What are the health costs of uranium mining? A case study of miners in Grants, New Mexico

Benjamin A. Jones

Department of Economics, University of New Mexico, Robert Wood Johnson Foundation (RWJF) Center for Health Policy at the University of New Mexico, USA

Background: Uranium mining is associated with lung cancer and other health problems among miners. Health impacts are related with miner exposure to radon gas progeny.

Objectives: This study estimates the health costs of excess lung cancer mortality among uranium miners in the largest uranium-producing district in the USA, centered in Grants, New Mexico.

Methods: Lung cancer mortality rates on miners were used to estimate excess mortality and years of life lost (YLL) among the miner population in Grants from 1955 to 2005. A cost analysis was performed to estimate direct (medical) and indirect (premature mortality) health costs.

Results: Total health costs ranged from \$2.2 million to \$7.7 million per excess death. This amounts to between \$22.4 million and \$165.8 million in annual health costs over the 1955–1990 mining period. Annual exposure-related lung cancer mortality was estimated at 2185.4 miners per 100 000, with a range of 1419.8–2974.3 per 100 000.

Conclusions: Given renewed interest in uranium worldwide, results suggest a re-evaluation of radon exposure standards and inclusion of miner long-term health into mining planning decisions.

Keywords: Uranium, Miner health, Radon exposure, Cost analysis, Health costs, Grants, Occupational hazard

Introduction

Uranium mining has long been associated with health problems among underground miners.^{1–5} Exposure to short-lived “radon gas” progeny, electrically charged radioactive daughter particles that attach themselves to natural aerosol in underground mines, is associated with miner health problems, particularly malignant lung cancer.^{6–12} It has been found that lung cancer risk depends on cumulative radon exposure, age at risk, time since exposure, and smoking habits.^{10,13,14}

Miners diagnosed with lung cancer often face large medical bills for diagnosis and treatment.^{15–17} However, the aggregate health costs of excess lung cancer incidence among this population are largely unknown. Given the considerable size and growth of global healthcare expenditures and renewed interest in uranium mining across the world, there is a need to quantify the long-term health costs of radon-related lung cancer.^{14,18–20} Knowledge of these health costs will contribute to our understanding of uranium mining’s

legacy on society with policy implications for renewed projects and miner exposure standards.

One way to quantify the health costs is through an economic cost analysis, which is an accounting of a defined set of market (e.g. medical, healthcare) and non-market (e.g. premature mortality) costs.²¹ While this methodology has been applied to coal mining counties in Appalachia, a uranium health cost analysis has never been published.²²

The study presented in this paper calculates health costs associated with excess miner lung cancer deaths in the Grants uranium district. This mining district in northwestern New Mexico was selected as the study area due to consistent findings linking radon exposure to lung cancer.^{7,12,23–25} Furthermore, the district yielded more uranium than any other mining district in the USA from 1948 to 2002, had large-scale operations dating back to the 1950s when radon exposure was significant, and had continuous underground mining for over 30 years.^{24,26,27} While no Grants uranium mining is occurring today, Roca Honda Resources, LLC has proposed a new project, which would be the largest uranium mine in the USA.²⁸

Excess annualized lung cancer deaths were calculated from extant cohort mortality studies with subsets of the Grants miner population.^{7,12} Annualized deaths were

Correspondence to: B.A. Jones, Robert Wood Johnson Foundation (RWJF) Center for Health Policy at UNM, Department of Economics, University of New Mexico, 1915 Roma Ave, NE, Albuquerque, NM 87131, USA. Email: bajones@unm.edu

converted into monetary costs using widely accepted value of statistical life-year (VSLY) and medical cost estimates.^{17,29–32} A sensitivity analysis was performed with the results to determine potential cost ranges.

Methods

Overall approach

This study investigated previously reported excess lung cancer mortality among Grants uranium miners over the exposure years 1955–1990, with vital status follow-up through 2005. This exposure period captures most active mining operations across varying exposure levels and economic conditions, including the early mining years when radon exposure was significant (the 1950s) and the industry “boom” of the 1970s. All major Grants mining ended in late 1989.

Previously reported lung cancer mortality rates among Grants uranium miners were used to estimate the health costs associated with premature loss of life. Following the person-years of life lost (PYLL) literature, premature miner mortality was calculated as the difference between the age of death and expected age of death based on life expectancy. This was done separately by radon exposure group based the calendar year(s) the miner(s) worked in the mines. “High” and “low” exposure groups were constructed according to the four working level month (WLM) federal radon exposure standard, first enforced in 1971.

