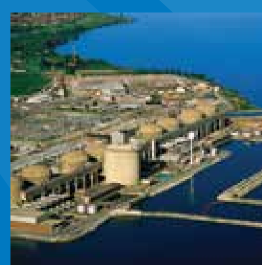
Canada's Nuclear Regulator

Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants From 1990 to 2008

(The RADICON Study)

SUMMARY REPORT



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Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants From 1990 to 2008 (The RADICON Study) - Summary Report

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From left to right: Bruce, Darlington and Pickering

Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants From 1990 to 2008 (The RADICON Study)

SUMMARY REPORT

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EXECUTIVE SUMMARY

The Canadian Nuclear Safety Commission (CNSC) has completed a groundbreaking ecological study on populations living near Ontario's three nuclear power plants (NPPs). The purpose of the *Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008* study (the "RADICON" study) was to determine the radiation doses to members of the public living within 25 km of the Pickering, Darlington, and Bruce NPPs and to compare cancer cases among these people with the general population of Ontario from 1990 to 2008. The study was conducted using data from the Canadian and Ontario Cancer Registries and the Census of Canada.

The most important finding of the RADICON study is that there is no evidence of childhood leukemia clusters around the three Ontario NPPs. The rates of cancer incidence for children aged 0–4 and aged 0–14 were similar to the general Ontario population.

Overall, for all ages, there is no consistent pattern of cancer across the populations in question living near the three facilities studied. Some types of cancer in the communities studied were higher than expected (excess cancer); however, many types of cancer were lower than expected.

While this type of study cannot determine the causes of the cancer, excess cancers (increase in cancer above what's expected in Ontario) are unlikely to be due to radiation. Radiation doses from NPPs to members of the public are extremely low – at least 100 to 1,000 times lower than natural background radiation and public dose limits. As such, doses are a minor risk factor compared to the high prevalence of major risk factors like tobacco, poor diet, obesity and physical inactivity, which account for about 60% of all cancer deaths in developed countries. These factors represent a public health concern throughout Ontario, including the communities located near NPPs. Other important Ontario studies found that once these main risk factors were taken into account, there was no evidence of a cancer risk due to environmental factors like radiation. Given the high frequency of these factors, the current scientific understanding of radiation risk, and the miniscule public doses, it is not realistic to attribute any excess cancers to the radiation doses from NPPs found in these communities.

The main strength of the RADICON study is the use of detailed public dose information around each NPP that was generated from radiological releases and environmental monitoring data. The data collected for this study takes into account any emission spikes from the NPPs. This methodology improves on recent epidemiological studies of childhood cancer that have used distance from an NPP as a substitute for radiation dose. Doses closest to the NPPs were not consistently higher than doses further away. Many factors influence doses to the public as a result of the operation of a NPP, including prevailing wind directions and lifestyle characteristics (i.e., diet and lifestyle habits) of the surrounding communities. Therefore, distance is not a good substitute for dose.

To conclude, public radiation doses resulting from the operation of the NPPs are 100 to 1,000 times lower than natural background radiation and there is no evidence of childhood leukemia clusters around the three Ontario NPPs. All cancers for all age groups are well within the natural variation of the disease in Ontario. Thus, radiation is not a plausible explanation for any excess cancers observed within 25 km of any Ontario NPP.

TABLE OF CONTENTS

1.0 INTRODUCTION

Epidemiology is the study of the distribution and determinants of diseases in human populations, and the application of this study to control disease [1, 2]. It is based on observation, not experiments, so there are always varying degrees of bias. A well-designed study will try to minimize potential biases. In ecological studies, the observed occurrence of a specified disease within a defined population (for example, those residing within a 25-km radius of a nuclear power plant (NPP)), time and geographical area is compared with the expected occurrence of the disease, based on a stable reference population (i.e., the general population of Ontario).

Since the 1980s, many descriptive epidemiological studies around the world have been conducted to determine whether people living near NPPs have higher rates of disease, especially childhood leukemia, compared to the general population [3, 4, 5, 6].

All people are exposed to radiation, most of which comes from natural sources such as the sun (i.e., cosmic radiation), in the food we eat (i.e., potassium-40), and from radon, a decay product of uranium that exists naturally in the ground [7].

Dose from radiation is measured in millisieverts (mSv). The mSv is a measure of how radiation is absorbed in the human body. Every year, Canadians receive an average dose of 1.8 mSv from natural background radiation [8]. Globally, the average background radiation dose is higher at 2.4 mSv per year (mSv/yr), with a range of 1.0 to 13.0 mSv/yr [1].

Routine NPP operation contributes minimally to the radiation dose to members of the public. In fact, the dose from NPP operations is so low that it is 100 to 1,000 times below that of natural background and typically cannot be measured directly.

Under the *Nuclear Safety and Control Act*, the Canadian Nuclear Safety Commission (CNSC) regulates the use of nuclear energy and materials to protect the health, safety and security of all Canadians and the environment. The *Radiation Protection Regulations* are a major enforcement tool that the CNSC uses to ensure that releases from nuclear facilities remain low. This includes the regulatory public dose limit of 1 mSv per calendar year and the “ALARA principle” that ensures that radiation doses to all Canadians are kept as low as reasonably achievable, social and economic factors taken into account.

Three NPPs (Pickering, Darlington and Bruce) are currently operating in Ontario. Together, there are twenty CANDU (CANada Deuterium Uranium) reactors that have been in operation at various times since 1971. CANDU reactors are pressurized heavy water reactors that use heavy water for the moderator and coolant, and natural uranium for fuel.

The purpose of this study was to assess ionizing radiation doses to members of the public living within a 25-km radius of the three Ontario NPPs and to compare cancer incidence among these people with the general population of Ontario.

2.0 BACKGROUND

To ensure that NPPs are operating below the regulatory public dose limit of 1 mSv/yr, licensees are required to control releases through the use of internal investigation levels and action levels that are set well below their licence release limits. Internal investigation levels and action levels are used to identify when environmental releases may be deviating from normal amounts, to control and prevent emission spikes from occurring. Doses to members of the public from the routine operations of NPPs are so low that it is difficult to directly measure doses to people from all contributing sources. Therefore, doses are estimated indirectly from the modelling of environmental releases and from the results of radiological environmental monitoring programs (REMPs).

Environmental releases from a well-controlled and operated facility generally come from two different sources:

- atmospheric emissions (gaseous or particulate releases to air, usually from a stack or building ventilation exhaust)
- liquid effluent discharges (liquid releases from a pipe to surface water, such as a flowing river or lake)

At NPPs, the release of radioactive nuclear substances and their fate in the environment (i.e., how they disperse, degrade, or accumulate) are described by an environmental transfer model. The means by which these releases come into contact with people (i.e., inhalation, immersion, and ingestion) can be depicted by a pathway exposure model that is an extension to the environmental transfer model [9, 10, 11]. Together, these models are used to estimate doses to members of the public from the operation of a NPP.

Radiological environmental monitoring programs are in place at all operating NPPs in Canada to measure levels of radionuclides in the various environmental media contributing to radiation doses (i.e., air, water, food, and milk). These REMP results are factored into the pathway exposure models to allow for the assessment of more realistic dose contributions [12]. The dose received by a person is calculated by adding all dose contributions from the various pathways that are related to specific characteristics (i.e., time spent indoors/outdoors and types and amounts of food consumed).

It is not feasible to model the radiation doses received by each individual member of the public from an operating NPP based on each individual's diet and lifestyle. For this reason, human receptors have been classified to calculate public dose. Over time, the definition of the receptors evolved to reflect more realistic conditions. These receptors have been classified as a "hypothetical individual", a "critical group", and a "representative person".

- Prior to 2001 (Pickering and Bruce NPPs) and 2003 (Darlington NPP), calculations using maximum dose estimates to a hypothetical individual living near an NPP were used. The dose received by a hypothetical individual was very conservative, since pathway exposure models assumed that the individual lived at the facility fence line and consumed only local food and water.

- After 2001 (Pickering and Bruce NPPs) and 2003 (Darlington NPP), a more realistic human receptor was defined as a critical group [9] representing a uniform group of people whose location, age, habits, diet and other factors caused them to receive higher doses than other groups in the exposed population.
- The concept of a critical group was replaced in 2008 by a representative person, representing the average member of the critical group [10].

The reason for the evolution of the receptor in public dose calculations from a hypothetical individual to a representative person was to provide more realistic dose estimates. This study examined a period prior to 2008; therefore, only doses to hypothetical individuals and critical groups are presented and they are conservative.

The Pickering, Darlington, and Bruce NPPs each have multiple potential critical groups as part of their REMPs. At each critical group location, age classes are defined to reflect different diet and consumption rates, and lifestyle habits within the respective groups. The age classes are adult, 15-year-old, 10-year-old, 5-year-old, 1-year-old, and nursing infant. The characteristics assigned to potential critical groups (i.e., diet and lifestyle habits) are often exaggerated and hence conservative. The critical group for each year is the group and age class with the highest dose.

Site-specific population surveys of residents and local farms surrounding the NPPs are often conducted to obtain information on the characteristics of the potential critical groups [9, 10, 12, 13, 14, 15, 16, 17]. Surveys generate information on the number of people living at each residence or farm, their age distribution, sources of water for various uses, as well as fractions of local and store bought food consumed (i.e., meat, poultry, fish, fruit, vegetables, dairy and grains), along with several other characteristics. If information could not be obtained from surveys, default values presented in the CSA standard are applied [9, 10, 12, 13, 14, 15, 16, 17]. Thus, distance from an NPP is only one factor that plays a part in the dose received.

3.0 METHODS

3.1 Radiation Doses to Members of the Public Living near Ontario Nuclear Power Plants

An analysis of the spatial representation of the estimated doses to various potential critical groups surrounding the Pickering, Darlington, and Bruce NPPs was performed. The analysis consisted of compiling all available annual total dose data for each critical group and age class from 1985 to 2008 [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33] and mapping the estimated doses to critical groups using ESRI® ArcGIS™ Desktop version 10.1 (ArcGIS) mapping software. A set of maps were generated, one for each NPP, showing the highest doses received to each potential critical group over the study period. The doses were compared to the regulatory public dose limit of 1 mSv/yr and the natural background radiation dose in the region of each respective NPP. The maximum doses received from each critical group were also compared to one another to assess the relationship of distance and dose.

The analysis included boundaries extending at a radius every 5 km, up to 25 km from the facility, in order to provide an indication of relevant distance of each critical group from their respective NPPs. The Darlington and Pickering NPPs are on the shore of Lake Ontario and the Bruce NPP is on the shore of Lake Huron; therefore, much of the 25 km radius included water.

