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The First Six Years

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SRBT Licence Application

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Intervenor

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Executive Summary

Annual tritium emissions to air from SRBT's light factory at Pembroke, Ontario are large compared to most nuclear power stations in the world, and are comparable to those from Canadian reactors which are prolific tritium sources. These emission levels were extremely large in the early to mid 2000s. Following a brief decline, these appear to be increasing again in recent years.

Major international agencies recognise that tritium, the radioactive isotope of hydrogen, has unusual properties marking it as a hazardous nuclide. It is extremely mobile in the environment, contaminates all biota in nearby areas including humans to ambient levels and binds with organic matter to form organically bound tritium (OBT) with long residence times in the body making it more radiotoxic.

Environmental measurements of soils, foodstuffs, wells and sewage near the SRBT facility indicate pervasive continuing tritium contamination. Tritium levels in most wells are higher than the CNSC's design guide for groundwater tritium, and much higher than the Ontario Government's recommended level for tritium in drinking water. It appears that neither CNSC nor SRBT understands the factors responsible for the continuing high groundwater contamination near SRBT. Tritium levels in environmental samples are erratic but do not appear to be declining. Recent tritium measurements in foodstuffs and municipal sewage reveal unexpectedly high levels of OBT.

We estimate that annual tritium intakes for local residents amount to 200,000 Bq. This is mainly from inhalation and skin absorption of tritiated water vapour. The estimate assumes residents neither consume their own garden produce nor drink from their own wells. These amounts are higher than a yardstick of 10,000 Bq/a for acceptable intakes and the natural background intake of 6,000 Bq/a. More hazardous OBT intakes will also occur.

These intakes increase the probability of cancer and other diseases in exposed people. It is not possible to ascertain in advance who will be affected but embryos, fetuses, babies, infants and children are more radiosensitive than adults, and females more than males. Due to long latency periods, these cancers will arise in the future. Probabilistic effects mean exposed people will have each been handed "negative" lottery tickets, and that some will get cancer in future.

Epidemiology studies of Canadian facilities emitting tritium suggest increases in cancer and congenital malformations: these could be confirmed with case-control or cohort studies. More important is that considerable evidence from cell and animal studies, and radiation biology theory indicates that radiogenic effects will occur. This is backed by evidence from recent, large scale, statistically powerful epidemiology studies from other countries.

Specific recommendations are made to improve the situation at Pembroke.

A. Overview

1. "The First Six Years", a Pembroke-based NGO, has requested Dr Ian Fairlie to review SRBT's proposal for this hearing, and to prepare an independent report summarizing our current understanding of the biological and health effects of exposures to tritium and commenting on the risks faced by local citizens.

2. Dr Ian Fairlie is a Canadian citizen currently resident in the United Kingdom. He is an independent consultant on radioactivity in the environment with degrees in chemistry and radiation biology. His doctoral studies at Imperial College, UK and Princeton University, US examined nuclear waste technologies. His area of expertise is the dosimetric impacts of nuclear reactor emissions. He has authored many articles in peer-reviewed journals on epidemiology studies of child leukemias near radiation facilities and on the hazards of radionuclides. He has been a consultant to UK Government Departments, the European Parliament, the World Health Organisation, environment NGOs, and UK local authorities. Between 2000 and 2004, he was head of the Secretariat to the UK Government's Committee Examining the Radiation Risks of Internal Emitters (CERRIE).

3. Of particular relevance to the hearing, Dr Fairlie has written numerous scientific articles discussing the hazards of tritium emissions, including the following:

- Fairlie I. (2014) A hypothesis to explain childhood cancers near nuclear power plants J Environ Radioact. 133 (2014) pp 10- 17
- Fairlie I. Hypothesis to Explain Childhood Cancer near Nuclear Power Plants. Int J Occup Environ Health 2010;16:341–350.
- Fairlie I. The hazards of tritium – revisited. Medicine, Conflict and Survival. Vol 24:4. October 2008. pp 306 -319. http://www.informaworld.com/smpp/content~content=a904743144~db=all~order=page
- Fairlie I. RBE and w_R values of Auger emitters and low-range beta emitters with particular reference to tritium. Journal of Radiological Protection. 2007; 27:157-168. http://www.iop.org/EJ/abstract/0952-4746/27/2/003/
- Fairlie I. Tritium Hazard Report: Pollution and Radiation Risk from Canadian Nuclear Facilities. Published by Greenpeace Canada. June 2007. http://www.greenpeace.org/raw/content/canada/en/documents-and-links/publications/tritium-hazard-report-pollu.pdf
- Fairlie I. Tritium Hazard Report on Cernavoda 3/4: Environment Impact Analysis: Report for Greenpeace Romania. Published by Greenpeace Central Europe. November 2007. http://www.greenpeace.ro/uploads/articole/Cernavoda%20Report%20for%20GP%20Central%20Europe.pdf
- Fairlie I. Uncertainties in Doses and Risks from Internal Radiation. Medicine, Conflict and Survival, Vol 21:2. pp 111 – 126. (2005) http://www.informaworld.com/smpp/content~content=a714004320~db=all~order=page
- Fairlie I. Tritium: The Overlooked Nuclear Hazard. The Ecologist. 22 No 5. 228-232 (1992)

B. Tritium Releases from SRBT

4. In recent years, SRBT has been emitting very large quantities of tritium – the radioactive isotope of hydrogen. See table 1. These are of the order of tens of terabecquerels per year (TBq/a – see radioactivity units at Annex B). One terabecquerel is 10^{12}, or one trillion Bq, a large amount or radioactivity. This tritium is released mainly in two forms – tritium gas (HT) and tritiated water vapour (HTO).

5. As a result of molecular exchange - explained in BOX 1 below - these two types of releases may be added together and treated as HTO. This is an important matter as the ICRP (in its Annual Limits of Intake) considers HTO, ie radioactive water, 25,000 times more radiotoxic than HT, radioactive hydrogen gas.

BOX 1. Molecular Exchange

SRBT and CNSC reports commonly distinguish between elemental tritium (HT) and tritiated water vapour (HTO) emissions. However in the environment, tritium atoms in HT rapidly exchange with stable H atoms in water through the phenomenon of molecular exchange. Therefore here all tritium releases are treated as HTO. This is common practice in OPG and AECL (Davis et al, 1997)

In more detail, in matter, all atoms engage in exchange reactions with like atoms in other molecules to varying degrees. This means that tritium atoms in HT swap positions with stable H atoms in the environment in the hydrosphere and in biota, including humans. H and T, the smallest atoms (apart from deuterium) are prominent as regards exchange reactions. These exchange reactions are very quick, taking about 10^{-15} seconds on average.

As the most common hydrogenous material in the environment is water in liquid or vapour forms, this means that tritium in HT relatively quickly transfers to HTO. In practical terms, open water surfaces and biota downwind, including food growing in the area, plants, animals and humans, would become contaminated with tritium up to the tritium concentration in the atmosphere. For example, it would include vegetables and fruit in exposed market stalls and shops (Inoue, 1993).

Table 1. Annual Tritium Emissions from SRB

Year	(HT and HTO) TBq
2014	66
2013	79
2012	30
2011	56
2010	36
2009	42
2008	40
2007***	42
2006**	285
2005*	1,224
2004	4,315
2003	6,758
2002	9,266
2001	13,868
2000	17,986

*In a letter dated November 17, 2005 and orally on November 18, 2005, SRBT informed the CNSC staff that “the tritium emission monitoring system may not be providing reliable measurements of the concentration and quantity of tritium released to the environment.” (Source: Canadian Nuclear Safety

Commission, document CMD 05-H26.C http://www.nuclearsafety.gc.ca/eng/commission/pdf/2005-11-30-H34C-UpdatedAgenda.pdf) This may have affected measurements during the 5-year licensing period, 2001-2005.
** During 2006, SRBT's Nuclear Substance Processing Facility Operating Licence NSPFOL-13.00/2006 restricted the company to use only one unit - the reclamation unit or a single beta light production filling rig to process tritium – at any given time. Prior to 2006, SRBT operated many units simultaneously.
***On January 31, 2007 the company's licence to process tritium was not renewed by the CNSC.

6. These annual emissions are lower than those from CANDU nuclear reactors - widely known to be prolific sources of tritium - but significantly higher than other reactor types – see table 2.