To estimate health costs, widely accepted economic cost results were applied to determine the lifetime medical costs of lung cancer diagnosis and treatment (direct costs) and the cost to society of premature miner mortality (indirect costs). Direct and indirect health costs were estimated separately by exposure group for miners succumbing to lung cancer. This approach utilizes individual uranium miner outcomes to investigate miner population health costs. Individual Grants miners were followed over time in two epidemiology cohort mortality studies, which captured about one-third of the unique miner population.^{7,12} Results from these representative subsets of Grants miners provided micro-level estimates of radon-related lung cancer. However, because of the assumptions made in the base analysis, a number of sensitivity analyses were conducted.

Data

Unique miner population

The unique Grants uranium miner population was identified using primary source employment data from the New Mexico State Inspector of Mines (NMSMI) for the years 1955–1990.³³ The NMSMI reported annual employment by mine and mill. Using the employment data on Grants mines, 73 903 miners were identified.

It was common for miners to work in the industry for multiple years, sometimes decades. Thus, the aggregate NMSMI data (73 903 miners) over-counts the unique miner population because any miner who worked for more than 1 year would be counted separately for each year of work. To estimate health costs, I needed to identify the 1955–1990 unique uranium miner population, where each miner was counted as “employed” only once, after removing any over-counts. This was done using uranium miner employment statistics.^{12,24,34}

Specifically, extant literature on Grants miners has found that about 52.4% of the NMSMI identified miner population over 1957–1976 were unique.²⁴ Using this data, I estimated that 38 754 unique miners worked in Grants between 1955 and 1990. Therefore, approximately $(73\,903 - 38\,754) = 35\,149$ miners were the same miner being counted twice or more in the NMSMI data. The sensitivity of the final results to the choice of this point estimate is examined at the end of the paper.

In occupational exposure-related analyses on miners, it is common to set a minimum work experience threshold to eliminate any miners who worked for only a few days or weeks from the analysis, since such miners would have low cumulative radon exposure.^{4,7,12} Following recent trends in this literature, only Grants miners who had more than 6 months’ work experience were included.¹² This subset of the unique miner population was identified using average uranium miner work experience from relevant Grants district studies, which varied from 17.36% of unique miners with >1-year underground work experience, to 73.76% of miners with >3-year mine or mill experience.^{4,12,34} Based on the most recent study of Grants miners, it was assumed that 65.0% of unique miners had >6 months’ work experience, or $n = 25\,190$ miners.¹² This is the final unique miner population estimate used in the health cost analysis.

Mortality data

District mortality data come from two cohort mortality studies of miners: the “UNM study” and the “Homestake study.”^{7,12} The UNM study used Grants Clinic data and company personnel records to create a cohort of miners meeting certain data and work experience eligibility criteria. The Clinic performed most pre-employment and follow-up physical examinations for Grants uranium miners from 1957 onward. The 3469 subjects in the study worked underground in New Mexico mines for at least 1 year by 31 December 1976, were white or Native American, and were male. Vital status was determined through 31 December 1985. Expected deaths were calculated from ethnic- and race-specific mortality rates for New Mexico.

The Homestake study used proprietary company personnel data from the Homestake Mining Company; a large extraction firm operating mines in Grants from 1955 to 1990. Results from the 1 735 subjects in the study with mining experience were used. White and non-white male and female miners were included and vital status was determined from 1 January 1979 (or the date of first employment) to 31 December 2005. Expected deaths were calculated from age-, year-, and sex-specific mortality rates in the general US population. Race was accounted for in the standardized mortality ratio (SMR) analysis.

Table 1 provides select mortality findings from each study. Both studies consistently found significant excess deaths due to all malignant neoplasms, malignant neoplasms of the bronchus, trachea, and lung (e.g. lung cancer), and external causes (e.g. accidents). The SMRs for all malignant neoplasms and lung cancer are larger for the UNM study (1.9 and 4.0, respectively) than for the Homestake study (1.46 and 2.17, respectively). Homestake study miners had significantly elevated levels of all cause death and non-malignant respiratory disease, compared to UNM study miners. Finally, the elevated levels of external causes of death observed in both studies underscores the fact that workplace accidents were not uncommon. In the health cost analysis, the lung cancer SMRs from each study ($SMR_{UNM}=4.0$; $SMR_{HMC}=2.17$) were used to estimate lung cancer PYLL.

There was undoubtedly some overlap between the two mortality studies. The UNM study cohort was created from a match of over 21 000 persons who went through the Grants Clinic between 1957 and 1976 as verified against company records, including Homestake.²⁴ The Homestake study cohort was selected from a complete listing of all miners and millers who were ever employed for Homestake from 1955 onward. Thus, miners working for Homestake might have been included in both studies. Given the proprietary nature of the Homestake data set, the

extent of the overlap was not calculated. However, impacts of the overlap are considered in the sensitivity analysis.

