



PAPER • OPEN ACCESS

Projecting thyroid cancer risk to the general public from radiation exposure following hypothetical severe nuclear accidents in Canada

To cite this article: Burt JJ *et al* 2020 *J. Radiol. Prot.* **40** 1091

View the [article online](#) for updates and enhancements.

You may also like

- [Thyroid cancer among Ukrainians and Belarusians who were children or adolescents at the time of the Chernobyl accident](#)
P Jacob, T I Bogdanova, E Buglova et al.
- [The effects of iodine blocking on thyroid cancer, hypothyroidism and benign thyroid nodules following nuclear accidents: a systematic review](#)
M Pfinder, S Dreger, L Christianson et al.
- [Dynamics of thyroid cancer incidence in Russia following the Chernobyl accident](#)
V K Ivanov, A I Gorsky, A F Tsyb et al.

Projecting thyroid cancer risk to the general public from radiation exposure following hypothetical severe nuclear accidents in Canada

Burt JJ^{1,4}, M Rickard¹, A McAllister¹, L Bergman² and Zablotska LB³

¹ Canadian Nuclear Safety Commission, 280 Slater Street, Ottawa, Ontario, K1P 5S9, Canada

² Health Canada, 775 Brookfield Road, Ottawa, Ontario, K1V 6J4, Canada

³ University of California, San Francisco, 550 16th Street, 2nd floor, San Francisco, California 94158, United States of America

⁴ Author to whom any correspondence should be addressed.

E-mail: Julie.Burt@canada.ca

Received 6 May 2020; revised 8 July 2020

Accepted for publication 14 July 2020

Published 22 September 2020



CrossMark

Abstract

A robust emergency management framework can limit radiation exposures and effectively minimise the potentially devastating consequences of a nuclear emergency. We projected thyroid cancer risk resulting from two hypothetical severe nuclear accidents occurring at the Darlington nuclear power plant (NPP) located in Ontario, Canada. Single- and multi-unit accidents were considered. A dose assessment was previously performed using the MELCOR Accident Consequences Code System. The generic criteria used to select the appropriate protective actions are described in the Ontario Provincial Nuclear Emergency Response Plan (PNERP). We hypothesised protection actions only within the 10 kilometre (km) radius of the NPP given the time sensitivity of iodine thyroid blocking. The excess risk of developing thyroid cancer was projected using the US National Cancer Institute's radiation risk assessment tool RadRAT. We projected zero dose, and subsequently zero risk of developing thyroid cancer for people living within 10 km of the NPP, due to effective implementation of selected protective actions. Based on centreline doses, at the 12 km radius,



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

excess childhood thyroid cancer risks for a one-year-old female as the most critical receptor were projected to be approximately 600% and 130% compared to the baseline were projected for the single- and multi-unit scenarios, respectively. The risk of developing thyroid cancer was projected to be low for adults for both scenarios. The results of this modelling study provide insights into the effectiveness of protective actions in reducing radiation-related thyroid cancer risk when considering hypothetical severe nuclear accidents. Implementation of select protective actions protects the population living near the Darlington NPP. The projected increase of developing thyroid cancer for children living beyond 10 km could potentially be eliminated with additional mitigation measures specified in the PNERP.

Keywords: nuclear, accident, model, radiation, thyroid, cancer, risk

(Some figures may appear in colour only in the online journal)

1. Introduction

Exposure to radiation may increase the short- and long-term health risk of some cancer and non-cancer diseases for the exposed population [1]. A robust emergency management framework with detailed ERPs can limit radiation exposures and effectively minimise the potentially devastating consequences of a radiological or nuclear event. These plans include references to protective actions such as evacuation, sheltering, iodine thyroid blocking (i.e. the ingestion of potassium iodide, or KI pills), temporary relocation, and ingestion controls placed on contaminated food or water. The implementation of protective actions is intended to be flexible to allow the authorities having jurisdiction to consider factors such as the meteorological conditions, the presence of vulnerable groups, and public policy considerations [2].

Lessons learned from real emergencies such as the Fukushima-Daiichi and the Chernobyl nuclear accidents have contributed to improving the robustness of emergency response worldwide [3–5]. Additional insights can be gained through modelling hypothetical severe nuclear accidents, applying domestic ERPs, and estimating the long-term radiation-related health risks [6–8].

In Canada, the response to a nuclear emergency would be a coordinated multi-jurisdictional effort. The province in which the emergency occurs is the designated lead agency for the offsite response. In Ontario, Emergency Management Ontario would activate the PNERP [9]. The PNERP sets out the overall principles and policies, as well as the responsibilities for nuclear and radiological ERP. At the federal level, Public Safety Canada and Health Canada would provide assistance by activating their respective ERPs [10, 11]. The Canadian Nuclear Safety Commission, as the national nuclear regulator, would determine whether onsite actions taken by the licensee are appropriate as well as provide technical advice to partners (e.g. calculating source term, dispersion calculations, deploying specialists if requested, etc) [12].

Here we present the results of an analysis that projects thyroid cancer risk following two hypothetical severe accident scenarios occurring at the Darlington nuclear power plant (NPP) located in Ontario, Canada. We applied the protective actions described in the PNERP [9] to a previous dose assessment performed by Ontario Power Generation (OPG). We then used a radiation risk assessment tool (RadRAT) developed by the US National Cancer Institute (NCI) to assess thyroid cancer risk to the population [13].

