Canada's Nuclear Regulator

Tritium Studies Project Synthesis Report

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Tritium Studies Project Synthesis Report

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

EXECUTIVE SUMMARY

In January 2007, the Commission Tribunal directed staff of the Canadian Nuclear Safety Commission (CNSC) to initiate research studies on tritium releases in Canada, and to study and evaluate tritium processing facilities exercising the best practices around the globe. In response, the CNSC has undertaken several research projects under the banner of the Tritium Studies Project. This research is intended to enhance the information used in the regulatory oversight of tritium processing and tritium releases in Canada.

This report provides a summary of the results of these studies, along with CNSC staff conclusions and recommendations. While studies have been released as they have been completed, conclusions and recommendations are presented here for the first time.

The first objective of the project was to assemble data on the status and nature of impacts of tritium releases from all significant licensed facilities and activities in Canada. Information was also compiled on standards and guidelines for tritium in drinking water.

- *Tritium Releases and Dose Consequences in Canada in 2006* (INFO-0793)
- *Standards and Guidelines for Tritium in Drinking Water* (INFO-0766)

The second objective was to review engineering controls on releases from facilities producing, handling or managing tritium in Canada. This activity included evaluations and field visits to all major tritium facilities in Canada, and selected facilities abroad. Technologies, practices and the operating performance of Canadian facilities were evaluated in terms of best practices internationally.

- *Evaluation of Facilities Handling Tritium* (INFO-0796)

The third objective was to investigate the fate of tritium releases to the atmosphere. To evaluate current scientific knowledge, the CNSC contracted a literature review and predictive modeling of the fate of tritium releases. To evaluate environmental compliance monitoring information and current monitoring strategies, the CNSC contracted research on the amounts of "total" tritium in soils and in plant and animal products sampled near representative nuclear facilities between 2007 and 2009. Research was conducted at two nuclear generating stations and two tritium processing facilities.

- *Investigation of the Environmental Fate of Tritium in the Atmosphere* (INFO-0792)
- *Tritium Activity in Garden Produce from Pembroke in 2007 and Dose to the Public* (INFO-0798)
- *Environmental Fate of Tritium in Soil and Vegetation* (study in progress)

The fourth objective was to conduct an independent staff review of the scientific literature, in order to assess the health risk to workers and the public from exposures to tritium. This review also included an assessment of dosimetry practices for tritium intakes, and a review of the approaches for limiting exposure to tritium.

- *Health Effects, Dosimetry and Radiological Protection of Tritium* (INFO-0799).

Findings

Tritium Releases and Dose Consequences in Canada in 2006

The review of the nature and impacts of tritium releases in Canada for 2006 found that tritium releases to either air or water from all facilities were only a small fraction of licence limits. Tritium activity in the off-site surface environment near most facilities was nevertheless elevated relative to the natural background. Activity declined rapidly with distance from release points, typically approaching natural background levels after several kilometres.

Although tritium activity in the surface environment near facilities was generally low, high levels of tritium (e.g. significantly above background) were found in groundwater at some facilities. This occurred at nuclear reactors, research facilities and tritium processing facilities, largely due to historical practices or accidents/malfunctions. Activity in municipal drinking water sources near power reactors was below 100 Bq/L.

At power reactors, the dose from tritium accounted for much of the total public dose. At all facilities releasing tritium, estimates of doses to the public or workers were well below regulatory limits, and were also well below doses known to cause health effects.

Standards and Guidelines for Tritium in Drinking Water

The review of drinking water standards found that most jurisdictions have adopted similar internationally-accepted radiation protection concepts for drinking water protection for tritium. These include the International Commission on Radiological Protection's (ICRP) dose-risk estimations and dose conversion factors, as well as the reference dose level of 0.1 mSv per year adopted by the World Health Organization (WHO). Tritium activity in drinking water near nuclear facilities in Canada is much lower than the Health Canada guideline level of 7,000 Bq/L, and generally well below a radionuclide indicator "screening value" of 100 Bq/L for tritium, used in the European Union.

Evaluation of Facilities Handling Tritium

The review of facility designs and pollution prevention technologies identified best practices for the handling and control of tritium, in 13 topic areas related to design and/or control technologies: containment, double-walled getter beds, vacuum pumps, vacuum technology, loss due to leakage, loss due to pipeline purging, abatement, ventilation, release point design, tritium recovery, tritium storage, performance metrics, and releases to sewers. The overall conclusion was that Canadian practices are comparable to those in overseas facilities. Effective management of tritium is being achieved through a wide variety of mechanisms. Current

losses from the operation of various processes at tritium facilities are estimated to range from 0.01% to 0.40%.

Investigation of the Environmental Fate of Tritium in the Atmosphere

The literature review on the environmental fate and behaviour of tritium in the atmosphere and the surface environment found that tritium behaviour in the environment is reasonably well understood. The review also assessed recent data on tritium activity in air, soils, surface and groundwater around nuclear facilities relative to predictions from a standard environmental model used for regulatory purposes (Canadian Standards Association CSA N288.1-08). The CSA model was found to be somewhat conservative, and hence suitable for compliance purposes for calculating release limits and annual dose to the public. Some uncertainties in predicting environmental concentrations were nevertheless identified, especially in situations near facilities or at facilities with fluctuating releases.

Soils and Vegetation Research

Research was funded by the CNSC at the University of Ottawa on tritium in the environment near four facilities in 2008 and 2009 (Darlington and Gentilly-2 nuclear generating stations, SRB Technologies [SRBT] and Shield Source Incorporated [SSI] tritium processing facilities). An initial survey was also conducted at SRBT in 2007, when the licensee temporarily ceased processing tritium after 16 years of operations.

Near SRBT in 2007, tritium activity in the environment agreed with general expectations based on releases and models of tritium behaviour. First-time measurements of organically-bound tritium (OBT) in Pembroke did not reveal significant accumulation of tritium from past releases, but did reveal some higher than expected ratios of OBT relative to tritiated water (HTO). The dose to Pembroke residents from the consumption of local produce was less than 0.004 mSv per year during 2007 when both OBT and HTO are taken into account.

The most important finding in this large research project was that OBT activities in the environment were higher and more variable than assumed in current tritium environmental models. These models assume that levels of OBT are similar to levels of HTO (OBT/HTO ratio ~1). However, near nuclear sites, average OBT/HTO ratios were about 2-3 for plant products and 10 for animal products. This suggests that although doses to members of the public are very low, more dose is delivered through consumption of local plant and animal products than currently assumed. These results need to be validated before their significance for public dose estimates can be confirmed. This study is ongoing.

Health Effects, Dosimetry and Radiological Protection of Tritium

CNSC staff conducted a comprehensive review and assessment of radiation protection principles and practices specific to tritium. The topics addressed were tritium's physical, chemical and radiological properties, the health effects of tritium radiation as indicated from laboratory and epidemiological studies, the relative biological effectiveness (RBE) of tritium radiation, and biokinetic models and dosimetry of tritium. The approach of the International Commission on Radiological Protection (ICRP) for protection from tritium and possible modification of the radiation weighting factor (w_R) was also addressed.

Based on extensive epidemiological research and the lack of excess risk from total radiation exposures, the review found little evidence of increased cancer incidence or mortality in populations exposed to tritium at current environmental or occupational levels. This suggests that any tritium-specific risk is small and not distinguishable from the risk of similar health outcomes in the general population. Taking into account the very high levels of tritium required to induce detrimental effects in laboratory studies with animals, the review found that tritium emissions are highly unlikely to cause adverse health effects in the public or in workers. The doses to which these groups are exposed are below regulatory limits and far below doses where radiation effects have been shown.

The RBE is a concept used to compare different types of radiation in terms of the same biological effect. Correcting for the RBE of different types of radiation allows one to add up similar effects from different kinds of radiation in one common unit of dose, the sievert (Sv). More than 50 different estimates for the tritium RBE were reviewed. These studies indicate that where x-rays are the reference radiation, the RBE of tritium is about 1.4, and where gamma radiation is the reference radiation, the RBE is about 2.2. This means that the health risk of tritium is respectively 1.4 and 2.2 times higher than for these other types of radiation.

Radiation doses from tritium cannot be measured directly, and are usually estimated by measuring the tritium in bioassay samples (such as urine) or through environmental monitoring. Once an estimate of the quantity of tritium in the body is made, the dose can be calculated by using biological models that estimate the concentration of tritium in organs and tissues. The review found that the validation, expansion and incorporation of new models, such as the Taylor (2003) model, would make it easier to assess doses from OBT. However, for current public and worker exposures, the ICRP models provide reasonable estimates of dose and hence of risk.

Conclusions and Recommendations

The main conclusion of the Tritium Studies Project is that Canada's current regulatory framework has effectively controlled tritium exposures, so as to protect the health and safety of Canadians. Canadian practices in the handling and control of tritium are currently comparable to those in overseas facilities, with effective control being achieved through a variety of mechanisms.

To improve on the framework for health protection, the following actions are recommended:

- *That CNSC staff establish a multi-stakeholder, tritium working group to assist with epidemiology studies examining health risks associated with lifetime exposure to tritium at low doses, and to consider additional studies in radiobiology and dosimetry, including review of the radiation weighting factor for low LET radiations such as tritium.*
- *That the CNSC continue its research into the variability of OBT/HTO ratios, in order to better understand the underlying mechanisms, while assessing the sensitivity of dose estimates to high OBT/HTO ratios in foods.*

Although the existing regulatory framework has been adequate for the protection of human health, in order to enhance the framework for environmental protection, the following actions are recommended:

- *That the CNSC address groundwater protection issues at existing facilities at the policy level, in consultation with the provinces, which have legal jurisdiction over groundwater resources. In the interim, CNSC staff is drafting regulatory documents providing expectations for groundwater protection, and providing guidance on contaminated site assessments to support clean-up and other corrective measures.*
- *That the CNSC address groundwater protection issues for all new Class I Nuclear Facilities that release tritium to the atmosphere by considering new design requirements, including:*
  - *a design objective for tritium level in groundwater of 100 Bq/L*
  - *a controlled zone within the licensee's control of sufficient size to ensure that the design objective of 100 Bq/L would be achieved at the perimeter given discharges of tritium to the atmosphere under normal operations*
  - *design criteria for release points (stacks) to ensure the effective dispersion of tritium in an atmospheric plume and to minimize environmental contamination through entrainment to the surface environment.*
- *That the CNSC undertake work to identify factors that need to be taken into account for adequate calibration of active and passive air samplers for tritium. In the interim, licensees should be requested to provide data on the uncertainty in measurements conducted as part of their monitoring programs.*

Altogether, the Tritium Studies Project has achieved its objectives of enhancing the CNSC's knowledge of the production, management and release of tritium in Canada. The results and recommendations of this project are being used and will be used by CNSC staff to improve the regulatory oversight of tritium releases in Canada.

1 INTRODUCTION

1.1 Tritium Regulation in Canada

In Canada, the control of tritium releases to the environment is particularly important. Canadian-designed CANDU (Canada Deuterium Uranium) reactors produce more tritium than most other types of reactors, and Canada has several special facilities that process large quantities of tritium. For example, some of the tritium generated by reactors is recovered in a facility at Darlington, and some if this material is then processed to produce self-luminescent lights and paints at facilities in Pembroke and Peterborough. Hospitals use small quantities of tritium in diagnostic tests, pharmaceuticals and radiotherapeutics. Tritium is also used in research laboratories, and as a tracer in oil and gas exploration. As a result of these many activities, there is a clear need in Canada for a thorough understanding of all aspects of the environmental and health and safety consequences of tritium production and use.

Releases of man-made tritium are regulated and carefully monitored by the Canadian Nuclear Safety Commission (CNSC), in order to protect the health and safety of Canadians and the environment. CNSC regulations limit the dose that any member of the public can receive from a licensed facility or activity to 1 mSv. The public dose resulting from emissions from nuclear facilities is very low. The actual doses are estimated, since they are too low to be measured directly. Estimates are mostly based on environmental monitoring, conducted by licensees to demonstrate compliance with the public dose limit. Monitoring programs typically include measurements of radionuclides and/or radioactivity in air and water, and in the foods grown near nuclear facilities. By combining this information with the activities and dietary habits of people living near nuclear facilities, one can estimate public doses with confidence.

Tritium is the only radioactive isotope of the element hydrogen (symbol T or ^{3}H). It has a nucleus that contains one proton and two neutrons. Tritium emits low energy beta particles, a form of ionizing radiation, when it decays to a stable isotope of helium. Tritium occurs both naturally, in the Earth's upper atmosphere, and as a byproduct of the operation of nuclear and research reactors. As a form of hydrogen, it readily forms water molecules and can also be incorporated into organic materials. This is why natural background levels of tritium can be found everywhere in the environment where water is present — including precipitation, surface water, groundwater, ice, soil moisture, animals and plants.

As a source of ionizing radiation, tritium can pose a health risk if it is ingested through drinking water or food, or if it is inhaled or absorbed through the skin. It is one of the lowest-energy beta particle emitters. Therefore, when it enters the body, it gives a lower radiation dose per disintegration than other radioisotopes. For radiation protection purposes, it is assumed that as exposure to ionizing radiation increases, the probability of developing some health effects, such as some cancers, increases at a similar rate.

Given certain assumptions, the dose that results from being exposed to radiation is related to the probability of developing health effects because of that exposure. The unit of dose which is used for radiation protection purposes to protect from stochastic effects (i.e. cancer) is called the effective dose. It also provides an approximate measure of the probability of developing health effects because of that exposure. Effective dose is expressed in units of sieverts, or, more commonly, as thousandths of a sievert (millisieverts, or mSv). Health risks in people exposed chronically to radiation doses of approximately 100 mSv or less are low and cannot be distinguished from similar health risks (e.g. cancer) in the general Canadian population.

Natural radiation causes us to receive on average about 2 mSv every year from exposure to radon, cosmic radiation, and naturally-occurring radioactive materials in the earth's crust and in our bodies (for example carbon-14 and potassium-40). The dose from natural radiation varies among locations, and can be as high as several mSv per year.

