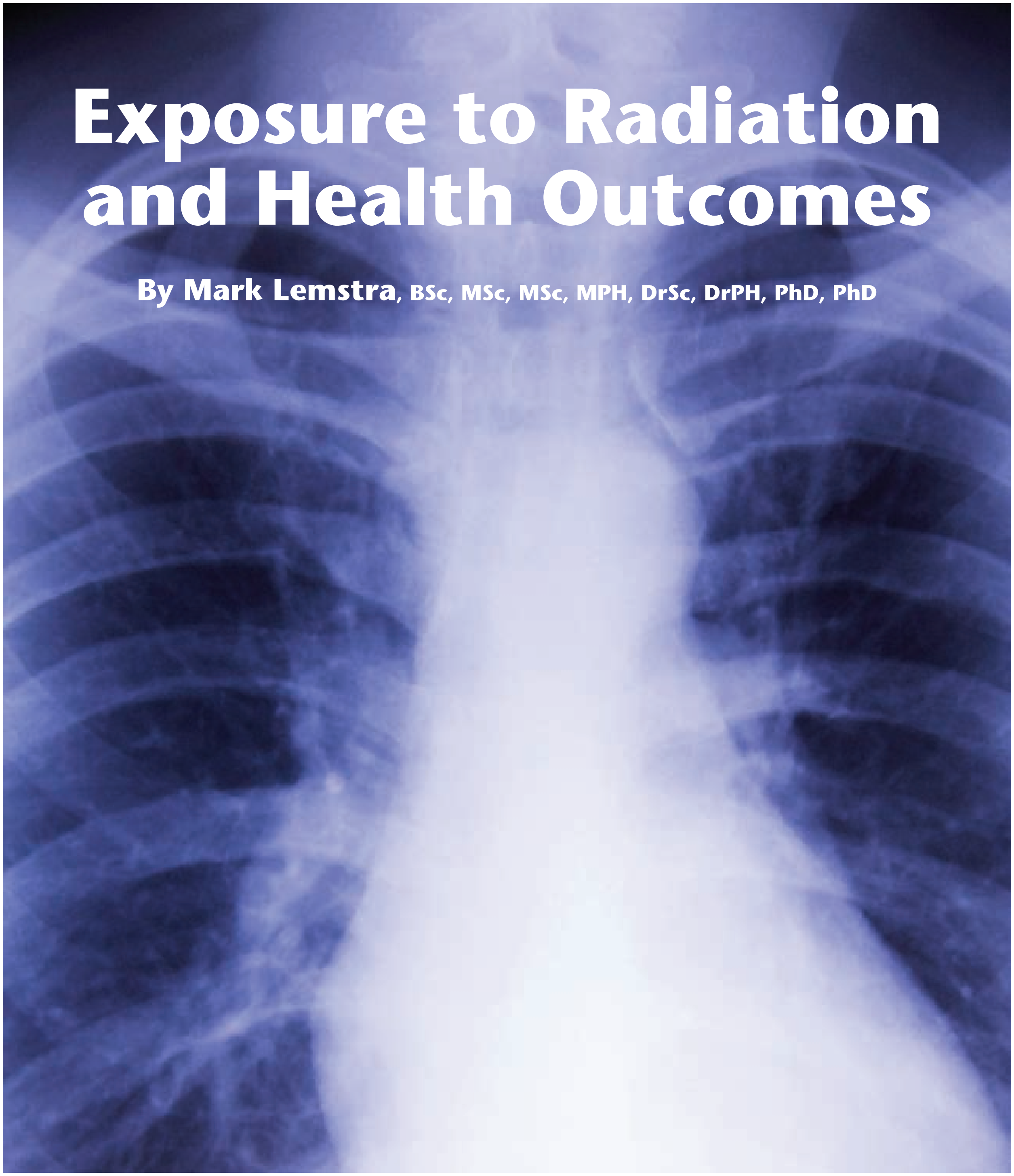
Exposure to Radiation and Health Outcomes

By Mark Lemstra, BSc, MSc, MSc, MPH, DrSc, DrPH, PhD, PhD



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June 2009

Commission: This report was commissioned by the Canadian Center for Policy Alternatives (Saskatchewan office) and the Saskatchewan Union of Nurses. Verbal agreement to proceed was granted on May 28, 2009 for a report to be completed by June 18, 2009. The report is to be presented to the *Future of Uranium in Saskatchewan Public Consultation Process* on June 23, 2009.

Context: In October 2008, the Government of Saskatchewan established the Uranium Development Partnership to examine uranium resources. The report *Future of Uranium in Saskatchewan* was submitted March 31, 2009. On April 8, 2009, the Government of Saskatchewan initiated a public consultation process on the recommendations of the report. One of the recommendations was that "further work needs to be done to understand the social, environmental … feasibility of adding nuclear power to the province". This report (Exposure to Radiation and Health Outcomes) is in response to that recommendation.

Objective of Report: The main objective of this report was to provide an evidence-based epidemiological review on the impact of exposure to radiation on subsequent health outcomes. Articles were accepted for inclusion only if they were of high scientific quality with information coming from peer review publications or credible sources like the World Health Organization or the United Nations.

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Conflicts of Interest: There are no direct or indirect conflicts of interest to declare. This report is an independent review of the association between exposure to radiation and subsequent health outcomes. At no time was the author asked to lead the discussion of this report in one direction or another. This report is not for profit without copyright and to be used for educational or information services alone.

The hope is that this independent summary of the evidence provides some understanding of the social and environmental feasibility of adding nuclear power to the province of Saskatchewan.

Printed copies: $10.00. Download free from the CCPA website.

ISBN 978-1-897569-70-2

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Executive Summary

The main objective of this report was to provide an evidence-based summary of the impact of exposure to radiation on subsequent health outcomes.