Table 1. Fission product groupings of the modelled source term.

Fission Product Group	Release Fraction ^a
Noble gases	4.12×10^{-1}
Halogens	1.52×10^{-3}
Alkali metals	1.52×10^{-3}
Alkaline earths	2.30×10^{-8}
Refractory metals	2.53×10^{-4}
Lanthanides	8.51×10^{-9}
Actinides	5.16×10^{-8}
Barium	1.68×10^{-7}

^a Fraction of equilibrium core inventory of each radionuclide in the group released to the environment

2. Methods

2.1. Site-specific description

The Darlington NPP is located on the north shore of Lake Ontario in the Municipality of Clarington, approximately 70 km east of Toronto. OPG is the operator of the four unit NPP that came into service in 1990 and has a capacity of 3 500 megawatts.

OPG used population statistics from the 2006 Census to conduct the dose assessment. Canadian and U.S. population information were included given the 100 km geographical region considered in this study. In 2006, the population of the municipality of Clarington was 77 820, whereas the population of metropolitan Toronto was 5 113 149 [14].

2.2. Source term for the hypothetical nuclear accident

The source term used for this study was composed of 1×10^{14} becquerels (Bq) of cesium-137 (^{137}Cs) with a mix of other radionuclides scaled to reflect the distribution of fission products associated with the CANDU reactor design at the Darlington NPP [15]. The full spectrum of the major radionuclide releases was assessed by OPG using a validated software program called modular accident analysis program for CANDU reactors (MAAP4-CANDU) [16]. The fission products were grouped and added to ^{137}Cs to form the total source term (table 1), expressed as release fractions or percentage of total inventory released.

The accident scenarios considered here are both beyond-design-basis accidents (BDBAs), with frequencies of occurrence of less than 10^{-5} per reactor year [15]. One of the major assumptions of this study is that a release occurs; making the frequency of the scenarios evaluated here effectively one.

Of note, the source term considered for the planning basis of the PNERP is also a BDBA [9]. The iodine-131 activity in the source term used for the planning basis of the PNERP (2.23×10^{16} Bq) [17] is approximately an order of magnitude greater than that of the single-unit scenario (3.93×10^{15} Bq), but only 1.5 times greater than that of the multi-unit scenario (1.57×10^{16} Bq) used in this study.

2.3. Hypothetical nuclear accident scenarios

The scenarios used for this study are hypothetical and do not reflect a specific accident progression. Two accident scenarios were modelled: a single-, and a multi-unit reactor accident. The source term for the multi-unit scenario was obtained by multiplying the radionuclide release of the single-unit scenario by four to represent a hypothetical failure event that affects four reactor units simultaneously; this is an overly-conservative limiting case. In reality, a severe accident affecting four units would have staggered release times for the different units, resulting in a lower dose than a simultaneous release. For example, staggered releases were observed at the Fukushima-Daiichi power plant for unit one (23 h), unit two (89 h), and unit three (47 h) following the start of the accident [18].

We assumed that no radioactive material was released to the environment during a 24 h hold-up period for both scenarios. This is reasonable, given the design of CANDU reactors which includes large bodies of water in the calandria, as well as the shield tank acting as a heat sink and slowing accident progression. Following the 24 h hold-up period, a short and long release duration were assessed. We assumed a short release duration of 1 h for the single-unit scenario. A 24 h long release duration for the multi-unit scenario was used to represent the longer-term releases seen in the Fukushima example. These scenarios are generic and were chosen to allow us to conduct a human health risk assessment with diverse dose estimates.

2.4. Radioactive plume dispersion and dose modelling

OPG performed the atmospheric dispersion modelling and dose assessment using the MELCOR Accident Consequences Code System (MACCS2) from Sandia National Laboratories [19]. The code is based on a straight-line Gaussian plume model that assumes horizontal and vertical distribution of the pollutant concentrations in the plume.

For the single-unit scenario, the wind direction and speed were assumed to be constant due to the relatively short duration of the release. For the multi-unit scenario, wind direction and speed were varied over time. The long release time allows for the decay of noble gases, resulting in lower doses. Hourly-averaged meteorological data records for wind speed, direction, and atmospheric stability for one year (i.e. 8 760 hourly-averaged sets of data), collected from the Darlington NPP meteorological tower were used. Throughout that year, the average measured wind speed is 2.6 m s^{-1} and calm conditions are present approximately 8% of the time which is typical of Lake Ontario shore conditions. It should be noted that averaging of the meteorology in this manner, while generally appropriate for long-term chronic releases, can have the effect of removing the possible extremes in real meteorology that could be experienced during acute accidental releases.

The dose assessment was calculated for a period of seven days, which is considered the early phase of the accident within MACCS2, when protective actions would be taken. The radiation dose assessment was completed for a 30-year-old male. This study did not consider the exposure period that may occur after the first seven days, as this involves complex assumptions about continued exposure and the transition to recovery strategies. The recovery phase is currently a focus of national and international efforts [20]. Once detailed recovery plans are developed, continued exposure assumptions could be included in modelling studies. During the first seven days, five exposure pathways are relevant for dose assessment: cloudshine, groundshine, skin deposition, cloud inhalation, and re-suspension inhalation. The MACCS2 grid structure consisted of a series of ten annular rings (0–2 km, 2–4 km, etc.) and 16 radial sectors, for a total of 160 ring sectors extending from the Darlington NPP out to 100 km. The

Table 2. Generic criteria of the Ontario PNERP [9].