1.2 The Tritium Studies Project

In 2007, the CNSC initiated several research studies on tritium releases in Canada, to expand the body of knowledge on the subject and to enhance regulatory oversight of tritium-related activities. This synthesis report is a summary of the main findings of the resulting *"Tritium Studies"* project. It is based on the "INFO" documents produced from 2008 to 2010. These were produced as a result of CNSC staff reviews of tritium regulation in Canada, and also include results of CNSC-funded research on tritium in the environment. The documents on which this synthesis report is based are available to the public at nuclearsafety.gc.ca.

The project originated in the *"Record of Proceedings, Including Reasons for Decision"* published by the Commission on January 31, 2007, in the matter of SRB Technologies (Canada) Inc. (SRBT) *"Application for the renewal of Class IB operating licence for the gaseous tritium light source facility in Pembroke, Ontario"*. The Commission directed CNSC staff to:

- Initiate research studies on tritium releases in Canada
- Study and evaluate tritium processing facilities in the world exercising best practices

A project plan was presented as a technical briefing to the Commission on September 12, 2007, and is documented in CMD-07-M34.

The goal of the project was to enhance the information available to guide regulatory oversight of tritium processing and tritium releases in Canada. The scope included facility design and release issues that are important to the protection of human health and the environment.

The project's first objective was to assemble data on the status and nature of current impacts of tritium releases from all significant licensed facilities and activities in Canada, to support all other project activities. The regulation of the impacts of tritium releases are within the

mandate of the CNSC, through the *Nuclear Safety and Control Act* (NSCA). Tritium release information was compiled and interpreted in terms of dose to nuclear energy workers and the public. Tritium activity levels in the environment were also summarized in detail, from compliance reports submitted by licensees. Information was also compiled on standards and guidelines for limiting tritium activity in drinking water. Some provinces in Canada enforce drinking water standards that include tritium and/or radionuclides. Both information reports were prepared by CNSC staff.

- **2009: *Tritium Releases and Dose Consequences in Canada in 2006* (INFO-0793)**
  Information on tritium releases, environmental levels and dose consequences for all licensees with significant releases of tritium in 2006.

- **2008: *Standards and Guidelines for Tritium in Drinking Water* (INFO-0766)**
  Information on tritium drinking water standards and guidelines in developed countries throughout the world, and the levels of tritium in drinking water in Canada.

The project's second objective was to review the engineering controls on releases from facilities producing, handling or managing tritium in Canada. This activity included evaluations and field visits by CNSC staff to all major tritium facilities in Canada, and selected facilities abroad. Technologies, practices and the operating performance of Canadian facilities were evaluated in terms of international best practices.

- **2010: *Evaluation of Facilities Handling Tritium* (INFO-0796)**
  Information on the design and mitigation technologies of processing facilities releasing tritium to the atmosphere, with an evaluation of what constitutes best practices internationally.

The project's third objective was to investigate the fate of tritium releases to the atmosphere relative to environmental compliance information reported by licensees. Nearly all of the tritium released from tritium processing facilities is released to the atmosphere. To evaluate current scientific knowledge of environmental pathways of tritium, the CNSC contracted a literature review of the fate of tritium released to the atmosphere to Ecometrix Inc., in association with RWDI Air Inc. This review included a comparison of tritium activity in air, soils, surface water and groundwater at representative CNSC licensed facilities. Observed data were compared to predictions from a typical numerical model, used to demonstrate compliance with CNSC requirements to protect the health and safety of persons and the environment.

To evaluate current monitoring practices for tritium in the terrestrial environment, the CNSC contracted the University of Ottawa to independently measure "total" tritium in soils, as well as in garden produce and other local foods. With a few recent exceptions, licensees measure only HTO (tritiated water) in environmental media for estimating the dose to the public, since this form of tritium accounts for most of the dose. For practical reasons, organically-bound tritium (OBT), which is also present in foods, is typically estimated rather than measured. Overall, the study aimed to contribute to our knowledge of the pathways and mechanisms of transformation

of tritium emissions from nuclear activities to the biosphere and the food supply. Research was conducted at two nuclear generating stations and two tritium processing facilities, to reflect different types of emissions (HTO and/or HT – tritiated hydrogen gas). Experiments were also conducted on the dynamics of tritium uptake in soils and vegetation, and on the characterization of OBT in tree rings as a measure of historical releases. Two reports were issued and one is in preparation under this objective.

- **2010: *Investigation of the Environmental Fate of Tritium in the Atmosphere* (INFO-0792)**
  A detailed literature review of the environmental fate of tritium released to the atmosphere, with a comparison of recent environmental compliance data relative to predictions from current models of tritium environmental behaviour.

- **2010: *Tritium Activity in Garden Produce from Pembroke in 2007 and Dose to the Public* (INFO-0798)**
  A survey of tritium activity in home garden produce and soils conducted in the first growing season (2007) after SRB Technologies (Canada) Inc. ceased processing tritium, after 16 years of operations.

- ***Environmental Fate of Tritium in Soil and Vegetation*** (study in progress)
  A large-scale survey of tritium activity at four nuclear facilities in Canada in 2008 and 2009, and results of experimental research on HT transformation and OBT in tree rings.

The project's fourth objective was to conduct an independent staff review of the scientific literature, to assess the adverse health risk to workers and the public from exposures to tritium. This review also included an assessment of Canadian and international dosimetry practices for tritium intakes, and a review of the approaches for limiting exposure to tritium. Altogether, it addressed the adequacy of the current radiation protection requirements for this radionuclide.

- **2010: *Health Effects, Dosimetry and Radiological Protection of Tritium* (INFO-0799)**
  A comprehensive review and analysis of the following topics:
  - Tritium's physical, chemical and radiological properties
  - Adverse health effects of tritium radiation, including reviews of laboratory and epidemiological studies
  - Experimental studies estimating the relative biological effectiveness (RBE) of tritium radiation
  - Biokinetic models and dosimetry of tritium
  - The International Commission on Radiological Protection's (ICRP) approach for protection from tritium, and possible modification of the radiation weighting factor

A general objective of the project was to produce high-quality and up-to-date information for the public on tritium in the context of tritium in Canada. This was achieved mainly through the production of public INFO documents, as listed above. In addition, the CNSC held two major

public information sessions. The first session was held in Ottawa on January 8, 2008, on the topic of tritium health risks. Several international experts with differing views were invited to present talks. A full summary of the event was published in the Journal of Radiological Protection[1]. A public open house on the final results of the project was also held in Ottawa, on April 28, 2010.

1.3 History of Tritium Processing Facilities

The two tritium processing facilities in Canada are SRB Technologies (Canada) Inc. (SRBT) in Pembroke, Ontario and Shield Source Inc. (SSI) in Peterborough, Ontario. They are among only a handful of similar facilities around the world. Both facilities are classified as Class IB nuclear facilities by the CNSC, and are subject to the regulations made under the *Nuclear Safety and Control Act* (NSCA), in particular the *Class I Nuclear Facilities Regulations*. Prior to when the NSCA came into force in June 2000, both facilities were regulated through radioisotope possession licences under the *Atomic Energy Control Act* (AECA). This act was administered by the Atomic Energy Control Board (AECB), the organization replaced by the CNSC. In addition to the new licensing basis in 2000, the transition from the AECA to the NSCA included a major new requirement. The new act now included a clause that required licensees to *"make adequate provision for the protection of the environment"*, in addition to the requirement for protection of the health and safety of persons (Section 24.4(b)).

2 FINDINGS

This section presents a summary of the findings from public reports produced during the information-gathering activities in the project. A synthesis of cross-cutting issues from each report is presented in the concluding section of this document.

2.1 *Tritium Releases and Dose Consequences in Canada in 2006* (INFO-0793)

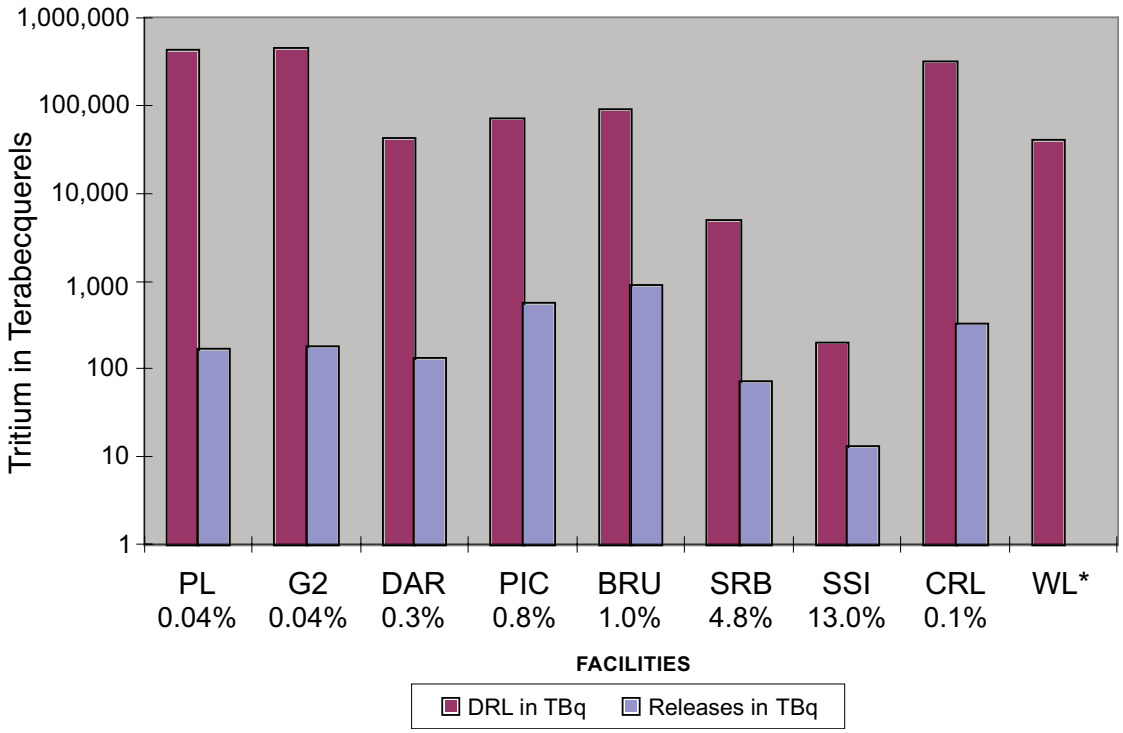
This report is a CNSC staff compilation of the status and nature of the impacts of tritium releases in Canada. Information was assembled from data submitted to the CNSC for the calendar year 2006. The report provides a comprehensive inventory of tritium releases for all facilities releasing significant quantities of tritium in Canada (power reactors, research reactors, nuclear waste management facilities, tritium processing facilities, research facilities, and chemical laboratories). Tritium activity levels in environmental media are then summarized from compliance reports submitted by licensees, and from a few special studies. Lastly, doses to nuclear energy workers and the public are tabulated and compared to regulatory limits.

2.1.1 Tritium Releases

All licensed nuclear facilities release, in a controlled manner, small quantities of radioactive substances into the atmosphere and bodies of water. Releases are measured in becquerels (Bq) and are reported at regular intervals. Releases are maintained at levels As Low As Reasonably Achievable (ALARA) and are restricted by Derived Release Limits (DRLs). A DRL is an upper limit on the release of a nuclear substance, which cannot be legally exceeded. It is derived from information on the location, lifestyle, food habits etc. of representative individuals who live or could potentially live near a nuclear facility. DRLs provide assurance that the public dose limit of 1 mSv per year is not exceeded. A DRL is a quantity whose derivation involves taking into account all pathways of exposure, and therefore represents a release that could result in a dose of 1 mSv/year to a critical group. This group represents the members of the public most likely to receive the highest dose from exposure to releases of nuclear substances.

In 2006, all tritium releases to air and water from all facilities were only a small fraction of Derived Release Limits (DRLs). Tritium releases relative to DRLs for all major facilities are presented in Figures 1 and 2. Minor releases not shown on these graphs also occurred from the Western Waste Management Facility at the Bruce Power site, and two engineering facilities in Brampton, Ontario (Kinectrics Limited and Monserco Limited).

Figure 1. Tritium emissions to air in 2006 compared with Derived Release Limits (with the percent released indicated on the x-axis)

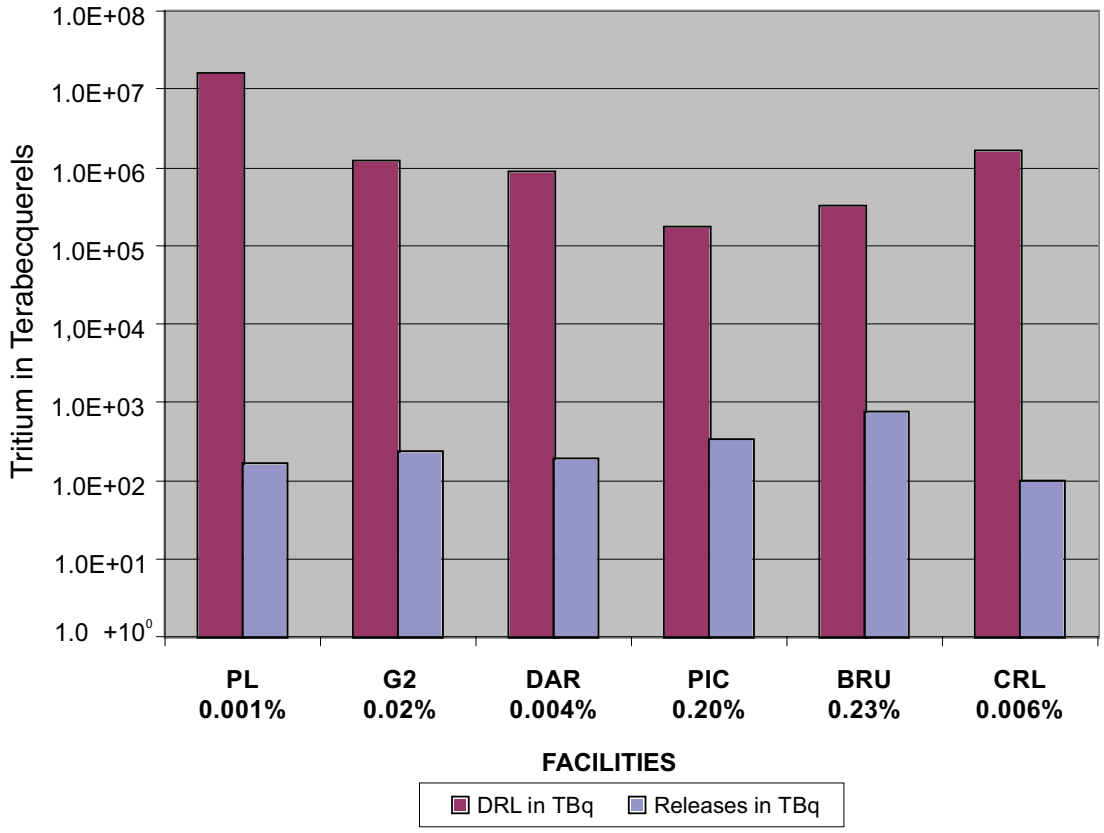


** Whiteshell Laboratories released only 0.0076 Tbq (1.84 x 10^{-5} % of the DRL).*

Abbreviations:

PL: Point Lepreau Generating Station (New Brunswick Power)
G2: Gentilly-2 Nuclear Generating Station (Hydro-Québec)
DAR: Darlington Nuclear Generating Station (Ontario Power Generation)
PIC: Pickering Nuclear Generating Station (Ontario Power Generation)
BRU: Bruce Nuclear Generating Stations A & B (Bruce Power)
SRB: SRB Technologies (Canada) Incorporated tritium processing facility
SSI: Shield Source Incorporated tritium processing facility
CRL: Chalk River Laboratories of Atomic Energy of Canada Limited
WL: Whiteshell Laboratories of Atomic Energy of Canada Limited

Figure 2. Tritium liquid emissions in 2006 compared with Derived Release Limits (with the percent released indicated on the x-axis)



** SRBT, SSI, WL each released less than 1 TBq (below the scale). Abbreviations as in Figure 1.*

2.1.2 Tritium Activity in the Environment

Tritium activity in environmental media, (air, water, vegetation, terrestrial and aquatic animals, including food items) was compiled for 2006. Activities in the surface environment near most facilities were low, approaching natural background at several kilometres from release points.