Table 2 Annual Tritium air emissions from various sources

Facility	**Year**	**TBq/a**
Darlington NPP, Ontario	2002-7	200 (average)
SRBT, Ontario	2014	66
Dungeness B (AGR) UK	2013	12
Sizewell B (PWR) UK	2013	3
Dungeness A (Magnox) UK	2013	2.6
All German NPPs (BWRs, PWRs)	2003	0.5 (average)

7. Table 1 also indicates that, before 2008, SRBT - apparently with CNSC's permission – released extremely large amounts of tritium to air each year. These emissions were higher than the annual tritium emissions from the large Candu nuclear power plants in Ontario, combined. These past emissions are still a matter of concern for reasons explained below.

8. In 2007, SRBT was required by CNSC to cease operations as a result of heavy groundwater tritium contamination around its Pembroke facility. However in 2010, SRBT was permitted by CNSC to resume tritium processing under a 5-year licence which will expire in May 2015.

9. According to its 2014 Annual Compliance Report[1], SRBT emitted 66 TBq of tritium in 2014. Although this is a welcome decrease from 79 TBq in 2013, there still is a upward trend since 2007. During the week of October 28 - November 4, 2014, SRBT reported a 2.14 fold "exceedance" of its weekly action level for tritium releases - releasing 16 TBq of tritium.

10. Canada's only other tritium light factory (SSI in Peterborough, Ontario) was abandoned by its operating company in 2012, partly as a result of local opposition arising from health concerns about its large tritium releases. http://www.nuclearsafety.gc.ca/eng/the-commission/pdf/2015-03-27-Report-on-the-Clean-up-and-Abandonment-of-Shield-Source-Inc-eng.pdf

[1] SRB Technologies (Canada) Inc, 2014 Annual Compliance and Performance Report http://srbt.com/ACR2014.pdf

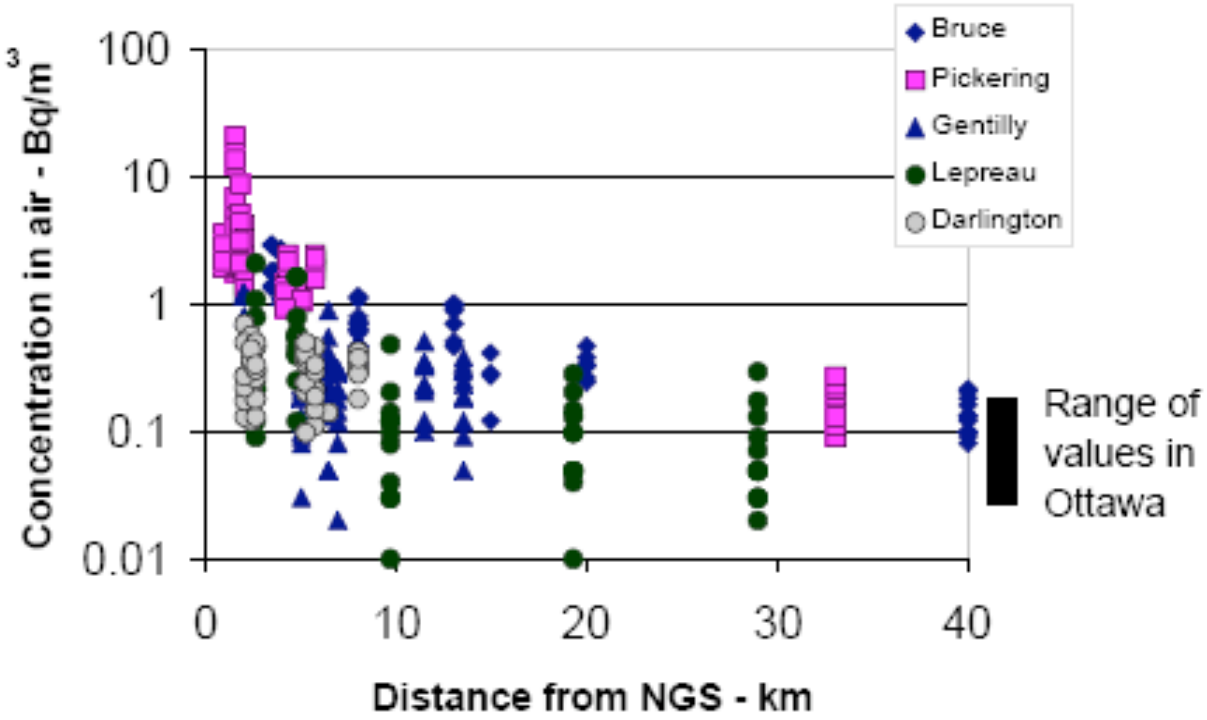
11. In the assessment of risk, aerial emissions are more important than liquid discharges for two reasons. First, the key parameters in estimating radiation doses to local people are nuclide concentrations in environmental materials. Contrary to what many people think, air emissions result in higher environmental concentrations than water discharges. The reason is dilution. A cubic metre of water contains a million grams of water which dilutes radioactive contaminants far more effectively than a cubic metre of air with a mass of ~10 grams: ie >100,000 times more effectively. This is not to accept that dilution is the solution to pollution. It isn't: it merely reflects the fact of existing (ill-advised) methods of disposing nuclear wastes. Second, individual and collective doses from air emissions are much larger than from discharges to water. Accordingly this report deals mainly with air emissions.

C. Are these Tritium Levels Safe?

12. To assess risks to local people, the official approach is to estimate tritium's radiation doses in mSv units, but there are many major problems with tritium's dosimetry – see Fairlie, 2007. Estimates of internal doses and risks from tritium are highly unreliable - see the conclusions of the CERRIE Report (2004). Instead of radiation doses, I shall use radioactivity: in other words I shall estimate tritium's Bq annual intakes and concentrations in local people and the resulting likely levels of risks. This approach has been used by other scientists (Osborne, 2002).It consists of four STEPS as follows.

13. STEP 1. Tritium emissions will result in raised tritium air concentrations near the plant as indicated in Figure 1 which shows tritium concentrations near nuclear power. These emit higher amounts of tritium compared to SRBT in recent years, but we can still use the following graphs to see what actually occurs and what the trends are.

Figure 1. Tritium concentrations in air near tritium-emitting facilities



(Figure reproduced with permission from Tritium in the Canadian Environment: Levels and Health Effects. Report RSP-0153-1. Prepared for the Canadian Nuclear Safety Commission under CNSC contract no. 87055-01-0184 by Ranasara Consultants and Richard Osborne. Data from Health Canada, 2001)

14. This graph indicates that the closer people live to a tritium-emitting facility, the higher the air concentrations of tritium. The logarithmic scale of the Y-axis compresses the data range: the highest air concentrations (30 Bq per cubic metre) are 3,000 times greater than the lowest (0.01 Bq per cubic metre).

15. Another point is that we need to know tritium concentrations in the air's water vapour rather than the air itself. If we assume a reasonable value of 10 grams of water per cubic metre of air (Davis et al, 1996) then the tritium water vapour concentration 1 to 2 km from (say) Pickering in the graph is 100 to 3,000 Bq per litre.

16. These data are point measurements. Air concentrations vary considerably and large spikes of tritium emissions may occur. Pulsed tritium emissions could result in heavy labelling of cells being formed in the embryos and fetuses of nearby pregnant women at that particular moment. This fear was expressed by Professor Edward Radford in his 1979 testimony to the Ontario Government's Select Committee on Ontario Hydro Affairs: Hearings on The Safety of Ontario's Nuclear Reactors, July 10 1979. See http://www.ccnr.org/tritium_2.html#scoha. This provides the basic mechanism for our hypothesis explaining the large observed increases in leukemias in subsequent children born near nuclear reactors (Fairlie, 2014).

