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Radiation Exposure and Cancer Incidence (1990 to 2008) around Nuclear Power Plants in Ontario, Canada

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ABSTRACT

Radiation doses and cancer incidence among the population living within 25 km of three nuclear power plants (NPPs) in Ontario, Canada were investigated for the period 1985 to 2008 for radiation exposure and 1990 to 2008 for cancer incidence. This study design provided at least a five-year latency period between potential radiation exposure and cancer incidence. Around the NPPs, the incidence of childhood cancers, leukemia and non-Hodgkin lymphoma, in young children (aged 0 - 4) was lower than the general Ontario population, but not statistically so. Cancer incidence in children aged 0 - 14 was similar to the Ontario population. Overall, for all ages there was no consistent pattern of cancer incidence (all cancers combined and radio-sensitive cancers) across the population living within 25 km of the three NPPs. Some types of cancers were statistically higher than expected, others were statistically lower than expected, and others were similar to the general Ontario population. Although variations in all cancers combined and radiosensitive cancers were found in this study, the pattern was found to be within the natural variation of cancer in Ontario. During the period 1985 to 2000 (Pickering and Bruce NPPs) and 1985 to 2002 (Darlington NPP) radiation doses to members of the public from the operation of the NPPs, estimated on the basis of a hypothetical individual at the facility fence line, were ≤0.052 mSv/year; while for the period 2001 to 2008 (Pickering and Bruce NPPs) and 2003 to 2008 (Darlington NPP) radiation doses, more realistically estimated using the critical group concept for six age classes, were ≤0.0067 mSv/year. Hence, public doses from environmental releases of radionuclides from Ontario NPPs represent a very small fraction of natural background radiation (1.338 and 2.02 mSv/year) in the regions where the NPPs are located. Our study shows no evidence of childhood leukemia clusters around the three NPPs and that the incidence of all the cancers investigated for all age groups is within the natural variation of the disease in Ontario. The radiation exposure from NPP operation is a small contributor to the public's total exposure to radiation and is not a plausible explanation for any excess cancers observed within 25 km of any Ontario NPP.

Keywords: Cancer; Childhood Leukemia; Radiation Doses; Population; Nuclear Power Plants

1. Introduction

Several studies have evaluated the relationship between distance from a nuclear facility and cancer incidence, but few studies have assessed the relationship between radioactive discharges or radiation dose to members of the public from a nuclear facility and cancer incidence.

In Germany, a case-control study (1980 to 2003) found a statistically significant excess risk of leukemia among children under 5 years old living within 5 km of a nuclear power plant (NPP) [1,2]. However, an increasing trend with the inverse distance from the sites, considered as a continuous variable, was not detected when the distance was categorical [2]. Likewise, the risk estimates obtained in the incidence analysis [3] also appeared to be lower than those obtained with the case-control approach [2]. The results were largely attributed to cases in previous studies from 1980 to 1990 [4] and 1991 to 1995 [5], especially in the 5 km zone. Likewise, the estimated risk in the 5 km zone was highly sensitive to whether or not the Krümmel NPP was included [6,7]. Individual radiation exposures from the NPP emissions and other sources were not available. The authors concluded the observed positive distance trend remained unexplained and no statements on the cause of the increase cancer rates could be made. A further analysis [8] observed the trend in risk decreased over time, and a reassessment of the results

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showed a marked impact of the urban/rural status of the residence on the estimated risk [9]. An independent review of the study [9] concluded there was no support for a causal relationship between any chemical or physical risk factor and the observed risk of childhood leukemia. Several reviews of this study came to similar conclusions [6,10,11].

Other studies have been conducted in the United Kingdom [12], France [10], Switzerland [13] and Finland [14]. No relationship between childhood leukemia and distance from an NPP was found. A recent study conducted in France used a methodology allowing the assignment of radiation doses from nuclear facilities to the cases of leukemia [7]. This study found a significant relationship between distance and childhood leukemia; however, when dose-based geographic zoning was used, childhood leukemia could not be explained by the radiation exposures from the NPPs' gaseous discharges. Earlier, French studies found no relationship between childhood leukemia incidence and distance from NPPs [10] or radiation exposures in the municipalities near the sites [15].

In Canada, McLaughlin *et al.* [16] examined leukemia mortality (1950 to 1987) and incidence (1964 to 1986) among children aged 0 - 14 within communities near (25 km) two Ontario NPPs (Pickering, Bruce). Childhood leukemia in the vicinity of the Bruce and Pickering NPPs was greater than expected although not statistically significantly so. Prior to the opening of the Pickering NPP (1950 to 1970), the mortality ratio by residence at birth for the 25 km area was also higher than expected. The confidence intervals included the null value and were generally wide because of the small observed and expected numbers of deaths and cases. The results for leukemia in children aged 0 - 4 were similar. When the areas near Bruce and Pickering NPPs were pooled, the evidence became weaker. The statistical power of the study was also limited due to the rarity of childhood leukemia and the small number of observed and expected cases and deaths. In conclusion, there was no statistical evidence the difference was due to anything but the natural variation of the disease.

Also in Canada, rates of cancer incidence and mortality, congenital anomalies and stillbirths were examined from 1981 to 2004 in areas surrounding the Pickering and Darlington NPPs [17]. The authors concluded that although there were some elevated cancer rates (*i.e.*, thyroid, breast, brain, and kidney cancer, and leukemia (excluding CLL)), there was no clear pattern found across time periods, sexes, and for incidence and mortality statistics. All childhood cancer mortality and incidence rates were similar to the Ontario population. All other health indicators were significantly low or at provincial levels. Overall, the results were consistent with an earlier analysis for the region from 1979 to 1993 [18]. In general, disease rates did not indicate a pattern to suggest the Pickering and Darlington NPPs were causing health effects in the population.

To date, no Canadian study of cancer incidence among the population has included an analysis of exposure of members of the public to radioactive emissions from an NPP. In Ontario, twenty nuclear power reactors located on three NPP sites (Pickering, Bruce and Darlington) which began operation between 1971 and 1989. The objective of this work was to conduct an ecological hypothesis-screening study providing radiation dose estimates for members of the public from environmental radiation monitoring data and updated cancer incidence data for populations living within 25 km of the three Ontario NPPs from 1990 to 2008.

2. Methods

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

Radionuclides released to the environment from Canadian NPPs are listed in **Table 1**.

Data on annual radiation dose assessments for members of the public using internal and external environmental exposure pathways were collected from Ontario Power Generation (OPG) and Bruce Power annual reports [19-34]. Exposure pathways included in the dose assessments were inhalation and ingestion of food and water, exposure from air and water immersion, groundshine, and incidental soil and sediment ingestion. Concentrations of radionuclides in various environmental compartments were obtained from the results of radio-

Table 1. Major radionuclide and radionuclide groups released from Canadian NPPs.

Atmospheric Emissions	Tritium Oxide as water vapor (HTO) Elemental Tritium (HT) Carbon-14 (C-14) Radioactive Iodine (mixed fission products of iodine)[1] Radioactive Particulates (mixture of alpha emitting radionuclides)[2] Noble Gases (mixture of Argon-41, and Xenon and Krypton radioisotopes)
Liquid Effluent Discharge	Tritium Oxide as water (HTO) Carbon-14 (C-14) Gross Beta/Gamma (mixture of beta and gamma emitting radionuclides)

[1]At Pickering A and Pickering B NPPs, radioactive iodine and radioactive particulate emissions, have continually been below limits of detection (limit of detection has ranged from 1.0E+04 Bq per month to 1.0E+07 Bq per month); [2]At Pickering A and Pickering B NPPs, noble gas emissions have continually been below limits of detection (limit of detection has ranged from 1.0E+12 Bq-MeV per month to 1.0E+13 Bq-MeV per month).

logical environmental monitoring programs (REMP). Doses were calculated for members of the public using either a hypothetical individual (1985-2001 for the Pickering and Bruce NPPs; 1985-2003 for the Darlington NPP) or critical groups (2001-2008 for the Pickering and Bruce NPPs; 2003-2008 for the Darlington NPP). **Table 2** summarizes the environmental media and radionuclides monitored through the REMP and used in the dose calculations.

While the use of a hypothetical individual resulted in very conservative radiation dose estimates (individual living at the NPP fence line and consuming exclusively local food and water), critical group doses were more realistic. A critical group represents a uniform group of people whose location, age, diet, lifestyle, etc., caused them to receive higher doses than other groups in the exposed population. The three NPPs each have multiple potential critical groups. At each critical group location, age classes (adult, 15-year-old, 10-year-old, 5-year-old, 1-year-old, and nursing infant) have been attributed characteristics to reflect different diet consumption rates, and lifestyle habits. Site-specific surveys of residents and local farms surrounding the NPPs were conducted to obtain information on the characteristics of the potential critical groups [35-43]. Surveys generated information on the number of people living at each residence or farm, their age distribution, sources of water for various uses, as well as the proportion of local and store bought food consumed. If information could not be obtained from surveys, default values in the CSA standard N288.1 [36,37] were used.

Table 2. Environmental media and radionuclides monitored for the purpose of estimating doses to members of the public.

Pathway	Radionuclides Measured[1,2,3]
Atmospheric Sampling	HTO, C-14 Boundary External Gamma from Noble Gases (mainly Ar-41, Xe-133, and Xe-135) Ir-192, I-131[4] HTO and Gross Beta from precipitation and dry/wet fallout
Terrestrial Sampling	Garden and Inland Soils: Cs-137, Cs-134, Co-60 Local Fruits, Vegetables, Silage and Honey: HTO, C-14 Milk and Animal Feed: HTO, C-14, I-131[5]
Aquatic Sampling	Lake Water and Water Supply Plants: HTO, Gross Beta Well Water: HTO, Gross Beta Fish: HTO, C-14, Gamma Spectrometry (Cs-137, Cs-134, Co-60) Sediment: C-14, Cs-137, Cs-134, Co-60 Beach Sand/Silt: Gamma Spectrometry (Cs-137, Cs-134, Co-60)

[1]Cs-134 and Co-60 measured in the environment are solely from reactor operation; [2]C-14 and Cs-137 measured in the environment are from both reactor operation and nuclear weapon test fallout; [3]Organically Bound Tritium is taken into account in model equations based on relationship with HTO; [4]At all Ontario NPPs Radioactive Iodine measured in ambient air has consistently been too low to measure [19-34]; [5]At all Ontario NPPs radioactive Iodine measured in milk samples have consistently remained below detection limits (limit of detection ranges from 0.1 Bq/L - 0.2 Bq/L) [19-34].

