Canada's Nuclear Regulator

# Study of Consequences of a Hypothetical Severe Nuclear Accident and Effectiveness of Mitigation Measures

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**Study of Consequences of a Hypothetical Severe Nuclear Accident and Effectiveness of Mitigation Measures**


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## Document availability

This document can be viewed on the CNSC website at nuclearsafety.gc.ca. To request a copy of the document in English or French, please contact:

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Further to the August 2015 version of the study that was made available on request, the CNSC has corrected figures in tables A1.1 and A1.2. These changes do not impact the conclusions of the report.

# Extended executive summary

## Introduction

The *Study of Consequences of a Hypothetical Severe Nuclear Accident and Effectiveness of Mitigation Measures* is the result of a collaborative effort of research and analysis that arose out of the Commission's decision on the environmental assessment (EA) of the refurbishment and continued operation of the Darlington Nuclear Generating Station (DNGS) in the Municipality of Clarington, Ontario. The Commission directed Canadian Nuclear Safety Commission (CNSC) staff to undertake an assessment of health and environmental consequences of severe nuclear accident scenarios and to update the Commission accordingly. The update was to reflect severe accident-related matters discussed by intervenors during the hearing, and be made available to the public (i.e., published).

At a high level, the study involved identifying and modelling a large release of radionuclides to the atmosphere from a hypothetical severe nuclear accident (referred to as a generic large release) at the DNGS; estimating the doses to individuals at various distances from the nuclear power plant, factoring in emergency response protective actions such as evacuation; and, finally, determining human health and environmental consequences due to radiation exposure from a severe nuclear accident.

## What was done

Modelling a hypothetical severe nuclear accident meant starting with certain conservative assumptions in order to simplify a complex topic, yet be responsive to the concerns raised during the public hearing on the EA. For instance, it was assumed that there was a radioactive release from a nuclear power plant without full credit given for plant-specific design features and operator actions to mitigate the release. Canadian nuclear power plants are regulated and designed to minimize risk to the public and the environment. They are fundamentally designed and operated to withstand events or minimize releases from events such as loss of onsite and offsite power, loss of standby generators, total station blackout, depletion of steam generators, overheating of the reactor fuel and reactor core damage. These aspects were further strengthened through the implementation of the CNSC-led lessons learned from the nuclear accident at Fukushima (known as Fukushima enhancements). Had all of the plant-specific safety design features, operator actions and other Fukushima enhancements (e.g., such as offsite emergency mitigating equipment (EME) that provides redundant and independent means for back-up power and water to the plant) been fully credited/realized, the likelihood of a severe accident would have been practically eliminated to the point where the release of radioactive material considered in this study and its impact on human health and the environment would have been significantly reduced.

The starting point of the study was to establish a source term. "Source term" is the term used to describe the radionuclides and their respective quantities that are released into the environment; it serves as the basis for the generic large release. The magnitude of the source term in this study was equal to or greater than that previously assessed for nuclear accidents in nuclear power plant EAs. In addition, it was based on CNSC safety goals which are derived from modern international recommendations established to ensure plant design features are in place to limit the risk to society and the environment to acceptably low levels. The relative composition of radionuclides in the source term reflected that of the reactor units at the DNGS. In addition, to simulate an accident affecting all four reactor units at the DNGS, the amount of radionuclides released was increased fourfold for two of the scenarios.

With respect to the actual release, it was important to establish the holdup period and release duration. "Hold up" refers to the period of time between the onset of the accident at the reactor and when

radioactive material is released into the environment – it is normally "held up" by containment prior to release in the environment. Release duration is the length of time that the radioactive material is being released to the environment. For all accident scenarios examined, the release was held up for 24 hours within the plant, consistent with the understanding of accident progression at Darlington. Three hypothetical accident scenarios were assessed with short (1 hour), medium (24 hours) and long (72 hours) release durations of radionuclides into the atmosphere. Modelling then simulated the transport and dispersal of the radioactive plume throughout the landscape out to 90 km away from the plant, reflective of meteorological data around the DNGS such as wind speed and direction. The outputs of the modelling were doses (reported in millisieverts (mSv)) to individuals at different distances from the nuclear power plant.

Estimated doses are essential inputs into emergency preparedness and response as they inform decision makers on actions that should be taken to protect the public. Short-term protective actions include evacuation (i.e., relocate to a safe area), sheltering (i.e., people are instructed to stay inside) and the ingestion of potassium iodide (KI) pills (i.e., saturates the thyroid gland with KI to inhibit the absorption of radioactive iodines from a release). In the event of an actual incident at a nuclear power plant, there are responsibilities across multiple jurisdictions and stakeholders for emergency response. Offsite response is led by the province and in the case of Ontario, the Office of the Fire Marshall and Emergency Management is the central organization responsible for administering Ontario's Provincial Nuclear Emergency Response Plan (PNERP). The PNERP establishes, amongst other things, predefined emergency planning zones (known as the Contiguous, Primary and Secondary Zones around a nuclear power plant) as well as protective action levels. Protective action levels (PALs) are levels or ranges of doses intended to assist emergency response authorities on choosing appropriate protective actions to protect public health – for example, whether to evacuate.

For this study, Ontario provincial PALs were applied to the estimated doses to determine how far to evacuate, shelter and administer KI pills for ingestion. Where the PAL was reported as a range of doses, the lowest end of the dose range was used. For the study, it was assumed that all individuals within the zone to be evacuated were done so successfully (i.e., received zero dose). For those individuals requiring sheltering, a 20-percent reduction to the dose was assumed. For KI pills, it was assumed that within the Primary Zone (analogous to 12 km in this study) at distances that exceeded the PAL for thyroid blocking, KI pills were successfully ingested in a timely fashion, resulting in zero dose.

The residual doses that remained after the application of protective actions were used as inputs into the human health risk assessment. A human health risk assessment is intended to provide complete information to make the best possible decisions to protect people's health and to communicate the highest quality information to the public. In terms of human health, the focus of this study was to examine the possible impact on cancer incidence. Cancer is described as a stochastic or latent effect where the probability of occurrence is proportional to exposure or dose. Deterministic effects, such as acute radiation sickness were not examined as the estimated doses in this study were below the thresholds for these types of effects.

Using a methodology consistent with international practice, increased cancer risk for all cancers combined, leukemia and thyroid cancer (both adult and children) were quantitatively assessed based on an exposure to radiation from the hypothetical accident scenarios for the first seven days. The types of cancer chosen were reflective of those demonstrating sensitivity to radiation. Likewise, children were chosen specifically when assessing thyroid cancer, as the child's thyroid is known to be radiosensitive. Risk was reported in a couple of ways: excess future risk, which is the risk that can be attributed to the radiation exposure – in this case, from the accident (i.e., the time of exposure to radionuclides) until the end of expected lifetime; and baseline future risk, which is the risk that would exist in the absence of the radiation exposure from the accident. Both were needed to put the overall risk into context.

## Results

The study demonstrated that for all hypothetical scenarios examined, doses would decrease rapidly with distance from the plant. From an emergency response perspective, for some scenarios, evacuations of up to 3 km would be needed. For the worst case scenario, evacuation beyond the Primary Zone, analogous to 12 km in this study, would not be required given the estimated doses.

With respect to the human health results, it would be nearly impossible to distinguish most radiation-induced cancers (all cancers combined, leukemia, adult thyroid cancer) from baseline cancers examined in this study. To put this finding into perspective, the baseline future risk of developing cancer in Ontario is approximately 49 percent. The increased risk of developing all cancers combined from exposure to a hypothetical accident scenario (24-hour holdup followed by a 1-hour release) would result in an additional 0.0004-percent chance of developing cancer on top of the 49 percent baseline future risk – an indistinguishable increase.

Conversely, childhood thyroid cancer was the only radiation-induced cancer that could be distinguished from baseline cancers. Increased risk for childhood thyroid cancer was predicted for all scenarios. For example, in the worst-case scenario, where the radiological release was increased fourfold to be representative of a multi-unit accident, the predicted excess future risk of developing childhood thyroid cancer in close proximity to the plant was an additional 0.3 percent above the baseline future risk of approximately 1 percent. This is not unexpected given the radiosensitivity of a child's thyroid gland. Findings are also broadly consistent with the experience following the accident at Chernobyl.

Psychosocial effects would be anticipated for all scenarios and could include fear of radiation exposure, anxiety, and stress. Clear, credible and regular communication from responsible parties before, during and after the emergency would help to minimize these effects. In addition, these effects would be expected to decline rapidly once the affected population returns to their normal life patterns. For non-human biota, like birds and mammals, no acute effects would be expected.

## Insights and conclusions

In framing the human health results, risk is likely overestimated as it is based on modelled radionuclide transport, dispersion and dose estimates, rather than actual environmental and/or individual measurements. The overestimation resulting from preliminary modelling has been demonstrated following the Fukushima accident where doses estimated based on post release measurements were shown to be 2 to 5 times less than the preliminary estimated modelled doses. For additional perspective, the measured doses at Fukushima are comparable to the estimated doses in this study, and international authorities have indicated an increased incidence in cancer (e.g., thyroid cancer) is unlikely to be observed in the future in Japan.

Further, what this study does not take into account are enhancements in the plant's design, operating provisions, accident management and emergency preparedness emanating from the Fukushima Action Plan. These ongoing enhancements would ensure that the likelihood of a severe accident is further reduced, and if it were to occur, emergency response measures would be effective in protecting the public (i.e., by means of evacuation, sheltering and KI pill ingestion).

Emergency planning is inherently flexible and consideration of sensitive receptors such as children in emergency planning is an integral part of federal and provincial emergency decision making. In the event of an actual accident with this level of predicted risk, decision makers could further mitigate the risk in those areas most likely to be affected through the administration of KI pills or by evacuation.

In summary, this study has responded to the Commission's request to evaluate the human health and environmental consequences due to radiation exposure from a severe nuclear accident. The study is of a theoretical nature, using hypothetical severe accident scenarios. Overall, while conclusions point to a non-detectable increased health risk for most of the population, the theoretical increased childhood thyroid cancer risk findings in relatively close proximity to the DNGS further strengthens the continued importance of considering sensitive receptors (i.e., children) in emergency planning, such as KI pill administration.

From a risk acceptability perspective, the ability of the PNERP to effectively reduce the health risk, combined with the very low likelihood associated with severe nuclear accidents given Fukushima enhancements (i.e., such an event will be practically eliminated), allows these risks to be effectively managed to an acceptable level in alignment with international risk and radiological frameworks.

**Acknowledgements**

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# Table of Contents

# 1. Project overview

This chapter explains the purpose, provides context and outlines the overall process that was followed for this study.

## 1.1 About this study

The purpose of the study is to consider hypothetical severe accident scenarios and to assess the subsequent consequences to human health and the environment, when aspects of emergency response plans have been implemented.

The need for this study arose out of the Commission's *Record of Proceedings, Including Reasons for Decision – Ontario Power Generation Inc. – Environmental Assessment (EA) Screening Regarding the Proposal to Refurbish and Continue to Operate the Darlington Nuclear Generating Station (DNGS) in the Municipality of Clarington, Ontario* (CNSC 2013a). The Commission directed Canadian Nuclear Safety Commission (CNSC) staff to undertake an assessment of health and environmental consequences of severe nuclear accident scenarios and to update the Commission accordingly. The update was to be in the form of an information document or equivalent, and reflect severe accident-related matters discussed by intervenors during the public hearing.

