# Review of the Greenpeace report:

# "Tritium Hazard Report: Pollution and Radiation Risk from Canadian Nuclear Facilities" I. Fairlie, 2007 June

**by**

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**Prepared for the**

**Canadian Nuclear Association**

**2007 August 13**

# Review of the Greenpeace report: "Tritium Hazard Report: Pollution and Radiation Risk from Canadian Nuclear Facilities"

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## Summary

The report has been written in two main parts. Part 1 discusses the basic properties of tritium and the levels of tritium in the Canadian environment. It is based largely on the data in a document prepared for the Canadian Nuclear Safety Commission in 2002. In that document, the exposures to tritium of individual members of the public were estimated for three environments; one representative of the tritium levels distant (~ 40 km or more) from nuclear facilities, another representative of the area around a nuclear facility where tritium is produced or handled and the diet is of locally produced foods, and a third area, very close to a nuclear facility with a diet that includes some fruit and vegetables from a garden adjacent to the facility. Although it is clear from the text that some of the aspects of behavior of tritium in the environment and of the biokinetics of tritium are misunderstood by the author of the Greenpeace report, the analysis yields similar values for the exposures except for the environment with the highest levels. Here, the quite unrealistic assumption was made that the complete diet could be provided by the local garden; an assumption that more than doubled the estimated exposure. Nevertheless, the Greenpeace report notes that based on the current understanding of the dosimetric implications of these levels of tritium, even with the unrealistically high value calculated in this report, the doses to the general public "are miniscule", and are not a health concern. However, the report claims that the current understanding of the dosimetry and biological effects of tritium is wrong, that the doses from tritium are much more significant than currently acknowledged (by a factor of ten at least, which is supposedly shown in Part 2 of the report and its appendices), and that there are real implications for health. The analysis in Part 2 and the appendices does not support this contention. There are misinterpretations and misunderstandings of the scientific literature and no new points are made. The text is largely based on a paper prepared by a European NGO

for a review by a UK committee in 2003; a review that found the analysis unpersuasive. The additional material presented in this Greenpeace version is a review of Canadian epidemiological studies but it has misinterpretations of the various studies and provides no evidence for the observation of any effects on health from tritium.

Based on the claimed hazard from tritium near nuclear facilities in Canada, Greenpeace make six recommendations. Two in particular are completely unjustified; namely that pregnant women and young children should not live near nuclear facilities and that food from gardens near nuclear facilities should not be consumed. This is unwarranted fear-mongering. Even if the doses from tritium were to be ten times those that could conceivably be the maximum, such recommendations would be unnecessary. The recommendation to set up a committee in Canada to examine tritium dosimetry and risks is reasonable, given the nature of the Canadian nuclear power program, but it should comprise experts in the relative scientific and medical fields (much like the CNSC's former Advisory Committee on Radiological Protection) rather than representatives from particular groups as suggested. Given the low doses to members of the public from tritium, it is difficult to see how further epidemiological studies to examine possible adverse effects of tritium—a further recommendation—could yield any worthwhile result. The remaining two recommendations, which are on steps that should be taken to reduce emissions of tritium, are not based on any analysis in the text. At the very least there should have been some kind of analysis that assessed the benefits of such actions. Given the small doses to the public from tritium, relative to any regulatory limits and to variations in natural background radiation, the actions suggested are unlikely to be warranted based on any ALARA analysis.

# Contents

# Review of the Greenpeace report: "Tritium Hazard Report: Pollution and Radiation Risk from Canadian Nuclear Facilities"

## The reason for this review of the Greenpeace document

Greenpeace assert that the radiation hazard from tritium emitted by nuclear facilities in Canada is grossly underestimated by regulatory authorities. As this review shows, Greenpeace is wrong and there is no justification for the recommendations in the Greenpeace report, several of which are nothing more than fear-mongering. The levels of tritium in the Canadian environment, the behaviour of tritium in the environment and the radiological hazards from tritium are sufficiently well understood that there can be confidence that the radiation doses to the public from tritium are small compared with regulatory limits and with variations in the natural radiation background.

Tritium is a radioactive form of hydrogen that occurs naturally in the environment as a result of cosmic ray interactions in the atmosphere. There is also residual tritium in the environment from the testing of nuclear weapons in the atmosphere in the 1950s and 1960s. Tritium is produced in nuclear reactors by the fissioning of nuclear fuel and by the neutron irradiation of heavy water used in nuclear research and power reactors. Emissions from these nuclear facilities, and from some industrial facilities that use tritium, add to the naturally- and weapons-produced tritium in the environment. (A brief guide to tritium and its properties in the form of questions and answers is Osborne [2002a].)

The environmental, biological and radiological properties of tritium have been studied and reviewed for many years by individual scientists and by national and international agencies. Particular examples of committee reviews are the early set from the National Council on Radiation Protection and Measurements in the USA—on the measurement of tritium [NCRP 1976] on tritium in the environment [NCRP 1979a], and on organic compounds of tritium [NCRP 1979b]. In Canada, the Advisory Committee of the Atomic Energy Control Board (AECB, the former name of the current Canadian Nuclear Safety Commission, the CNSC)

published a review in the early nineties [Myers and Johnson 1991]. More recently, in the UK, the Committee Examining the Radiation Risks from Internal Emitters looked in detail at the literature on tritium hazards [CERRIE 2004]. At regular intervals since its formation in 1955, the United Nations Scientific Committee on the Effects of Atomic Radiation has provided definitive reviews of the literature on the levels and behaviour of radionuclides in the environment and on the effects of radiation, including that radiation from tritium. The most recent review was in 2000 [UNSCEAR 2000]. The International Commission on Radiological Protection has had the benefit of these reviews and those of its own Committees in arriving at its recommendations on radiological protection, which have explicitly included consideration of the hazards from tritium. Its last general recommendations were published in 1991 [ICRP1991]. The regulations in Canada are based on these ICRP recommendations. The latest set if its recommendations is in press and is available on its website [ICRP 2007a].

There is therefore a wealth of expert experience and knowledge on the levels and behaviour of tritium in the environment, on its behaviour in humans and its radiological hazards. It is against this base of knowledge that the claims of the Greenpeace report need to be examined.

Estimating the hazard to the Canadian public from tritium involves a number of steps:

- Determining the concentrations and chemical forms of tritium in the atmosphere, in surface waters and in food at various places;
- Estimating the amounts of tritium that are taken in by members of the public, since tritium only delivers a radiation dose if it is inside a person's body;
- Estimating the radiation doses from the tritium that are taken in; and
- Assessing the potential for any effects from such tritium doses in the light of the knowledge of the biological effects of radiation doses.

