calculate the WL values shown in Tables 1 and 2a. These have been apparently based on the average values measured under specific ventilation conditions, but the original records could not be found.

The median value of the equilibrium factor, F, obtained in U.S. uranium mines in the late 1960s was F=0.23 (95% confidence interval 0.16–0.37). The value recommended for indoor environments by International Commission for Radiological Protection is F=0.5. (ICRP, 1977). For Příbram, we calculated the average measured equilibrium ratio in 1967 on basis of 124 measurements as 1:0.39:0.25:0.19, which gives F=0.24 and thus agrees with the U.S. value. The conversion factor is applied only for periods prior to 1968.

Estimation of cumulative radiation exposure in a pilot study

In a pilot study done in 1993, we selected from the employment registry from Příbram a sequential sample of 25 underground miners who started mining during individual decades between 1948 and 1991. In total, 124 miners were selected and their cumulative radon exposure estimated in terms of working level months (WLM). Table 6 shows the average WLM values and the years of mining, according to the decade when mining started. For miners with previous exposure in Jáchymov, the exposure was calculated separately for both regions.

The exposure in WLM before 1968 was calculated as a sum of products of the mine average radon concentration, the relevant equilibrium factor (Table 5), and the number of underground shifts spent in the mine, divided by 21.25 (the expected number of shifts per months based on 170 hours per month). The employment records dated before 1968 show the number of underground shifts, the mine identity and the profession (rock-breaker or other). From 1967–68, the personal dosimetric cards were used for the estimation of individual exposure. The cumulative WLM was calculated as a sum of products of the monthly average measure of the PAEC in a workplace (MeV/liter), and the monthly number of shifts spent in a workplace, and divided finally by 21.25.

Estimation of dust exposure

Up to 1960, total airborne dust was measured by the konimetric method, and from 1959 to 1960, the gravimetric method replaced gradually the konimetric method. Figure 4 and Table 7 show results of total airborne dust in gravimetric values from 1952 up to 1990. For years 1952–57, averages published by Ševc (Ševc, 1970) were used, as the original measurements were missing in the archives. From 1958, we used the average values calculated by the dosimetric service on the basis of the available original records of measurements for

Příbram. The values for period 1952–57 have been derived by conversion of konimetric to gravimetric measurements, using regression relationship between the two types of measurements for period 1959–60, and provide only a crude indicator of dustiness in the mines.

The average percentage of free crystalline silica content in the total dust in Příbram has been measured as 15%, ranging between 10–35% (based on 4,406 measurements made from 1958–60). In stopes, the average has been measured as 17.5%, based on 2,754 results. The averages were rather constant over the years. The results in the Jáchymov region were similar.

Arsenic has been measured from samples of lead ore and the reported average value in Jáchymov was 0.5%, with the maximum value of 7.1% (Ševc et al., 1972). A geological survey has also reported high arsenic content in minerals in Jáchymov (Mrňa, 1960). In Příbram the occurrence of arsenic in minerals has been found small. The average content in the load ore has been reported as 25 mg/kg (0.0025%), with the maximum of 175 mg/kg (0.018%). In the pilot study, dust sediments collected from accessible mines were analyzed for heavy metals, including arsenic. The results, reported in Table 8, show that in Příbram the average arsenic content was much lower and had less variability.

Estimation of other exposures

Diesel engines were not used in the uranium mines in Jáchymov or in Příbram.

In the pilot study we obtained smoking data on a sample of miners whose mining started during different decades. For 76% of the miners we obtained satisfactory information from archived medical records (periodical and specialist exams) on age when started smoking, intensity of smoking while employed, and for some miners on smoking after retirement. For 18% of the miners information was obtained by correspondence with the miners or their relatives. For 6.5% of the miners information on smoking could not obtained.

Discussion

It is possible to distinguish five broad phases in the development of exposure conditions and the methods of recording of workers exposures in tile uranium mines in Czechoslovakia. These phases determine the precision with which radon exposure or dust exposure can be estimated in these miners.

A first phase represents the normal technical development in the mines in Jáchymov during the pre-World-War-II years. During this phase, radon concentration in the mines started to be measured, the limit for admissible radon concentration was set (730 pCi/liter) and use of artificial ventilation and wet drills introduced. There was not substantial development during the World War II years when Germany occupied the mines.

The second phase started with the Soviet takeover of the management of the mines in 1945. The existing natural ventilation was mostly insufficient for the rapid expansion of the mines. Thus the radon concentrations were higher than during the pre-war years and also have large variability. Thus the error associated with the cumulative radon exposure is likely to be large. Only after 1955 did the ventilation system in some mines in Jáchymov reach the required capacity, see Table 1.

The third phase started in 1957, when the exposure limit for radon concentration in working areas was set to 100 pCi/liter and workplace hygienic cards were introduced. Monthly measurements in each workplace lead to greater control over exposures and to lower and more consistent radon concentrations in workplaces. From 1957, radon measurements averaged for four main types of workplaces in each mine are available. However, the personal records do not indicate in detail where in the mine the person worked, they only specify his profession (rock-breaker, stoper or developer, or other). Use of this information will increase the precision of the exposure estimate, as the rock-breakers were at a greater risk of lung cancer. Monthly averages for the workplaces can be used to develop more complex profiles of exposure.

The conversion from radon concentration to the PAEC has been made by using the equilibrium factors measured under different conditions in the mines (see Table 5). It may be possible to extract existing archived data on equilibrium ratios and mining conditions and construct more detailed tables of equilibrium factors.

Regular measurements of total airborne dust exist from records of the dosimetric service, for each mine and workplace from 1957. Respirable fraction of dust was not measured. Silica fraction of dust was measured, but less regularly.

The forth phase started in 1968, when personal dosimetric cards were introduced and the average time-weighted yearly exposure to PAEC was set to 0.31 WL (6.4 µJ/m^3). Thus exposure estimates calculated from 1968 will be most precise. The fifth phase started from 1975, when limits were further decreased, by taking into account the inhaled air, to yearly cumulative exposure of 3.4 WLM.

The number of men exposed over the years in Jáchymov and Příbram is shown in Figure 2. In Příbram, approximately 19,400 underground workers were registered, of these 15,665 had more than one year of underground service (8,508 and 7,151 miners started working before 1968 and after 1968, respectively).

An earlier epidemiologic study of Czechoslovakian uranium miners follows a cohort of 4,043 miners from Western Bohemia (Jáchymov and Horní Slavkov), who started mining from 1948 to 1959 and who had more than four years of underground exposure. In that study the standardized mortality ratio for lung cancer, SMR=5.07 95% confidence interval (4.71 – 5.47) (Tomašek, 1993), was higher than in other cohorts of uranium miners, and the risk for a given dose is also higher. Given the variability of the early radon concentration measurements, the fact that dust and arsenic were also present in the mines in Jáchymov, and the extreme working conditions that prevailed during the post-war years, the estimate of lifetime attributable risk (Ševc et al., 1988) due to radon is unlikely to be independent of the specific working and living conditions in the mines in Jáchymov. A second cohort of uranium miners followed by others consists of 5,360 miners from Příbram who started working after 1968.

