A Critique of the RADICON Study

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The Canadian Nuclear Safety Commission (CNSC) recently (May, 2013) completed an epidemiological study of populations living near Ontario's three nuclear power plants (NPPs), entitled *Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008* – also referred to as the RADICON Study [R1]. The stated purpose of this study was to "determine the radiation doses to members of the public living within 25 km of the Pickering, Darlington, and Bruce NPPs and to compare cancer cases among these people with the general population of Ontario from 1990 to 2008".

The authors of this report state (among other things) that:

(i) The study was based on detailed public dose information around each NPP compiled from "all available annual total dose data"
(ii) Data collected for the study take into account any emission spikes from the NPPs
(iii) Radioactive iodine, which is the primary cause of radiation-related thyroid cancer, was below detection limits of the in-stack sampling monitors at all three NPPs for the entire study period. Thus, public radiation dose from the two NPPs is not a likely cause of thyroid cancer.
(iv) An analysis of the hypothetical dose plumes at each NPP shows that based on average meteorological conditions; the majority of exposure to air immersion and inhalation would occur over Lake Ontario (Pickering and Darlington NPPs) and Lake Huron (Bruce NPP). Near the Pickering NPP, prevalent winds travel towards the south; near the Darlington NPP they travel towards the south-south-east (SSE); and over Lake Huron near the Bruce NPP, towards the north.

Unfortunately for the RADICON study, these four claims are simply not true as will be demonstrated below:

<u>Claim (i) Concerning Dose Data</u>

The authors of the RADICON report state that the study was based on "all available annual total dose data". This statement implies that doses to members of the public were <u>*measured*</u>, when in reality <u>*average doses*</u> to hypothetical individuals were estimated using models that are crudely compartmentalized and based on the assumption that radioactive species are released at a constant rate. In fact, radionuclide emissions from CANDU NPPs are periodic at best, as with system purges or tank discharges, or are random and unpredictable as with "accidents" or "operational errors". Either way, the basic premise of the RADICON dose calculations – *that radionuclide emission rates are constant* – is almost always <u>*not*</u> the case.

Section 3.0 of the RADICON report states that: "The maximum doses received by each critical group were compared to one another to assess the relationship of distance and dose". Then, according to its authors, the study showed that distance is an inappropriate substitute for radiation dose to a member of the public. Unfortunately, however, this is a tautological argument because any dose-to-distance relationship confirmed or rejected by this approach is, by definition, already built into or excluded from the model. Furthermore, the claimed "maximum" doses derived in the study cannot capture real cases of high exposures that do occur, for example, when an acute release such as a spill coincides with certain weather conditions, e.g. heavy rainfall, or specific behaviours of exposed individuals, e.g. consumption of local fish, swimming, sun bathing, etc.

The RADICON study is based on the EcoMetrix® code IMPACT which uses site-specific weather data and release characteristics for each NPP to create a dispersion plume. However, this model does *not* include plume depletion caused by precipitation. It is well documented (See COG-06-3090-R2-1, [R2]) that adverse weather, such as periods of heavy rainfall, results in poor atmospheric dispersion conditions that may lead to critical group doses up to 15 times higher than those obtained using average weather conditions.

Claim (ii) Concerning Emission Spikes

Section 5.1 of the RADICON report states that:

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

This statement demonstrates that the authors of the RADICON report lack an understanding of how CANDU stations operate and what causes most NPP's radionuclide emissions. Certainly "emission spikes" do occur, and these events are captured by a battery of effluent monitors installed in key station systems such as exhaust stacks and ALW holding tanks. However, as noted above, current dose assessments used by the CNSC, do *not* accurately evaluate radiation doses from short-term releases. This is due to the inability of dose assessment software to deal with factors such as the variability in the wind direction, periods of calm weather and other short-term conditions that include exposures associated with localized uptakes of deposited radioactive species.

Dose per unit release for short-term releases has been addressed in a recent study published by the UK National Dose Assessment Working Group in its Report No. NDAWG/2/2011: "*Short-term Releases to the Atmosphere*"[R3]. This issue has also been addressed in a recent paper by G. Ghirga,[R4].

The NDAWG report shows that, for the example of a release under Pasquill-Gifford atmospheric stability category F, the estimated adult annual dose per unit *continuous* release of 1 TBq/year of tritium is 0.259 µSv, compared to the corresponding dose from a *short-term* release of 1 TBq of tritium of 14.3 µSv. Thus, for this example, the dose per TBq of tritium is 55 times higher for a short-term release compared to a long-term continuous release.

An additional problem with Section 5.1 of the RADICON report is the statement:

"*CANDU reactors refuel while still online; therefore, the occurrence of spikes is very low*".

Emission "spikes" from refuelling operations generally have nothing to do with a CANDU station's dose-to-public, (except in rare cases of severely damaged fuel). It is the tritium and carbon-14 components of a station's emissions that are the main sources of public dose from CANDU NPPs; and these emissions are almost entirely due to *non-fuel related events* such as tritium spills or moderator cover gas releases.

Consider another statement from Section 5.1 of the RADICON report:

> *The CNSC's strong licensing and compliance program requires the establishment of internal investigation levels and action levels to monitor and control releases before any potential emission spikes occur. As such, unexpected emissions must be reported to the CNSC and action must be taken to identify and correct the cause.*

Once again, operating experience at a CANDU station shows that "*internal investigation levels and action levels*" do not "*control releases before any potential emission spikes occur*". It is unrealistic to believe that internal investigation levels and action levels prevent emission spikes. Action levels are merely desirable operational targets much like speed limits on our roads. However, emission spikes are invariably caused by unexpected phenomena such as air ingress leading to Ar-41 emissions, leaks from system failures or operator errors such as heavy water spills leading to tritium and carbon-14 emissions.

Finally, consider the last part of the statement noted above from Section 5.1 of the RADICON Report:

> *Exceedances of internal investigation levels or of action levels are rare. Hence, it is unrealistic to conclude that occasional spikes in atmospheric releases result in high short-term exposure of members of the public.*

The invalidity of this claim is proven by an analysis of actual airborne emissions from the CANDU reactors at Pickering, Darlington and Bruce. Such an analysis shows that emissions of important radionuclides such as tritium, carbon-14, iodine and noble gases are almost entirely due to short-term spikes. Furthermore, many of these spikes are so large they account for a major percentage of the annual emissions of the radionuclide in question. Indeed, there are many examples of a single acute emission of tritium, carbon-14, iodine or noble gases from Pickering, Darlington and Bruce that contributes over 80% of these station's annual emissions.