For each NPP, all annual total dose data for each hypothetical individual or critical group from 1985 to 2008 were compiled [19-34]. The highest annual doses to critical groups were mapped using ESRI® ArcGIS™ Desktop version 10.1 (ArcGIS) mapping software. A set of maps was generated, one for each NPP, showing the highest doses received to each potential critical group over the study period. A polygon shape file was created with boundaries extending at a radius every 5 km up to 25 km from the NPP, corresponding to the geographic distribution of cancer incidence data used for this study. The Darlington and Pickering NPPs are on the shore of Lake Ontario and the Bruce NPP is on the shore of Lake Huron; therefore, a large portion of the 25 km radius included water.

For each NPP, the year with the highest critical group dose within the study period were identified and a second set of maps was created. For each NPP, atmospheric dispersion plumes for each radionuclide were generated, based on the atmospheric emissions data for the given year. The dispersion plumes were produced using the EcoMetrix® IMPACT™ (IMPACT) modelling software, which is based on CSA standard N288.1 [36,37]. Site-specific weather data and release characteristics obtained from each NPP were used in the model (available upon request). From the model outputs, a dose plume was generated in ArcGIS using air inhalation and immersion dose conversion factors. For each NPP, the dose plume represents a hypothetical annual dose that would be received by an individual due to air immersion and inhalation if that person spent the entire year outdoors at a particular location (full time occupancy).

The following equation was used to calculate the dose due to air immersion and air inhalation:

$$X_9 = X_0 \cdot P_{01}\left[P(e)_{19} + P(i)_{19}\right]$$

where

X_9 is the dose received ($\mu Sv \cdot yr^{-1}$);

X_9 is the air emission release rate ($Bq \cdot s^{-1}$);

P_{01} is the dilution factor due to atmospheric dispersion ($s \cdot m^{-3}$);

$P(e)_{19}$ is the transfer parameter for dose to humans via air immersion ($Sv \cdot yr^{-1} \cdot Bq^{-1} \cdot m^3$);

$P(i)_{19}$ is the transfer parameter for dose to humans via air inhalation ($Sv \cdot yr^{-1} \cdot Bq^{-1} \cdot m^3$).

Parameters and assumptions used in the atmospheric dispersion plume modelling and dose assessment are

based on air emission data for each radionuclide and average annual Triple Joint Frequency meteorological conditions (*i.e.*, wind speed, stability class, and wind direction) and release characteristics (*i.e.*, stack height, stack exit velocity, gas and ambient temperatures). This information came from industry reports formally submitted to the national regulator, the Canadian Nuclear Safety Commission (CNSC) [26,29,31,39-43]. Each report has undergone a critical technical review by the CNSC. Transfer parameters, $P(e)_{19}$ and $P(i)_{19}$ and dose conversion factors, DCF_a and DCF_i for air immersion and air inhalation used in the dose assessment were adopted from CSA standard N288.1 [36,37].

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

Cancer incidence data collected by the Ontario Cancer Registry (OCR) [44] from 1990 to 1991 and the Canadian Cancer Registry (CCR) [45] from 1992 to 2008 were obtained for the following: all cancer sites 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 lymphoma. These types of cancer were chosen because they are sensitive to radiation [46-48]. Disease coding was based on the 3rd edition of the International Classification of Diseases for Oncology [49]. Cases coded to the 2nd edition were converted.

Population counts from the Census of Canada [50] for the census years 1991, 1996, 2001, and 2006 were obtained for the areas within 25 km of the three NPPs in Ontario (data not shown). The tables prepared in this study start in 1990 since it was the first year that Cancer Care Ontario (CCO) data had sufficient completeness for postal code information.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 to be consistent with a previous study [16] and because of the low population density around the Bruce NPP. This is less specific than information at the individual census subdivision (CSD) level and not as broad as the census division (CD) level.

CCO conducted a data quality study to investigate residence code errors at the census division (CD) and census subdivision (CSD) level through a record linkage to the Ontario property assessment files. The accuracy of the CSD of residence was 84.4% whereas the accuracy of the CD level of residence was 97.9% for the 1025 cases having this information [51]. The CD is considered the gold standard.

Standardized incidence ratios (SIRs) (O/E) based on residence at diagnosis, observed (O) and expected (E) number of cancer cases and 95% confidence intervals (CIs) were calculated [52] based on the age- and sex-specific rates of the comparison population (*i.e.*, Ontario) for the corresponding period (1990 to 2008) for the 25 km radius of each NPP. Internal calculations of observed and expected cases were stratified by five-year age groups and periods, and controlled for socio-economic status using income quintile.

The statistical power of this study depends on the statistical significance criterion used, the magnitude of the effect of interest, and the sample size. Table 7.2 given by Breslow and Day [53] was used to calculate the power using 80% as a standard for acceptance [54]. Using Ontario as the reference population and the expected cases for leukemia (all ages, both sexes combined) for people living within 25 km of the Bruce NPP (which had the smallest population) for example, the probability (%) of obtaining a result significant at the 0.01 level (one sided) of the expected value (E) of 70 (68.0 actual expected cases) assuming no excess risk, and of the true R (or SIR in our case), the sample power for R = 1.2 is 24%. For childhood cancer (leukemia and NHL) near Bruce NPP at a significance of 0.01, and E of 5, (5.2 actual) assumeing no excess risk, and a true R, the sample power for R = 1.5 is only 8.0%. As a result, the small population size and the rareness of some cancers limited the statistical power of our findings among the population living near Bruce NPP. This was generally not an issue near Darlington and Pickering NPPs which had large observed and expected numbers of cancer cases.

Age-standardized incidence rates (ASIRs), per 100,000 population, were calculated using the direct method, which involves weighing the age-specific rates for each of the age groups (<1, 1 - 4, 5 - 9 ⋯ 80 - 84, 85+) according to the age distribution of the standard 1991 Canadian population. The 95% CIs are not provided for the ASIRs when the number of rounded cases is ≤ 5 since the approximation used is less accurate for a small number of cases. SIRs were also calculated at the CD level by cancer site and for all ages and both sexes combined, for Durham Region (location of Pickering and Darlington NPPs) and Bruce County (location of Bruce NPP) using Ontario rates as the comparison population. This provided an additional comparison of cancer incidence around the NPPs with that of the 25 km radius analysis.

3. Results

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

Data on radiation doses to members of the public were obtained for the period 1985 to 2008 to provide exposure

information during a minimum 5-year latency period from the start of the cancer incidence data (1990-2008). Annual doses to hypothetical individuals varied from 0.052 to 0.004 mSv and from 0.016 to 0.002 mSv between 1985 and 2000 for the Pickering and Bruce NPP respectively. Annual doses for a hypothetical individual at the Darlington NPP from 1985 to 2002 were slightly lower and ranged from 0.010 to 0.001 mSv.

Tables 3-5 present the highest annual radiation dose to each age class for each critical group at each NPP over the study period. The highest estimated dose received to a critical group over the study period was in 2005 for the Pickering NPP, 2003 for the Darlington NPP and 2008 for the Bruce NPP. For comparison purposes, the annual dose from natural background radiation at each site is also presented. Radiation doses to members of the public from the operation of Ontario NPPs (represented by conservatively estimated doses to critical groups (≤ 0.0067 mSv/year)) are much less than the difference in natural background radiation between the Darlington/Pickering area and the Bruce area (0.682 mSv/year) and hence only represent a very minor contribution to the public's overall radiation exposure.

Table 3. Highest Estimated Annual Dose to Potential Critical Groups Age Classes Surrounding the Pickering NPP (2001-2008).

Potential Critical Groups at Pickering NPP	Highest Annual Dose (mSv) to Each Age Group					
	Nursing Infant	1 year old	5 years old	10 years old	15 years old	Adult
Farm Residents	0.0020	0.0012	0.001	0.0011	0.0012	0.0015
Dairy Farm Residents	0.0016	0.0018	0.0012	0.0012	0.0012	0.0016
Sport Fishers	0.0008	0.0004	0.0004	0.0005	0.0006	0.0006
Urban Residents	0.0022	0.0019	0.0013	0.0015	0.0016	0.0025
C2 Correctional Institution	NA	NA	NA	NA	0.0034	0.0037
Industrial Workers	NA	NA	NA	NA	NA	0.0041
Squires Beach Residents	0.0052	0.0033	0.0031	0.0035	0.0036	0.004
C1 Correctional Institution	NA	NA	NA	NA	0.0061	0.0067
Annual Dose from Natural Background	1.338	1.338	1.338	1.338	1.338	1.338

NA: not applicable

Table 4. Highest Estimated Annual Effective Dose to Potential Critical Group Age Classes Surrounding the Darlington NPP (2003-2008).

Potential Critical Groups at Darlington NPP	Highest Annual Dose (mSv) to Each Age Group					
	Nursing Infant	1 year old	5 year old	10 year old	15 year old	Adult
Rural Residents	0.0010	7E-04	0.0006	0.0007	0.0006	0.0008
Bowmanville Residents	0.0006	4E-04	0.0003	0.0004	0.0004	0.0004
Oshawa Residents	0.0006	3E-04	0.0003	0.0003	0.0003	0.0003
Campers	0.0004	3E-04	0.0003	0.0003	0.0003	0.0004
Non-Dairy Farm Residents	0.0017	0.001	0.0012	0.0012	0.0012	0.0009
Dairy Farm Residents	0.0008	0.001	0.0009	0.0008	0.0008	0.0007
West/East Beach Residents	0.0012	8E-04	0.0008	0.0009	0.0009	0.001
Sport Fishers	0.0001	1E-04	0.0001	0.0001	0.0001	0.0001
Industrial/ Commercial Workers	NA	NA	NA	NA	NA	0.0003
Annual Dose from Natural Background	1.338	1.338	1.338	1.338	1.338	1.338

NA: not applicable

The relative contribution of different radionuclides to the total dose was analyzed. Doses from tritium are higher in adults than in children or infants due to higher inhalation rates, whereas the reverse is observed for doses due to noble gases (as a result of increased shielding due to higher assumed body fat in adults).

Critical group doses for Pickering (2005), Darlington (2003), and Bruce (2008) were analyzed for spatial relationship between dose and distance from the three NPPs (**Figures 1-3**). The analysis revealed that the highest doses were not necessarily associated with critical groups closest to the NPP. For example, 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 was also observed when comparing the doses to urban residents (0.0020 mSv) with those of 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 workers 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

Table 5. Highest Estimated Annual Dose to Potential Critical Group Age Classes Surrounding the Bruce Power NPP (2001-2008).