Regarding the general applicability to the present assessment of risk due to indoor radon exposure, the population of miners from Příbram is likely to be more useful epidemiologically, as their exposures were better recorded and had less variability. Also, the arsenic level was insignificant, and the working and living conditions were “normal”.

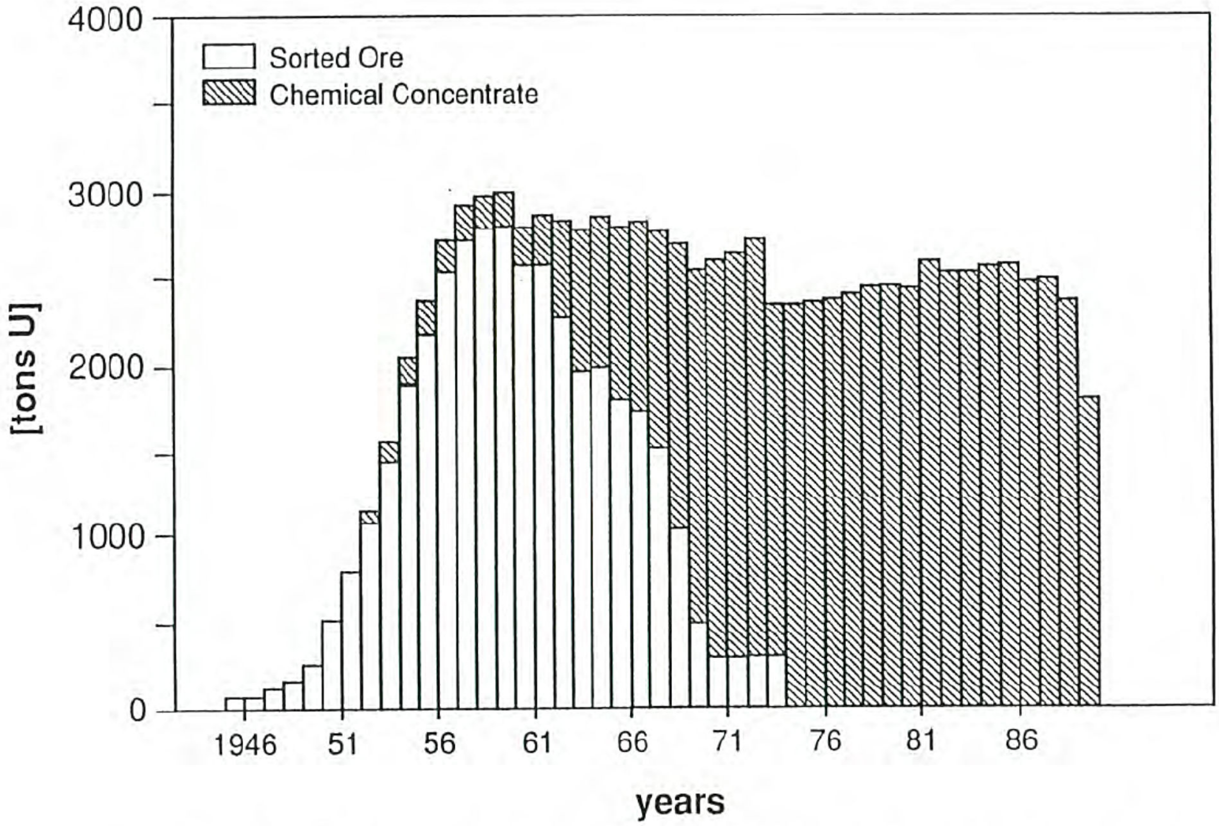

Figure 1.
Production of uranium ore during 1946 to 1990 in Czechoslovakia

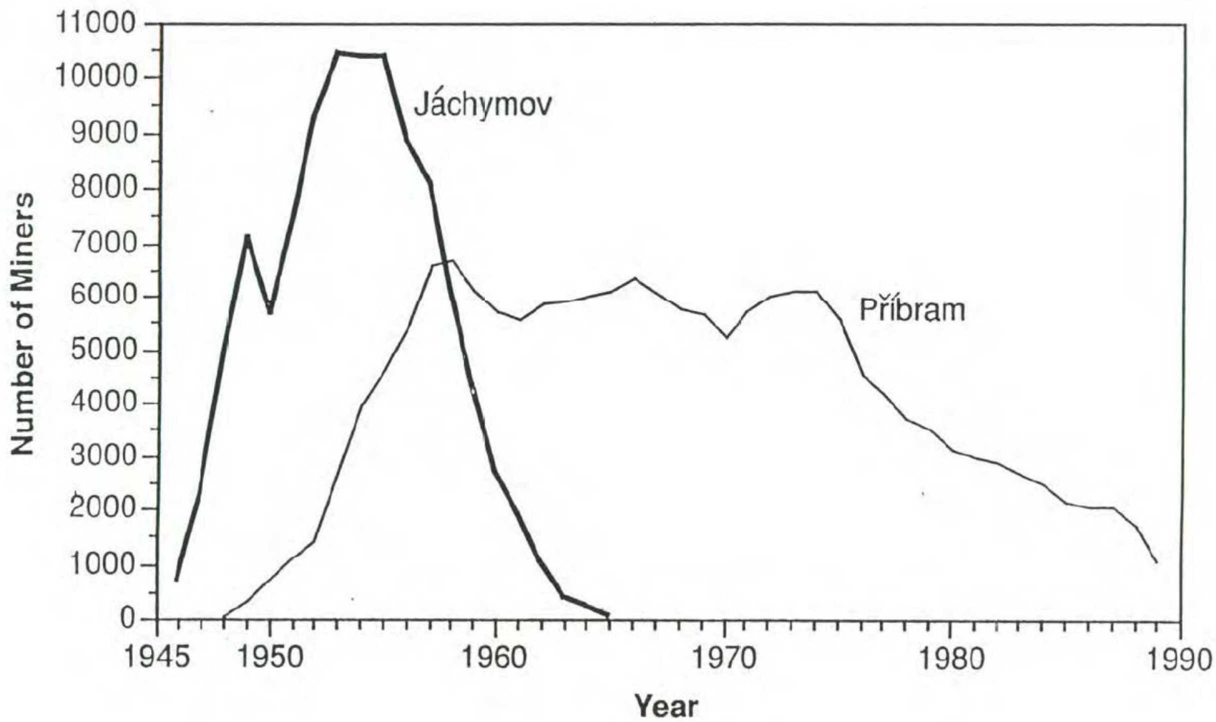

Figure 2.
Number of underground miners employed in mines in Jáchymov and Příbram, by year