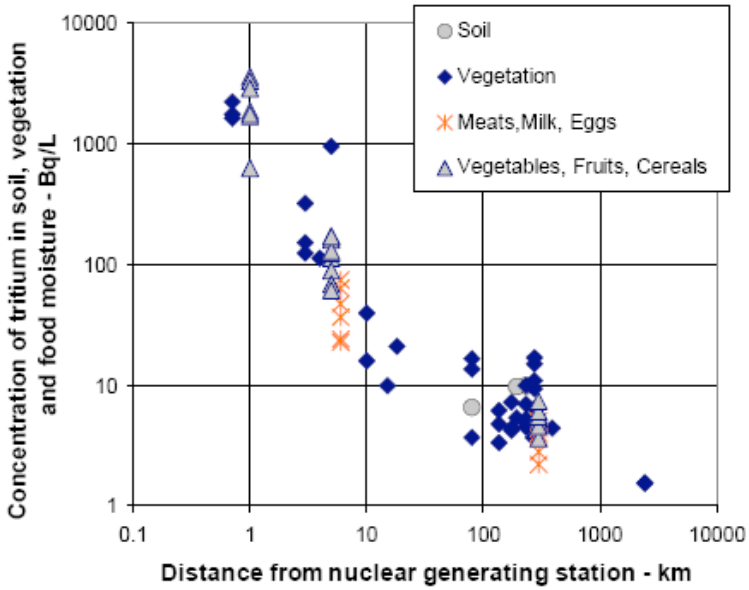
17. Appendix C of SRBT's 2013 Compliance Report[2] indicates about 8 such spikes in 2013 with tritium releases of 2 - 3 TBq and one of 6 TBq, compared to the average weekly release rate of about 1 TBq. Appendix B of SRBT's 2014

[2] http://www.srbt.com/ACR2013.pdf

Compliance report indicates 2 large spikes. Spikes are discussed further in Appendix D of this report.

18. STEP 2. The second step is that high tritium air concentrations result in raised tritium concentrations in foodstuffs, as seen in figure 2. In fact, several reports show raised tritium levels in foodstuffs near SRBT as discussed below.

Figure 2. Tritium concentrations in foodstuffs near tritium-emitting facilities



(Figure reproduced with permission from Tritium in the Canadian Environment: Levels and Health Effects. Report RSP-0153-1. Prepared for the Canadian Nuclear Safety Commission under CNSC contract no. 87055-01-0184 by Ranasara Consultants and Richard Osborne. Data from Health Canada, 2001)

19. STEP 3. The next step is to estimate tritium intakes in local people living near the SRBT facility. They will be exposed by

- ingesting foodstuffs contaminated with tritiated water vapour, eg from local markets and fruit stalls
- inhaling tritium gas and tritiated water vapour
- drinking tritiated water and milk, and
- skin absorption of tritiated water vapour

20. This means that local people could have high intakes of tritium, so that, ideally speaking, tritium concentrations in local people should be measured using urine analyses for HTO and non-invasive bioassays such as nail clippings and hair clippings for OBT.

21. Using the approach in Osborne et al (2002), we estimate annual HTO uptakes in people living close (within 2 km) to the SRBT plant to be about **200,000 Bq/year** to one significant figure**.** The calculations are set out in BOX B. Note this estimate assumes that people do not consume their own garden produce and do not drink

water from their own wells. It assumes people obtain one third of their food from local markets.

22. The estimate is given to one significant figure in recognition of the inherent uncertainties here. Some uncertainty exists about the estimated tritium concentrations in food and water, but these amounts are the smallest of the four intake categories below. Even if incorrect, they would not significantly affect the overall estimate. The largest source of uncertainty is the single (point) measurement of the HTO concentration in air. It would have been better to have used an average of several measurements, but these did not exist.

BOX B – Estimate of Annual HTO Intakes near SRBT

To calculate annual tritium intakes by residents near SRBT, we multiply together two parameters. First, average annual dietary, breathing and eating rates for adult Canadians. Second, HTO concentrations as measured by CNSC (2015) http://nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/srb-tech.cfm and by SRBT (2015) http://srbt.com/PRODUCE.pdf

Average breathing and eating rates for adult Canadians have been compiled by Health Canada (1994) from a national habit and diet survey. These values, together values for air and drinking water intakes from Health Canada (2001) are shown in the following table.

table i. Annual food, water and air intakes by adult Canadians

Source	**Average Intake**
Total foods	490 kg per year
Drinking water and made-up drinks	550 litres per year
Air	8,400 cubic metres per year

source: Health Canada (1994)
daily rates in Health Canada (2001) are multiplied by 365 days per year

table ii. Estimate of Annual HTO Intakes in people living near to SRBT (< 2 km)

Source of HTO	**Intake per year**	**HTO Concentration**	**HTO Bq/year**
Air Inhalation	8,400 m^3	12 Bq/m^3 (sample code SR03-A01) from http://nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/srb-tech.cfm	100,000
Skin absorption	60% of inhalation intake (Osborne, 1966)	12 Bq/m^3 (sample code SR03-A01) from http://nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/srb-tech.cfm	60,000
Food	33% of 490 kg = 160 kg (Assumptions *1/3 of food from local	177 Bq/kg (from local market 1.75 km distant) average reported by SRBT http://srbt.com/PRODUCE.pdf	28,000

	market *no home-grown food)		
Water in drinks	550 litres *no well water	9 Bq/L (from Lake Allumette 2 km distant) (sample code SR11-W04) from http://nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/srb-tech.cfm	5,000
TOTAL			~200,000 correct to one significant figure

23. Our 200,000 Bq/a estimate is higher than estimates near other tritium-contaminated sites. For example, Osborne et al (2002) estimated an annual HTO uptake of 67,000 Bq in people within 5 - 10 km of nuclear reactors[3]. Trivedi et al (1997) calculated annual HTO uptakes of 20,000 Bq in adults living in Deep River, Ontario (10 km from the AECL Chalk River reactor). Our estimate is also considerably larger than annual intakes of 6,000 Bq of HTO by adults from background (Osborne, 2002), about 30 times higher.

BOX C – Estimation of annual OBT Intake < 2km SRBT

To calculate annual OBT intake by residents near SRBT, we multiply together three parameters. First, average annual dietary intake for adult Canadians. Second, the parameter of 20% solid matter in foods. Third, the average OBT concentration in foods as measured by CNSC (2015) http://nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/srb-tech.cfm
table iii

Source of OBT	**Intake per year**	**Bq/kg -see table 4 on p 36 below**	**OBT Bq/year**
food	160 kg/a x 20% solid matter in foods	average = 116	4,000

24. As for OBT, our calculation in Box C above using tritium in food data from Thompson et al (2015) indicates that people within 2 km of the SRBT plant would also annually ingest approximately 4,000 Bq of OBT in their food. This compares with the Osborne et al (2002) OBT estimate of 7,000 Bq/a in people living within 5 - 10 km from nuclear reactors, and the Trivedi et al (1997) estimate of 800 Bq/a OBT in people living 10 km from the AECL Chalk River reactor. The 4,000 Bq/a OBT level is also larger than annual intake of 350 Bq OBT from background (Osborne et al, 2002), ie about 10 times higher. Table 2 sets out the comparisons for HTO and OBT annual intakes.

Table 2. Annual Tritium Intakes near various sites- Bq/a

[3] Osborne et al 2002 also estimated very high intakes of over 1,000,000 Bq/a for residents living very close to NPPs (within 1-2 km) but they assumed residents consumed produce from their highly contaminated gardens –the cause of such high intakes.

Source	Exposed people	HTO	OBT
this report	within 2 km of SRBT	200,000	4,000
Trivedi et al, 1997	10 km from Chalk River reactor	20,000	800
Osborne et al, 2002	5-10 km of Canadian NPPs	67,000	7,000
Osborne et al, 2002	background level in Canada	6,000	350

25. STEP 4. The last step is to address the original question in this section, ie are these annual tritium levels hazardous? To answer this we need a yardstick, which we construct in the next paragraph.

26. It is widely accepted that an annual risk of one in a million (10^{-6}) of fatal cancer from an exposure to a toxic agent is acceptable. Using this acceptable risk level, the Ontario Government's Ontario Drinking Water Advisory Council (ODWAC, 2009) http://www.odwac.gov.on.ca/reports/minister_reports.htm recommended a maximum concentration for tritium in drinking water of 20 Bq/L, after an initial period at 100 Bq/L. If we multiply the former concentration by Health Canada's average annual water intake (see Box B) of 550 litres for adult Canadians, we get **~10,000 Bq** of tritiated water per year, correct to one significant figure**.** This may be used as rough yardstick for an acceptable annual intake of tritium. It is true the yardstick depends on the value chosen for the drinking water limit, and different views exist on this - table 3 shows the various limits in play. In our view, it is reasonable to use the Ontario Government's 20 Bq/L limit.

Table 3. Tritium Concentration Limits in drinking water - Bq per litre

Agency	Date	Tritium Limit Bq per litre
Ontario Government's Advisory Committee on Environmental Standards	1994	20 (during initial 5 yr period -100)
EC (European Commission,1998)	1998	100
US State of Colorado target	2008	18
US State of California future aim	2008	15
Ontario Government (ODWAC,2009)	2009	20
CNSC design guide for groundwater (CNSC,2011)	2011	100

27. The 200,000 Bq per year we estimate for nearby people is 20 times higher than our annual yardstick. However even if a drinking water limit of 100 Bq/L were used, the annual intake at SRBT would still exceed the resulting limit by a factor of 3.