This is the approach followed in the review on tritium in the Canadian environment prepared for the CNSC [Osborne 2002b]. The conclusion in the report was very explicit: "The radiation doses from tritium that are being received by members of the general public in Canada are in a range well below the doses at which effects on health have been observed in any populations. The radiation doses estimated to be resulting from tritium are an appropriate measure to the potential impact of tritium exposures on health. This follows even if the information on the

particular effects of tritium and its beta particle radiation is interpreted in a very cautious, conservative way. The conclusion, therefore, is that the levels of tritium in the Canadian environment, even close to nuclear facilities, and the resulting intakes of tritium by the public are too low for the radiation doses from tritium to have any observable health consequences."

The Greenpeace report takes a similar approach to estimating the hazard to the Canadian public from tritium but at each step adjusts the estimations and comes to a different conclusion.

The main points in the Greenpeace report are reviewed below, chapter by chapter. Chapters 1–10 constitute Part 1 of the Greenpeace report, which is concerned with tritium in the Canadian environment. In Chapter 1 there is a brief introduction to tritium and in Chapters 2 through 4 there is a discussion of releases from nuclear facilities, taken from various Canadian nuclear utility and international reports, and of regulatory emission limits. Chapters 5 through 10 cover the steps, noted above, needed to estimate the risks to the public from tritium. The input data that are used by Greenpeace in the estimation of doses to the public are largely taken from the review, noted above, that was prepared by for the Canadian Nuclear Safety Commission [Osborne 2002b]. The estimates of the biological effectiveness of tritium that are used by Greenpeace in this Part 1 are based on material in Part 2 to this report. Chapters 11–15 constitute Part 2 and these, together with appendices to Part 2, are closely based on a previous document that was prepared for review by the Committee Examining Radiation Risks of Internal Emitters in the UK [CERRIE 2003]. There is also an appendix that discusses epidemiological studies that have been carried out on populations close to Canadian nuclear facilities.

## Part 1: Tritium Releases in Canada

### Chapter 1

The basic properties of tritium are described. It is correctly noted that tritium is emitted to the environment from nuclear facilities in two chemical forms, as tritiated hydrogen and as tritiated water and that, as a result, tritium spreads throughout the biosphere with some of the tritium from the tritiated water becoming bound in organic materials. It is also correctly noted that the

radioactive decay of tritium is by emission of a beta particle (an electron) the energy of which is so low (it is in the range ~zero to ~18.6 keV) that it.penetrates only a few micrometres in tissue. The mean range of the tritium beta particles in tissues is ~0.7 μm, and the maximum is ~6 μm [NCRP 1979b]. Tritium is therefore is only a potential hazard if it is taken into the body. The greater the energy deposited into a mass of tissue (the "dose") the greater the physical damage and potential biological impact. Nevertheless, the Greenpeace author objects to tritium being described as a "weak" radionuclide on the basis of its relatively low decay energy, mistakenly asserting that it is a "paradox". There is confusion here between the decay energy of the tritium beta particle and the pattern of energy deposited along the beta particle track in tissue. It is known that the rate at which energy is deposited along a beta particle track tends to be higher the lower the beta particle energy and that the biological effectiveness of the denser track tends to be higher than less dense tracks for the same total energy deposited. (For a general discussion of biological effectiveness see NCRP [1990] and, more specifically in relation to tritium, Myers and Johnson [1991].) But the variation is only by a small factor and tritium is correctly regarded as a "weak" radionuclide because the maximum energy of the tritium beta is low compared with those of most beta-emitting radionuclides (by one or two orders of magnitude in some cases). Per decay, its impact is very small compared with most beta-emitting radionuclides. The supposed paradox is nonexistent.

**Chapter 2**

The emissions from nuclear facilities in Canada are discussed, based on data from utility and international reports.

The emissions of tritium as the oxide (HTO) and the elemental form (HT) are measured and reported separately by the nuclear utilities and other agencies that have tritium in their facilities for the valid reason that the dose from the inhalation of HT is orders of magnitude less than that from the inhalation and ingestion of HTO (see, for example ICRP [1995]). However, in the Greenpeace report, the activities of the two forms released are summed on the author's mistaken impression that, since HT is eventually converted globally in the long term to HTO, this addition

is meaningful for local dose assessments. This is quite wrong. In assessing the long-term global dispersion of tritium both forms can be considered together (for example in the models used by UNSCEAR [2000]). Such consolidation is not appropriate when doses to local (or critical) groups are being assessed. Only a small percentage of released HT is converted quickly enough to the oxide to contribute to the local (or critical group) doses [Peterson and Davis 2002].

There is a suggestion in the Greenpeace report that "few tritium emissions" from nuclear facilities in Canada are by way of a stack or chimney and that "tritiated water vapour literally oozes out of practically every surface, nook and cranny of the reactor building". No reference is cited. The suggestion is plain nonsense. For a start, reactor buildings are operated at negative pressure with respect to the ambient atmospheric pressure and have to meet stringent leakage tests. Further, any tritiated water in the liquid phase that does escape from reactor systems within the reactor buildings is collected in tanks and is monitored and handled as liquid waste. Any tritiated water that escapes in the vapour phase within the reactor buildings is captured with 99% efficiency in dryers; residual vapour being emitted via monitored stacks. The Greenpeace author seems to be unaware of the nature of the design of CANDU stations and their operation.

There is also the implication by Greenpeace that increasing concentrations of tritium (in the moderator and coolant of CANDU reactors) have caused radiation degeneration of seals, resins and filters, without any reference being cited. Again, this claim is wrong. The text in the section of problems with high tritium concentrations actually reads "These increasing tritium concentrations caused considerable problems in the past. An important problem was the increasing exposures to radiation to operators, from ingestion and inhalation of tritiated water vapour. There also were problems with radiation degeneration of seals, resins and filters, resulting in increased shutdowns and lower capacity factors . . . In addition, in the late 1980s, the emissions caused high levels of tritium contamination . . ." So the text does not actually state that it was radiation from tritium that caused degradation but the juxtaposing of the statement between tritium-related points certainly gives the reader that impression. Radiation doses to materials within a reactor are predominantly from gamma or neutron irradiation so if the intention of the author was to claim that the tritium beta particles caused degradations leading to shut downs, it is clearly wrong. If the comment was out of context and referred to radiation in general then it is still wrong. Elastomeric seals are known to degrade with usage, due to many

factors including radiation. In all nuclear power plants (not just CANDUs), elastomers with high resistance to radiation are used and any degradation is caught in the inspection and preventive maintenance programs.

Further, in commenting on the processing of heavy water moderator and coolant from the nuclear power plants at Pickering and Bruce, the author refers to the "problem of the estimated 4,000 truckloads per year" estimated to be needed to transport the heavy water to the Darlington facility. There are not 4000 truckloads per year. The estimate is high by at least an order of magnitude even if all the heavy water going to the Darlington facility had to be trucked there, but of course it does not since the Darlington reactors are on the same site.