Ionizing radiation is measured as absorbed dose in gray or Gy. The effective dose measured in sievert or Sv takes into account the amount of ionizing radiation energy absorbed, the type of radiation and the susceptibility of various organs and tissues to radiation damage.[1]

A. Exposure to radiation and impact on health outcomes

There are many studies that review exposure to radiation and impact on health outcomes.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reviewed over 1000 publications on the risks of ionizing radiation on cancer and heart disease.[2,3] The best estimate for excess relative risk of incidence of total solid cancers (excluding leukemia) after exposure to radiation is 43% for males and 81% for females. The best estimate for excess relative risk of mortality from total solid cancers (excluding leukemia) after exposure to radiation is 34% for males and 65% for females.[2]

Clear evidence of site specific cancers associated with doses of radiation include lung cancer, breast cancer (females), thyroid cancer, salivary gland cancer, rectal cancer (females), bone cancer (males), non melanoma skin cancer, ovarian cancer, urinary bladder cancer, kidney cancer (females) and brain cancer (males).

Lifetime solid cancer risk estimates for those exposed as children are 2-3 times higher than estimates for the adult population.[2] A report from Atomic Energy of Canada provides a biological explanation as to why infants and children are more vulnerable to internal uptake of radionuclides.[4]

The association between leukemia incidence and mortality from radiation exposure is very strong. The greatest risks are found for youth under the age of 20.[2]

B. Exposure to radiation and impact on health outcomes to nuclear power workers

There are many studies that review chronic exposure to low dose radiation and the subsequent impact on health outcomes to nuclear power workers. Radiation protection standards have been based on extrapolations from acute, high dose rates.[5] These extrapolations are subject to substantial uncertainty.[5] Recent studies have confirmed significant excess relative risks of health problems and mortality from chronic exposure to low doses of radiation previously believed to be safe.

The largest study to review the effects of chronic low-dose exposure of ionizing radiation on health outcomes and mortality is the 15 Country Study of Nuclear Industry Workers.[5,6] This study included 407,391 nuclear industry workers that were followed for an average duration of 12.8 years. All-cause mortality had a dose-related excess relative risk of 42% and all cancer mortality (excluding leukemia) had a dose-related excess relative risk of 97%. The most significant site specific association was for lung cancer with an excess relative risk of mortality of 186%. Risk estimates were not driven by the highest dose categories meaning excess risk was present even with relatively low doses of radiation.[5]

Perhaps surprisingly, the only country with a statistically significant difference in all cancer mortality in comparison to the other 14 countries was Canada. In Canada, the excess relative risk of all cancer mortality was 665%.[5] This is significantly higher than the average of the 15 countries (97%) and in comparison to similar countries like the United States (78%).[5]

Current recommendations from the International Commission on Radiological Protection are to limit occupational doses to 100 mSv over five years.[6] In the 15 Country Study, the workers had an average exposure of 19.4 mSv (Canada was 19.5 mSv).[6] The results suggest that current radiation protection standards need to be at least reviewed and possibly revised based on recent evidence.

It is important to note that the excess relative risks for all cancer mortality for nuclear power workers (151%) at less than 100 mSv (the International Commission on Radiological Protection standards) are higher than the excess relative risks for all cancer mortality for those who survived the atomic bomb in Japan (62%).[6]

In Canada, a review of 45,468 nuclear power workers with a mean follow-up period of 7.4 years found an excess relative risk of mortality from all solid cancers of 280%.[7] The average dose of radiation was 13.5 mSv. The results from this exclusively Canadian study confirm that chronic exposure to low doses of radiation are associated with an excess relative risk of cancer mortality and that radiation protection standards in Canada need to be at least reviewed and possibly revised based on recent evidence.

C. Exposure to radiation and impact on community residents

Many papers have been written about the health effects from the explosion of the nuclear power plant at Chernobyl in the Ukraine. The World Health Organization summarized the findings.[1] The 240,000 workers responsible for the clean-up (liquidators) had a doubling in their incidence of leukemia and an increased risk of death from cardiovascular disease. In total, the World Health Organization predicts 4000 additional cancer deaths from the most exposed groups (liquidators and evacuees).

Considerable attention, however, has also been focused on community residents that lived great distances from the actual explosion cite that were exposed to low levels of radiation. Significant increases in thyroid cancer in children were not only found in the Ukraine but also in Belarus, Russia, Czechoslovakia and as far as the United Kingdom (a 484% increase in Belarus).[10] As well, increases in leukemia in children were found in contaminated areas across Europe including the Ukraine, Belarus, Russia, Turkey, Greece and Germany (a 350% increase in Ukraine).[10,11] No increases in thyroid cancer or leukemia were found in adults.

In total, 346,000 residents had to be evacuated and relocated. The relocation of people, economic insecurity and threats to health led to considerable mental health problems.[1]

Studies from the Techa River also demonstrate the impact of chronic low doses of radiation on the health of community residents. In the 1950's, the Russian government discharged liquid radioactive wastes into the Techa River exposing riverside residents to chronic low doses of radiation. 18,382 residents were followed for 48 years. Overall, the residents along the Techa River had 100% excess relative risks in solid cancer incidence, 500% excess relative risks in breast cancer incidence and 360% excess relative risks for chronic lymphoid leukemia all per 1 Gy.[12-14]

Lastly, it is important to discuss the incidence of health problems for people that live near nuclear power facilities. The only known health concern is leukemia in children. A review of the literature finds that there is a range of increased risk of leukemia from 0% to 119% between countries for youth below the age of 20.[15] A closer review of the evidence finds that very young children that live within close proximity to nuclear facilities have an increased risk of leukemia. A German study found that children below the age of 5 that live within 5 kilometers of a nuclear facility have a 119% increased risk of leukemia whereas children that live within 10 kilometers have a 33% increased risk.[16] This study has been cited as a reason to continue the phase out of all nuclear power in Germany by 2020. The German study was replicated in England but found only a 23% increased risk of leukemia for children below the age of five that live within 5 kilometers of a nuclear facility.[17]

Search Strategy

The databases PubMed and Web of Science were searched using the key words "Nuclear Energy", "Nuclear Power Plants", "Worker Health", Occupational Exposure", "Community Health" and "Health". An internet search identified seven relevant web sites that were scanned for literature.