Tritium activity in air near all facilities varied from 0.4 Bq/m^3 to 35.7 Bq/m^3 relative to a natural background far away from nuclear facilities of roughly 0.1 Bq/m^3. Near power reactors, activity in precipitation, municipal water supplies, off-site wells, surface water and milk was mostly lower than about 50 Bq/L relative to a background of 2-7 Bq/L. A few high values for tritium activity were found in precipitation near the Pickering Nuclear Generating Station (493 Bq/L), and in surface water near the spent fuel waste disposal area of the Gentilly-2 Nuclear Generating Station (892 Bq/L). Near power reactors, tritium activity in vegetables, fruits, silage and honey, and terrestrial and aquatic animals was also mostly lower than 50 Bq/L, with a few exceptions (e.g., deer meat up to 819 Bq/L near the Bruce Nuclear Generating Station, and fruit up to 1,194 Bq/L near the Pickering Nuclear Generating Station).

Tritium activities in surface water, meat, milk and vegetables and fruits collected near tritium processing facilities, and at the Chalk River Laboratories (CRL), were sometimes higher than typical values near power reactors. At the two tritium processing facilities, samples are collected much closer to atmospheric release points than at power reactors where there is a large exclusion zone. Hence, tritium activity in vegetables and fruits growing near these facilities reached levels up to 3,091 Bq/L, with surface water up to 1,490 Bq/L. At CRL, tritium activity in vegetation or animals reached levels up to 1,447 Bq/L. Largely as a result of uncontrolled seepage from the waste management areas at CRL, the tritium activity in the Ottawa River is high very near the facility (114 Bq/L). A further nine kilometres downstream, the river water used for drinking is only slightly above background levels (6 Bq/L at Petawawa).

Although tritium activity in the surface environment near facilities was generally not significantly above background, there were instances where surface water concentrations were elevated as a result of elevated groundwater concentrations. This occurred at nuclear reactors, research facilities and tritium processing facilities. At CRL, water bodies within the waste management areas are affected by groundwater contamination (e.g., Perch Lake at 6,530 Bq/L, Duke stream Weir at 20,400 Bq/L). At other sites, surface waters are not greatly affected, due to the location of plumes or high dilution factors in nearby water bodies. In all of these situations, as required by the CNSC, licensees have addressed, or are addressing groundwater contamination through mitigation of sources or adaptive management. Frequent and comprehensive environmental monitoring is also ongoing at contaminated sites.

The extent, context and origins of groundwater contamination vary considerably among locations (Table 1). Most situations are due to historical practices or malfunctions. At the two tritium processing facilities (SRBT and SSI), groundwater contamination has resulted from precipitation washout of tritium in the plume in the immediate vicinity of atmospheric release points (stacks). Historically, the low stacks and ventilation rates used at these facilities were less than optimal for the quantities of tritium being released. Current atmospheric dispersion capabilities at these facilities are now adequate, as a direct result of CNSC compliance enforcement actions.

With the exception of these two processing facilities, tritium plumes are all within the fenced and protected boundaries of licensed facilities. At all sites, groundwater contamination within or outside facilities does not contribute significantly to radiation doses to workers or the public (Figures 3 & 4, next section). This is because the groundwater near major tritium plumes is not used for drinking water or other purposes (e.g. irrigation).

Tritium activity in municipal drinking water sources near power reactors is routinely monitored. Average values ranged from 7 to 18 Bq/L in 2006 (more comprehensive information for Canada was published in INFO-0766). Current levels near power reactors are similar, and remain below both the *Guidelines for Canadian Drinking Water Quality* limit of 7,000 Bq/L, and the limit of 20 Bq/L recently proposed by the Ontario Drinking Water Advisory Council. The highest value found for a potential drinking water well in 2006 was 1,875 Bq/L. This was for a residential well near SRBT that is not currently used for drinking water. Since this document was published, tritium activity in this well has declined to 423 Bq/L (as of March 2010).

Table 1. Tritium concentrations in groundwater at nuclear reactors, research facilities and tritium processing facilities (as per the information submitted to the CNSC up to January 2008)

Facility	Number of Monitoring Wells	Maximum Concentration (Bq/L)	Comments on the Contamination Sources	Data Year
SRB Technologies	15	108,879	Stack emission washout by precipitation	2007
Shield Source Inc.	4	6,996	Stack emission washout by precipitation	2007
Darlington Nuclear Site	8	Below detection limit		2005
Bruce A	12	667	Airborne emission washout by precipitation	2005
Bruce B	14	1,593	Airborne emission washout by precipitation	2005
Bruce Western Waste Management Facility	18	41,000	Foundation and subsurface drainage	2005
Point Lepreau Plant and Waste Management Facility Area	11	1,100	Emission washout by precipitation	2006
Point Lepreau Solid Radioactive Waste Management Facility	34	400	Airborne emission washout by precipitation	2006
Gentilly-2 Waste Management Area: ASSCI	7	20,553	Emission washout by precipitation	2006
Pickering Nuclear (PN)	Most tritium in groundwater at the site is captured by the foundation drains that are the lowest points acting as a hydraulic sink			2006
PN Unit 1-4 Area	30	128,800,000	Sources: (1) Leaking concrete pit in the Moderator Purification room. The pit gets tritium from spills on the floor; (2) Leaking RAB (Reactor Auxiliary Building) sumps receiving tritium from spent resin storage tank. Problem fixed. Tritium concentration is decreasing.	

Facility	Number of Monitoring Wells	Maximum Concentration (Bq/L)	Comments on the Contamination Sources	Data Year
PN UPP (Upgrading Plant Pickering Area)	32	888,000	Past practice of discharging tritiated water onto the ground. Practice stopped. No new releases. Tritium concentration in ground is decreasing.	2006
PN Irradiated Fuel Bay A&B (Wells and Sumps)	13	21,100,000	Due to tritium migration from Unit 1 area and sump leaking. Repairs under way in 2007.	
PN Vacuum Building Area	11	1,200,000	Due to tritium migration from Unit 1 area and sump leaking. Repairs under way in 2007.	
PN Catchbasin-97	6	108,410	Historical sources in 70s and 80s from Moderator Upgrader (Sulzer).	
PN "B" Reactor Auxiliary Bay (Sumps)	4	10,200,000	Leaking sump pipes. Repaired at Units 5 and 7. Repairs at Unit 6 were completed in 2007. Sump tritium concentration is decreasing. Unit 8 is normal.	
Chalk River Laboratories – NRU Reactor Site	8 monitoring wells are around the fuel rod bay room and 21 monitoring well between the NRU building and Ottawa River	Between the NRU Building and Ottawa River: 3,240,000	AECL identified the rod bay leakage as the source. AECL is in the process of addressing the leakage issue.	2006
Chalk River Laboratories – NRX Fuel Bay Area		3,000,000	Due to fuel rod bay leaking. The bay water was emptied in June 2006.	2005

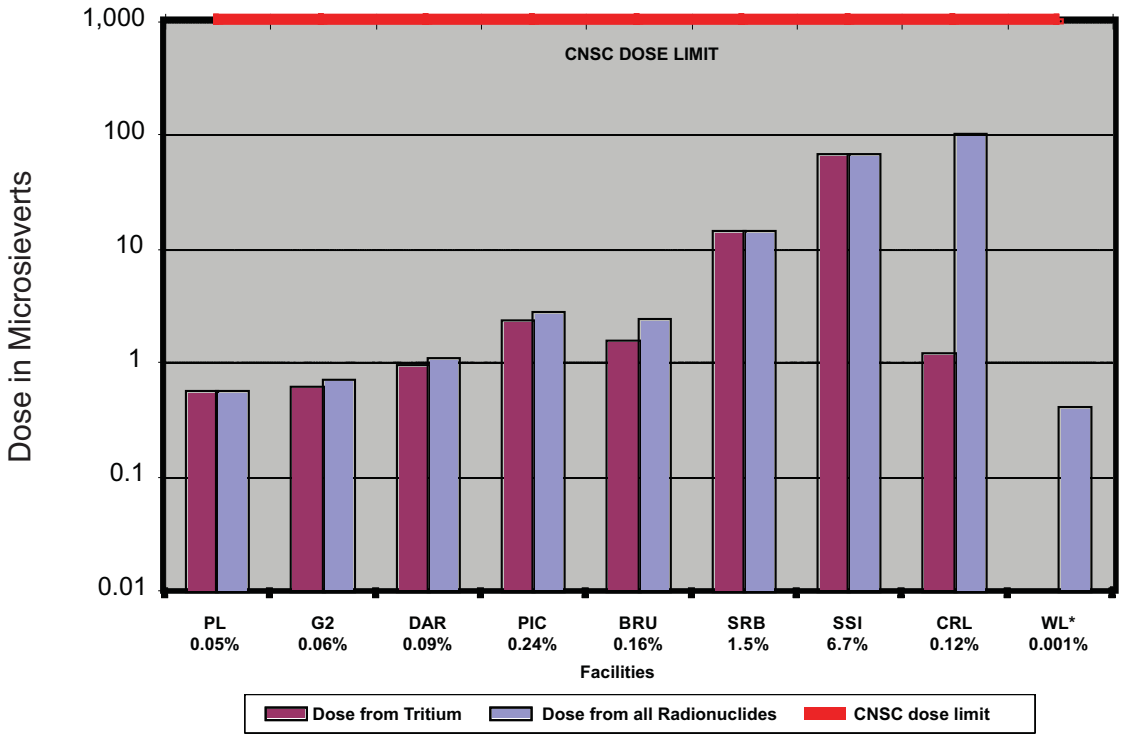
2.1.3 Dose Consequences to the Public and Nuclear Energy Workers

Tritium concentrations in the environment (in air, water, vegetation, animals and milk) are measured to estimate public doses around nuclear facilities. This is done to confirm that the dose consequences of authorized releases are below the CNSC public dose limit of 1 mSv per year.

In 2006, the radiation doses due to exposure to tritium for people living near nuclear generating stations varied from 0.00045 to 0.00236 mSv/year (Figure 3). Realistic estimates of tritium doses to the public around processing facilities were also very low (0.00001 to 0.0145 mSv/year, excluding the dose estimate for SSI where the value of 0.067 mSv/yr is calculated on a very conservative basis for a hypothetical individual).

With the exception of the Chalk River Laboratories, tritium exposure accounts for much of the total radiation dose received by members of the public as a result of emissions from all facilities. At all facilities, estimates of public exposure to tritium and other radionuclides are well below the regulatory dose limit, and are also orders of magnitude below doses known to cause health effects.

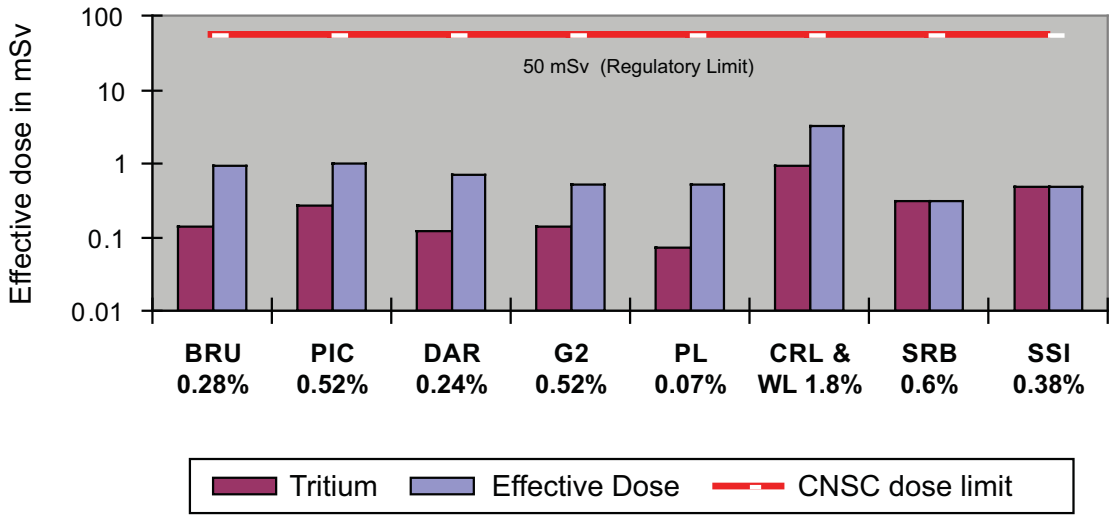
Figure 3. Tritium dose received by members of the public in 2006 as a result of emissions from licensed facilities compared to the dose from all radionuclides and the CNSC public dose limit (with the dose due to tritium as a percent of the public dose limit shown on the x-axis)



Dose to the public from tritium at the Whiteshell Laboratories is 0.01 µSv/y and therefore does not show on the figure. Abbreviations as in Figure 1.