Finally, a word should be said about how much of the unique uranium miner population was captured by these two studies. Both cohorts are subsets of the unique Grants uranium miner population. The UNM study used a subset of 3469 miners identified from approximately 21 000 records that covered most of the miner population employed between 1957 and 1976. Therefore, the study captured approximately 25% of the 1957–1976 unique miner population with >6 months' experience. The Homestake cohort of 1735 miners represented approximately 31% of the unique Homestake Mining Company worker population, or about 7% of the >6 months' experience unique miner population over 1955–1990. Combined, assuming no overlaps, the two studies captured about 32% of the unique Grants uranium miner population with >6 months' work experience over the study period. Overlaps would reduce this figure. In addition, there is no evidence that the miner cohorts were unrepresentative samples of the population.

Economic cost data

The economic approach to valuing mortality and morbidity risk reductions is based on observations of market choices that involve tradeoffs between risk and money.³² Of interest is society's willingness to pay for a risk reduction benefit, which in the case of miner mortality is the value of the reduced probability of death experienced by the miner population. This is not the value of a human life or the value of lives saved, as is sometimes mistakenly reported. Instead, it is the amount that some population of interest would be willing to pay for saving one life in expectation, which economists call the value of a statistical life or VSL.

One approach for estimating the VSL is to survey employed persons. For example, 100 000 people might be asked what their willingness to pay is for a

Table 1 Summary of two Grants mining district cohort mortality studies

Cause of death	UNM Study (1991)			Homestake study (2008)		
	(n=3469)			(n=1735)		
	Observed deaths	Expected deaths	SMR ^a (95% CI)	Observed deaths	Expected deaths	SMR ^a (95% CI)
All causes of death	408	363.4	1.1 (1.0–1.2)	541	426.4	1.27 ^b (1.16–1.38)
All malignant neoplasms	110	56.9	1.9 ^b (1.6–2.3)	177	121.6	1.46 ^b (1.25–1.69)
Malignant neoplasms of bronchus, trachea, and lung (e.g. lung cancer)	68	17.0	4.0 ^b (3.1–5.1)	95	43.8	2.17 ^b (1.75–2.65)
Non-malignant respiratory disease	22	18.9	1.2 (0.7–1.8)	55	33.6	1.64 ^b (1.23–2.13)
All external causes of death	173	116.7	1.5 ^b (1.3–1.7)	58	35.1	1.65 ^b (1.26–2.14)

Note: ^aStandardized mortality ratio. A statistically significant SMR greater than 1.0 is suggestive of excess deaths.

^b $P<0.05$.

1-in-100 000 decrease in their risk of dying during the next year. If the average willingness to pay is \$60 for this change in occupational mortality risk, then the VSL in this population would be $(\$60) \times (100\ 000) = \6 million. VSL estimates differ depending on country, age, occupation, wealth, and other socioeconomic factors.³² Several federal agencies (US Department of Transportation, US Environmental Protection Agency, Office of Management and Budget) routinely use VSLs synthesized from dozens of studies to estimate the net benefits associated with proposed policy changes (e.g. improved urban air quality, highway safety improvements). Use of the VSL is widely accepted in the economics literature and has been recently applied to estimating the mortality costs of Appalachian coal mining.^{22,35}

While the VSL is often used in cost-mortality studies, it would overestimate the costs in the present setting because miners lost years of life (e.g. 20 years) due to excess radon exposure and not entire statistical lives. Therefore, the value of a statistical life-year (VSLY) is more appropriate and is estimated by discounting the remaining expected statistical life-years.²⁹ Extant literature using surveys of employed populations (mostly in the USA) have estimated ranges on the VSLY from roughly \$100 000 to \$400 000.^{29–32} The VSLY used in the present study is \$210 000 per year of life lost. This is in 2013 US dollars and based on the \$150 000 in 1999 dollars recommended for health cost analyses, which has been used to calculate the annual life-saving benefits of US tobacco settlements.^{29,30} This VSLY is a synthesis of over 25 willingness to pay studies of mostly US employed populations across varying occupations (including mining). In the sensitivity analysis, I consider a lower-value of \$110 000 and an upper-value of \$310 000 to incorporate commonly used ranges in the literature.^{29,31}

I estimated lifetime lung cancer costs using recent calculations of cancer care costs in the USA.¹⁷ I used estimates for men under the age of 65 in order to more closely match the Grants miner cohort. Costs were aggregated for lung cancer and inflation adjusted to 2013 US dollars. The resulting lifetime medical cost estimate was \$231 713 per diagnosed patient who succumbed to lung cancer.