A total of 716 articles were obtained and reviewed. The references lists of these articles were then reviewed to gather additional papers. The review of reference lists resulted in another 1009 articles for a total of 1725 articles.

After determining relevance to the topic, 73 articles were reviewed in detail.

After conducting a check for scientific quality, 22 papers were accepted for inclusion in this paper.

Search Strategy

Search through PubMed and Web of Science and Internet search for websites	716 articles
Search through reference lists	1009 articles
Total articles before relevance review	1725 articles
Articles after relevance review	73 articles
Articles accepted after scientific quality review*	22 articles

*Articles were accepted for inclusion only if they were of high scientific quality with information coming from peer review publications or credible sources like the World Health Organization or the United Nations. If a very high quality paper was accepted, there was no need to accept a lower quality paper on the same topic.

A. Exposure to Radiation and Impact on Health Outcomes

Ionizing radiation is measured as absorbed dose in gray (or Gy). The effective dose measured in sievert (or Sv) takes into account the amount of ionizing radiation energy absorbed, the type of radiation and the susceptibility of various organs and tissues to radiation damage.[1]

There are, however, other considerations when reviewing the evidence on exposure to radiation and its impact on health outcomes including:

- The overall scientific quality of the study
- Study design (i.e. prospective cohort, retrospective cohort, case-control)
- Sample size and statistical power
  - Working with rare diseases (i.e. leukemia)
- Duration of follow-up
  - Long follow-up durations are required due to latency period
- The presence of bias (i.e. selection bias, information bias, confounding bias)
  - Dose measurement errors
  - Uncertainty in accuracy of diagnosis or cause of mortality
  - Loss to follow-up
- The assessment and control for confounding variables
  - Uncertainty about confounding variables (i.e. smoking status over lifetime)
- The assessment for effect modification
  - Natural background exposure to radiation
  - Genetic susceptibility
- Multivariate adjustment to determine independent effect of one exposure on outcome while statistically controlling for other explanatory exposures (i.e. independent effect of radiation on lung cancer after controlling for smoking)
- Transfer of radiation risk between populations
  - Different countries, populations and ages (age is particularly important)

There are many studies that review exposure to radiation and impact on health outcomes. The most well known and best designed is the life span study (LSS) in Japan for survivors of the atomic bomb. The exposure data can be stratified by dose (i.e. within 10 kilometers of blast), gender, age at exposure and time since exposure. The dataset is very comprehensive with information on 10,127 deaths due to solid cancer with about 5% (479 cases) directly attributable to radiation exposure. Although it might seem odd to use data from an atomic blast, the only relevant information is knowledge of the exposure to radiation and not the source of the exposure. As such, the LSS represents the best available evidence to determine the strength of the association between exposure to radiation (0.005 Sv or more) and subsequent health outcomes.

The best estimate for excess relative risk of incidence of total solid cancers (excluding leukemia) after exposure to radiation is 43% (range 35% to 53%) for males and 81% (range 71% to 92%) for females.[2] Lifetime solid cancer risk estimates for those exposed as children are 2-3 times higher than estimates for the adult population (Table 1).

Table 1. Incidence of total solid cancers (apart for leukemia) after exposure to radiation[2]

	Excess Relative Risk*	95% Confidence Interval
Gender		
Males	43%	35% to 53%
Females	81%	71% to 92%
Age at exposure		
Less than 20	100%	86% to 115%
21-40	50%	39% to 61%
Above 40	36%	25% to 48%

*Excess relative risk is per 1 Sv

The best estimate for excess relative risk of mortality from total solid cancers (excluding leukemia) after exposure to radiation is 34% (range 24% to 45%) for males and 65% (range 52% to 78%) for females (Table 2).[2]

Table 2. Mortality from total solid cancers (apart for leukemia) after exposure to radiation[2]

	Excess Relative Risk*	95% Confidence Interval
Gender		
Males	34%	24% to 45%
Females	65%	52% to 78%
Age at exposure		
Less than 20	80%	62% to 100%
21-40	49%	36% to 63%
Above 40	28%	17% to 41%

*Excess relative risk is per 1 Sv

Clear evidence of site specific cancers associated with doses of radiation include lung cancer, breast cancer in females, thyroid cancer, salivary gland cancer, rectal cancer in females, bone cancer in males, non melanoma skin cancer, ovarian cancer, urinary bladder cancer, kidney cancer in females and brain cancer in males (Table 3).[2]

Table 3. Incidence of site specific cancers after exposure to radiation[2]

	Excess Relative Risk*	95% Confidence Interval
Lung cancer		
Males	32%	13% to 55%
Females	148%	104% to 199%
Breast cancer		
Females	149%	117% to 185%
Thyroid cancer		
Males	78%	15% to 177%
Females	189%	128% to 265%
Salivary gland cancer		
Males	450%	132% to 1268%
Females	95%	<0% to 409%
Rectal cancer		
Females	46%	8% to 97%
Bone cancer		
Males	224%	90% to 969%
Non-melanoma skin cancer		
Males	127%	65% to 217%
Females	137%	81% to 212%
Ovarian cancer		
Females	61%	8% to 135%
Urinary bladder cancer		
Males	127%	65% to 217%
Females	137%	81% to 212%
Kidney cancer		
Females	104%	2% to 283%
Brain cancer		
Males	154%	66% to 287%

*Excess relative risk is per 1 Sv

The association between leukemia incidence and mortality from radiation exposure is very strong. The greatest risks are found for youth exposed to radiation under the age of 20 (Table 4 incidence and Table 5 mortality).