Potential Critical Groups at Bruce Power NPP	Highest Annual Dose (mSv) to Each Age Group					
	Nursing Infant	1 year old	5 year old	10 year old	15 year old	Adult
Scott Point Residents	0.00151	0.00245	0.00211	0.00167	0.00168	0.00234
Baie du Dore Residents	0.00215	0.00174	0.00217	0.00238	0.0024	0.0027
Trailer Park Albert Street Residents	0.00103	0.00123	0.00108	0.00119	0.00119	0.0014
South of site Residents	0.00100	0.00152	0.000977	0.00103	0.00101	0.00161
Inverhuron Residents	0.00209	0.00116	0.00212	0.00233	0.00236	0.00268
Dairy Farm South of Tiverton Residents	0.00197	0.00071	0.00163	0.00162	0.00147	0.00185
Farm nearest Bruce A Residents	0.00111	0.00162	0.00112	0.00117	0.00112	0.0017
Farm nearest Bruce B Residents	0.00181	0.00131	0.00177	0.00185	0.0018	0.00227
Bruce Eco-Industrial Park Workers	NA	NA	NA	NA	NA	0.000285
Annual Dose from Natural Background	2.020	2.020	2.020	2.020	2.020	2.020

NA: not applicable.

the Bruce NPP (0.0012 mSv) have lower doses than residents who lived further away (0.0021 mSv). Both groups are non-farm residents with the same dietary characteristics (e.g., food coumption rates; proportion of local vs. store-bought food). The difference in doses is due primarily to differences in location relative to prevailing wind conditions.

Figures 1-3 overlay onto the year with the highest critical group doses the hypothetical atmospheric dose plume for full time occupancy of an infant, child and adult within the plume. The high value represents the dose from inhalation and immersion for full time occupancy at the stack and the low value bounds the fully dispersed atmospheric release. These dose plumes, based on site-specific average annual weather data, clearly indicate a plume extending towards and over the lake, and generally away from populated areas. The dose estimates in the dispersion plumes are higher than critical group doses not only because of the hypothetical full time occupancy in the plume but also because the IMPACT software assumes that the stack is at ground level. Actual emissions from the three NPPs are released from stacks at elevations greater than 10 m, allowing for increased air dispersion before reaching the ground (point of impingement).

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

Cancer incidence data were collected for all cancer sites combined and for cancer sites sensitive to radiation. Incidence data were analyzed for the following age groups: 0 - 4, 0 - 14, 0 - 24, 25 - 64, 65+ and 0 - 65+ when the number of cases was sufficient. A blank is given if the number of cases is less than 6 and, therefore, not reported.

Table 6 shows that the SIRs for childhood cancer (leukemia and non-Hodgkin lymphoma) among children aged 0 - 4 living within 25 km of the Pickering and Darlington NPPs were lower than expected for the Ontario population but not statistically significantly so. Similarly, the incidence of childhood cancer in children aged 0 - 14 living near the three NPPs was similar to Ontario. 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 lymphoma were combined to preserve confidentiality of observed cases fewer than 6.

Table 7 shows the results for all cancer sites combined and leukemia for those aged 0 - 24, 25 - 64, and 65+. Other cancer sites were not provided for those aged 0 - 24 since, in general, few cases were observed; especially near Bruce NPP. For all cancer sites combined and especially leukemia, the SIRs were either significantly less than 1.0 or similar to Ontario for those aged 0 - 24 living near all three NPPs.

The age groups 0 - 64 and 65+ were used for all other cancer sites. **Tables 8** to **10** present for all three NPPs the SIRs for all the cancer sites, by age group and for both sexes. For all three NPPs, it is very evident that lung and bronchus, female breast and colon and rectum cancer are the most common cancer sites. However, the number of cases varies considerably between the three NPPs due to the large differences in population size of people living within 25 km of Pickering, Darlington and Bruce NPPs (1,580,000; 380,000; and 24,500 respectively, based on the 2006 census year). This is expected, as these are also the most common types of cancer in the province, and in Canada [55]. 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

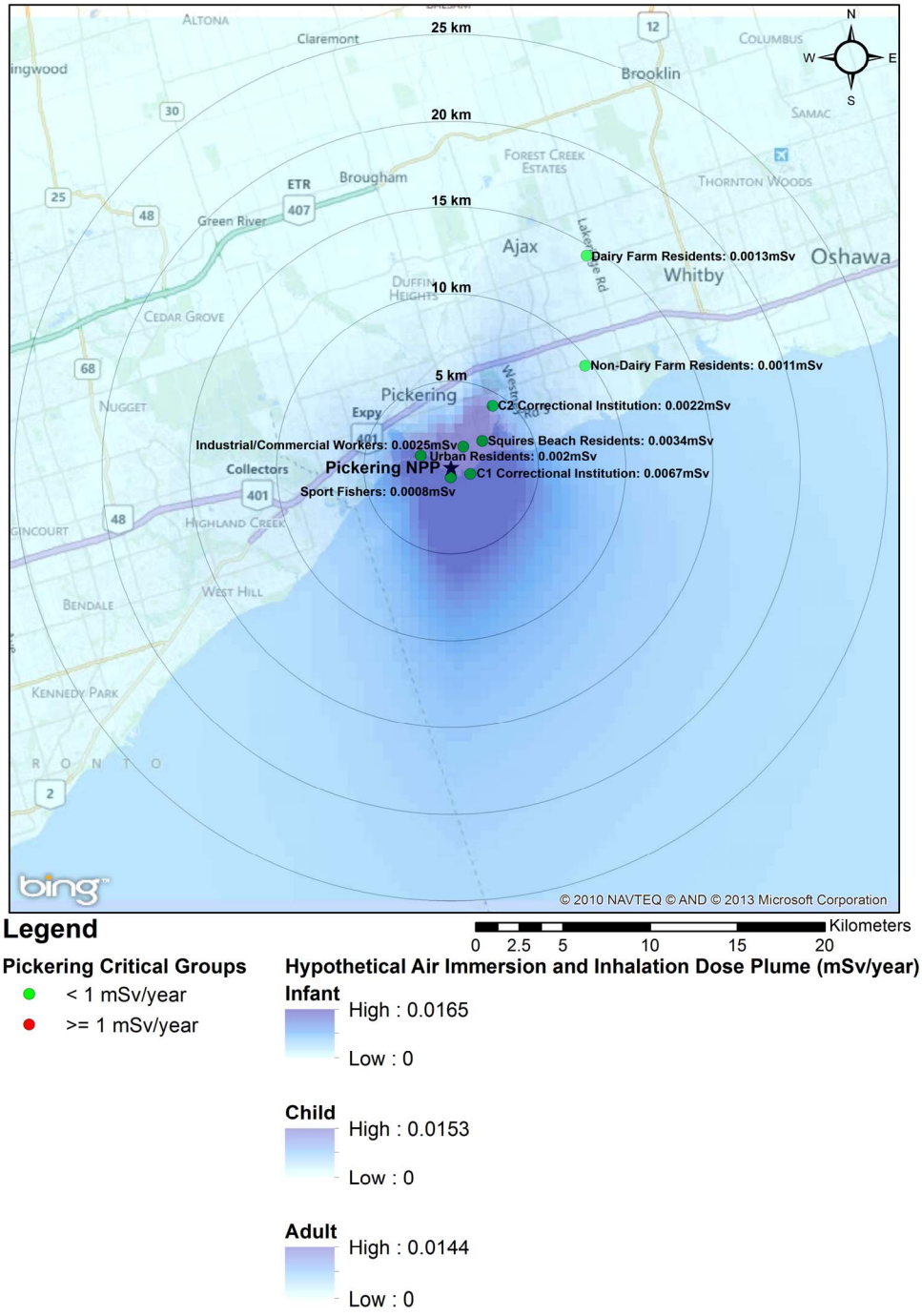

Figure 1. 2005 Critical Group Doses and Hypothetical Air Dispersion Plume for Pickering NPP.

of cancer were the same as expected compared to the general Ontario population.

As seen in **Table 8**, near the Pickering NPP all cancer sites combined had a SIR significantly less than 1.0 (SIR = 0.95, 95% CI: 0.94, 0.95, $p < 0.01$). Similarly, seven cancer sites also had SIRs significantly less than 1.0 (lung and bronchus: SIR = 0.84; female breast: SIR = 0.97; colon and rectum: SIR = 0.92; bladder: SIR = 0.91; brain and other nervous system: SIR = 0.92; esophagus: SIR = 0.84; and leukemia: SIR = 0.89). However, three cancer sites had SIRs significantly greater than 1.0 (thyroid: SIR = 1.41; stomach: SIR = 1.06; and liver: SIR = 1.32). Thyroid and liver cancer were elevated in both males and females and all age groups; whereas, the elevated incidence of stomach cancer was limited to women and those age 65+.