The results of the study provide insights that are useful for the purposes of emergency planning and response. Most importantly, it informs the public and other stakeholders of the possible consequences of a hypothetical severe nuclear accident, the effectiveness of emergency planning, and the inherent safety of Canadian nuclear power plants.

## 1.2 Definition of a severe accident

To understand what a severe accident is, it is necessary to go through the hierarchy of classification of nuclear accidents:

- A transient or an anticipated operational occurrence refers to deviation from normal operating conditions but within the design limits and does not create challenges to the safety functions. Anticipated operational occurrences are events with frequencies greater than 1 in 100 years.
- A design-basis accident refers to accident conditions for which a reactor facility is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits. A design-basis accident is reflective of a 1 in 100,000 ($10^{-5}$) probability of occurrence or greater in any year.
- A beyond-design-basis accident is an accident which is more severe and less frequent than a design basis accident. A severe accident represents a beyond-design-basis accident involving core degradation or significant fuel degradation in the spent fuel pool (also called the irradiated fuel pool).

## 1.3 How this study differs from past and ongoing studies

Beyond-design-basis accidents (including severe accidents) with an annual probability of occurrence of greater than 1 in 1,000,000 ($10^{-6}$) have been assessed in previous nuclear-related environmental assessments (EAs). These EAs included those for the refurbishment and continued operation of the Darlington Nuclear Generating Station (DNGS); construction and operation of new nuclear power plants at Darlington; refurbishment and continued operation of the Pickering B Nuclear Generating Station; refurbishment and continued operation of the Bruce A Nuclear Generating Station; and the refurbishment and continued operation of the Gentilly-2 Nuclear Generating Station. For these EAs, beyond-design-basis accidents with offsite releases were assessed for human health and environmental consequences largely using probabilistic risk assessments emanating from the station-specific safety analyses.

This study assumes the radiological releases happen regardless of probability and are of an equal or greater magnitude than releases previously assessed in EAs. In other words, credit is not fully given to operator actions or specific plant design features that would prevent or mitigate such releases. Chapter 2 of this document provides an overview of these aspects. Though this is unrealistic from an operational perspective, it is appropriate to consider hypothetical accident scenarios for emergency plan implementation and assessment of subsequent consequences.

For modelling purposes for emergency protective actions, this study assumes evacuation and/or sheltering are successfully completed out to distances corresponding to the protective action levels outlined in the Ontario Provincial Nuclear Emergency Response Plan (PNERP). For thyroid blocking, this study assumes successful ingestion of potassium iodide (KI) pills at distances within the Primary Zone established in the PNERP, corresponding to a 50-mSv dose to the adult thyroid. Further details on emergency preparedness and response, including whether emergency plans can be effectively executed under severe accident conditions, are provided in chapter 4.

Under the Fukushima Task Force's Integrated Action Plan, emphasis has been placed on severe accident prevention and mitigation and is further described in chapter 2.

This study is being done to specifically address the direction given to CNSC staff by the Commission. As such, it does not examine economic consequences. Canada does, however, have a compensation regime in place for damages incurred in the event of a nuclear incident.

Though the study results are useful in support of other initiatives, they are not meant to represent specific reactor accident scenarios, nor be part of the actions emanating from the Fukushima Action Plan or activities being undertaken by other parties (e.g., updating of nuclear emergency response plans).

**What is the Canadian Nuclear Safety Commission's role?**

The CNSC is mandated under the *Nuclear Safety and Control Act* to regulate the use of nuclear energy and materials to protect health, safety, security and the environment, to implement Canada's international commitments on the peaceful use of nuclear energy, and to disseminate objective scientific, technical and regulatory information to the public.

There are many stages in the lifecycle of nuclear facilities. An approval from the Commission is needed for each of these stages before a person or company can undertake

related activities. These stages include: site preparation, construction, operation, decommissioning and abandonment.

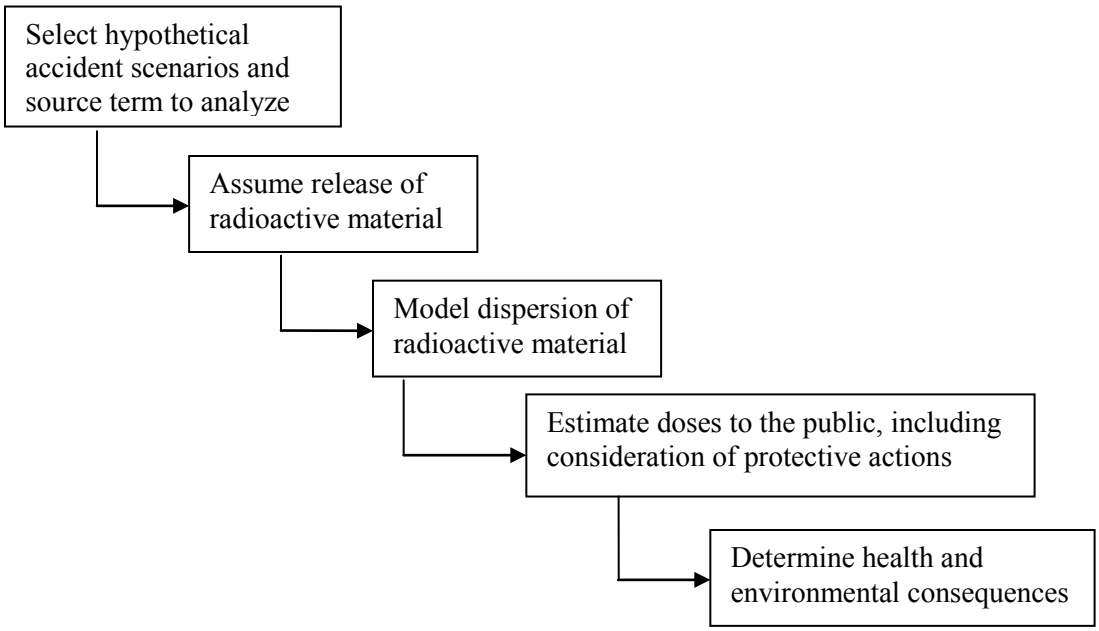
The CNSC has resident inspectors at all nuclear power plants who continuously verify and enforce compliance with stringent licence conditions, to ensure protection of the health, safety, security and environment.

Throughout this document, reference will be made to relevant aspects of the CNSC's regulatory framework that help ensure its mandate is met.

## 1.4 Steps taken in this study

During the course of the hearings on the EA for the refurbishment and continued operation of the DNGS, intervenors raised concerns regarding the severity of the accident assessed, the absence of an "early release" scenario, adequacy of offsite emergency planning, including evacuation, and potential health effects to the public. Every attempt was made to capture these concerns in the approach to this study, recognizing the inherent aspects of the CANDU design and improvements emanating from the Fukushima Action Plan. Figure 1.1 shows the high-level steps of this study.

**Figure 1.1: Flow chart of study of consequences of a hypothetical severe nuclear accident**



**How did the CNSC respond to the events at Fukushima?**

On March 11, 2011, a magnitude 9.0 earthquake, followed by a devastating tsunami, struck Japan. It left an estimated 20,000 people dead or missing, about half a million homes destroyed or damaged, and 560 square kilometers inundated. The combined impact of the earthquake and tsunami on the Fukushima Daiichi nuclear power plant caused one of the world's worst nuclear accidents.

The nuclear event prompted many countries to evaluate the safety of their nuclear infrastructure. The CNSC launched a review of all major nuclear facilities in Canada. Led by a multidisciplinary CNSC task force, the review confirmed the ability of Canadian facilities to withstand and respond to credible external events, such as earthquakes. A four-year action plan is underway to strengthen defence in depth, enhance emergency preparedness and response capabilities and improve CNSC's regulatory framework and processes.

The study presented in this document is compared and contrasted with the accidents at Fukushima and Chernobyl, where appropriate.

# 2. Nuclear reactors in Canada

This chapter explains the regulatory requirements for nuclear power plants, provides an overview of the CANDU design, and describes how Canadian nuclear power plants are focused on safe operation, and accident prevention and mitigation.

## 2.1 Regulatory requirements

The CNSC has a robust regulatory framework that starts with the *Nuclear Safety and Control Act* (NSCA) and associated regulations. The CNSC's regulatory documents provide greater detail on requirements set out in the NSCA and regulations on a broad range of topics, such as safety analysis, site evaluation, licensing, life extension of existing nuclear power plants, emergency planning, and severe accident management programs.

CNSC staff use safety and control areas, which are established across all regulated facilities and activities and set out in a comprehensive framework, to assess, evaluate, review, verify and report on regulatory requirements, compliance and performance.

## 2.2 Defence in depth

Defence in depth is a comprehensive approach to safety to ensure with reasonable confidence that the public and the environment are protected from any hazards posed by a nuclear power plant. The concept of defence in depth is applied to all organizational, behavioural, and design-related safety and security activities to ensure that they are subject to overlapping provisions. With the defence-in-depth approach, if a failure were to occur it will be detected and compensation made, or it would be corrected. This concept is applied throughout the design and operation of a nuclear power plant to provide a series of levels of defence aimed at preventing accidents, and ensuring appropriate protection in the event that prevention fails.

Defence in depth is structured in five levels. Table 2.1 identifies the levels and associated means to achieve the objective of that level. The general objective of defence in depth is to ensure that a single failure, whether equipment or human, at one level of defence (and even combinations of failures at more than one level), would not propagate to jeopardize defence in depth at subsequent levels.

**Table 2.1: Levels of defence in depth and associated means to achieve objectives**

| Levels of defence in depth | Means to achieve objective |
|---|---|
| **Level 1**<br>Prevention of abnormal operation and failures | Conservative design and high-quality construction, operation and maintenance to provide confidence that plant failures and deviations from normal operations are minimized and accidents are prevented. |
| **Level 2**<br>Control of abnormal operation and detection of failures | Controlling plant behaviour during and following postulated events using both inherent and engineered design features and procedures to minimize or exclude uncontrolled transients to the extent possible. |
| **Level 3**<br>Control of accidents within the design basis | Provision of inherent safety features, fail-safe design, engineered design features, and procedures that minimize the consequences of design-basis accidents. These provisions are capable of leading the plant first to a controlled state, and |

| Levels of defence in depth | Means to achieve objective |
|---|---|
| | then to a safe shutdown state, and maintaining at least one barrier for the confinement of radioactive material. Automatic activation of the engineered design features minimizes the need for operator actions in the early phase of a design-basis accident. |
| **Level 4**<br>Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents | Provision of equipment and procedures to manage accidents and mitigate their consequences as far as practicable. Adequate protection is provided by way of a robust containment design. This includes the use of complementary design features to prevent accident progression and to mitigate the consequences of selected severe accidents. The containment function is further protected by severe accident management procedures. |
| **Level 5**<br>Mitigation of radiological consequences of significant releases of radioactive materials | Provision of an adequately equipped emergency support centre, and plans for onsite and offsite emergency response. |

The CNSC has licensed Canadian nuclear power plants on the basis of comprehensive safety reports and supplementary analyses, which demonstrate that the facility designs and operations meet regulatory requirements and expectations. This includes the evaluation of safety functions implemented in the facility design.