Table 4. Incidence of leukemia after exposure to radiation[2]

	Excess Relative Risk*	95% Confidence Interval
Gender		
Males	466%	307% to 688%
Females	505%	324% to 761%
Age at exposure		
Less than 20	827%	495% to 1366%
21-40	359%	201% to 597%
Above 40	398%	232% to 645%

*Excess relative risk is per 1 Sv

Table 5. Mortality from leukemia after exposure to radiation[2]

	Excess Relative Risk*	95% Confidence Interval
Gender		
Males	407%	275% to 584%
Females	396%	257% to 587%
Age at exposure		
Less than 20	663%	421% to 1026%
21-40	307%	181% to 487%
Above 40	315%	174% to 524%

*Excess relative risk is per 1 Sv

Children are more vulnerable to the internal uptake of radionuclides. Why? A report from Atomic Energy of Canada explains that the early stages of development are more sensitive than adulthood to adverse health effects from inhalation, ingestion and other forms of internal exposure due mainly to increased gut absorption rates and reduced body mass.[4] More specifically, the increased vulnerability is due to: a) smaller body masses result in higher concentration of unit activity (A 1 Bq intake of a 3 month baby will have 11-fold greater specific unit activity than an adult), b) longer turnover time of body carbon causing dose coefficients to be higher, c) the rapid growth in youth can result in a significant percentage of the radiation intake being incorporated into long-lived somatic cells (like the brain and bone) and d) newborns have increased oxidative stress due to substantial increases in the partial pressure of oxygen in their blood in comparison to in utero. This results in free radical damage and lower levels of antioxidants. The reduced levels of free radicals cause infants to be more vulnerable to radiation than older children. Health risks for infants exposed to radiation can be up to 10 times higher in comparison to adults.[4]

Site specific cancers with little evidence, or conflicting evidence, of an association with radiation include esophageal cancer, stomach cancer, liver cancer, pancreatic cancer, prostate cancer, non-Hodgkin's lymphoma, Hodgkin's disease, multiple myeloma, cervical cancer, testicular cancer and uterine cancer.[2]

Site specific cancers with no evidence of an association with radiation include cutaneous malignant melanoma and chronic lymphocytic leukemia.

The present scientific data suggests there is a small causal relationship between low doses of ionizing radiation and cardiovascular disease or other non-cancer disease (Table 6).[3] In contrast, radiotherapy for Hodgkin's lymphoma or breast cancer has a much stronger causal relationship with cardiovascular disease or other non-cancer disease.

Table 6. Mortality from heart disease and other non-cancer disease after exposure to radiation[3]

	Excess Relative Risk*	95% Confidence Interval
Heart disease	14%	5% to 22%
Stroke	9%	2% to 17%
Respiratory disease	18%	5% to 22%
Digestive disease	11%	0% to 24%

*Excess relative risk is per 1 Sv

B. Exposure to Radiation and Impact on Health Outcomes to Nuclear Power Workers

There are many studies that review chronic exposure to low dose radiation and the subsequent impact on health outcomes to nuclear power workers. Radiation protection standards have been based on extrapolations from acute, high dose rates.[5] These extrapolations are subject to substantial uncertainty.[5] Recent studies have confirmed significant excess relative risks of health problems and mortality from chronic exposure to low doses of radiation previously believed to be safe.

The largest and most comprehensive epidemiological study to review the effects of chronic low-dose exposure of ionizing radiation on health outcomes and mortality is the 15 Country Study of Nuclear Industry Workers.[5,6] The 15 countries included Australia, Belgium, Canada, Finland, France, Hungary, Japan, Korea, Lithuania, Slovakia, Spain, Sweden, Switzerland, the United Kingdom and the United States. This study included 407,391 nuclear industry workers that were followed for an average duration of 12.8 years (5.2 million person years of follow-up). The workers had an average exposure of 19.4 mSv (Canadian workers had an average exposure of 19.5 mSv) as measured by recorded dosimetric history. Ninety percent of the workers received doses below 50 mSv (or 50 mSv below current International Commission on Radiological Protection standards). All analyses were stratified by gender, age, follow-up duration, facility, duration of employment and socioeconomic status (occupation, education and income). Smoking information was inadequate so cancers were presented by smoking related, and non-smoking related, cancers.

All-cause mortality had a dose-related excess relative risk of 42% (range 7% to 79%) and all cancer mortality (excluding leukemia) had a dose-related excess relative risk of 97% (range 28% to 177%). The most significant site specific association was for lung cancer with an excess relative risk of mortality of 186% (range 49% to 363%). Risk estimates were not driven by the highest dose categories meaning excess risk was present even with relatively low doses of radiation (Table 7).[5]

Table 7. Mortality rates for nuclear power workers in 15 country study[5]

	Excess Relative Risk*	95% Confidence Interval
All cause mortality	42%	7% to 79%
All cancer mortality	97%	28% to 177%
All cancer excl leukemia	97%	27% to 180%
Solid cancer mortality	87%	16% to 171%
Lung cancer mortality	186%	49% to 363%
Leukemia mortality	193%	<0% to 714%

*Excess relative risk is per 1 Sv

Perhaps surprisingly, the only country with a statistically significant difference in all cancer mortality in comparison to the other 14 countries was Canada (Table 8). In Canada, the excess relative risk of all cancer mortality was 665% (range 256% to 1300%).[5] This is significantly higher than the average of the 15 countries (97%) and in comparison to similar countries like the United States (78%) and the United Kingdom (66%).[5]

Table 8. Mortality rates for nuclear power workers in Canada in 15 country study[5]

	Excess Relative Risk*	95% Confidence Interval
Cancer mortality (excl leukemia)	665%	256% to 1300%
Lung cancer mortality	1160%	363% to 2780%

*Excess relative risk is per 1 Sv

Excess relative risk per 100 mSv is 66% for cancer mortality and 216% for lung cancer mortality

Current recommendations from the International Commission on Radiological Protection are to limit occupational doses to 100 mSv over five years.[6] In the 15 Country Study, the workers had an average exposure of 19.4 mSv.[6] At 100 mSv, the excess relative risk for all cancer mortality for nuclear power workers is 151% (Table 9). The results suggest that current radiation protection standards need to be at least reviewed and possibly revised based on recent evidence.