For each NPP, the year with the highest critical group doses within the study period were also identified. These were 2005 for Pickering, 2003 for Darlington, and 2008 for Bruce. From this dataset, a second set of maps were generated, one for each NPP, with the dose to each potential critical group that specific year mapped. In addition, atmospheric dispersion plume modeling was conducted for each nuclear substance based on the releases from the facility for the given year. The dispersion plume was created using the EcoMetrix® IMPACT™ (IMPACT) modeling software, which is based on CSA standard N288.1-08 [11]. The model used site-specific weather data and release characteristics obtained from each NPP to create the dispersion plume. From the model outputs, a dose plume was generated in ArcGIS using air inhalation and immersion dose conversion factors and layered onto the map of critical group doses. The dose plume represents an estimate of the annual dose that would be received by an individual due to air immersion and inhalation if they spent the entire year at a particular location. This hypothetical dose does not account for doses due to diet and lifestyle activities, such as time spent at the local beach. The latter doses are part of the critical group dose.

3.2 Cancer Incidence in Members of the Public Living near Ontario Nuclear Power Plants

The Ontario Cancer Registry (OCR) and the Canadian Cancer Registry (CCR) collect information on cancer incidence in Ontario and Canada, respectively [34, 35]. The Census of Canada collects population, demographic and other statistical information on all people living in Canada every five years and is Canada's largest and most comprehensive data source [36].

Cancer incidence data collected by the OCR from 1990 to 1991 and the CCR from 1992 to 2008 were obtained for the following: all cancer types combined; cancer of the thyroid, lung and bronchus; female breast; ovary; esophagus; stomach; colon and rectum; bladder; brain and other nervous system; liver; and leukemia and non-Hodgkin’s lymphoma. These types of cancer were chosen because they are sensitive to radiation [1, 37, 38].

Population counts from the Census of Canada for the census years 1991, 1996, 2001, and 2006 were obtained for the areas within 25 km of the three NPPs in Ontario. The geographical areas in our study included combined municipalities in the 25-km radius from an NPP, based on its latitude and longitude. This study focused on a 25-km radius from each Ontario NPP in order to be consistent with a previous study [39] and because of the low population density around the Bruce NPP.

Standardized incidence ratios (SIRs) are commonly used for comparisons in ecological studies. SIRs represent the ratio of the number of observed cases divided by the number of expected cases in the reference population. SIRs based on residence at diagnosis, observed (O) and expected (E) number of cancer cases, and 95% confidence intervals (CIs) were calculated [40] based on the age- and sex-specific rates of the reference population (i.e., Ontario) for the corresponding period (1990 to 2008).

A ratio (or SIR) of 1.0 indicates that the observed number of cases for the specified area was the same as that expected in the reference population. A ratio of 1.4 indicates a rate of 40% higher than the reference population. A ratio of 0.7 indicates a rate that is only 70% that of the reference population.

A confidence interval (i.e., 95% CI) gives an estimated range of values that include the true SIR for a given set of sample data. If the confidence interval is wide, the ratio is based on few observed cases; if it is narrow, the ratio is based on many observed cases. If the confidence interval does not include 1.0 (i.e., no difference in risk from the reference population) it is considered statistically significant at the 95% confidence level. Internal calculations of observed and expected cases were stratified by five-year age groups and periods, and controlled for socioeconomic status using income quintile.

Interpreting SIRs must be done with a good deal of caution, and departures from 1.0 must also be viewed cautiously. When an elevated risk for a particular disease (such as cancer) that is statistically significant is observed in an area, it is only an indication that there may be an elevated risk in the area associated with environmental, social, behavioural or genetic factors. For example, the population within 25 km of the Bruce NPP (approximately 25,000) is a relatively small population in which to observe rare diseases (i.e., childhood cancer). Incidence rates calculated for small populations are unstable (in a statistical sense) – especially for less common types of cancer – even if studied over extended periods of time. Therefore, excess rare diseases in such areas must be interpreted with the greatest caution; the stability of the rate must be carefully examined. Thus, a high cancer rate in a given region is not sufficient evidence to implicate specific risk factors or require more epidemiological investigation to assess the relative importance of various factors. The more rare the type of cancer and the smaller the population, the more important the role of chance (natural random variation in disease) and the less dependable (unstable, variable) the risk estimate is [1, 41].

Observed and expected incident cancer cases and SIRs were presented by sex and age group (ages 0–4, 0–14, 0–64, 65+, 0–65+) for the population living within a 25-km radius of each NPP from 1990 to 2008. The present report restricts reporting for less than 6 cases, so some of the combined values were suppressed to preserve confidentiality. In this situation, SIRs are not calculated because of the high degree of variability in risk estimates when using small numbers. Only the direction of the SIR and significance are provided. Residual disclosure checks were applied where totals are provided. Information for both sexes combined was presented for childhood cancers because of the small number of cases.

4.0 RESULTS

4.1 Radiation Doses to Members of the Public Living near Ontario Nuclear Power Plants

Table 1 provides a summary of dose data for populations surrounding the three Ontario NPPs. The second column provides the annual dose from natural background radiation at each site. The third column provides the range of doses estimated to a hypothetical individual at the fence line of each NPP from 1985 to 2002 for the Pickering and Bruce NPPs and from 1987 to 2002 for the Darlington NPP. The fourth column provides the highest doses to the critical groups. The data accounts for doses before the study period, to account for the lag time between exposure and the potential onset of cancer.

Table 1: Annual doses from natural background radiation and from each nuclear power plant to hypothetical individuals and critical groups

Nuclear power plant	Dose from natural background radiation (mSv/yr)[1]	Range of doses (mSv/yr) to hypothetical individuals (1985–2002)	Highest estimated dose (mSv/yr) to critical group (2001–08)
Pickering NPP	1.338	0.052–0.004	0.0067[3]
Darlington NPP	1.338	0.010–0.001[2]	0.0017[4,5]
Bruce NPP	2.020	0.016–0.002	0.0027[3]

[1] [8, 42]
[2] Range from 1987 to 2002
[3] Adult
[4] Nursing infant
[5] Data from 2003 to 2008

The highest dose to a hypothetical individual was 0.052 mSv/yr, 0.010 mSv/yr, and 0.016 mSv/yr from the Pickering, Darlington, and Bruce NPPs, respectively, from 1985 to 2002. Doses to the hypothetical individual are at least 100 times lower at the Darlington and Bruce NPPs and at least 50 times lower at the Pickering NPP than the annual regulatory public dose limit of 1 mSv/yr, and are well below natural background levels.

From 2001 to 2008 (Pickering and Bruce NPPs), and 2003 to 2008 (Darlington NPP), doses were assessed for six critical groups versus a hypothetical individual at the fence line. From 2001 to 2008, the highest dose to an adult resident at the correctional institution near the Pickering NPP was 0.0067 mSv/yr; to a nursing infant resident at the non-dairy farm near Darlington NPP, it was 0.0017 mSv/yr; and to an adult resident living at Lake Street, Inverhuron, near the Bruce NPP, it was 0.0027 mSv/yr. These doses are 10 times lower than those to the hypothetical individual, and 1,000 times lower than the regulatory public dose limit and natural background.

Figures A.1, A.2 and A.3 in Appendix A represent the set of maps depicting the dispersion plume from air emissions for the single year in the study period with the highest critical group dose for Pickering (2005), Darlington (2003) and Bruce (2008). These dispersion plumes, based on site-specific weather data, clearly indicate a plume extending towards and over the lake, and generally away from populated areas.

4.2 Cancer Incidence in Members of the Public Living near Ontario Nuclear Power Plants

Figure B.1 in Appendix B shows that the incidence of childhood cancer among children aged 0–4 living near (within 25 km) the Pickering and Darlington NPPs was similar to what was expected for the Ontario population. Similarly, the incidence of childhood cancer in children aged 0–14 living near the three NPPs was similar to Ontario, as indicated in Figure B.2 in Appendix B. Near the Bruce NPP, no information was available for young children (aged 0–4) because there were fewer than 6 cancer cases from 1990 to 2008. Similarly, for children aged 0–14, leukemia and Non-Hodgkin's lymphoma were combined to preserve confidentiality of observed cases fewer than 6.

Figures C.1, C.2 and C.3 in Appendix C provide cancer incidence results for all of the selected types of cancer among people of all ages combined living near the three Ontario NPPs. Cancers of the lung, breast and colon and rectum are the most frequent types of cancer observed in this study; this is expected, as these are also the most frequent types of cancer in the province of Ontario. There was no consistent cancer incidence pattern among people living near the three NPPs. Some types of cancer were statistically significantly higher than expected; however, some types of cancer were statistically significantly lower than expected, and some types of cancer were the same as expected compared to the general Ontario population.

5.0 DISCUSSION

5.1 Radiation Doses to Members of the Public Living near Ontario Nuclear Power Plants

The analysis of doses to the public from Ontario NPPs showed that during the study period the highest doses were about 100 to 1,000 times lower than natural background radiation dose levels (as well as the regulatory public dose limit of 1 mSv/yr). As a result, public doses are well within the fluctuations of natural background radiation.

An analysis of the hypothetical dose plumes at each NPP shows that based on average meteorological conditions; the majority of exposure to air immersion and inhalation would occur over Lake Ontario (Pickering and Darlington NPPs) and Lake Huron (Bruce NPP). Near the Pickering NPP, prevalent winds travel towards the south; near the Darlington NPP they travel towards the south-south-east (SSE); and over Lake Huron near the Bruce NPP, towards the north. It can also be observed that almost all exposure is contained within 5 km from the centre point of the facility, much of which is located above the facility itself.

Based on 2006 census data for the Durham Region, it is estimated that within 5 km of the Darlington NPP only 0.01% of the population living within a 25 km radius is exposed [43, 44]. It is estimated that within 5 km from the Pickering NPP only 1% of the population living within 25 km is exposed [43, 44]. Therefore, the majority of the members of the public are exposed to little or no radiation from atmospheric releases.

The plume modelling also found that the hypothetical doses from air emissions (inhalation and immersion) for full-time occupancy were primarily due to releases of noble gases (i.e., gamma radiation as a result of immersion) and tritium oxide (beta radiation as a result of inhalation), each of which contributed to 75% and 25% of the total dose from immersion and inhalation. Carbon-14, radioactive particulates and radioactive iodines contributed very little to the dose (<1%) as a result of their miniscule releases. Doses from tritium are higher in adults than in children or infants due to increased inhalation rates, whereas doses due to noble gases were lower (as a result of increased shielding due to higher assumed body fat).

An analysis assessing the spatial relationship between dose and distance from an NPP in Ontario was conducted. Radiation dose to members of the public from routine operation of NPPs is based on several factors, including: the type of release (i.e., air emissions or liquid effluent discharges); the characteristics of the release (i.e., stack height); the quantity, type and radioactive decay properties of the nuclear substances released; the meteorological conditions at the facility (i.e., direction of prevailing winds and mixing height); and the diet and lifestyle habits of people [9, 10, 11]. Thus, distance from an NPP is only one factor among many that contributes to dose to members of the public, and it should not be used in isolation for dose estimation. In fact, this study has shown that distance is an inappropriate substitute for radiation dose to a member of the public.