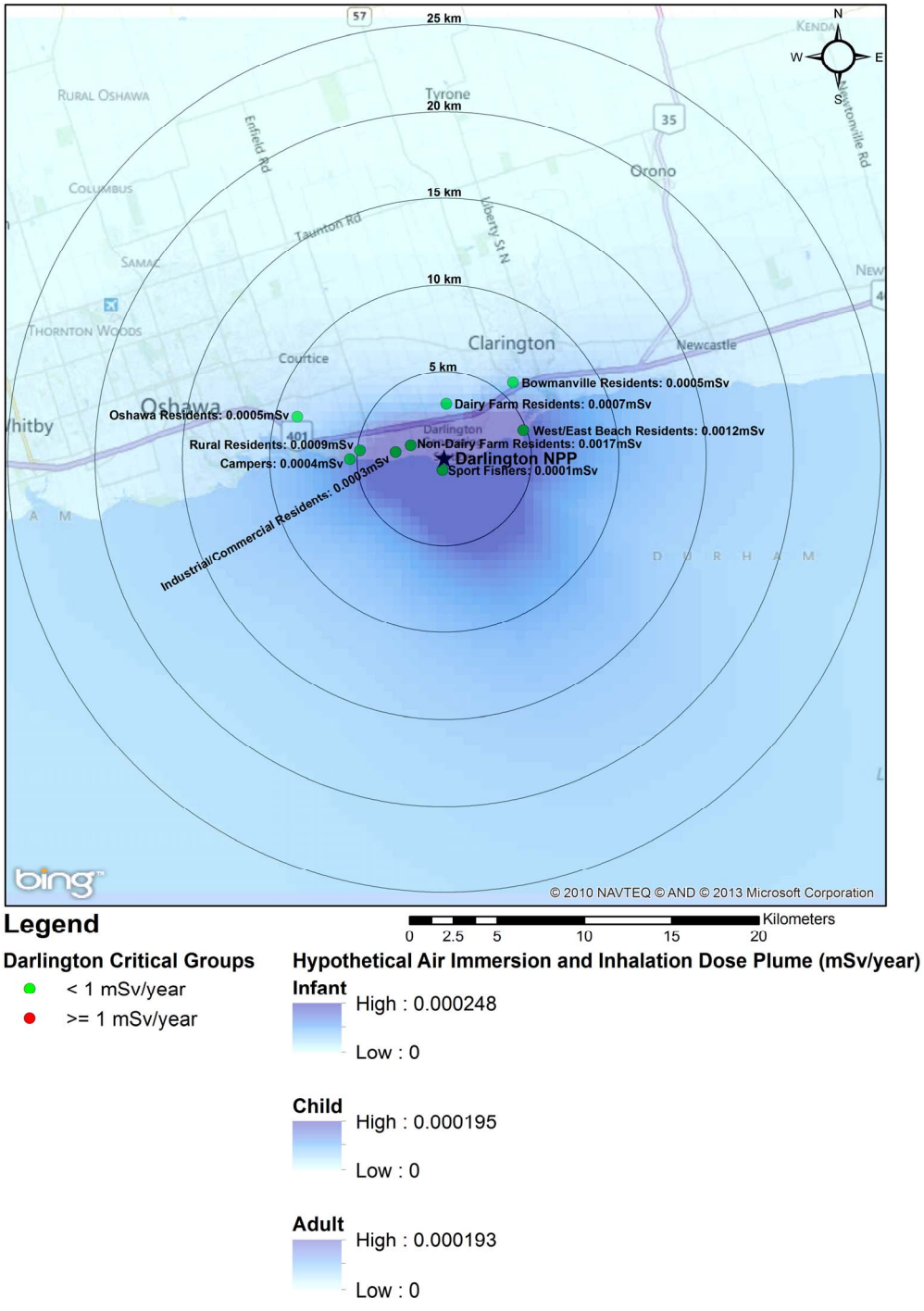

Figure 2. 2003 Critical Group Doses and Hypothetical Air Dispersion Plume for Darlington NPP.

Near the Darlington NPP, the data in **Table 9** show that for all cancer sites combined the SIR is significantly greater than 1.0 (SIR = 1.08, 95% CI: 1.07, 1.09, $p < 0.01$). Five cancer sites also had SIRs significantly greater than 1.0 (lung and bronchus: SIR = 1.12; colon and rectum: SIR = 1.07; thyroid: SIR = 1.08; bladder: SIR = 1.19; and leukemia: SIR = 1.26). While three of these cancers (lung and bronchus, bladder and leukemia) were elevated in males and females and all age groups, the increased incidence of colon and rectum and thyroid cancer were essentially attributable to men and those aged 65+, and all men, respectively. In contrast to Pickering, near Darlington liver cancer had a SIR significantly less than 1.0 (SIR = 0.83).

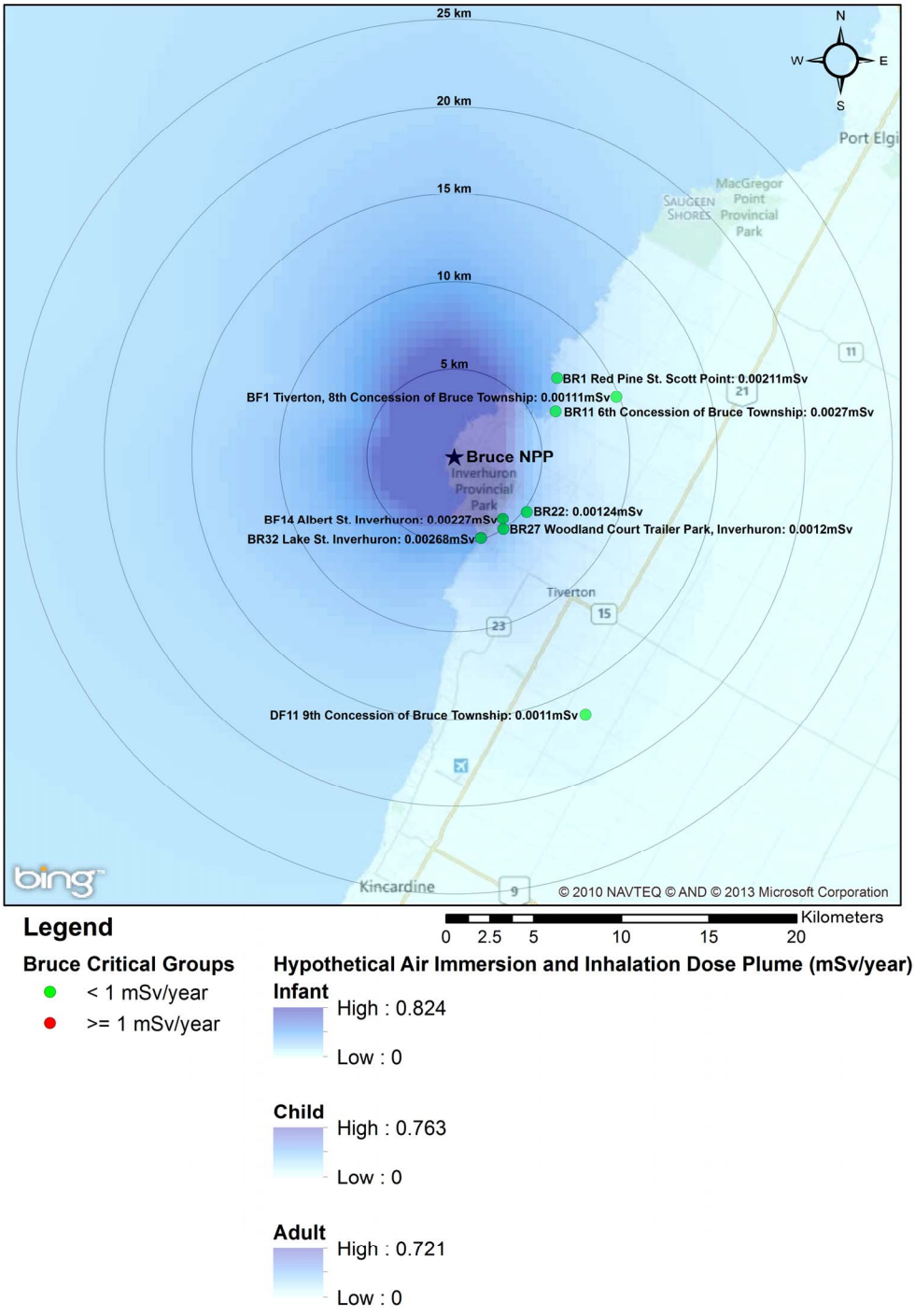

Figure 3. 2008 Critical Group Doses and Hypothetical Air Dispersion Plume for Bruce NPP.

Table 10 shows that near the Bruce NPP, all cancer sites combined had a SIR significantly greater than 1.0 (SIR = 1.09, 95% CI: 1.05, 1.13, $p < 0.01$). While SIRs were significantly greater than 1.0 for two cancer sites (lung and bronchus: SIR = 1.17; colon and rectum: SIR = 1.17), two cancer sites had SIRs significantly less than 1.0 (bladder: SIR = 0.78; and liver: SIR < 1.00). Lung and bronchus cancer was elevated in males in the 0 - 64 age group; whereas the elevated incidence of colon and rectum cancer was attributed to those aged 65+.

The SIR analysis for people living within the 25 km radius of the three NPPs was found, in general, consistent with the CD analysis of SIRs. The incidence of childhood leukemia and non-Hodgkin lymphoma in children

Table 6. Cancer incidence for children aged 0 - 4 and 0 - 14 years living within a 25 km radius of an Ontario NPP at time of diagnosis, 1990-2008.

NPP	Cancer	Age 0 - 4					Age 0 - 14				
		O	E	SIR	95% CI		O	E	SIR	95% CI	
Pickering	Non-Hodgkin lymphoma	8	11.2	0.72	0.31	1.41	42	50.4	0.83	0.60	1.**13**
	Leukemia	123	142.3	0.86	0.72	1.03	261	265.9	0.98	0.87	1.11
	Leukemia and NHL	131	153.5	0.85	0.71	1.01	303	316.3	0.96	0.85	1.07
Darlington	Non-Hodgkin lymphoma		2.7				10	12.9	0.77	0.37	1.42
	Leukemia	34	36.0	0.94	0.65	1.32	74	68.1	1.09	0.85	1.36
	Leukemia and NHL		38.7	<1.00			84	81.0	1.04	0.83	1.28
Bruce	Leukemia and NHL						6	5.2	1.16	0.42	2.51

Table 7. Cancer incidence for all cancer sites and leukemia for people living within a 25 km radius of an Ontario NPP at time of diagnosis, by age group, 1990-2008.

NPP	Cancer	Age	O	E	SIR	SIR flag	95% CI	
Pickering	All sites	Total	103259	109015	0.95	--	0.94	0.95
		0 - 24	1742	1852	0.94	-	0.9	0.99
		25 - 64	46867	49097	0.95	--	0.95	,0.96
		65+	54650	58066	0.94	--	0.93	0.95
	Leukemia	Total	2819	3151	0.89	--	0.86	0.93
		0 - 24	344	349	0.99	°	0.88	1.1
		25 - 64	1061	1163	0.91	--	0.86	0.97
		65+	1414	1639	0.86	--	0.82	0.91
Darlington	All sites	Total	24707	22853	1.08	++	1.07	1.09
		0 - 24	443	438	1.01	°	0.92	1.11
		25 - 64	11413	10597	1.08	++	1.06	1.1
		65+	12851	11817	1.09	++	1.07	1.11
	Leukemia	Total	847	674	1.26	++	1.17	1.34
		0 - 24	92	87	1.06	°	0.86	1.3
		25 - 64	299	254	1.18	++	1.05	1.32
		65+	456	334	1.37	++	1.24	1.5
Bruce	All sites	Total	2570	2362	1.09	++	1.05	1.13
		0-24	31	32	0.97	°	0.66	1.37
		25 - 64	1048	973	1.08	+	1.01	1.14
		65+	1491	1357	1.1	++	1.04	1.16
	Leukemia	Total	80	68	1.18	°	0.93	1.46
		0 - 24		6		°		
		25 - 64		23	>1.00	++		
		65+	37	39	0.95	°	0.67	1.3

$^{++}$ significantly high, **p**-value < 0.01; $^{+}$significantly high, **p**-value < 0.05; ° not significant; $^{-}$ significantly low, **p**-value < 0.05; $^{--}$ significantly low, **p**-value < 0.01.

Table 8. Cancer incidence for people living within a 25 km radius of Pickering NPP at time of diagnosis, by sex and age group, 1990-2008.