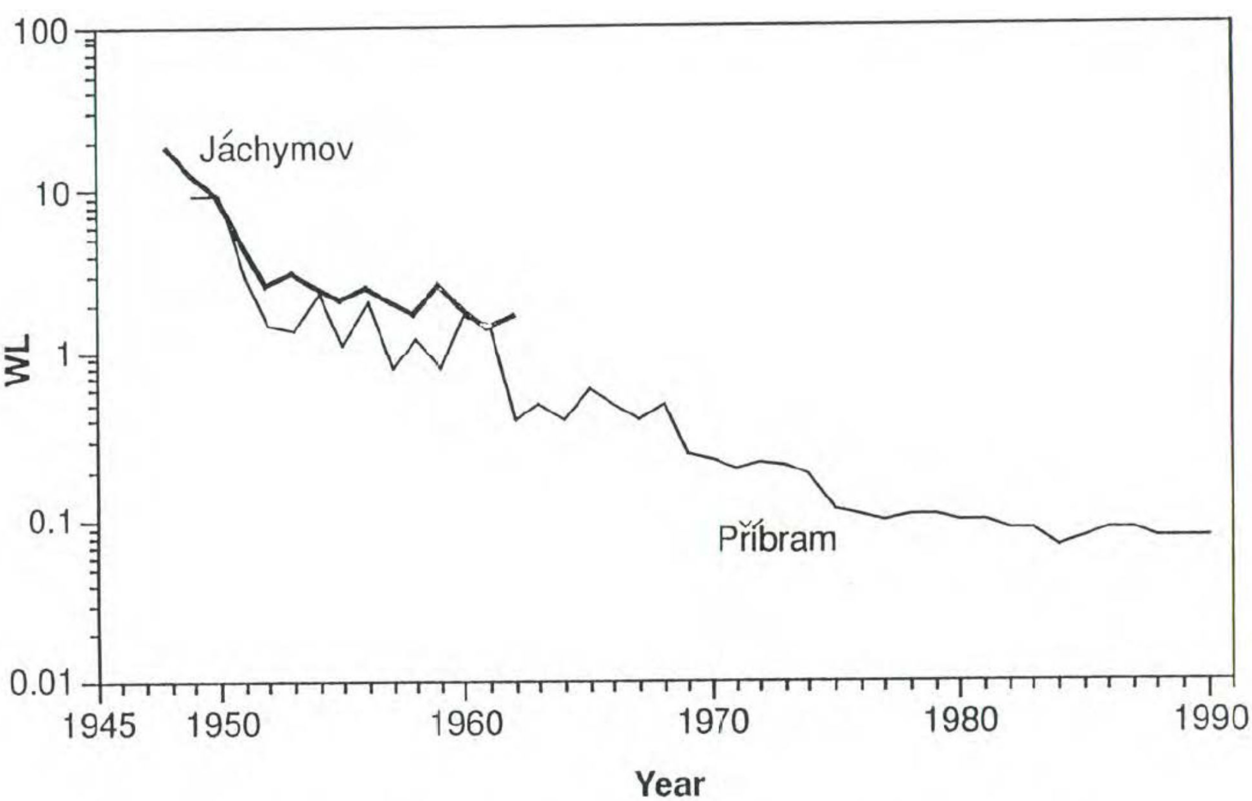

Figure 3.

Average radon progeny concentration (WL) for mines in Jáchymov and Příbram, by year (values up to 1968 were calculated from Rn concentration)

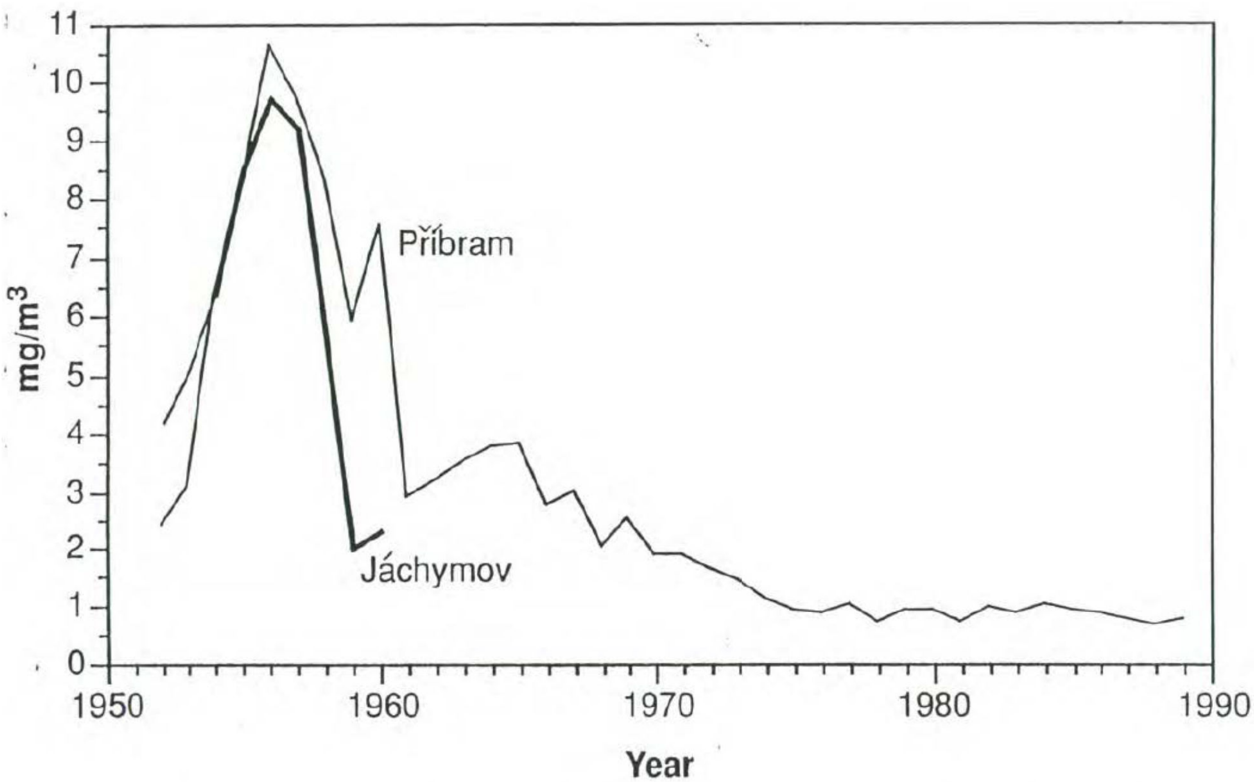

Figure 4.

Average concentration of total airborne dust in mines in Jáchymov and Příbram, by year

Table 1

Yearly average mine concentration of ^{222}Rn for the Jáchymov region

	^{222}Rn concentration in pCi/l			WL	Measurements[a]	Mines[b]
Year	**Mean**	**S.D.**	**Range**	**Estimated**	**N**	**N**
1924	2982.1	2858.1	291–8954	26.3	12	2
1928	4138.7	3273.5	633–7116	36.6	3	1
1930	2816.7	2077.6	0–7728	24.9	70	3
1932	613.5	504.1	36–1965	3.3	36	3
1933	223.3	213.7	0–659	1.2	15	1
1934	839.4	496.3	36–2293	4.5	33	3
1948	2000			17.7	>308	7
1949	1016.3	607	466–1913	9	1476	7
1950	1058.6	401.7	533–1547	9.4	4113	7
1951	889.6	499.9	248–1336	4.8	453	5

	^{222}Rn concentration in pCi/l			WL	Measurements[a]	Mines[b]
Year	Mean	S.D.	Range	Estimated	N	N
1952	401.5	168	111–629	2.2	308	14
1953	520.3	171.9	326–818	2.8	2750	12
1954	425.9	117.7	233–659	2.3	3639	15
1955	397.3	144.9	215–625	2.1	4331	12
1956	389.6	216.5	104–810	2.1	3539	11
1957	344.3	147.2	71–515	1.9	771	11
1958	188.9	152.9	20–437	1	996	10
1959	402.4	215.4	85–710	2.2	685	9
1960	342.5	248	85–760	1.9	573	8
1961	270	-	-	1.5	-	2
1962	300	-	-	1.6	-	1

[a.]Total number of measurements on which the mine means were based.