Occupational tritium doses (i.e. to workers) are shown in Figure 4. The doses to these nuclear energy workers are compared with the applicable annual regulatory dose limit of 50 mSv/year. Workers are also subject to a five-year cumulative dose limit of 100 mSv. In 2006, the average occupational doses from tritium exposures ranged from 0.07 to 0.26 mSv for workers at nuclear generating stations, and from 0.30 to 0.90 mSv for workers at processing and research facilities. In all cases, doses received were far less than the CNSC annual occupational dose limits.

Figure 4. Average tritium dose and total effective dose from all radionuclides in nuclear energy workers in 2006, compared with the CNSC annual occupational dose limit (with the dose due to tritium as a percent of the annual occupational dose limit shown on the x-axis)



Abbreviations as in Figure 1.

2.2 *Standards and Guidelines for Tritium in Drinking Water* (INFO-0766)

This report is a CNSC staff compilation of national and international tritium drinking water standards or guidelines, along with their underlying scientific and policy basis. Current levels of tritium activity in drinking water in Canada are also summarized.

The national standards, regulations or guidelines for radionuclides in drinking water, as adopted by the majority of the international community, are based on internationally-accepted radiation protection concepts. These include the International Commission on Radiological Protection's (ICRP) dose-risk estimations and dose conversion factors, as well as the reference dose level of 0.1 mSv per year adopted by the World Health Organization (WHO). Together, these concepts suggest a rounded maximum acceptable concentration of 7,600 Bq/L. The *Guidelines for Canadian Drinking Water Quality* contain a rounded guideline level of 7,000 Bq/L.

Two notable exceptions to this approach are the United States of America (USA) and the European Union (EU). The USA adopted a 20,000 pCi/L (740 Bq/L) limit for tritium in drinking water in 1976. The 1976 limit was based on radiological concepts that now differ from current ICRP and WHO opinion. The USA continues to retain this old criterion on a risk management basis. The EU has elected to use a tritium guideline value of 100 Bq/L as a screening parameter for the presence of other, potentially more harmful, artificial radionuclides. It has not adopted a mandatory water quality parameter for tritium.

In Canada, the current tritium activity in drinking water is orders of magnitude less than the guideline level of 7,000 Bq/L near nuclear facilities, and generally well below the EU's screening value of 100 Bq/L. Tritium is measured routinely in municipal drinking water supplies. Near nuclear facilities discharging tritium, the concentrations in drinking water range from less than 1.9 Bq/L to 20 Bq/L.

A few authorities have recommended alternative guidelines for tritium in drinking water, based on much lower levels of acceptable lifetime cancer risk than promulgated by the ICRP in its overall radiation protection framework. In 2006, the Office of Environmental Health Hazard Assessment in the California Environmental Protection Agency adopted a public health goal (PHG) of 400 pCi/L (14.8 Bq/L) for tritium in drinking water. However, PHGs are not regulatory, and represent only non-mandatory goals. They are based solely on scientific and public health considerations, without regard to economic cost or technical feasibility. California still enforces the federal regulatory limit for tritium in drinking water (20,000 pCi/L, 740 Bq/L).

In 1994, the Ontario Advisory Committee on Environmental Standards (ACES) published the report *A Standard for Tritium. A Recommendation to the Minister of Environment and Energy [of Ontario]*, which recommended an interim guideline of 100 Bq/L for tritium in drinking water. A joint federal working group was formed shortly afterwards, in January 1995, to address the ACES recommendation. It was composed of representatives from the AECB, the Advisory Committees on Nuclear Safety and on Radiological Protection, Health Canada, and the Group of Medical Advisors. The working group concluded that the value proposed by the ACES study was inconsistent with international regulatory philosophy. It instead supported a guideline of 7,000 Bq/L, and further concluded that the risk-management strategy behind the 1995 guidelines provided a high degree of health protection[2]. Ontario formalized the 7,000 Bq/L interim guideline for tritium as a standard many years later, in Ontario Regulation 242/07 [MOE, 2007].

Tritium in drinking water was revisited in Ontario in 2007 by the successor to ACES. The Ontario Drinking Water Advisory Council (ODWAC) reexamined the Ontario Drinking Water Quality Standard for tritium, at the request of the Ontario Minister of the Environment. In 2009, the ODWAC recommended that a standard of 20 Bq/L would meet the requirements for an appropriate level of risk and public safety, while remaining practicable and achievable by the nuclear power industry. As yet, there has been no public action from the Ontario government in response to the ODWAC recommendations.

2.3 *Evaluation of Facilities Handling Tritium* (INFO-0796)

This report is a compilation of facility designs and pollution prevention technologies used by major CNSC licensees releasing tritium to the atmosphere. The report also includes a CNSC staff evaluation of best practices, based on visits to similar facilities processing tritium outside Canada. Specifically, this report:

- Identifies appropriate best practice for the handling and control of tritium in Canada.
- Evaluates the operating performance of Canadian tritium producers, processors and major users.
- Compares the operating practices of the Canadian tritium processing licensees to industry best practice.

The evaluation of Canadian facilities included six licensees that produce or process tritium, or manage tritium wastes:

- Darlington Tritium Removal Facility (largest tritium handling facility in Canada)
- Atomic Energy of Canada Limited Chalk River Tritium Laboratory (dispenses tritium for Ontario Power Generation tritium customers)
- SRB Technologies (Canada) Inc. (gaseous tritium light source manufacturer)
- Shield Source Inc. (gaseous tritium light source manufacturer)
- Kinectrics Inc. (engineering design company doing tritium development work)
- GE Hitachi Nuclear Energy Canada Inc. (designing a tritium removal facility)

Three facilities were also visited overseas:

- United Kingdom: GE Healthcare Ltd. (tritium separation facility)
- South Africa: NTP Radioisotopes (Pty) Ltd. (gaseous tritium light source facility)
- Switzerland: Mb Microtec AG (gaseous tritium light source manufacturer)

Findings are reported in 13 topic areas related to design and/or control technologies: containment, double-walled getter beds, vacuum pumps, vacuum technology, loss due to leakage, loss due to pipeline purging, abatement, ventilation, release point design, tritium recovery, tritium storage, performance metrics, and releases to sewers.

The overall conclusion from this staff review of tritium processing industry practices is that the current Canadian practice is comparable to that in overseas facilities. The effective management of tritium is being achieved through a wide variety of mechanisms, and includes many custom-designed strategies that achieve good levels of tritium control through diverse mechanisms.

Examples of best practices in current use in various combinations are:

1. Use of high performance vacuum equipment for gaseous tritium handling.
2. Focus on high quality primary containment, i.e. maintain a nearly leak-proof facility as the most important control feature, through the use of reliable, high quality valves, pipes and pipe connections.
3. Use of uranium getter beds for operational storage of tritium gas.
4. Use of titanium getter beds for the long-term storage of tritium gas.
5. Use of direct adsorption onto getter beds, or inert gas purging and capture onto getter beds during processing operations. Intentional release of tritium gas from pipe work and vessels is not good practice.
6. Use of oil-free scroll pumps wherever possible.
7. Removal of tritium gas and HTO (molecule of hydrogen + tritium + oxygen) from vacuum pump exhaust, provided there is a treatment or disposal route for the abated tritium.
8. Reduction of chronic releases through additional secondary containment of getter beds, particularly for beds that are used at elevated temperatures over prolonged periods of time.
9. Focusing of abatement technology at the point of generation of the release.
10. Use of appropriately designed release points (stacks) for ventilation systems to achieve good dispersion of tritium gas and tritiated water vapour.

Current losses from the operation of various processes at tritium facilities are estimated to be:

- 0.01% for transferring tritium from getter bed to getter bed
- 0.03% for complex tritium removal processes
- 0.40% for production of gaseous tritium light sources

As a result of this evaluation, the report suggests that losses could be routinely measured, and that it would be possible to establish a performance metric to facilitate continual improvement at Canadian facilities. Licensees would report percentage losses to the environment to the CNSC, along with transfers to waste facilities. This would complement existing regulatory performance statistics based on doses to workers and the public and levels in the environment (e.g. groundwater). For new facilities, these performance metrics could be used as design targets.

2.4 *Investigation of the Environmental Fate of Tritium in the Atmosphere* (INFO-0792)

This report is a literature review by Ecometrix Inc., in association with RWDI Air Inc., on the environmental fate and behaviour of tritium in the atmosphere and the surface environment. It also includes comparisons of tritium activity in air, soils, surface and groundwater around nuclear facilities, relative to predictions from a standard tritium environmental model. The objective was to review current science and provide practical and scientific information on tritium environmental behaviour, in order to support regulatory approaches for tritium.

Tritium is typically released from stacks as tritiated water vapour (HTO), or as a gas in its elemental form (HT). HT can be converted to HTO in the environment through chemical or

biological oxidation. The dynamics of tritium behaviour are governed by both physical and chemical phenomena with different residence times in environmental compartments. Scavenging of tritium from the atmosphere occurs through precipitation with impacts on soils, vegetation and groundwater. Numerous models exist for predicting the fate of atmospheric releases of tritium under different weather conditions, and for both dry and wet deposition under different release conditions.

The literature review begins with a description of the anthropogenic and natural sources of tritium in the atmosphere. The chemical forms, as well as the physical and chemical behaviour of tritium are also described. The report then summarizes the full dynamic behaviour of tritium in the hydrological cycle. This includes the transfer of tritium from air to soil water and surface water, tritium transport from soil water to groundwater, and tritium behaviour in lakes and rivers. Finally, modeling approaches are described in detail for atmospheric dispersion of tritium from point sources, and for the partitioning of tritium (HTO) from air to soil water, surface water, and groundwater.

The report concludes with comparisons of observed and predicted levels of tritium activity in environmental media at several nuclear facilities. The ability to predict environmental concentrations based on current science is discussed, and factors contributing to model uncertainty are identified. The sector-averaged Gaussian dispersion model described in the Canadian Standards Association (CSA) N288.1-08 was used. It was applied at three nuclear power stations and at two tritium light manufacturing facilities.

In all cases for tritium activity in air, the CSA model was conservative, tending to over-predict tritium concentrations (with observed values generally coming within a factor of two of predictions). In compliance monitoring programs, measured values are most often obtained by using passive diffusion samplers with high inherent variability. Some unresolved issues remain in recent studies, concerning the precision of tritium in air data from passive versus active samplers, which are assumed to provide more accurate data but are more difficult to operate. Hence, it is important that atmospheric dispersion models (on which public dose estimates are based) be conservative.

Predicted tritium activity in soil water was compared to either measured soil water or measured rain water (since soil water derives from rain water and should be similar). In three cases, predictions were slightly higher than measured values (35-62% on average, generally within a factor of two). In one case, tritium in soil water was over-predicted more substantially (by two times on average). When air concentrations are changing rapidly, concentrations of tritium in soil water will take some time to respond to higher or lower concentrations in air.

Predicted tritium activity in groundwater was compared to measured values at one facility. Predicted values were conservatively 52% higher on average (generally within a factor of three). Predictions for groundwater are influenced by many additional and sometimes uncontrolled factors. These include the effects of snow storage, and local variation in horizontal groundwater flow, vertical infiltration, and sub-surface conditions. Groundwater concentrations may take considerable time to respond to changes in tritium soil water concentrations based on well depth and vertical travel time, e.g. years.

Predicted tritium activity in pond water was compared to measured pond water at one facility and was 28% higher on average (generally within a factor of two). Ponds and marshes may be subject to up-gradient inflows of soil water or groundwater, and thus may not be at equilibrium with current local air concentrations.

The review and application of current science to predict environmental concentrations resulted in the following general observations:

- Tritium behaviour in air and water is reasonably well understood. This includes dispersion in air and water, partitioning from air to soil water and surface water, and partitioning from soil water to groundwater.
- Long-term average Gaussian air models are somewhat conservative (over-predicting) and are suitable for use in demonstrating compliance with the public dose limit. For modeling of short-term events or releases in complex terrain more sophisticated models are available and should be used.
- There appears to be a lack of precision in tritium levels in air in current compliance monitoring data that has been revealed in comparisons between active and passive air samplers. In some circumstances, passive samplers produce results about two-times higher than active samplers. While this phenomenon is being investigated, the highest values recorded with any type of sampler are always used for public dose estimation.
- Air concentrations drive tritium in soil water and groundwater below a long-term atmospheric plume, assuming no nearby upgradient release to groundwater.
- Lag times can be important in soil water and groundwater since these media take months to years to equilibrate with an atmospheric plume. The lag in response of these media is particularly evident when there is a long-term trend in air concentrations. Lag times depend on substrate texture and vertical travel times.
- Groundwater flow from up-gradient, along with partitioning from the air above a well, can substantially influence tritium concentrations in well water.

As a result of this review and associated analyses, the report recommends studies to resolve the discrepancies seen between active and passive air sampler results. It also recommends near-field studies of air, soil water and groundwater designed to better understand the time lags in soil water and groundwater, and the importance of up-gradient effects.

2.5 Investigations of the Environmental Fate of Tritium in Soils and Vegetation

2.5.1 *Tritium Activity in Garden Produce from Pembroke in 2007 and Dose to the Public* (INFO-0798)

This report summarizes results of CNSC-funded research at the University of Ottawa on tritium activity in garden vegetables and fruits, and a few matching soils collected by CNSC staff in mid-August 2007. Collections were made from Pembroke and from other areas at natural background. Samples were obtained during the first growing season when tritium was not being processed by SRB Technologies (Canada) Inc. after 16 years of operations. The objective was to document how the local environment recovers when a long-term atmospheric source

of tritium is removed. Similar produce data were collected by CNSC staff in 2005, providing a suitable point of comparison. Dose estimates for people consuming local produce were also calculated.