<u>Claim (iii) Concerning Radioactive Iodine Emissions</u>

In Section 5.2 of the RADICON report we read:

> *Radioactive iodine, which is the primary cause of radiation-related thyroid cancer, was below detection limits of the in-stack sampling monitors at all three NPPs for the entire study period.*

This claim is not credible when one looks at the actual radioactive iodine emissions data that have been reported for Pickering, Darlington and Bruce for the study period of the RADICON investigation, namely 1990 – 2008. And what is most remarkable about these data is that they have been published in two documents from the CNSC, the publishers of the RADICON report. I am referring to:

(i) CNSC Report: INFO-0210/REV.10: *Radioactive Release Data from Canadian Nuclear Generating Stations 1990 to 1999*[R5]

(ii) CNSC Report: INFO-0210/REV.13: *Radioactive Release Data from Canadian Nuclear Generating Stations 1999 to 2008*[R6]

These reports include data for the maximum airborne radioiodine releases from each station as presented in Table 1.

Table 1: Maximum Airborne Radioiodine Released by Pickering, Darlington and Bruce (For the Period 1990 – 2008)

Station	Maximum Release GBq/year	Year of Maximum Release
Pickering A	0.32	1990
Pickering B	0.10	2001
Darlington	0.15	2002
Bruce A	0.06	1990
Bruce B	0.12	2007

Contrary to the claims of the RADICON Report, the data in Table 1 clearly show that Pickering, Darlington and Bruce all had significant radioiodine emissions in the period 1990 – 2008. Furthermore, a detailed analysis of station data shows that the detection limit of a stack sampler for radioiodine, calculated as 2 times the standard deviation in the background, is typically about

0.2 MBq per weekly sample, showing that a station's radioiodine background is about 0.01 GBq/yr. Thus it is undeniable that Pickering, Darlington and Bruce had measurable radioiodine emissions between 1990 and 2008. The fact that the RADICON Report claims radioactive iodine "*was below the detection limits of the in-stack sampling monitors at all three NPPs for the entire study period*" clearly raises questions about the veracity of the Report.

Claim (iv) Concerning Meteorological Conditions at Pickering, Darlington and Bruce

Section 5.1 of the RADICON Report claims that for people living near the NPPs at Pickering, Darlington and Bruce:

> *The majority of exposure to air immersion and inhalation occurs over Lake Ontario (Pickering and Darlington NPPs) and Lake Huron (Bruce NPP). Near the Pickering NPP, prevalent winds travel towards the south; near the Darlington NPP they travel towards the south-south-east (SSE); and over Lake Huron near the Bruce NPP, towards the north.*

This is an example of the questionable information to be found in the RADICON Report. Actual average wind frequencies by direction for the Pickering, Darlington and Bruce NPPs are regularly published for these facilities - See for example OPG's Report No.N-REP-03481-10005, (2006), [R7], and BP's Report No.B-REP-03419-00007, (2006) [R8].Representative wind frequency data taken from these reports is presented in Table 2.

Table 2. 2006 Annual Average Wind Frequency by Direction

Wind Direction From	Pickering Wind Frequency (%)	Darlington Wind Frequency (%)	Bruce Wind Frequency (%)
N	6.77	7.39	7.69
NNE	2.95	7.72	5.12
NE	4.22	5.88	3.90
ENE	7.06	5.35	4.06
E	4.95	3.01	3.75
ESE	3.40	4.60	3.91
SE	1.45	5.51	6.04
SSE	2.00	2.07	5.53
S	8.74	4.14	7.44
SSW	10.27	9.86	8.90
SW	5.41	6.12	9.27
WSW	6.44	7.62	7.24
W	7.41	6.84	6.46
WNW	9.47	9.82	6.34
NW	9.59	8.24	6.07
NNW	9.83	5.84	8.27
TOTAL LANDWARD	49.7	42.9	51.3

The data in Table 2 show how the term "*prevalent winds*" used in the RADICON Report is open to interpretation and can in fact be quite ambiguous. Thus, if we take the term to mean the wind direction with the highest annual frequency of occurrence, the frequencies in Table 2, (which are taken from OPG and BP published data), clearly contradict the RADICON Report as shown in Table 3 below:

Table 3

Station	**Prevalent Wind Direction**	
	RADICON Report	**Station Data (2006)**
Pickering	S	SSW
Darlington	SSE	SSW
Bruce	N	SW

However, the determination of a prevalent wind direction becomes questionable when it is realized that wind directional frequencies at a particular site in Ontario vary significantly, not only from season to season, but also from one year to another. And what is *not* factored into most atmospheric dispersion models is the amount of precipitation associated with a wind direction. This is important because the dispersion of species such as Cs-137 and I-131 is strongly affected by wet deposition processes.

Finally it should be noted that atmospheric dispersion models cannot deal with periods when winds are calm, which usually means wind velocities between zero and 1 m/s. In real situations these "calm" hours may account for up to 10 % of the data but are usually excluded from the calculations altogether because the wind velocity appears in the denominator of the IMPACT software's plume dispersion equation and therefore cannot be assigned a value of zero, a fact that is not mentioned in the RADICON Report.

Discussion

A. The Results of Other Cancer Cluster Epidemiological Studies

Exposure to ionizing radiation is a well established risk factor for cancer and a small excess risk of cancer exists, even at the low doses typically received by nuclear industry workers – See for example, E. Cardis et al. "*Risk of Cancer after Low Doses of Ionizing Radiation: Retrospective Cohort Study in 15 Countries*", British Medical Journal 331, 77, (2005) [R9].The Radiation Safety Institute of Canada was founded in 1980 in response to the uranium mining disaster in Elliot Lake, Ontario, where more than 200 healthy miners died of lung cancer from excessive exposure to alpha radiation from radon progeny in uranium mines.

Many studies have also revealed an increased incidence of second primary cancers after radiotherapy. For example leukemia has been observed as a complication of radiotherapy for Wilms' tumor indicating the need to employ lower radiation doses that would cure the original cancer without causing leukemia – See R.W. Miller - Modern Trends in Human Leukemia III, 1979, [R10].