Analysis

To estimate indirect health costs, I followed the PYLL literature. PYLL is defined as the difference between the actual death age stemming from a disease and the expected age of death based on life table data for a person of given age, sex, and race, multiplied by the total number of persons dying from that disease.³⁶

First, years of life lost (YLL) were determined using the median age of miner lung cancer death and

the birth year of the median miner from each study cohort to calculate the life table expected age of death. Life-expectancy data came from Centers for Disease Control and Prevention life tables.³⁷

Second, total excess lung cancer deaths were estimated. This was calculated as the ratio of excess lung cancer deaths to cohort size, by study, multiplied by the >6 months' experience unique miner population ($n = 25\ 190$). The resulting figure is the aggregate excess miner lung cancer deaths over the exposure period 1955–1990.

Third, PYLL for the entire population was calculated by multiplying estimated YLL by the aggregate number of excess lung cancer deaths. That is, $PYLL = (YLL) \times (\text{aggregate number of excess lung cancer deaths})$. The value of miner PYLL was calculated by multiplying estimated PYLL by the VSLY. The resulting dollar figure is the indirect health cost. Specifically:

$$\text{Indirect health costs} = (PYLL) \times (VSLY)$$

Indirect costs were estimated separately by exposure group. Exposure groups were defined by calendar year of employment, using the 1971 federal NIOSH standard of ≤ 4 WLM annual miner exposure as the basis for the split.¹⁴ Before 1971, cumulative radon exposure was significantly greater than four WLM per year, as high as 23.2 WLM in 1967, though falling over time as mines complied with the federal standard.³⁸ Since 1972, annual mean WLM exposure in Grants mines was approximately 1.0, with a ninety-fifth percentile below 4.²⁴

Based on these findings, the unique miner population with greater than 6 months' experience ($n = 25\ 190$) was split into a "high exposure group" for miners who worked between 1955 and 1970 ($n_H = 9177$) and a "low exposure group" for miners who worked between 1971 and 1990 ($n_L = 16\ 013$). This split at 1971 was also utilized by the UNM study since available WLM measurements of Grants mines clearly indicated that pre-1971 miners "had higher exposures than those employed later."³⁸ Thus, the distinction between "high" and "low" exposure groups in 1971 is consistent with the extant literature and underground readings of radon levels.

To estimate indirect health costs separately by exposure groups, excess lung cancer deaths were calculated using the lung cancer SMR found in each study: $SMR_{UNM} = 4.0$ (high exposure group); $SMR_{HMC} = 2.17$ (low exposure group). The UNM study was constructed to be a representative sample of pre-1971 long-term miners. Therefore, applying the UNM lung cancer SMR to the high exposure group was appropriate. By contrast, the Homestake study was mostly composed of short- and medium-term miners (72.9% of Homestake miners worked less than 5 years), a majority of whom were first employed post-1971.¹² Thus, the Homestake study SMR is more representative of the low exposure

group. The implicit assumption made is that the study cohorts were representative samples of the miner population during these years.

However, the overlap between samples may introduce uncertainty. For example, the representativeness of the Homestake study of the post-1971 low exposure group may be limited if many of the miners in the cohort worked pre-1971 and were picked up in the UNM study. In order to assess the potential impact of this, I estimated the extreme overlap possibilities as part of the sensitivity analysis. That is, I assumed at one extreme that both high and low exposure groups had the high SMR ($SMR_{UNM}=4.0$) and at the other extreme that both exposure groups had the low SMR ($SMR_{HMC}=2.17$). This check on results eliminates the exposure group distinctions and provides extreme bounds on the health costs due to study overlap.

To estimate direct health costs, the number of excess lung cancer deaths in each exposure group were multiplied by the lifetime medical costs of lung cancer. The resulting dollar figure is interpreted as the lifetime medical costs for miners succumbing to lung cancer at rates in excess of expectation. Direct health costs were also estimated separately by exposure group.

Lung cancer associated with uranium mining occurs years after exposure.^{1,2,4} The economic literature suggests discounting future health costs to account for delayed effects, but this is not universally accepted.^{39–43} In addition, there is debate about the proper discount rate.^{44,45} I follow best practices in the literature and US Public Health Service guidelines, and use a 3% discount rate for each year of health costs post-2013.^{46–51}

Results

Unique miner population

Figure 1 presents the identification of the unique miner population with greater than 6 months' work experience by exposure group. The high exposure group has fewer miners because it covers five fewer years than the low exposure group and misses the industry "boom years" of the late-1970s when annual employment was at its peak. As previously discussed, UNM study miner demographics and lung cancer SMR are associated with the high exposure group. The low exposure group is associated with Homestake study miner characteristics and SMR.

Premature lung cancer mortality

Table 2 presents the PYLL results by exposure group. The average high exposure miner had an earlier birth year and died of lung cancer at a younger age than the average low exposure miner. This is consistent with differences in cumulative exposure between the two groups. Life expectancy for the average miner who died of lung cancer ranged from

20.6 to 21.7 years. These are the average YLL by a uranium miner due to excess lung cancer mortality. In other words, miners succumbing to lung cancer and working before 1971, died on average 21.7 years prematurely compared to an average of 20.6 years for miners working after 1971.