Protective Action Strategy	Projected Dose	Protective Action
Exposure Control Measures	50 mSv equivalent dose ^a to the thyroid in the first 7 d	Iodine Thyroid Blocking
	10 mSv effective dose ^b in 2 d	Sheltering
	100 mSv effective dose in the first 7 d	Evacuation

^a The product, in sievert, obtained by multiplying the absorbed dose of radiation by the radiation weighting factor, reflects the amount of harm caused, regardless of the type of radiation.

^b The sum of the products, in sievert, obtained by multiplying the equivalent dose of radiation by the tissue weighting factor, reflects the overall detriment to the whole body.

central radius of the ring sector is provided throughout this paper as the distance from the NPP (e.g. 1 km, 3 km, etc.).

The mean of both the centreline and average doses were calculated. Mean centreline doses were calculated at the vertical and horizontal centreline of the plume. The centreline dose is representative of the highest mean anticipated individual dose in any sector at a given distance from the reactor. However, most individuals would experience average doses as they are assumed to be located outside of the horizontal and vertical centreline of the radioactive plume where the wind is blowing.

2.5. Provincial nuclear emergency response plan (PNERP)

Generic criteria are specified in the PNERP; they are expressed as dose levels in millisievert (mSv) over a specified time interval which, when exceeded, signal that protective actions are warranted (table 2). Centreline doses are compared to the generic criteria in order to make decisions with regards to the appropriate protective action.

Planning zones define the areas beyond the boundary of a reactor facility, in which implementation of operational and protective actions are, or might be, required during a nuclear emergency, in order to protect public health, safety, and the environment.

The planning zones outlined in the PNERP include a detailed planning zone (0–10 km), a contingency planning zone (10–20 km), a sub-zone A ingestion planning zone (20–30 km) and a subzone B ingestion planning zone (30–50 km) (see figure 1) [9]. The two sub-zones for ingestion planning are grouped together here.

Currently, KI pills are pre-distributed within the detailed planning zone surrounding the Darlington NPP [9]. Within the contingency and ingestion planning zones, KI pills are available upon request and the province maintains stockpiles for potential targeted emergency distribution. Given that the effectiveness of iodine thyroid blocking is highly time sensitive, no credit was given to this dose reduction strategy outside of the detailed planning zone. It is recognised that this assumption underestimates potential dose reduction strategies available and subsequently overestimates thyroid cancer risk in the contingency and ingestion planning zones. It highlights the importance of availability of KI pills in all of the planning zones.

2.6. Assumptions on the effectiveness of mitigation measures

We applied protective actions systematically starting with evacuation, then sheltering, followed by iodine thyroid blocking based on centreline doses. Mitigated doses are the doses experienced after taking into account all protective actions; also referred to as received dose.



Figure 1. Planning zones as specified in the 2017 PNERP [9].

Evacuation was assumed to be 100% effective with evacuated individuals receiving no radiation dose. This assumption was supported by the latest evacuation time estimate study which considered 700 unique evacuation runs [21]. The report indicates that the 100th percentile (i.e. worst case) could take approximately 12 h to evacuate the designated planning zone (i.e. 10 km from the NPP), which has 130 781 permanent residents. The evacuation time estimate of 12 h falls well within the 24 h hold-up time assumed for this study. A 20% dose reduction factor was applied to the thyroid dose to account for sheltering; this value is consistent with the MACCS2 emphasis on the pathways of most relevance in the first seven days following a release [19]. Despite being sheltered, those individuals in addition to some individuals where sheltering was not necessary, would be advised to take KI pills as their projected thyroid doses exceeded the generic criteria for iodine thyroid blocking. For those with KI pills in their possession due to pre-distribution within the detailed planning zone, ingestion was assumed to occur within one hour of the exposure (as instructed by the medical officer of health) and therefore to be 100% effective in blocking the uptake of radioactive iodine [22].

2.7. Estimation of thyroid cancer risks

We focused our study on projecting thyroid cancer risk given the radionuclides in the source term considered here as well as findings from past accidents. Estimation of thyroid cancer risk was performed using the NCI's radiation risk assessment tool RadRAT; this tool is described elsewhere [13]. The authors determined that the reference population used in RadRAT could provide reasonable risk estimates for a population within the province of Ontario, given the comparable cancer incidence rates observed between the United States, Canada, and Ontario (table 3) [23, 24].

Briefly, risks are given as excess future risk (i.e. attributable to radiation) and the baseline future risk (i.e. risk in the absence of exposure to radiation). The RadRAT program estimates lifetime risk of incident cancer per 100 000 and provides 90% confidence intervals (CI). Given the selected parameters, excess future risk (i.e. the risk from 2019 to the end of the expected lifetime) is equivalent to lifetime risk (i.e. the risk from the time of exposure to the end of the expected life).