Tritium activity in the water (HTO) in produce grown close to SRBT in 2007 was about 20 times natural tritium background; altogether, activity levels were about 100 times lower than during normal operations in 2005. Total tritium activity in produce and soils declined considerably with distance from SRBT; it approached natural tritium background at or beyond about 3 km (the last sampling point). The dose resulting from the consumption of tritium in home-grown fruits and vegetables also declined considerably with distance of the garden from SRBT.

First-time measurements of organically bound tritium (OBT) in produce and surface soils from Pembroke in 2007 did not reveal significant accumulation of tritium from past releases, but did reveal some higher than expected ratios of OBT relative to HTO. HTO results from the CNSC and the University of Ottawa were in general agreement with compliance monitoring data reported by SRBT. On the whole, tritium activity in produce and soils agreed with expectations based on reported releases from SRBT and models of tritium behaviour in the environment.

Based on measurements of HTO and OBT in garden produce, dose to Pembroke residents from the consumption of local produce was less than 0.004 mSv per year. This is well below the public dose limit of 1 mSv per year and orders of magnitude below doses known to cause health effects. This dose can also be compared to the annual doses from tritium in produce calculated from the background tritium samples, which was 0.0002 mSv.

Altogether, this study found expected levels of tritium in local garden vegetables and fruits in Pembroke in 2005 and 2007. There was no evidence of significant accumulation of tritium in surface soils after 16 years of tritium releases. However, measurements of OBT from fruits in Pembroke, and from several items at background locations, revealed greater diversity in OBT/HTO ratios than expected. Similar results were obtained in the larger body of research conducted by the CNSC in 2008 and 2009 (see section 2.5.2).

2.5.2 *Environmental Fate of Tritium in Soil and Vegetation* (study in progress)

Introduction

This study consists of CNSC-funded research at the University of Ottawa on measurements of total tritium (HTO + OBT) in soils, vegetation and animal products in 2008 and 2009 near four sites of sustained atmospheric releases of tritium. The goal was to provide independent measurements of tritium activity to validate and/or improve monitoring strategies for human foods and the biosphere. Two natural background areas served as controls; one site in a province with several man-made sources of tritium in Ontario (Russell, near Ottawa), and one site remote from any man-made source of tritium (Warman-Langenburg, Saskatchewan). Close to atmospheric sources of tritium, studies were conducted at four well-established nuclear facilities with contrasting releases: Darlington Nuclear Generating Station (NGS), Gentilly-2 Nuclear Generating Station (NGS), SRB Technologies (Canada) Inc. (SRBT), and Shield Source Inc.

(SSI). Darlington is the newest NGS in Canada with four CANDU reactors, and a tritium removal facility (HTO is removed from moderator water to extend its lifespan).

Darlington NGS is the only power reactor site that releases significant quantities of HT to the atmosphere (9.5×10^{13} Bq/year in 2006) in addition to HTO. Groundwater tritium activity is below detection limits; all other sites have some tritium in groundwater and hence some man-made tritium underlying soils. Gentilly-2 NGS has one power reactor releasing HTO, and a waste management facility with passive tritium emissions. SRBT and SSI release both HT and HTO during processing operations. Their releases differ from those at other facilities in that they occur mostly in pulses when tritium processing takes place during working hours.

A key objective of this research was to detect any potential for accumulation of atmospheric tritium in human foods or the environment at sites with a long history of tritium releases. This was done by measuring both OBT and HTO in diverse media, including animal products and soils. Typical compliance programs for monitoring foods focus on measuring HTO in garden produce, with limited work in other contexts. OBT data are particularly sparse in all but a few contexts. Current methods for environmental risk assessment and public dose estimates (e.g. the CSA N288.1-08 model) rely on the assumption that HTO and OBT are at similar concentrations in food under equilibrium conditions (i.e. an OBT/HTO ratio of 0.7 when expressed in equivalent units)[4]. This assumption has been only partially consistent with field data, and has only been tested in a limited number of contexts. In particular, recent results for OBT in natural background areas have revealed puzzling trends with high ratios of OBT to HTO[3], contradicting this important assumption.

Given limited research on the dynamics of HT in soils and plants, experimental studies were also conducted in an environment rich in HT. Studies were performed next to SSI's stacks on the uptake of tritium in soils and plants in an experimental greenhouse.

Laboratory analyses have only just been completed in this large project. CNSC staff are currently reviewing the integrated results received in late March 2010. Hence, only a brief summary of findings is provided here, with an example of the data collected. A staff interpretation of the research conducted by the University of Ottawa will be prepared as a public INFO document in 2010, after staff review and synthesis of the results. Given the controversial nature of the results, this report will be peer-reviewed before it is finalized.

Observations at Natural Background Sites

- HTO activity in soil water ranged from 1.5 to 3.0 Bq/L and OBT activity ranged from 0.9 to 3.6 Bq/kg. Typical natural tritium activity in precipitation, which reflects the tritium being formed continuously by cosmic radiation and the gradually decaying legacy contribution from weapons testing in the mid twentieth century, is about 1.2-1.8 Bq/L, similar to the values found in background soils.

- HTO activity in plants was correlated with HTO activity in soil water. In contrast, OBT activity in plants was often enriched relative to soil water, with up to 12.2 Bq/L found in OBT in Ontario and 19.9 Bq/L in Saskatchewan[1].
- Results from background areas suggest that plants may sequester tritium not only from water, but also (significantly) from soil organic matter. This is a new finding in tritium environmental science. To determine the mechanisms involved will require more sophisticated characterization of the form(s) of tritium that remain in soils once all the water has been extracted. This result may underlie the high OBT/HTO ratios that are sometimes found when measuring tritium in background areas.

Observations Near Nuclear Facilities

- At all facilities, the HTO and OBT activity in soils, fruits, vegetables, fodder and animal products typically approached natural background within several km.
- At SRBT, HTO activity was highest at 225 Bq/L (apples), and OBT activity was highest at 210 Bq/kg (soil) at 400 m from the facility (the closest distance from which samples were obtained, Figures 5, 6). Levels were near background at 6 km, the farthest distance from which samples were obtained. The resumption of tritium processing was accompanied by much lower levels of stack emissions relative to the historical record. Altogether, with optimized emission controls in place in recent years, tritium activities in soils and plants were low and comparable to results for 2007 (INFO-0798), when processing was not occurring.
- At SSI, the highest activity was found at 800 m from the facility in a sample of potatoes at 1,012 Bq/L HTO and at 208 Bq/kg OBT. Levels were a few times above background at 8 km.
- At the Darlington Nuclear Generating Station, HTO activity peaked at 25 Bq/L (tomato at 5 km), and OBT activity peaked at 138 Bq/kg (milk at 4 km). Levels were a few times above background at 6 km.
- At the Gentilly-2 Nuclear Generating Station, HTO activity peaked at 25 Bq/L (corn at 1.5 km), and OBT activity peaked at 82 Bq/kg (beans at 9 km). Levels were a few times above background at 14 km, and similar to background at 20 km.

Tree Rings as Records of Atmospheric Tritium

- Analysis of OBT in tree rings from recently-felled trees collected opportunistically near SRBT (20 m away), SSI (340 m) and Darlington NGS (1,760 m) was undertaken on an exploratory basis. OBT activity (not corrected for decay since the year of formation) peaked at 25,700 Bq/L at SRBT. Year-to-year variation in OBT activity was considerable at SRBT and only partially consistent with multi-year trends in releases.

1 OBT in vegetation has been converted from measured units of Bq/kg to Bq/L water equivalents *since the organic material in plants has been well characterized and hence it is possible to interpret these results in a straightforward manner. Other OBT values are expressed in Bq/kg. Hence great care should be taken when expressing OBT in relation to HTO.*

- OBT activity peaked at 3,000 Bq/L at SSI with most values on the order of 1,000 Bq/L, and with some variability among years. As for SRBT, tree ring data were not always consistent with multi-year trends in releases.
- OBT activity in the tree sampled near the Darlington NGS was very low, on the order of 15 Bq/L or about five times background with minimal year-to-year variation. Year-to-year variation in tritium releases from the Darlington NGS was not well-represented in the tree ring record.

Greenhouse Studies of Soil and Plant Uptake of Tritium

- In the main experiment in 2009, four types of plants were grown in pots with three soil types: mushroom compost, standard potting soil consisting of a mixture of peat, compost manure and black loam, and very high organic matter potting soil. The only complete data set was for tomatoes; other vegetables did not grow well.
- OBT values were close to HTO, an indication that these plants derived most of their hydrogen from actively cycled HT and HTO rather than from inventories of soil organics. Soils had comparable levels of HTO to plants, but very low levels of OBT.
- Despite watering plants with low-tritium water, confounding effects of exchange between soil water and atmospheric HTO limited the usefulness of experiments. HT diffusion membranes attached to soil-filled bottles were therefore used to more accurately measure processes occurring in soils.
- Free extracellular hydrogenase enzymes in soil were important in HT conversion, but overall, conversion rates in all soil types were similar to natural H_2 conversion rates.

General Observations of Cycling of Tritium in the Environment

- OBT activities in soils and plants showed significantly higher variability when compared to corresponding HTO data.
- HTO and OBT activities in garden produce can quickly respond to changes in stack emissions.
- Maximum HTO activities in plants were much higher than those observed in soil and animal products, likely due to the rapid exchange of HTO between water vapour and plants.
- OBT/HTO ratios calculated for soils, plants and animal products demonstrated large variations
- OBT activity in animal products was often enriched over HTO with inconsistent relationships with tritium levels in local fodder.
- Near nuclear sites, average OBT/HTO ratios were on the order of 2-3 for plant products and 10 for animal products. These ratios are significantly higher than expected from current physiological models of HTO and OBT behaviour in plants and animals.
- No significant difference was found in experimental studies in the conversion rate of HT to HTO and/or OBT for various plants and soils.
- OBT in tree rings is a useful indicator of historical emissions only in some circumstances.

Figure 5. Tritium activity (HTO) in water extracted from soils and foods collected near SRBT in Pembroke in the summers of 2008 and 2009. The points represent soils, garden produce (vegetables and fruits), and animal fodder and animal products (honey, meat, milk, eggs). Note that activity is expressed in Bq/L water.

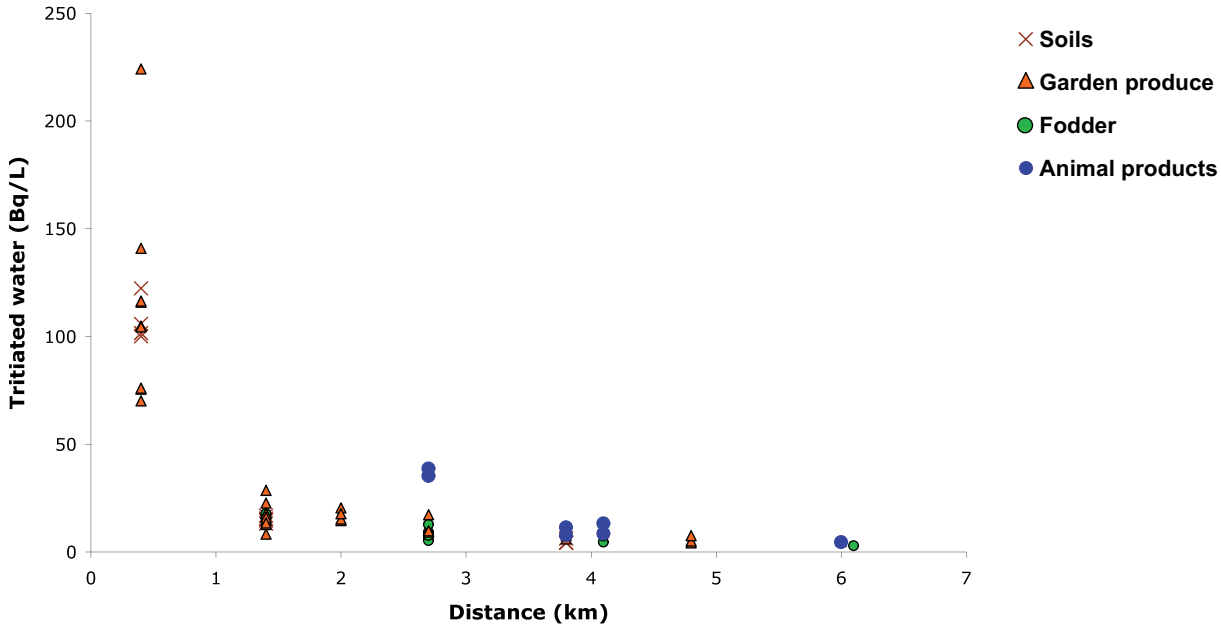
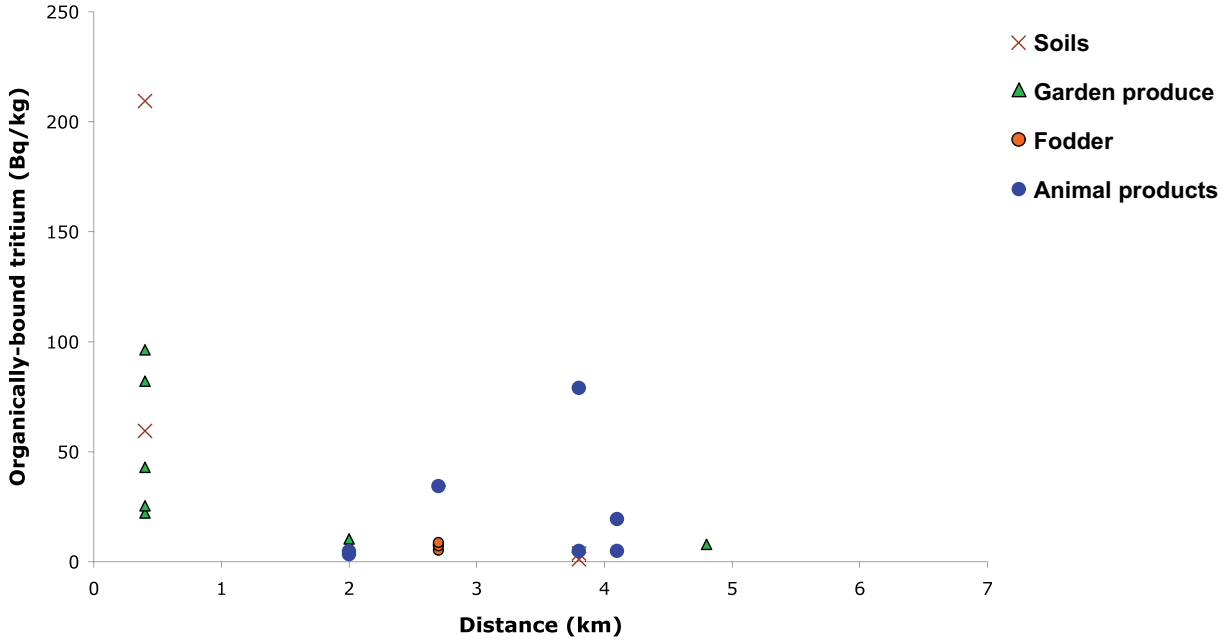


Figure 6. Tritium remaining in soils and foods after the water has been extracted for the same samples as in Figure 5. This tritium is organically-bound tritium (OBT) in all items except for soils where other forms of tritium may be present. The points represent soils, garden produce (vegetables and fruits), and animal fodder and animal products (honey, meat, milk, eggs). Note that activity is expressed in Bq/kg fresh weight.