28. It is concluded from this analysis that people living near SRBT are being exposed annually to hazardous levels of tritium. We estimate that each year they will take up more tritium than people living within 5-10 km of nuclear facilities and much more tritium than they would normally take in from background levels. This will result in added radiation exposures which will increase their cancer risks.

D. The Hazards of Tritium

29. In order to appreciate the risks to local people from tritium uptakes and exposures, we need to discuss tritium's properties in some depth. In the past, nuclear scientists had tended to minimise the risks from tritium and to regard it as being only weakly radiotoxic. This is changing: in recent years, 10 major reports on tritium have been published by radiation safety agencies in the UK (AGIR, 2008), Canada (CNSC, 2010a; 2010b) and France. In France, the French Nuclear Safety Authority (ASN, 2010) published a comprehensive White Paper on tritium and the French Institute de Radioprotection and Nuclear Safety published six major reports on tritium (IRSN, 2010a; 2010b; 2010c; 2010d; 2010e; 2010f). In particular, the reports noted that tritium exposures resulted in internal radiation doses whose estimation contained uncertainties which could render them unreliable.

30. The most comprehensive report on tritium was published by the UK Government's senior Advisory Group on Ionising Radiation (AGIR, 2008). This report strongly recommended that tritium's hazard (ie, its radiation weighting factor) should be doubled from 1 to 2. However other scientists (Fairlie, 2008; Fairlie, 2007a; Fairlie, 2007b; Melintescu et al, 2007; Makhijani et al, 2006) have presented evidence for even larger increases in tritium's radiotoxicity, including the US EPA (2006) which recommended a 2.5 fold increase.

31. These reports draw attention to tritium's properties which mark it out as an unusually hazardous radionuclide. These include

a. its relatively long half life of 12.3 years
b. its mobility and cycling (as H_2O) in the biosphere,
c. its multiple pathways to man,
d. its ability to swap instantaneously with H atoms in adjacent materials,
e. its relatively high relative biological effectiveness (RBE) of 2 to 3,
f. its binding with cell constituents to form organically-bound tritium (OBT) with heterogeneous distribution in humans, and
g. its short-range beta particle, meaning that its damage depends on location within cellular molecules, eg DNA

32. For these reasons, tritium presents severe challenges to conventional dosimetry and health-risk assessment. Also, in its elemental form, tritium diffuses through most containers, including those made of steel, aluminium, concrete and plastic. In the oxide form, tritium is generally not detected by commonly-used survey instruments (Okada et al, 1993).

33. When tritium is emitted from SRBT (whether as water vapour or elemental tritium), it travels via multiple environmental pathways to reach humans. It cycles in the environment, as tritium atoms exchange quickly with stable hydrogen atoms in the biosphere and hydrosphere. This means that open water surfaces, rivers, streams and all biota, local crops and foods in open-air markets (Inoue, 1993) and humans will become contaminated by tritiated moisture up to ambient levels – that is, up to the air concentrations of the emitted tritium.

34. Humans can become tritiated by skin absorption, by inhalation of contaminated water vapour, and by ingestion of contaminated food and water. When tritium enters the body, it is readily taken up through exchange mechanisms and used in metabolic reactions and in cellular growth: over 60 per cent of the body's atoms are hydrogen atoms and every day about five per cent of these are engaged in metabolic reactions and cell proliferation. The result is that a proportion of the tritium taken in is fixed to proteins, lipids and carbohydrates, including nucleo-proteins such as DNA.

35. This is termed organically bound tritium (OBT) which is non-uniformly distributed and is retained for longer periods than tritiated water. ICRP dosimetric models assume the opposite – that tritium is homogenously distributed in the body/tissue/ organ of interest and is relatively quickly excreted. Exposures from OBT are therefore higher than from HTO. The longer people are exposed to tritiated water emissions, the higher their levels of OBT become until, in the case of exposures lasting years, equilibria is established between HTO and OBT levels. Again ICRP dosimetric models assume the opposite: only single exposures are considered so that OBT levels remain low.

36. Tritium, therefore, has unusual properties which suggest that it should be regarded as hazardous in radiation protection advice. Unfortunately these properties are not recognised by the ICRP and authorities which take their lead from the ICRP. This bad situation is made worse by the ICRP's incorrect dose model for tritium which results in the underestimation of tritium 'doses' and its risks. This is discussed further in Appendix F.

37. The main controversy is over the radiotoxicity of tritium as regards the ICRP's radiation weighting factor (w_R) for tritium of 1. See Fairlie (2007a). The debate has lasted more than fifty years. It should be borne in mind that the ICRP is not an official body, but a voluntary one. It operates rather like a trade association, principally concerned with protecting the interests of its members rather than those of the general public. It appears that non-scientific considerations may have played a part in the ICRP's decisions on tritium, as regards nuclear weapons production plants in the past and proposed fusion facilities more recently.

E. Organically Bound Tritium

38. The form of organically bound tritium (OBT) which is bound to carbon atoms is produced through photosynthesis in plants and by metabolic processes in animals. It is detected in most organic materials such as plants, animals and soils. A second form of OBT which is more loosely bound to P, N and S atoms is called exchangeable OBT.

39. The behaviour of OBT (both forms) in the environment is not well understood, eg it is very heterogenously distributed in natural ecosystems. Nevertheless OBT is increasingly recognized as being more significant than HTO in understanding tritium's behaviour in the environment. (Kim et al, 2013). This is partly because OBT

measurements provide a more accurate representation of tritium in the environment due to its longer retention time than HTO. (Kim and Roche, 2012)

40. OBT can be incorporated into all biochemical compounds, including amino acids, sugars, starches, lipids and cell structural materials: it therefore has longer retention times than tritiated water which only has a half life of about 10 days. Some biomolecules are very long-lived, e.g. phospholipids in nerve cells and the DNA and RNA macromolecules. These longer retention times result in OBT's greater radiotoxicity than tritiated water. The ICRP has recommended an OBT ingestion exposure coefficient 2.3 times greater than that for HTO[4]. However much evidence suggests it should be at least 5 times greater. (Fairlie, 2008).

41. Following a single HTO intake, the current ICRP model assumes 3% is bound as OBT and may be neglected. But Trivedi et al (1997) estimated that up to 9% is bound as OBT. Animal studies also indicate that OBT levels must be considered – essentially because OBT is cleared from the body more slowly than HTO. Commerford et al (1982) found, after a transient HTO exposure, tritium remained bound to DNA and histone 8 weeks later. They concluded that the OBT doses from them would exceed HTO doses overall.

42. The same goes for chronic exposures except more so. Commerford, Carsten and Cronkite (1977) found most of the tritium dose came from OBT, 2 to 3 days after stopping chronic HTO administration to mice. Rogers (1992) concluded OBT was the principal determinant in tritium doses to mice following chronic HTO exposure. Recently, Kim et al (2013a) discussed the OBT contribution to tritium exposures from chronic tritium releases to air. They compared 11 studies whose mean OBT contribution to total tritium exposures was 21%. In other words, any estimates of HTO exposures from SRBT emissions should be multiplied by the factor 5/4.

Longevity of OBT in the environment

43. Eyrolle-Boyer et al (2014) have suggested that OBT levels can persist in the environment for several decades. They found that terrestrial biomass pools, contaminated by global atmospheric fallout from nuclear weapons testing in the 1950s and 1960s, constituted a significant delayed source of OBT, resulting in an apparent enrichment of OBT levels of compared to HTO. This finding helps explain OBT/HTO ratios greater than 1 observed in areas not affected by industrial radioactive wastes. This finding supports the findings by Ichimasa (1995) of long-term raised OBT levels near Chalk River following chronic HT releases.

44. A recent study (Thompson et al, 2015) has emphasised the importance of OBT in the environment. It stated that, as soil acts as a repository for decaying organic matter, OBT soil concentrations represents long-term reservoirs of past tritium releases. It added "Our data support the mounting evidence suggesting that some parameters used in environmental transfer models approved for regulatory assessments should be revisited to better account for the behavior of HTO and OBT

[4] ICRP dose coefficients for adults are 1.8×10^{-11} Sv/Bq for tritiated water and 4.2×10^{-11} Sv/Bq for OBT.

in the environment and to ensure that modelled estimates (eg plant OBT) are appropriately conservative."