[b.]Number of mine averages on which the presented means are based.

[c.]For year 1948 the value from 1950 was assigned

Table 2a

Yearly average mine concentration of ^{222}Rn for the Příbram region

	^{222}Rn concentration in pCi/l			WL	Measurements[a]	Mines[b]
Year	Mean	S.D.	Range	Estimated	N	N
1949	1058[c]	-	-	9.3		0
1950	1058	-	-	9.3	35	
1951	592.8	326.8	97–1030	3.2	115	6
1952	313.8	57.6	239–381	1.7	129	6
1953	276.0	59.0	200–360	1.5	-	5
1954	414.4	108.3	200–525	2.2	554	7
1955	160.6	96.7	37–307	0.9	64	5
1956	425.5	287.7	204–843	2.3	553	4
1957	144.3	82.3	79–261	0.8	918	4
1958	267.3	157.8	152–488	1.4	4962	4
1959	136.0	66.6	80–222	0.7	2387	4
1960	311.7	153.5	137–425	1.7	2006	3
1961	255.3	94.2	91–349	1.4	3944	6
1962	239.7	33.5	202–266	1.3	3623	3
1963	134.3	70.5	42–210	0.5	3302	4
1964	120.0	61.6	63–194	0.4	6852	4
1965	142.2	81.0	54–247	0.5	7862	5
1966	132.0	85.0	58–274	0.5	9968	5
1967	132.6	48.5	96–216	0.4	1369	5
1968	137.0	67.0	92–255	0.5	1315	5

[a.]a. Total number of measurements on which the mine means were based.

b. Number of mine averages on which the presented means are based.

c. For year 1948 the value from 1950 was assigned

Table 2b

Yearly average potential α-energy concentrations (PAEC) for Příbram mines

	PAEC in WL			Measurements[a]	Mines[b]
Year	Mean	S.D.	Range	N	N
1969	0.26	0.03	0.23–0.29	>12000	4
1970	0.22	0.06	0.18–0.31	>12000	4
1971	0.2	0.04	0.16–0.25	>12000	4
1972	0.23	0.05	0.15–0.26	>12000	4
1973	0.21	0.08	0.12–0.31	>12000	4
1974	0.18	0.05	0.11–0.23	>12000	4
1975	0.12	0.01	0.11–0.14	>12000	4
1976	0.11	0.01	0.10–0.12	>12000	4
1977	0.09	0.01	0.08–0.09	>8000	3
1978	0.09	0.02	0.07–0.10	>8000	3
1979	0.09	0.03	0.06–0.11	>8000	3
1980	0.08	0.02	0.07–0.10	>8000	3
1981	0.08	0.02	0.06–0.10	>8000	3
1982	0.09	0.02	0.07–0.11	>8000	3
1983	0.09	0.02	0.06–0.10	>8000	3
1984	0.07	0.01	0.07–0.08	>6000	2
1985	0.08	0.02	0.06–0.10	>6000	2
1986	0.09	0.03	0.05–0.12	>5000	2
1987	0.09	0	0.08–0.09	>5000	2
1988	0.08	0.01	0.07–0.08	>2000	2
1989	0.08	0.01	0.07–0.08	>2000	1
1990	0.08	0.01	0.07–0.08	>2000	1
1991			end of mining		

a. end Total number of measurements on which the mine means were based.

b. Number of mine averages on which the presented means are based.

Table 3

Average radon concentration for Jáchymov mines calculated from individual measurements in a pilot study

	Radon concentration pCi/liter			
Year	Mean	SD	Range	N
1948[a]	1100.3	1424.4	0.0 – 1,4196	308
1949	1456.1	2184.7	36 – 28,901	736
1950	1119.4	1807.1	0.0 – 23,551	990
1951	796.1	1200.7	73 – 14,305	1120
1952	605.5	977.2	36 – 13,978	1068

[a]Only winter month measurements were available in the archives.

Table 4

Average radon concentration (or PAEC) for Příbram mines (Bytiz) -a pilot study calculations

	Radon concentration (pCi/liter or WL)					Official value	
Year	Mean	S.D.	Range	CV%	N	Mean	N
1957	746.2[a]	696.8	36–2730	93.4	60	261	267
1958	461.7[a]	534.4	4–5351	115.8	3138	488	794
1959	236.6[a]	318.0	1.0–4110	134.4	3014	222	882
1960	288.7[a]	348.3	1.0–3300	120.6	644	373	799
1965	276.4[a]	411.3	0.0–4480	148.8	869	223	2893
1970	0.54[b]	1.22	0.01–13.9	226.2	2000	0.31	2000
1975	0.15[b]	0.38	0.0–15.4	255.3	2078	0.14	4065
1980	0.11[b]	0.14	0.01–1.1	123.3	2084	0.09	4172
1985	0.13[b]	0.23	0.0–5.7	186.1	4445	0.10	4729

[a]- pCi/liter.

[b]- working level (WL).

Table 5

Estimated equilibrium ratio and equilibrium factor, used by the uranium industry to estimate miner exposure, by period of mining and Rn concentration

Period	Rn concentration pCi/liter	Equilibrium ratio	Equilibrium factor
1948–1959	> =1000	1:0.98:0.88:0.81	0.863
	< 1000	1:0.85:0.60:0.40	0.549
1960–1967	> 200	1:0.85:0.60:0.40	0.549
	< =200	1:0.60:0.40:0.25	0.363
1968+	> 100	1:0.60:0.40:0.25	0.363
	<=100	1:0.60:0.20:0.10	0.202

Table 6

Average radon exposure (WLM) and years of mining by decade of mining-a pilot study on a sample of 125 miners

Period started mining	mean	s.d.	(range)	mean	s.d.	(range)
< 1950	342.8	165.9	(34.9–677.4)	13.9	8.0	(2.8–33.3)
1950 – 1959	127	76.7	(19.0–337.4)	11.7	5.2	(2.1–19.7)
1960 – 1969	29.2	22.7	(2.6–78.5)	7.3	4.1	(1.3–15.1)
1970 – 1979	9.4	6.3	(0.7–22.6)	9.2	5.4	(1.9–17.8)
1980 – 1989	6.7	11.2	(0.5–58.4)	5.7	2.6	(1.3–9.7)
Total	103.6	151.3	(0.5–677.4)	10.5	6.1	(1.4–33.3)

Table 7

Average concentration of total airborne dust (mg/m^3) calculated for samples of industry measurements in a pilot study, and official averages produced by the uranium industry