Because of concerns about exposure to *any* level of ionizing radiation, considerable emphasis is now being placed on the cancer-inducing potential of low-dose radiation in the general population. Cases of cancer and congenital anomalies such as Down's syndrome have been of special interest in people living near nuclear power stations. In 1984 an Independent Advisory Group in the U.K. chaired by Sir Douglas Black issued a report that concluded there was an increased incidence of leukemia in young people living in the village of Seascale, which is situated adjacent to the Sellafield nuclear site in northern England.

More recently additional evidence for an increased risk of leukemia in children living close to a NPP has been reported in a German study completed in 2008 – See P. Kaatsch et al. "Childhood Leukemia in the Vicinity of Nuclear Power Plants in Germany", *Deutsches Ärzteblatt International* 105(42), 725, (2008), [R11], and a French study reported in 2012 – See C. Sermage-Faure et al. "Childhood Leukemia Around French Nuclear Power Plants – the Geocap study, 2002-2007" *International Journal of Cancer* 131(5), 769, (2012), [R12].

What is remarkable about these studies is that in each case the dose expected from the radiological emissions reported for the NPPs in question were deemed to be insufficient to account for the increased incidence of cancer. Thus the researchers concluded that "cancer clusters" observed in the vicinity of English, German and French NPPs "remain unexplained".

Turning to Canadian studies of cancers near NPPs, the RADICON Report mirrors the findings of its European predecessors. Thus leukemia incidence was observed to be significantly elevated in Clarington from 1993 to 2004 – the period after the Darlington NGS began operating. Similarly, thyroid cancer incidence in Ajax-Pickering males was significantly elevated from 1993 to 2004, and thyroid cancer incidence in males and females from 1981 to 1992 was also elevated.

In addition, a 1996 report on the impact of radiation on health in Durham Region observed that the occurrence of the congenital anomaly Down's syndrome was elevated in Ajax-Pickering during the 1980s and was found to be significantly higher than the rate in Ontario for the time period 1978-1991, [R13].It is also noteworthy that these results were consistent with a study done by Health and Welfare Canada for the Atomic Energy Control Board which found significantly high rates of Down syndrome in Pickering in the 1973-1988 time period.

Nevertheless, and regardless of these findings, studies of the epidemiology of cancer in populations located in the vicinity of CANDU NPPs have consistently concluded that radiation is *not* a plausible explanation for any excess cancers observed within 25 km of Pickering, Darlington or Bruce NPPs; the stated reason for rejecting radiation as a causative factor being that *the magnitude of the predicted doses is insufficient to induce cancers in exposed individuals*.

B. How Reliable are the RADICON Dose Estimates?

Let's consider how radiation doses were determined in the RADICON study. Certainly they were *not* measured directly, a fact that is acknowledged in the introduction to the Report:

> *Doses to members of the public from the routine operations of NPPs are so low that it is difficult to directly measure doses to people from all contributing sources. Therefore, doses are estimated indirectly from the modelling of environmental releases and from the results of radiological environmental monitoring programs*

Thus the authors of the RADICON Report admit that a process of "*dose reconstruction*", rather than direct measurement, was used to investigate cancer epidemiology in the vicinity of NPPs in Ontario. This process involves modelling the dispersion of radionuclides in air and water using computer codes. Generally speaking, every country with operating NPPs has developed their own computer codes for dose reconstruction and it is very instructive to compare the predictive capabilities of some of these codes.The IAEA has carried out a number of such studies as documented in:

(i) *Modelling the Environmental Transport of Tritium in the Vicinity of Long Term Atmospheric and Sub-Surface Sources*, IAEA-BIOMASS-3, 2003, [R14]

(ii) *Modelling the Environmental Transfer of Tritium and Carbon-14 to Biota and Man* IAEA Report of the Tritium and Carbon-14 Working Group of EMRAS Theme 1, 2007, [R15]

From 1996 to 2000, the BIOMASS-3 component of the IAEA Tritium Working Group (TWG) developed and analysed six model test exercises and carried out a specifically commissioned field sampling and analysis programme in order to study and understand more fully the behaviour of long-term releases of tritium in the environment. The first task of the TWG was devoted to a model-model inter-comparison exercise on the transport of tritium in the vicinity of permanent atmospheric sources. Eleven institutions participated in this exercise and agreed to an exchange of results and ideas. Canada was involved in the programme and the IMPACT code was one of the models evaluated.

The IAEA also established an Environmental Modelling and Radiation Safety (EMRAS) group in 2002. The goals of EMRAS were achieved through nine test scenarios in which model predictions were compared with observations obtained in laboratory or field studies. A given scenario included information on the source term for the release rate of tritium or C-14 to air or water, and parameter values describing the environment through which these radionuclides passed (meteorological conditions, plant and animal properties, ingestion rates, etc). Given this information, participants were asked to calculate tritium or C-14 concentrations in specific environmental compartments at specific times for comparison with observations.

Pickering NPP was the focus of one of the IAEA's tritium release scenarios which was largely based on measurements made in the vicinity of the Pickering NPP in July and September of 2002. HTO concentrations were measured in air, precipitation, soil, drinking water, plants (including the crops that make up the diet of the local farm animals) and products derived from the animals themselves. Given information on food intakes by the farm animals and the measured HTO concentrations in air, precipitation and drinking water, participants in each scenario studied were asked to calculate:

(1) HTO and non-exchangeable organically bound tritium (OBT) concentrations in sampled plants and animal products for each site and sampling period.

(2) HTO concentrations in the top 5 cm soil layer for each site and sampling period.

The modeling approaches used by the participants in the Pickering scenario varied widely. However, all the models used by the participants were based for the most part on simple analytical equations that described transfers between compartments using empirically-based bulk parameters. The air concentrations used to drive the models were averaged over different time periods, with some participants employing the average over the May to September period and others using averages over the month prior to sampling.

All participants calculated the wet deposition flux of HTO from air to soil as well as the concentration of HTO in rainwater. Predictions for the rainwater concentrations ranged over a factor of 3, from 28 Bq/litre to 87 Bq/litre. Significantly, all the predictions were substantially lower than the observed value of 218 Bq/litre. This result is not that surprising because it is known that all of the models used assume that material in the plume has a Gaussian distribution in the vertical, which is not necessarily the case, especially for a source near ground level. In addition, the models probably do not work well for heavy rains or for a plume that meanders.