Cancer	Age	Observed	Expected	SIR (O/E)	SIR flag	95% CI LL	95% CI UL
All sites	Total	103259	109015	0.95	--	0.94	0.95
	M	51439	55378	0.93	--	0.92	0.94
	F	51820	53637	0.97	--	0.96	0.97
	0 - 64	48609	50949	0.95	--	0.95	0.96
	65+	54650	58066	0.94	--	0.93	0.95
Lung and bronchus	Total	12358	14694	0.84	--	0.83	0.86
	M	6918	8371	0.83	--	0.81	0.85
	F	5440	6323	0.86	--	0.84	0.88
	0 - 64	4347	5493	0.79	--	0.77	0.82
	65+	8011	9201	0.87	--	0.85	0.89
Female breast	Total	15043	15444	0.97	--	0.96	0.99
	F	15043	15444	0.97	--	0.96	0.99
	0 - 64	9599	9478	1.01	°	0.99	1.03
	65+	5444	5966	0.91	--	0.89	0.94
Colon and rectum	Total	8942	9768	0.92	--	0.90	0.93
	M	4415	4910	0.90	--	0.87	0.93
	F	4527	4858	0.93	--	0.90	0.96
	0 - 64	3058	3277	0.93	--	0.90	0.97
	65+	5884	6491	0.91	--	0.88	0.93
Thyroid	Total	3879	2755	1.41	++	1.36	1.45
	M	823	572	1.44	++	1.34	1.54
	F	3056	2183	1.40	++	1.35	1.45
	0 - 64	3338	2384	1.40	++	1.35	1.45
	65+	541	371	1.46	++	1.34	1.59
Bladder	Total	3183	3512	0.91	--	0.88	0.94
	M	2337	2599	0.90	--	0.86	0.94
	F	846	912	0.93	-	0.87	0.99
	0 - 64	950	1062	0.89	--	0.84	0.95
	65+	2233	2450	0.91	--	0.87	0.95
Leukemia	Total	2819	3151	0.89	--	0.86	0.93
	M	1575	1804	0.87	--	0.83	0.92
	F	1244	1347	0.92	--	0.87	0.98
	0 - 64	1405	1512	0.93	--	0.88	0.98
	65+	1414	1639	0.86	--	0.82	0.91
Stomach	Total	2348	2221	1.06	++	1.01	1.10
	M	1446	1411	1.02	°	0.97	1.08
	F	902	810	1.11	++	1.04	1.19
	0 - 64	850	839	1.01	°	0.95	1.08
	65+	1498	1382	1.08	++	1.03	1.14
Ovary	Total	1857	1928	0.96	°	0.92	1.01
	F	1857	1928	0.96	°	0.92	1.01
	0 - 64	1090	1107	0.98	°	0.93	1.04
	65+	767	821	0.93	°	0.87	1.00

Continued

Brain and other nervoussystem	Total	1805	1959	0.92	--	0.88	0.96
	M	962	1068	0.90	--	0.84	0.96
	F	843	891	0.95	°	0.88	1.01
	0 - 64	1188	1295	0.92	--	0.87	0.97
	65+	617	665	0.93	°	0.86	1.00
Liver	Total	1095	832	1.32	++	1.24	1.40
	M	845	622	1.36	++	1.27	1.45
	F	250	210	1.19	++	1.05	1.35
	0 - 64	544	407	1.34	++	1.23	1.45
	65+	551	426	1.29	++	1.19	1.41
Esophagus	Total	898	1068	0.84	--	0.79	0.90
	M	603	766	0.79	--	0.73	0.85
	F	295	302	0.98	°	0.87	1.09
	0 - 64	313	408	0.77	--	0.68	0.86
	65+	585	660	0.89	--	0.82	0.96

$^{++}$significantly high, **p**-value < 0.01; $^{+}$significantly high, **p**-value < 0.05; °not significant; $^{-}$significantly low, **p**-value < 0.05; $^{--}$significantly low, **p**-value < 0.01.

aged 0 - 14 in Durham Region and Bruce County was similar to Ontario. Breast ovary, stomach, brain and other nervous system, liver and esophagus cancer were either significantly low or similar to Ontario in Durham Region and Bruce County. All cancers sites combined, lung and bronchus, thyroid, bladder, and leukemia were significantly high in Durham Region but either significantly low or similar to Ontario in Bruce County. Colon and rectum cancer was significantly high in Bruce County but similar to Ontario in Durham Region (**Table 11**).

Finally, data on cancer incidence for the cancer sites analyzed in this study across all census divisions (CDs) in Ontario were used for comparison with cancer incidence around the three Ontario NPPs. The data in **Table 12** for all ages (0 - 85+) indicate that there is a large geographical variation in cancer age-standardized incidence rates (per 100,000 population) across the province of Ontario. These data show that the incidence rates for all the cancers found in this study to be significantly greater than expected (*i.e.*, all cancer sites combined, lung and bronchus, colon and rectum, thyroid, bladder, leukemia, stomach, liver) were well within the range of cancer incidence within the province. Likewise, the CDs with the highest cancer incidence rates were not those included in our study (Durham Region, Bruce County).

4. Discussion

The primary strength of this study is its inclusion of dose information for various age groups around each NPP 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 surrogate for radiation dose data.

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 [44,45]. Likewise, the Census of Canada undergoes vigorous quality and confidentiality procedures to assure the accuracy and privacy of census information [50]. 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 [46,52,56]. 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 used in this study provide assurance that actual residents around the NPPs had lower doses. Ecological studies do not typically provide this type of detailed information.

Radioactive emissions from the three Ontario NPPs result in very low concentrations of radionuclides in the environment around the plants and consequently doses to members of the public from all exposure pathways are a small fraction of the natural background radiation in the

Table 9. Cancer incidence for people living within a 25 km radius of Darlington NPP at time of diagnosis, by sex and age group, 1990-2008.

Cancer	Age	Observed	Expected	SIR O/E)	SIR flag	95% CI LL	95% CI UL
All sites	Total	24707	22853	1.08	++	1.07	1.09
	M	12761	11695	1.09	++	1.07	1.11
	F	11946	11158	1.07	++	1.05	1.09
	0 - 64	11856	11036	1.07	++	1.06	1.09
	65+	12851	11817	1.09	++	1.07	1.11
Lung and bronchus	Total	3375	3016	1.12	++	1.08	1.16
	M	1851	1731	1.07	++	1.02	1.12
	F	1524	1285	1.19	++	1.13	1.25
	0 - 64	1317	1134	1.16	++	1.10	1.23
	65+	2058	1882	1.09	++	1.05	1.14
Female breast	Total	3230	3232	1.00	°	0.97	1.03
	F	3230	3232	1.00	°	0.97	1.03
	0 - 64	2040	2034	1.00	°	0.96	1.05
	65+	1190	1198	0.99	°	0.94	1.05
Colon and rectum	Total	2146	2014	1.07	++	1.02	1.11
	M	1115	1026	1.09	++	1.02	1.15
	F	1031	988	1.04	°	0.98	1.11
	0 - 64	739	697	1.06	°	0.99	1.14
	65+	1407	1317	1.07	+	1.01	1.13
Thyroid	Total	672	620	1.08	+	1.00	1.17
	M	172	131	1.31	++	1.12	1.52
	F	500	489	1.02	°	0.93	1.12
	0 - 64	580	544	1.07	°	0.98	1.16
	65+	92	76	1.20	°	0.97	1.48
Bladder	Total	861	724	1.19	++	1.11	1.27
	M	636	539	1.18	++	1.09	1.28
	F	225	185	1.21	++	1.06	1.38
	0 - 64	301	226	1.33	++	1.19	1.49
	65+	560	499	1.12	++	1.03	1.22
Leukemia	Total	847	674	1.26	++	1.17	1.34
	M	472	389	1.21	++	1.11	1.33
	F	375	285	1.32	++	1.19	1.46
	0 - 64	391	340	1.15	++	1.04	1.27
	65+	456	334	1.37	++	1.24	1.50
Stomach	Total	462	459	1.01	°	0.92	1.10
	M	294	294	1.00	°	0.89	1.12
	F	168	165	1.02	°	0.87	1.18
	0 - 64	163	178	0.92	°	0.78	1.07
	65+	299	281	1.06	°	0.95	1.19
Ovary	Total	433	400	1.08	°	0.98	1.19
	F	433	400	1.08	°	0.98	1.19
	0 - 64	260	235	1.11	°	0.97	1.25
	65+	173	165	1.05	°	0.90	1.22

Continued

Brain and other nervous system	Total	447	427	1.05	°	0.95	1.15
	M	255	236	1.08	°	0.95	1.22
	F	192	191	1.01	°	0.87	1.16
	0 - 64	306	292	1.05	°	0.93	1.17
	65+	141	135	1.05	°	0.88	1.23
Liver	Total	145	175	0.83	-	0.70	0.98
	M	114	131	0.87	°	0.72	1.04
	F	31	43	0.72	°	0.49	1.02
	0 - 64	75	87	0.86	°	0.67	1.08
	65+	70	87	0.80	°	0.63	1.01
Esophagus	Total	240	222	1.08	°	0.95	1.23
	M	167	160	1.04	°	0.89	1.21
	F	73	61	1.19	°	0.94	1.50
	0 - 64	87	87	1.00	°	0.80	1.23
	65+	153	135	1.14	°	0.96	1.33

++ significantly high, **p**-value < 0.01; + significantly high, **p**-value < 0.05; ° not significant; - significantly low, **p**-value < 0.05; - - significantly low, **p**-value < 0.01.

two regions where the NPPs are located (see **Table 3**). The doses are also well below the regulatory public dose limit of 1 mSv/year under the CNSC's *Radiation Protection Regulations*.

An analysis of the hypothetical dose plumes based on full time occupancy in a ground level atmospheric release shows that based on average meteorological conditions, the majority of exposure to atmospheric releases would occur over Lake Ontario (Pickering and Darling ton NPPs) and Lake Huron (Bruce NPP) (**Figures 1-3**). Near the Pickering NPP, prevailing 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 this hypothetical exposure is contained within 5 km from the centre point of the facility, much of which is located over the site of the facility itself. Even for such unrealistic exposure conditions, all annual doses remained below the 1 mSv/year public dose limit even for an individual hypothetically located at the stack for a full year.

Using the geographical representation of the dose plumes and the critical group doses (**Figures 1-3**) together with the 2006 census data for the Durham Region [57,58], we estimated that approximately 0.01% of the 25 km radius population reside within 5 km of the Darlington NPP (approximately 40 individuals). Hence, the majority of the population within the 25 km zone receives little or no exposure to radiation from the NPP. An analysis using the same data sources was also conducted for the area around the Pickering NPP. Approximately 1% of the 25 km radius population resides within 5 km of the Pickering NPP (approximately 16,000 people). The Bruce NPP is located in a semi-rural area with low population density; approximately 565 people reside within 5 km of the facility.