For consistency with the dose assessment, we used a 30-year-old male for the human health risk assessment. Based on the modelled 30-year-old male dose, we derived a dose estimate for the childhood thyroid using ICRP dose conversion coefficients (doses per unit intake),

Table 3. Annual incidence rates of thyroid cancer per 100 000 for the United States, Canada and Ontario, stratified by age-group.

Annual incidence rates per 100 000 men and women	SEER 9 Registries (White and non-White), 2012 [23]				Canada (excluding Nunavut, Québec and Yukon), 2012 [23]				Ontario, 2003–2007 [24]			
	0–19	20–49	50–64	65 +	0–19	20–49	50–64	65 +	0–19	20–49	50–64	65 +
Age category	0–19	20–49	50–64	65 +	0–19	20–49	50–64	65 +	0–19	20–49	50–64	65 +
All cancers excluding leukaemia and non-melanoma skin cancer	26.7	268.7	1557.6	3576.3	27.4	257.1	1480.7	3555.0	25.4	251.1	1598.7	3827.9
Thyroid cancer	2.1	32.8	52.2	49.6	2.3	33.4	51.1	46.9	1.8	33.5	48.4	35.4
All leukaemia	9.8	9.2	39.6	122.6	10.1	8.5	38.6	116.4	8.9	7.4	36.4	111.9

assuming a one-year-old female to represent the most critical receptor. We determined the ratio of the adult thyroid dose to infants taking into account exposure and breathing rates. Adult thyroid doses were multiplied by a factor of 2.3 [25] to obtain a thyroid dose for the one-year-old female child. The data inputs for RadRAT include gender (male or female), year of birth (2018 or 1989, respectively for a one-year-old or a 30-year-old at age of exposure), exposure year (2019), exposure rate (acute), organ (thyroid), type of distribution (fixed value), and absorbed dose in milligray (mGy). For the purposes of this study, mSv and mGy are considered to be equivalent.

3. Results

3.1. Dose assessment prior to mitigation measures

The mean of both the centreline and average doses were provided by OPG. Some centreline doses modelled exceed the generic criteria outlined in table 2, requiring implementation of various protective actions for both accident scenarios (table 4). None of the modelled average doses (table 5) exceed any generic criteria.

The generic criteria for evacuation is exceeded at 1 km for both accident scenarios. The generic criteria for sheltering is exceeded at 12 km for the single-unit scenario, and at 3 km for the multi-unit scenario. Given the structure of the ring sectors (i.e. 12 km represents 8 km to 16 km), the generic criteria for sheltering may be exceeded beyond the detailed planning zone. The generic criteria for iodine thyroid blocking is exceeded as far as 36 km for the single-unit scenario and 12 km for the multi-unit scenario. The exceedance of the generic criteria for iodine thyroid blocking is limited to the ingestion planning zone (<50 km from the NPP).

The single-unit scenario results in larger doses, despite the smaller source term, due in part to the short one hour release duration (with contribution from noble gases not present due to decay in the longer release scenario) as well as the constant wind speed and direction. The single-unit scenario therefore requires the application of protective actions to a greater distance when compared to the multi-unit scenario.

3.2. Human health risk assessment

Tables 6 and 8 show estimates of excess future risk of developing thyroid cancer as an adult for the single- and multi-unit scenarios, respectively. Tables 7 and 9 show estimates of excess future risk of developing childhood thyroid cancer for the single- and multi-unit scenarios respectively. Both the centreline and average mitigated doses are used for the risk calculations from 0 to 100 km from the NPP. The baseline future risk is also provided in tables 6–9, it is 1 077 out of 100 000 for childhood thyroid cancer, and 366 out of 100 000 for adult thyroid cancer.

4. Discussion

We projected thyroid cancer risk following two hypothetical severe accident scenarios occurring at the Darlington NPP. These projected risks were based on mitigated doses determined by effective implementation of protective actions within the detailed planning zone. Doses were modelled for a 30-year-old male and then estimated for a one-year-old female using ICRP dose coefficients. The risk of developing thyroid cancer as an adult were projected to be very low for both scenarios and are not discussed further. We also examined risks for other age and sex

Table 4. Projected centreline whole body and thyroid doses according to distance from the NPP for the hypothetical single-unit and multi-unit reactor accident scenarios.

Distance (km) from NPP	Centreline (single-unit)			Centreline (multi-unit)		
	Whole body effective dose (mSv)	Adult thyroid equivalent dose (mSv)	Child thyroid equivalent dose (mSv)	Whole body effective dose (mSv)	Adult thyroid equivalent dose (mSv)	Child thyroid equivalent dose (mSv)
1	324.0 ^a	5470.0 ^c	12 581.0 ^c	101.6 ^a	1724.0 ^c	3965.2 ^c
3	78.6 ^b	1210.0 ^c	2783.0 ^c	17.8 ^b	282.8 ^c	650.4 ^c
6	33.0 ^b	479.0 ^c	1101.7 ^c	7.0	106.8 ^c	245.6 ^c
12	12.7 ^b	179.0 ^c	411.7 ^c	2.7	39.3	90.4 ^c
20	5.7	77.4 ^c	178.0 ^c	1.3	17.6	40.5
28	4.1	57.2 ^c	131.6 ^c	0.7	10.0	23.0
36	1.9	25.0	50.7 ^c	0.5	7.0	16.1
50	1.1	13.9	32.0	0.3	3.8	8.7
70	0.5	6.8	15.6	0.2	2.1	4.8
90	0.4	5.2	12.0	0.1	1.6	3.7

^a Dose exceeds evacuation projected dose of 100 mSv whole body dose

^b Dose exceeds sheltering projected dose of 10 mSv whole body dose

^c Dose exceeds iodine thyroid blocking projected dose of 50 mSv equivalent dose to the thyroid.