The prediction of average values of HTO concentrations in soil moisture was also made in these IAEA studies using a variety of approaches. Some of the modellers derived the concentration from a balance of tritium inputs and outputs to and from the soil surface. Others based their calculations on semi-empirical considerations. *The diversity of approaches led to results that were spread over a factor of nearly seven*. This raises questions of how to explain the reasons for such a spread, and how to determine which approach is the best. Significantly, the models evaluated by these IAEA studies have all previously claimed some degree of validity based on the results of comparisons with measured data. However, a model that gives excellent predictions from within a limited range of input parameters may perform poorly when used beyond that range of inputs.

N. Oreskes, et al. [R16] have argued that verification and validation of numerical models of natural systems is inherently impossible. This is because natural systems are never closed and because model results are always non-unique. Models can be partially confirmed by the demonstration of agreement between observation and prediction. However, complete confirmation is logically precluded by the fallacy of affirming the consequent and by incomplete access to natural phenomena. This may be something of a moot point when it comes to the RADICON Report because its authors present no information on how the calculated doses were verified and also fail to discuss the question of data uncertainty. Nevertheless, as the above discussion shows, the RADICON doses are certainly uncertain by at least a factor of ten.

C. Why Averaged Emissions Data Provide Poor Dose Estimates

1. The Example of Tritium

As previously noted, the RADICON study was based on radionuclide release data for Pickering, Darlington and Bruce for the period 1990 to 2008. The study used these station emissions data averaged over one-year intervals, to determine doses to the public using water and atmospheric dispersion modelling. This is similar to the approach generally used to determine DRLs for NPPs operating here in Canada – see D. Hart: *Derived Release Limits Guidance* CANDU Owners Group Report COG-06-3090-R2-I, November 2008, [R2]. However, as shown below, this approach is subject to significant error when the emissions are highly variable over time especially if the emissions include large short-term spikes caused by leaks or spills from systems containing high activity liquids such a stritiated moderator D_2O.

In order to understand how data averaging leads to erroneous dose estimates we need to look at real station emissions data such as those presented in Figure 1 below which show actual airborne tritium releases from an operating CANDU station.

Figure 1: Airborne Tritium Emissions from a CANDU NPP: One Year of Weekly Data

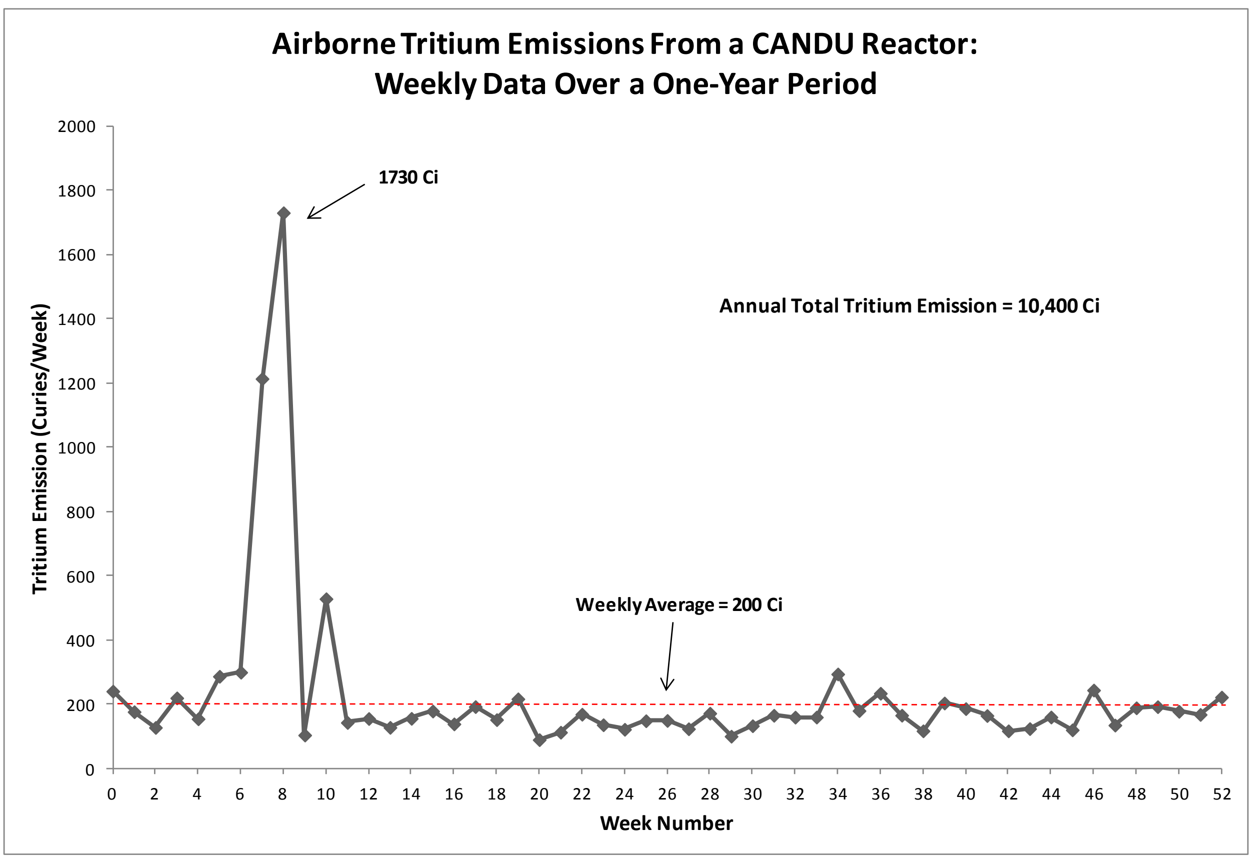

Figure 1 shows a large tritium emission spike of 1730 Ci in the 8th week of data collection. This spike is almost 9 times the weekly average of 200 Ci/week and was caused by a major spill of 20 Ci/kg moderator D_2O.What is noteworthy about this tritium release is that Environment Canada records show there was a period of heavy rain, (totalling 14.2 mm), at the time of the tritium release. In addition, rainwater samples collected on-site after this period of rainfall showed tritium levels up to 30,000 Bq/liter.