Excess exposure-related lung cancer deaths were estimated at 550.5 miners for the period 1955–1990, or 134.9 between 1955 and 1970 and 415.6 between 1971 and 1990. In standardized terms, excess lung cancer mortality over the entire mining period was 2185.4 per 100 000 miners. This was approximately 1.4% of the unique Grants miner population who worked over 1955–1990, or about 2.2% of the unique miner population who worked >6 months over the same time period. Results are significantly lower than comparable studies on Colorado Plateau uranium miners, where the most recent excess lung cancer mortality estimate is 13 052.8 per 100 000 miners.⁵²

There were 35 years of underground uranium mining operations in Grants. If excess deaths were uniformly distributed through time, then on average there were 62.4 annual excess lung cancer deaths per 100 000 over the 1955–1990 period. This was calculated by dividing 2185.4 by 35 years. In reality, there were more excess deaths in the later years (mid-1970s onward) than in the early years (pre-1970) since the health effects of radon-exposure are typically delayed.¹ However, more data would be required to estimate year-by-year specific death rates, which is outside the scope of the present study.

PYLL were 2927.3 person-years (high exposure group) and 8561.3 person-years (low exposure group). Results were lower for the high exposure group because there were fewer miners (i.e., persons) working in Grants over 1955–1970 compared with 1970–1990. This is a consequence of the mining "boom" in the late 1970s. Thus, while YLL were the largest for this group of miners, in terms of person-years, there were fewer of them. The distinction to make is one between significant radon exposure/fewer miners (1955–1970) and less significant exposure/more miners (1971–1990).

Assuming a uniform distribution of premature mortality, dividing PYLL by 35 years of underground operations resulted in annual lung cancer PYLL of 83.6 (high exposure group) and 244.6 (low exposure group), on average. As before, uniform distribution of PYLL is unlikely, though provides a reasonable first-approximation.

Health costs of uranium mining

Two health costs were estimated: (1) lifetime medical costs of lung cancer (direct health costs); and (2) costs to society of premature lung cancer mortality (indirect health costs). I used an estimate of \$231 713 for

Figure 1 Identification of unique Grants district uranium miners with >6 months' mining work experience over 1955–1990 (split by exposure group). Source: constructed by author using data cited in text.

lifetime lung cancer medical costs and a VSLY estimate of \$210 000.^{17,29,30} Table 3 summarizes the health cost estimates of Grants uranium mining after multiplying the VSLY estimate with the estimates of excess lung cancer deaths and YLL across exposure groups (indirect) and multiplying the medical cost estimate by excess deaths only (direct).

Direct health costs of lung cancer treatment ranged from \$31.3 million to \$96.3 million, with a combined group total of \$127.6 million. Indirect health costs stemming from premature mortality ranged from \$614.8 million to \$1.8 billion, with a combined total of \$2.4 billion. For both direct and indirect costs, the low exposure group had costs approximately three times larger than the high exposure group; a product of significantly more unique miners having worked in 1971–1990 than 1955–1970, with some overlap between the two time periods (i.e. some miners in the low exposure group worked in uranium mines pre-1971, effectively increasing their lifetime cumulative

exposure).¹² For both groups, indirect health costs are about 19 times larger than direct health costs.

Estimated total health costs of Grants uranium mining are \$2.5 billion, which is \$4.6 million per excess lung cancer death. Dividing total health costs by 35 years of mining operations, resulted in annual health costs of \$72.6 million (direct and indirect combined). On a per-pound (lb) basis, total health costs ranged from \$1.96/lb to \$5.73/lb, with a combined group total of \$7.69/lb. That is, for every lb of uranium concentrate produced in the Grants district over 1955–1990, it produced an estimated \$7.69 in direct and indirect health costs.

Health cost sensitivity analysis

The previous analysis relied on literature driven estimates of the unique miner population, the >6 months' work experience population, the median age of death, and the choice of a VSLY. This section evaluates how reasonable changes in these assumptions impact the

Table 2 Person-years of life lost (PYLL) due to lung cancer mortality among Grants district uranium miners, by exposure group

Group statistic	"High exposure group" 1955–1970 (n=9177)	"Low exposure group" 1971–1990 (n=16 013)
Median miner birth year ^a	1934	1945
Median miner mortality age (years) ^a	56	60
Life expectancy at age and year of death (YLL) ^b	21.7	20.6
Excess lung cancer deaths (no. of miners)	134.9	415.6
Person-years of life lost (PYLL) ^c	2927.3	8561.3

Note: ^aLow exposure group estimated from Table 1 of Homestake study. That study does not directly report miner birth year or mortality age. The sensitivity analysis allows for uncertainty in the estimates.