Year	Average	S.D.	Range	CV%	N	Official Average
1958	8.3	101.0	(0.5–2324.8)	1216.4	2129	-
1959	5.9	29.5	(0.0–850.0)	500.1	2087	-
1960	7.5	19.3	(0.0–462.0)	256.4	1582	-
1964	5.6	11.4	(0.2–239.6)	202.1	925	3.76
1965	4.3	4.9	(0.3–47.6)	114.2	195	3.80
1970	2.2	4.4	(0.1–40.0)	198.0	307	1.87
1975	1.3	2.7	(0.1–63.5)	213.6	673	0.89
1980	0.7	0.7	(0.1–5.6)	97.0	983	0.88
1985	0.9	1.2	(0.1–18.0)	128.8	958	0.88

Table 8

Metal content (mg/kg) measured in samples of dust sediments obtained from mines in Jáchymov and Příbram

		Mine Bytiz in Příbram (n=3)		Mine Svrnost in Jáchymov (n=3)	
Element	(Symbol)	Mean	Range	Mean	Range
Arsenic	(As)	144.3	72–254	789	154–2300
Chromium	(Cr)	264.3	156–444	170.5	77–362
Nickel	(Ni)	51.3	44–62	96	58–163
Cadmium	(Cd)	19.3	8–27	2	2–3
Antimony	(Sb)	6.0	2.6–8.8	1.7	1.1–3.2
Bismuth	(Bi)	< 5	–	43.3	< 5–157
Lead	(Pb)	1036.7	269–1871	112.3	43–250
Molybdenum	(Mo)	< 30	-	< 30	-

REFERENCES

Běhounek F Über die Verhältnisse der Radioaltovotat Uranpecherzberg-baurevir von St. Joachimsthal in Bohmen, Phys. Z. 1927; 28: 322–342.

Běhounek F History of the exposure of miners to radon, Health Phys 1970; 19:56–57. [PubMed: 4935311]

National Academy of Sciences. Health risks of radon and other internally deposited alphaemitters. Washington, DC: National Academy Press; 1988.

Čech J Results of measurements of radon and its daughter products concentrations in Czechoslovak uranium and non uranium mines. In Proc. Symp. Mining Příbram in Science and Technology, Příbram 1967

Cohen BL. Failures and critique of the BEIR-ill lung cancer risk estimates. Health Phys 1982; 42:267–284. [PubMed: 7068390]

Czechoslovak Deposits of Uranium; printed by Czechoslovak Uranium Industry, Příbram 1984

Domanski T, Chruscielewski W, Orzechowski W. Health Phys 1981; 41:175–178. [PubMed: 7275595]

International Commission on Radiological Protection; Recommendations of The ICRP; ICRP Publication 9; Pergamon Press, Oxford 1965

International Commission on Radiological Protection; Publication 24: Radiation protection in uranium and other mines, Annals of ICRP, Pergamon Press 1977

Kaplan K and Pacl V. Secret zone Jáchymov. (In Czech.) PROTISK Ceske Budejovice 1993.

Löwy J Über die Joachimstaler Bergkrankheit: die vorLäufige Mitteilung. Med.Klin 1929; 25:141–142.

Mrňa F, Pavlů D, Sattran V. Geochemical research of complex ore mineralization of Jáchymov region (In Czech.) Report No W16 for Central Geological Institute Prague 1960

Pacina V, Vfch Z, Smetana J. Bronchogenic cancer in miners of Czechoslovak uranium mines. (In Czech.) Pracov Uk 1989; 41:387–389.

Pelnář P Occurrence of occupational cancers in Czechoslovakia during 10 last years. (In Czech.) Review report, Prague 1962, unpublished.

Pirchan A, Šilkl H. Cancer of the lung in miners in Jáchymov (Joachymsthal). Am J Cancer 1932; 51:681–722.

Pluskal 0. Czechoslovak uranium (In Czech.) Uhlí-Rudy 1/8, 1992, 259–267

Polášek F, Mayer R, Hofman Z. Technical and organization measure for the prevention of occupational diseases and accident rates in practice.(In Czech.) In Proc. Symp. Mining Příbram in Science and Technology; part Occupational Safety and Hygiene, Příbram 1969.

Řeřicha V, Šnajberk J. Incidence of bronchogenic lung cancer and its dependence on the length of exposure in uranium miners in Jáchymov and Horní Slavkov mines. (In Czech.) Secret research paper ZÚNZ UP, Příbram 1966; 4:21–31.

Ševc J Development of hygienic preventive measures in the Czechoslovak uranium mines. Report of the Institute of Occupational Hygiene of uranium Industry for the Ministry of Health of the Czech Republic, Příbram 1970.

Ševc J, Plaček V. Lung cancer risk and long-term exposure to radon daughters. (In Czech.) Research report P09 – 335 - 053 – 02/01, Příbram 1972

Ševc J, Kunz E, Plaček V, Šmid A. Comments on lung cancer risk estimates. Health Phys 1984; 46:961–964. [PubMed: 6706608]

Ševc J, Kunz E, Tomašek L. Cancer in man after exposure to Rn daughters. Health Phys 1988; 54:27–45. [PubMed: 2826364]

Ševc J, Tomašek L, Kunz E, et al. A survey of the Czechoslovak Follow-up of lung cancer mortality in uranium miners. Health Phys 1993; 64:355–69. [PubMed: 8449717]

Šrám RJ, Binková B, Dobiaš L, Rössner P, Topinka J, Veselá D, et al. Monitoring genotoxic exposure in uranium miners. Environmental Health Perspectives 1993; 99:303–305. [PubMed: 8319649]

Tomašek L, Darby S, Swerdlow A, et al. Radon exposure and cancer other than lung cancer among uranium miners in West Bohemia. Lancet. 1993; 341:919–23. [PubMed: 8096265]

Urban J Jachymov - a cradle of the atomic age. Czechoslovak Scientific and Technical Society. Jáchymov 1965.

Vancl V Safety measures of workers against ionizing radiation in uranium mines. (In Czech.) Rudy 1985; 33:283–287.

Appendix

Appendix B, Table 1:

Cancer mortality other than lung by cumulative working level month radon exposure among male Příbram uranium miners 1977–1992*

Cancer Site	Cumulative radon exposure (WLM)	n	Relative Rate (95%CI)		Cancer Site	Cumulative radon exposure (WLM)	n	Relative Rate (95%CI)