## 2.3 Overview of Canadian nuclear power plants

Canadian nuclear power plants are designed to minimize risk to the public and the environment. Each nuclear power plant in Canada has redundant and diverse safety systems designed to prevent accidents and reduce their effects, should they occur. All of these systems are maintained and inspected regularly to ensure plants meet or exceed the CNSC's safety requirements. The safety systems perform three fundamental safety functions known as the 3Cs: controlling reactor power, cooling the fuel and containing radiation.

### 2.3.1 The 3Cs and normal operations

**Controlling reactor power**

During normal operations, controlling the reactor power level involves increasing, decreasing or stopping the chain reaction (or power level). When the reactor is operating, the chain reaction is controlled by multiple and independent reactivity control devices that can stop the reaction quickly. Sensitive detectors constantly monitor the temperature, pressure and reactor power level. When necessary, CANDU reactors through independent shutdown systems can safely and automatically shut down within a few seconds.

**Cooling the fuel**

Fuel cooling during operations involves the primary heat transport system, which uses heavy water to bring the heat produced in the reactor to the steam generators. The secondary system, the steam system, uses normal water to extract the heat from the primary heat transport system. The heat from the reactor turns this water into steam to run the turbines and generators.

That steam is then cooled and condensed using a system that pumps in cold water from a body of water such as a lake or reservoir. This is called the condenser cooling water system.

**Heavy water inventory**

CANDU reactors have a greater water inventory available to keep the fuel cool than the inventory present in light-water reactor (LWR) designs, with CANDU reactors having between 1.5 to 7.5 times the mass of water than an LWR. Furthermore, the water inventory available in a CANDU reactor per unit of electrical power produced by the reactor (i.e., the ratio of water inventory to electrical power) is more than twice as much as is available in a pressurized water reactor and more than 3.5 times as much as is available in a boiling water reactor. However, the likelihood of all the emergency core cooling systems failing in a CANDU, leading to heat being rejected through the aforementioned water inventories, is very low.

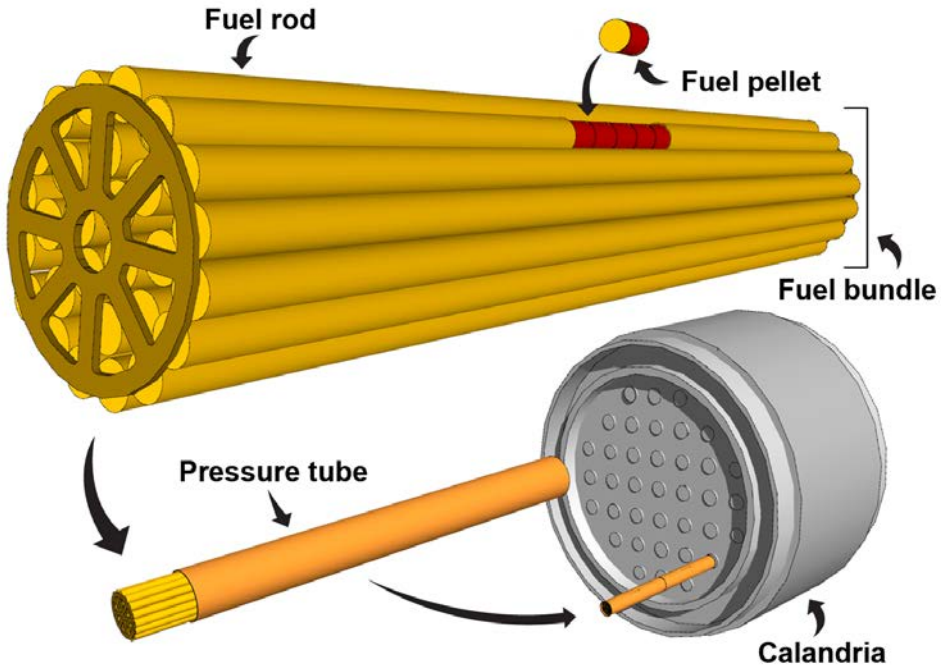
**Containing radiation**

Nuclear reactors are built with multiple barriers to safely contain radiation. At the heart of all CANDU reactors are hardened ceramic pellets made of natural uranium. These ceramic pellets contain and form the first barrier to the release of radioactive material.

The pellets are enclosed in rods, which form the second barrier. CANDU fuel rods are made of zircaloy, a metal alloy resistant to heat and corrosion.

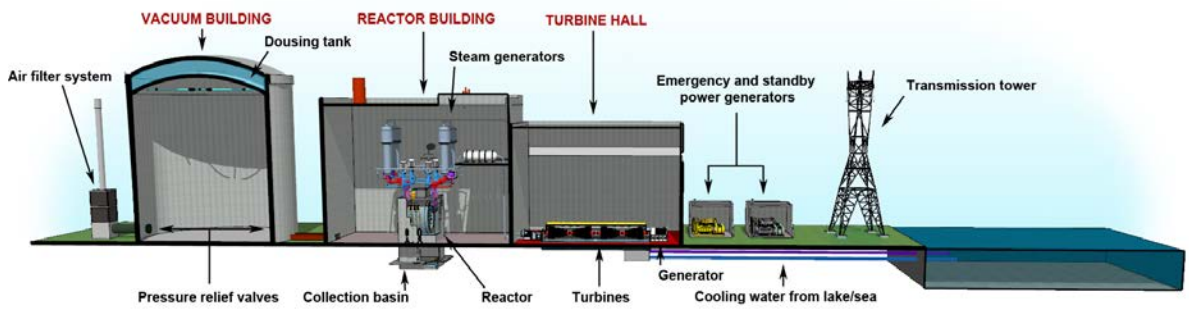
The rods, assembled in the so-called fuel bundles, are then loaded into pressure tubes, which are part of the primary heat transport system. These tubes represent the third barrier. The pressure tubes are contained inside a metal tank called the calandria, which itself is contained inside a thick vault made of reinforced concrete. These three barriers to release of radioactive material are shown in figure 2.1.

**Figure 2.1: Barriers to release of radioactivity in a CANDU reactor**




The fourth barrier, called the containment, is the building that houses and protects the reactor. The walls of the containment (i.e., reactor building) are made of at least 1 metre of reinforced concrete, which incorporates the systems that regulate pressure inside the reactor building under accident conditions. In a single-unit station, this involves a water-spraying system from a dousing tank. In a multi-unit station, steam and hot gases that could pressurize containment are passively released into a vacuum building that also has a spray system and air coolers (see figure 2.2). The fifth barrier, the exclusion zone, is a buffer of land surrounding the nuclear power plant on which there is no permanent dwellings and over which the licensee has the legal right to exercise control.

**Figure 2.2: Reactor building (CANDU multi-unit), surrounded by an exclusion (buffer) zone**



**Fukushima Task Force findings and the path forward**

The CNSC Task Force confirmed that Canadian nuclear power plants are robust and rely on multiple layers of defence.

The Task Force issued the *CNSC Integrated Action Plan* to further enhance the safety of operating nuclear facilities in Canada and reduce the associated risk to as low as reasonably practicable. The Plan also integrated reviews and recommendations from the Task Force and External Advisory Committee.

The recommendations were reconfirmed by an independent review completed by the International Atomic Energy Agency's Integrated Regulatory Review Service follow-up mission and comments received from the public and stakeholders during three rounds of public consultations.

The *CNSC Integrated Action Plan* applies to all operating nuclear facilities and the CNSC. The areas for continuous improvement that emerged from the Plan are:

- strengthening defence in depth
- enhancing emergency response
- improving regulatory framework and processes
- enhancing international collaboration
- enhancing communications and public education

The Canadian nuclear power industry is on track to complete all Fukushima action items identified in this Plan by December 2015.

The safety improvements being implemented at all Canadian nuclear sites as a result of Fukushima lessons learned, through enhanced design and operating procedures will further increase safety margins by reducing the likelihood of a severe accident and mitigating its consequences.

Further information on the event that happened in Japan and the Fukushima Task Force is available on the CNSC's website.

### 2.3.2 The 3Cs and the potential for accidents

In response to the March 11, 2011 accident at the Fukushima Daiichi Nuclear Power Plant, the CNSC convened a task force to evaluate lessons learned and the operational, technical and regulatory implications for Canadian nuclear power plants.

The CNSC Task Force strengthened each layer of defence built into the Canadian nuclear power plant design and licensing philosophy to ensure that the likelihood of accidents with serious radiological consequences is extremely low. Since the current regulatory framework largely relates to design-basis accidents, the Task Force placed particular emphasis on systematic application of the defence-in-depth approach to severe accidents (Level 4), using insights from deterministic and probabilistic safety analyses, as well as emphasis on mitigation of radiological consequences (Level 5) through emergency preparedness and response. In this way, the Task Force evaluated potential design and procedural improvements to enhance effectiveness of the fundamental safety functions, namely controlling the reactor, cooling the fuel and containing radiation.

An examination of a loss of offsite power accident scenario and its progression is described below as an example to illustrate the number of provisions in the plant design, and that there are multiple means to mitigate such an event. The effect of these provisions can be assessed through the operator's ability to prevent, slow down or arrest the progression of the accident and, as a result, maintain a series of physical barriers to confine the radioactive material.

**Controlling reactor power**

Two diverse and independent shutdown systems are automatically activated in less than two seconds, terminating the fission process and safely shutting down the reactor.

**Cooling the fuel**

Following shutdown, the reactor core continues to produce decay heat that needs to be removed by cooling. Cooling of the fuel is achieved by the natural circulation flow that takes over from pumped flow within a few minutes of the reactor shutdown due to the density difference between the cold coolant in the steam generators and the hot coolant in the reactor core.

A number of provisions outlined below are designed to continue to cool the fuel and are representative of Level 4 defence-in-depth measures that control severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents.

- **Provision 1: Preventing fuel failure**

As long as the steam generators are kept filled with water and are vented to the atmosphere (as clean steam), they will be capable of maintaining natural circulation and thus remove heat from the reactor core and prevent fuel failure. In the case of an offsite power accident scenario and in the unlikely event where active (powered) heat sinks are unavailable, heat will be removed from the reactor core by providing diverse sources of water supply to the steam generators (e.g., feedwater from reserve tanks, firewater, and the use of fire trucks) through multiple connections.

- **Provision 2: Preventing fuel channel failure**

Considering the unlikely event where water addition to the steam generators is unavailable, after three hours there will be no more water in the primary heat transport system and limited fuel damage will occur due to overheating. After four hours, the water level in the calandria vessel will start to fall due to evaporation.

Supplying water to the calandria vessel (moderator system boundary) will prevent the fuel channels from overheating and will terminate the accident progression before core damage. Means of providing additional water supplies to the calandria vessel are being designed or have already been implemented by the nuclear power plant licensees, as part of the Fukushima action follow-up activities to prevent fuel channel failure and consequential core damage.

- **Provision 3: Preventing calandria vessel failure**

Considering the unlikely event that water addition to the steam generators or calandria vessel is not successful and no operator actions are taken, after 11 hours there will be no more water in the calandria vessel and molten fuel debris will eventually accumulate at the bottom of the vessel.

Providing a supply of water to the calandria vault (shield tank) will terminate the accident progression and retain molten fuel debris in the calandria vessel through heat removal from the surrounding water in the calandria vault.