For instance, residents living closer to the Pickering NPP (such as the non-dairy-farm resident), have lower doses (0.0011 mSv) than the dairy-farm residents living several km further away (0.0013 mSv). This can also be observed when comparing the doses to urban residents (0.002 mSv) compared to residents of the correctional institution (0.0022 mSv). At the Darlington NPP, the dairy-farm residents also have a lower dose (0.0007 mSv) than the rural residents (0.0009 mSv) located further away. Sport fishers near both the Pickering and Darlington NPPs have the lowest doses of all the critical groups, as they are expected to spend at most 1% of the year at the fishing location. Similarly industrial and commercial residents are expected to spend only 20% of the time at the critical group location, also resulting in lower doses. Residents living within 5 km of the Bruce NPP (0.0012 mSv) have lower doses than residents who lived further away (0.0021 mSv).

These findings are especially important since in 2008, a German case-control study of childhood leukemia, referred to as the KiKK Study, used distance from an NPP as a substitute for radiation dose [45, 46]. Although a statistically significant excess risk of leukemia among children (aged 0–4) living within 5 km of an NPP was found in the KiKK study, subsequent case-control studies found no such relationship [47, 48, 49, 50]. Moreover, a recent study [51], referred to as the Geocap study, used a methodology allowing the assignment of doses from gaseous discharges from French NPPs. Although a significant relationship between distance and childhood leukemia was initially found, when dose-based geographic zoning was used, childhood leukemia could not be explained by the radiation doses from the NPPs' gaseous discharges.

A general decrease in the estimated dose to a member of the public over time was also found in the current study. This is due to two main factors: first, the change in human dose receptor from a hypothetical individual who lived at the fence line of the NPP and whose entire diet intake consisted of locally grown food, to a critical group whose relative diet and lifestyle were assessed based on surveys; and second, the improved and optimized operational control as a result of increased operational experience of the facility and engineering control changes. For these reasons, one can expect doses to continue to remain very low.

The annual dose to a member of the public is based on the modelling of all controlled environmental releases of nuclear substances into the environment during the entire year, as well as the inclusion of measured monitoring results of the REMPs; thus any emission spikes are captured in the overall dose assessment. CANDU reactors refuel while still online; therefore, the occurrence of spikes is very low. The CNSC's strong licensing and compliance program requires the establishment of internal investigation levels and action levels to monitor and control releases before any potential emission spikes occur. As such, unexpected emissions must be reported to the CNSC and action must be taken to identify and correct the cause. Exceedances of internal investigation levels or of action levels are rare. Hence, it is unrealistic to conclude that occasional spikes in atmospheric releases result in high short-term exposure of members of the public.

5.2 Cancer Incidence in Members of the Public Living near Ontario Nuclear Power Plants

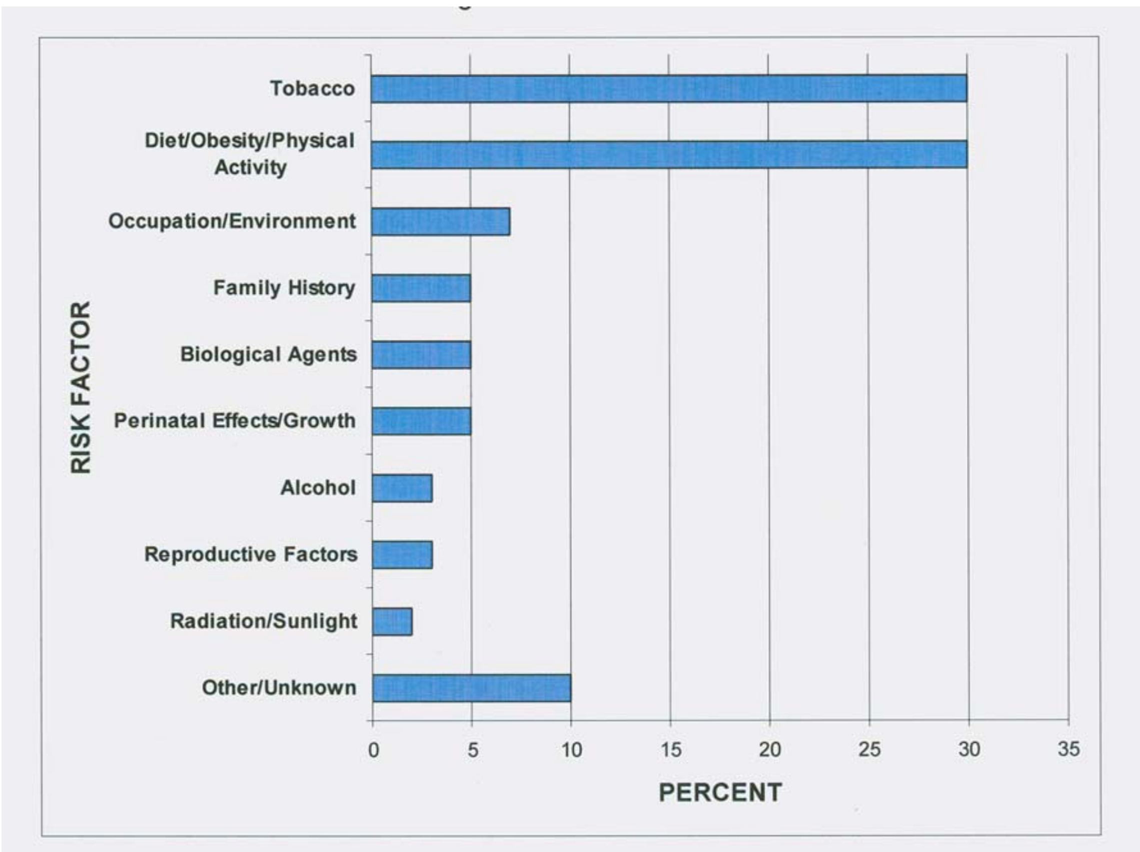
The most important finding of this study is that there is no evidence of childhood cancer clusters around the three Ontario NPPs. In fact, cancer incidence in young children (aged 0–4) was lower than the general Ontario population (but not statistically significantly so). Cancer incidence in children aged 0–14 was similar to the general Ontario population.

Childhood cancer is rare. As a result, patterns that appear to be important may actually be due to random fluctuations in the natural variation of disease. Findings involving few cases and those with wide 95% confidence intervals need to be interpreted cautiously [52]. This is particularly true for childhood cancer incidence near the Bruce NPP, based on only 6 observed cases from 1990 to 2008. It is difficult to understand how underlying risk factors may influence incidence rates since the causes of childhood cancer remain poorly understood [53]. This is perhaps the main limitation when studying childhood leukemia around nuclear facilities [5]. About 5–15% of childhood cancers may be attributable to familial and genetic factors, and less than 5–10% to known environmental exposures [54, 55].

Cancer is the leading cause of death in Canada [56]. The most common cancers observed among people living near the three Ontario NPPs were cancer of the lung and bronchus, female breast, and colon and rectum. This is consistent with the rest of Ontario and Canada. The three leading causes of cancer account for the majority of new cases: prostate, lung and colorectal in males; and breast, lung and colorectal in females [35, 57]. Prostate cancer is not radiosensitive, so was not included in our study [1, 37, 38].

Tobacco, poor diet, obesity and physical inactivity account for 60% of cancer deaths in Ontario, as illustrated in figure 1 [58]. The Durham Regional Health Department and Grey Bruce Health Unit have assessed the socioeconomic determinants of the community as well as main health indicators, since many factors can contribute to cancer development [58, 59]. The high prevalence of these risk factors is a public health concern throughout Ontario and Canada, and Durham Region (location of the Pickering and Darlington NPPs) and Grey Bruce County (location of the Bruce NPP) are no exception [60, 61]. Thus, health authorities have programs targeted at reducing these risk factors within their communities. The multifactorial nature of cancer needs consideration when assessing cancer incidence near NPPs, since radiation is just one of many factors related to cancer, and is not the main risk factor of concern for most types of cancer.

Figure 1: Causes of cancer deaths in developed countries [58]



Overall, there is no consistent cancer incidence pattern among people living near the three NPPs. Some types of cancer were statistically significantly higher than expected; however, some types of cancer were statistically significantly lower than expected, and some types of cancer were the same as expected compared to the general Ontario population. The incidence of female breast, ovary, brain and nervous system and esophagus cancer were either significantly low or similar to Ontario for people living near all three Ontario NPPs.

There was no consistent pattern for all cancers combined near the three NPPs. While, it was statistically significantly higher than expected for people living near Darlington and Bruce, it was significantly lower near Pickering. It is not possible to know all of the cancers contributing to this finding, since only radiation-sensitive cancers were selected for this study. However, cancers of the lung and bronchus, breast and colon and rectum represent about 35% of all cancers combined, for all three NPPs. Cancer incidence was statistically significantly higher than expected for cancer of the lung and bronchus among people living near the Darlington and Bruce NPPs. Cancer of the lung and bronchus was not elevated near the Pickering NPP.

The most important risk factor for lung cancer is tobacco smoking, with relative risks for current smokers being greater than 10- to 20-fold higher than that of non-smokers [62, 63, 64]. Tobacco smoking and second-hand smoke are the leading risk factors of lung cancer risk in Canada [59]. Durham Region has significantly high tobacco smoking rates [60]; however, the rate of smokers in Grey Bruce was not significantly different than Ontario from 2000–08 [61]. Other risk factors for lung cancer include family history, radon, air pollution, asbestos, other chemicals, HIV and low socioeconomic status [59, 65, 66]. Cancers of the bladder, stomach, and liver have been shown to be caused by tobacco smoking [64, 66]. Bladder cancer was significantly high near the Darlington NPP, but significantly low at the Pickering and Bruce NPPs. Stomach cancer was significantly high near the Pickering NPP, but was similar to the Ontario average near the Darlington and Bruce NPPs. Liver cancer was significantly high near the Pickering NPP, but was significantly low near the Darlington and Bruce NPPs. The statistically significant higher-than-expected incidence for cancer of the lung and bronchus, bladder, stomach and liver in this study suggests that tobacco smoking may be a confounding factor. Other risk factors for bladder cancer include exposure to chemicals, personal history of bladder cancer, cancer treatment history, arsenic, and family history. Other risk factors for stomach cancer include helicobacter pylori infection, long-term inflammation of the stomach, family history, poor diet (low in fruit and vegetables, high in nitrates and nitrites [i.e., in water and preserved foods]), lack of physical activity and obesity and low socioeconomic status. Other risk factors for liver cancer include infection with hepatitis B and hepatitis C virus, heavy alcohol use, aflatoxins, iron storage disease, cirrhosis, obesity, and diabetes [59, 65, 66].

There was no consistent pattern for colon and rectum cancer near the three NPPs. Colon and rectum cancer incidence was significantly higher than expected near the Darlington and Bruce NPPs (especially among men aged 65+ years), but was significantly lower near the Pickering NPP. This is consistent with the main risk factors for colorectal cancer: age (particularly those over the age of 50), sex (males), polyps, family history of colorectal cancer, diet (high in fat and low in fibre), obesity, physical inactivity, alcohol, high socioeconomic status, and tobacco smoking [59, 65, 66].