Throughout the text the qualifiers "large", "very large", "extremely large" and "surprisingly large" are applied to tritium releases without any indication of the criterion on which this characterization is based. Indeed the whole chapter and the recommendation at the end to reduce tritium emissions are written without any indication of the dosimetric implications of the releases. As will be seen in subsequent chapters, these doses are low, even for the most highly exposed, relative to regulatory standards and to the magnitude of fluctuations experienced by the public from natural sources of radioactivity.

**Chapter 3**

The discharge limits for tritium are discussed. The Greenpeace author notes that the emissions from CANDU NPPs are way below the release limits that are derived from the Canadian regulatory limit of one mSv/a to a member of the public. The author then argues that the regulatory agency (the CNSC) therefore does not "restrict" the amounts of radioactive materials that are being released, as is claimed by that agency. This argument by Greenpeace is just playing with words and, in effect, completely ignores the application of the well-established ALARA[1] principle, reflected in the conditions in site licences and the imposition of action levels.

[1] As Low As Reasonably Achievable

The Greenpeace report also compares emission limits in different countries with those set in Canada solely in terms of activity per year. Authorities chose particular activities and emission rates for their administrative and regulatory purposes that are appropriate to their particular circumstances and facilities. There is not much point in comparing, as Greenpeace does, emissions from and emission limits for nuclear facilities in Canada with emissions and emission limits set for different facilities in different environments in different countries. If the only tritium produced in, say, a European reactor is that from fission (as it the case) then of course the emission of tritium will be lower and the regulatory authority would expect it to be lower. The comparison made by Greenpeace is completely irrelevant.

**Chapter 4**

The limits on tritium in drinking water are discussed. In the discussion there is confusion between the different approaches taken to setting drinking water guides for chemicals and for radionuclides. There is even the implication that detection limits would be appropriate for setting the guides. Given the sensitivity with which radionuclides can be detected, and in particular that for tritium in water (~one part per million million million), such a criterion would lead to an absurd standard that corresponded to a dose rate less than 2 nSv/a from continuous ingestion of water with this concentration; the dose rate is less than one millionth of the dose rate from the natural radiation background. Even the level of naturally-produced tritium in drinking water is greater than this.

The coherent approach for radionuclides is to base them on radiation dose, the hazards from which are well established, for which limits have been prescribed based on risk to health, and for which the doses from natural background radiation provide a further comparison. Treating each radionuclide separately, as the Ontario Advisory Committee on Environmental Standards attempted [ACES 1994] and which is cited with approval in this Greenpeace report, is not necessary; indeed is inappropriate, and would impose unnecessary costs on the taxpayer without providing any benefit, given the annual doses involved. These different approaches were considered in detail by a joint committee from the AECB Advisory Committee and Health

Canada at the request of the Ontario Ministry of the Environment [Health Canada 1998]. In its report, the joint committee examined the risk assessment and decision making frameworks used for ionizing radiation and genotoxic chemicals. It found that risk assessment methods for ionizing radiation and genotoxic chemicals were well developed and generally similar in principle; that radiation risk estimates were based mainly on epidemiological data while genotoxic chemical risk estimates were based mainly on toxicological data derived from laboratory experiment; and that in radiation risk assessment, the combined risks for exposures to different radionuclides by different pathways were routinely calculated. It noted that this was generally not done for genotoxic chemicals, given their varying nature, their large and increasing number, and the synergistic and antagonistic effects which could exist among them. Further, it found that risk management strategies for both ionizing radiation and genotoxic chemicals were also well-developed and were similar in that both of them led to legal limits to exposures, endorsed the ALARA principle, and employed approaches such as source controls, point-of-use controls, and education. The Joint Committee concluded that the risk management strategies for regulated practices for both ionizing radiation and genotoxic chemicals provide a high degree of health protection.

Therefore we can conclude here that the current approach in radiological protection is providing a high degree of protection, as the joint committee noted, and does not need to be converted to the approach developed for chemicals, which is what Greenpeace are suggesting.

In the case of doses from radionuclides, different authorities take different dose levels as the appropriate criteria, depending on the national circumstances. All the radiological protection principles come into play – justification, dose limitation and optimization of protection (the ALARA principle). In the case of the Canadian Federal Standard, the criterion is 100 μSv/a, which leads to a derived concentration in drinking water of 7000 Bq/L.

The Greenpeace report comments on the values used by other jurisdictions without examining the bases or circumstances for their selection. Not mentioned is that agencies in different countries chose different criteria to suit their particular needs. In the case of the USEPA, one of the agencies cited by Greenpeace, the judgment was to take 40 μSv/a as the criterion, as is noted in the Greenpeace report. However, the Greenpeace author does not notice that the USEPA

value is miscalculated. The original derivation of the standard gave the corresponding tritium in water concentration of 20,000 pCi/L (~740 Bq/L). In a subsequent revision to the standards in 1991 the value for tritium was calculated as 60,900 pCi/L, which corresponds to 2253 Bq/L. The USEPA decided to leave the value of tritium concentration at 20,000 pCi/L. The current EPA standard is therefore anomalous by its own criterion in that it is based, not on the primary standard equal to 40 μSv/a, but on 13 μSv/a [NRC 2006].

**Chapter 5**

Tritium concentrations measured during 1997/1998 in the Great Lakes are summarized. The values given are the same as those quoted in Osborne [2002]—the reference papers are the same—but the Greenpeace report does not include the values for earlier years. These show that the concentrations in the Great Lakes have been decreasing since the mid-sixties when fallout from nuclear weapons tests was at a maximum—even those in Lake Huron and Lake Ontario—despite the emissions from the nuclear facilities. For example, the value measured in Lake Ontario in 1965 was 43 Bq/L; by 1997 it was 7 Bq/L [King and Workman 1997].

Despite these clear data, the Greenpeace author contends that there is a "continued rise in tritium levels in most Great Lakes" and add that they are a "matter of concern". Greenpeace also list incidents in which there have been transient tritium releases and contends that these too are matters of concern. The discussion in the Greenpeace report about concentrations and concerns about them is entirely in terms of Bq/L without any indication of, or appreciation for, the dosimetric implications either of the incidents reported or of consequent transient concentrations of tritium in the receiving water bodies. As will be seen later in this review, the radiation doses from any of the concentrations in the Great Lakes are but tiny increments on natural radiation background doses or their variations from place to place. The suggestion by Greenpeace that there need be concern for health with tritium concentrations in water at a few tens of Bq/L has no context and is completely nonsensical.