The dose plume modeling data (not shown) reveal that the hypothetical doses from air emissions were primarily due to releases of noble gases (*i.e.*, external dose from immersion) at Pickering (~75%), Bruce (~75%), and Darlington (~95%), with some dose being due to tritium oxide (internal dose from inhalation) at Bruce (~25%) and Pickering (~25%), and Carbon-14 (internal dose from inhalation and external dose from immersion) at Darlington (~5%). Radioactive particulates and radioactive iodines contributed very little to the dose (<1%). Doses from exposure to radioactive iodine were conservatively estimated using values set at the detection limit of the in-stack monitor because of extremely low releases. Milk samples have been collected weekly at farms around all three NPPs (part of the REMP) and values were below detection limits during the entire study period.

Recent epidemiological studies of childhood leukemia around nuclear facilities have used distance from the facility as a surrogate for data on exposure to radiation from the plants [1,2,10,12-14,59]. Our study has shown that doses to members of the public do not decrease uniformly with distance from an NPP; in fact the data presented in **Figures 1-3** for the three Ontario NPPs show that doses further away from the plants can be higher than doses to the closest critical groups. Radiation dose to members of the public from routine operation of NPPs is controlled by several factors, including: the type of

Table 10. Cancer incidence for people living within a 25 km radius of Bruce NPP at time of diagnosis, by sex and age group, 1990-2008.

Cancer	Age	Observed	Expected	SIR (O/E)	SIR flag	95% CI LL	95% CI UL
All sites	Total	2570	2362	1.09	++	1.05	1.13
	M	1441	1252	1.15	++	1.09	1.21
	F	1129	1110	1.02	°	0.96	1.08
	0 - 64	1079	1005	1.07	+	1.01	1.14
	65+	1491	1357	1.10	++	1.04	1.16
Lung and bronchus	Total	334	284	1.17	++	1.05	1.31
	M	197	164	1.20	+	1.04	1.38
	F	137	120	1.14	°	0.96	1.35
	0 - 64	118	93	1.26	+	1.05	1.51
	65+	216	191	1.13	°	0.98	1.29
Female breast	Total	331	333	0.99	°	0.89	1.11
	F	331	333	0.99	°	0.89	1.11
	0 - 64	181	192	0.94	°	0.81	1.09
	65+	150	141	1.06	°	0.90	1.25
Colon and rectum	Total	255	219	1.17	+	1.03	1.32
	M	128	112	1.14	°	0.95	1.36
	F	127	106	1.19	°	1.00	1.42
	0 - 64	75	67	1.12	°	0.88	1.40
	65+	180	152	1.19	+	1.02	1.37
Thyroid	Total	40	51	0.79	°	0.57	1.08
	M	13	12	1.08	°	0.57	1.84
	F	27	38	0.70	°	0.46	1.02
	0 - 64	31	42	0.74	°	0.51	1.06
	65+	9	9	1.01	°	0.46	1.92
Bladder	Total	62	79	0.78	-	0.60	1.00
	M	46	60	0.77	°	0.56	1.03
	F	16	20	0.80	°	0.46	1.31
	0 - 64	13	22	0.60	°	0.32	1.03
	65+	49	58	0.85	°	0.63	1.12
Leukemia	Total	80	68	1.18	°	0.93	1.46
	M	42	40	1.05	°	0.76	1.42
	F	38	28	1.36	°	0.96	1.86
	0 - 64	43	29	1.49	+	1.08	2.00
	65+	37	39	0.95	°	0.67	1.30
Stomach	Total	41	46	0.88	°	0.64	1.20
	M	29	30	0.97	°	0.65	1.40
	F	12	17	0.73	°	0.38	1.27
	0 - 64	18	15	1.17	°	0.69	1.85
	65+	23	31	0.74	°	0.47	1.12
Ovary	Total	32	40	0.80	°	0.55	1.13
	F	32	40	0.80	°	0.55	1.13
	0 - 64	17	21	0.82	°	0.48	1.31
	65+	15	19	0.78	°	0.44	1.29

Continued

Brain and other nervous system	Total	34	41	0.83	°	0.58	1.16
	M	15	23	0.65	°	0.36	1.07
	F	19	18	1.07	°	0.64	1.67
	0 - 64	23	25	0.93	°	0.59	1.40
	65+	11	16	0.67	°	0.34	1.21
Liver	Total		15	<1.00	--		
	M		11				
	F		4	<1.00	-		
	0 - 64		7				
	65+		9				
Esophagus	Total	32	22	1.46	°	1.00	2.06
	M	21	16	1.35	°	0.84	2.07
	F	11	6	1.72	°	0.86	3.09
	0 - 64	13	7	1.75	°	0.93	2.99
	65+	19	14	1.31	°	0.79	2.05

++ significantly high, **p**-value < 0.01; + significantly high, **p**-value < 0.05; ° not significant; - significantly low, **p**-value < 0.05; - - significantly low, **p**-value < 0.01.

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 lifestyles of people. Thus, distance from an NPP as shown in this study is only one factor affecting exposure of members of the public to plant emissions, and it should not be used in isolation as a surrogate for radiation exposure data.

Cancer incidence, especially childhood leukemia, in populations living near nuclear facilities has been the topic of much scientific interest [6,59-61] and public concern since the 1980s. Authoritative reviews confirmed only three leukemia clusters have persisted over time around nuclear facilities (Sellafield in England, Dounreay in Scotland and Krümmel in Germany). Although some clusters of childhood leukemia cases exist locally, 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, but up to now, none of the proposed hypotheses (*i.e.*, parental pre-conception exposure [16], infectious agent associated with population mixing [62,63]) can explain them [59].

The most important finding of this study is that there is no evidence of childhood cancer clusters within 25 km of the three Ontario NPPs. In fact, cancer incidence (*i.e.*, leukemia, non-Hodgkin lymphoma) 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. Finally, childhood cancer (aged 0 - 14) was similar to Ontario within 10 km of the Pickering NPP (SIR = 0.84, 95% CI: 0.61, 1.13) and Darlington NPP (SIR = 0.97, 95% CI: 0.57, 1.53). Information was not provided for Bruce NPP or within the 5 km radius of the Darlington and Pickering NPPs because of few cases.

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 other 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 cancer sites combined near the three Ontario NPPs. While, it was statistically significantly higher than expected for people living near Darlington and Bruce, it was significantly lower near Pickering (the NPP with the highest critical group doses (0.0067 mSv/year) among the three NPPs). 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, the most common cancers observed among people living near the three Ontario NPPs were cancers of the lung and bronchus, breast, and colon and rectum, which represent about 35% of all cancers combined, for all three NPPs. This is consistent with the rest of Ontario and Canada [44,55].

Table 11. Cancer incidence, Ontario by 2006 census division, all ages (0-85+) unless otherwise specified, 1992-2010.

Census Division	Cancers	O	E	SIR	SIR flag	95% CI	
	All sites	39565	37905	1.04	++	1.03	1.05
	Lung and bronchus	5150	4830	1.07	++	1.04	1.10
	Female Breast	5390	5340	1.01	°	0.98	1.04
	Colon and rectum	4675	4600	1.02	°	0.99	1.05
	Thyroid	1215	1140	1.07	+	1.01	1.13
	Bladder	1300	1155	1.12	++	1.06	1.19
	Leukemia	1255	1130	1.11	++	1.05	1.18
Durham Region	Stomach	715	725	0.98	°	0.91	1.06
	Ovary	660	655	1.01	°	0.94	1.09
	Brain and other nervous system	690	690	1.00	°	0.93	1.08
	Liver	235	310	0.76	--	0.67	0.87
	Esophagus	370	370	0.99	°	0.89	1.10
	Non-Hodgkin Lymphoma (aged 0 - 14)	15	20	0.75	°	0.43	1.23
	Leukemia (aged 0 - 14)	110	105	1.05	°	0.87	1.27
	NHL and Leukemia (aged 0 - 14)	130	130	1.00	°	0.84	1.19
	All sites	7090	7025	1.01	°	0.99	1.03
	Lung and bronchus	925	970	0.96	°	0.90	1.02
	Breast	835	890	0.94	°	0.88	1.00
	Colon and rectum	1000	910	1.10	++	1.03	1.17
	Bladder	185	235	0.79	--	0.68	0.91
	Leukemia	215	205	1.06	°	0.92	1.21
	Stomach	105	145	0.75	--	0.62	0.91
Bruce County	Ovary	90	110	0.81	-	0.65	0.99
	Thyroid	110	145	0.73	--	0.60	0.88
	Brain and other nervous system	105	110	0.94	°	0.77	1.14
	Esophagus	70	75	0.97	°	0.76	1.23
	Liver	25	55	0.43	--	0.27	0.63
	Non-Hodgkin Lymphoma (aged 0 - 14)	0	0	0.86	°	0.10	3.10
	Leukemia (aged 0 - 14)	15	10	1.17	°	0.62	1.99
	NHL and Leukemia (aged 0 - 14)	15	10	1.11	°	0.62	1.83

++ significantly high, **p**-value < 0.01; + significantly high, **p**-value < 0.05; ° not significant; - significantly low, **p**-value < 0.05; - - significantly low, **p**-value < 0.01.

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 significantly low 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 [64-66]. Cancers of the bladder, stomach, and liver have been shown to be caused by tobacco smoking [66,67]. Bladder cancer was significantly high near the Darlington NPP, but significantly low near 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

Table 12. Age-standardized incidence rates (ASIRs) per 100,000 population, Ontario by 2006 census division, all ages (0-85+), 1992-2010; presented from highest to lowest ASIR.