The occurrence of large spikes in a station's airborne tritium releases obviously leads to an increased dose to residents living near the facility. However, as demonstrated in detail below, the increased dose will be underestimated if the spike release is simply added to other weekly data and averaged as part of the yearly releases. Furthermore, the chance coupling of an emission spike with a period of heavy rainfall serves to further amplify the dose to nearby residents, particularly if they are farmers using well water. To quantify these dose enhancement effects it is necessary to compare doses calculated for short-term acute releases with doses derived from annual average "routine" releases.

For off-site doses from short-term releases it is normally assumed that the wind is blowing steadily in the direction of a receptor under stable atmospheric conditions. Such conditions assume no crosswinds or plume meander and are also assumed to prevail for periodsup to 2 hours following an accidental release. The receptor is thus exposed to the maximum possible concentration of the released radionuclide. The associated atmospheric dilution factor is usually referred to as the "2-hr (X/Q)" where X is the atmospheric concentration of the species of interest, in units of Bq/m^3, and Q is its release rate from the source in units of Bq/s.

By comparison, for the assessment of annual "routine" releases, a sector-averaged Gaussian plume model is usually adopted rather than one in which the plume is directed at the receptor location throughout the exposure period. For this reason, routine release calculations typically use site-specific meteorological data to construct joint-frequency tables which categorize hourly observations of wind speed and direction into 7 stability classes, 16 compass directions, and 6 wind-speed ranges. Such tables are then used to calculate annual-average atmospheric dilution factors, also referred to as long-term (X/Q)s.

To demonstrate the importance of the proper choice of dilution factors in making reliable dose estimates we have used both short-term and long-term (X/Q)sto determine the doses from the tritium emissions presented in Figure 1– which are real data for an operating CANDU plant. The dose calculations were for inhalation, skin absorption, potable water and vegetable consumption for an individual residing 1 kilometer from the plant. In addition, because it is known that the large spike release of tritium seen in Figure 1 was accompanied by a period of heavy precipitation, the effects of wet deposition of tritium were included in the calculations.

Tritium washout near CANDU stations has been discussed in the open literature – see for example: "*Investigation of the Environmental Fate of Tritium in the Atmosphere*" CNSC Report INFO-0792, issued 2009, [R17] – but the full extent of this phenomenon is very complex and difficult to model. Nevertheless, for the purposes of the present study a simplified formalism is used as described below:

The wet deposition flux F_w ($Bq.m^{-2}.s^{-1}$) is assumed to be proportional to the tritium release rate multiplied by a washout coefficient Λ which is the fraction of HTO removed per second. Allowing for plume dispersion we then have,

$$F_w = Q \, \Lambda \, \Phi / (x \, \bar{u} \, \theta)$$

Where,

Q is the tritium release rate in $Bq.s^{-1}$
Λ is the washout coefficient in s^{-1}
Φ is the joint frequency of occurrence of wind direction and rainfall in the receptor sector
x is the distance from source to receptor in m
$\bar{u}$is the average wind speed in $m.s^{-1}$
θ is the angular width of the sector in radians

It follows that the concentration of tritium in rainwater, C_w(Bq/liter), is given by:

$$C_w(\text{Bq/liter}) = F_w \, T / (1000 \, P)$$

Where,

T is the duration of the study period in s
P is the total amount of rain in the study period in m
1000 is the factor to convert $Bq.m^{-3}$ to Bq/liter

This washout coefficient formalism was used to calculate the concentration of tritium in rainwater for the annual average (200 Ci/week) and short-term (1730 Ci) releases shown in Figure 1. The average wind speed was set at 3 $m.s^{-1}$ and the washout coefficient was conservatively assumed to be $1 \times 10^{-5} s^{-1}$. The annual average rainfall at the site was 1045 mm and the short-term (24 hr) rainfall accompanying the tritium emission spike was 14.2 mm.

The resulting tritium concentrations in rainwater were 217 Bq/liter and 38,000 Bq/liter for the annual average and short-term releases, respectively. However, to allow for some dilution by additional, post-release precipitation, the short-term tritium concentration was reduced to 20,000 Bq/litre in the dose calculations. Table 4 below presents the tritium dose estimates for these exposures and shows how the averaging of emissions data effectively masks the contribution of emission spikes.This effect comes about because tritium concentrations downwind from a source decrease with time due to increased plume meander. Thus the long-term calculation averages out the dose impact to a specific group by sharing it with a hypothetical “average dose recipient”. However, real emission peaks are capable of delivering significant doses to real individuals fortuitously located at the plume’s point of impingement, and the dose impact is only increased by concurrent periods of heavy precipitation.

Table 4: Doses for a Receptor Exposed to the Tritium Emissions Shown in Figure 1:

1. **Calculated for the Annual Average Releases (Left hand Column)**
2. **Calculated for the Single Short-Term Release (Right Hand Column)**

Dose from Inhalation/Skin Absorption	Annual Average	Short Term Release
Release Rate (Bq/s)	1.06E+07	7.41E+08
Dilution Factor X/Q (s/m^3)	2.00E-06	7.50E-05
Breathing Rate (m^3/day)	20	20
Dose Conversion Factor (uSv/Bq)	2.60E-05	2.60E-05
Dose (microSv)	**4.03**	**144.19**
Dose From Potable Water Consumption	Annual Average	Short Term Release
Tritium Concentration (Bq/litre)	200	20000
Water Consumption (litre/year)	730	60
Dose Conversion Factor (uSv/Bq)	1.73E-05	1.73E-05
Dose (microSv)	**2.53**	**20.76**
Dose From Consumption of Plants	Annual Average	Short Term Release
Intake Rate (kg/year)	64	64
Tritium Conc for Plant 100% Water (Bq/kg)	60	2000
Dose Factor (uSv/Bq)	1.73E-05	1.73E-05
Dose (microSv)	**0.07**	**2.21**
TOTAL Dose (microSv)	**6.62**	**167.16**

2. The Example of Radioiodine

In spite of the RADICON Report's claims that CANDU NPPs do _not_ release significant quantities of radioiodines, I-131 is routinely detected in airborne emissions from Pickering, Darlington and Bruce. This I-131 is generally emitted as a steady "background", but also occasionally as a short duration spike. All of these emissions are subject to rain washout if the release coincides with a local rain event. Thus, although Pickering, Darlington and Bruce typically have relatively constant I-131 emissions ~1×10^{-5} Ci/week, single short-lived spikes up to 10 mCi have also been observed.