Table 9. All cancer mortality rates for nuclear power workers by different dose levels in 15 country study[5]

	Excess Relative Risk*	95% Confidence Interval
All cancer mortality (excl leukemia)	97%*	27% to 180%
<100 mSv**	151%	<0% to 351%
<150 mSv	139%	2% to 292%
<200 mSv	252%	131% to 387%

*Average exposure for all workers was 19.4 mSv

**International Commission on Radiological Protection standards

It is important to note that the excess relative risks for all cancer mortality for nuclear power workers (151%) at less than 100 mSv (the International Commission on Radiological Protection standards) are higher than the excess relative risks of all cancer mortality for those who survived the atomic bomb in Japan (62%).[6] It is also important to note, however, that the large relative risks do not translate into large absolute risks. For example cumulative exposure of 100 mSv would lead to 9.7% overall increase in mortality from all cancers (excluding leukemia).[6]

As stated previously, the 15 Country Study of Nuclear Industry Workers is the largest and most comprehensive epidemiological study to review the effects of chronic low-dose exposure of ionizing radiation on health outcomes and mortality. Of the 51 authors for the 15 Country Study, Canadian scientists were represented by the Atomic Energy Commission of Canada, the AECL Radiation Biology and Health Physics Branch of Chalk River Laboratories, the Radiation Protection Bureau of Health Canada and the McLaughlin Center for Population Health Risk Assessment at the University of Ottawa.

In Canada, another research paper (other than the 15 Country Study) studied 45,468 Canadian nuclear power workers for an average follow-up period of 7.4 years (607,979 person years).[7] The study looked at mortality rates within Canadian nuclear power workers after exposure to chronic low doses of ionizing radiation. The average dose of radiation was 13.5 mSv. The potential confounders considered were gender, age at exposure, year at risk, duration of monitoring, facility, monitoring status and socioeconomic status.

The study found an excess relative risk of mortality from all solid cancers of 280% (range 0% to 713%) with site specific elevations for lung cancer, colon cancer, rectal cancer and leukemia (Table 10).

Table 10. Mortality rates for nuclear power workers in Canada[7]

	Excess Relative Risk*	95% Confidence Interval
All solid cancer mortality	280%	0% to 713%
Lung cancer mortality	434%	0% to 1270%
Colon cancer mortality	1070%	<0% to 1650%
Rectal cancer mortality	3410%	1% to 16510%
Leukemia (excl chronic lymphocytic leukemia)	5250%	397% to 22500%

*Excess relative risk is per 1 Sv

The objective of the study was to evaluate cancer risks among nuclear workers chronically exposed to low doses of radiation at low dose rates. The results from this exclusively Canadian nuclear power worker study confirm that chronic exposure to low doses of radiation are associated with an excess relative risk of cancer mortality and that radiation protection standards in Canada need to be at least reviewed and possibly revised based on recent evidence. The research was conducted by scientists at the Radiation Protection Bureau of Health Canada, the McLaughlin Center for Population Health Risk Assessment at the University of Ottawa and Columbia University.

Another Canadian study looked at the association between low dose ionizing radiation and cardiovascular disease mortality.[8] The cohort was devised from 337,397 workers exposed to radiation; mainly nuclear power workers but also medical, dental and veterinary practitioners. The worker database is maintained by the Radiation Protection Bureau of the Government of Canada. The worker statistics were linked by Statistics Canada with the Canadian Mortality Database. The study period was 1951 to 1995 with an average duration of follow-up of 15.8 years. Only 12% of males and 3% of females received more than 10 mSv of radiation during the follow-up period.

Overall, the excess relative risk for mortality during the study period for males was 122% and for females it was 737% for an overall excess relative risk of 135%. Table 11 discusses excess relative risks by dose category.

Table 11. Mortality rates for Canadian workers exposed to radiation by different dose levels[8]

	Excess Relative Risk
All mortality	135%
10 mSv	119%
20 mSv	110%
50 mSv	126%
100 mSv*	115%
200 mSv	144%
400 mSv	164%

*International Commission on Radiological Protection standards

The authors of the study conclude that there is an excess risk of disease after exposure to doses of radiation that were previously considered safe.[8]

In Russia, workers at the Mayak nuclear facility provide information on the cancer risks after exposure to plutonium.[9] In total, 9496 workers with positive plutonium doses hired between 1948 and1972 were included in the review conducted in 2003. The mean plutonium doses to the lung, liver and bone were 0.19, 0.27 and 0.98 Gy respectively. The excess relative risks for lung cancer mortality was 710% for males and 1500% for females. The excess relative risk for liver cancer mortality was 260% for males and 2600% for females. The excess relative risk for bone cancer mortality was 76% for males and 340% for females. Table 12 discusses excess relative risks by dose category. Once again, low doses of exposure are associated with excess relative risk of cancer mortality.