Table 5. Projected average whole body and thyroid doses according to distance from the NPP for the hypothetical single-unit and the multi-unit reactor accidents.

Distance (km) from the NPP	Average (single-unit)			Average (multi-unit)		
	Whole body effective dose (mSv)	Adult thyroid equivalent dose (mSv)	Child thyroid equivalent dose (mSv)	Whole body effective dose (mSv)	Adult thyroid equivalent dose (mSv)	Child thyroid equivalent dose (mSv)
1	4.68	77.30	177.79	17.90	304.00	698.00
3	1.41	22.00	50.60	4.84	78.80	181.00
6	0.56	8.61	19.80	1.73	28.10	64.70
12	0.26	4.07	9.36	0.79	12.80	29.40
20	0.14	1.99	4.58	0.50	8.16	18.80
28	0.09	1.30	2.99	0.32	5.04	11.60
36	0.04	0.56	1.28	0.17	2.60	5.97
50	0.02	0.30	0.70	0.09	1.39	3.19
70	0.01	0.14	0.31	0.06	0.84	1.92
90	0.01	0.09	0.20	0.03	0.38	0.87

Table 6. Excess future risk of developing adult thyroid cancer per 100 000 (single-unit scenario) based on mitigated doses (centreline and average).

Distance (km) from NPP	Mean baseline future risk (90% CI)	Centreline adult thyroid dose (mGy)	Mean excess future risk based on centreline dose (90% CI)	Average adult thyroid dose (mGy)	Mean excess future risk based on average dose (90% CI)
<10	366 (344; 389)	0 ^a	0	0 ^a	0
12	366 (344; 389)	179 ^b	41.3 (10.9; 97.7)	4.1	0.7 (0.1; 1.7)
20	366 (344; 389)	77 ^b	17.1 (4.6; 39.6)	2.0	0.3 (0.1; 0.8)
28	366 (344; 389)	57 ^b	12.0 (3.0; 28.7)	1.3	0.2 (0.1; 0.5)
36	366 (344; 389)	25	4.5 (1.1; 11.3)	0.6	0.09 (0.02; 0.2)
>40	366 (344; 389)	<2	<2.3 (0.5; 5.8)	<0.3	<0.05 (0.01; 0.1)

^a Assumes iodine thyroid blocking

^b Value exceeds projected dose of 50 mGy to the thyroid

Table 7. Excess future risk of developing childhood^c thyroid cancer per 100 000 (single-unit scenario) based on mitigated doses (centreline and average).

Distance (km) from NPP	Mean baseline future risk (90% CI)	Centreline child thyroid dose (mGy)	Mean excess future risk based on centreline dose (90% CI)	Average child thyroid dose (mGy)	Mean excess future risk based on average dose (90% CI)
<10	1077 (1037; 1118)	0 ^a	0	0 ^a	0
12	1077 (1037; 1118)	412 ^b	6410 (1710; 15 400)	9.4	103 (22.9; 257)
20	1077 (1037; 1118)	178 ^b	2270 (746; 6510)	4.6	50 (11.1; 125.0)
28	1077 (1037; 1118)	132 ^b	2050 (553; 4830)	3.0	33 (7.2; 81.9)
36	1077 (1037; 1118)	58 ^b	814 (204; 1920)	1.3	14 (3.1; 35.1)
>40	1077 (1037; 1118)	<32	<409 (98.5; 1020)	<0.7	<8 (1.7; 19.1)

^a Assumes iodine thyroid blocking

^b Value exceeds projected dose of 50 mGy to the thyroid

^c One-year-old female to represent the most critical receptor

Table 8. Excess future risk of developing adult thyroid cancer per 100 000 (multi-unit scenario) based on mitigated doses (centreline and average).

Distance (km) from NPP	Mean baseline future risk (90% CI)	Centreline adult thyroid dose (mGy)	Mean excess future risk based on		Average adult thyroid dose (mGy)	Mean excess future risk based on average dose (90% CI)
			centreline dose (90% CI)	thyroid dose		
<10	366 (344; 389)	0 ^a	0	0 ^a	0	0
12	366 (344; 389)	39.3	7.7 (1.8; 19.7)	12.8	2.1 (0.5; 5.4)	2.1 (0.5; 5.4)
20	366 (344; 389)	17.6	3.0 (0.7; 7.4)	8.2	1.3 (0.3; 3.4)	1.3 (0.3; 3.4)
28	366 (344; 389)	10.0	1.6 (0.4; 4.1)	5.0	0.8 (0.2; 2.1)	0.8 (0.2; 2.1)
36	366 (344; 389)	7.0	1.1 (0.3; 3.0)	2.6	0.4 (0.1; 1.1)	0.4 (0.1; 1.1)
>40	366 (344; 389)	<3.8	<0.6 (0.1; 1.6)	<1.4	<0.2 (0.05; 0.6)	<0.2 (0.05; 0.6)

^a Assumes iodine thyroid blocking

Table 9. Excess future risk of developing childhood^c thyroid cancer per 100 000 (multi-unit scenario) based on mitigated doses (centreline and average).