**Containing radiation**

- **Provision 4: Preventing containment failure**

In the event that none of the fuel cooling provisions are available, after about 46 hours controlled venting would be required to protect the containment from high internal pressure[1], and the possibility of hydrogen detonation that might cause structural damage and consequently the uncontrolled release of radioactivity to the environment. At this stage of this unlikely event, officials responsible for emergency response would have evacuated the area in preparation for venting the containment.

Passive autocatalytic hydrogen recombiners and a high efficiency emergency containment filtered venting system (CFVS) would mitigate these challenges. The CFVS is designed to reduce the release of radioactive material to the environment and will subsequently reduce the evacuation zone by a significant factor.

- **Provision 5: Protecting the public**

In addition to the design provisions such as CFVS to minimize release of radioactive material to the environment, nuclear power plant licensees have undertaken measures to enhance onsite emergency response (representative of Level 5 defence-in-depth measures). These measures include the evaluation and revision of existing emergency plans with local authorities with regard to multi-unit accidents and severe external events (drills and exercise programs), and to review and update emergency facilities and equipment. Emergency plans incorporate beyond-design-basis accidents and severe accident management guidelines.

[1] The description and timing of the event sequence is broadly correct for CANDU-6, particularly in the early stages. The exact sequence, timing and consequences will vary between reactors.

### 2.3.3 Operator actions

Inherent in controlling the reactor, cooling the fuel and containing radiation are operator actions. Though this study does not take full credit for operator actions, they are fundamental to the safe operation of a nuclear power plant and addressing potential accidents. Nuclear operators are carefully selected, highly trained and qualified, and are authorized by the CNSC. Operator actions are described in licensees' policies, programs and procedures and, as appropriate, are regularly reviewed, tested and verified.

The effect that operator actions can have on accident progression is illustrated in a study undertaken by the U.S. Nuclear Regulatory Commission (U.S. NRC) that examined long-term station blackouts at two U.S. nuclear power plants, comparing cases where operator actions are credited to cases where they are not (U.S. NRC 2012). The study demonstrated that operator actions were able to halt the progression of the accidents within 5 hours. However, in their absence, releases of radioactive material occurred in 20 and 45 hours for the two nuclear power plants examined, respectively.

### 2.3.4 Additional layers of protection – Plant-specific design features

Though the accident scenarios chosen for this study (see chapter 3) credit general design features in nuclear power plants (e.g., containment), specific plant design features are not fully considered in this study. A number of safety improvements have been implemented or are planned for the DNGS emanating from the *CNSC Integrated Action Plan*, and the integrated safety review undertaken for the DNGS to define the scope of refurbishment. These improvements are representative of Level 4 defence-in-depth measures that control severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents.

Table 2.2 provides a brief description of some of the key improvements that have been implemented or are planned to be implemented at the DNGS. These improvements, applied to enhance the defence-in-depth concept, are focused primarily on severe accident prevention and mitigation (Levels 4 and 5 – see table 2.1) in order to effectively deal with highly unlikely events, regardless of economic consequences, and thereby ensuring appropriate protection to the public and the environment. For example, the CFVS can be operated manually or remotely (no external power) and is capable of filtering out 99-99.9 percent of most radionuclides (except for noble gases) (OPG 2014). That means the public risk of exposure to a large radioactive release in the event of a beyond-design-basis accident would be much reduced with this safety improvement.

**Table 2.2: Planned/implemented safety improvements and associated objectives for the Darlington Nuclear Generating Station**

| Safety Improvement | Objective |
|---|---|
| Containment filtered venting system (CFVS) | The objective of the CFVS is to provide a filtered pressure relief path from containment to the atmosphere. This addition, in conjunction with additional relief capacity for the reactor shield tanks, is aimed at ensuring containment integrity post-severe, multi-unit, beyond-design-basis accidents. |
| Powerhouse steam venting system | The objective is to improve the reliability of powerhouse venting through duplication of the powerhouse steam venting system singleton programmable logic controllers. Powerhouse venting is an important mitigating action for post-secondary side (steam and feedwater) line breaks occurring in the powerhouse. |
| Third emergency power generator | This is aimed at improving the reliability of emergency back-up power for a variety of common mode failures (including improved seismic capacity and flood protection). |
| Improvements to the emergency heat sink | This is aimed at providing a new, independent water supply directly to the heat transport system. This will enhance the operators' ability to respond to a beyond-design-basis accident and further reduces the already low likelihood of a beyond-design-basis accident from progressing to a severe accident. |
| Passive autocatalytic recombiners (PARs) | PARS aim to mitigate hydrogen build-up in the containment and preserve its integrity. |
| Upgrades to electrical power | The objective of upgrading the electrical power is to supply power to key instrumentation and controls during total loss of AC power (i.e., station blackout). |
| Make-up WATER CAPABILITIES | The objective is to supply make-up water cooling to the reactor core through multiple paths, and to prevent and/or arrest progression to a severe accident through the deployment of emergency mitigating equipment (EME). This includes portable diesel pumps and diesel generators/portable uninterruptible power supplies. Ontario Power Generation (OPG) has installed and is currently in the process of enhancing EME connection points to station systems to streamline and simplify EME deployment in the case of a severe accident.<br>These additional connection points involve the ability to provide make-up water to the steam generators, calandria (moderator), primary heat transport system and shield tank using EME pumps. |

In CANDU designs, the reactors have the capability of passively removing decay heat through natural circulation flow called thermosyphoning (i.e., movement due to the coolant's own density differences). Therefore, the need for immediate operator actions to mitigate a severe accident is

significantly extended – for up to 5.5 hours (the exact time depends on the plant), even in the absence of normal power supplies.

For instance, during the August 14, 2003 blackout of southern Ontario and the northeastern United States, the fuel in the reactors in the Pickering B Nuclear Generating Station was cooled by thermosyphoning for up to nine hours. According to OPG's estimates, thermosyphoning would have continued to be an effective heat sink for many more hours if restoration of offsite power had been delayed.

### 2.3.5 Additional layers of protection – Severe accident management guidelines and emergency mitigating equipment

During the progression of a severe accident at a Canadian nuclear power plant, the procedures and actions detailed in the plant's severe accident management guidelines are applied. These provide guidance on using various onsite equipment and systems to ensure that the fuel is cooled, the containment remains intact, and any releases are minimized during a severe accident. The strategies within the severe accident management guidelines are all symptom-based, and therefore applicable to any severe accident regardless of its cause or progression. Also, multiple means of achieving the same results are identified so that the loss or unavailability of any one piece of equipment or system can be overcome and the associated safety function maintained.

**Figure 2.4: Example of emergency mitigating equipment – emergency portable pump**

The procedures and actions in the severe accident management guidelines all make use of the equipment available onsite. As part of its assessment, the CNSC Task Force found that the onsite resources were adequate to deal with many beyond-design-basis accidents. However, for a serious accident lasting several days, external equipment and materials may be needed to mitigate that accident (e.g., figure 2.4). As part of the lessons learned from Fukushima, Canadian nuclear power plants (e.g., DNGS) have procured such equipment and materials, including portable generators and pumps to provide redundant and independent means for back-up power and water to the plant. This equipment, designated as emergency mitigating equipment (EME), will be stored offsite so it is not affected by an accident and can be brought onsite in a timely manner. From a probabilistic safety assessment perspective, EME is estimated to provide a risk reduction of up to a factor of ten (OPG et al. 2014). Since Fukushima, nuclear power plant licensees have developed and tested EME deployment procedures and guidelines through planned exercises and drills, to demonstrate that this equipment can be deployed in the requisite timeframe to prevent fuel failure.

**Why an accident like Chernobyl cannot happen in Canada**

It is important to remember that a Chernobyl-like disaster cannot occur in Canada. The accident at Chernobyl was the result of an extremely rapid power increase. However, the physical design of the CANDU reactor and its safety systems do not allow for the progression of events that occurred at Chernobyl.

To summarize, the accident at Chernobyl unit #4 occurred when the reactor was placed in an unstable and improper configuration. This not only prevented the single shutdown system from working properly, but also caused the shutdown system to exacerbate the problem. Furthermore, the lack of a complete containment structure meant that the accident could not be contained. In contrast, CANDU reactors cannot be put in such an unstable state if a problem arises, because at least one of two independent fail-safe systems whose sole purpose is to shut down the reactor (regardless of how it is being operated) will be activated. Furthermore, a vacuum building containment system will contain the energy and radioactive materials released from the core during an accident.

**Why an accident like Fukushima is unlikely to happen in Canada**

A magnitude 9.0 earthquake near Japan generated an estimated 15-metre tsunami at the Fukushima Daiichi nuclear power plant, leading to an accident at the plant. The scale of earthquake and resulting tsunami is not credible for Canadian nuclear generating stations. The CNSC requires reactor designs to consider natural events appropriate to the site (e.g., earthquake, tsunami, tornado, flooding) that are credible and may pose a threat to the plant. These are considered in the design of the plant, in accordance with applicable codes and standards.

In addition, the existing CANDUs have these inherent design features that differ from the boiling water reactors that were affected in Fukushima:

- CANDU reactors contain a large inventory of water that can be used for cooling purposes, including the primary and secondary coolants, moderator, shield tank or dousing tank water, emergency coolant and other reservoirs.
- CANDU reactors make use of steam generators located at higher elevation than the reactor, which provide passive fuel cooling through natural circulation. These steam generators themselves also have a passive back-up water supply.
- CANDU uses natural (not enriched) uranium for fuel. Therefore, the likelihood of the spent fuel becoming critical in spent fuel bays is not a credible event.
- CANDU spent fuel bays are robust to leakage as the pool structure is seismically qualified and below grade.
- CANDU designs have containment, with multi-unit designs equipped with a vacuum building which provides another layer of defence in depth for containment - in contrast, the reactor designs in Fukushima have confinement.

**Understanding nuclear power plants: Total station blackout**

This CNSC video shows the progression of an accident scenario involving a total station blackout at a Canadian nuclear power plant. It describes multiple safety system layers and highlights that even during an extremely severe accident, nuclear reactors in Canada will safely shut down and contain radioactivity. This and other informative nuclear-related videos can be found on the CNSC's YouTube channel.

# 3. Radiological releases

This chapter details the radionuclide releases (also referred to as a source term) for several hypothetical severe accident scenarios at the DNGS examined in this study. Also detailed in this chapter are the conditions under which the releases are assumed to occur.

## 3.1 How a hypothetical severe nuclear accident was identified for this study

REGDOC-2.5.2, *Design of Reactor Facilities: Nuclear Power Plants* – based on international and Canadian design standards and previously known as RD-337, *Design of New Nuclear Power Plants* – provides modern nuclear power plants with a reference point for describing and assessing severe accidents. The safety goals, which are based on modern international recommendations, have been established to ensure plant design features are in place to limit the risk to society and the environment to acceptably low levels. REGDOC-2.5.2 defines a large release as a release of radioactive cesium (Cs-137) greater than $1 \times 10^{14}$ becquerels (Bq) over the duration of the accident. The underlying goal has been defined in terms of avoiding undue public disruption, in the case of the large release of Cs-137, to avoid long term relocation. It is a release of this magnitude that was examined in this study. The release of a greater magnitude is practically eliminated in light of the improvements emanating from the Fukushima Task Force.