There was no consistent pattern of thyroid cancer near all three NPPs. Thyroid cancer incidence was statistically significantly higher than expected near the Pickering and Darlington NPPs, but was similar to the Ontario population for Bruce NPP. Exposure to large amounts of ionizing radiation, family history and iodine (high or low) in the diet are the main risk factors for thyroid cancer [59]. The number of thyroid cancers is rising in Canada [57] and worldwide [67]. The upward trend in thyroid cancer could be due to the increasing use of diagnostic technologies for the detection of subclinical tumours, increased exposure to diagnostic ionizing radiation, or increased exposure to an as yet unidentified environmental risk factor [68, 69]. Mounting evidence also exists for a role of body weight and female reproductive factors [70]. Radioactive iodine, which is the primary cause of radiation-related thyroid cancer [71], was below detection limits of the in-stack sampling monitors at all three NPPs for the entire study period. Thus, public radiation dose from the two NPPs is not a likely cause of thyroid cancer.

There was no consistent pattern for leukemia near all three NPPs. Leukemia was statistically significantly higher than expected near the Darlington NPP. However, cancer incidence for children aged 0–4, 0–14, and young adults aged 0–24 was either less than or similar to the general Ontario population at all three NPPs. Therefore the 25–64 age group is driving the significant finding at the Darlington NPP. Although high radiation doses can cause leukemia [1], the lack of significant findings among children (who are most vulnerable to radiation) suggests that other risk factors are involved, especially considering the very low doses found in this study. The risk factors for leukemia include tobacco smoking, benzene, chemotherapy, Down syndrome, certain blood disorders and family history [59, 65, 66].

Radiation levels in the air, soil, water and vegetation around Ontario NPPs are very low – 100 to 1,000 times below natural background levels and the CNSC public dose limit. Industrial sources of radiation only contribute a small fraction of total radiation dose levels in the areas near the plants. Radiation doses from the three NPPs do not provide a plausible explanation for any observable increases in cancer incidence above baseline levels. The main risk factors for cancer are common among the Ontario population [58] and the communities around the three NPPs are no exception [60, 61]. The common risk factors for cancer previously discussed are more likely to explain any observed increases in cancer incidence than the low radiation doses to the public from the NPPs. This is supported by Bradford-Hill's criteria to establish causation (i.e., does factor A cause disorder B?) [72]. These criteria are: strength of association; the consistency of association; specificity; temporal relationship; biological gradient (dose-response); biological plausibility; coherence; experimental evidence; and reasoning by analogy [72]. It is clear from the scientific evidence that radiation can cause cancer at high doses. According to Bradford-Hill's criteria, a causal relationship exists between ionizing radiation and cancer [1, 37, 38]. Similarly, based on the experimental and epidemiological literature, the cancers selected are known to be radiosensitive [1, 37, 38]. However, when considering the biological gradient (dose-response) and experimental evidence criteria, none of the types of cancers observed near the NPPs are plausibly attributable to the miniscule radiation exposures from the NPPs. In fact, cancer incidence is generally more elevated around the Darlington NPP than the other two NPPs (i.e., Pickering and Bruce) in this study; this is despite the fact that doses to the public living near Darlington are lower than those to the public living near the Pickering and Bruce NPPs.

5.3 Strengths and limitations

The primary strength of this study is its inclusion of dose information for various age groups around each NPP that was generated from radiological releases and environmental monitoring data. This improves on the recent epidemiological studies that used distance of a residence from an NPP as a substitute for radiation dose data. The assumption that distance is a good substitute for dose was found to be flawed in this study; some doses close to the NPPs were found to be smaller than some doses further away. This study considered information about both historical and current operations, total annual releases (that take into account any daily fluctuations and emission spikes), various groups and age classes surrounding NPPs. It provides very conservative dose estimates for members of the public based on maximum dose estimates over the study period.

Ecological studies also easily assess the relationship between cancer incidence among people living near an NPP and the general Ontario population. This type of study is a very useful monitoring tool for epidemiologists to identify high and low rates of disease in a population over time that may warrant further study. In other words, these types of studies provide an indication of the frequency of diseases in a population.

Another strength of this study is the quality of the cancer incidence data. Cancer reporting to the OCR and the CCR is virtually complete and of high quality, since it is routinely checked for accuracy through regular assessments by Statistics Canada and the cancer registries [34]. Likewise, the Census of Canada undergoes vigorous quality and confidentiality procedures to assure the accuracy and privacy of census information [36]. Incidence data is preferred to mortality data, since detailed clinical and demographic information is collected on individual cases. If any advances in treatment occur during the study period, mortality would become a less sensitive outcome, whereas incidence would be unaffected. Likewise, cancers with high survival rates, such as thyroid cancer, would not be detected by mortality statistics.

The main limitation of an ecological study is that associations at the population level do not necessarily reflect the biological effect at the individual level [1, 40, 41]. Uniform doses are assigned to the group, whereas the doses received by individuals vary, and at the individual level are also highly uncertain. The very detailed and conservative public doses were estimated and the highest public doses were derived, providing assurance that actual residents around the NPPs had lower doses. Ecological studies do not typically provide this type of detailed information.

This type of study involves interpretational problems arising from the aggregated form of the data (population-level data) such as variation in the size of the regional population, migration and disease latency. Ontario has wide variations in population size and area. For example, the population is 1.6 million near the Pickering NPP and 25,500 near the Bruce NPP, which impacts statistical power. The exposures related to cancer risk probably occur 10 to 20 years before diagnosis. The population growth varied in Durham Region, ranging from 0.2% (Pickering) to 27.7% (Whitby) from 2001 to 2006, and 1.0% (Pickering) to 21.6% (Ajax) from 2006 to 2011. From 2001 to 2006, the population growth rate in Grey and Bruce counties was 3.7% and 2.3%, respectively [73]. Recent residents will have their residence at diagnosis as Durham Region, but were exposed to risk factors up to 20 years earlier. Therefore, migration is likely a cause of bias in this study [74]. The use of incidence data in this study eliminates potential bias association with post-diagnosis migration.

This type of study is also limited because it is not possible to make conclusions or determine whether a risk factor (or a combination of risk factors) caused a disease. This becomes especially important when a risk factor (i.e., tobacco smoking) is known to be strongly associated with the disease (i.e., lung cancer). Since several types of cancer are associated with tobacco smoking, it has a substantial potential for bias in this study since the risk factor is not controlled for. The main risk factors for the types of cancers found to be statistically significantly higher than the Ontario average were tobacco smoking, poor diet, inactivity and/or obesity [58]. These risk factors account for approximately 60% of all cancer deaths in developed countries and are the most plausible explanations for any excess cancer incidence found in this study. The different prevalence of these risk factors may explain the significant differences in cancer incidence between people living near the Pickering and Darlington NPPs, which are about 30 km apart. The following section looks at comparison with other studies and provides a good indication to the types of lifestyle choices that have been documented in the communities surrounding Ontario NPPs.

Errors in the assignment of place of residence are known to occur and are often not specific. These types of errors are more common with smaller geographical areas. However, this is less an issue in this study since a 25-km radius from the three NPPs was used. In fact, the 25-km range overlaps between the Pickering and Darlington NPPs. As well, 25 km from the station goes outside the Durham region toward Toronto to the west and into Northumberland County to the east. The municipalities closest to the Darlington NPP include Oshawa and Clarington and those closest to the Pickering NPP include Pickering and Ajax. Whitby is between the two NPPs, in the area where the two 25-km zones overlap. It is important to note that the dose estimates provided by modelling indicate that exposure to the public did not typically exceed the 5-km zone. However, it would not be feasible to limit the study area to the 5-km radius because of the extremely low population density and the rarity of some of the studied types of cancer.

The statistical power of a study depends on the statistical significance criterion used, the magnitude of the effect of interest, and the sample size. Many researchers assess the power of their tests using 80% as a standard for acceptance [75]. This was generally not an issue for populations living near the Darlington and Pickering NPPs, which had large observed and expected numbers of cancer cases. However, the small population size and the rareness of some cancers limited the statistical power of our findings among the population living near the Bruce NPP.

5.4 Comparison with Other Studies

The incidence findings in the current study were consistent with previous studies of childhood and other cancers near Ontario NPPs [39, 60, 76, 77, 78]. These studies concluded there was no statistical evidence that differences in disease rates were due to anything but natural variation of the disease. Given the extremely low levels of radiation exposures (which included tritium exposures) from the operation of the NPPs studied, radiation-related effects are extremely unlikely.

Since the 1980s, many descriptive epidemiological studies around the world have been conducted to determine whether people living near nuclear facilities have higher rates of disease, especially childhood leukemia, compared to the general population. Authoritative reviews of these studies have confirmed that only three childhood leukemia clusters have persisted over time around three nuclear facilities (Sellafield in England, Dounreay in Scotland, and Krümmel in Germany). Although some clusters of childhood leukemia cases exist, results based on multi-site studies around nuclear facilities do not indicate an excess of cancer globally. Many studies have investigated possible origins of the observed clusters around specific sites; however, up until now, none of the proposed hypotheses (i.e., routine environmental releases, parental pre-conception exposure, or infectious agent associated with population mixing) can explain them [3, 4, 5].

Recent studies have used distance as a substitute for radiation doses. Although one case-control study (the KiKK study) found a relationship [45, 46] between a residence's distance from an NPP and childhood leukemia, the observed positive distance trend remains unexplained and no statements on the cause of the increased cancer rates can be made. An independent review of the study concluded there was no support for a causal relationship between any chemical or physical risk factor and the observed risk of childhood leukemia [79]. Several other reviews of the study came to similar conclusions [5, 6]. Radionuclide discharges, in particular tritium and carbon-14 discharges, are not considered to be responsible for the excess incidence of leukemia in the KiKK study [6, 80, 81, 82, 83, 84].

Other studies of childhood cancer near nuclear facilities also provide no evidence that excess cancers are related to radiation doses from the facilities [3, 4, 5, 6, 47, 48, 49, 50]. This is consistent with the current scientific understanding of radiation risk [1].

Although variations in all cancers combined and other radiosensitive cancers were found in the current study, this pattern is well within the natural variation of cancer in Ontario and the prevalence of leading risk factors in the studied communities. Further support for the findings of this study are presented in tables 2 and 3, which summarize geographical variations in cancer incidence in Ontario. Tables 2 and 3 provide the ranking (from highest to lowest) of age-standardized incidence rates (ASIRs) per 100,000 population based on local health integration network (LHIN) [85] information for selected types of cancer (see Appendix D). The LHIN information separates the province of Ontario into 14 different regions. The Bruce NPP is within the South West health region and the Pickering and Darlington NPPs are within the Central East health region. The information in these tables clearly shows the wide geographical variation of cancer incidence across Ontario and the existence of elevated rates of cancer far from regions with NPPs. Table 2 (males) lists ASIRs for all cancers combined, as well as for lung, colon and rectum and leukemia. Table 3 (females) also lists these ASIRs, in addition to breast cancer. Overall, the selected cancer incidence rates for males and females in LHINs containing NPPs are ranked lower than (few cases of cancer per 100,000 population) or very close to the Ontario average. This information supports a previous study [66] that found spatial patterning when looking at geographic variation of cancer incidence in Ontario. Other studies of geographical variation in cancer found similar results [86, 87, 88, 89].