**Chapter 6**

Tritium-in-air concentrations at various distances from nuclear facilities are reviewed. The data are those in the review by Osborne [2002]. The Greenpeace author emphasizes that it is the concentration of tritium in the air moisture that is important (it is said to be "the crucial parameter"), rather than the concentration in air. Although this concentration sets the theoretical upper limit to the concentration of moisture that can be attained in vegetation that might be exposed to it, the actual concentration attained will depend on the relative contributions of soil moisture uptake and transpiration of atmospheric moisture. Further, in the exposure of persons, inhalation, absorption though the skin, and exchange through surfaces are driven primarily by the concentration in air. For example, if you breathe in 10 litres of air with tritium at 10 Bq/L of air, you take 100 Bq of tritium into the body, irrespective of the air humidity. Expressing the concentrations of tritium-in-air as concentrations of tritium in water vapour and then comparing these values with drinking water standards for members of the public or with background values in water bodies makes no scientific or radiological sense. The question always has to be "How much will be taken into the body and what are the resulting radiological doses?"

The comment is made that the build up of organically bound tritium (OBT) in biota from repeated exposure is ignored in dose models. There is ambiguity about whether the author means that build up in the environment of nuclear reactors is ignored when doses from releases are assessed or whether the reference is to the treatment of organically bound tritium in human biokinetic models. The point is wrong either way. In the case of environmental modelling, OBT is measured in food chain samples (by OPG for example), and dose is assigned according to current ICRP models. Such doses typically amount to only a few percent of the various potential critical group doses. In the case of dose models, they do include OBT, as discussed below.

The comment is made that the annual averages of the tritium concentrations in air are inadequate as an indicator of hazard because pulses of tritium emissions that may occur are "obscured" and these may lead to "heavy" labeling of embryos and fetuses. We shall come back to this topic later. Suffice to note here that the assertion stems from a misunderstanding of biokinetics. Analysis of this type of scenario (for example, by the Agency for Toxic Substances and Disease

Registry [ATSDR 2002] has shown that even if the annual release is within such a pulse and the labelled cells retained the tritium (*i.e.* turnover of the organic material is ignored), the resulting dose over time from such a one-off exposure would not be large compared with that from annual intakes over the same period.

The Greenpeace report does show the variation of annual airborne emissions of tritium from Pickering, Darlington and Bruce nuclear power stations, all of which shown a general downward trend. Greenpeace find this "reassuring".

**Chapter 7**

Tritium concentrations in food measured at various distance from nuclear facilities are reviewed; again the data are those from Osborne [2002]. The emphasis in the Greenpeace text is the comparison with the concentration (~2 Bq/L) in Canadian waters of naturally-produced and weapons-produced tritium in water. Ignored is that the relevant and only meaningful measure with respect to the implications for health is the dose associated with the levels. As is shown later, these are small relative to any regulatory limits and to variations in radiation doses from natural background radiation.

**Chapter 8**

The author estimates the intake of tritium for three environments that have different levels of tritium. The approach is similar to that followed in the Osborne [2002b] review. In that review, the three environments had tritium levels representative, respectively, of the tritium levels distant (~ 40 km or more) from nuclear facilities; of the area around a nuclear facility where tritium is produced or handled and the diet does include locally produced foods; and of an area very close to a nuclear facility with a diet that includes some produce from a garden very close to the nuclear facility. The latter could be regarded as akin to the exposure of a member of a critical group (or reference individual). The environments chosen by Greenpeace were slightly different. The one with the lowest concentrations of tritium in air, water and food was taken to be much farther away than that chosen by Osborne (> 300 km compared with > 40 km) such that it reflected only the natural and weapons-produced tritium. As a consequence, the estimate by Greenpeace of tritium intake in this distant environment is approximately an order of magnitude less than that for the closer environment. A more significant difference is in the choice of values for the area with the highest tritium levels. The Greenpeace report bases the concentrations of tritium in all food throughout the year on the values found in some fruits and vegetables grown close to nuclear facilities. This latter is an unrealistic model. Only a small proportion of food could come from a local garden and to assume, in addition, that such values apply to all foods throughout a complete year makes no sense. In the Osborne review, the more realistic value of 100 Bq/L was used for most foods, with fruits and vegetables at 3000 Bq/L consumed during the Ontario growing season. The unrealistically high value for tritium in foods assumed by Greenpeace accounts for the estimated intake of tritium in this environment being higher than those in the Osborne report, which are conservative themselves. For OBT the value was 25% higher; for HTO the value was more than twice higher.

The conclusion by the Greenpeace author in this chapter is that these levels are hazardous. However, the conclusion is not in terms of radiation dose; it is, as before, in terms of various drinking water standards and a “rule of thumb” (100,000 Bq) for investigating intakes of beta/gamma emitters. None of these is relevant. More useful “rules of thumb" would be that an intake by an adult of one million becquerels of tritium as HTO results in a radiation dose of ~20 μSv. If the intake is by a child, one multiplies by three; if the tritium is in the form of OBT one

multiplies by a further factor of up to two [see Osborne 2002b]. Even with the highest annual exposure in the noted scenarios, the annual dose to an adult would be about 13 μSv; to a child, up to a factor of two greater.

**Chapter 9**

In discussing in this chapter whether the estimated tritium levels are hazardous to health, the Greenpeace author correctly notes that when the doses from the exposures discussed in the previous chapters are estimated with the dose factors used by the regulatory authorities, the "resulting doses are miniscule". He goes on to state: ". . . the highest exposed persons . . . only receives about 20 μSv per year from tritium (*i.e.* 50 times lower than the 1000 μSv safety limit)."

In passing the Greenpeace author notes that there is a problem because the "tiny" dose factors for tritium are the smallest by a considerable margin of all common radionuclides (~ 700 times compared with $^{137}$Cs for example). Given the relative energetics of the tritium compared with most of the common radionuclides (*i.e.* the energy absorbed per disintegration), together with its relatively short retention time, it is to be expected that the dose factors would show such a disparity. The comparison between tritium and $^{137}$Cs is something of a red herring.

The Greenpeace claim in this chapter, however, is that the dose factors for tritium in the forms of HTO and OBT are far too low and that the factor for tritium as HTO should be increased by an order of magnitude and that the factor for tritium as OBT should be five times that for the tritium as HTO. (It is currently taken as 2.3 times.) This claim is based on conclusions from Part 2 of this report, which reviews the radiological hazards of tritium. Such increases in the dose factors, it is claimed, would result in the annual doses to the most exposed individuals discussed being "well over the public dose limit of 1000 μSv". It is a mystery to me how these changes in dose factors would increase even the doses as estimated by Greenpeace, which are about 20 μSv, to greater than 1000 μSv.

There are, however, serious mistakes in the analysis of Part 2 and its appendices, discussed below, and the statement here that the dose factors are grossly underestimated is clearly in error.

This was also the conclusion of the majority of the UK committee that reviewed the 2003 document on which Part 2 is based [CERRIE 2003, 2004].