To derive the source term, other radionuclides have to be added to the large release of $1 \times 10^{14}$ Bq of Cs-137 as that release would contain a number of other radionuclides. The total radionuclide mix that would be released has to be scaled to reflect those fission products associated with the CANDU reactor design at the DNGS. The resulting generic large release is larger than the representative nuclear accident described in the EA for the refurbishment and continued operation of the DNGS (CNSC and DFO 2013).

The full spectrum of the major radionuclide releases were examined using an accepted nuclear power plant software program called MAAP4-CANDU[2]. By studying a number of hypothetical accident sequences with similar Cs-137 releases, an appropriately scaled mixture of other fission products categorized into groups based on chemical properties, such as volatility, was derived for DNGS-like power plants[3]. A range of release scenarios with greater quantities of Cs-137 were examined from this base case using MACCS2 software that evaluates dispersion in the environment and calculates doses during and after a radiological accident[4].

Table 3.1 shows the fission products as they are grouped in the MACCS2 software. Also shown in table 3.1 is the fraction released of the total amount of each fission product group present in the reactor. The fission products are more or less ordered by their relative contribution to the total release value. Most of the radioactive material released from the core in such an event is anticipated to remain within containment and will not be released. Noble gases, if released early, are the largest single contributor to the total release, and yet most also quickly decay. Noble gases are also chemically inert which means they will not interact in the human body's biological processes or chemical reactions, and will not accumulate in the body like iodine or strontium.

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[2] The Modular Accident Analysis Program (MAAP) Version 4-CANDU is an Electric Power Research Institute -owned and licensed computer software that simulates the response of CANDU nuclear power plants. It can simulate severe accident sequences.

[3] $1 \times 10^{14}$ Bq Cs 137 (large release) = 0.152% of the initial DNGS Cs-137 core inventory of $6.7 \times 10^{16}$ Bq (based on a single unit)

[4] MACCS2, (MELCOR Accident Consequences Code System) is based on the straight-line Gaussian plume model developed originally for the United States. MACCS2 evaluates doses and health risks from the accidental atmospheric releases of radionuclides. The principal phenomena considered in MACCS2 are atmospheric transport and deposition under time-variant meteorology, short-term and long-term mitigation actions and exposure pathways.

Essentially, the contribution to the total radiological, long-term dose from noble gas releases is small, particularly if the release occurs 48 hours or more after the accident started. In the generic large release scenarios, it was assumed that 40 percent of the noble gases present from a single unit are released.

Some radioactive materials which would also be released in the event of severe fuel damage (e.g., gaseous water vapours) are not included, as they have a very small contribution to offsite dose.

**Table 3.1: Fission product groupings of the generic large release source term**

| Fission product group | Release fraction[1] |
|---|---|
| Noble gases (e.g., xenon) | $4.12 \times 10^{-1}$ |
| Halogens (e.g., iodine) | $1.52 \times 10^{-3}$ |
| Alkali metals (e.g., cesium) | $1.52 \times 10^{-3}$ |
| Alkaline earths | $2.30 \times 10^{-8}$ |
| Refractory metals | $2.53 \times 10^{-4}$ |
| Lanthanides | $8.51 \times 10^{-9}$ |
| Actinides | $5.16 \times 10^{-8}$ |
| Barium | $1.68 \times 10^{-7}$ |

[1]Fraction of equilibrium core inventory of each radionuclide in the group released to the environment

The total radionuclide release, called the "generic large release" (GLR) was created to quantify the emissions from a hypothetical severe nuclear accident, in order to consider the implementation of emergency planning and to subsequently assess the human health and environmental consequences of such a hypothetical large release at the DNGS.

## 3.2 Generic large release assumptions

The selected severe accident source term is based on the CNSC large release safety goal for new nuclear power plants (CNSC 2014). It compares the current design basis of the Ontario PNERP with the goal of providing meaningful insight into the effectiveness of existing protective actions, as well as human health and environmental consequences, in the event of a hypothetical severe accident.

The selected generic large release (GLR) was created based on the large release safety goal values, rather than on a specific accident sequence that has been identified in the DNGS probabilistic risk assessment (OPG 2012); however, it is of a similar magnitude to a postulated accident with a frequency of $3.74 \times 10^{-7}$ (known as Release Category 2) in this probabilistic risk assessment. Though not specific to a single- or multi-unit accident, the GLR is of a magnitude that could cover both types of postulated events. From the range of possible release scenarios initially considered, three release event scenarios (short, medium and long duration) were selected and all used the GLR initial release values.

In order to simplify a complex topic, yet be responsive to the concerns raised by interveners, conservative assumptions have been made throughout the study. This is reflected from a defence-in-depth perspective – the GLR scenarios are assumed to be released, not fully considering the existing/planned design, safety systems, operator actions and additional measures in place to prevent and mitigate accidents and to protect members of the public from any offsite release. This implies that some elements of the first four levels of defence in depth have failed. Therefore, the GLR is situated within Level 5 of defence in depth – mitigating radiological consequences.

As such, the study is of a theoretical nature, and uses hypothetical severe accident scenarios with a number of conservative assumptions. It is not meant to reflect the state of readiness of Canadian nuclear power plants, its operators or responsible jurisdictions when it comes to addressing the potential for accidents or their consequences.

### 3.3 Timing and duration of releases

Three release scenarios were derived for this study, all releasing the same GLR for different durations (short, medium and long).

Scenario 1: A severe accident that progresses for 24 hours, after which a short one-hour release of the GLR occurs (also referred to as the 24-01 scenario).

Scenario 2: A severe accident that progresses for 24 hours, after which a medium-length GLR release starts and continues for 24 hours (also referred to as the 24-24 scenario).

Scenario 3: A severe accident that progresses for 24 hours, after which time a long-length GLR release starts and continues for 72 hours (also referred to as the 24-72 scenario).

The release timing of 24 hours (i.e., 24 hour holdup period after accident initiation[5]) is consistent with the current understanding of the release timings for the DNGS, with respect to containment and the vacuum building functioning as designed. For comparison, the accident at Chernobyl essentially had no holdup period because of lack of containment. For Fukushima, unit 1 had a hold up period of approximately 24 hours, unit 2 was approximately 74.5 hours, and unit 3 had a holdup period of approximately 43 hours.

The GLR scenarios also allow for analysis of consequences of both short-term releases and continuous releases. The first scenario with its short release time (one hour release at 24 hours into the accident) is typically associated with a significant failure of containment due to unmitigated pressure rise. If the pressure rise in containment is not effectively mitigated by the dousing sprays, air cooling units and containment venting, then the containment structure will become overloaded leading to cracks and/or holes in the structure. The large pressure difference between the inside of containment and the environment results in a rapid discharge of radioactive gases as the reactor building depressurizes. It is important to note that a release of this magnitude over the very short time period of one hour is highly unlikely. It would imply a significant breach of containment. In reality, in the event of a release, the release rate is not uniform throughout the duration (see section 2.3.2). As was seen from Fukushima, releases from units 2 and 3 earlier on were related to venting activities to relieve pressure buildup.

The other two GLR scenarios (24-24 and 24-72 scenarios) are more representative of a continuous release. Unlike the short-term release, where containment likely has suddenly and significantly failed, a continuous release is more indicative of containment retaining some functionality as a release barrier. Situations that could result in a continuous release are controlled venting or a relatively small leak in the containment structure. Radioactive material is still discharged from containment during a continuous release, but at a slower rate. In comparison, the dose consequence of a continuous release is more influenced by dispersion (as weather and wind direction shift over time) and by the decay of the radioactive materials released.

[5] Accident initiation refers to the point in time that the reactor is tripped, which may have occurred after the accident has started.

### 3.4 Radioactive plume dispersion

The MACCS2 code was used to model the radioactive plume dispersion and calculate the resulting doses over a seven-day period, referred to as the early phase.

Mean centre-line doses (herein referred to as centre-line), based on ground-level releases and calculated at the vertical and horizontal centre line of the plume, were derived and are representative of the highest mean anticipated individual dose in any sector[6] at a given distance from the reactor.

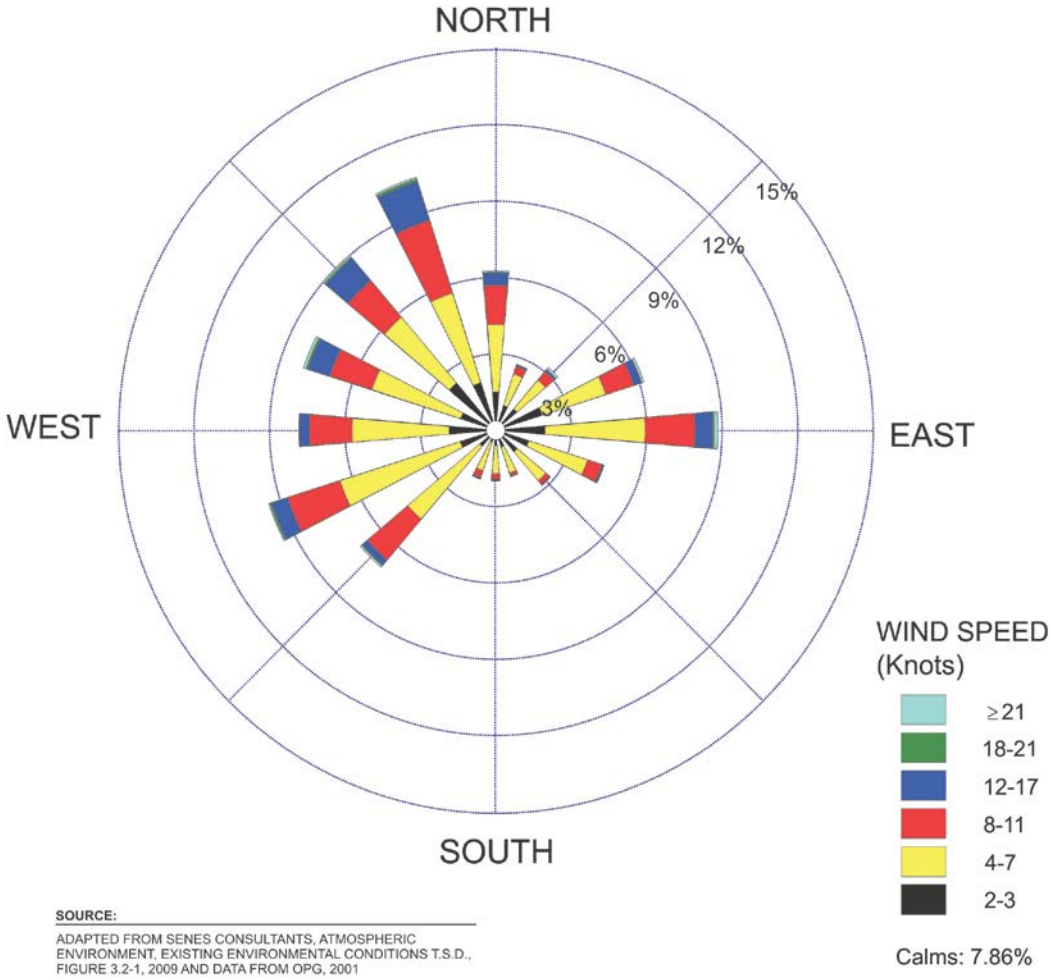
Variations in wind speed and direction over the course of a release have a large impact on how radioactive material is dispersed and likewise, an impact on resulting doses, especially when the release occurs over an extended period of time. In the 24-01 scenario, the wind direction and speed were assumed to be constant for each model run due to the relatively short duration of the release. The wind direction and speed were varied over time for each model run in the other two scenarios (24-24 and 24-72). The doses presented are the result of a large sample of trials that cover the different meteorological conditions present over the course of a year. The representative dose for an individual was selected based on the radial sector demonstrating the overall highest mean dose (calculated over a representative year of meteorological data). The variability in wind direction for the longer release scenarios reflects the fact that dose to any fixed location would be affected by changes in wind direction. Note that the distribution functions for dose generated from atmospheric dispersion calculations do not follow a standard distribution function. The mean value referred to above, while not the maximum value, is very close to the maximum and is therefore considered a conservative representation of dose.