Walter et al. [90] followed up the initial study to investigate if regional effects could be identified after adjustment for known socioeconomic (i.e., population density, income, education, employment, and immigration) and lifestyle risk factors (i.e., smoking, diet, alcohol, obesity/exercise, and occupational exposures) for cancer [91, 92]. Most of the geographical variation in cancer rates was found to be associated with variation in known risk factors, and no broad regional effects remained after adjustment for these factors. In summary, the overall message was reassuring: after known risk factors are taken into account, there is no evidence of a strong difference in cancer risk in Ontario that would be expected if environmental factors (i.e., related to air or water quality) were operative at a regional scale. Another Ontario study of premature mortality found similar results [93].

Durham Region and Grey Bruce County also looked at known cancer risk factors within their communities. Durham Regional Health Department assessed socio-demographic and health information of municipalities (and neighbourhoods) in Durham Region as part of its preliminary Health Neighbourhoods Project, from 2001 to 2011. Overall, the leading risk factors for cancer were a public health concern for the Durham Region. The region is currently reporting high prevalence of the leading risk factors for cancers, including tobacco smoking (21%), overweight/obesity (58%), low vegetable and fruit consumption (64%) and low physical activity (45%). Moreover, the health status of the municipalities varied substantially. For example, the smoking rate varied from 14% in Pickering to 27% in Oshawa [74].

Socio-demographic, health, and lifestyle factors have also been assessed by the Grey Bruce Health Unit using the Canadian Community Health Survey (CCHS) [61, 94, 95] over the 2000–08 time period. Grey Bruce County residents (aged 12 years and older) were compared with people living in Ontario, Canada, and with a health region peer group (i.e., health regions that have a similar socio-demographic distribution to Grey Bruce County) [61]. Overall, the leading risk factors for cancer were a public health concern for the Grey Bruce region, reporting high prevalence of the leading risk factors for cancers, including heavy tobacco smoking (24%), overweight/obesity (61.5%), low vegetable and fruit consumption (45%) and low physical activity (48%).

Thus, the most likely reason to explain the higher incidence rates in these regions is differences in the populations' main socioeconomic and lifestyle risk factors for cancer [91, 92], similar to what was found in the rest of Ontario [90]. Based on the very low environmental radiation doses found in this study, it is inappropriate to attribute any elevated cancer rates among people living within 25 km of an Ontario NPP to radiation.

Table 2: **Age-standardized incidence rates per 100,000 population for all cancers, the most common cancers, and leukemia by Local Health Integration Network, males, Ontario, 2007 [85]**

	All cancers combined		Lung		Colon and rectum		Leukemia	
Rank	**Local Health Integration Network**	**Age-standardized incidence rate**	**Local Health Integration Network**	**Age-standardized incidence rate**	**Local Health Integration Network**	**Age-standardized incidence rate**	**Local Health Integration Network**	**ASIR**
highest	North Simcoe Muskoka	529.4	North East	76	North East	70.7	North Simcoe Muskoka	22.8
	Hamilton Niagara Haldimand Brant	515.9	South East	74.8	North West	60.6	North East	19.7
	Erie St. Clair	500.7	Hamilton Niagara Haldimand Brant	74	North Simcoe Muskoka	63.6	Champlain	19.5
	North East	496.6	Erie St. Clair	69.4	Champlain	62	Hamilton Niagara Haldimand Brant	18.7
	South East	492.3	North West	68.7	Central East	61	Toronto Central	17.7
	South West	475.7	North Simcoe Muskoka	64.5	Central	60.9	Waterloo Wellington	17.5
	Ontario	468.6	Champlain	61.6	Hamilton Niagara Haldimand Brant	60.6	Ontario	17.3
	Mississauga Halton	468	Ontario	60	Erie St. Clair	60.5	Mississauga Halton	16.9
	North West	462	South West	56.3	Ontario	58.5	Central East	16.7
	Waterloo Wellington	454.1	Waterloo Wellington	55.6	South West	57.7	South West	16.6
	Central	450.8	Central East	55.1	South East	56.9	Central	16.4
	Champlain	450.7	Mississauga Halton	53.7	Central West	53	North West	14.5
	Central East	448	Central	51.1	Mississauga Halton	51.8	South East	14.4
	Toronto Central	442.2	Toronto Central	48.8	Waterloo Wellington	50.4	Erie St. Clair	13.6
lowest	Central West	402.5	Central West	48.2	Toronto Central	47.7	Central West	13.2

Ontario Average (reference)
South West (includes Bruce NPP)
Central East (includes Pickering and Darlington NPPs)

Table 3: Age-standardized incidence rates per 100,000 population for all cancers, the most common cancers, and leukemia by Local Health Integration Network, females, Ontario, 2007 [85]

	All cancers combined		Breast		Lung		Colon and Rectum		Leukemia	
Rank	Local Health Integration Network	Age-standardized incidence rate	Local Health Integration Network	Age-standardized incidence rate	Local Health Integration Network	Age-standardized incidence rate	Local Health Integration Network	Age-standardized incidence rate	Local Health Integration Network	Age-standardized incidence rate
highest	North East	394.9	North West	111.8	North West	63.1	North West	47.7	North East	15.7
	Hamilton Niagara Haldimand Brant	387.2	Mississauga Halton	109.7	North East	59.7	North Simcoe Muskoka	47	Erie St. Clair	13.7
	North West	387	Hamilton Niagara Haldimand Brant	107.1	South East	56.2	North East	45.2	Central East	13.1
	Central	386.2	Central	106.6	North Simcoe Muskoka	52.8	Hamilton Niagara Haldimand Brant	44.2	Waterloo Wellington	12.8
	North Simcoe Muskoka	380.8	North Simcoe Muskoka	101.9	Champlain	51	Erie St. Clair	41.7	South West	12.7
	Mississauga Halton	380.3	North East	101	Hamilton Niagara Haldimand Brant	50.9	Waterloo Wellington	41.6	Hamilton Niagara Haldimand Brant	11.8
	Erie St. Clair	377.4	Champlain	100.4	Erie St. Clair	48.6	Central	41.6	North West	11.5
	Ontario	371.4	Ontario	100.1	South West	44.4	Champlain	40.8	Ontario	11.4
	Central East	371.2	Central East	97.5	Ontario	43.9	Ontario	40.4	Mississauga Halton	11.4
	South East	367.1	Erie St. Clair	96.6	Central East	43.3	Central East	40.1	Toronto Central	10.9
	Champlain	366.4	South West	96.3	Waterloo Wellington	39.9	South West	39.8	Champlain	10.8
	South West	363.1	Waterloo Wellington	95.1	Mississauga Halton	37.9	South East	39.7	Central	9.3
	Waterloo Wellington	362.7	Toronto Central	91.3	Central	33.7	Mississauga Halton	37.3	North Simcoe Muskoka	8.5
	Toronto Central	345.1	Central West	91.1	Toronto Central	31.6	Central West	32.7	Central West	8.1
lowest	Central West	312.6	South East	89.9	Central West	27.1	Toronto Central	32.1	South East	7.8

Ontario Average (reference)
South West (includes Bruce NPP)
Central East (includes Pickering and Darlington NPPs)

6.0 CONCLUSIONS

There is no evidence of childhood cancer clusters (especially childhood leukemia) near the three Ontario NPPs studied (Pickering, Darlington and Bruce). Overall, for all ages, there is no consistent pattern of elevated cancer incidence at any of these three NPPs; this finding is generally consistent with previous studies. There is higher-than-expected and lower-than-expected cancer incidence for some types of cancer among people living within a 25-km radius of the three NPPs, especially near the Darlington NPP. In other words, some types of cancers were found to be elevated in some communities (but never at all three sites), and some types of cancers were found to be lower than expected in some communities. Equally, many types of cancers were found to be similar to the expected Ontario average. Overall, the cancers are well within the natural variation of disease within Ontario.

Radiation doses to members of the public living near the three NPPs as a result of historical and current-day operations are 100 to 1,000 times lower than natural background radiation and public dose limits. Emission spikes from the NPPs are captured in the overall dose assessment, and distance from a NPP was found to be an inappropriate substitute for radiation dose.

The main causes of cancer (tobacco, poor diet, obesity and physical inactivity) account for about 60% of all cancer deaths in developed countries. These risk factors are the most plausible explanation for any higher-than-expected cancer incidence found around the three NPPs examined in this study. However, limitations of ecological studies prevent any causal inference to be made.

Therefore, on the basis of current radiation risk estimates and the supporting epidemiological literature, radiation is not a plausible explanation for any excess cancers observed within 25 km of any Ontario NPP.

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APPENDIX A: SPATIAL MAPPING OF AIR DISPERSION PLUME AND CRITICAL GROUP LOCATIONS