The material in Part 2 (Chapters 11–15 and Appendices) is reviewed below, after the comments on the Greenpeace recommendations from Part 1 in Chapter 10.

**Chapter 10**

Given that there is no persuasive case for the currently used dose factors for tritium substantially underestimating doses from tritium, there is no support for the contention by Greenpeace that hazards from tritium are inadequately recognized by Canada's nuclear regulators.

Nevertheless, based on the claimed hazard from tritium near nuclear facilities in Canada, Greenpeace make six recommendations. Two in particular are completely unjustified; namely that pregnant women and young children should not live near nuclear facilities and that food from gardens near nuclear facilities should not be consumed. This is unwarranted fear-mongering. Even if the doses from tritium were to be ten times those that could conceivably be the maximum, such recommendations would be unnecessary. The recommendation to set up a committee in Canada to examine tritium dosimetry and risks is reasonable, given the nature of the Canadian nuclear power program, but it should comprise experts in the relative scientific and medical fields (much like the CNSC's former Advisory Committee on Radiological Protection) rather than representatives from particular groups as suggested. Given the low doses to members of the public from tritium, it is difficult to see how further epidemiological studies to examine possible adverse effects of tritium—a further recommendation—could yield any worthwhile result. The remaining two recommendations, which are on steps that should be taken to reduce emissions of tritium, are not based on any analysis in the text. At the very least there should have been some kind of analysis that assessed the benefits of such actions. Given the small doses to the public from tritium, relative to any regulatory limits and to variations in natural background radiation, the actions suggested are unlikely to be warranted based on any ALARA analysis.

# Part 2: The Radiation Hazards of Tritium

Chapters 11–15 constitute Part 2 and these, together with appendices to Part 2, are closely based on a previous document that was prepared for review by the Committee Examining Radiation Risks of Internal Emitters (CERRIE) in the UK [CERRIE 2003]. The material has been rearranged slightly but the wording is identical for much of the text. There is very little new material; a few values of experimentally measured *in vitro* RBEs have been added to a table in Chapter 14 and there is a discussion in an appendix of epidemiological studies that have been carried out on populations close to Canadian nuclear facilities.

## Chapters 11 and 12

In discussing the dose coefficients (called dose factors in Part 1), the author states that there is a paradox in tritium having the lowest dose coefficients among the common (radio)nuclides. Given tritium's radiological and biokinetic properties, it would be remarkable if it did not. It is claimed that a greater biological effectiveness of tritium beta particles compared with gamma rays should disqualify tritium from being classed as a "weak" radionuclide and of "low" radiotoxicity. This comparison, of course, ignores all the other relevant relative radiological properties that have far greater influence on radiotoxicity. The radiological hazard from tritium is, in fact, appropriately classified as low.

The suggestion is made that in estimating the ingestion dose coefficient for HTO, the retention function is a single exponential with a 10–day half-life and that OBT doses are neglected. This is not correct, and indeed, in continuing the discussion in the next Chapter, the Greenpeace author contradicts this by noting that conversion from HTO to OBT is taken into account. The confusion here is discussed below.

**Chapter 13**

In discussing the ICRP model for tritium dose coefficients, the author states: "It assumes that 3% of HTO administered is bound as OBT and that OBT doses from HTO administration may be safely neglected." Arguing that the contribution of OBT has been underestimated, the claim is made that the dose coefficient for tritium ingested as HTO should be increased from the value in current models by a factor of 3 to account for OBT.

This is not a valid claim. Throughout this chapter it is clear that there is a misunderstanding of tritium biokinetics and a misinterpretation of the literature. The quoted sentence illustrates some of that confusion. The fraction of tritium intake that is modeled as converting to OBT and the fraction of the dose that arises from that conversion are not the same as the author appears to believe. The retention time of the OBT has also to be taken into account.

Because of the confusion, the Greenpeace author finds that the current ICRP model conflicts with the findings of Trivedi, Galeriu and Richardson [1997]. It does not. The current model takes the fraction of intake that is converted to OBT as 3%. The dose from this component is about 10% of the total. Trivedi, Galeriu and Richardson [1997] and more recently, Trivedi, Galeriu and Lamothe [2000] estimated from their measurements on individuals who had taken in tritium that the dose from this component should be 3%–9% (4.7%–9.9% in the more recent paper) of that from HTO alone. The author incorrectly takes this value (i.e., the relative dose from OBT) to be the fraction of the intake that is converted to OBT.

There is a further misunderstanding of the biokinetics of labelling of organic components. For a component that is turning over slowly, the proportion of the material in it that is labelled from a given exposure to HTO will be smaller than the proportion of material that is labelled in a component that is turning over more quickly [NCRP 1979b]. What is important for dose estimation is the fraction of the hydrogen in an organic component that can be derived from water. This is the essence of the argument in Osborne [1972] that the Greenpeace report references though apparently without the recognition that it places a natural limit on the fraction of an intake of HTO that can enter a particular OBT component.

The confusion about biokinetics is further illustrated by the suggestion that the total dose from OBT relative to that from HTO will be greater when the exposure to HTO is chronic. The relative doses do not depend on whether the exposure is an acute one or a chronic one as the Greenpeace author appears to believe. In a chronic exposure there is a build up of tritium associated with components that have the longer incorporation and excretion time constants relative to the HTO component. This does not mean that the cumulative dose from these components is relatively greater than the dose from the HTO than it would have been had the exposure been an acute one. Simply thinking from first principles makes this evident. Why would the history of a tritium atom in the body after ingestion as HTO depend on whether there were other tritium atoms being taken in on the same day or two weeks later? Remember the concentration of tritium atoms in water at 100 Bq/L is less than one part per thousand million million; there are no second-order kinetics resulting from high concentrations. It is therefore incorrect to argue, as the author does, that in a long term exposure to HTO, doses from tritium in the OBT component become relatively more important contributors to the total dose.

In discussing the retention of OBT, the author incorrectly assigns the readily exchangeable forms of tritium (*i.e.* tritium bonded to N, P and S) to a 40-day retention component and the non-exchangeable form of tritium (*i.e.* tritium bonded to C, referred to as OBT) to a much longer retained (550-day) component. This is counter to the known physical-chemical and biokinetic properties of the various forms of tritium [NCRP 1979b].

A consequence of these misunderstandings is that there is no valid basis for the argument advanced that, because of inadequacies in biokinetic models, the dose coefficient for tritium as HTO is three times too low and that for OBT is 4–5 times too low. No one would claim that the dose coefficients recommended for use by the ICRP are without uncertainty but, as is clear from the recent analysis by Harrison, Khursheed and Lambert [(2002] who investigated the influence of such uncertainties in the biokinetics, there is no appreciable bias in the values for either of the dose coefficients.