Darlington site-specific average meteorological data from one representative year was used. Sensitivity analyses were conducted on the meteorological data to ensure it is representative of site conditions.

To graphically depict the variable wind conditions considered in this study, realistic wind speed and wind direction data are illustrated for the southern part of Durham Region in figure 3.1. The graphic illustrates that the dominant winds in the region blow from the northwest quarter 28 percent of the time, from the west-southwest 10 percent of the time, and 9 percent of the time from the east. The average measured wind speed is 2.6 metres per second and calm conditions are present approximately 8 percent of the time.

[6] The MACCS2 grid structure is made up of a series of annular rings (0-2, 2-4, etc) and 16 radial sectors corresponding to the compass directions. The PNERP refers to annular rings as “zones”. For clarity in terminology, a “ring sector” in this study refers to a mesh region (i.e., one ring and one sector). There are 16 sectors and 10 rings radiating out from 1 to 100 km around the DNGS, for a total of 160 ring sectors (see annex 2).

**Figure 3.1: Wind rose from the Darlington site (source: OPG)**




Conservative assumptions in calculating centre-line doses are as follows:

- the wind is held constant keeping the individual on the centre line, or variable wind is determined based on the dominant wind sector with the highest doses
- the initial release is cold and at ground level leading to the greatest concentration of radioactive materials and dose at ground level
- the receptor is assumed to be located in both the horizontal and vertical centre line of the radioactive plume when the wind is blowing into the sector containing the receptor
- the receptor is assumed to remain in a fixed location for seven days

The modelled centre-line doses described in this study are unlikely to be experienced. It would be expected that doses that individuals would actually receive could be affected by a number of factors:

- variations in initial release height and energy content – higher release heights and energy content would result in a more dispersed radioactive plume, and consequently lower doses close to the plant compared to a cold, ground-level release
- wind speed and wind direction – actual wind conditions in the event of a release would greatly influence the plume dispersion – for example, the dominant winds in the region blow from the northwest quarter out over Lake Ontario
- plume characteristics – movement of the ground-level release plume through the landscape is influenced by local topography; the "rougher" (e.g., undulating) the topography, the more limited the plume's dispersion
- the receptor's movements within the seven day period – the ability of an individual to move on their own volition or in response to direction from emergency response decision makers, as opposed to remaining in a fixed location over seven days

## 3.5 Sensitivity analyses – Increased source term

The GLR source term was increased to examine the potential effects of an even greater hypothetical release, by multiplying the radionuclide release by four to be comparable to a hypothetical common-cause failure event that affects all four reactor units at the Darlington site simultaneously. This is an overly simplistic analogy as it is recognized that all reactor units share aspects of containment so accident progression in one unit could affect what happens in another. These scenarios are referred to as sensitivity cases and are denoted as 24-24x4 and 24-72x4, respectively. The 24-01 scenario was excluded as a sensitivity case as a multi-unit event with this short release duration would be indicative of sudden and complete failure of containment and all related safety systems across multiple units – this is not considered plausible and would be indicative of an external event of unimaginable magnitude.

For comparison purposes, table 3.2 shows selected radionuclides within the GLR that will have a significant impact on the dose, including the sensitivity case (GLR increased fourfold), as well as the corresponding radionuclides released from the nuclear accidents at Chernobyl and Fukushima. A more complete list of representative radionuclides released can be found in annex 1. Note that Chernobyl was a single-unit accident and Fukushima involved three reactors.

**Table 3.2: Releases of selected radionuclides for the hypothetical nuclear accidents considered in this study and for previous nuclear accidents**

| Isotope | Fission product releases (becquerels) | | | |
|---|---|---|---|---|
| | Chernobyl | Fukushima | GLR | GLR x 4 |
| Cesium-134 | $5.90 \times 10^{16}$ | $1.80 \times 10^{16}$ | $3.21 \times 10^{13}$ | $1.29 \times 10^{14}$ |
| Cesium-137 | $8.20 \times 10^{16}$ | $1.50 \times 10^{16}$ | $1.02 \times 10^{14}$ | $4.08 \times 10^{14}$ |
| Iodine-131 | $1.50 \times 10^{18}$ | $1.60 \times 10^{17}$ | $3.93 \times 10^{15}$ | $1.57 \times 10^{16}$ |

## 3.6 Dose – Next steps

Doses are first assessed for each of the three scenarios and two sensitivity cases to illustrate the consideration of emergency planning aspects whereby the release occurs and there are no protective actions (such as evacuation) taken. The results describe the radiological dose received by a person who is exposed to the radiation for the entire duration of the event. The unmitigated scenarios are not realistic from an emergency response perspective (e.g., in the event of an accident, protective actions would be undertaken). Rather, they are a useful point of reference when examining different aspects of emergency planning such as emergency planning zones and protective action levels as described more fully in chapter 4 in this document.

The dose calculations for scenarios with protective actions are provided to illustrate the effects that early protective actions (i.e., evacuation, sheltering and KI pill ingestion) would have on persons otherwise exposed during the first seven days of the event and is the focus of the human health risk assessment.

Chapter 5 in this document describes how one goes from determining dose to estimating health risks and provides additional details on the study methodology and assumptions.

# 4. Emergency preparedness and response

This chapter outlines the key principles and goals of emergency preparedness and response, and how they are implemented and validated.

## 4.1 About emergency management

Many countries, including Canada, have adopted the "Four Components" model of emergency management (shown below). The federal *Emergency Management Act* defines emergency management as the "prevention and mitigation of, preparedness for, response to and recovery from emergencies".

**The four components of emergency management**

1. **Prevention and mitigation:** Prevent accidents from occurring in the first place (e.g., by adding safety margins to operational procedures and systems design) or mitigate the impact of potential accidents (e.g., by implementing redundant safety systems such as a vacuum building).
2. **Preparedness:** Prepare to respond to all types of accidents (e.g., by developing and exercising emergency response plans).
3. **Response:** Respond effectively to minimize consequences (e.g., by implementing emergency mitigating equipment and public protective actions during an accident).
4. **Recovery:** Remediate the situation and return to normal (e.g., by cleaning up after an accident).

The aim of this model is to ensure that emergency planners consider the full spectrum of actions that may be, or may become necessary, to ensure public safety from prevention to recovery. It is worth noting the model aligns well with the defence-in-depth design philosophy described earlier; indeed, an effective emergency response may be seen as the last line, or fifth layer, of defence.

## 4.2 Principles and goals of emergency preparedness and response

Emergency preparedness and response may be defined as activities undertaken to prepare for, and respond to, the adverse consequences of natural disasters and man-made accidents on persons, property and the environment.

The goal of emergency preparedness is to ensure a capability is in place at the facility and at local, regional, provincial and federal levels to effectively respond to a nuclear emergency.

In order to protect the public from the risks of radiological exposure, Canada has adopted the following internationally-accepted nuclear emergency response goals:

1. prevent immediate health effects (e.g., tissue effects)
2. minimize the likelihood of possible, future health effects (e.g., cancer)

These goals are achieved by taking appropriate and timely protective and/or precautionary actions to prevent or minimize the public's exposure to radiation.

Precautionary measures are actions taken to facilitate the application and effectiveness of the implemented protective actions. Examples include the closing of beaches, workplaces and schools to facilitate the eventual possibility of an evacuation or sheltering.

Protective actions consist of three key actions that the public may be called upon to take in order to minimize their exposure level or dose through:

1. **Sheltering:** By remaining indoors and limiting ventilation, the dose from a radioactive plume can be reduced by up to 40 percent. Buildings offer partial protection from external and internal exposure. Under certain circumstances, such as when the plume is overhead, sheltering may be a better option than evacuation.
2. **Evacuation:** By getting away, preferably before the passage of a plume, people will simply avoid exposure altogether, or receive much reduced doses.
3. **Ingestion of stable potassium iodide (KI):** By ingesting KI pills before exposure or shortly after, one can prevent or reduce the intake via inhalation of radioactive iodine likely present in a plume. Once in the human body, iodine is collected by the thyroid gland. By saturating this organ with stable KI, retention of radioactive iodine is inhibited.

For the purposes of this study, dose reductions from all three protective actions and their associated assumptions were considered in the modelling as appropriate (see section 5.3).

### 4.3 Emergency decisions and actions relative to the phases of a nuclear accident

The different phases of a nuclear accident are depicted in a sequential fashion in figure 4.1, with the different emergency decisions and actions overlaid across the phases as appropriate. This study focused on the “pre-release” and “post-release” phases, looking at doses to individuals over the first seven days of exposure. It is important to note that leading up to a release, emergency decisions/actions are, in part, based on the status of the plant and dispersion and dose modelling. Once the release occurs, emergency decisions and actions are based primarily on actual measurements of the levels of environmental contamination and resulting projected doses.

Protective actions that are implemented leading up to or during a release (i.e., evacuation, sheltering, KI pill ingestion), as depicted in figure 4.1, can be taken in a flexible manner (e.g., in combination, applicable to a certain distance), reflective of the PNERP and the specific conditions related to the release and surrounding environment.

Longer-term protective actions are those that need to be taken in the weeks and months following a release of radioactive material, and are expected to be in place for an extended period. Longer-term protective actions include food control measures, temporary relocation, and resettlement. This study did not examine this “ongoing recovery” phase from an emergency response perspective, nor from a human health risk assessment perspective, as this involves complex and in-depth consideration of numerous factors surrounding continued exposure after the first seven days. Development of protection strategies in the ongoing recovery phase is a focus of international and national efforts in light of the Fukushima nuclear accident. The international community has, however, addressed exposure situations of contamination following a nuclear emergency and has considered them as “existing exposure situations”. During this phase it is recommended that planning be such that doses remain below 1–20 mSv/year. This recommendation is currently being considered by CNSC staff for inclusion in a framework for the implementation of longer-term protective actions and recovery.