2.6 *Health Effects, Dosimetry and Radiological Protection of Tritium* (INFO-0799)

This report is a CNSC staff review and assessment of radiation protection principles and practices specific to tritium. It provides:

- an overview of tritium's physical, chemical and radiological properties
- a detailed analysis of the adverse health effects of tritium radiation, including reviews of laboratory and epidemiological studies
- a review of experimental studies estimating the relative biological effectiveness (RBE) of tritium radiation
- a description of biokinetic models and dosimetry of tritium
- a review of the approach taken by the International Commission on Radiological Protection (ICRP) for protection from tritium and possible modification of the radiation weighting factor (w_R)

2.6.1 Health effects

Based on the extensive epidemiological research and the lack of excess risk found from total radiation exposures, there is little evidence to suggest that increased cancer incidence or mortality occurs in populations exposed to tritium at current environmental or occupational levels. The lack of current evidence of an excess risk among these populations suggests that any tritium-specific risk is small and not distinguishable from the risk of similar health outcomes in the general population.

Laboratory studies

Laboratory studies with animals have demonstrated that tritium, like other sources of radiation, can interfere with the development of an embryo or foetus. Tritium can induce genetic and reproductive effects and cell death, but only if delivered at doses that are millions of times higher than those to which the public is exposed. Tritium does induce and promote cancer in animals under some experimental conditions, but only at similarly high doses. The quantity of tritium required to induce these severe effects is on the order of gigabecquerels (that is, billions of tritium atoms decaying and emitting a beta particle per second). This equates to doses above 500 millisieverts (mSv). In comparison, the public dose limit for non-medical, man-made sources of radiation is just 1 mSv per year. The worker dose limits are 50 mSv per year or 100 mSv over a 5-year period.

Epidemiology

Epidemiological studies based on good-quality radiation exposure data provide the best source of evidence for estimating human health risks from radiation exposure. This is because such studies assess actual health outcomes in humans from radiation exposure.

Many epidemiological studies involving radiation workers, their offspring, and the public living near nuclear facilities and several major authoritative reviews of the scientific literature were

assessed in this review. However, they did not contain enough detail to directly estimate the specific health risks due to tritium exposure. This is because of a lack of tritium-specific doses, low total radiation doses, small numbers of cases and low statistical power.

Studies of populations living near nuclear facilities have major limitations. They provide no evidence of adverse health outcomes related to radiation exposure. It is highly unlikely that these types of epidemiological studies would add meaningful information to our understanding of the health risks of tritium. Similarly, studies of the offspring of radiation workers generally do not contain enough detail to estimate risks specifically from tritium exposure. Studies of radiation workers provide the best information to date. However, few studies have directly measured tritium exposure, and even fewer have assessed the health risks of tritium alone. It is presently difficult to distinguish the component of risk associated with tritium, since its contribution to total exposure is very small compared to other sources of radiation.

When assessing the scientific literature, CNSC staff considered these shortcomings. Altogether, extensive epidemiological research has been conducted and has found a lack of excess risk from total radiation at low levels of exposure. For the populations studied, the scientific literature provides little evidence that increased birth defects, cancer incidence or mortality occur in populations exposed to tritium at current environmental or occupational levels. The lack of current evidence of an excess risk suggests that any tritium-specific related risk would be negligible and not distinguishable from the risk of similar health outcomes in the general population.

Future epidemiological studies would need to be specifically designed to provide insights into tritium-specific doses. They could be based on epidemiological studies of workers with tritium-specific exposures and good quality dosimetric information. However, there are relatively few tritium workers in countries with relevant data (Canada, UK, USA, France). Generally low tritium exposures would also make it difficult to detect any health effects of tritium exposure with confidence (that is, the studies would have low statistical power). An international collaborative study combining tritium data on tritium workers from multiple countries would be required to provide the necessary statistical power to assess tritium risk with any precision.

In conclusion, tritium exposures are highly unlikely to cause adverse health effects in the public or in workers. The doses to which these groups are exposed are far below doses where radiation effects have been shown:

- In Canada, doses to the public from tritium releases from nuclear facilities are far below the public dose limit. Doses from tritium exposures among people living near Canadian nuclear facilities are in the range of 0.0001 to 0.1 mSv/year (see INFO-0793 in a previous section for details). These doses are not only well below the limit, but also are negligible compared to natural background radiation, including that from radon (approximately 2 to 3 mSv/year depending upon geographic location).
- Workers in tritium handling facilities receive only a small part of their total radiation doses from tritium, and receive on average a typical total average dose of under 1 mSv per year.

2.6.2 Relative Biological Effectiveness

Relative Biological Effectiveness (RBE) is a concept that is used to compare different types of radiation in terms of the same biological effect. Correcting for the RBE of different types of radiation helps in the interpretation of radiation effects through the formation of a special unit of dose — the sievert (Sv). This unit can be used for adding up similar effects from different kinds of radiation. It is also useful when conducting retrospective studies when a more exact measurement of dose is desired. Typically, this is when there has been an exposure high enough to require medical treatment. In epidemiological studies, one also uses RBE values to obtain the best estimate of each individual dose.

Much of the discussion in this report and other reviews has focused upon choosing an appropriate value for the RBE for tritium. There are more than 50 different estimates for this RBE. However, there is considerable variation and uncertainty in these radiobiological data. This makes it difficult to specify a straightforward nominal RBE value for radiation protection purposes. Tritium RBE estimates differ among studies for many reasons, but a major source of variation is the reference radiation used to determine the RBE. Two types of reference radiation (orthovoltage x-rays and high-energy gamma-rays) are typically used and have different RBE values of their own.

Studies to determine a single value for tritium radiation's RBE indicate:

- Where orthovoltage x-rays are the reference radiation, the RBE would be about 1.4.
- Where high-energy gamma-radiation is the reference radiation, the RBE would be about 2.2.

Gamma radiation is the preferred reference, based on the arguments presented in ICRP 92 (2003). This argument is based on the fact that radiation protection principles rely heavily on data from atomic bomb survivors, and they were mostly exposed to gamma radiation. Gamma radiation is also usually the radiation studied in experiments that examine the effects of chronic (long-term) radiation exposure. It is the largest source of radiation exposure to workers.

For chronic occupational and public exposures, the most relevant health outcome for the determination of an RBE is cancer caused by radiation.

2.6.3 Dosimetry

Radiation doses from tritium cannot be measured directly and so are usually estimated by measuring the tritium in bioassay samples (such as urine) or through environmental monitoring. Once an estimate of the quantity of tritium in the body is made, the dose can be calculated by using biological models that estimate the concentration of tritium in organs and tissues.

To estimate the dose resulting from the intake of tritium, compounds that contain tritium are often categorized as one of the following: those that behave as tritiated water (HTO) after they have entered the body, and those that behave as organically-bound tritium (OBT) after entering the body. This report also addresses other routes of exposure such as tritium absorbed through

the skin from HT-contaminated surfaces. The biokinetics of tritiated compounds in relation to pregnancy and to nursing are also discussed.

The ICRP recommends two main metabolic models to estimate the dose from compounds that contain tritium:

1 **ICRP HTO model**, used to estimate the dose resulting from intakes of tritiated water or other tritiated compounds that partially convert to HTO after being taken into the body.

   This model is used to assess doses from intakes of HTO in the form of liquid and for HTO formed from intakes such as tritium gas (HT), tritiated hydrocarbon vapours and gases (such as methane), and tritiated particulates (for example, airborne particles that contain tritium). The compounds in this category that give the greatest dose-per-unit intake are tritiated particulates of moderate and low solubility as well as tritiated water. Tritiated water by far results in the highest doses from intakes of tritiated compounds by workers and the public.

In the case of pregnancy, maternal intakes of tritiated water or organically-bound tritium result in doses to the foetus of about twice those received by adults for equal intakes of tritium.

2 **ICRP OBT model**, used to estimate doses from intakes of various tritiated organic compounds.

   This model applies to the inhalation and ingestion of organically-bound tritiated compounds, which yield dose-per-unit intakes about double those of tritiated water. It is used to estimate doses to the public resulting from dietary intakes of organically-bound tritium; for example, from tritium bound to nutrients.

A new model (Taylor, 2003) has recently been proposed for HTO. This model differs from the ICRP model in its treatment of OBT formed in the body after tritiated water is inhaled or ingested. It applies only to adults and would need to be expanded to account for various age groups before it could be used to estimate doses to the public in a regulatory context. While the ICRP OBT model appears to be generally consistent with experimental results, it does not account for the different ways that OBT deposits in organs versus tissues. The validation and incorporation of models, such as the Taylor (2003) model, in computer codes would make it easier to assess doses from OBT. Furthermore, the expansion of such a model to include age dependency for all age groups — including the breast-feeding infant exposure pathway — would be valuable particularly in the case of very high exposures, such as in accidents. For current public and worker exposures to tritium the ICRP models provide reasonable estimates of dose and hence of risk.

2.6.4 Options for Assessing and Controlling Risks

As the world's foremost group in radiation protection, the ICRP has formulated a practical, working system of radiation protection that is scientifically based with straightforward

assumptions. The ICRP's principles and recommendations from ICRP 60 (1991) have been adopted largely both in Canada and internationally to protect radiation workers and the public from radiation (the ICRP's 2007 recommendations, ICRP 103, did not change substantially from the 1991 version).

The ICRP radiation protection framework is based upon three key principles:

- The principle of justification: Any decision that alters the radiation exposure situation should do more good than harm.
- The principle of optimisation of protection: the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should, all be kept as low as reasonably achievable, taking into account economic and societal factors.
- The principle of application of dose limits: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the Commission.

The ICRP has developed a broad but simplified system of protection to implement this framework. The system allows exposures from all types of radiation to be added together, and it provides limits for both stochastic risks (such as cancer) and deterministic risks (such as skin reddening and radiation burns).

The ICRP has designated the sievert (Sv) as a measure of the equivalent and effective dose, for radiation protection purpose. It does this by applying weighting factors (w_R) for the different types of radiation (i.e. alpha, beta and gamma) and for the radiation sensitivities of different organs and tissues. Some of the characteristics of the sievert are:

- The sievert is strictly a unit for radiation protection purposes.
- It provides a single unit for dose from all ionizing radiations for optimization and for comparison against the dose limit.
- Due to simplifications, the wR loosely reflects the relative biological effectiveness of the type of radiation and so is only an approximate indicator of the risk.
- All electrons (beta radiation) and photons have a weighting factor of one.
- The w_R is not based upon the source of the radiation (for example, X-ray machines or specific radioisotopes).
- Doses are gender neutral; equivalent and effective doses are calculated for a "representative person" based on a population of males and females, ethnicity and age.
- The sievert should not be used for assessing doses where individual risk assessments are required such as special investigations where high intakes are suspected or in epidemiological studies. In those cases, tissue weighted absorbed doses with appropriate RBE values should be used. As well, characteristics specific to the individual should be taken into account.

The ICRP approach has been criticized in how it treats exposure to tritium because it assigns a weight of one to all low linear energy transfer (LET) radiation, including tritium's beta

radiation. Experiments however indicate that the RBE may be more than twice that of some other low-LET radiations such as high-energy gamma-rays and megavoltage x-rays. The RBE, is somewhat greater than (but much less than twice) that of orthovoltage x-rays, but is similar to that of other low-LET radiations such as low-energy x-rays such as are used in, for example, many medical imaging procedures. The use of a different radiation weighting factor closer to experimental RBE values would be more reflective of the radiation risk. However:

- The apparent improvement in correlation with risk may be misleading given the many other uncertainties due to other significant variables specific to each individual (sex, age, weight, metabolic rates, genetic susceptibilities, etc.) that are not taken into consideration for the broad system of radiation protection.
- It would be inconsistent with the ICRP system of radiological protection:
  - there are no other isotope-specific w_R values
  - use of the sievert unit for equivalent and effective dose and other ICRP radiation protection quantities (i.e. tissue and radiation weighting factors), would not be appropriate
  - it would be difficult to compare radiation protection practices nationally and internationally because the unit of measurement would be different

3 DISCUSSION

The Tritium Studies project had the goal of expanding the body of knowledge on tritium to enhance regulatory oversight. It was initiated as a result of a Commission decision in January 2007 that revoked the tritium processing license held by SRBT in Pembroke, Ontario. This occurred because the Commission was of the opinion that SRBT had not taken all reasonable precautions to protect the environment, and had not taken all reasonable precautions to control the release of a radioactive nuclear substance into the environment. Groundwater protection issues were in the forefront of this decision.

The project had four main objectives:

- documenting the status and nature of current impacts of tritium
- evaluating best engineering practices for controlling tritium
- investigating the fate of tritium released to the atmosphere
- reviewing the health effects of tritium

The key messages from each of these objectives are discussed below, followed by an overview of outstanding common issues, and a discussion of their regulatory implications.