Cancer Site	Cumulative radon exposure (WLM)	n	Relative Rate (95%CI)				Cancer Site	Cumulative radon exposure (WLM)	n	Relative Rate (95%CI)		
Extrathoracic airway (140–148, 160, 161)	<25 WLM	22	1				Hodgkin lymphoma (201)	<25 WLM	5	1		
	25 – <50 WLM	11	0.93	(0.43 –	2.00)			25 – <50 WLM	1	0.51	(0.06 –	4.65)
	50 – <150 WLM	15	0.83	(0.42 –	1.65)			50 – <150 WLM	1	0.31	(0.03 –	2.98)
	150+	11	1.27	(0.60 –	2.72)			150+	1	0.67	(0.07 –	6.49)
Stomach (151)	<25 WLM	30	1				Myelom^(203)	<50 WLM	3	1		
	25 – <50 WLM	22	1.18	(0.68 –	2.05)			50 – <150 WLM	3	1.41	(0.28 –	7.15)
	50 – <150 WLM	33	0.95	(0.57 –	1.57)			150+	2	1.95	(0.32 –	11.84)
	150+	17	1.05	(0.57 –	1.91)							
Liver (155)	<25 WLM	12	1				CLL (204.1)	<25 WLM	3	1		
	25 – <50 WLM	11	1.43	(0.63 –	3.27)			25 – <50 WLM	2	1.08	(0.18 –	6.55)
	50 – <150 WLM	18	1.27	(0.60 –	2.68)			50 – <150 WLM	4	1.18	(0.25 –	5.45)
	150+	7	1.04	(0.40 –	2.66)			150+	2	1.23	(0.20 –	7.56)
Kidney (189)	<25 WLM	8	1				Myeloid leukemia (205.0, 205.1)	<25 WLM	5	1.00		
	25 – <50 WLM	14	3.56	(1.45 –	8.72)			25 – <50 WLM	2	0.67	(0.13 –	3.50)
	50 – <150 WLM	12	1.78	(0.70 –	4.55)			50 – <150 WLM	4	0.76	(0.20 –	2.95)
	150+	7	2.18	(0.76 –	6.26)			150+	1	0.39	(0.04 –	3.44)
Non-Hodgkin lymphoma (200, 202)	<25 WLM	7	1				All Hematopoietic (200 – 208)	<25 WLM	23	1		
	25 – <50 WLM	1	0.47	(0.05 –	4.07)			25 – <50 WLM	8	0.72	(0.31 –	1.63)
	50 – <150 WLM	7	2.16	(0.64 –	7.36)			50 – <150 WLM	19	1.00	(0.52 –	1.90)
	150+	2	1.36	(0.24 –	7.63)			150+	8	0.88	(0.38 –	2.04)

* adjusted for age

^ <25 WLM and 25 – <50 WLM categories collapsed

REFERENCES

1. Lubin JH, Boice JD, Edling C, et al. Lung cancer in radon-exposed miners and estimation of risk from indoor exposure. J Natl Cancer Inst 1995;87:817–27.http://www.ncbi.nlm.nih.gov/pubmed/7791231 (accessed 24 Mar 2016). [PubMed: 7791231]

2. National Research Council. Health Effects of Exposure to Radon. Washington, D.C.: : National Academies Press 1999. doi:10.17226/5499

3. Tirmarche M, Harrison J, Laurier D, et al. Risk of lung cancer from radon exposure: contribution of recently published studies of uranium miners. Ann ICRP 2012;41:368–77. doi:10.1016/j.icrp.2012.06.033 [PubMed: 23089036]

4. IARC. Monographs on the evaluation of carcinogenic risks to human, volume 43: man-made mineral fibres and radon. Lyon, France: 1988.

5. Hornung RW, Deddens J, Roscoe R. Modifiers of exposure-response estimates for lung cancer among miners exposed to radon progeny. Environ Health Perspect 1995;103 Suppl :49–53.http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1518841&tool=pmcentrez&rendertype=abstract (accessed 19 May 2016).

6. Hornung RW, Deddens JA, Roscoe RJ. Modifiers of lung cancer risk in uranium miners from the Colorado Plateau. Health Phys 1998;74:12–21.http://www.ncbi.nlm.nih.gov/pubmed/9415577 (accessed 19 May 2016). [PubMed: 9415577]

7. 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. doi:10.1667/RR2237.1 [PubMed: 21128801]

8. Navaranjan G, Berriault C, Do M, et al. Cancer incidence and mortality from exposure to radon progeny among Ontario uranium miners. Occup Environ Med 2016;73:838–45. doi:10.1136/oemed-2016-103836 [PubMed: 27651479]

9. 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. doi:10.1093/aje/kwn406 [PubMed: 19208723]

10. Samet JM, Pathak DR, Morgan M V, et al. Lung cancer mortality and exposure to radon progeny in a cohort of New Mexico underground uranium miners. Health Phys 1991;61:745–52.http://www.ncbi.nlm.nih.gov/pubmed/1659563 (accessed 11 Jun 2018). [PubMed: 1659563]

11. Tomásek L, Zárská H. Lung cancer risk among Czech tin and uranium miners--comparison of lifetime detriment. Neoplasma 2004;51:255–60.http://www.ncbi.nlm.nih.gov/pubmed/15254655 (accessed 10 Jan 2016). [PubMed: 15254655]

12. Tomásek L Czech miner studies of lung cancer risk from radon. J Radiol Prot 2002;22:A107–12.http://www.ncbi.nlm.nih.gov/pubmed/12400957 (accessed 17 May 2016). [PubMed: 12400957]

13. Tomasek L, Rogel A, Tirmarche M, et al. Lung cancer in French and Czech uranium miners: Radon-associated risk at low exposure rates and modifying effects of time since exposure and age at exposure. Radiat Res 2008;169:125–37. doi:10.1667/RR0848.1 [PubMed: 18220460]

14. Rogel A, Laurier D, Tirmarche M, et al. Lung cancer risk in the French cohort of uranium miners. J Radiol Prot 2002;22:A101–6.http://www.ncbi.nlm.nih.gov/pubmed/12400956 (accessed 16 May 2016). [PubMed: 12400956]

15. Laurier D, Tirmarche M, Mitton N, et al. An update of cancer mortality among the French cohort of uranium miners: extended follow-up and new source of data for causes of death. Eur J Epidemiol 2004;19:139–46.http://www.ncbi.nlm.nih.gov/pubmed/15074570 (accessed 16 May 2016). [PubMed: 15074570]

16. Vacquier B, Caer S, Rogel A, et al. Mortality risk in the French cohort of uranium miners: extended follow-up 1946–1999. Occup Environ Med 2008;65:597–604. doi:10.1136/oem.2007.034959 [PubMed: 18096654]

17. Grosche B, Kreuzer M, Kreisheimer M, et al. Lung cancer risk among German male uranium miners: a cohort study, 1946–1998. Br J Cancer 2006;95:1280–7. doi:10.1038/sj.bjc.6603403 [PubMed: 17043686]

18. Kreuzer M, Fenske N, Schnelzer M, et al. Lung cancer risk at low radon exposure rates in German uranium miners. Br J Cancer 2015;113:1367–9. doi:10.1038/bjc.2015.324 [PubMed: 26393888]

19. Protection against radon-222 at home and at work. A report of a task group of the International Commission on Radiological Protection. Ann ICRP 1993;23:1–45.http://www.ncbi.nlm.nih.gov/pubmed/8179237 (accessed 1 Jun 2018).