**Decisions on protective actions during Fukushima**

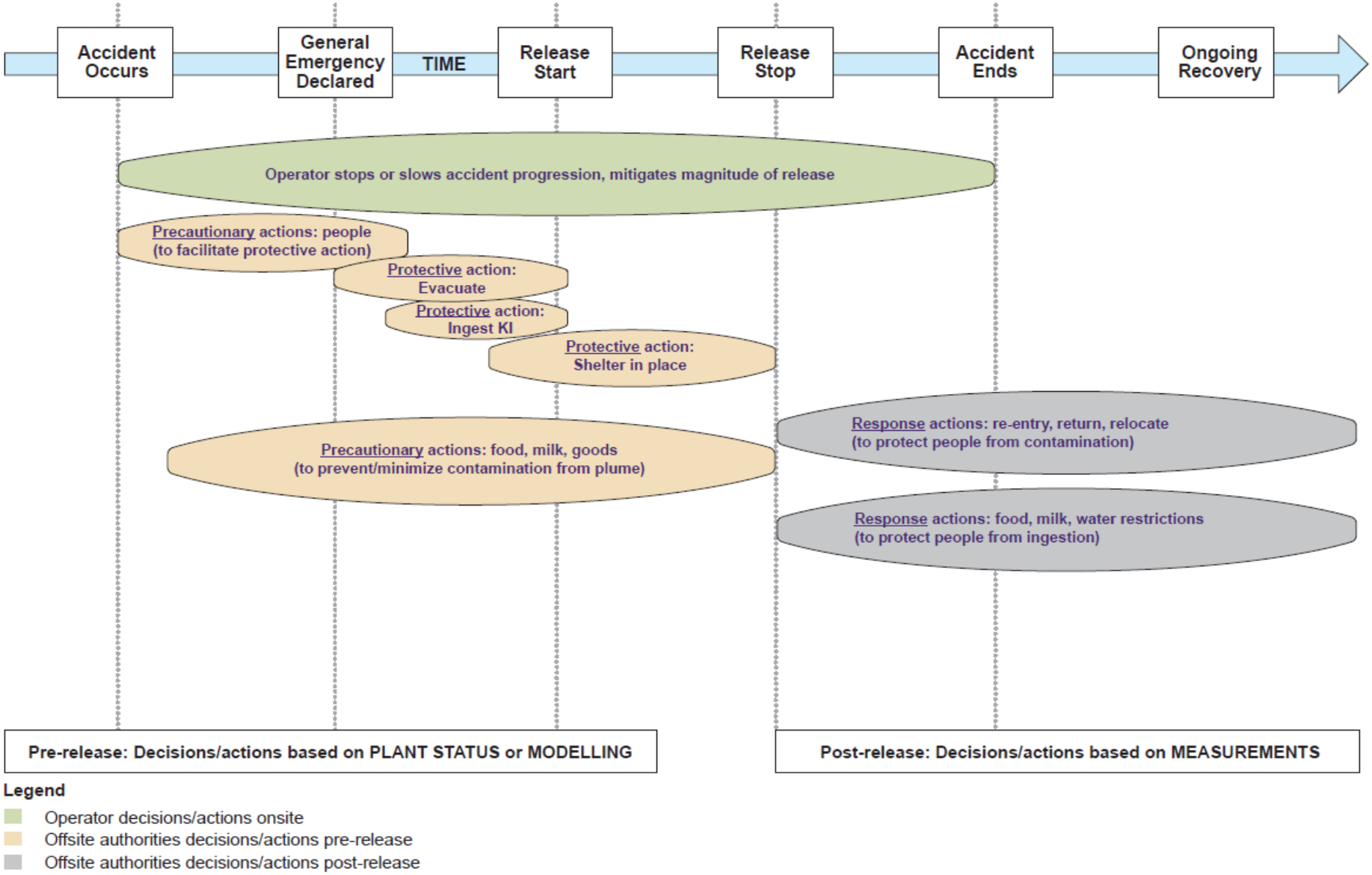
The decisions on protective actions during Fukushima clearly demonstrate how, in the case of an actual nuclear emergency, decisions on protective actions are made leading up to a release (based on the status of the plant and dispersion and dose modelling) and after a release occurs (based on actual measurements of environmental contamination and resulting projected doses).

On March 11, 2011, the decisions were made to evacuate first to 2, 3, 10 and then to 20 km around the Fukushima Daiichi nuclear power plant, prior to any release of radioactive material and based on the available information of conditions at the site.

Immediately following the hydrogen explosions on March 15, 2011, an order was given for all residents located between 20 and 30 km around the nuclear power plant to shelter in place. This sheltering order was changed to a voluntary evacuation on March 25, 2011.

After the releases were completed, environmental contamination measurements were initiated. On April 22, 2011, further evacuations were ordered based on elevated levels of radioactive contamination measured on the ground (UNSCEAR 2014).

**Figure 4.1: Nuclear emergency response conceptual implementation in Canada**



## 4.4 How a nuclear emergency response is implemented

In Canada, public safety falls primarily under provincial jurisdiction, and responsibility for emergency response is delegated to regional and municipal authorities. Resources from any higher level of government are generally leveraged only when the situation exceeds the means available to the lower echelon. Hence, regional, then provincial, and ultimately, federal agencies are called to act as part of an incremental response to an escalating situation. Notwithstanding, all response capabilities may be activated quickly if a large-scale accident were to occur.

Onsite response refers to those emergency actions taken by the operator within the boundaries of the nuclear power plant site in the case of a nuclear emergency. The operator is responsible for the onsite response to stop, slow or mitigate the accident.

Offsite response refers to those emergency actions taken outside the boundaries of the accident site. Responsibility for the offsite response is shared by many governmental agencies and civil authorities; however, provincial governments have final authority for the safety of their residents.

In the case of a nuclear emergency involving a radiological release, it is known that local capacities alone may not suffice. In addition, the plume may travel beyond municipal and regional boundaries, necessitating coordination across multiple jurisdictions. For these reasons, the province of primary interest becomes the lead agency for the offsite response. In Ontario, the Office of the Fire Marshal and Emergency Management (formerly known as Emergency Management Ontario) would therefore activate the PNERP. Federal agencies such as Public Safety Canada and Health Canada would, however, provide assistance upon provincial request by activating the Federal Emergency Response Plan, including the associated Federal Nuclear Emergency Plan referenced therein. The CNSC, as the national regulator, would continue to ensure that appropriate actions are being taken to protect Canadians throughout all phases of the response. Ultimately, the response to a nuclear emergency would therefore be a coordinated, multi-agency, multi-jurisdictional effort.

Table 4.1 outlines the roles and responsibilities when responding to a nuclear emergency at the DNGS.

**Table 4.1: Emergency response roles and responsibilities**

| Organization | Role and responsibilities |
|---|---|
| Licensee<br>OPG | Leads onsite response:<br>• takes actions to prevent the accident from escalating (by re-establishing control, cooling and/or containment)<br>• takes actions to protect workers and other persons onsite<br>• notifies and liaises with local and provincial authorities<br>• provides support to the offsite response<br>• notifies and keeps the CNSC aware of plant state and actions |
| Province<br><br>Office of the Fire Marshall and Emergency Management (OFMEM) | Leads offsite response:<br>• alerts the public and provides information<br>• advises the public on what and when to take protective actions (KI pill ingestion, sheltering, evacuation)<br>• coordinates execution of the PNERP<br>• facilitates other measures such as traffic management, establishment of reception centres, etc.<br>• provides or coordinates support to the licensee in their accident response onsite |
| Federal government (e.g., Public Safety Canada, Health Canada) | Leads federal response and provides assistance:<br>• provides federal support, generally focused on managing consequences after a release<br>• provides support to province, in accordance with existing arrangements or upon request manages cross-jurisdictional issues (inter-provincial, other countries)<br>• keeps the public and international partners (including the International Atomic Energy Agency) abreast of the offsite situation/status<br>• manages areas of federal jurisdiction<br>• does not make protective action decisions |
| CNSC | Ensures regulatory oversight and provides assistance:<br>• provides oversight of licensee's response<br>• provides technical support to province<br>• participates in the federal response<br>• keeps the International Atomic Energy Agency, public, government and regulators abreast of onsite situation/status<br>• does not take over operation of the facility, nor lead in the decision making regarding protective actions; maintains regulatory role before, during and after an emergency |

## 4.5 Protective action levels

With respect to the Ontario PNERP, evacuation, sheltering and thyroid blocking (i.e., KI pill ingestion) have protective action levels (PALs), which are projected doses, either a whole body effective dose (whole body dose) or equivalent dose to the thyroid gland (thyroid dose). PALs represent levels of risk from potential exposure, which justify the initiation of various protective actions. The exposure period used to determine the application of these PALs was based on an exposure period of 7 days which is regarded as the appropriate time frame in which urgent protective measures should be taken. As described in table 4.2, PALs for evacuation and sheltering are prescribed as a range for each protective action because the decision on applying

protective actions is based not only on technical factors, but also on operational and public policy considerations.

The PALs for thyroid blocking currently in the PNERP (100 mSv to 1,000 mSv thyroid dose) have been superseded in 2014 by a more protective dose of 50 mSv to the thyroid, according to OFMEM, in alignment with provincial (Ministry of Health and Long-Term Care *Radiation Health Response Plan*), federal (Health Canada *Canadian Guidelines for Protective Actions during a Nuclear Emergency*) and international guidance (International Atomic Energy Agency *Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor*).

**Table 4.2: Protective action levels for evacuation, sheltering and thyroid blocking under Ontario nuclear emergency response planning**

| Protective action | Whole-body dose | | Thyroid dose | |
|---|---|---|---|---|
| | lower level | Upper level | Lower level | Upper level |
| Evacuation | 10 mSv | 100 mSv | 100 mSv | 1,000 mSv |
| Sheltering | 1 mSv | 10 mSv | 10 mSv | 100 mSv |
| Thyroid blocking | Not applicable | | > 50 mSv | |

## 4.6 Emergency planning zones

Emergency planning zones are reasonably sized geographic areas that require detailed preparations. Emergency planners use the emergency planning zones to determine the level of preparation required to respond effectively to the consequences of a nuclear accident. These zones are established by assessing the likely extent of such an accident in geographical terms, often as a function of the distance from a known potential accident site such as a nuclear power plant. The size and number of these zones may vary, depending on such factors as the nature, severity and extent of the potential hazard, nearby population and densities, availability and location of resources, predominant weather patterns, existing urban planning and geopolitical boundaries.

**Darlington planning zones**

Within the PNERP is a site-specific Darlington Nuclear Emergency Plan that includes established emergency planning zones, consistent with international guidance. The Contiguous Zone is the area immediately surrounding the station from 0 to 3 km. Dominant features within this zone include a portion of Highway 401 and surrounding industrial and farming activities.

The Primary Zone, which includes the Contiguous Zone, is the area within 0–10 km around the station. Detailed planning and preparedness for measures against exposure to a radioactive emission is required for this area. Larger population centres within this zone include the City of Bowmanville and a portion of the City of Oshawa.

The Secondary Zone, which includes both the Contiguous and Primary Zones, is the area within 0–50 km around the station. It is necessary to plan and prepare for implementing ingestion control measures, such as monitoring the food chain for contamination, and banning consumption of contaminated food items, for this area. This zone encompasses areas of Durham Region, the City of Toronto, York Region, the City of Kawartha Lakes, and the counties of Northumberland and Peterborough within a 50-km radius of the DNGS.

The Darlington Nuclear Emergency Plan has a planning basis accident of a 250-mSv whole-body effective dose at 1 km from the reactor, which informed the establishment of the emergency planning zones.

**Evacuation time estimate study**

To assess the feasibility of evacuation as a protective action in the unlikely event of a nuclear emergency, evacuation time estimate studies are used to help inform decision makers. An evacuation time estimate study, as the title suggests, generates evacuation time estimates through modelling for the different emergency planning zones (3 and 10 km). A number of scenarios are examined comprehensively to reflect variations in population estimates and distribution as well as traffic demand and road capacity, all associated with different seasons, day of week, time of day and weather conditions.