Figure A.1: 2005 Critical Group Doses and Air Dispersion Plume for Pickering NPP

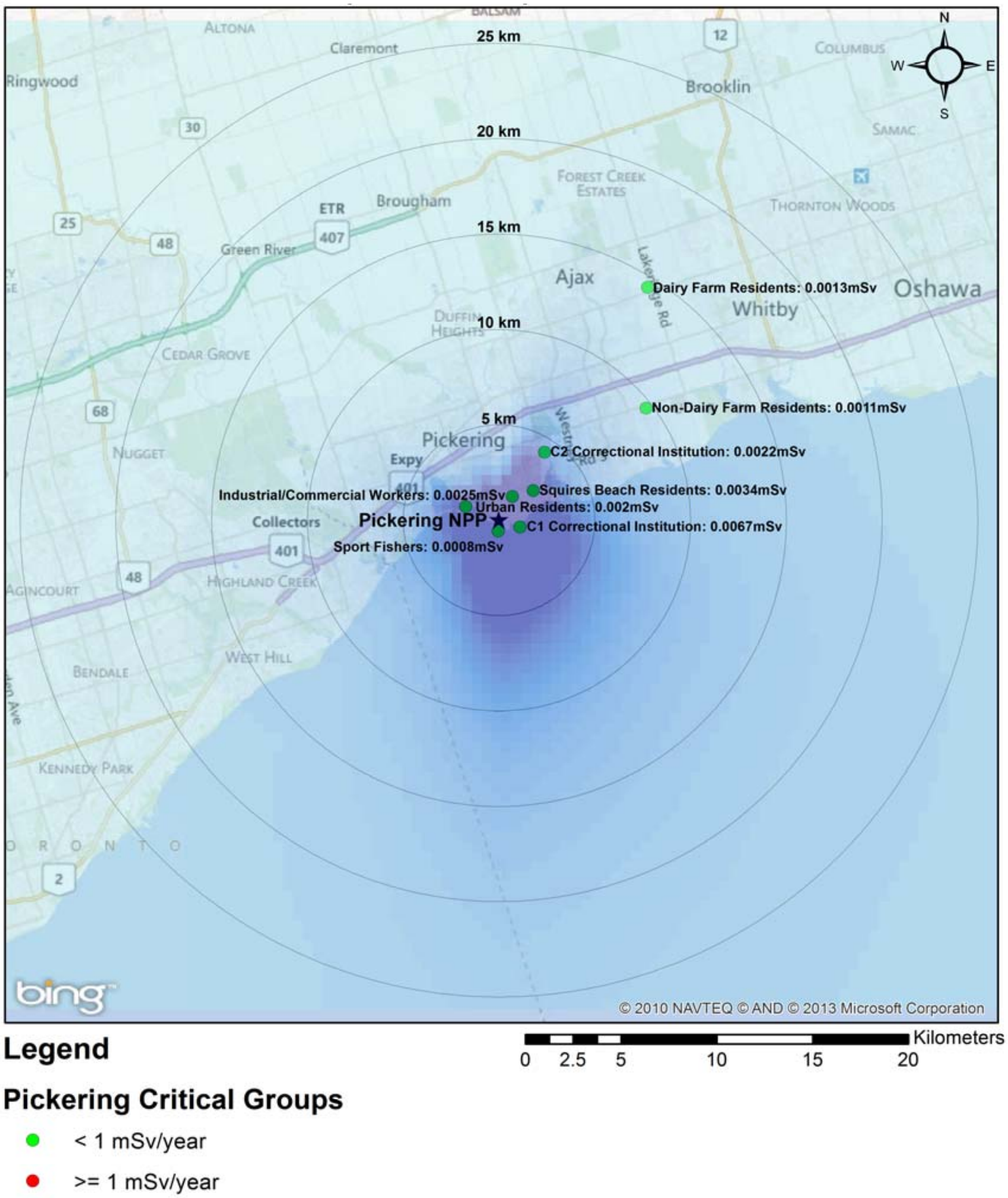


Figure A.2: 2003 Critical Group Doses and Air Dispersion Plume for Darlington NPP

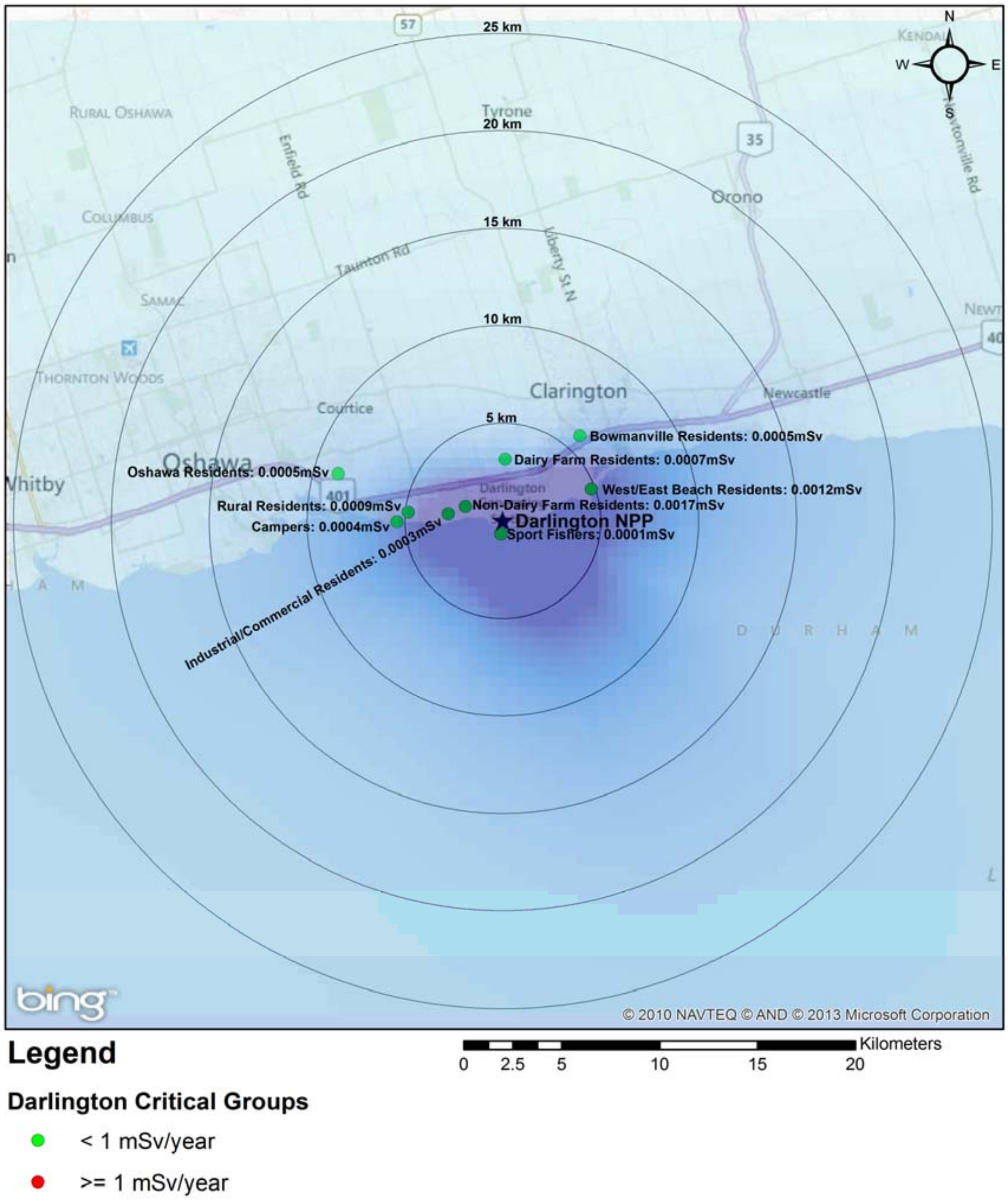
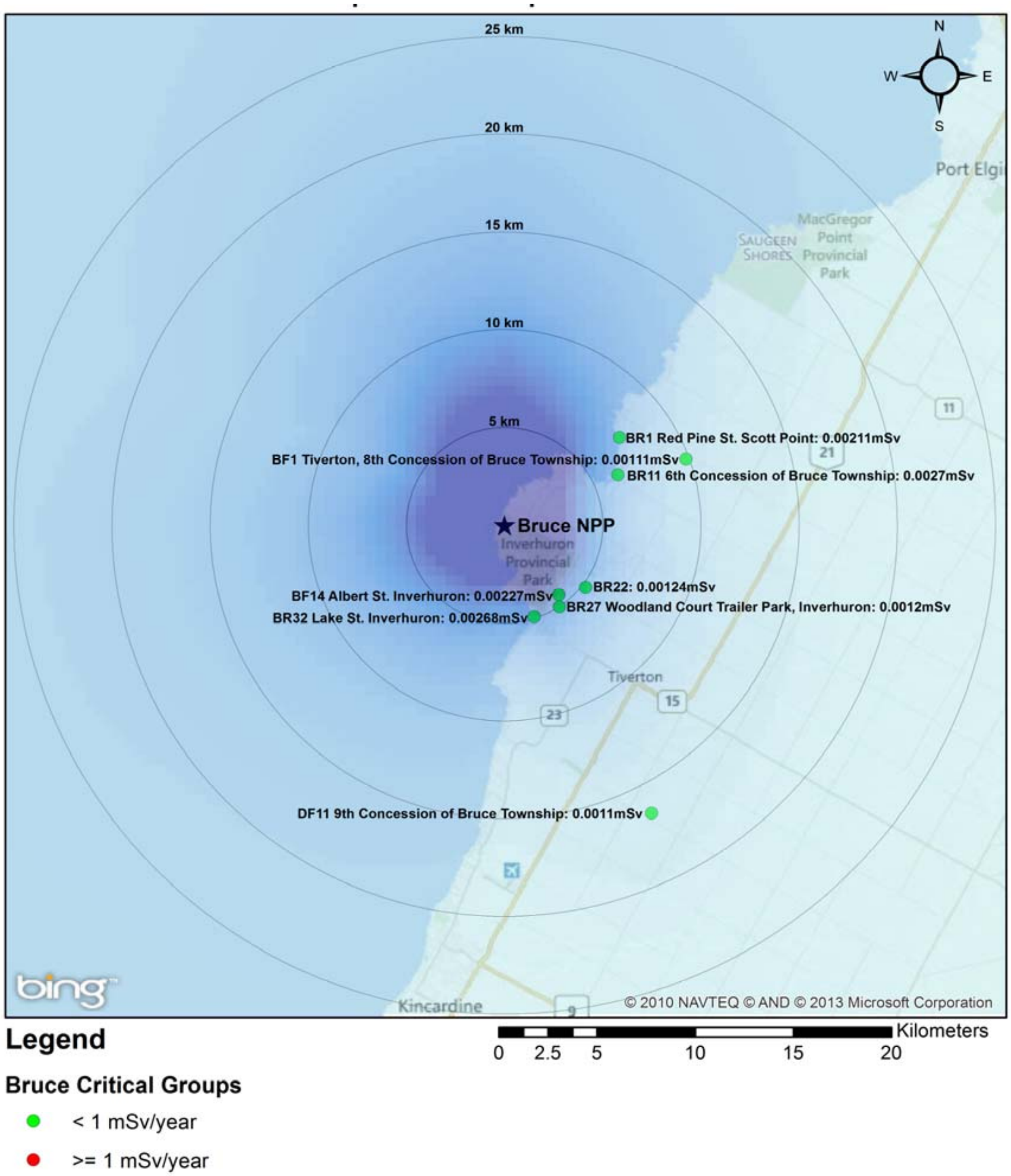
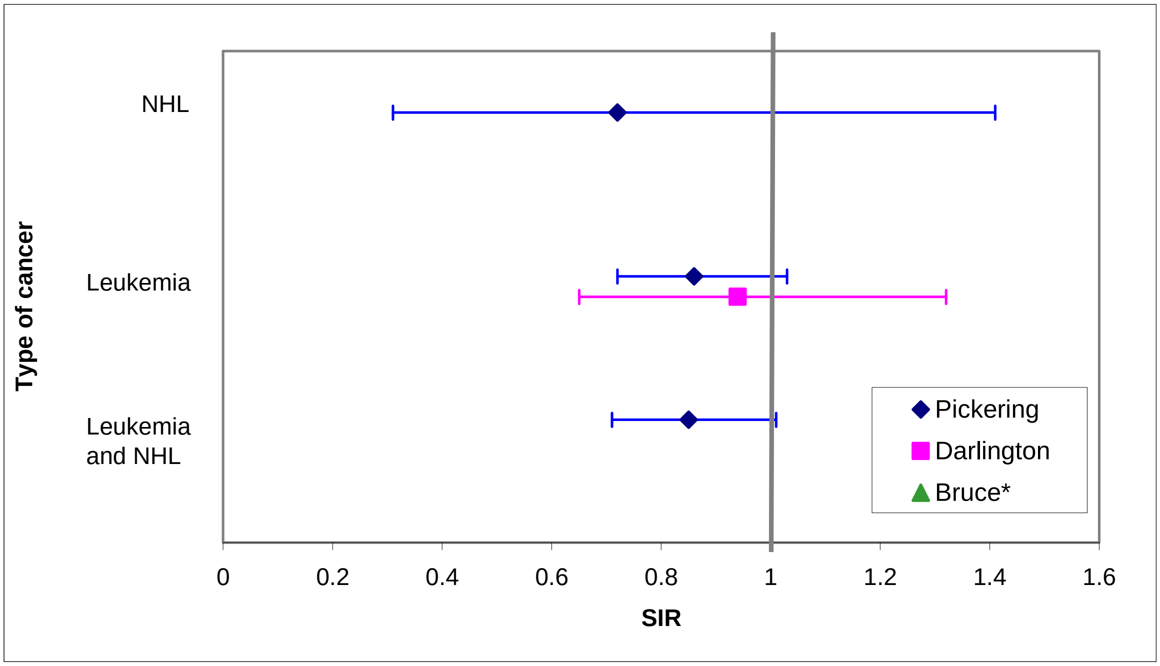