**Chapter 14 and Appendices I–VI**

Although entitled "Internal dosimetry of tritium" the discussion in Chapter 14 is actually of the relative biological effectiveness (RBE) of tritium.

It is well known that the values of RBE for any particular radiation, depend on many experimental variables; for example, the different spatial patterns of ionizing radiation events from the radiations being compared, the biological end point measured, the particular organism, tissue or cell studied, the absolute magnitude of the radiation doses and the radiation dose rates from the two radiations that are being compared [NCRP 1990]. For tritium, there is the possibility of the various influences resulting from location within a cell and of transmutation effects [Myers and Johnson 1991].

It is also well known that for the first variable—the pattern of ionizing events—there is a range of relative effectiveness even within the spectrum of what are termed low-LET radiations (for example, gamma radiation, X-rays and beta particles, including those from tritium). The lower-energy radiations such as X-rays, which have a higher average LET, tend to have a higher biological effectiveness than higher energy radiation such as gamma rays. The pattern of ionization along a tritium beta of average energy is similar to that from 65 $kV_p$ X-rays, *i.e.* between the patterns from X-rays used for mammography and general purpose diagnostic X-rays [Myers and Johnson 1991].

The biological effectiveness of a given radiation is usually expressed relative to gamma radiation or to X-rays. Hence, in so far as LET is determining the RBE, measured values for tritium would be expected to be about unity when compared with X-rays and slightly greater when compared with gamma rays. Variation in the RBE is expected with dose since the effectiveness of radiation at the low end of the LET scale tends to fall away more quickly with dose than does that for radiation at the high end of the LET scale.

There have been many experimental determinations of the RBE for tritium for a wide variety of end points, reference radiations and combinations of experimental conditions. The Greenpeace report reproduces from the earlier report [CERRIE 2003] the table of values of RBE that have been reported in the literature from *in vivo* determinations and adds a few values from *in vitro*

determinations that have been reported in the literature. Quoted values range from unity to 5.9 but most do not have any confidence intervals and are therefore not very useful as given. The highest values are those associated with the *in vitro* determinations.

Not noted in the Greenpeace report is that the values that are relevant for radiological protection purposes are those concerned with cancer induction. These values are close to unity when the comparison is to X-rays and slightly above when the comparison is with gamma rays. (See, for example, the summaries by Myers and Johnson [1991]; Harrison, Khursheed and Lambert [2002] and ICRP [2007a].)

The influence of factors that are peculiar to tritium (for example, transmutation and DNA hydration shell effects) should be seen to some extent in these experimental determinations of RBE. Further, the conclusion from studies of these phenomena has been that, though they may occur, their relative contribution to damage and to RBE is small relative to that from the radiation dose (for example, Myers and Johnson [1991]).

In deducing what the appropriate value for weighting doses from tritium for protection purposes should be, the Greenpeace report includes all estimates of RBE irrespective of whether the experiments were relevant to protection or what confidence there might be in any particular value. The result is the contention by Greenpeace that the ICRP is wrong to assign a radiation weighting factor of unity to doses from all low LET radiations. Based on the range of measured RBE values from all the experiments, Greenpeace suggests that a weighting factor of two should be applied. As noted above, the measured values for tritium and carcinogenesis, which do not differ substantially from unity and which are the relevant values, do not support this contention.

The recommendation by the ICRP in its published recommendations on which current Canadian regulations are based [ICRP 1991] is that for practical purposes in radiological protection, at the low doses involved, differential weighting of the doses from low LET radiations is not needed. This is also the conclusion and recommendation in the recommendations that are currently being published [ICRP 2007b]. Given the experimental evidence, this appears to be a sensible recommendation.

**Chapter 15**

The conclusions in the Greenpeace report are that the dose coefficient for tritium as HTO should be increased by 12 times (rounded to an order of magnitude) and the dose coefficient for tritium as OBT should be increased to 5 times that for HTO from the current 2.3 times. These conclusions are examined in Table 1 below.

Table 1: Rationale presented for the factors by which the dose coefficients for tritium should be increased and an assessment of their justification.

| Component | Factor | Capsule comment |
|---|---|---|
| Radiation weighting factor | 2 | Not justified. The relevant measured RBEs do not warrant the increase for protection purposes. |
| Long-lived OBT and chronic exposures | 3 | Not justified. The biokinetics of HTP and OBT are misunderstood and the literature is misinterpreted. |
| Rapid transport and uptake | 2 | Not justified. This one comes out of the blue; there is nothing to support it |
| Tritiated protein intake (OBT) | ~2 | Not justified. Though there is a range of retention times for different chemical species, there is no evidence that there is an overall bias low in the dose from OBT. |

As indicated in the Table, my conclusion from this review of the Greenpeace report is that there is no justification for the changes to the dose coefficients for tritium that Greenpeace recommend.

In the final paragraph of this chapter 15 there is the suggestion that transient high concentrations of HTO could lead to tritium labelling at crucial parts of embryo development, resulting in increased rates of untoward pregnancy outcomes, including stillbirth, congenital malformations and neonatal deaths. That such outcomes could result from any radiation doses experienced by members of the public is plain unjustified speculation, without any evidence to support it. Further, even if during embryo development there was a transient, much higher-than-average, intake of tritium from the environment with the highest levels of tritium, the labelling of long-

lived cells in the embryo would not result in appreciably increased doses relative to those from tritium as HTO, even for the labelling of oocytes [ASDTR 2002].

**Appendix VII**

The author correctly notes some of the difficulties in interpreting the results of epidemiological studies, particularly ecologic ones. Nevertheless, in the discussion of studies on various Canadian populations, reviewed below, the Greenpeace author appears to disregard some of these caveats.

***Leukaemia in children near CANDU nuclear facilities*** [Clarke, McLaughlin and Anderson 1989, 1991]

In this ecologic study of leukaemia incidence and mortality in children near Canadian nuclear facilities, there was no evidence of excess cases. The 95% confidence intervals on all estimates of the ratio of number of observed cases to number of expected cases (O/E) included unity. The assertion in the Greenpeace report that there could be an excess of leukaemia cases (in the combined Pickering and Bruce areas) because the upper confidence limit is greater than one is not very meaningful; it could just as well have been asserted that there could be a deficiency in leukaemia cases because the lower confidence limit was less than one. There is also the assertion that there were higher death rates from leukaemia after the reactors had started than before. This again ignores the wide, overlapping confidence intervals.

There is a curious assertion that the confidence intervals given in the former of the pair of reports were less stringent, being 90%, compared with those in the latter report (95%) and that had such 90% been estimated in the second report the results would have been statistically significant. It is true that if you reduce the width of the confidence interval (*i.e.* reduce the stringency of the test) applied in such a study the chances of a particular criterion (in this case unity for the value of O/E) being outside the interval is increased. But the preliminary report did not use 90% limits so why the comment is made here is a mystery.