As shown above for the example of tritium, studies such as those described in the RADICON Report use station emissions data _averaged over one-year time periods_. This averaging results in tritium doses that significantly underestimate the dose to members of the public living at or close to the point of impingement of an emission plume. It will now be shown that this type of data averaging also effects the estimation of doses from I-131.

Consider, for example, an accidental puff release from a CANDU NPP of 1mCi (3.7×10^{7} Bq) of I-131 over a 24-hour period compared to the same total release averaged as 1/52mCi per week over 1 year. The associated ground level air concentrations, C_a, 1 km from the emission source are 3.2×10^{-2} Bq/m^3 and 2.3×10^{-6} Bq/m^3, respectively. Considering dry deposition only, with an assumed deposition velocity, v_d , for iodine gas of1.0×10^{-2} m/s, the total I-131 surface concentrations are 27.7 Bq/m^2 (over 24 hours), vs. 0.74Bq/m^2 (over 1 year).

It is further assumed that the critical group for exposure to an iodine-laden plume is a dairy farming family that consumes its own milk. The I-131 activity of the farm's pasture grass, C_p, is given by:

$$C_p \text{ (Bq kg}^{-1}) = C_a [v_d . (r/Y)] \times [1 - \exp(- \lambda_{eff} . t)]/\lambda_{eff}$$

Where,

C_a is the I-131 ground level concentration in air (Bq.m^{-3})
v_d is the dry deposition velocity (m.d^{-1})
(r/Y) is the mass interception factor for dry deposition (m^2.kg^{-1})
λ_{eff} is the effective removal rate constant from weathering and radioactive decay (d^{-1})
t is the exposure period of the pasture biomass (d)

The concentration of I-131 in the farm's milk is then given by:

$$C_m \text{ (Bq litre}^{-1}) = C_p . Q_m . p_m . F_m$$

Where,

Q_m is the pasture ingestion rate for dairy cows (kg. d^{-1})
p_m is the fraction of feed that is contaminated (unitless)
F_m is the feed-to-milk transfer coefficient for dairy cattle (d. litre^{-1})

Values for these parameters have been taken from the CDC Report "*Doses to the Public from Atmospheric Releases of Radionuclides from the Idaho Chemical Processing Plant at the Idaho National Engineering Laboratory (1957 – 1959)*", Contract No. 200-2002-00367, July 2005, [R18], and the doses resulting from consumption of this milk have been calculated using the methodology presented in this CDC Report. The calculated values for the two scenarios under consideration are:

Dose to a critical group member from an acute release of 1mCi ofI-131 = 68.4 μSv

Dose to a critical group member from a chronic release of 1mCi of I-131 = 3.8 μSv

Thus, as was the case for the tritium example discussed above, the averaging of iodine emissions data significantly underestimates the dose-to-public when the emissions are dominated by spike releases. Similar conclusions have been reported by other researchers [R21].However, it is important to also note that the dose calculated above for an acute release of I-131 is based solely on dry deposition and does *not* include the effects of wet deposition. Wet deposition of iodine is extremely difficult to model, but empirical evidence from the Chernobyl and Fukushima accidents shows that it can substantially increase iodine uptake by plants, animals and man.

Information on the deposition of iodine from the Chernobyl accident is documented in: "The Chernobyl I-131 Release: Model Validation and Assessment of the Countermeasure Effectiveness", *Report of the Chernobyl I-131 Release Working Group of EMRAS* Theme 1, August 2007, [R19]. Data for the contamination of rural locations near Prague in the Czech Republic are especially useful in assessing the contribution of wet deposition. The first indications of the presence of a contaminated plume over Czech territory were detected during the night of April 29th 1986. In the morning of April 30th measurements were started by the Czech monitoring network which subsequently detected three passages of contaminated air through the territory. The first one occurred during the night between the 29th and 30th of April; the second one occurred on May 3rd and 4th, and the third one began on May 7thand ended on May 10th, 1986.

Data reported in Annex IV of the EMRAS Report, [R19], show that daily I-131 fallout activities in three locations near Prague rose sharply after periods of rainfall on April 30th and May 9th, 1986. Thus, while surface concentrations of I-131 in the Czech Republic were typically less than 1000 Bq/m^2 throughout this period, I-131 "hot-spots" in excess of 8000 Bq/m^2 were observed immediately after these rain events.

The radiation dose from the Fukushima accident was impacted by iodine washout in a similar manner. Thus, starting on March 15th, 2011, radioactive releases from Unit 2 of the Fukushima Dai-ichi plant were dispersed over Japan during a period when meteorological conditions were changing rapidly. The releases occurring in the morning of March 15th are believed to have moved in a southerly direction, along the coast, whereas those occurring during the nights of the 15th and 16th of March moved to the northwest, crossing an intense precipitation front moving in the opposite direction – see for example: "Fukushima, one year later: Initial analysis of the accident and its consequences" *IRSN Report IRSN/DG2012-003*, March 2012, [R20].

The villages of Iitate, Namie, Kawamate and Katsurao, all located within 50 km of the plant and all more or less directly in the path of the Fukushima plume, experienced heavy rainfall on March 16th, 2011, and were subject to I-131 deposition >1000kBq/m^2. By comparison, villages within 50 km of Fukushima Dai-ichi, but located southwest of the plant, experienced much less rainfall, and deposition of I-131 was typically <10 kBq/m^2. This illustrates how detailed weather patterns, and particularly periods of heavy precipitation, influence wet deposition of radionuclides and must be factored into the estimation of doses due to the consumption of contaminated milk.

Conclusions

The RADICON Report on radiation and the incidence of cancer around Ontario NPPs from 1990 to 2008 has been reviewed and shown to contain a number of false assertions which invalidate most of its conclusions. One of the most remarkable claims in the RADICON Report that is demonstrably untrue is that CANDU NPPs have no detectable radioiodine emissions. Nevertheless, a simple check of CNSC reports on radioactive releases from Canadian NPPs, (See [R5] & [R6]), shows these plants typically release 2×10^8 Bq of I-131 per year.

However, the most serious problem with the RADICON study is its use of averaged meteorological data coupled with averaged annual emissions to estimate doses to members of the public living near Canadian NPPs. Now it is true that averaging data in this way is commonly employed in the calculation of derived release limits (DRLs) and is arguably a valid approach todose estimation for relatively constant (continuous) emissions. However, CANDU NPP's emissions are far from constant; on the contrary, they are dominated by short-term spike releases and are therefore subject to far less dispersion than long-term "routine" emissions. In addition, doses resulting from the wet deposition of radionuclides – especially doses from spike releases that coincide with periods of heavy precipitation- are inevitably underestimated by long-term averaging.