Distance (km) from NPP	Mean baseline future risk (90% CI)	Centreline child thyroid dose (mGy)	Mean excess future risk based on centreline dose (90% CI)	Average child thyroid dose (mGy)	Mean excess future risk based on average dose (90% CI)
<10	1077 (1037; 1118)	0 ^a	0	0 ^a	0
12	1077 (1037; 1118)	90.4 ^b	1370 (366; 3100)	29.4	370 (88.3; 916)
20	1077 (1037; 1118)	40.5	540 (127; 1320)	18.8	217 (52.9; 533)
28	1077 (1037; 1118)	22.9	274 (68; 687)	11.6	128 (28.4; 318)
36	1077 (1037; 1118)	16.1	182 (45; 452)	6.0	65 (14.6; 164)
>40	1077 (1037; 1118)	<8.7	<95 (21; 239)	<3.2	<35 (7.7; 87.4)

^a Assumes iodine thyroid blocking

^b Value exceeds projected dose of 50 mGy to the thyroid

^c One-year-old female to represent the most critical receptor

groups (data not shown). There was minimal difference in the risk estimates of a five-year-old female compared to the one-year-old female. The risks for five- and one-year-old males were an order of magnitude lower than that of the corresponding females, as expected, given the prevalence of thyroid cancer in Canada [26]. For this reason, we focused the following discussion on the one-year-old female to represent the most critical receptor.

4.1. Single-unit scenario

The mitigated centreline doses for the single-unit scenario exceeded the generic criteria for iodine thyroid blocking beyond the detailed planning zone. Subsequently, the estimated excess future risk of developing childhood thyroid cancer is elevated between 10 km and 50 km in comparison to the baseline future risk. This is a consequence of KI pills not being credited beyond the detailed planning zone. The projected doses were below the generic criteria for iodine thyroid blocking, resulting in low risk beyond 50 km. The excess future risk of developing childhood thyroid cancer was projected to be approximately 600% compared to the baseline for children at the 12 km radius using centreline doses. This estimate was derived for a one-year-old female as the most critical receptor and thus represents the higher end of risk projection. A combined excess future risk for all children in this scenario is expected to be much lower. At the 40 km radius, the excess risk fell to approximately 40% compared to the baseline when considering centreline doses. As expected, the projected excess future risk of developing childhood thyroid cancer is lower when considering average doses varying between 10% and 1% compared to the baseline, at 12 and 40 km respectively. The elevated risks associated with the centreline doses are representative of the highest mean anticipated individual dose, however most people would experience the much lower risks associated with average doses.

4.2. Multi-unit scenario

The mitigated centreline doses for the multi-unit scenario fall below the generic criteria for iodine thyroid blocking beyond the detailed planning zone, with the exception of the 12 km ring. Subsequently, the estimated excess future risk of developing childhood thyroid cancer is lower in this scenario compared to the single-unit scenario. The excess future risk was projected to be approximately 130% compared to the baseline for children at the 12 km radius using centreline doses. At the 40 km radius, the excess risk fell to approximately 10% compared to the baseline when considering centreline doses. Again, the projected increased risk in developing childhood thyroid cancer is lower when considering average doses varying between 34% and 3% compared to the baseline, at 12 and 40 km respectively. These findings are also a consequence of KI pills not being credited beyond the detailed planning zone.

4.3. KI pills

During a real emergency, protective action decisions would be taken considering the most critical receptor. Specifically for iodine thyroid blocking, children would likely experience greater thyroid doses than adults, thus driving decisions to implement that protective action.

Based on the evidence from the lifespan studies of the atomic bomb survivors, the risk of developing thyroid cancer among those exposed as adults is very low [27]. Following the Chernobyl and the more recent Fukushima-Daiichi nuclear accidents, many jurisdictions conducted reviews of their nuclear ERPs and recognised the effectiveness of KI pills in blocking the uptake of radioactive iodine and subsequently preventing thyroid cancer. Specifically, some

jurisdictions (e.g. Switzerland, France, Netherlands, and Sweden) have pre-distributed KI pills to the population beyond 10 km from the NPP [28]. In a public health context, administration of KI pills is an effective protective action that carries negligible non-radiological health risks when taken for short periods of time. However, prolonged intake of KI pills may carry greater risk [22]. It should be noted that KI pills only protect the thyroid gland from radioactive iodine and do not offer any protection from exposure to other radionuclides, or other organs.

In our study, focusing on the child, iodine thyroid blocking is required in both accident scenarios outside of the detailed planning zone (i.e. beyond 10 km of the NPP), and does not exceed the ingestion planning zone (up to 50 km from the NPP). The mandatory pre-distribution of KI pills protects the population within the detailed planning zone. These results highlight the effectiveness and importance of this protective action when evacuation and sheltering are not used in conjunction with iodine thyroid blocking. Detailed plans for targeted emergency distribution of KI pills in the contingency and ingestion planning zones could potentially eliminate any residual thyroid cancer risk for the vulnerable child population as reported here.