F. Tritium Concentrations in Food and Environment

45. Recently there has been a flurry of reports on observed tritium concentrations in the environment near SRBT. For example, Thompson et al (2015) measured HTO and OBT in soils and foodstuffs near the SRBT facility: these are set out in table 4. Both HTO and OBT concentrations are relatively high in comparison with normal background levels in Canada of about 1-2 Bq/L. OBT levels in most instances unexpectedly exceeded HTO concentrations: this is evidence of the past high tritium releases at SRBT. More data are set out by SRBT at http://srbt.com/PRODUCE.pdf

46. In addition, HTO concentrations in about 60 wells near SRBT over the past decade are set out at http://srbt.com/WELLS.pdf. These often indicate very high HTO levels –higher than the 4,000 Bq/L limit used by OPG for its liquid water tritium discharges, for example. Most also exceed the CNSC's design guide (CNSC,2011) for groundwater tritium of 100 Bq/L and the Ontario Government's recommended level of 20 Bq per litre for tritium (ODWAC,2009).

47. It would appear that groundwater contamination from SRB's tritium releases is out of control. When the CNSC issued SRBT its current 5-year licence in 2010, it carried out a modelling study which predicted reduced groundwater tritium concentrations for five of SRBT's monitoring wells through to 2019. During 2014, average groundwater tritium concentrations in these wells exceeded CNSC's modelled predictions by considerable margins, and in one case, by a factor of ten. It appears that neither CNSC nor SRBT understands the factors responsible for the continuing high groundwater contamination near the SRBT facility, as the highly variable well data reveal no downward pattern in HTO levels in recent years.

48. A partial explanation for these continuing high levels in local wells may be the relatively high annual discharges of tritium in liquid form. Appendix D of SRBT's Annual Compliance Report for 2014 http://srbt.com/ACR2014.pdf states that the liquid effluent tritium discharge in 2014 was 13 GBq (up from 9 GBq in 2013) although this amount is small compared to SRBT's 2014 air emissions (66,000 GBq).

49. Finally, data on tritium concentrations in local sewage have recently been released (CNSC, 2015a). These are also set out in table 4: they show higher than expected levels of (especially) OBT which appear to be increasing in recent years.

Table 4. HTO and OBT concentrations in foods, soils and sewage sludge near SRBT

	Year	Distance from SRBT km	Water content	HTO Bq/L	OBT Bq/L	OBT/HTO
soil	2008	0.4	0.19	102	1010	9.9
soil	2008	3.8	0.24	4.3	14.9	3.5
apple	2009	0.4	0.87	224	234	1.0
carrot	2008	0.4	0.91	75.5	69.1	0.9

carrot	2009	0.4	0.90	116	103	0.9
potato	2008	0.4	0.77	76	206	2.7
potato	2009	0.4	0.75	105	90	0.9
tomato	2008	2	0.94	15.3	66.3	4.3
tomato	2009	2	0.95	17.7	40.3	2.3
cucumber	2009	4.8	0.95	7.6	117	15.4
food average				80	116	1.5
sewage sludge*	2013	-	-	33 Bq/kg	290 Bq/kg	8.8
sewage sludge*	2014	-	-	34 Bq/kg	400 Bq/kg	11.8

sources: Thompson et al (2015) see table A3
*CNSC (2015a) Measurements and Dose Consequences of Tritium in Municipal Sewage Sludge. e-Doc: 4655459 (PDF) see table A.1

50. The overall conclusion from this data is that the local area around SRBT is very contaminated with tritium. Tritium levels do not appear to be decreasing. More HTO and OBT concentrations in foodstuffs and soil near the SRBT facility should be measured. Urine samples for HTO and non-intrusive bioassays (eg hair, nail clippings) of OBT levels should be undertaken in order that the risks of radiation exposures from OBT can be estimated.

G. Epidemiological Evidence of Risks

51. Because of methodological limitations, epidemiology studies are often a blunt tool for discovering whether adverse effects result from radiation exposures. These limitations include:

- underascertainment, ie people move away, or cases are not found or reported
- strict data requirements: ideally, epidemiology data is required with good case identification, uniform registration, clear diagnostic criteria and uniformity of data collation. These data requirements are often difficult to fulfil and make large demands on time and resources.
- confounding factors: the true causes of morbidity or mortality can be uncertain due to confounding factors such as socio-economic status and competing causes of death
- bias: smoking and alcohol cause major increases in overall mortality and morbidity, and in cancer and cardiovascular disease. These require careful handling of the raw data to avoid bias.
- poor signal to noise: only large, expensive and lengthy epidemiology studies are able to reveal effects where the signal (added cancers) is weak, and the noise (large numbers of spontaneous cancers) is strong.
- uncertain doses: establishing causality often requires estimating doses in order to show a dose-effect relationship. However, large uncertainties often exist in estimating doses - especially from internal radiation, eg from tritium.
- wide confidence intervals: usually findings (eg risks or odds ratios) are expressed with 95% confidence intervals- that is, the range of values within which the true value lies 95% of the time. But often this range can be very wide - simply because of low numbers of cases. This can severely limit what we can conclude from the findings.

52. Many epidemiology studies are ecologic studies, that is, quick studies which look at health or population stats and not individual data. Their findings are usually regarded as indicative not conclusive. If their findings suggest an adverse effect then these should be investigated further by more detailed cohort or case-control studies. The latter match “cases” (ie those who have an adverse effect) with randomly-selected similar individuals, in order to minimise underascertainment. However fewer of these are carried out because of their expense and long time-spans.

53. We need to be aware of the many factors to be taken into account when considering epidemiology studies, and we need to interpret their findings with care. Readers are advised to lower their expectations when considering the following studies - which are all ecologic.

(i) Leukaemia in children near Candu nuclear facilities

54. Clarke et al. (1989, 1991) studied mortality and incidence of childhood leukaemia near nuclear facilities in Ontario. The first report (Clarke et al. 1989) considered leukaemia deaths and cases at ages 0-4, and the second (Clarke et al. 1991) considered cases and deaths at ages 0-14. Data for areas “nearby” (<25 km) the 16 reactors at Bruce and Pickering over the period 1971-1987 were pooled together to increase statistical significance. The findings were 36 leukemia deaths aged 0-14 vs 25.7 expected (SMR = 1.40, 95% CI 0.98 - 1.9) indicating excess leukemia mortality with borderline statistical significance. However the confidence intervals were wide: the data were consistent with there being no increase and with there being a 90% increase in leukemia.

55. However there were indications which warranted further investigation: higher leukemia death rates after the reactors had started than before; more deaths when counted at place of birth than at place of death; and the size of the higher confidence interval. It is notable that different levels of statistical significance were adopted by the two reports. The first was 10%, and the second 5%. If the 10% level had been used in the second study as it had been in the first, the leukemia increase would have been considered "statistically significant". The authors recommended further case-control research which was not carried out.

(ii) Birth defects and infant mortality in the vicinity of the Pickering nuclear facility, Ontario

56. Johnson and Rouleau (1991) studied birth defects, stillbirths, perinatal, neonatal and infant mortality within 25 km of the Pickering nuclear station. They also studied these endpoints in relation to airborne and waterborne discharges of tritium from Pickering, concentrating on the Pickering and Ajax townships closest to the Pickering plant.

57. The incidence of central nervous system defects was significantly elevated in Pickering township for the highest level of airborne tritium emissions (odds ratio in highest group = 4.01 (95% CI; 1.25, 14.04), based on 6 cases) but no statistically significant trends with tritium emissions (p=0.197) or ground monitoring data (p=0.24) were observed.

58. Births with Down Syndrome in Pickering township were significantly increased (24 observed vs 12.9 expected (relative risk = 1.85, 95% CI = 1.19, 2.76). But 23

other birth defect endpoints did not show such an excess. The raised incidence of Down Syndrome cases was notable, as many Chernobyl studies also indicate excesses in areas exposed to radioactive fallout. However the authors of the study queried why the incidence of Down Syndrome alone should be increased and not other forms of congenital malformation. This does not provide a reason to discount the observed association between tritium exposures and Down Syndrome.

(iii) Offspring of Canadian nuclear workers

59. Green et al (1997) assessed cases of congenital abnormalities and matched controls in the offspring of Canadian nuclear workers. (763 case-control pairs of fathers, and 165 case-control pairs of mothers.) Tritium doses were assessed for those cases/controls having a recorded tritium dose 60 days before conception vs those with no dose. The study revealed increased chromosomal disorders with tritium exposure, but the number of cases (two) is small and confidence intervals wide.