The use of long-term averaging has additional problems besides the loss of detail of specific events; the very concept of "an average value" loses its meaning if the data being averaged do not exhibit a Gaussian distribution. A detailed analysis of CANDU emissions over extended periods of time (up to 10 years) shows that the data invariably exhibit power law, rather than Gaussian distributions. Gaussian distributions drop off quickly, because under this statistic large release events are extremely rare; by comparison, power law distributions drop off more slowly. Thus large release events – the events in the tail of the distribution – are more likely to happen in a log-normal or power law distribution than in a Gaussian. Given that detailed (weekly) emissions data and the associated meteorological conditions are available for all NPPs operating in Ontario, it is recommended that future epidemiological studies of populations living near these plants use disaggregated data to assess doses to exposed individuals. Only in this way will causative links between these exposures and cancer clusters in the vicinity of NPPs ever be revealed – if indeed such links exist.

F. R. Greening
Hamilton, ON

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Abstract

A Canadian Nuclear Safety Commission (CNSC) Report entitled: *Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008* – also referred to as the RADICON Study – was released in May 2013. The purpose of the RADICON study was to determine the radiation doses to members of the public living within 25 km of the Pickering, Darlington, and Bruce NPPs and to compare cancer cases among these people with the general population of Ontario from 1990 to 2008". The study found no evidence of childhood cancer clusters (especially childhood leukemia) near the three Ontario NPPs studied (Pickering, Darlington and Bruce), and concluded that radiation from NPPs is not a causative factor in cancer in Ontario because the magnitude of the predicted doses is deemed to be insufficient to induce cancers in exposed individuals. However, as described in this paper, a number of claims and assumptions that form the technical basis of the RADICON study are questionable or demonstrably false. Thus, for example, the RADICON Report asserts that radioiodine was below the detection limits of the in-stack sampling monitors at Pickering, Darlington, and Bruce NPPs for the entire study period and therefore could not be a cause of thyroid cancer in Ontario. Nevertheless, a simple check of CNSC reports on radioactive releases from Canadian NPPs shows these plants typically release 2×10^8 Bq of I-131 per year.

However, the most serious problem with the RADICON study is its use of averaged meteorological and annual emissions data to estimate doses to members of the public living near Canadian NPPs. Averaging data in this way is commonly employed in the calculation of derived release limits (DRLs) and is arguably a valid approach to dose estimation for relatively constant (continuous) emissions. However, CANDU NPP's emissions are far from constant being dominated by short-term spike releases. Such releases are subject to far less dispersion than long-term "routine" emissions. In addition, doses resulting from the wet deposition of radionuclides – especially doses from spike releases that coincide with periods of heavy precipitation – are inevitably underestimated by long-term averaging. A detailed analysis of CANDU emissions over extended periods of time (up to 10 years) shows that the data invariably exhibit power law, rather than Gaussian distributions. Gaussian distributions drop off quickly, because under this statistic large release events are extremely rare; by comparison, power law distributions drop off more slowly. Thus large release events - the events in the tail of the distribution - are more likely to happen in a power law distribution than in a Gaussian. Given that detailed (weekly) emissions data and the associated meteorological conditions are available for all NPPs operating in Ontario, it is recommended that future epidemiological studies of populations living near these plants use disaggregated data to assess doses to exposed individuals.

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REVIEWER's REPORT (Received Jan 8th 2014)

This article criticizes the RADICON report.

The most important finding of the RADICON study is that there is no evidence of childhood leukemia clusters around the three Ontario NPPs.

Interestingly, RADICON showed an increase of thyroid cancer risk among residents in the vicinities of Pickering and Darlington during the period 1990-2008. On the other hand, thyroid cancer risk in people living within the 25 km radius of Bruce NPP was not increased. According to the report of Canadian Nuclear Safety commission, a minuscule amount of I-131 was released from those reactors (INFO-0210/REV.14). However, those observations do not necessarily indicate a causal association between an excess thyroid cancer risk and I-131 released from nuclear power plants.

The amount of I-131 released is too small to cause any health effects among the residents. If the author suspects an unlikely possibility that a large amounts of radioactive iodine were accumulated in the thyroid of particular residents, authors should present direct evidence for that assertion, such as data obtained from the measurements of residents.

As the author pointed out, RADICON did not measure doses to the members of public but estimated them. However, since the released amount of radioactive iodine is so small, possible errors do not matter a lot as far as absolute thyroid cancer risk possibly associated with radioactive iodine is concerned.

The author seems to argue that intermittent release of large amount of radionuclides may be masked by presenting the average data. That may be true. However, the author does not present any persuasive argument for a possibility that such "spikes" are more strongly associated with the risk of cancer risk when compared to average concentrations.

Regarding the "spike", the author makes arguments using the data on tritium (lines 3-11, p2). However, the author does not present persuasive arguments regarding the possible "spike" of radioactive iodine.

Physicians in the areas around the nuclear facilities may suspect the increase of thyroid cancer. If that is the case, the incidence of thyroid cancer, which is frequently asymptomatic, can be increased. The authors should provide the reason why such an explanation is unlikely.

Lines 31-33, p3
The author writes as follows: "It is unrealistic to believe that internal investigation levels and action levels prevent emission spikes."

Comments:
This statement is subjective. The author should present evidence (with references) to support this notion.

Lines 55-56, p3
The author writes as follows: "Indeed, there are many examples of a single acute emission of tritium, carbon-14, iodine or noble gases from Pickering, Darlington and Bruce that contributes over 80% of these station's annual emissions."
Comments:
The author should present evidence (with references) to support this notion.

The author should present the data source of Table 1.

In the first part of discussion section, the author presents a brief summary of epidemiological data. The arguments of the author are not well balanced.

I am sorry to say that publication in the present journal is not supported.

Letter reference: DSR01

My Response (Sent Jan 8th, 2014)

Dear Sir,

I am very disappointed with the reviewer's recommendation that my paper be rejected. However, I must say that most of his or her reasons are not acceptable since they are largely invalid or unreasonable. For example:

The reviewer states:

1. If the author suspects an unlikely possibility that a large amounts of radioactive iodine were accumulated in the thyroid of particular residents, authors should present direct evidence for that assertion, such as data obtained from the measurements of residents.