3.1 Status and Nature of Current Impacts of Tritium

The data compiled on the impacts of all significant tritium-related activities in Canada show minimal dose consequences to the public or nuclear energy workers of current operational releases of tritium to both air and water. Doses are a small fraction of regulatory limits and are several orders of magnitude below doses that cause health effects. At this time, previously uncontrolled releases of tritium resulting from historical practices or malfunctions/accidents also do not pose a health risk to workers or members of the public. However, such practices have resulted in unacceptably high concentrations in groundwater in some areas. This has had an impact on the environment (groundwater as a resource) that is not in conformity with sound environmental protection practices.

Operational releases of tritium at most Canadian facilities are on the order of 1% of the global cosmogenic production rate of tritium, a conceptually high value, given the small global footprint of the Canadian nuclear industry. Hence, man-made tritium activity can easily be detected and is ubiquitous in the environment near nuclear facilities that release tritium. This activity decreases rapidly and approaches background only at kilometres or tens of kilometres from release points. Where there are large releases of tritium from nuclear reactors, man-made tritium is also present at very low levels at considerable distances. This occurs in Ontario in water bodies downstream from facilities that release about one hundred or more TBq of tritium in liquid form annually (power reactors on Lakes Huron and Ontario, CRL on the Ottawa River). Atmospheric releases have had very little impact on tritium activity in air far from nuclear facilities.

There are several examples of tritium activity in environmental media or food items near nuclear facilities in the order of 100 or more times higher than natural background. Nevertheless, average tritium activity in local foods and drinking water near major nuclear facilities is low overall, and hence public dose from consuming local items is low. These results are generally consistent with measurements of tritium in precipitation, and are reflected in environmental media such as surface water and groundwater. Some information is now being collected on organically-bound tritium in foods in monitoring programs, but there is still hardly any information on tritium in soils, other than from studies of groundwater.

Municipal drinking water supplies near facilities have tritium activity levels a few to several times natural background, with the highest value being about 18 Bq/L. Much higher tritium activity is present in a few residential wells near nuclear facilities, but all levels are below the Canadian Drinking Water Quality Guideline of 7,000 Bq/L. However, many of these wells are not used for drinking water purposes. Drinking water criteria in Canada are based on the radiation protection principles recommended by the ICRP, and are similar to those adopted by most jurisdictions, with a few exceptions. An important new development on this issue is the possibility of a lowering of the Ontario standard from 7,000 to 20 Bq/L. If this were to occur, it could have a considerable impact on how tritium releases are managed at power reactors and tritium processing facilities. There could also be major implications on use of groundwater near existing contaminated areas.

Contamination of groundwater with tritium at Canadian nuclear facilities is an emerging issue of concern. Most situations have been characterized in detail only in the last several years. Existing tritium plumes in groundwater are mostly related to historical practices (e.g. radioactive waste management, inadequate stack design and ventilation) and/or malfunctions or accidents (e.g. spills and fuel bay leaks), and are mostly within the licensed boundaries of facilities. Significant contamination of groundwater on public lands has nevertheless occurred at the two tritium processing facilities in Canada (SRBT and SSI). This occurred mostly as a result of atmospheric washout of tritium by precipitation. Similar tritium washout also occurs at power reactors as shown by high tritium activity levels in on-site precipitation samples. However, impacts on surrounding public lands at power reactors have been minimal due to the large exclusion zones surrounding these facilities. During the Tritium Studies project, limits on releases in the licences of SRBT and SSI have been greatly reduced to take into account impacts to groundwater and the absence of an exclusion zone.

Groundwater contamination with tritium has arisen despite regulatory controls on releases, the application of ALARA, and the many measures taken to prevent accidents and/or malfunctions. Given this project's findings on the fate of tritium released to the atmosphere from licensed activities, tritium levels in the environment near facilities releasing this radionuclide will inherently be elevated above background for a few to several km. This can occur even for controlled atmospheric releases as a result of washout by precipitation, with consequent impacts on local groundwater.

To protect the environment, the licensing of new Class I nuclear facilities should therefore explicitly take special measures specific to the environmental fate and high mobility of tritium.

This would best be achieved through the use of a design objective for groundwater protection, e.g. at the perimeter of a delineated zone within the licensee's control. Given the 12.3-year half-life of tritium, any contamination that could result within a controlled zone would have minimal impacts on the nearby environment. Distance and the slow migration rate of groundwater would provide a reasonable degree of environmental protection, given a suitably low design target for activity in groundwater. Although there are many site-specific considerations in the delineation of such a controlled zone, the incorporation of this concept in CNSC's regulatory framework should preclude the development of tritium contaminated groundwater on public lands near facilities that release tritium to a level precluding the use of this resource for drinking water purposes. This proposed approach would also ensure through regulatory controls and radioactive decay of tritium that groundwater quality within the licensed site is not impaired over the long-term.

> **Recommendation:** *The protection of groundwater would be improved by the consideration of design requirements for all new Class I Nuclear Facilities that release tritium to the atmosphere, including:*
>
> - *a design objective for tritium level in ground water of 100 Bq/L*
> - *a controlled zone within the licensee's control of sufficient size to ensure that the design objective of 100 Bq/L would be achieved at the perimeter given discharges of tritium to the atmosphere under normal operations*
> - *design criteria for release points (stacks) to ensure the effective dispersion of tritium in an atmospheric plume and to minimize environmental contamination through entrainment to the surface environment.*

Groundwater is a critical drinking water resource for future generations; it is difficult if not impossible to remediate after it becomes contaminated. Groundwater therefore warrants special considerations in terms of protection from degradation over the long term. Staff is recommending a tritium level in groundwater of 100 Bq/L for this specific purpose. A value of 100 Bq/L of tritium for the protection of a potential drinking water resource represents a balanced consideration of science, public health policy, achievability/practicality and societal expectations. In particular, society has an expectation that drinking water will be not just safe, but also "clean".

It is recognized that the current Canadian drinking water guideline of 7,000 Bq/L for tritium is safe (0.1 mSv per year for this one pathway compared to the integrated CNSC public dose limit of 1 mSv per year), meaning that no health effects are expected at this level. For CNSC licensing, a groundwater protection design objective of 100 Bq/L is better aligned with the *Nuclear Safety and Control Act* requirement to take all reasonable precautions to control the release of radioactive nuclear substances and hazardous substances within the site of the licensed activity and into the environment. Furthermore, the *Canadian Environmental Protection Act* (CEPA, 1999) highlights the importance of endeavouring to achieve the highest level of environmental quality. CEPA identifies pollution prevention as a national goal and a priority approach to environmental protection.

On the basis of a detailed analysis of levels of tritium in groundwater around existing Class 1 nuclear facilities discharging tritium, and of the circumstances that led to contamination of groundwater by tritium, an objective of 100 Bq/L for groundwater protection was determined to be practical and achievable. Much of industry has also already adopted this level of tritium as a voluntary target for the protection of drinking water. This objective can also be achieved for the planned Darlington new nuclear reactors, given due consideration of a controlled zone for the protection of groundwater around the facility.

In the process of deriving a groundwater protection objective for CNSC regulatory purposes, staff also considered public health goals identified by the World Health Organization (WHO) and Health Canada for non-threshold chemical carcinogens in drinking water. These organizations have deemed a cancer risk between one in one hundred thousand and one in a million (1×10^{-5} to 1×10^{-6}) to be an "essentially negligible" lifetime risk. Based on the ICRP framework (including the linear no-threshold model (LNT)), a level of 100 Bq/L in drinking water represents an essentially negligible lifetime cancer risk of five in a million (5×10^{-6}). Although these goals have only rarely been applied to radionuclides (e.g. California public health goal for tritium as shown in INFO-0766), their use for tritium as the major contributor to public dose in Canada as shown in INFO-0793 is appropriate.

Groundwater contamination within controlled areas of licensed facilities (nuclear generating stations and the Chalk River Laboratories of AECL) arose as a result of various legacy practices. These included the authorized direct discharge of tritium contaminated wastewater to the ground, accidents (e.g. spills) and malfunctions (e.g. leaks from fuel bays, pipes and containment). Since the coming into force of the NSCA in 2000, the CNSC has the necessary regulatory authority (e.g. sections 12.(1)(c) & (f) of the *General Nuclear* Safety *and Control Regulations* and section 6 of the *Class I Nuclear Facilities Regulations*) to preclude the use of outdated wastewater management practices and to require the implementation of engineering (e.g. secondary containment) and administrative (e.g. monitoring and preventive maintenance) controls to prevent or minimize the occurrence of accidents and malfunctions. For areas of significant on-going groundwater contamination, the CNSC has requested that licensees implement corrective measures. CNSC staff is drafting a regulatory guide to provide guidance to licensees on contaminated site assessments to support clean up and other corrective measures.

One area of tritium-specific regulation that remains an issue is future groundwater use at existing facilities emitting tritium where historical practices or malfunctions/accidents have resulted in groundwater contamination. Source protection is an emerging issue with many site and context-specific considerations that require regulatory attention. Unexpected groundwater contamination with tritium at processing facilities was one of the main factors leading to the initiation of this project. Reasonable use of groundwater resources therefore needs to be considered in the licensing basis of tritium facilities. The criteria for these considerations need to be developed as there are few precedents for establishing transparent criteria.

> **Recommendation:** *Groundwater protection issues at existing facilities should be addressed by the CNSC at the policy level in consultation with the provinces, which have legal jurisdiction over these resources. In the interim, CNSC staff is drafting regulatory documents*

outlining regulatory expectations for groundwater protection and providing guidance on contaminated site assessments to support clean-up and other corrective measures.

3.2 Review of Best Engineering Practices for Controlling Tritium

Management of releases in the tritium processing industry internationally is being achieved through various strategies and mechanisms. Effective best practices exist to minimize worker exposure and to control releases to the environment. Strict controls on tritium releases at the point of generation are both possible and practical, and in common use. Use of appropriately designed release points (stacks) for ventilation systems is an important aspect of best practices and many suitable codes and standards exist.

Canadian facilities are now all using appropriate combinations of best practices to achieve adequate levels of control at source. Dilution and dispersion of releases from stacks is also adequate. In the case of SRBT and SSI, upgrades to align with best practices required regulatory action to improve both controls and ventilation systems. These actions were taken prior to and in parallel with the *Tritium Studies* project, but there is still room for continuing improvement. The best practices identified in this review provide a sound basis for continuing regulatory action on the designs of new or refurbished facilities. The CNSC's routine licensing and compliance program is appropriate for this purpose, and can be guided by the information in this review.

Recommendation: *These findings should be used at the design stage of any new or refurbished tritium handling facility to ensure that good practice is designed into each process operation. CNSC staff should use the report as part of their review of regulatory practice for tritium. In particular, release points (stacks) should be designed to available codes and guidelines to ensure effective dispersion of atmospheric releases of tritium.*

It is also recommended that for existing and future facilities, continual improvement and enhanced regulatory oversight would be facilitated by the collection of performance statistics on the amounts of tritium lost relative to tritium processed. These statistics have not been collected routinely, as there is no mechanism in place to collect or report this information.

3.3 Investigations on the Fate of Tritium Released to the Atmosphere

3.3.1 Current Science

The fate of tritium after it is released to the atmosphere from stacks at nuclear facilities is well understood, as shown by a comprehensive review of current science. For regulatory purposes, long-term equilibrium activity levels in the environment can be predicted with reasonable conservatism in air, water, vegetation, soils, etc. by the CSA N288.1-08. This is the model typically used for this purpose in Canada. Model predictions match observed values best at distances far from release points (e.g. > 1 km), but useful inferences can still be made for distances on the order of hundreds of metres. Overall, recent environmental monitoring data from five facilities in Canada generally agree with predictions from the CSA model.

Deficiencies in our understanding of tritium environmental behaviour nevertheless do exist. These deficiencies relate to long-term tritium dynamics in groundwater, and short-term dynamics at the surface in air, vegetation, surface water, soil, etc. In particular, the impacts of fluctuating releases typical of tritium processing facilities on OBT formation and retention in soils and plants have hardly been studied. Simple dynamic models to date have mainly been developed for accidental releases, and mainly for HTO behaviour in the environment. Improved models are currently being developed through the International Atomic Energy Agency's Environmental Monitoring for Radiation Safety II program. These will only be available in a few years. CNSC staff should continue active participation in this international initiative.

Validation of tritium releases to air relative to atmospheric dispersion models is a minor deficiency identified in terms of the regulatory application of available techniques. Validation is typically achieved through a combination of stack monitoring and air monitoring at various distances from stacks. Passive diffusion samplers are typically used for air monitoring and are just adequate for ensuring that dose to the public is very low from this pathway. However, there are discrepancies in tritium activity levels measured with different techniques. Hence, precise measurements at these low doses have been difficult to obtain. For this and other reasons, models of tritium atmospheric dispersion are structured to be conservative, i.e. to overestimate public dose. Technical issues with various types of sampling devices remain unresolved after several years of research by the CANDU Owner's Group. Although not significantly affecting public dose estimates, improvements to air monitoring with diffusion samplers are desirable. Deployment of individually-calibrated passive diffusion samplers seems to be the best interim solution while research continues on this topic. Similarly, there is room for improvement in obtaining more comprehensive information on the performance of active samplers to reduce uncertainties in the measurement of both HTO and HT in air.

> **Recommendation:** *That the CNSC undertake research to identify factors that need to be taken into account for adequate calibration of active and passive samplers for tritium. In the interim, licensees should be requested to provide data on the uncertainty in measurements conducted as part of their monitoring programs*.

3.3.2 Soils and Vegetation Research

Prior to this project, very little research had been conducted on tritium in the environment near tritium processing facilities. These facilities release mostly HT whereas other nuclear facilities release mostly, if not entirely, HTO. HT is converted to HTO at a low rate by bacteria in soil and then becomes indistinguishable from the HTO released directly to the environment. Hence, the ultimate fate of HT in soils can be important when it is released in very large amounts.

Along with the fate of HT at the soil-air interface, very little is known about the fate of HTO in soils in terms of the formation of OBT or other forms of tritium (e.g. complexes with mineral soil). In contrast, HTO dynamics and its incorporation in OBT in plants are well documented. In plants, gaps in scientific knowledge are mostly related to how OBT is formed under different circumstances. Hence, the CNSC funded research at the University of Ottawa to address some uncertainties in tritium dynamics in soils and plants at representative operating facilities. This

research also served the purpose of providing independent data on tritium near nuclear facilities, for comparison with similar data reported by licensees to the CNSC.