^bDetermined for the median miner using Centers for Disease Control and Prevention life tables for white males.

^cCalculated as (YLL) × (Excess lung cancer deaths), separately by group.

Table 3 Health costs of uranium mining by exposure group with totals across groups

Cost	Cost estimates in millions of 2013 dollars for excess lung cancer deaths across exposure groups		
	"High exposure" group 1955–1970	"Low exposure" group 1971–1990	Combined group totals 1955–1990 ^a
Direct health costs	\$31.3	\$96.3	\$127.6
Indirect health costs	\$614.8	\$1797.8	\$2412.6
Total health costs (direct + indirect)	\$646.1	\$1894.1	\$2540.1
Total cost per lb. of uranium produced (\$/lb.) ^b	\$1.96/lb.	\$5.73/lb.	\$7.69/lb.
Number of excess lung cancer deaths	134.9	415.6	550.5

Note: ^aCombined totals are the horizontal sum of costs across both exposure groups. This yields a cost estimate due to exposure over the entire 1955–1990 underground mining period.

^bBased on an estimate of 330 453 000 lb. of uranium concentrate produced in the Grants district over 1955–1990.²⁶

overall health cost results. The lower- and upper-bounds on excess lung cancer deaths and health costs using revised assumptions were evaluated.

Changes were motivated by uncertainties in the literature that fell under three categories: (1) uncertainty in the number of unique miners with >6 months' work experience; (2) uncertainty in study representation and exposure group overlap; and (3) uncertainty in economic costs.

Uncertainty in the unique miner population

Previously, 52.4% of miners counted by the NMSMI were assumed to be unique based on Grants miner employment statistics reported in the UNM study. While this statistic accurately describes the employment situation over the UNM study period (1957–1976), it may be an inaccurate representation of the unique miner population post-1976. To incorporate this possibility, I re-estimated the unique miner population allowing a lower-bound of 42.4% and an upper-bound of 62.4% (a 10% range) on the number of NMSMI miners who were unique persons. A range greater than 10% would be unrealistic and unreasonable based on the literature.

There are also discrepancies in the literature regarding the percentage of unique miners who had >6 months' uranium mine work experience. The Homestake study reported that 51.95% of unique miners and millers had >6 months' work experience and no missing employment data.¹² In a recent survey of Grants uranium miners employed after 1971, 73.76% had >3 years mine experience.³⁴ Given these differences, the unique miner population was re-estimated using 51.95% as a lower-bound and 73.76% as an upper-bound on the >6 months' work experience population. These compare to the 65.0% used previously.

Uncertainty in exposure group overlap and mortality study representation

Both studies used in the cost analysis were comprised of subsets of the Grants miner population. It is possible that they were not representative samples, that lung

cancer YLL were different in the studied miner cohorts than in the population, or some combination of the two. This might be the case if the UNM and Homestake miners were more or less predisposed to contract radon-related lung cancer either earlier or later in life than miners not included in the study cohorts. Or, perhaps studied miners had different cancer survival times than those in the population. Both these possibilities would impact miner YLL. Second, perhaps the overlap between exposure groups was large. In this case, the exposure group split at 1971 would fail to capture actual exposures for miners working before and after 1971. Undoubtedly, some miners working post-1971 had exposures more consistent with UNM study miners, while some short-term miners working pre-1971 would have lifetime exposures more consistent with post-1971 Homestake miners. Other possibilities exist depending on the size and scope of the overlap, which would affect estimated lung cancer mortality rates *vis-à-vis* exposure levels.

While there is no evidence that either study was unrepresentative or that the overlap was large, the analysis was checked incorporating these two possibilities. To assess the impact of study representativeness, YLL were re-estimated using a ± 5 year range on median miner mortality age for each exposure group. Specifically, high exposure group miners died at age 61 years (lower-bound) and age 51 years (upper-bound), while low exposure miners died at age 65 years (lower-bound) and age 55 years (upper-bound). These compare to ages 56 and 60 years for the high exposure and low exposure groups, respectively, used previously.

To assess the potential impact of overlap between the exposure groups, a continuous exposure group was assumed with no split at 1971. Costs were re-estimated at the two extremes: (1) the larger UNM lung cancer SMR was applied to the entire 1955–1990 miner population; and (2) the smaller Homestake lung cancer SMR was applied to the entire miner population. This robustness check produced little change in health costs compared to those previously reported. Thus, it is not reported in the sensitivity analysis results.