Figure A.3: 2008 Critical Group Doses and Air Dispersion Plume for Bruce NPP



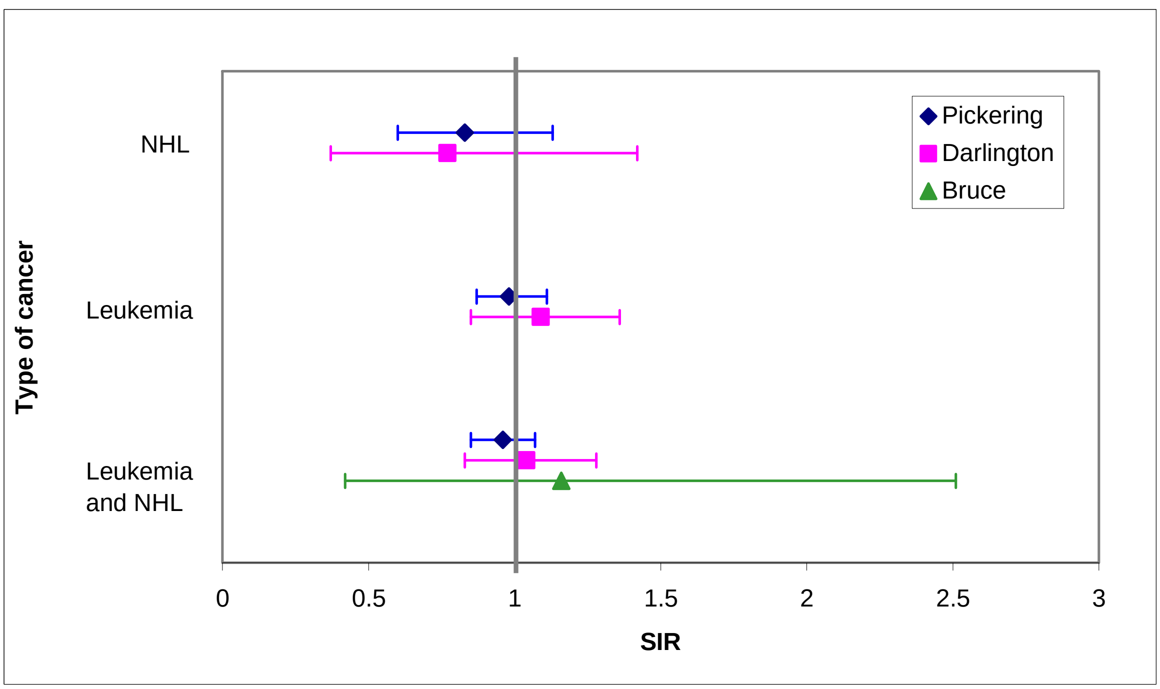
APPENDIX B: CHILDHOOD CANCER INCIDENCE

Figure B.1: Childhood cancer incidence (1990-2008) in children aged 0-4 living within a 25-km radius of an Ontario NPP at time of diagnosis



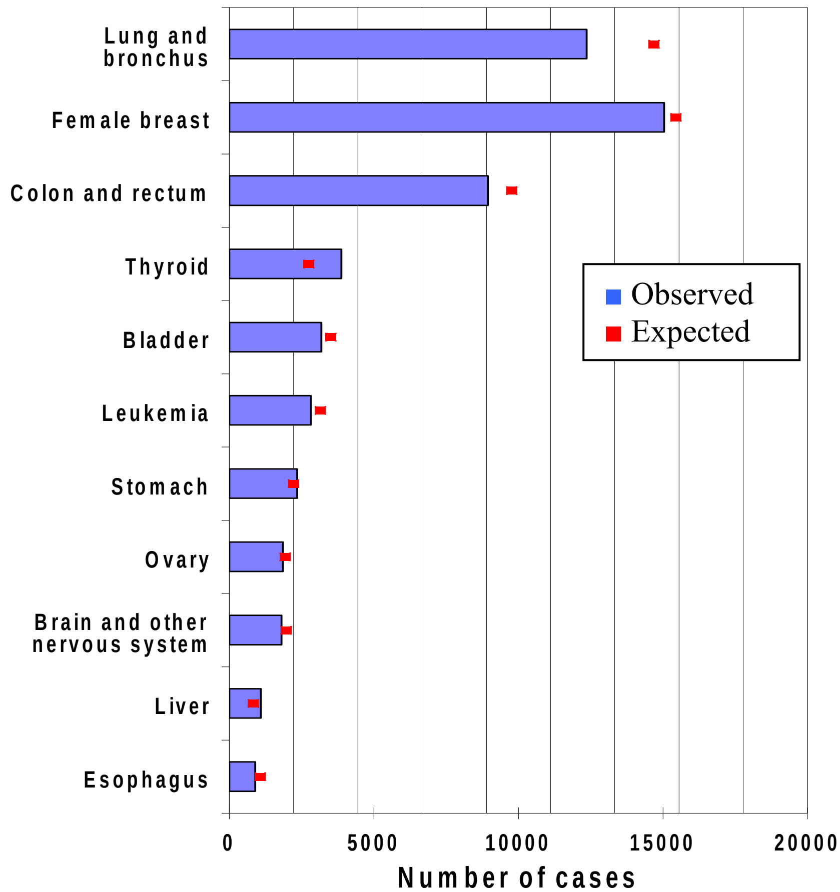
* No information was available for the Bruce NPP because there were fewer than 6 cancer cases.

Figure B.2: Childhood cancer incidence (1990–2008) in children aged 0–14 living within a 25-km radius of an Ontario NPP at time of diagnosis



APPENDIX C: DISEASE SURVEILLANCE RESULTS

Figure C. 1: Cancer incidence (1990–2008) in people living within a 25-km radius of the Pickering NPP at time of diagnosis (both sexes, all ages combined)



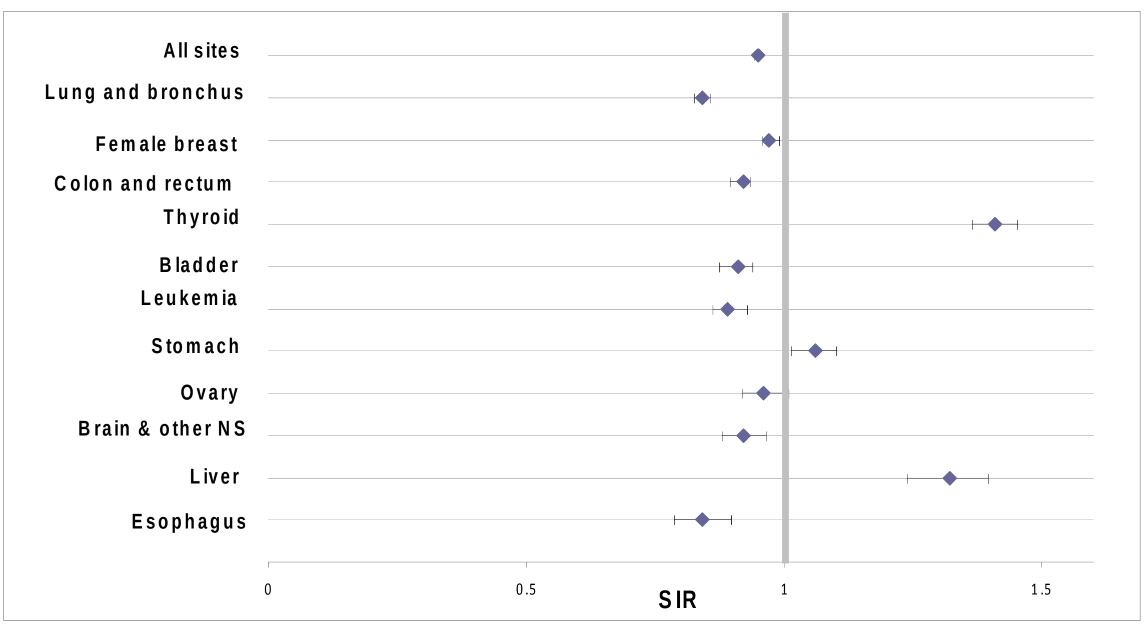
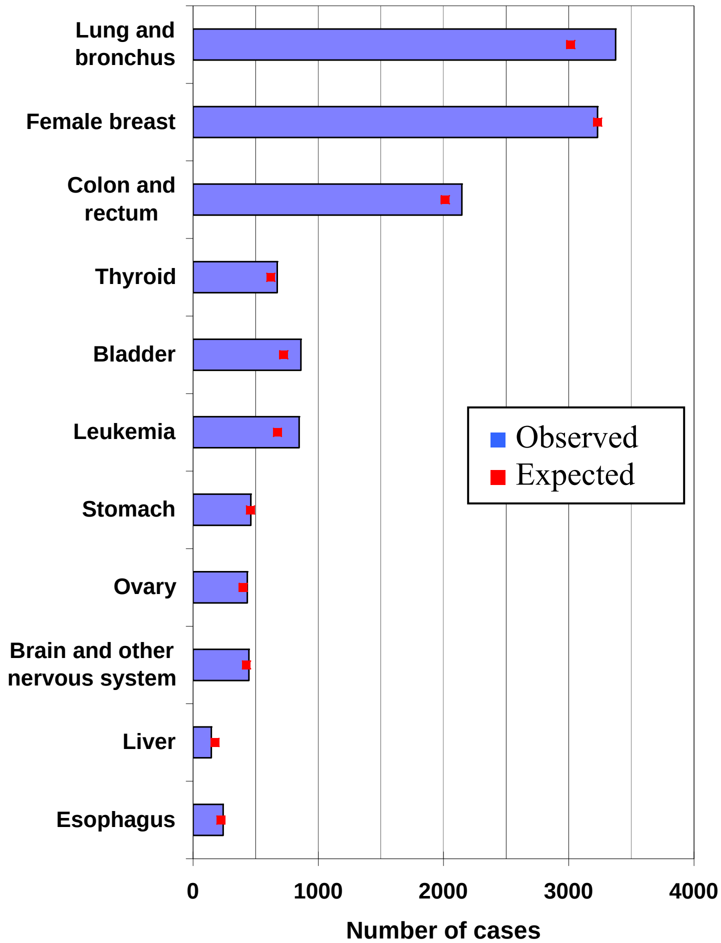