4.4. Psychosocial issues

Thyroid cancer has been a primary cancer outcome from past accidents, which is the reason we focused our study on projecting thyroid cancer risk. However, lessons learned from the Chernobyl and Fukushima-Daiichi accidents indicate that non-cancer endpoints (e.g. heart disease, high blood pressure, mental health, and psychosocial issues) could outweigh the burden of disease (i.e. cancer) in the exposed population [5, 29]. Specifically, the impact on the Japanese people after the triple disaster include post-traumatic stress responses, chronic anxiety and guilt, ambiguous sense of loss experienced, separated families and communities, as well as self-stigma [30]. These non-radiological health impacts or psychosocial issues were not assessed in this study. However, given these observed effects, robust emergency management frameworks should include detailed plans for medical care, mental health care, public health and prevention of lifestyle diseases, effective crisis and risk communication and social assistance for community coherence [31].

4.5. Strengths and limitations

The major limitation of this study is the short, seven day exposure period modelled in the MACCS2 code. Doses incurred beyond the first seven days following a nuclear accident could provide a more accurate assessment of the increased thyroid cancer risk. Also, the results should be considered in light of the limitations in the use of averaged meteorological data which was based on available data and the Gaussian dispersion model. The MACCS2 code should be applied with caution at distances greater than 16 to 24 km. The results presented in this study represent the risks from the accident scenarios considered and could vary significantly if protective actions were applied differently. The hold-up and release times are also major factors impacting the dose assessment. However, the assumptions made for this study were straightforward, systematic, and reasonable in order to evaluate the health impact from different hypothetical severe nuclear accident scenarios.

The major strengths of this study include the use of reactor-specific source term, detailed population statistics, and site-specific meteorological data and the use of an existing provincial nuclear ERP. Additional conservatism is built into the study through the use of the MACCS2 code with the application of the straight-line Gaussian plume and initial ground-level release. These assumptions resulted in conservative estimates of pollutant concentrations which were used to estimate dose. Lastly, the risk models used in RadRAT are robust, built upon those

developed by the Biological Effects of Ionizing Radiation Committee which were based on the life span studies of the atomic bomb survivors [32].

5. Conclusions

The results of this study provide insights into the effectiveness of protective actions in reducing radiation-related thyroid cancer risk through modelling hypothetical severe nuclear accidents. Implementation of select protective actions described in the current PNERP protects the population living near the Darlington NPP for the accident scenarios assessed here. The projected increased thyroid cancer risk for children living between 10 and 50 km could potentially be eliminated with emergency distribution of KI pills prior to any radioactive material being released from the NPP, as specified in the PNERP. Future studies could substantiate our conclusions by evaluating different accident scenarios including hold-up and release times, different age categories, and changing some of the assumptions surrounding emergency response and exposure time. Future studies may also wish to consider changes in meteorology as a result of climate change, or consider extreme meteorological events (i.e. tornados, high winds, flooding) as bounding scenarios.

By comparing excess future thyroid cancer risk to baseline future risks, we were able to place the consequences of radiation exposure from a nuclear accident into a public health context by considering the implementation of protective actions. During an emergency exposure situation, authorities having jurisdiction have the important role of balancing and assessing all adverse health impacts (including psychosocial impacts) when implementing protective actions to obtain the optimal level of protection for the affected population.

Acknowledgments

The authors would like to thank the numerous Health Canada and Canadian Nuclear Safety Commission staff for their guidance, detailed review, and artistic talents. Several staff members at Ontario Power Generation were instrumental in the early development of the dose assessment, notably, John Peters, Alex Brittain Boisvert, Dave Burger, and Carlos Lorencez.

References

- [1] International Agency for Research on Cancer 2000 Ionizing radiation, part1: X- and gamma radiation and neutrons *IARC Monogr. Eval. Carcinog Risks Hum.* **75** 1–492
- [2] International Atomic Energy Agency 2007 Arrangements for preparedness for a nuclear or radiological emergency IAEA Safety Standards Series No. GS-G-2.1 (Vienna: IAEA)
- [3] United Nations Scientific Committee on the Effects of Atomic Radiation 2017 Developments since the 2013 UNSCEAR report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami (New York: United Nations)
- [4] United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Sources and Effects of ionizing radiation 2008 Report to the General Assembly including scientific annexes vol II (New York: United Nations)
- [5] Zablotska L B 2016 30 years after the Chernobyl accident time for reflection and re-evaluation of current disaster preparedness plans *J. Urban Health* **93** 407–413
- [6] Andrade E R, Stenders R, Castro M S C, Santos C V V, Prah M and Silva A X 2020 Evaluation of cancer risk after a release from a hypothetical nuclear reactor steam generator tube rupture accident (SGTR) *Ann. Nucl. Energy* **136** 107023