Uncertainty in choice of VSLY

Finally, the economics literature typically places bounds on the VSLY used in mortality cost analyses to incorporate heterogeneity in VSLY estimates, allowing for uncertainty created by population-level socioeconomic differences and discount rates.³¹ To this end, indirect health costs were re-estimated using a \$100 000 range on the previous benchmark estimate of \$210 000. This is consistent with average value ranges reported in the literature and yielded a lower-bound of \$110 000 and an upper-bound of \$310 000 on the VSLY.²⁹

Results of sensitivity analysis

Health costs and excess lung cancer deaths were re-estimated using the revised assumptions. Table 4 summarizes the range in bounds of the sensitivity analysis for the combined group totals. Total health costs ranged from \$783.9 million to \$5.8 billion with a point-estimate of \$2.5 billion. The range in health costs was driven primarily by the high sensitivity of the indirect cost estimates to the VSLY chosen. For example, reducing the VSLY from \$310 000 to \$210 000 *ceteris paribus* reduces the upper-bound on indirect costs to \$3.8 billion; a drop of \$1.8 billion. Changes in the calculation of the miner population produced far smaller changes in health costs (no more than a few hundred million dollars).

Estimated excess lung cancer deaths ranged from 357.7 to 749.2, with a point-estimate of 550.5. Ranges in these bounds were most sensitive to the estimation of the unique miner population with >6 months' work experience.

Discussion

This study investigated miner health costs associated with Grants district uranium mining over 1955–1990. Results indicate that the indirect health costs of uranium mining are significantly larger than direct costs. This disparity persists across a range of VSLY

estimates and miner population specifications. The relative magnitude of indirect health costs is due to the high number of YLL among underground miners. Average Grants miners died between 55 and 60 years of age, which was premature by 20–22 years based on their life expectancy. The economic costs of this excess loss of life are underscored by the fact that miners in this age group were at their peak income-earning potential.

While only malignant lung cancer mortality was analyzed, health literature suggests that uranium mining may be positively associated with leukemia, stomach cancer, liver cancer, non-malignant respiratory diseases (e.g. silicosis, obstructive airways disease, non-specific chronic lung disease), and diseases of the blood and other blood-forming organs, though causation is inconclusive.^{4,5,7,10,53–56} Including the costs of these other diseases will raise the health costs associated with uranium mining.

The average contract/market price of uranium over 1955–1990 was \$71.63/lb. Based on the results in this study, every \$1 of uranium sold in the Grants district created health costs of \$0.11 with a range of \$0.03–\$0.25. This implies that the price of uranium was from \$2.37/lb to \$17.56/lb lower than it would have been if the mining firms incurred these costs. While some of the direct health costs might have been covered through employer-provided health insurance, the indirect health costs due to premature mortality were not.

Results from the low exposure group are suggestive that the current federal requirement of ≤4 WLM/year cumulative exposure (in effect since 1971) is insufficient to prevent excess miner deaths. At least 40% of the miners in this group were first employed after 1971, yet an elevated lung cancer SMR was observed. This is consistent with the conclusions of a NIOSH study group that the 4 WLM/year standard “does not provide an adequate degree of protection

Table 4 Lower- and upper-bounds on total health costs of Grants uranium mining (1955–1990)

Cost	Cost estimates in millions of 2013 dollars for excess lung cancer deaths (combined exposure group totals)		
	Lower-bound ^a	Benchmark ^b	Upper-bound ^c
Direct health costs	\$82.9	\$127.6	\$173.6
Indirect health costs	\$701.1	\$2412.6	\$5630.8
Total health costs (direct+indirect)	\$783.9	\$2540.1	\$5804.4
Total cost per lb. of uranium produced (\$/lb.) ^d	\$2.37/lb.	\$7.69/lb.	\$17.56/lb.
Number of excess lung cancer deaths	357.7	550.5	749.2

Note: ^aCalculated assuming 42.44% of miners are unique, 51.95% of unique miners have >6 months' uranium mining work experience, median age of death of 61 years (65 years) for the “high exposure” (“low exposure”) group, and a VSLY of \$110 000.

^bPreviously reported as “Combined group totals 1955–1990” in Table 3. This is the point-estimate.

^cCalculated assuming 62.44% of miners are unique, 73.76% of unique miners have >6 months' uranium mining work experience, median age of death of 51 (55) for the “high exposure” (“low exposure”) group, and a VSLY of \$310 000.

^dBased on an estimate of 330 453 000 lb. of uranium concentrate produced in the Grants district over 1955–1990.²⁶

for underground miners.”⁵⁷ The significant health costs of excess lung cancer deaths found in the present study suggest a re-evaluation of the current federal standard.