Table 12. Mortality rates for Russian nuclear workers exposed to plutonium by different dose levels[9]

	Excess Relative Risk	95% Confidence Interval
Lung cancer mortality		
Males	710%	490% to 1000%
Females	1500%	760% to 2900%
Dose		
0.2-0.3 Gy	330%	170% to 580%
0.3-0.5 Gy	450%	240% to 770%
0.5-1.0 Gy	640%	350% to 1100%
1-2 Gy	1500%	810% to 2500%
2-3 Gy	1800%	830% to 3500%
3-5 Gy	1700%	710% to 3500%
5-10 Gy	2700%	1000% to 5800%
Liver cancer mortality		
Males	260%	70% to 690%
Females	2900%	980% to 9500%
Dose		
2-3 Gy	400%	120% to 1300%
3-5 Gy	1600%	330% to 5800%
5-10 Gy	4300%	1200% to 13400%
Bone cancer mortality		
Males	76%	<0% to 520%
Females	340%	40% to 2000%
Dose		
10 Gy	8200%	1700% to 33800%

C.
Exposure to Radiation and Impact on Community Residents

Many papers have been written about the health effects from the explosion of the nuclear power plant at Chernobyl in the Ukraine. The World Health Organization has summarized the findings.[1] The 240,000 workers responsible for the clean-up (liquidators) had the highest levels of exposure which resulted in a doubling of their incidence of leukemia and an increased risk of death from cardiovascular disease. In total, the World Health Organization predicts 4000 additional cancer deaths from the most exposed groups (liquidators and evacuees).

Considerable attention, however, has also been focused on community residents that lived great distances from the actual explosion cite that were exposed to low levels of radiation. Significant increases in thyroid cancer in children were not only found in the Ukraine but also in Belarus, Russia, Czechoslovakia and as far as the United Kingdom (a 484% increase in Belarus, range 96% to 1630%).[10] The main problem was contamination of fresh grass which was eaten by cows which led to contamination of milk ingested by children. As well, increases in leukemia in children were found in contaminated areas across Europe including the Ukraine, Belarus, Russia, Turkey, Greece and Germany (a 350% increase in Ukraine).[10,11] No increases in thyroid cancer or leukemia were found in adults.

In total, 346,000 residents had to be evacuated and relocated. The relocation of people, economic insecurity and threats to health led to considerable mental health problems.[1]

In 1986, the IAEA attributed the main cause of the accident to the actions of operators. In 1993, the IAEA issued a revised analysis attributing the main cause to the reactor's design. Both are probably right. An unstable reactor design, poor and inadequate safety features, poorly trained operators and a lack of a containment building all likely played a significant role in the accident. There are only 15 other water cooled graphite moderated nuclear reactors like the one from Chernobyl left in the world (all in Russia or Lithuania).

Chernobyl is an example of a nuclear disaster. Studies from the Techa River demonstrate the impact of chronic low doses of radiation on the health of community residents.

In the 1950's, the Russian government discharged liquid radioactive wastes into the Techa River which exposed riverside residents to chronic low doses of radiation. 18,382 residents were followed for up to 47 years (depending on each study) to determine the impact on health outcomes.

Overall, the residents along the Techa River had 100% excess relative risks in solid cancer incidence, 500% excess relative risks in breast cancer incidence and 360% excess relative risks for chronic lymphoid leukemia all per 1 Gy.[12-14]

Table 13 demonstrates breast cancer incidence by levels of dose. These results controlled for background rates, age, number of children, time of arrival on the contaminated territory and linear birth cohort effect. Very low doses of radiation were associated with increased breast cancer incidence in Techa River residents.

Table 13. Breast cancer incidence for Techa River residents by different dose levels[13]

	Excess Relative Risk	95% Confidence Interval
Breast cancer incidence		
Dose		
<5 mGy	30%	4% to 60%
5-9.9 mGy	100%	20% to 210%
10-24.9 mGy	110%	20% to 220%
25-49.9 mGy	200%	40% to 410%
>50 mGy	910%	170% to 1870%

It is also important to discuss the incidence of health problems for people that live near nuclear power facilities. The only known health concern is leukemia in children. A review of the literature finds that there is a range of increased risk of leukemia from 0% to 119% between countries for youth aged 0-24.[15]

A closer review of the evidence finds that very young children that live within close proximity to nuclear facilities have an increased risk of leukemia. A German study found that children below the age of 5 that live within 5 kilometers of a nuclear facility have a 119% increased risk of leukemia whereas children that live within 10 kilometers have a 33% increased risk.[16] This study has been cited as a reason to continue the phase out of all nuclear power in Germany by 2020. The German study was replicated in England but found only a 23% increased risk of leukemia for children below the age of five that live within 5 kilometers of a nuclear facility.[17]

On the topic of living near a nuclear facility, it is relevant to briefly discuss the partial core meltdown of a pressurized water reactor in 1979 at Three Mile Island in Pennsylvania. The average radiation dose to residents living within ten miles of the plant was eight millirem- which is about the same as a chest X-ray. A review of 159,684 residents living within 10 km of the nuclear power plant found no convincing evidence of increased cancer risk within the first 10 years of follow-up.[18] Another review of 32,135 residents within the first 20 years found no difference on overall cancer mortality in comparison to non-exposed populations; with only a slight (non statistically significant) increase in breast cancer mortality.[19]

D. Electricity Generation and Health

The provision of electricity has been a great benefit to society, particularly in health terms, but is also carries health costs.[20]

The prestigious medical journal The Lancet published a six part series on Electricity Generation and Health in 2007.[20] The articles summarize the health burdens for coal, natural gas and nuclear energy not just for the generation stage but for the other stages of the full process. This includes extraction of the fuel, transportation of the fuel, transformation into electric energy, disposal of the waste and the transport of the electricity. Regrettably, the data only includes occupational mortality and does not include occupational illnesses. Occupational mortality is obviously a rare event. However, very good information is provided on the effects of air pollution to the general public. The results are for Europe alone and are summarized in Table 14.