(iv) Offspring of Ontario radiation workers

60. McLaughlin et al (1992, 1993) considered cases of childhood leukaemia in the offspring (aged 0-14) of Ontario radiation workers and matched cases. Tritium workers were those employed at the AECL laboratories at Chalk River, and 5 power stations (Rolphton, Pickering (A, B), Bruce (A, B)). (112 cases and 896 controls). Preconceptional tritium doses were assessed for this group. There was some evidence of raised risks with internal tritium + external radiation exposures but with wide confidence intervals.

(v) Durham Region Health Department (2007)

61. This study showed statistically significant elevated rates of several radiogenic cancers near the NPPs east of Toronto. Leukemia incidence in males were significantly increased in Ajax-Pickering and Clarington males in 1993-2004. This study was based on municipal borders, about 10 km from the reactors. The authors admitted some findings were of concern and recommended further more accurate studies, but none have been done. However the report was at pains to conclude that the overall findings did not indicate a pattern.

(vi) **Lane Study (Lane et al, 2013)**

62. This study purportedly sought to determine whether radiation doses to members of the public living within 25 km of the Pickering, Darlington and Bruce nuclear power plants (NPPs) were causing an increase in cancer rates from 1990-2008. It reported that some types of cancers were statistically higher than expected but no overall pattern could be seen.

(vii) Wanigaratne et al Study (2013)

63. This study examined cancer incidences (1985–2005) among Pickering and north Oshawa residents, including all cancers, leukemia, lung, thyroid and childhood cancers (6–19 years). Person-years analysis showed female childhood cancer cases to be significantly higher than expected (SIR = 1.99, 95% CI: 1.08–3.38). It concluded that “multiple comparisons were the most likely explanation for this finding”.

64. The above studies mostly show increased ill effects, some statistically significant and others with borderline statistical significance. Some studies showed no increases for specific illnesses, but as Altman and Bland (1995) stated “absence of evidence is not evidence of absence”. In addition, the methodological limitations and small sizes of some of these studies mean they were simply unable to detect effects with statistical certainty.

65. Despite the positive numerical findings, the published conclusions of these studies were invariably negative, often on the flimsy grounds of inconsistent results, too many comparisons, lack of an overall pattern etc.

66. With this in mind, our conclusion is that the above studies taken together provide suggestive, albeit limited, evidence for increased health effects from exposure to tritium. These could be confirmed with case-control or cohort studies. More important, considerable evidence from cell and animal studies and radiation biology theory indicates that adverse effects will occur. This is backed by evidence from recent, large scale, statistically powerful epidemiology studies – see http://www.ianfairlie.org/news/recent-evidence-on-the-risks-of-very-low-level-radiation/

H. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

67. Annual tritium emissions to air from SRBT’s light factory at Pembroke, Ontario are large compared to most nuclear power stations in the world, and are comparable to those from Canadian reactors which are prolific tritium sources. Tritium emissions were extremely large in the early and mid 2000s, and following a brief decline appear to be increasing.

68. Major international agencies recognise that tritium has unusual properties marking it as a hazardous nuclide. It is extremely mobile in the environment, contaminates all biota in nearby areas including humans to ambient levels, and binds with organic matter to form OBT with long residence times in the body making it more radiotoxic.

69. Environmental measurements of soils, foodstuffs, wells and sewage near the facility indicate pervasive tritium contamination of local areas. Tritium levels in wells are in most cases higher than the CNSC’s design guide for groundwater tritium, and much higher than the Ontario Government’s ODWAC recommended level for tritium in drinking water. It appears that neither CNSC nor SRBT understands the factors responsible for the continuing high groundwater contamination near the SRBT facility. Tritium levels in environmental samples are erratic but do not appear to be declining. Recent tritium measurements in foodstuffs and municipal sewage reveal unexpectedly high levels of OBT. These lead to increased concerns about tritium contamination in the area.

70. We estimate that annual tritium intakes for local residents (who neither consume their own garden produce nor drink from their own wells) amount to about 200,000 Bq, mainly from inhalation and skin absorption of tritiated water vapour in

the vicinity of SRBT. These amounts are higher than the yardstick of 10,000 Bq/a for acceptable intakes and higher than the natural background intake of 6,000 Bq/a. OBT exposures will also occur.

71. These intakes increase the probability of cancer and other diseases in exposed people. It is not possible to ascertain in advance who will be affected but embryos, fetuses, babies, infants and children are more radiosensitive than adults, and females more than males. These cancers will arise in the future because they have long latency periods in most cases. Probabilistic effects mean exposed people will have each been handed "negative" lottery tickets, and some tickets will come up in future.

72. Epidemiology studies of Canadian facilities emitting tritium suggest increases in cancer and congenital malformations: these could be confirmed with case-control or cohort studies. More important, considerable evidence from cell/animal studies and radiation biology theory indicates that adverse effects will occur. This is backed by evidence from recent, large scale, statistically powerful epidemiology studies – see http://www.ianfairlie.org/news/recent-evidence-on-the-risks-of-very-low-level-radiation/

Justification

73. The most important of the ICRP's three basic principles of radiation protection (Justification, Optimisation and Limitation) is that of Justification. This requires SRBT and CNSC to justify the radiation exposures from SRBT by assessing their health detriment in relation to any economic or social benefits they may have. In other words, the advantages have to be balanced with the disadvantages As far as can be seen, this assessment has not been carried out.

74. In Europe, Euratom Directive 96/29 requires all European Governments to introduce legal provisions "*for the protection of the general public from the dangers of ionising radiation*". Under Article 6.1 of the Directive, any practice involving radiation exposures is required to be justified "*by its economic, social and other benefits in relation to the health detriment they may cause*". This includes numerical assessments of the number of cancer deaths likely to be caused.

75. This is a stiff requirement and is likely the reason SRBT's predecessor company Saunders and Roe moved its tritium lamp-filling operations from the UK to Canada in the 1980s. In other words, these operations could not be "Justified" under European law in Europe.

76. The principle of Justification should be applied by CNSC and SRBT "*for the protection of the general public from the dangers of ionising radiation"*, as regards the 25,000 people living near Pembroke.

Recommendations

77. It is recommended that the following steps are implemented

i. SRBT and CNSC should justify the proposed radiation exposures from SRBT as required by the ICRP's basic principles and by all EU countries. In other words, they should assess their health detriment in relation to any economic or social benefits they may have.

ii. CNSC should ensure the Ontario Government's ODWAC recommendation of 20 becquerels per litre (Bq/L) for drinking water is met for all Pembroke citizens.

iii. CNSC should implement its own design guide for groundwater for tritium of 100 Bq/L for tritium levels in wells near SRBT.

iv. In view of the apparent increases in HTO and OBT levels in the local environment, the CNSC's annual release limits for tritium emissions should be reduced by considerable margins. Current DRLs, based on unreliable "dose" estimates, should be discarded.

v. In view of the unexpectedly high OBT levels, the CNSC should commission an independent report on the findings of OBT levels in food and sewage sludge near SRBT with a mandate to make recommendations.

vi. Urine tests and non-invasive bioassay tests should be carried out on volunteers from the community to ascertain HTO/OBT levels.

vii. Local residents should continue to avoid consuming locally-grown foods and water from local wells.

viii. In view of the discussion in Appendix E, local women intending to have a family, and families with babies and young children should consider moving elsewhere. It is recognised this recommendation may cause concern but it is better to be aware of the risks to babies and young children than ignorant of them.

ix. SRBT employees, especially the teenagers, should be informed about the hazards of tritium.

x. In the longer term, it is recommended that the SRBT facility be relocated to a more remote area. This may be overtaken by events, as it is likely that the use of radioactive lamps will decline due to increasing market penetration of solar powered photo-voltaic (PV) lamps, especially in Europe and US. The recent steep declines in the costs of PV materials and energy storage systems contrast sharply with the high costs of tritium lamps.

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APPENDICES

APPENDIX A. NEW INFORMATION ON RADIATION'S EFFECTS

The SRBT's application and the CNSC's response fail to discuss the new information of non-targeted (ie on DNA) effects of radiation. These effects include genomic instability where effects occur many generations later, and bystander effects where adjacent cells not hit by radiation are damaged and minisatellite mutations.