The only sensible conclusion is that there is nothing in these results that points to there being an excess of leukaemia cases in the areas around the nuclear facilities.

***Birth defects and infant mortality in the vicinity of the Pickering nuclear facility*** [Johnson and Rouleau 1991]

The conclusion by Johnson and Rouleau was that ". . . the analysis did not support a hypothesis of increased rates of stillbirths, neonatal mortality or infant mortality in the vicinity of Pickering Nuclear Generating Station. Since the plant's start up in 1971, the rates of these conditions was neither high overall, nor were the patterns of yearly rates unexpected among any of the communities in the vicinity of the plant. Furthermore, the analysis does not support a hypothesis of increased birth prevalence of birth defects in the vicinity of the Pickering Nuclear Generating Station for 21 of the 22 diagnostic categories into which birth defects were divided for analysis."

The Greenpeace report focuses on the one diagnostic category (Down Syndrome) for which the confidence interval on the estimated O/E did not include unity. There is no acknowledgement that with over 20 diagnostic categories and 95% confidence limit finding at least one set of confidence limits that excluded unity might well be expected. Although the authors of the study looked for correlations between cases of Down syndrome in Pickering and in Ajax with airborne releases of tritium and with ground monitoring data, they found none that was significant. Nevertheless, the Greenpeace conclusion is that there could be a possible connection between tritium and Down syndrome and a list of papers on the topic of Down syndrome after the Chernobyl accident is presented as evidence of "excess cases in areas exposed to radioactive fallout, including tritium". The tag at the end of the quote, "including tritium" is something of a stretch in trying to involve tritium, given its very small contribution to the total core inventory at the time of the accident (see Volume II, Annex J of UNSCEAR [2000]). More importantly, this simple citing of the titles of papers does not reflect that two of them [Burkart, Grosche and Schoetzau 1997; Little 1993] are detailed reviews that demolish the claims made that any increases in Down syndrome are related to fallout from Chernobyl. The list does not include a further paper on a study of 19 birth defect registries in Europe that showed that there was no increase in rates after the Chernobyl accident [De Wals, Bertrand, De la Mata *et al*. 1988]. In the area covered by this survey the highest exposures roughly corresponded to a doubling of the

annual dose from natural radiation. Nor does the list include the detailed review of Down syndrome and radiation by UNSCEAR that concluded that there was no unambiguous evidence for increases in any genetic effects, including Down syndrome, resulting from the Chernobyl accident [UNSCEAR 2001].

***Offspring of Canadian nuclear workers*** [Green, Dodds, Miller et al. 1997]

The Greenpeace report tries to find something of significance in the results from this case-control study of congenital abnormalities and matched controls in the offspring of nuclear workers. There were no significant associations with tritium exposures. Nevertheless, the Greenpeace review, despite acknowledging the statistical insignificance of the results, still sees the two observed cases with chromosomal disorders as "revealing possible evidence" of a link to tritium exposure. There is just nothing meaningful here. The conclusion by the study authors, Green, Dodds, Miller *et al*. is very clear: "Overall, workers in a nuclear power industry, and specifically those exposed before conception to low levels of ionising radiation, do not appear to be at an increased risk of having a live born child with a congenital anomaly."

***Offspring of Ontario nuclear workers*** [McLaughlin, Anderson, Clarke *et al.* 1992; McLaughlin, King, Anderson *et al.* 1993]

The conclusion by the authors of this study of cases of childhood leukaemia in the offspring of Ontario nuclear workers and in matched controls was unambiguous in the 1993 paper. "The findings of this study in Ontario did not support the hypothesis that childhood leukaemia is associated with the occupational exposure of fathers to ionising radiation before the child's conception." Also "We conclude that there was no association between childhood leukaemia and occupational exposure of fathers to ionising radiation before time of conception. No association was detected for external whole body dose, tritium dose, or radon exposures, or for any of the preconception or prediagnosis periods of exposure." [McLaughlin, King, Anderson *et al*. 1993] This is a strong finding. Nevertheless Greenpeace see "some evidence of raised risks with internal tritium plus external radiation exposures". This statement appears to be on the basis of the one result (odds ratio = 1.19) that is pulled from a table of results in the cited paper.

A more complete listing of those results is shown in Table 2 below and illustrates the "cherry picking" by Greenpeace.

Table 2: Results from Table III of McLaughlin, King, Anderson *et al*. [1993]

| Number of cases of leukaemia in children with paternal exposure greater than or equal to 0.1 mSv | | Odds ratio | 95% confidence interval |
|---|---|---|---|
| *Total whole body dose (external plus internal due to tritium* | | | |
| Before conception | 6 | 0.87 | 0.32–2.34 |
| During 6 months before conception | 5 | 0.96 | 0.34–2.77 |
| During 3 months before conception | 9 | 0.96 | 0.34–2.77 |
| Before diagnosis | 9 | 1.19 | 0.54–2.73 |
| *External whole body dose* | | | |
| Before conception | 6 | 0.87 | 0.32–2.34 |
| *Tritium dose* | | | |
| Before conception | 0 | 0 | 0–2.39 |

Again, the selection of the one tests made and the wide confidence interval on the criterion being used—the odds ratio—point to the complete disregard by the Greenpeace author for the statistical realities. There is no evidence for leukaemia resulting from parental exposures, which is what the authors of the study concluded.

***Canadian nuclear workers*** [Zablotska, Ashmore and Howe 2004]

In this study of mortality in Canadian radiation workers, Zablotska, Ashmore and Howe were testing two hypotheses—that there were relationships between radiation dose and leukaemia excluding chronic lymphatic leukaemia (CLL) and between radiation dose and solid cancers. Greenpeace speculate on the implications of the point values of the estimated excess relative risks, again ignoring the wide confidence limits on the values. Given the starting hypotheses of the study, it makes no sense to troll though the results, as Greenpeace does, to find the one type of solid cancer (rectal cancer) out of eight types for which the confidence interval on an estimated excess relative risk did not include zero.

More egregious though is the complete misunderstanding of the results involving tritium doses. In the study the estimated risks from exposures when gamma and tritium dose were included were compared with the estimated risks when only gamma doses were included. The analysis showed that the addition of tritium doses to the gamma doses did not materially change the risk estimates. Greenpeace completely misunderstand what was done here, imagining that there was a comparison between the risks in a set of workers that received only gamma exposures and the risks in a different set that received both gamma and tritium exposures. There was only one set of workers. The subsequent analysis in the Greenpeace report is, as a result, completely wrong.