- [7] Ahangari R and Noori-Kalkhoran O 2019 A study of the protective actions for a hypothetical accident of the Bushehr nuclear power plant at different meteorological conditions *Radiat. Environ. Biophys.* **58** 277–285
- [8] Yangmo Z, Jianghua G, Chu N and Youhua Z 2014 Simulation and dose analysis of a hypothetical accident in Sanmen nuclear power plant *Ann. Nucl. Energy* **65** 207–213
- [9] Emergency Management Ontario 2017 Provincial Nuclear Emergency Response Plan (PNERP) master plan Prepared for the Office of the Fire Marshal and Emergency Management (Toronto: Ontario)
- [10] Government of Canada, Public Safety Canada 2011 Federal Emergency Response Plan (Ottawa: Government of Canada)
- [11] Government of Canada, Health Canada 2014 Federal Nuclear Emergency Plan (5th ed) (Ottawa: Health Canada)
- [12] Canadian Nuclear Safety Commission 2016 Emergency Management and Fire Protection: Nuclear Emergency Preparedness and Response REGDOC 2.10.1, Version 2 (Ottawa: Canadian Nuclear Safety Commission)
- [13] de Gonzalez A B, Apostoaei A I, Vega L H, Rajaraman P, Thomas B A, Owen Hoffman F, Gilbert E and Land C 2012 RadRAT: a radiation risk assessment tool for lifetime cancer risk projection *J. Radiol. Prot.* **32** 205–222
- [14] Statistics Canada 2006 Community Profiles 2006 (Ottawa, Canada)
- [15] Canadian Nuclear Safety Commission 2014 Physical Design: Design of Reactor Facilities: Nuclear Power Plants REGDOC 2.5.2 (Ottawa: Canadian Nuclear Safety Commission)
- [16] Blahnik C, Kim C S, Thuraisingham R and Nijhawan S 1991 Modular accident analysis program for CANDU reactors *Proc. of the Canadian Nuclear Society 12 Annual Conf.* pp 557
- [17] Canadian Nuclear Safety Commission 2017 Letter to David Nodwell Planning accident B description and conservative assumptions. eDoc 5197714 (Ottawa: Canadian Nuclear Safety Commission)
- [18] International Atomic Energy Agency 2015 The Fukushima Daiichi Accident Report by the Director General (Vienna: IAEA)
- [19] Chanin D I and Young M L 1997 Code Manual for MACCS2, Pre-Processor Codes COMIDA2, FGRDCF, IDCF2. NUREG/CR-6613, Vol. 2 SAND97-0594 (Albuquerque, New Mexico: Sandia National Laboratories)
- [20] Organisation for Economic Co-operation and Development 2018 Post-Accident Recovery Planning and Management: Stakeholder-Involvement Lessons from Fukushima. Nuclear Energy Agency/Committee on Radiological Protection and Public Health. NEA/CRPPH/R(2017)1/PROV
- [21] KLD Engineering, P.C 2019 Darlington nuclear generating station, development of evacuation time estimates Work performed for Ontario Power Generation. *Final Report* Rev. 0. KLD TR-1065
- [22] Lebsir D et al 2018 Effects of repeated potassium iodide administration on genes involved in synthesis and secretion of thyroid hormone in adult male rat *Mol. Cell. Endocrinol.* **474** 119–126
- [23] Bray F, Colombet M, Mery L, Piñeros M, Znaor A, Zanetti R and Ferlay J eds 2017 *Cancer Incidence in Five Continents* vol XI (Lyon: International Agency for Research on Cancer) <http://ci5.iarc.fr> (Accessed January 30, 2020)
- [24] Forman D, Bray F, Brewster D H, Gombe Mbalawa C, Kohler B, Piñeros M, Steliarova-Foucher E, Swaminathan R and Ferlay J eds 2014 *Cancer Incidence in Five Continents* Vol. X IARC Scientific Publication No. 164 (Lyon: International Agency for Research on Cancer)
- [25] International Commission on Radiological Protection 1995 *Age-dependent Doses to Members of the Public from Intake of Radionuclides - Part 4 Inhalation Dose Coefficients*, ed H Smith (London: Elsevier)
- [26] Topstad D and Dickinson J A 2017 Thyroid cancer incidence in Canada: a national cancer registry analysis *CMAJ Open* **5** E612–16
- [27] Furukawa K, Preston D, Funamoto S, Yonehara S, Ito M, Tokuoka S, Sugiyama H, Soda M, Ozasa K and Mabuchi K 2013 Long-term trend of thyroid cancer risk among Japanese atomic-bomb survivors: 60 years after exposure *Int. J. Cancer* **132** 1222–1226
- [28] European Commission 2010 Director general for energy. medical effectiveness of iodine prophylaxis in a nuclear reactor emergency situation and overview of European practices Radiation Protection NO 165, TREN/08/NUCL/SI2.520028; European Union

- [29] Hasegawa A *et al* 2015 Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima *Lancet* **386** 479—488
- [30] Hasegawa A, Ohira R, Maeda M, Yasumura S and Tanigawa K 2016 Emergency responses and health consequences after the Fukushima accident; evacuation and relocation *Clin. Oncol.* **28** 237—244

- [31] Ohtsuru A *et al* 2015 Nuclear disasters and health: lessons learned, challenges, and proposals *Lancet* **386** 489—497
- [32] National Research Council 2006 *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* Board on Radiation Effects Research The Committee on the Biological Effects of Ionizing Radiation (BEIR) (Washington, DC: The National Academies Press)