The New Effects of Radiation

These "new" effects were in fact discovered about 18 years ago[5], for example, Khadim et al (1992) discovered genomic instability effects in 1992. However they have not been not widely discussed in the popular press. Indeed, there is little public awareness of these effects in Canada and the US. This is partly due to their absence in mainstream reviews such as those published by the former NRPB, USEPA, ICRP and BEIR (and only recently by UNSCEAR in 2009). Nevertheless these new effects have resulted in a "paradigm shift" in scientists' views as evidenced by the articles in the Box below, and they continue to be intensively discussed among radiation biologists.

Box: Untargeted effects: a paradigm shift?

Baverstock K (2000) Radiation-induced genomic instability: a **paradigm-breaking** phenomenon and its relevance to environmentally induced cancer. Mutation Research 454 (2000) 89–109.
Baverstock K and Belyakov OV (2005) Classical radiation biology, the bystander effect and **paradigm**s: a reply. Hum Exp Toxicol 24(10):537–542.
Bridges BA (2001) Radiation and germline mutation at repeat sequences: Are I in the middle of a **paradigm shift**? Radiat Res 156 (5 Pt 2):631-41.
Hall EJ and Hei TK (2003) Genomic instability and bystander effects. Oncogene vol 22, pp 7032-7042. "Both genomic instability and the bystander effect are phenomena, discovered relatively recently, that result in a **paradigm shift** in our understanding of radiation biology."
Matsumoto H, Hamada N, Takahashi A, Kobayashi Y, Ohnishi T. (2007) Vanguards of **paradigm shift** in radiation biology: radiation-induced adaptive and bystander responses. J Radiat Res (Tokyo). 48(2):97-106.
Morgan WF (2002) Genomic instability and bystander effects: a **paradigm shift** in radiation biology? Mil Med. 167(2 Suppl): 44-5.
Waldren CA (2004) Classical radiation biology dogma, bystander effects and **paradigm shifts.** Hum Exp Toxicol. 23(2):95-100.

Importance for risk estimation

[5] Some scientists (Baverstock, 2000; Baverstock and Belyakov, 2005) consider that non-targeted effects had in fact been observed in cell/animal studies many years previously but had been unrecognised as they fell outside the then accepted "paradigm" of radiation's effects.

Non-targeted effects are important in assessing radiation risks for a number of reasons.

First, they do not rely on structural damage to DNA or genetic structures for their effects, heretofore the classic explanation for radiation's effects. This is a vital matter because, up to recently, radiation protection authorities had relied on the classic theory to lend support to their estimates for radiation risks derived from epidemiology. That is, the classic theory of radiation's effects (ionisation-induced DNA strand breaks) buttressed[6] current estimates of radiation risks. The new effects do not do this.

Second, these effects occur at very low doses of radiation. In fact, some effects occur after the passage of a single alpha particle through a cell (resulting in a less than 10 mGy dose to the cell). A third reason is that, as many genome instability effects and bystander effects are present in malignant cells, most scientists now think that genomic instability is a precursor to cancer.

Annex C of the UNSCEAR 2009 report stated (paragraph 158) "it would seem prudent to consider the implications of non-targeted and delayed effects of radiation exposure when considering models of radiation carcinogenesis, particularly at low doses." And "…models of radiation-induced carcinogenesis should incorporate both direct and indirect effects when evaluating radiation risks."

When faced with the uncertainties posed by non-targeted effects, it would be wise to apply the Precautionary Principle. One means of doing this would be to recognise publicly that radiation risks are likely to be greater than currently estimated and to add a safety factor – by increasing current official estimates of doses by factor of 10.

APPENDIX B. UNCERTAINTIES IN "DOSE" ESTIMATES

The SRBT and CNSC reports contain tables with doses to members of the public: these are invariably very small. However these do not explain that these are estimates not measurements and may contain large uncertainties.

How these dose estimates are derived is not widely understood by scientists, and usually not at all by members of the public. In fact, the method is complicated, as they are derived using many computer models in sequence, with the median value from each model being plugged into the next model. Although there are many smaller sub models, the main models include

- environmental transport models for radionuclides, including weather models
- human metabolism models for nuclide uptake, retention and excretion
- dose models which estimate doses from internally retained nuclides, and
- risk models

[6] ie in dose terms, radiation's effects were related to the chances of damaging genes: the smaller the target gene, the larger the dose required to cause damage. Thus, effect and dose were related through radiation damage in irradiated DNA.

A major source of uncertainty is that we often do not know where radionuclides wind up inside the body after inhalation/ingestion. It is often assumed they are uniformly distributed but this is unknown.

Each of the above model results will contain uncertainties which have to be combined to gain an idea of the overall uncertainty in the final dose estimate (Fairlie, 2005). Further uncertainties are introduced by unconservative radiation weighting factors and tissue weighting factors in official models (Fairlie, 2007a). The cumulative uncertainty in dose estimates could be very large as formally accepted by the UK Government's CERRIE Committee in 2004 (www.cerrie.org) particularly for internal emitters.

APPENDIX C. OTHER PROBLEMS WITH THE CONCEPT OF "DOSE"

Indeed, there are problems with the concept of "dose" itself; including its various definitions and units (Sv and Gy): the sievert (Sv) unit has two different definitions for example. The "dose" concept may give reliable results when **external** radiation (eg X-rays or gamma rays) is physically measured by counting devices such as common Geiger counters, but not with **internal** radiation which cannot be measured except with whole body monitors- ie very rarely. It is noted that in the parallel field of chemical toxicity, "dose" is not used: concentrations per gram are used instead.

Since almost all of the radioactivity from SRBT emissions results in internal radiation, this report does not rely on radiation "dose" but instead uses concentrations of radionuclides measured in becquerels (Bq) per kg or per litre. When a radionuclide decays inside the body, it gives off radiation (alpha, beta or gamma) which results in body tissues being irradiated. The unit of radioactivity is the becquerel (Bq) defined as one atomic disintegration per second. Bq concentrations have the merit of being measurable: ie one can make relatively good measurements of how much radioactivity is inside a person (eg, from bioassays). These measurements are considerably more reliable than "dose" estimates from internal nuclides.

APPENDIX D. SPIKED RELEASES

Brief exposures to high concentrations are more hazardous to residents near SRBT than chronic exposures to low concentrations. This is partly due to environmental factors (eg wind direction) and partly to metabolic factors: exposures to high concentrations result in higher internal doses due to the labelling of dividing cells and cell proteins at high levels particularly with radioactive tritium inhaled/ingested from SRBT emissions.

Recently the UK National Dose Assessment Working Group published guidance on "Short Term Releases to the Atmosphere" http://www.ndawg.org/documents/NDAWG-2-2011_000.pdf. This states that "...exposures from the assessment of a single realistic short-term release are a factor of about 20 greater than doses from the continuous release assessment." An older German study (Hinrichsen, 2001) indicated that these exposures could be a factor of 100 greater.

The reason is partly related to the duration of the release, as short-term releases produce narrow plumes. Longer durations mean that the width of the plume

increases (widths vary non-linearly as a fractional power of duration) with the result that individual doses increase per Bq emitted with shorter releases. The reason is also partly due to the fact that spikes result in high concentrations especially in OBT in environmental materials and in humans: these have longer retention times in humans resulting in higher exposures.

APPENDIX E: INCREASED INCIDENCES OF CANCER NEAR NPPs

Recent epidemiological studies indicating increases in child leukemias near NPPs in Europe is of relevance to the SRBT situation, as both NPPs and SRBT emit relatively large amounts of tritium.(For example, the annual average for tritium emissions from all German nuclear power stations in 2003 (a representative year) was 0.53 TBq – much lower than the 79 TBq from SRBT.)

In the late 1980s and early 1990s, several UK studies revealed increased incidences of childhood leukemia near UK nuclear facilities. Recent epidemiological studies have reopened the child leukemia debate.

The most important of these is the KiKK study (Kinderkrebs in der Umgebung von Kernkraftwerken = Childhood Cancer in the Vicinity of Nuclear Power Plants) Spix et al (2007) and Kaatsch et al (2008). It found a 60% increase in solid cancer risk in embryos and a 120% increase in leukemia risk among children under 5 years living within 5 km of all German nuclear reactors. The KiKK findings are important because it was a large well-conducted study; because it was scientifically rigorous; because its evidence was very strong; and because the German Government, which commissioned the study, confirmed its findings.