Status of the Environment in Pembroke 2007-2009

The environmental survey conducted in 2007 in Pembroke documented rapid recovery in the first growing season after a large reduction in releases from SRBT starting in February 2007. SRBT had been continuously releasing tritium to the atmosphere for 16 years, particularly in the form of HT. Altogether, there was no evidence for significant accumulation or mobilization of tritium in surface soils after atmospheric releases stopped (e.g. accumulation of OBT). To our knowledge, this is the first time it has been possible to unequivocally test for the possibility of such processes. Low tritium activities were also observed in soils, plants and animal products in 2008 and 2009 after processing resumed. These results agreed with expectations based on the very effective control of tritium emissions when processing resumed in 2008.

In 2007 in Pembroke and in the expanded surveys in 2008 and 2009 at several other sites, a possibly unique form of tritium in soils was detected through mass spectroscopy and combustion techniques. This tritium may be organic, but more likely includes forms of tritium sequestered in the mineral component of soils. This finding is new, but has precedent in the ability of clays to strongly sorb and retain tritium. Soil results need to be researched further to document the nature of the tritium that remains after the HTO has been removed. It probably reflects tritium that is present in various forms besides OBT. Given low HTO activity in plants growing in Pembroke from 2007-2009, this soil tritium does not appear to be readily-available for plant uptake. Otherwise much higher HTO and/or OBT activity levels in plants would have been observed during recent years. Hence, there are no regulatory implications of this novel finding for facilities with high historical releases.

The surveys of home garden produce in Pembroke revealed relationships among HTO in air, soils and plants consistent with the scientific literature and regulatory environmental models. Activity of both HTO and OBT declined with distance from SRBT, as expected from atmospheric dispersion. HTO activity in produce was very low relative to previous years when SRBT was releasing large quantities of tritium, and hence public doses from consuming local produce were very low. Altogether, there were no legacy issues in the surface environment related to the protection of human health or the environment. However, a potential issue related to the future reasonable use of contaminated groundwater in Pembroke remains. This issue may need to be resolved if the provincial drinking water standard is significantly lowered. This would depend on whether Ontario identifies the groundwater in Pembroke as a resource to be protected and/or remediated to any new standards. Currently, enhanced regulatory oversight of this facility by the CNSC has resulted in significant reductions in tritium releases to the environment. Current licence release limits were developed on the basis of protection of groundwater. Hence, SRBT's releases are not expected to impair any future use of groundwater resources in Pembroke at current drinking water standards. Activity in groundwater is expected to decrease over time with the radioactive decay of tritium.

In this study, and in the larger body of research conducted at multiple sites in 2008 and 2009, the vast majority of results for HTO activity in the environment agreed with the more limited HTO compliance data provided by CNSC licensees. These data are critical to demonstrate that the public dose limit is not exceeded during routine operations of nuclear facilities. OBT results were also mostly consistent with HTO results, but with some exceptions; these are discussed in the next section. Overall, tritium activity near nuclear facilities is currently low and similar to activity levels in 2006 (INFO-0793). Hence, man-made tritium in Canada is not contributing significantly to public exposure to ionizing radiation relative to natural background and the public dose limit of 1 mSv per year.

Organically Bound Tritium

OBT results from near facilities with different sources and patterns of tritium releases and/or reservoirs revealed unexpectedly high amounts of OBT, relative to HTO in soils and a small number of food items. Extreme values were readily detected at natural background sites, likely reflecting the ability of these analyses to measure sequestered soil tritium (from the weapons testing era) in the absence of other confounding sources of man-made tritium. Near facilities with fluctuating emissions, fruits and some animal products sometimes contained high amounts of OBT versus HTO. Low OBT/HTO ratios were less common. Higher than expected OBT/HTO ratios have also been observed by others, but in more limited contexts[4]. Hence, average OBT/HTO ratios may be higher than previously estimated, and are clearly more variable than current models of tritium behaviour assume. This issue has been recognized by the scientific community and is the subject of ongoing research nationally (CANDU Owners Group, Atomic Energy of Canada Limited) and internationally (Institut de Radioprotection et de Sûreté Nucléaire, among others).

In the context of the low atmospheric releases presently arising from Canadian nuclear facilities, the high relative amounts of OBT in some locally-grown food items do not have any health and safety implications because doses remain very low (INFO-0793). Once new research results are confirmed, assumed default OBT/HTO ratios in soils, plants and animal products in tritium environmental transport models may need to be revised.

> **Recommendation:** *Whereas, in general OBT/HTO ratios exhibited values near unity, there was large variability in measured ratios near nuclear facilities. In the short-term, CNSC staff recommend that licensees include a sensitivity analysis in the calculation of doses to members of the public from facilities that release tritium such that the models consider the dose consequences of a maximum OBT/HTO ratio of 3 in locally grown garden produce and animal fodder and a maximum OBT/HTO ratio of 10 in locally farmed animal products (meat, milk, eggs).*
>
> *It is also recommended that CNSC staff continue its program of research in this area to better understand the mechanisms underlying observed OBT/HTO ratios. CNSC staff should work with other national and international organizations to develop more standard procedures for the analyses of OBT in various environmental media. Given the complexity of these measurements, laboratory inter-comparisons are particularly important.*

3.4 Review of the Health Risks of Tritium

Major reviews of tritium health risks in the context of the scientific literature and current radiation protection practices have been conducted by various authoritative groups in recent years. CNSC staff's review of this topic represents an additional independent and thorough assessment of the original literature. The following findings are well-supported in this review:

- The lines of evidence, based on both epidemiological and laboratory studies reveal that adverse health effects due to tritium exposure at current exposure levels in Canada are highly unlikely.
- The results of over 50 experimental studies related to the determination of a single RBE value for tritium confirm that tritium beta radiation is about 1.4 times more biologically effective than radiation from x-rays of 250 kVp and 2.2. times more biologically effective than high-energy gamma ray radiation.
- The use of a RBE of 1 in the current ICRP radiation protection framework has not decreased the level of protection afforded to workers or members of the public. This is because implementation of optimization has resulted in exposures to tritium that are very low and well below doses at which an increased risk of cancer has been observed.
- Current dosimetry and biokinetic models for assessing dose are acceptable for radiation protection purposes.

In the context of radiation protection, these findings indicate that Canada's current regulatory framework is effectively controlling tritium exposures.

> **Recommendation:** *To address gaps in knowledge of potential health risks for lifetime exposure to tritium at low doses, epidemiology studies specific to tritium are still warranted. It is recommended that CNSC staff continue its program of research in this area with particular emphasis on: (1) an international collaborative cohort study of mortality and cancer incidence of nuclear workers, and (2) case-control studies of cancer and birth defects resulting from in utero exposure of offspring of Canadian nuclear workers. To this end CNSC staff is proposing to establish a tritium working group, including public health agencies, cancer registries, universities, industry, and non-governmental organizations (NGOs) to assist with the design and review of proposed national and international studies.*
>
> *This working group would also examine the possibility of conducting additional dose response studies to assess the effect of tritium radiation on significant endpoints such as cancer. Organ specific estimates of the relative biological effectiveness should also be evaluated for their ability to provide better information for individual assessments in cases where there has been a large intake of tritium.*
>
> *Although doses from exposures to tritium are low, further research may be beneficial for epidemiological studies and for individual dosimetry to confirm that biokinetic models are adequate and to reduce uncertainties. Specifically, studies on the following topics should be considered:*

- *To address the retention of OBT in children and the effect of organ growth on OBT retention, an age-dependent biokinetic model for dietary intakes of OBT should be developed. This model would need to include all age groups, including the nursing infant, and account for physiological and anatomical variations associated with age.*
- *The Taylor HTO biokinetic model should be assessed against a broader set of available human data to improve the understanding of the consequences of the variation in the limited data. Such an assessment could be carried out by comparing urinary excretion data from workers exposed to tritiated water.*
- *The Taylor HTO biokinetic model applies only to adults. In order to satisfy the needs of public dose assessments, an expansion to various age groups should be carried out.*

Concern about the radiation weighting factor not being fully representative of the risk has been raised by others such as the U.K. Advisory Group on Ionizing Radiation. The proposed working group would also review the radiation weighting factor for low LET radiations such as tritium.

4 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of the project is that adequate provision has been made through existing regulatory mechanisms for the protection of the health and safety of Canadians against tritium. Canadian practices in the handling and control of tritium are currently comparable to those in overseas facilities, with effective control being achieved through a variety of mechanisms.

Effective controls are now uniformly in place in the Canadian nuclear industry as a result of compliance enforcement action at the two processing facilities previously licensed under the AECA through radioisotope possession licenses. This effort arose as a result of environmental protection considerations that became part of the expanded mandate of the CNSC after promulgation of the NSCA in 2000. Legacy issues of tritium contamination of groundwater remain at these and other facilities, but are being managed and monitored. Altogether, tritium management of routine operational releases is now following best practices internationally and is achieving a high level of control. Controls are therefore adequate and both environmental and public dose consequences of releases are generally ALARA, and appear to be close to the minimum practically achievable.

Environmental monitoring is a second fundamental requirement of CNSC Class I nuclear facility licensees. Tritium levels in the environment are being monitored effectively to ensure compliance with regulatory requirements. As with controls, increased sophistication in environmental monitoring programs has largely been the result of considerations that have arisen in recent years. Where scientific uncertainties remain (e.g. in the exact levels of tritium in air, or in the physical forms of tritium in food items), conservative regulatory approaches combined with strict limits on releases are being used. Gaps do exist in tritium environmental science, but they are not significant for people or the biosphere at current, low levels of exposure. This has clearly been shown by a thorough assessment of the health risks of tritium.

To improve on the framework for health protection, the following actions are recommended:

- *That CNSC staff establish a multi-stakeholder tritium working group to assist with epidemiology studies to examine health risks associated with lifetime exposure to tritium at low doses, and to consider additional studies in radiobiology and dosimetry, including review of the radiation weighting factor for low LET radiations such as tritium.*
- *That the CNSC continue its research into the variability of OBT/HTO ratios to better understand the underlying mechanisms, while assessing the sensitivity of dose estimates to high OBT/HTO ratios in foods.*

The existing regulatory framework has been adequate for the protection of human health. However, the approach to regulation of tritium on the basis of protection of the public has resulted in impacts to the environment, particularly groundwater resources. To enhance the framework for environmental protection, the following is recommended:

- *That the CNSC address groundwater protection issues at existing facilities at the policy level in consultation with the provinces, which have legal jurisdiction over*

groundwater resources. In the interim, CNSC staff are drafting regulatory documents providing expectations for groundwater protection, and providing guidance on contaminated site assessments to support clean up and other corrective measures.

- *That the CNSC address groundwater protection issues for all new Class I nuclear facilities that release tritium to the atmosphere by considering new design requirements, including:*
  - *a design objective for tritium level in groundwater of 100 Bq/L*
  - *a controlled zone within the licensee's control of sufficient size to ensure that the design objective of 100 Bq/L would be achieved at the perimeter given discharges of tritium to the atmosphere under normal operations*
  - *design criteria for release points (stacks) to ensure the effective dispersion of tritium in an atmospheric plume and to minimize environmental contamination through entrainment to the surface environment.*
- *That the CNSC undertake research to identify factors that need to be taken into account for adequate calibration of active and passive air samplers for tritium. In the interim, licensees should be requested to provide data on the uncertainty in measurements conducted as part of their monitoring programs.*

Altogether, the Tritium Studies project has improved on our knowledge of the production, management and release of tritium in Canada. This has been achieved through several information gathering activities and the publication of reviews of issues important to the protection of human health and the environment. The results and recommendations of this project are being used and will be used by CNSC staff to improve the regulatory oversight of tritium releases in Canada.

5 ACRONYMS

ACES	Advisory Committee on Environmental Standards
AECA	*Atomic Energy Control Act*
AECB	Atomic Energy Control Board
AECL	Atomic Energy Canada Limited
ALARA	As Low As Reasonably Achievable
CANDU	Canada Deuterium Uranium
CSA	Canadian Standards Association
CRL	Chalk River Laboratories
DRL	Derived Release Limits
ICRP	International Commission on Radiological Protection
LET	Linear Energy Transfer
NGO	Non-governmental Organization
NSCA	*Nuclear Safety and Control Act*
OBT	Organically bound tritium
ODWAC	Ontario Drinking Water Advisory Council
RBE	Relative Biological Effectiveness
SSI	Shield Source Inc.
SRBT	SRB Technologies (Canada) Inc.
WHO	World Health Organization

6 GLOSSARY

For simplicity, some terms are defined in plain language and may differ from definitions in standard references.

ALARA	Principle for radiation protection, according to which exposures are kept as low as reasonably achievable below regulatory limits, with social and economic factors taken into account.
becquerel	Unit of activity; the rate at which transformations occur in a radioactive substance. 1 Bq = 1 transformation or disintegration per second.
critical group	A homogeneous group of members of the public identified as being those individuals most likely to receive the highest doses from exposure to radioactive materials. Whereas the concept of critical group is the same for all CNSC licensees in Canada, the description of each critical group is unique, some being more conservative than others. It is based on analysis of site-specific radionuclide releases and exposure pathways and on site-specific land use information.
Derived Release Limit (DRL)	A limit on the release of a radioactive substance from a licensed nuclear facility, calculated so that compliance with the DRL gives reasonable assurance that the regulatory dose limit is not exceeded. It represents a release that would result in a dose of 1 mSv/year to the critical group.
dose limit	An upper limit on radiation dose specified in the CNSC *Radiation Protection Regulations*.
ionizing radiation	Any atomic or subatomic particle or electromagnetic wave with sufficient energy to produce ions (atoms that have become charged due to the loss or gain of electrons) in the material that absorbs it. Ionizing radiation includes alpha and beta particles and gamma radiation, as well as neutrons and some other particles.
tritium	A radioactive form of hydrogen produced both naturally and by human activities. Tritium is produced during normal operation of Canadian nuclear reactors. The ionizing radiation from tritium is a beta particle.

7 REFERENCES

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Canada's Nuclear Regulator

Canadian Nuclear Safety Commission

Commission canadienne de sûreté nucléaire

Canada