20. Rericha V, Kulich M, Rericha R, et al. Incidence of leukemia, lymphoma, and multiple myeloma in Czech uranium miners: a case-cohort study. Environ Health Perspect 2006;114:818–22.http://

www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1480508&tool=pmcentrez&rendertype=abstract (accessed 17 May 2016). [PubMed: 16759978]

21. Kulich M, Reřicha V, Reřicha R, et al. Incidence of non-lung solid cancers in Czech uranium miners: a case-cohort study. Environ Res 2011;111:400–5. doi:10.1016/j.envres.2011.01.008 [PubMed: 21256480]
22. Hu H, Yih K, Makhijani A, et al. Nuclear wastelands : a global guide to nuclear weapons production and its health and environmental effects. MIT Press 2000. http://search.lib.unc.edu/search?R=UNCb2742170 (accessed 17 Mar 2017).
23. Ishimori Y, Tanaka H, Sakoda A, et al. Measurements of radon activity concentration in mouse tissues and organs. Radiat Environ Biophys 2017;56:161–5. doi:10.1007/s00411-017-0682-9 [PubMed: 28124098]
24. National Research Council. Risk Assessment of Radon in Drinking Water. Washington, D.C.: : National Academies Press 1999. doi:10.17226/6287
25. Nussbaum E, Hursh JB. Radon solubility in rat tissues. Science 1957;125:552–3.http://www.ncbi.nlm.nih.gov/pubmed/13409007 (accessed 14 Jun 2018). [PubMed: 13409007]
26. Harley NH, Robbins ES. 222Rn Alpha Dose to Organs Other than Lung. Radiat Prot Dosimetry 1992;45:619–22.
27. Marsh JW, Blanchardon E, Gregoratto D, et al. Dosimetric calculations for uranium miners for epidemiological studies. Radiat Prot Dosimetry 2012;149:371–83. doi:10.1093/rpd/ncr310 [PubMed: 21816722]
28. Darby SC, Whitley E, Howe GR, et al. Radon and cancers other than lung cancer in underground miners: a collaborative analysis of 11 studies. J Natl Cancer Inst 1995;87:378–84.http://www.ncbi.nlm.nih.gov/pubmed/7853419 (accessed 21 Mar 2017). [PubMed: 7853419]
29. Kreuzer M, Walsh L, Schnelzer M, et al. Radon and risk of extrapulmonary cancers: results of the German uranium miners' cohort study, 1960–2003. Br J Cancer 2008;99:1946–53. doi:10.1038/sj.bjc.6604776 [PubMed: 19002172]
30. 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. doi:10.1007/s00420-014-0998-6 [PubMed: 25410273]
31. Kreuzer M, Sobotzki C, Fenske N, et al. Leukaemia mortality and low-dose ionising radiation in the WISMUT uranium miner cohort (1946–2013). Occup Environ Med 2017;74:252–8. doi:10.1136/oemed-2016-103795 [PubMed: 27815431]
32. Richardson DB, Wing S, Schroeder J, et al. Ionizing radiation and chronic lymphocytic leukemia. Environ Health Perspect 2005;113:1–5.http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1253701&tool=pmcentrez&rendertype=abstract (accessed 29 Dec 2015). [PubMed: 15626639]
33. Linet MS, Schubauer-Berigan MK, Weisenburger DD, et al. Chronic lymphocytic leukaemia: an overview of aetiology in light of recent developments in classification and pathogenesis. Br J Haematol 2007;139:672–86. doi:10.1111/j.1365-2141.2007.06847.x [PubMed: 18021081]
34. Schubauer-Berigan MK, Daniels RD, Fleming DA, et al. Chronic lymphocytic leukaemia and radiation: findings among workers at five US nuclear facilities and a review of the recent literature. Br J Haematol 2007;139:799–808. doi:10.1111/j.1365-2141.2007.06843.x [PubMed: 17922878]
35. ICRP. Human respiratory tract model for radiological protection. ICRP Publication 66 Oxford, UK: Pergamon Press: 1994.
36. Kreuzer M, Dufey F, Marsh JW, et al. Mortality from cancers of the extra-thoracic airways in relation to radon progeny in the Wismut cohort, 1946–2008. Int J Radiat Biol 2014;90:1030–5. doi:10.3109/09553002.2014.909074 [PubMed: 24678796]
37. Kelly-Reif K, Sandler DP, Shore D, et al. Mortality and cancer incidence among underground uranium miners in the Czech Republic 1977–1992. Occup Environ Med 2019;76:511–8. doi:10.1136/oemed-2018-105562 [PubMed: 31167952]
38. Loomis D, Richardson DB, Elliott L. Poisson regression analysis of ungrouped data. Occup Environ Med 2005;62:325–9. doi:10.1136/oem.2004.017459 [PubMed: 15837854]

39. Checkoway H, Pearce N, Hickey JLS, et al. Latency Analysis in Occupational Epidemiology. Arch Environ Heal An Int J 1990;45:95–100. doi:10.1080/00039896.1990.9935932

40. Kreuzer M, Grosche B, Schnelzer M, et al. Radon and risk of death from cancer and cardiovascular diseases in the German uranium miners cohort study: follow-up 1946–2003. Radiat Environ Biophys 2010;49:177–85. [PubMed: 19855993]

41. Tomasek L Lung cancer mortality among Czech uranium miners—60 years since exposure. J Radiol Prot 2012;32:301–14. doi:10.1088/0952-4746/32/3/301 [PubMed: 22809823]

42. Tomásek L, Darby SC. Recent results from the study of West Bohemian uranium miners exposed to radon and its progeny. Environ Health Perspect 1995;103 Suppl 2:55–7.http://www.ncbi.nlm.nih.gov/pubmed/7614948 (accessed 21 May 2018).

43. Kreuzer M, Fenske N, Schnelzer M, et al. Lung cancer risk at low radon exposure rates in German uranium miners. Br J Cancer 2015;113:1367–9. doi:10.1038/bjc.2015.324 [PubMed: 26393888]

44. National Cancer Institute. Chronic Lymphocytic Leukemia - SEER Stat Fact Sheets. Cancer Stat Facts Leuk. - Chronic Lymphocytic Leuk. 2017.http://seer.cancer.gov/statfacts/html/clyl.html (accessed 16 Feb 2016).