***Congenital malformations in India***

The sources for the suggestion that there is a high incidence of congenital malformations in India near an Indian reactor of similar design to the CANDUs are a UK Channel 4 TV program in 1991 and a paper published in the journal of the International Institute of Concern for Public Health in 1994. The extensive reviews of congenital malformations and radiation by various international agencies such as UNSCEAR and the ICRP have found no concrete evidence for such relationships. These sources do not appear to be offering substantive, peer-reviewed, evidence to the contrary.

***Unpublished studies***

Reference is made to an unpublished study [McArthur 1988] that reported a correlation between newborn infant mortality and tritium emissions. The Greenpeace report acknowledges that the paper has been criticized as having statistical inadequacies—as indeed it does. Johnson and Rouleau [1991], in the report cited above, endorsed criticisms by the Ontario Ministry of Health and the Durham Regional Health Unit who combined to criticize it in 1989 and added their own criticism. One of their most telling findings was that when the period over which the correlation of neonatal infant death rate and waterborne tritium annual release was extended beyond the period considered by McArthur, the inkling of a correlation of higher death rate with higher tritium release disappeared completely. The Greenpeace report does not mention this.

Nor does the Greenpeace report note that the claims from this study by McArthur were also included in a 1990 Greenpeace 16-page treatise entitled "Canada's radiation scandal" and that the AECB, in a document entitled "Canada's radiation scandal?" soundly rebutted this claim and the other points that were made in that treatise, characterizing them as "untrue, misleading and distorted" [Greenpeace 1990; AECB 1990].

***A study not included in the Greenpeace report***

The recent ecologic study by the Durham Region Health Department [2007] may have been too late for inclusion in the review by Greenpeace. Its findings are germane to this discussion.

The study examined how health indicators in Durham Region and municipalities within Durham Region compare with those Ontario. The indicators were grouped in three categories; those that are known most clearly to be associated with radiation exposure, namely leukaemia (excluding CLL) and thyroid cancer; those that are known to be associated with radiation exposure though they may be more strongly influenced by other risk factors than those in the first category; and those for which there is little or no evidence of association with radiation exposure. The expected variations and patterns of the indicators across the region and the expected trends if there was any impact from the nuclear facilities in some of the municipalities was defined on the basis of these categories. The results were methodically reviewed against these expectations.

The overall conclusion in the Durham Region Health Department study was that ". . . disease rates in Ajax-Pickering and Clarington did not indicate a pattern to suggest that the Pickering NGS and the Darlington NGS were causing health effects in the population. Many of the same patterns were shown in Simcoe County in particular, and some in Halton Region. Given the extremely low levels of radiation exposure from the stations, it would be unlikely that any effects would occur."

***Conclusion on the epidemiology studies***

The Greenpeace report concludes, on the basis of its interpretation of Canadian epidemiology studies, that they provide "suggestive, albeit limited, evidence for increased health effects from exposure tritium." As the review here has shown, the studies have been misinterpreted or misunderstood and the significance of results has been exaggerated. There is no evidence for increased health effects attributable to tritium from the cited epidemiological studies.

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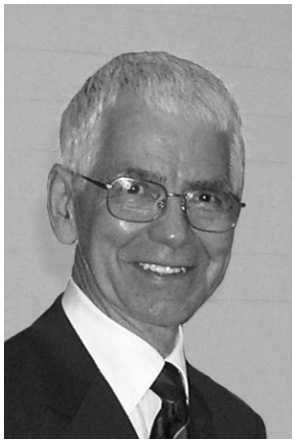
# Appendix

## Biography of the author



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Richard Osborne received his B.A. with Honours in Natural Sciences from Cambridge University in 1959, after which he undertook post-graduate research with Professor W.V. Mayneord at the Institute of Cancer Research, London, gaining his Ph.D. in biophysics from London University in 1962. He then accepted a research fellowship with Dr M. Eisenbud at the Institute of Environmental Medicine in the New York Medical Center.

In 1963 he joined AECL at Chalk River as a research officer in the Health Physics Branch. He was appointed Manager of the Environmental Research Branch at Chalk River Laboratories (CRL) in 1981 and in July, 1988 accepted a special assignment as Executive Assistant to the President of the AECL Research Company in Ottawa. He returned to CRL in November 1989 as Director of Health & Environmental Sciences Division. From 1991–1994 he had responsibility for all the programs in occupational safety and health protection in AECL Research in addition to the responsibility for directing the research program in health sciences. From 1994 until he retired from AECL in 1998 he directed the AECL research programs in radiation biology, health physics and environmental research. He chaired the AECL Health and Environment Working Group and also served on AECL's Safety Review Committee, and the AECL Environmental Panel. He is now President of Ranasara Consultants Inc., working in the general area of radiological protection. Clients have included Natural Resources Canada, the Canadian Nuclear Safety Commission, US Agency for Toxic Substances and Disease Registry, Atomic Energy of Canada Limited, SENES Consultants Limited, the International Atomic Energy Agency, the Nuclear Energy Agency (OECD), Natural Resources Canada, SRB Technologies, Ecometrix Incorporated, and the Canadian Nuclear Workers' Council.

Dr Osborne received the Elda E. Anderson Award of the Health Physics Society in 1975, was a member of the Society's Board of Directors from 1976–1979, was the Society's G. William Morgan Lecturer in 1992 and the Robert S. Landauer Lecturer in 2004, and was elected a Fellow of the Society in 2005. He founded and was first President of the Canadian Radiation Protection Association in 1979. He was Vice-President of the International Radiation Protection Association from 1992–1996.

He served on Committee 4 of the International Commission on Radiological Protection from 1980 to 1993 and from 1997 to 2001 when he was Vice-Chairman of that Committee. In 1989, he chaired the ICRP Task Group on Radon in Buildings and from 1997 to 2001 chaired the ICRP Working Party on controllable dose. Dr Osborne has worked with committees and advisory groups of the Nuclear Energy Agency (OECD) in Paris, the NCRP in the USA, the International Atomic Energy Agency in Vienna (including the Radiation Safety Standards Advisory Committee), and various Canadian Agencies, including the Advisory Committee on Radiological Protection of the Canadian Nuclear Safety Commission. He was a member of the US National Research Council's Committee on Radiological Safety in the Marshall Islands. He was the Canadian Representative to UNSCEAR in 1996 and 1997, and in 1997 was the Task Leader for Tritium Safety and Environmental Effects for the IEA Implementing Agreement on Environmental, Safety and Economic Aspects of Fusion Power. In the late 1990s, he served as a member of the Research Advisory Committee for the National Institute of Radiological Sciences in Japan.

Dr Osborne's early research and papers were on the behaviour and measurement of natural radioactivity in the biosphere. Later he led an R&D program on tritium health physics which resulted in many papers on topics ranging from biokinetics through instrumentation to operational protection. In his work for various

agencies he has been responsible for writing and editing many reports on the practical application of radiological protection principles.