Clearly I do not have data on the accumulation of radioiodine in residents since no such surveys have been conducted by anyone in Canada. The costs and logistics of obtaining such data are obviously a major obstacle to any scientist who wishes to investigate this issue in this way.

2. The released amount of radioactive iodine is so small, possible errors do not matter a lot as far as absolute thyroid cancer risk possibly associated with radioactive iodine is concerned.

The reviewer fails to address the issue that the RADICON study claims there are ***no*** radioiodine emissions from CANDU reactors, which is demonstrably untrue.

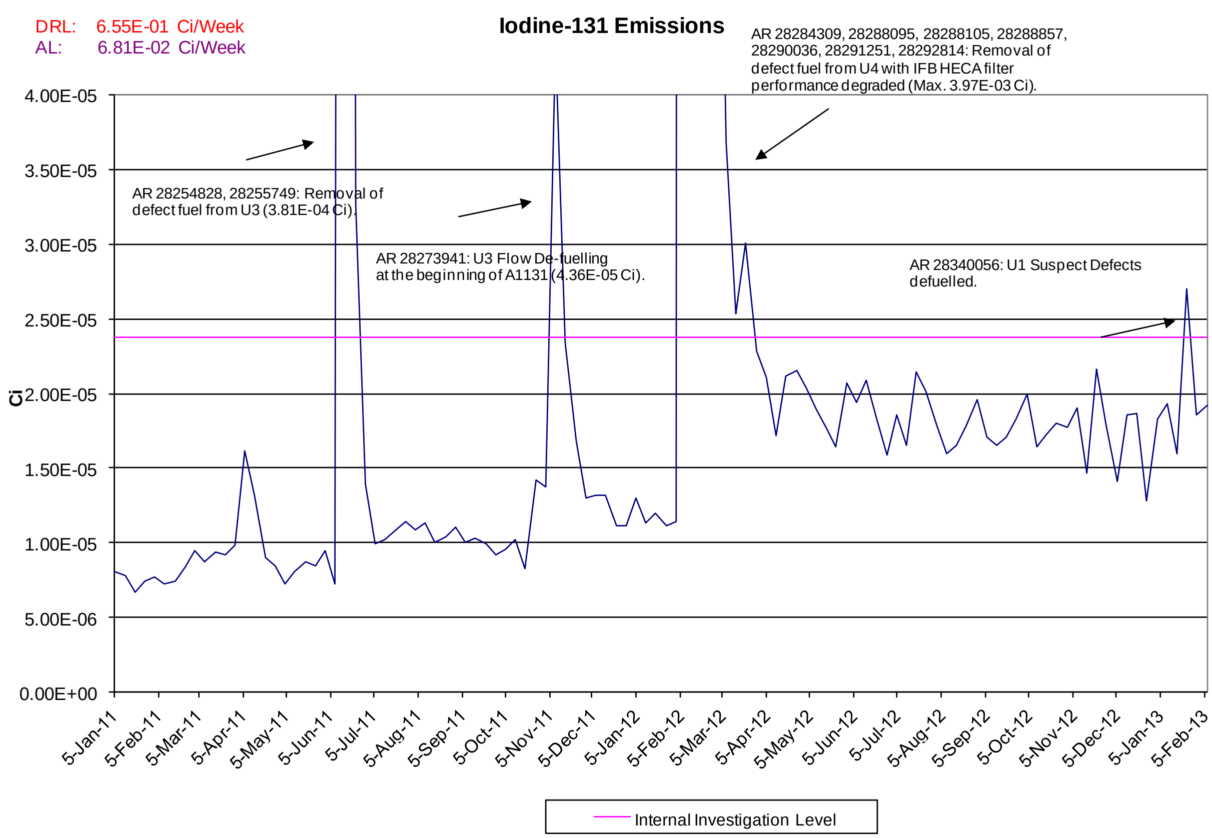
3. The author does not present any persuasive argument for a possibility that such "spikes" are more strongly associated with the risk of cancer risk when compared to average concentrations.

Here the reviewer evidently misses one of the main arguments of my paper: that averaging data smooths out spikes and thereby leads to a much lower dose estimates as follows:

Dose to a critical group member from an acute release of 10 mCi of I-131 = 68.4 μSv
Dose to a critical group member from a chronic release of 10 mCi of I-131 = 3.8 μSv

4. The author does not present persuasive arguments regarding the possible "spike" of radioactive iodine.

Here are data from Bruce A which speak for themselves:



5. The author writes as follows: "It is unrealistic to believe that internal investigation levels and action levels prevent emission spikes." Comments: This statement is subjective. The author should present evidence (with references) to support this notion.

I suspect that the reviewer has never worked in a nuclear plant, as I have, and seen “Station Condition Records”. These show that spike emissions are almost invariably caused by “accidents” such as pipe or valve ruptures, or operator errors. Internal investigation levels and action levels do not impact on the frequency of such events but are merely desirable *targets* that are established to satisfy regulatory requirements.

6. The author writes as follows: “Indeed, there are many examples of a single acute emission of tritium, carbon-14, iodine or noble gases from Pickering, Darlington and Bruce that contributes over 80% of these station’s annual emissions.” Comments: The author should present evidence (with references) to support this notion.

I have the data in question but it is proprietary to OPG. It is a well-known fact that nuclear power operators are unwilling to release such data to the public, the reason being that such data show that spike releases are the norm, not the exception.

7. The author should present the data source of Table 1.

I ***do*** provide the source of the data in Table 1 as follows:

(i) CNSC Report: INFO-0210/REV.10: *Radioactive Release Data from Canadian Nuclear Generating Stations 1990 to 1999* [R5]

(ii) CNSC Report: INFO-0210/REV.13: *Radioactive Release Data from Canadian Nuclear Generating Stations 1999 to 2008* [R6]

In conclusion let me add that the intent of my paper is simply to draw attention to the fact that although NPPs collect airborne emissions data on a weekly basis, averaging data over time intervals up to one year, (as most radionuclide emissions data are reported), leads to a significant underestimation of dose. Because the RADICON Study uses this data averaging methodology it’s inevitable that it finds no link between CANDU NPP emissions and the incidence of cancer in the vicinity of these plants. Thus it becomes a self-fulfilling prophecy.

Sincerely,

Dr. F. R. Greening