Table 14. Health effects of electricity generation in Europe[20]

	Occupational	Air Pollution	
	Deaths*	Deaths	Serious Injuries
Coal	0.10	24.50	225
Natural Gas	0.00	2.80	30
Nuclear Energy	0.02	0.05	0.22

*Deaths or injuries are per TWh (watts) produced

As stated, occupational illnesses are not reported in The Lancet article. In this paper, occupational illnesses for nuclear power workers have already been discussed in great detail. For workers in coal mines, 12% will develop a potentially fatal disease like pneumoconiosis, progressive massive fibrosis, emphysema, chronic bronchitis and accelerated loss of lung function.[20]

In terms of the general population, the use of coal as an electrical source clearly has the greatest burden on health effects. The health effects to the general population from natural gas are much lower than coal because the effects from primary and secondary particles are much smaller. The number of deaths or illnesses within the general public from nuclear power facilities is extremely small.

Table 14 does not include any information on the health burden due to global warming. The World Health Organization estimates that the increase in greenhouse gasses has resulted in 150,000 excess deaths from the year 1990 to 2000.[21] Almost all of these excess deaths took place in the third world where global warming has led to increased malnutrition, malaria, diarrhoea, malaria, floods and cardiovascular disease.[21] Table 15 summarizes the direct and indirect CO_2 emissions by primary energy source.[20]

Table 15. Direct and indirect CO_2 emissions by primary energy source[20]

	Direct Emissions	Indirect Emissions	Total
Coal	960	1290	2250
Natural Gas	460	1234	1694
Solar	30	279	309
Wind	11	75	86
Nuclear	9	30	39

Clearly, coal and natural gas produce the most direct and indirect CO_2 emissions with the least emissions coming from solar, wind and nuclear. Although nuclear energy has the least amount of overall CO_2 emissions, it is important to note that it still can not produce net energy in a controlled production. It will take at least 50 years before the technology is developed to the point of universal and commercial viability. As such, nuclear energy will not be a solution to climate change, although it can still have a positive impact on energy production.[20]

Coal and natural gas have clear health and environmental impacts. Nuclear energy has a perceived risk and remains controversial. As such, it is appropriate to discuss renewable energy like solar and wind.

The Lancet article has the following conclusions about the benefits of solar capture:

> "The theoretical potential of the direct capture of solar energy … is enormous."
>
> "The capture of less than 1% of photonic energy would serve all human energy needs."
>
> "The limited assessment by a full cycle analysis indicates few drawbacks. The constraint on much wider use is mostly technical."
>
> "From a health perspective, the potential benefits of direct solar capture seem very desirable."

The Lancet article has the following conclusions about the benefits of wind energy:

> "Wind energy, mainly produced by horizontal axis turbines, is one of the most cost-effective forms of renewable energy with today's technology."
>
> "The balance of health risks and benefits … seem strongly favorable."

The British Broadcasting Corporation reported on June 15, 2000 that Germany will phase out all nuclear power by 2020. All 19 nuclear power reactors will gradually close as other energy sources are developed. The British Broadcasting Corporation further reported on May 28, 2006 that the conversion from nuclear energy to mainly wind energy will cost an extra 17 Euros (about $24) a year for each household until completion.

The German Ministry of Technology and Economics reports that within eight years, Germany has installed 23,903 megawatts of wind power with another 24,000 approved for development. Currently, the wind power industry provides 73,800 jobs to German residents. German technology has developed modern turbines that make better use of available wind energy and as such more wind power can come from the same area of land. Modern turbines also offer much better grid integration since they use a connection method similar to conventional power plants.

E.
Implications of Nuclear Power Cost Over-runs to Population Health

The report *Future of Uranium in Saskatchewan* makes a number of observations that need to be addressed in terms of their implications to population health:

> v) "Capital cost overruns and schedule delays are key risks in any nuclear new build project, and they would need to be carefully mitigated in the project development process. To date, the cumulative risks of nuclear new build have been too large for the private sector to bear alone and governments have played some form of facilitation in the implementation of nuclear power projects in all jurisdictions."

Currently, 45 nuclear reactors are being built around the world. Of those 45, 22 are behind schedule and have encountered cost overruns. With new and complex technology, higher risks to capital costs follow. For example, the New York Times reported in their May 28, 2009 newspaper that that the $4.2 billion dollar nuclear reactor being built in Finland is already 50% over budget ($2.1 billion over budget) and will cost at least $8 billion to complete. The French engineers who are supervising the build are no longer willing to make predictions on when the nuclear reactor will be complete. Currently, the Finnish government is litigating the French nuclear agency Areva for at least $1.4 billion. Based on Finalnd's current experience, and assuming a 100% cost overrun, a projected $10 billion dollar nuclear reactor with new technology (i.e. Generation III+) in Saskatchewan might actually cost up to $20 billion.

If the government of Saskatchewan is responsible for some of the cost overruns (i.e. 50%), then there will be a strain on financial resources to provide health care and health enhancing services (like education). The government of Saskatchewan's budget for 2009-2010 projects revenue of $10.6 billion dollars and expenses of $10.3 billion. This leaves a modest surplus of $300 million annually to pay for potential cost over-runs.

In the United States, cost over-runs have been transferred to the electrical consumer. The United States has 104 nuclear reactors but public information is only available on 99. Of those 99 nuclear reactors, 79% are able to deliver electricity at 3 cents per kWh as planned. Due to cost over-runs, 16% of American reactors delivered electricity between 3 cents and 8 cents kWh (about twice as much than expected) and 5% of reactors delivered electricity for more than 12 cents KWh (about four times as much as expected).[22] The authors of this report from Georgetown University, Stanford, the University of California

(Berkley) and Oxford conclude that past experience suggests that high cost surprises should be included in the planning process. Given the litigation in Finland, we should also decide who will pay for the cost over-runs in advance.

i) "The lack of basic infrastructure in the North (Northern Saskatchewan), particularly roads and power, is likely to impede further mine development" and

x) "Transmission infrastructure, reserves and intertie investments would be required to support larger power generation units on the Saskatchewan grid, as well as to provide the capability to export additional power to Alberta. The detailed nature and cost of this infrastructure has yet to be determined."