The KiKK study is presently the subject of much discussion throughout the world. It is too early to provide an explanation for the increased cancers, although radiation exposures are implicated. One hypothesis (Fairlie, 2014) proposes that infant leukemias are a teratogenic effect resulting from *in utero* exposures to radiation from intakes of radionuclides during pregnancy. It suggests that exposures from NPP emissions to embryos/foetuses in pregnant women living nearby may be much larger than currently estimated, and that haematopoietic tissues may be considerably more radiosensitive in embryos and fetuses than in children.

Official organizations have found it difficult to accept that the large cancer increases near NPPs are due to radioactive emissions. This is mainly because their “dose” estimates from NPP emissions are too small by factors of 100 to 1000 times to explain the observed increases in risks. This of course assumes that official dose estimates and risk models are correct and without uncertainties. The UK Government CERRIE Committee in 2004 www.cerrie.org concluded the opposite.

APPENDIX F: NEED FOR A HAZARD INDEX OF RADIONUCLIDES

The hazards of tritium raise the question about how radiation protection authorities classify dangerous radionuclides: the short answer is that they do not. There is no comprehensive hazard index for radionuclides as there is for chemicals, for example. Many scientists consider there should be one because the properties of nuclides

would be better recognised if one existed. Kirchner (1990) has suggested the following characteristics should be included in a hazard index:

- large releases to environment;
- widely used in society (industrial/military/research/medical uses);
- rapid nuclide transport, solubility and cycling in biosphere;
- global distribution and resulting large collective doses;
- many environmental pathways to humans;
- rapid molecular exchange rates (that is, fast uptake by humans);
- large uptake fractions to blood after intake;
- organic binding in biota;
- long biological half-life in humans;
- long radiological half-life;
- long nuclide decay chains with radiotoxic daughters;
- high radiotoxicity (the dose coefficient of the nuclide, that is, the radiation dose imparted from the disintegration of one atom of the nuclide).

Tritium is unique in that it exhibits so many of these characteristics – in fact, ten of the above twelve, with most other nuclides exhibiting only three or four traits.

This raises a further question – how do radiation authorities gauge the relative hazards of nuclides at present? The answer is by estimating radiation ‘dose’ from the nuclide to an exposed person from one disintegration of that nuclide. This was discussed in Appendices B and C, but using ‘dose’ alone ignores the first six of the above twelve characteristics. In other words, ‘dose’ is an inadequate indicator of hazard for most radionuclides, and for tritium, it’s a very poor one.

SCIENTIFIC ANNEXES

ANNEX A. ACRONYMS AND ABBREVIATIONS

AECB	former Atomic Energy Control Board (now CNSC qv)
Bq	becquerel (SI unit of radioactivity)
CERRIE	UK Committee Examining the Radiation Risks of Internal Emitters
Ci	curie (US unit of radioactivity)
COMARE	UK Committee on the Medical Aspects of Radiation in the Environment
CNSC	Canadian Nuclear Safety Commission
DNA	deoxyribose nucleic acid
EC	European Commission
EPA	US Environmental Protection Agency
EU	European Union
Gy	gray (unit of absorbed radiation dose)
HTO	tritiated water
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LET	lineal energy transfer, energy transferred per unit length of track
LNT	linear no-threshold (radiation's dose-effect relationship)
NEA	Nuclear Energy Agency of the OECD
NCI	US National Cancer Institute
NPP	nuclear power plant
NRC	US Nuclear Regulatory Commission
NRPB	former UK National Radiological Protection Board
OBT	organically bound tritium
OPG	Ontario Power Generation Ltd
rad	US unit of absorbed radiation dose
rem	US unit of radiation dose
SI	Systeme Internationale
Sv	sievert (SI unit of equivalent or effective radiation dose)
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

ANNEX B. SYSTÈME INTERNATIONALE (SI) UNITS

E = exa	= 10^{18}	d = deci (one tenth)	= 10^{-1}
P = peta	= 10^{15}	c = centi (one hundredth)	= 10^{-2}
T = tera (one trillion)	= 10^{12}	m = milli (one thousandth)	= 10^{-3}
G = giga (one billion)	= 10^{9}	μ = micro (one millionth)	= 10^{-6}
M = mega (one million)	= 10^{6}	n = nano (one billionth)	= 10^{-9}
K = kilo (one thousand)	= 10^{3}	p = pico (one trillionth)	= 10^{-12}

Common examples are:

PBq	= petabecquerel (one million billion becquerels)	= 10^{15} Bq
TBq	= terabecquerel (one trillion becquerels)	= 10^{12} Bq
GBq	= gigabecquerel (one billion becquerels)	= 10^{9} Bq
mSv	= millisievert (one thousandth of a sievert)	= 10^{-3} Sv
μSv	= microsievert (one millionth of a sievert)	= 10^{-6} Sv
nSv	= nanosievert (one billionth of a sievert)	= 10^{-9} Sv

CONVERSION BETWEEN SI AND US UNITS

CURIES TO BECQUERELS

1 curie	= 1 Ci	= 37 x 10^{9} Becquerels
1 millicurie	= 1 mCi (10^{-3} Ci)	= 37 x 10^{6} Becquerels
1 microcurie	= 1 μCi (10^{-6} Ci)	= 37 x 10^{3} Becquerels
1 nanocurie	= 1 nCi (10^{-9} Ci)	= 37 x 10^{0} Becquerels
1 picocurie	= 1 pCi (10^{-12}Ci)	= 37 x 10^{-3} Becquerels

BECQUERELS TO CURIES

1 petabecquerel	= 1 PBq (10^{15} Bq)	= 27 x 10^{3}	curies
1 terabecquerel	= 1 TBq (10^{12} Bq)	= 27 x 10^{0}	curies
1 gigabecquerel	= 1 GBq (10^{9} Bq)	= 27 x 10^{-3}	curies
1 megabecquerel	= 1 MBq (10^{6} Bq)	= 27 x 10^{-6}	curies
1 kilobecquerel	= 1 kBq (10^{3} Bq)	= 27 x 10^{-12}	curies
1 becquerel	= 1 Bq	= 27 x 10^{-15}	curies

REMS TO SIEVERTS

1 rem	= 1 rem	= 10^{0} rem	= 10 millisieverts
1 millirem	= 1 mrem	= 10^{-3} rem	= 10 microsieverts
1 microrem	= 1 μrem	= 10^{-6} rem	= 10 nanosieverts

SIEVERTS TO REMS

1 sievert	= 1 Sv	= 1 Sv	= 100 rem
1 millisievert	= 1 mSv	= 10^{-3} Sv	= 100 millirem
1 microsievert	= 1 μSv	= 10-6 Sv	= 100 microrem

ANNEX C. GLOSSARY OF COMMON RADIATION TERMS

Absorbed dose — Quantity of energy imparted by ionising radiation to unit mass of matter such as tissue. 1 Gy = 1 joule per kilogram.

Activity — rate at which radioactive substances decay. Unit – the becquerel (Bq).
1 Bq = 1 disintegration per second.

Annual limit of intake (ALI) — The amount of material inhaled or ingested in 1 year that would result in a committed effective dose of 20 mSv.

Beta particle — An electron emitted by the nucleus of a radionuclide.

Decay — The process of spontaneous transformation of a radionuclide. The decrease in the activity of a radioactive substance.

Decay product — A nuclide or radionuclide produced by decay. It may be formed directly from a radionuclide or as a result of a series of successive decays through several radionuclides.

Dose — General term for quantity of radiation. See absorbed dose, effective dose, equivalent dose.

Dose factor — committed effective dose resulting from the inhalation or ingestion of 1 Bq of a given radionuclide. Unit - sievert per becquerel, symbol - Sv/Bq.

Effective dose — The quantity obtained by multiplying the equivalent doses to various tissues and organs by the tissue weighting factor appropriate to each and summing the products. Unit sievert, symbol Sv.

Equivalent dose — The quantity obtained by multiplying the absorbed dose by the appropriate radiation weighting factor to allow for the different effectiveness of the various ionizing radiations in causing harm to tissue. Unit sievert, symbol Sv.

Gamma ray — A discrete quantity of electromagnetic energy, without mass or charge.

Half-life — The time taken for the activity of a radionuclide to lose half its value by decay.

Ionisation — The process by which a neutral atom or molecule acquires or loses an electric charge. The production of ions.

Ionising radiation — Radiation that produces ionisation in matter.

Nuclear fission — The process in which a nucleus splits into two or more nuclei and energy is released.

Radionuclide — An unstable nuclide that emits ionizing radiation when it decays.

Risk factor — The probability of fatal cancer or leukaemia per unit effective dose.
Sievert — See effective dose.