(a)

All cancers combined		Lung and bronchus		Breast cancer (females only)	
Census Division	**ASIR**	**Census Division**	**ASIR**	**Census Division**	**ASIR**
Sudbury DIS	450.98	Timiskaming DIS	78.89	Halton RM	108.71
Timiskaming DIS	439.21	Stormont, Dundas and Glengarry UC	74.33	Ottawa CDR	106.62
Manitoulin DIS	433.89	Cochrane DIS	73.94	Frontenac MB	104.27
Cochrane DIS	429.54	Sudbury DIS	71.31	Middlesex CTY	102.46
Thunder Bay DIS	427.49	Prescott and Russell UC	69.32	Nipissing DIS	101.56
Nipissing DIS	426.85	Greater Sudbury CDR	69.20	Thunder Bay DIS	101.53
Lambton CTY	422.01	Hastings CTY	68.38	Renfrew CTY	101.48
Greater Sudbury CDR	421.93	Nipissing DIS	66.91	Simcoe CTY	101.46
Haldimand-Norfolk CDR	420.37	Haliburton CTY	66.28	Elgin CTY	101.41
Dufferin CTY	418.34	Algoma DIS	64.90	Essex CTY	100.98
Elgin CTY	415.50	Kawartha Lakes CDR	64.15	Oxford CTY	100.89
Kawartha Lakes CDR	415.01	Thunder Bay DIS	63.59	Perth CTY	100.80
Huron CTY	413.89	Renfrew CTY	63.16	Durham RM	100.34
Durham RM	412.53	Northumberland CTY	62.92	Brant CDR	99.93
Algoma DIS	411.88	Lanark CTY	62.61	Haliburton CTY	99.78
Simcoe CTY	411.24	Parry Sound DIS	61.97	Lambton CTY	99.66
Stormont, Dundas and Glengarry UC	410.39	Leeds and Grenville UC	61.95	Ontario	99.55
Haliburton CTY	410.03	Lennox and Addington CTY	61.33	Grey CTY	99.12
Brant CDR	408.99	Lambton CTY	61.09	Hamilton CDR	98.94
Middlesex CTY	408.35	Frontenac MB	60.84	Prince Edward CDR	98.82
Lanark CTY	408.23	Peterborough CTY	60.73	Lennox and Addington CTY	98.79
Chatham-Kent CDR	406.73	Rainy River DIS	60.13	Sudbury DIS	98.73
Oxford CTY	404.28	Essex CTY	59.98	Haldimand-Norfolk CDR	98.34
Leeds and Grenville UC	403.86	Simcoe CTY	59.40	York RM	98.19
Parry Sound DIS	402.93	Chatham-Kent CDR	58.71	Dufferin CTY	97.99
Essex CTY	401.46	Manitoulin DIS	58.65	Niagara RM	97.88
Peterborough CTY	401.32	Brant CDR	57.97	Lanark CTY	97.54
Grey CTY	400.74	Prince Edward CDR	56.98	Leeds and Grenville UC	97.45
Frontenac MB	400.39	Hamilton CDR	56.51	Toronto CDR	97.29
Northumberland CTY	399.88	Haldimand-Norfolk CDR	56.50	Chatham-Kent CDR	97.22
Hastings CTY	398.98	Kenora DIS	55.70	Algoma DIS	97.01
Renfrew CTY	398.94	Durham RM	55.29	Peterborough CTY	96.88
Niagara RM	395.82	Elgin CTY	54.94	Stormont, Dundas and Glengarry UC	96.75
Hamilton CDR	395.68	Niagara RM	54.81	Timiskaming DIS	96.60
Bruce CTY	395.39	Ottawa CDR	53.61	Northumberland CTY	96.33
Perth CTY	395.03	Muskoka DM	53.20	Waterloo RM	96.03
Ontario	394.59	Middlesex CTY	52.15	Hastings CTY	95.93
Prescott and Russell UC	393.93	Ontario	52.03	Greater Sudbury CDR	95.59
Muskoka DM	393.50	Huron CTY	50.91	Wellington CTY	94.88
Halton RM	392.09	Grey CTY	50.81	Kawartha Lakes CDR	94.58
Prince Edward CDR	390.34	Bruce CTY	50.31	Huron CTY	94.09
Ottawa CDR	384.35	Dufferin CTY	50.11	Cochrane DIS	93.99
Waterloo RM	382.52	Oxford CTY	49.63	Manitoulin DIS	93.95
Lennox and Addington CTY	380.13	Perth CTY	46.01	Muskoka DM	92.86
Wellington CTY	378.69	Wellington CTY	45.78	Peel RM	92.80
Toronto CDR	374.17	Waterloo RM	45.78	Prescott and Russell UC	91.75
Rainy River DIS	367.55	Halton RM	44.13	Bruce CTY	91.59
York RM	366.12	Toronto CDR	43.62	Rainy River DIS	90.71
Peel RM	356.54	Peel RM	40.67	Parry Sound DIS	89.99
Kenora DIS	337.04	York RM	39.13	Kenora DIS	84.69

(b)

Colon and rectum cancer		Thyroid cancer		Bladder cancer	
Census Division	**ASIR**	Census Division	**ASIR**	**Census Division**	**ASIR**
Manitoulin DIS	70.09	York RM	17.82	Sudbury DIS	17.63
Sudbury DIS	67.31	Toronto CDR	15.59	Timiskaming DIS	17.11
Nipissing DIS	60.15	Peel RM	13.15	Algoma DIS	16.25
Huron CTY	58.17	Halton RM	12.13	Leeds and Grenville UC	16.09
Rainy River DIS	57.62	Algoma DIS	11.82	Elgin CTY	14.86
Cochrane DIS	57.23	Durham RM	11.80	Stormont, Dundas and Glengarry UC	14.79
Renfrew CTY	56.96	Ontario	10.82	Kawartha Lakes CDR	14.67
Timiskaming DIS	56.93	Middlesex CTY	10.66	Brant CDR	14.47
Parry Sound DIS	56.72	Huron CTY	10.39	Simcoe CTY	14.42
Greater Sudbury CDR	56.50	Oxford CTY	9.49	Haldimand-Norfolk CDR	14.28
Prescott and Russell UC	54.85	Perth CTY	9.33	Nipissing DIS	14.25
Lanark CTY	54.69	Cochrane DIS	9.10	Haliburton CTY	14.15
Thunder Bay DIS	54.65	Essex CTY	8.85	Dufferin CTY	14.07
Lambton CTY	54.41	Simcoe CTY	8.68	Durham RM	13.92
Chatham-Kent CDR	54.25	Wellington CTY	8.61	Lambton CTY	13.87
Bruce CTY	53.40	Waterloo RM	8.60	Greater Sudbury CDR	13.87
Kenora DIS	53.25	Lambton CTY	8.53	Cochrane DIS	13.79
Muskoka DM	52.91	Elgin CTY	8.50	Northumberland CTY	13.53
Stormont, Dundas and Glengarry UC	52.83	Peterborough CTY	8.17	Oxford CTY	13.47
Haldimand-Norfolk CDR	52.64	Parry Sound DIS	7.99	Hamilton CDR	13.31
Perth CTY	52.64	Bruce CTY	7.74	Huron CTY	13.27
Algoma DIS	52.45	Muskoka DM	7.68	Hastings CTY	13.15
Middlesex CTY	52.40	Kawartha Lakes CDR	7.62	Thunder Bay DIS	13.09
Haliburton CTY	52.28	Dufferin CTY	7.47	Halton RM	13.01
Elgin CTY	52.13	Sudbury DIS	7.38	Middlesex CTY	12.93
Grey CTY	51.91	Grey CTY	7.28	Chatham-Kent CDR	12.90
Oxford CTY	51.85	Greater Sudbury CDR	7.18	Prince Edward CDR	12.78
Kawartha Lakes CDR	51.70	Thunder Bay DIS	6.83	Muskoka DM	12.73
Leeds and Grenville UC	51.60	Nipissing DIS	6.51	Peterborough CTY	12.68
Simcoe CTY	51.58	Northumberland CTY	6.44	Parry Sound DIS	12.67
Peterborough CTY	51.44	Ottawa CDR	6.33	Ontario	12.55
Hastings CTY	50.12	Haliburton CTY	6.16	Lanark CTY	12.42
Durham RM	49.79	Haldimand-Norfolk CDR	6.09	Frontenac MB	12.37
Brant CDR	49.77	Chatham-Kent CDR	5.84	Renfrew CTY	12.34
Waterloo RM	49.72	Timiskaming DIS	5.84	Lennox and Addington CTY	12.33
Northumberland CTY	49.69	Hamilton CDR	5.78	Essex CTY	12.16
Prince Edward CDR	49.44	Niagara RM	5.76	Prescott and Russell UC	12.15
Hamilton CDR	49.17	Manitoulin DIS	5.36	Toronto CDR	11.86
Niagara RM	49.08	Lanark CTY	5.33	Wellington CTY	11.84
Essex CTY	48.98	Brant CDR	5.13	York RM	11.71
Ontario	48.97	Rainy River DIS	5.08	Niagara RM	11.70
Wellington CTY	48.70	Hastings CTY	5.06	Waterloo RM	11.65
Frontenac MB	48.56	Renfrew CTY	5.04	Grey CTY	11.53
Dufferin CTY	48.10	Frontenac MB	4.82	Ottawa CDR	11.36
Ottawa CDR	48.07	Lennox and Addington CTY	4.58	Peel RM	11.09
Lennox and Addington CTY	47.56	Prince Edward CDR	4.49	Manitoulin DIS	10.81
Halton RM	46.17	Prescott and Russell UC	4.46	Perth CTY	10.46
York RM	45.32	Stormont, Dundas and Glengarry UC	4.40	Bruce CTY	9.94
Toronto CDR	44.19	Leeds and Grenville UC	3.39	Rainy River DIS	8.97
Peel RM	41.85	Kenora DIS	3.28	Kenora DIS	6.42

(c)