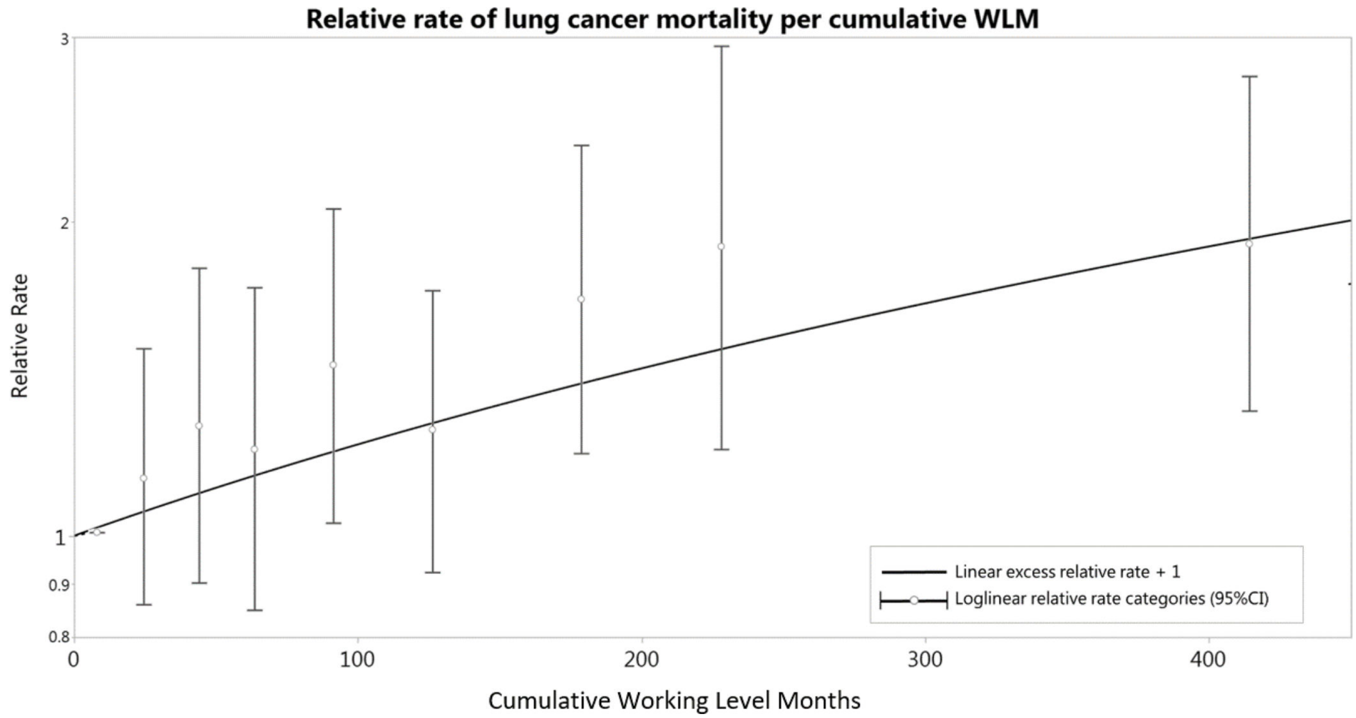

Figure 1:

Excess relative rate of lung cancer mortality per cumulative WLM lagged 5 years among male underground uranium miners in the Příbram region of the Czech Republic, 1977–1992

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Table 1.

Characteristics of the Příbram uranium miner cohort

Variable	
Miners, n	16,434
Follow-up period	1977–1992
Person-years	231,499
Employment Factors, mean (range)	
Duration of employment, years	7.0 (1.1–37.9)
Year of birth	1935 (1886–1957)
Year of hire	1963 (1946–1975)
Age at hire	27.8 (18.0–69.7)
Age at death	62 (22–102)
Vital status, n (%)	
Alive	12,209 (74.3)
Deceased	4212 (25.6)
Emigrated	12 (0.07)
Vital Status Unknown	1 (0.01)
Availability of cause of death	3776 (89.6)
Duration of follow-up in years, mean (range)	14 (0.1–16)
Radon	
Cumulative radon in WLM, mean (range)	53.2 (1.2–1121.9)
< 10 WLM radon exposure, n (%)	4883 (30)
< 50 WLM, n (%)	11678 (71)
<100 WLM, n (%)	13502 (82)

Table 2:

Linear excess relative rate and log linear relative rates of cancer types by cumulative working level month (WLM) radon exposure among male Příbram uranium miners 1977–1992

Cancer Site (ICD-9)	Number of Deaths	Crude Death Rate per 1000 person years	Linear ERR (95%CI) per 100 WLM[b]			Loglinear Rate Ratio at 100 WLM (95%CI)[b]		
Extrathoracic airway (140–148, 160, 161)	59	0.25	0.12	(ND,	0.69)	1.10	(0.87,	1.39)
Stomach (151)	102	0.44	0.00	(−0.03,	0.29)	1.00	(0.82,	1.21)
Liver (155)	48	0.21	0.06	(ND,	0.58)	1.08	(0.85,	1.37)
Lung (162)[c]	705	3.02	0.22	(0.10,	0.37)	1.31	(1.17,	1.48)
Kidney (189)	41	0.18	0.01	(−0.05,	0.70)	1.01	(0.74,	1.37)
Non-Hodgkin lymphoma (200, 202)[d]	17	0.07	0.11	(ND,	4.87)	0.99	(0.57,	1.72)
Hodgkin lymphoma (201)[d]	8	0.03	−0.09	(ND,	1.95)	0.52	(0.12,	2.21)
Myeloma (203)[d]	8	0.03	−0.09	(ND,	14.73)	0.98	(0.52,	1.86)
CLL (204.1)	11	0.05	0.24	(ND,	5.10)	1.15	(0.72,	1.82)
Myeloid leukemia (205.0, 205.1)[d]	12	0.05	−0.09	(ND,	1.37)	0.75	(0.33,	1.67)
All Hematopoietic (200 – 208)[d]	58	0.25	−0.09	(ND,	0.33)	0.91	(0.67,	1.23)

[a)] 5-year exposure lag assumption= extrathoracic airway, stomach, liver, lung, kidney, myeloma, CLL, and all hematopoietic cancers. 2-year exposure lag assumption = NHL, HL, Myeloid leukemia

[b)] Adjusted for age and birth cohort unless specified otherwise

[c)] Adjusted for age, birth cohort, and age-birth cohort interaction. Loglinear rate ratio model includes quadratic term for WLM.

[d)] Linear ERR model is adjusted for age only

ND = not determined if lower CI is less than the negative inverse of highest cumulative exposure, -0.09

Table 3:

Lung cancer mortality by cumulative working level month (WLM). Radon exposure by windows of time since exposure and by exposure less than 250 WLM, among male Příbram uranium miners 1977–1992

Cumulative Radon Exposure (WLM)		Excess Relative Rate/100WLM (95% CI)		
Windows of exposure^	5–15 yrs:	0.21	(−0.96,	1.37)
	15–30 yrs:	0.44	(0.21,	0.67)
	30+ yrs:	0.05	(−0.11,	0.20)
Restricted to < 250 WLM*		0.32	(0.11,	0.53)

^Adjusted for age and birth cohort

*Cumulative working level months under a five-year lag assumption

Table 4:

Summary of BERVI estimates and recent updates to several underground mining cohort

Study (publication)	Follow-up period	Lung Cancer Deaths	Mean cumulative WLM	Measured co-exposures	Mean duration of employment (years)	ERR/100WLM (95%CI)
BEIR VI (NRC, 1999)	Various cohorts	2,674	164.4	**None**	1 to 18	0.59 (SE = 1.32)
WISMUT, Germany (Walsh et al, 2010)	1946–2003	3,016	218	**Dust, arsenic, long-lived radionuclides, external gamma radiation**	12	0.19 (0.17, 0.22)
Western Bohemia, Czech Republic (Tomasek, 2012)	1952–2010	1,141	73	**None**	7	0.97 (0.74–1.27)
Příbram, Czech Republic (Present study)	1977–1992	705	53	**None**	7	0.22 (0.10–0.37)
CEA-COGEMA, France (Rage et al, 2015)	1946 – 2007	211	36.6	**long-lived radionuclides, external gamma radiation**	17	0.71 (0.31, 1.30)
Ontario, Canada (Navaranjan et al, 2016)	1954–2007	1,230	21	**None**	5.3	0.66 (0.44, 0.87)
WISMUT, Germany (Kreuzer et al, 2015)	**1960–2008**	**334**	**17**	**Dust, arsenic, long-lived radionuclides, external gamma radiation, smoking**	**10**	**1.3 (0.7–2.1)**