Figure C. 2: Cancer incidence (1990–2008) in people living within a 25-km radius of the Darlington NPP at time of diagnosis (both sexes, all ages combined)



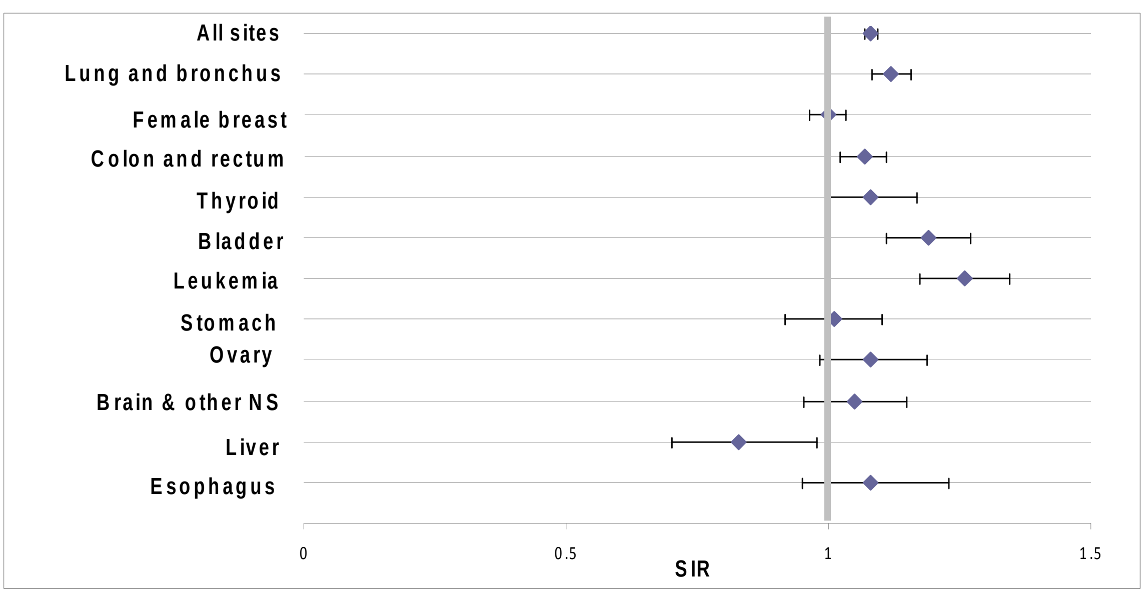
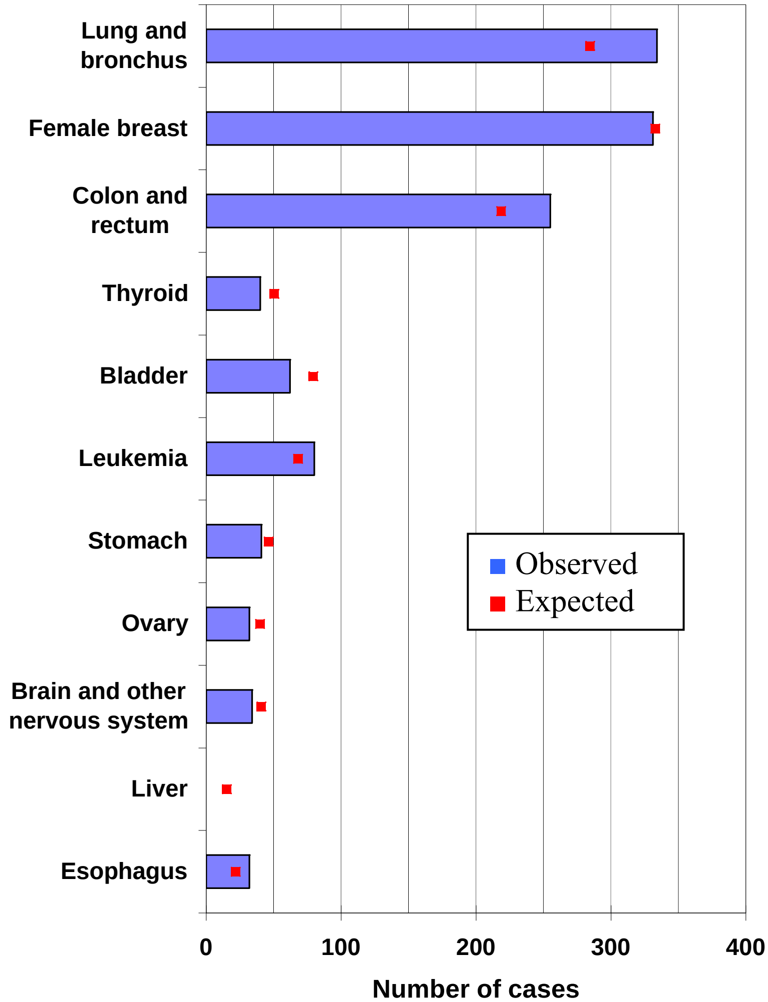
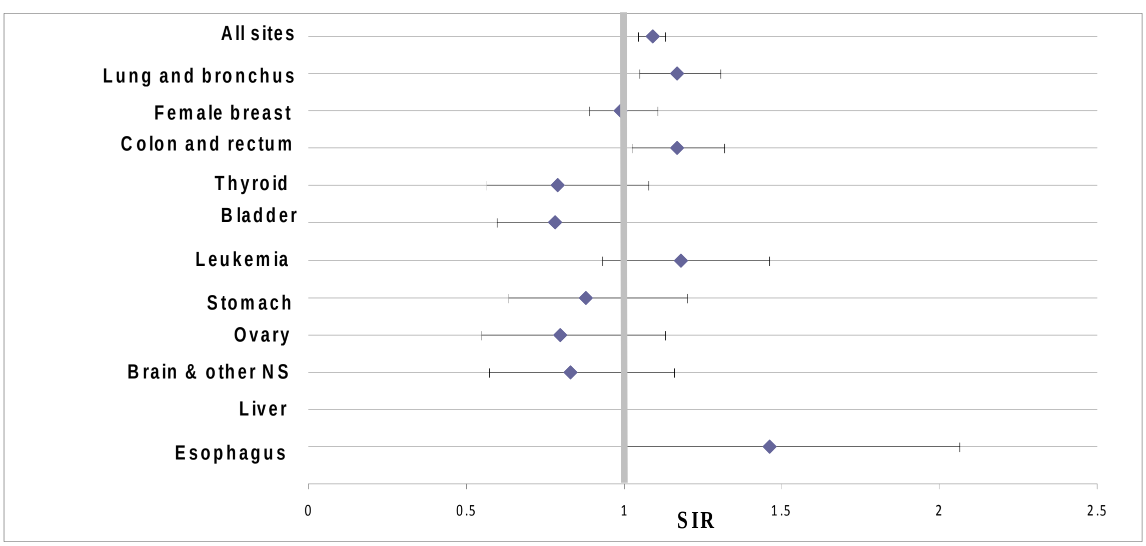


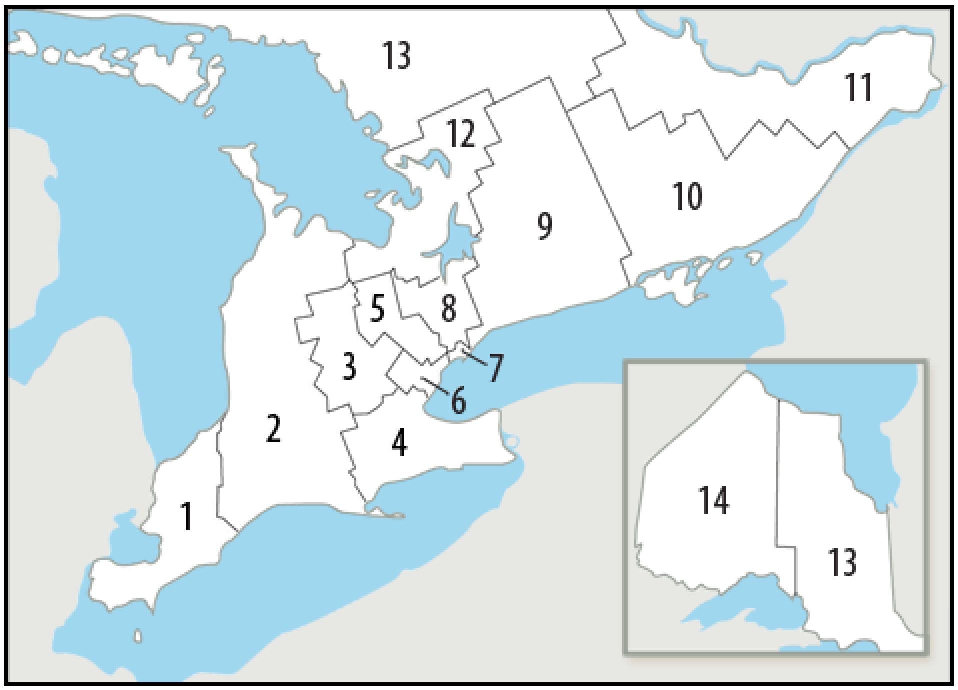
Figure C. 3: Cancer incidence (1990–2008) in people living within a 25 km radius of the Bruce NPP at time of diagnosis (both sexes, all ages combined)





APPENDIX D: LOCAL HEALTH INTEGRATION NETWORK, ONTARIO [96]

1. Erie St. Clair
2. South West
3. Waterloo Wellington
4. Hamilton Niagara Haldimand Brant
5. Central West
6. Mississauga Halton
7. Toronto Central
8. Central
9. Central East
10. South East
11. Champlain
12. North Simcoe Muskoka
13. North East
14. North West



Report date: September 2011. Data source: Cancer Care Ontario (Ontario Cancer Registry, 2010 for SEER Stat Release February 8, 2011)
For map of LHINs see http://www.lhins.on.ca/FindYourLHIN.aspx?ekmensel=e2f22c9a_72_254_btnlink
Cancer cases with unknown LHINs have been excluded.

Notes:
Cancer cases defined by SEER Site recode (see http://seer.cancer.gov/siterecode/icdo3_d01272003/)
All cancers excludes non-melanoma (basal cell and squamous cell) skin cancer
Only cancers with more than 500 cases in Ontario are shown
Rates are per 100,000 and standardized to the age distribution of the 1991 Canadian population.