Leukemias		Stomach cancer		Ovary Cancer (females only)	
Census Division	**ASIR**	**Census Division**	**ASIR**	**Census Division**	**ASIR**
Sudbury DIS	15.75	Cochrane DIS	9.99	Manitoulin DIS	16.81
Greater Sudbury CDR	14.27	Toronto CDR	9.39	Kenora DIS	15.00
Timiskaming DIS	14.22	Rainy River DIS	8.97	Parry Sound DIS	14.52
Manitoulin DIS	14.01	Peel RM	8.75	Timiskaming DIS	14.43
Nipissing DIS	13.60	Algoma DIS	8.47	Oxford CTY	13.95
Cochrane DIS	13.53	York RM	8.25	Huron CTY	13.93
Elgin CTY	13.49	Thunder Bay DIS	8.18	Haldimand-Norfolk CDR	13.84
Kawartha Lakes CDR	13.30	Hamilton CDR	8.15	Dufferin CTY	13.61
Durham RM	13.20	Greater Sudbury CDR	8.11	Essex CTY	13.41
Thunder Bay DIS	13.19	Nipissing DIS	8.02	Sudbury DIS	13.38
Lambton CTY	13.10	Chatham-Kent CDR	7.85	Niagara RM	13.16
Prince Edward CDR	13.04	Essex CTY	7.84	Brant CDR	13.16
Hastings CTY	12.95	Prescott and Russell UC	7.79	Greater Sudbury CDR	13.11
Perth CTY	12.92	Haldimand-Norfolk CDR	7.74	Ottawa CDR	13.05
Essex CTY	12.76	Ontario	7.73	Leeds and Grenville UC	13.04
Middlesex CTY	12.61	Sudbury DIS	7.62	Grey CTY	13.04
Oxford CTY	12.57	Durham RM	7.55	Stormont, Dundas and Glengarry UC	12.91
Haliburton CTY	12.56	Niagara RM	7.53	Prince Edward CDR	12.89
Bruce CTY	12.55	Timiskaming DIS	7.52	Perth CTY	12.88
Halton RM	12.54	Brant CDR	7.33	Chatham-Kent CDR	12.77
Muskoka DM	12.48	Muskoka DM	7.22	Waterloo RM	12.65
Huron CTY	12.40	Stormont, Dundas and Glengarry UC	7.03	Elgin CTY	12.64
Chatham-Kent CDR	12.34	Dufferin CTY	7.01	Hastings CTY	12.62
Grey CTY	12.32	Wellington CTY	6.96	Kawartha Lakes CDR	12.58
Northumberland CTY	12.23	Manitoulin DIS	6.92	Durham RM	12.56
Hamilton CDR	11.81	Middlesex CTY	6.87	Peterborough CTY	12.41
Parry Sound DIS	11.79	Renfrew CTY	6.87	Ontario	12.40
Ontario	11.76	Waterloo RM	6.83	Prescott and Russell UC	12.29
Waterloo RM	11.65	Oxford CTY	6.75	Middlesex CTY	12.27
Frontenac MB	11.61	Lambton CTY	6.67	Renfrew CTY	12.27
Simcoe CTY	11.36	Halton RM	6.61	Toronto CDR	12.26
Brant CDR	11.35	Ottawa CDR	6.59	Hamilton CDR	12.23
Algoma DIS	11.33	Elgin CTY	6.42	Northumberland CTY	12.20
Peterborough CTY	11.31	Simcoe CTY	6.39	Nipissing DIS	12.19
Wellington CTY	11.24	Grey CTY	6.12	Halton RM	12.17
Renfrew CTY	11.17	Hastings CTY	6.10	Haliburton CTY	12.13
Dufferin CTY	11.03	Kawartha Lakes CDR	6.06	Muskoka DM	12.10
Niagara RM	10.91	Parry Sound DIS	5.98	Lennox and Addington CTY	12.06
Prescott and Russell UC	10.80	Bruce CTY	5.79	Algoma DIS	11.95
Ottawa CDR	10.79	Huron CTY	5.75	Frontenac MB	11.79
York RM	10.71	Peterborough CTY	5.73	Peel RM	11.63
Stormont, Dundas and Glengarry UC	10.70	Lanark CTY	5.67	York RM	11.57
Lanark CTY	10.57	Kenora DIS	5.65	Simcoe CTY	11.25
Toronto CDR	10.55	Northumberland CTY	5.48	Lambton CTY	11.01
Haldimand-Norfolk CDR	10.54	Perth CTY	5.45	Lanark CTY	10.98
Peel RM	10.28	Frontenac MB	5.38	Thunder Bay DIS	10.80
Leeds and Grenville UC	10.15	Haliburton CTY	5.25	Wellington CTY	10.71
Lennox and Addington CTY	10.02	Lennox and Addington CTY	4.62	Rainy River DIS	10.55
Kenora DIS	9.25	Prince Edward CDR	4.47	Cochrane DIS	9.97
Rainy River DIS	7.91	Leeds and Grenville UC	4.25	Bruce CTY	9.60

(d)

Brain and other nervous system Cancer		Liver Cancer		Esophagus Cancer	
Census Division	**ASIR**	**Census Division**	**ASIR**	**Census Division**	**ASIR**
Prince Edward CDR	9.31	Toronto CDR	4.72	Sudbury DIS	6.90
Prescott and Russell UC	8.57	Frontenac MB	4.13	Lanark CTY	6.29
Dufferin CTY	8.55	York RM	4.13	Haliburton CTY	6.28
Chatham-Kent CDR	8.30	Peel RM	3.79	Muskoka DM	6.16
Thunder Bay DIS	8.13	Ottawa CDR	3.70	Dufferin CTY	6.05
Haliburton CTY	8.07	Hamilton CDR	3.38	Hastings CTY	5.73
Lennox and Addington CTY	7.96	Ontario	3.15	Algoma DIS	5.73
Wellington CTY	7.94	Middlesex CTY	3.00	Peterborough CTY	5.25
Frontenac MB	7.76	Peterborough CTY	2.97	Manitoulin DIS	5.22
Haldimand-Norfolk CDR	7.60	Lanark CTY	2.80	Cochrane DIS	5.22
Essex CTY	7.54	Hastings CTY	2.72	Lennox and Addington CTY	5.17
Northumberland CTY	7.49	Essex CTY	2.71	Stormont, Dundas and Glengarry UC	5.16
Hamilton CDR	7.46	Thunder Bay DIS	2.55	Timiskaming DIS	5.15
Kawartha Lakes CDR	7.44	Parry Sound DIS	2.54	Leeds and Grenville UC	5.11
Timiskaming DIS	7.37	Leeds and Grenville UC	2.45	Frontenac MB	5.08
Brant CDR	7.36	Stormont, Dundas and Glengarry UC	2.44	Kawartha Lakes CDR	5.08
Middlesex CTY	7.33	Durham RM	2.44	Prince Edward CDR	5.00
Simcoe CTY	7.31	Brant CDR	2.44	Chatham-Kent CDR	4.98
Huron CTY	7.30	Kawartha Lakes CDR	2.42	Thunder Bay DIS	4.89
Algoma DIS	7.23	Rainy River DIS	2.33	Renfrew CTY	4.83
Oxford CTY	7.20	Renfrew CTY	2.32	Greater Sudbury CDR	4.75
Niagara RM	7.17	Niagara RM	2.28	Parry Sound DIS	4.67
Peterborough CTY	7.15	Lennox and Addington CTY	2.27	Nipissing DIS	4.64
Ottawa CDR	7.13	Prescott and Russell UC	2.22	Brant CDR	4.56
Grey CTY	7.11	Grey CTY	2.21	Elgin CTY	4.54
Perth CTY	7.05	Simcoe CTY	2.19	Oxford CTY	4.53
Waterloo RM	7.02	Manitoulin DIS	2.17	Kenora DIS	4.52
Halton RM	7.01	Chatham-Kent CDR	2.16	Huron CTY	4.51
Ontario	7.00	Lambton CTY	2.10	Simcoe CTY	4.43
Lanark CTY	6.97	Northumberland CTY	2.06	Hamilton CDR	4.40
Durham RM	6.90	Cochrane DIS	2.02	Perth CTY	4.19
Parry Sound DIS	6.82	Perth CTY	2.00	Ottawa CDR	4.14
Lambton CTY	6.80	Muskoka DM	2.00	Niagara RM	4.02
Bruce CTY	6.73	Wellington CTY	1.97	Wellington CTY	3.98
York RM	6.72	Greater Sudbury CDR	1.97	Haldimand-Norfolk CDR	3.95
Elgin CTY	6.71	Haliburton CTY	1.92	Lambton CTY	3.95
Peel RM	6.65	Waterloo RM	1.89	Ontario	3.92
Greater Sudbury CDR	6.63	Sudbury DIS	1.84	Grey CTY	3.90
Toronto CDR	6.52	Haldimand-Norfolk CDR	1.83	Durham RM	3.87
Muskoka DM	6.50	Algoma DIS	1.83	Middlesex CTY	3.83
Cochrane DIS	6.48	Dufferin CTY	1.82	Bruce CTY	3.79
Nipissing DIS	6.43	Oxford CTY	1.82	Halton RM	3.78
Stormont, Dundas and Glengarry UC	6.42	Kenora DIS	1.80	Northumberland CTY	3.76
Renfrew CTY	6.41	Halton RM	1.76	Waterloo RM	3.68
Hastings CTY	6.34	Prince Edward CDR	1.75	Essex CTY	3.65
Leeds and Grenville UC	6.27	Nipissing DIS	1.62	Prescott and Russell UC	3.34
Manitoulin DIS	6.04	Elgin CTY	1.59	Toronto CDR	3.14
Sudbury DIS	6.03	Huron CTY	1.43	Peel RM	2.99
Rainy River DIS	5.91	Timiskaming DIS	1.40	Rainy River DIS	2.52
Kenora DIS	5.53	Bruce CTY	1.31	York RM	2.51

and bronchus, bladder, stomach and liver in this study suggests that tobacco smoking may be a confounding factor.

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 (e.g. age (particularly those over the age of 50) and sex (males)) [68,69].

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 near 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 [68]. However, radiation risk decreases sharply with increasing age-at-exposure and there is little evidence of increased thyroid cancer rates for those exposed after age 20 [70,71]. Releases of radioactive iodine, which is the primary cause of radiation-related thyroid cancer [72], have been extremely low, or below detection limits at all three NPPs during the study period. Concentrations of radioactive iodine in weekly milk samples have remained below the limit of detection during the entire study period. Thus, exposure of the public to radiological emissions from the Pickering and Darlington NPPs is not a likely cause of excess thyroid cancer around these two NPPs.

There was no consistent pattern for leukemia near all three NPPs. Leukemia was statistically significantly higher than expected near the Darlington NPP. However, leukemia 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 near all three NPPs. Therefore those aged 25 - 64 are driving the significant finding near the Darlington NPP. Although high radiation doses can cause leukemia [46], 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 (critical group doses $\leq$ 0.0067 mSv/year) found in this study.

In our study, industrial sources of radiation only contribute a small fraction of the public's overall exposure to radiation. While the critical group doses around the three NPPs are $\leq$0.0067 mSv/year, natural background radiation is on the order of 1.34 mSv/year around the Pickering and Darlington NPPs and 2.02 mSv/year around the Bruce NPP. Hence, radiation doses from the three NPPs do not provide a plausible explanation for any observable increases in cancer incidence above Ontario baseline levels.

Geographic variation of cancer incidence is not uncommon [67,73-76] and as illustrated in our spatial analysis of cancer incidence at the CD level in Ontario. A study in Ontario [77] showed that most of the geographic 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. After known risk factors were taken into account, there was 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 found similar results [78]. Both of these studies cover the earlier time period of our cancer incidence data suggesting that known risk factors are a likely explanation of the variations in cancer incidence observed in our study.

5. Conclusions

The most important finding of this study is that 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. Although there were some elevated cancer rates, there was no clear pattern found across age groups, sexes and NPPs. This finding is generally consistent with previous studies. Overall, the cancers are well within the natural variation of disease in Ontario.

Radiation doses to members of the public living near the three NPPs as a result of historical and current-day operations are significantly lower than natural background radiation and the public dose limit of 1 mSv/year. 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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