The extra costs for basic infrastructure development and transmission infrastructure for nuclear power should be determined and then this information should be transferred to the general public. These new expenditures might have an impact on the government of Saskatchewan's ability to provide health care and health enhancing services (like education).

F. Consultation with Registered Nurses and Registered Psychiatric Nurses

On June 18, the Saskatchewan Union of Nurses requested 3043 registered nurses and registered psychiatric nurses with known e-mail addresses to complete a survey on nuclear energy. The following context was provided in order for nurses to make an informed choice:

As an organization representing health professionals, SUN has been asked to present to *The Future of Uranium in Saskatchewan Public Consultation Process*.

The purpose of this survey is to get your professional opinion about the implications of nuclear energy on population health. Please read the following examples of evidence and answer the two questions at the end.

The survey website is 100% confidential — there is no way to track your name or your e-mail address.

1. The United Nations Scientific Committee on the Effects of Atomic Radiation found that the excess relative risk of incidence of total solid cancers after exposure to radiation is 43% for males and 81% for females. The excess relative risk of mortality from total solid cancers after exposure to radiation is 34% for males and 65% for females. Clear evidence of site specific cancers associated with doses of radiation include lung cancer, breast cancer (females), thyroid cancer, salivary gland cancer, rectal cancer (females), bone cancer (males), non melanoma skin cancer, ovarian cancer, urinary bladder cancer, kidney cancer (females) and brain cancer (males).
2. The largest study to review the effects of chronic low-dose exposure of ionizing radiation on health outcomes and mortality included 407,391 nuclear power workers that were followed for an average duration of 12.8 years. All-cause mortality within nuclear industry workers had an excess relative risk of 42% and all cancer mortality had an excess relative risk of 97%. In Canada, the excess relative risk of all cancer mortality for nuclear industry workers was 665%.
3. Many papers have been written about the nuclear power plant explosion at Chernobyl in the Ukraine. The World Health Organization predicts 4000 additional cancer deaths from the most exposed groups (emergency workers and evacuees). Significant increases in thyroid cancer in children were not only found in the Ukraine but also in Belarus, Russia, Czechoslovakia and as far as the United Kingdom (a 584% increase in Belarus). As well, increases in leukemia in children were found in contaminated areas across Europe including the Ukraine, Belarus, Russia, Turkey, Greece and Germany (a 350% increase in Ukraine).
4. The only known health concern for people that live near nuclear power facilities is leukemia in children. A German study found that children below the age of 5 that live within 5 kilometers of a nuclear facility have a 119% increased risk of leukemia whereas children that live within 10 kilometers have a 33% increased risk.

In total, 822 nurses completed the survey between June 18 and June 22, 2009. Their responses are as follows:

Question 1.

What is your professional opinion regarding the development of a nuclear power facility?

A. I support the development of a nuclear power facility.
78 counts
9.49%
(7.5-11.5%)*

B. I have conditional support for the development of a nuclear power facility providing all health concerns to residents, workers and children are addressed.
236 counts
28.71%
(25.9-32.1%)

C. I do not support the development of a nuclear power facility.
508 counts
61.80%
(58.7-65.3%)

Question 2.

Are you concerned about the health implications of a nuclear power plant?

A. Yes 739 counts
89.90%
(87.9-92.1%)

B. No 83 counts
10.10%
(8.0-12.0%)

*95% confidence interval

Conclusions

1. Exposure to radiation results in an excess relative risk in the incidence of total solid cancers.
2. Exposure to radiation results in an excess relative risk in mortality from total solid cancers.
3. Lifetime solid cancer risk estimates for those exposed as children are 2-3 times higher than estimates for the adult population.
4. Nuclear power workers have a dose-related excess relative risk of all-cause mortality.
5. Nuclear power workers have a dose-related excess relative risk of all cancer mortality.
6. Nuclear power workers in Canada have a much higher excess relative risk of all cancer mortality in comparison to other countries.
7. Current radiation protection standards for nuclear power workers need to be at least reviewed and possibly revised based on recent evidence.
8. Nuclear power plant explosions like Chernobyl in the Ukraine have health implications for children (thyroid cancer and leukemia) in countries that are thousands of miles away.
9. Living near a nuclear power facility is associated with leukemia in young children.
10. Although nuclear energy has the least amount of overall CO_2 emissions, it will take at least 50 years before the technology is developed to the point of universal and commercial viability. As such, nuclear energy will not be a solution to climate change, although it can still have a positive impact on energy production.
11. From a health perspective, the potential benefits of direct solar capture and wind power are very desirable. Wind power is one of the most cost-effective forms of renewable energy.
12. Past experience with nuclear energy suggests that high cost surprises should be included in the planning process.
13. 61.8% of registered nurses and registered psychiatric nurses indicated that they do not support the development of a nuclear power facility. 89.9% indicated that they were concerned about the health implications of a nuclear power plant.

Definitions

Gray or Gy

Ionizing radiation is measured as absorbed dose in gray or Gy.

Sievert or Sv

The effective dose measured in sievert or Sv takes into account the amount of ionizing radiation energy absorbed, the type of radiation and the susceptibility of various organs and tissues to radiation damage.

100 mSv = 0.1Sv

Total solid cancers

All cancers excluding leukemia

Relative Risk

How many times exposed persons (i.e. exposed to radiation) are more likely to get a disease (i.e. cancer) relative to non-exposed persons?

Confidence Interval (usually 95%)

The statistical precision of an observed effect size. If the study is unbiased, there is a 95% chance that the interval includes the true effect size.

Incidence

The proportion of a population initially free of a disease that develops the disease over a given period of time. For example, of those without cancer, how many new cases of cancer are observed within a one year period.

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