Owing to executive orders 12866 and 13563, signed by Presidents Clinton (1993) and Obama (2011), respectively, any changes to federal agency regulations must undergo a complete “Economic Impact Analysis” before the changes take effect. Consequently, modifications to the current 4 WLM/year standard would require NIOSH to complete an extensive analysis of the costs, benefits, and economic impacts of the proposed policy change. This study will directly contribute to future NIOSH benefit–cost analyses on strengthening the radon exposure standard, by providing an estimate of the health costs associated with miner exposure. In such an analysis, estimated health costs (\$7.69/lb with a range of \$2.37/lb–\$17.56/lb) would be an approximation of the miner health “benefits” of reduced exposure. These would have to be evaluated against the “costs” to the mining companies of meeting the new standard, as well as the economic impacts on employment rates, local economies, and tax revenue. Thus, the present study is a relevant contribution to the ongoing policy debates over the NIOSH exposure standard.

Limitations

First, lack of complete data on miner employment histories required some modeling assumptions. While assumptions made were consistent with the extant literature on uranium miners, uncertainties remain. Results from the sensitivity analysis suggest that alternative specifications had little impact on health cost results. However, if miner employment histories were drastically different than those investigated, results might be sensitive to further changes.

Second, smoking is a well-known risk factor for lung cancer and other respiratory diseases. The relationship between smoking, radon, and lung cancer is nuanced, with extant literature finding additive and sub-multiplicative interactions, particularly among uranium miners.^{13,58,59} However, miner smoking histories were unknown and not included in this analysis. Potential impacts of this on overall cost results are inconclusive from the literature, but likely insignificant. The UNM study found that while a control for “ever” smoking yielded a better model fit, it had relatively little impact on lung cancer relative risk values. Other studies have shown that lung cancer SMRs above 1.3 are unlikely to be accounted for by smoking habits and are likely occupational related.⁶⁰ In addition, a study of male Navajo uranium miners working in New Mexico, Arizona, and Utah and contracting lung cancer between 1969 and 1981, estimated a relative risk value consistent with the UNM study.⁶¹ Most of these miners did not smoke, but had lung cancer risks similar to

smoking miners in Grants over the same time period. Finally, recent work on European uranium miners confirms previous work that radon-related lung cancer persists even after controlling for smoking habits.⁵⁸ Overall, extant literature has found that adjusting for smoking has little effect on studies of radon and lung cancer among occupationally exposed populations. Therefore, the health cost results are unlikely to be significantly impacted by including miner smoking histories.

Third, using existing Grants cohort mortality studies to investigate miner population health costs may introduce potential bias. This approach rests on the assumption, justified by the extant literature, that the miners in the cohort studies were representative samples of the miner population. However, this was impossible to directly investigate without access to the proprietary primary source data. This might be problematic if the overlap between the two studies was large. Impacts of overlap and unrepresentativeness would be on miner YLL and the number of excess lung cancer deaths over 1955–1990. Both of these potential impacts were addressed in the sensitivity analysis. Results were robust to the changes investigated. Thus, while using micro-level miner outcome data on approximately one-third of the unique population may introduce potential bias, there were limited impacts on health cost results based on the study approach.

Finally, the cost estimates represent the lower-bound since only underground miners with excess lung cancer mortality were studied. This analysis did not incorporate miner disability adjusted life years associated with lung cancer, costs of excess deaths among uranium mill workers, costs of problems not leading to excess mortality (e.g. respiratory symptoms), or the costs of contaminated water supplies on local residential populations.^{5,23,62–68} In addition, longer vital status follow-up on the UNM study cohort may reveal more excess lung cancer deaths than previously estimated. Subsequent updates of the Colorado Plateau uranium miner cohort have found progressively higher rates of excess lung cancer mortality.^{4,52} If the UNM study is updated and a larger lung cancer SMR is estimated, then the cost estimates calculated in the present study would constitute the lower-bound of actual health costs.

Conclusions

This research contributes to the growing international literature of uranium legacy impacts. Uranium mining brings jobs, tax revenue, and critical infrastructure to rural areas, but has nontrivial impacts on the environment and human health. While the qualitative impacts of mining have been presented in media outlets such as *The New York Times*, *USA Today*, and through several books — *Yellow Dirt*, *The Navajo*

People and Uranium Mining; Yellowcake Towns — its quantitative costs are largely unknown.^{69–74} This is the first study of its kind to quantify the human health costs from the mining perspective. This is relevant today given renewed interest in uranium mining across the world.^{14,28,75}

This study finds that the costs of uranium extraction are not inconsequential. Miners have the highest exposure to radon, but are only a subset of the potential exposure population. Qualitative work and media outlets have identified other exposure populations, including Native Americans, families of miners, pregnant women, and communities adjacent to mines and mills. Additional studies that delineate the relationship and associated costs between exposure and human health can inform policy concerning future uranium mining. In addition, comparisons of financial benefits (e.g. jobs, taxes, and infrastructure) to long-term health and environmental costs associated with uranium mining would further elucidate uranium legacy impacts. While the distribution of uranium benefits and costs are still uncertain, identifying and quantifying impacts can be admissible evidence in questions about how and under what conditions future operations should proceed.

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