An evacuation time estimate study (OPG 2009a) was undertaken for the Darlington site, as part of the joint review panel for the construction and operation of new nuclear power plants at Darlington. This study has confirmed the anticipated evacuation time estimate (valid until approximately 2025) to be less than 9 hours from the 10-km emergency planning zone, which is considered to be well before the earliest time of an offsite radiation release from a severe accident at the Darlington site.

## 4.7 How emergency plans are assured of being robust and successful

In Canada, all levels of government – local, regional, provincial and federal – are required by law to maintain effective emergency plans commensurate with the risks that the populations under their jurisdiction may be exposed to in the event of a natural disaster or man-made accident. The relevant federal responsibilities are outlined in the *Emergency Management Act*, while provincial

emergency planning is subject to provincial legislation; in Ontario, the *Emergency Management and Civil Protection Act*.

In addition to these legislations, regulations under the *Nuclear Safety and Control Act* prescribe emergency planning requirements linked to licensed operations. Nuclear power plant operators in particular must develop and exercise appropriate emergency response plans, including the capability to protect persons present on their site(s), and to minimize the risk to nearby populations, in the unlikely event of a nuclear emergency. These plans must further be compatible with and include provisions for technical, communication, logistical, and financial support to the offsite emergency preparedness and response programs managed by civil authorities.

Dissemination of information and raising awareness regarding emergency planning through various means by those organizations with emergency planning responsibilities is done on an ongoing basis. In the event of an actual incident, effective, coordinated communication amongst responsible organizations is essential before, during and after the actual incident.

In summary, the CNSC requires major, licensed facilities, such as nuclear power plants to have effective emergency preparedness programs and associated emergency response plans. These licensees are required to conduct appropriate training, drills and regular exercises with all affected stakeholders to validate their emergency preparedness program.

**Strengthening emergency preparedness and response at nuclear power plants and beyond**

In its review, the CNSC Fukushima Task Force confirmed that emergency preparedness and response measures in Canada remain adequate. Nonetheless, improvements were identified to enhance emergency plans and capabilities to respond effectively in a severe event or multi-unit accident.

The Task Force recommended that regular and challenging exercises be conducted, and that the lessons learned from the exercises be discussed transparently. It also called for an exhaustive review of measures in place, including public alerting systems, KI pill stocking and distribution strategies, and the authorities' capability for predicting offsite effects. These recommendations are being actively undertaken by the licensees, and projects are currently in progress to address the Task Force recommendations. For example, a full scale nuclear exercise was held at the DNGS in May 2014 for which the findings and recommendations will assist participating organizations in their review of emergency plans.

The CNSC has modified its regulatory framework and oversight measures to address concerns in this area. In addition, a national standard has been developed to address the requirements for nuclear emergency management programs for emergency response organizations responding to nuclear power plant emergencies. Finally, licensees are required to pre-distribute KI pills within the Primary Zone in cooperation with all government authorities.

# 5. Human health and environmental consequences

This chapter describes how doses are modelled and health risks estimated, along with an explanation of other consequences from accidents such as psychosocial effects. Effects on non-human biota are also considered. It should be noted however, that in real exposure situations, the best estimates of risks will always be derived from doses that are based on either direct personal dosimetry results, or modelling that combines measured environmental sampling data with habit data.

## 5.1 Dose assessments

In the context of this study, a dose assessment is the first part of the overall risk assessment and estimates radiation dose to a representative person or population where nuclear substances are released into the environment following a nuclear accident. It is based on: the radionuclides and the associated radiological characteristics (e.g., type of radiation emitted, half-life, energy of radionuclide emissions, behaviour in the body), the concentrations of these radionuclides in the environment, the physical characteristics of critical receptors (e.g., age, sex), and their associated lifestyle characteristics (e.g., time spent outdoors and indoors). The estimated doses are subsequently used in combination with risk models to estimate health consequences (e.g., development of cancer).

An explanation of the term "dose" is provided below. Within the radiation protection framework, there are three different (but related) types of dose often discussed. For this study, all three types are discussed where appropriate. Absorbed dose is expressed as milligrays (mGy). Equivalent and effective doses are expressed as millisieverts (mSv).

**What is a radiological dose?**

When ionizing radiation penetrates the human body or an object, it deposits energy. The energy absorbed from exposure to radiation is called a dose. Radiation dose quantities are expressed in three ways: absorbed, equivalent, and effective.

**Dose quantities**

**Absorbed dose (mGy)**

⇩

Energy "deposited" in a kilogram of a substance by radiation

**Equivalent dose (mSv)**

⎍

Absorbed dose weighted for the degree of the effect of different radiations (radiation weighting factor $w_R$)

**Effective dose (mSv)**

⎍

Equivalent dose weighted for susceptibility of different tissues to the effects of radiation (tissue weighting factor $w_T$)

In Canada, the yearly dose limit for persons who are not nuclear energy workers (referred to here as members of the public) is 1 millisievert (mSv), as set out in the *Radiation Protection Regulations*. The limit applies to individual exposures that may occur as a result of authorized activities that are carried out in accordance with a CNSC licence.

Dose limits have mistakenly been regarded as the line between what is safe and what is not safe**.** The dose limit of 1 mSv per year is a regulatory limit – not a health limit. In addition to taking measures that ensure dose limits are not reached, licensees must adopt engineering or administrative practices that further minimize doses.

## 5.2 Dose modelling

The release time frame modelled in this assessment was the first seven days after an initial release. This is identified as the early phase in the MACCS2 code. This time frame is also recommended by the International Atomic Energy Agency for the implementation of urgent protective actions. This period is regarded as the duration immediately after the start of the emergency where decisions must be taken quickly to avoid adverse health impacts in the population and is related to the nature of severe events and the time frames in which the releases are expected to occur. Further it is also recognized that from a psychosocial point of view, actions must be taken shortly after the onset of an emergency in order to ease public fear and uncertainty.

Note however, that the population would likely also be exposed to radiation after the first seven days, depending on the extent of the resulting contamination and the protective actions taken, including decisions regarding the return of individuals after initially being evacuated. The longer-term decision making involving the return of people to a contaminated area involves complex and in-depth consideration of numerous factors. The radiological exposure to people (beyond the first seven days) and its resulting short and long-term health impacts are not assessed in this study. However, it is expected that authorities would take protective actions during the post-emergency recovery period that are aligned with international recommendations so that doses to members of the public would be kept in the range of 1–20mSv per year.

The dose assessment considers five pathways:

- exposure to the passing plume (cloudshine)
- exposure to materials deposited on the ground (groundshine)
- exposure to materials deposited on skin (skin deposition)
- inhalation of materials directly from the passing plume (cloud inhalation)
- inhalation of materials re-suspended from the ground by natural and mechanical processes (re-suspension inhalation)

The estimation of doses from these pathways involves consideration of the radionuclide concentrations and the duration of exposure, amongst other factors. Note that the ingestion was not considered as a contributing pathway during the first 7 days after exposure. This is due to the existence of guidelines and processes, both provincial and federal that would limit exposure from food and water sources such that doses from ingestion would be very small and would thus not impact the conclusions of the study. For example, in the case of drinking water, the province would independently detect and monitor the presence of radioactivity in the lakewater and isolate and redirect drinking water supplies if necessary. Monitoring of drinking water supplies and provision of uncontaminated drinking water is a key feature of the PNERP.

## 5.3 Inputs to the risk assessment

In order to determine the appropriate dose inputs to the human health risk assessment, the following approach was taken with respect to the dose assessment.

**Step 1: Determine the applicability of protective actions based on centre-line doses**

In the first step, doses were modelled where it was assumed that no emergency protective actions (e.g., evacuation) were employed – this generated centre-line doses (see chapter 3 for more details). The centre-line dose is representative of the mean value of the highest dose received by any individual at a given distance from the plant, and is used for emergency planning purposes.

These centre-line doses were then compared to the evacuation, sheltering and thyroid blocking PALs provided in the PNERP to determine the distances from the plant to which these protective actions would be applied for each accident scenario and sensitivity case. Evacuation was the first protective action applied, starting at the plant out to a distance[7] reflective of a centre-line dose that corresponded to the lower whole body effective dose PAL (10 mSv). Sheltering was then applied from this point onwards to a distance reflective of the centre-line dose corresponding to the lower whole body dose PAL for sheltering (1 mSv). For KI pill ingestion, this protective action was applied to those areas where doses were above the thyroid blocking PAL of 50 mSv to the thyroid (for the purposes of this study, adult thyroid doses were used since they were in alignment with the adult whole body effective doses which determined evacuation and sheltering protective action decisions), at distances where people were instructed to shelter within the Primary Zone (analogous to 12 km in this study).

The above process established at what distances protective actions would be applied (hence contribute to dose reductions) in the modelling for each scenario and sensitivity case, and was applied in step 3 of this process.

**Step 2: Determine the population-weighted (average) dose values**

A population-weighted approach, consistent with what has been done in previous EAs for nuclear power plants, was used as a key input to the human health risk assessment.

MACCS2 considers and calculates the impact of the variation of dose away from the plume centre-line (i.e., "off-centre-line doses") for each ring sector when computing population dose. This result is used to calculate the population dose in each of the 160 ring sectors to obtain many values of population dose from each sample case (see annex 2 for the depiction of the 10 concentric rings and 16 radial sectors for the Darlington area, resulting in 160 ring sectors). The probability of each value of dose in a given sector is obtained from the average annual wind rose. Many sample cases are run, reflective of the meteorological conditions over a year. The average dose in a ring corresponds to the calculated average population dose over all the sample results

[7] For the purposes of the MACCS2 model, distances correspond to radial segments from the plant at distances of 1, 3, 6, 12, 20, 28, 36, 50, 70 and 90 km respectively.

divided by the population in that ring[8]. Therefore, the average dose represents the average individual's dose in the ring being evaluated.

The average dose described previously would however underestimate the risk to the most exposed individual. For that reason, the centre-line dose was used as a surrogate to represent a hypothetically most exposed person. This value was used in the human health risk assessment in an attempt to estimate the worst case health impact for the scenarios examined.

**Step 3: Adjust the average (population-weighted) and centre-line dose values according to the protective actions taken**

For each scenario and sensitivity case, average and centre-line individual doses were adjusted to reflect the application of evacuation, sheltering and KI pill ingestion, in a manner consistent with the PNERP and those authorities with emergency decision-making responsibilities.

For those distances evacuated, the modelling assumed that individuals were successfully evacuated and received 0 mSv in dose. For those distances where sheltering was applied, a conservative dose reduction of 20 percent was applied to the average and centre-line dose values. Twenty percent was chosen to reflect the MACCS2 model where emphasis is on those pathways of most relevance during the first seven days after the release (cloudshine, skin deposition and cloud inhalation – see section 5.2). Beyond the sheltering distances, the unmitigated population-weighted doses were used.

For KI pill ingestion, for those areas sheltered within the Primary Zone (analogous to 12 km in this study) and above the thyroid blocking PAL of 50 mSv to the thyroid (based on adult exposures as explained in step 1 above), the doses would be greatly minimized when KI pill ingestion is applied. It is assumed that KI pills are available to residents in advance of the radiological exposure and that ingestion is done in the time frame prior to or immediately after exposure. With successful ingestion of KI pills, uptake of iodine-131 directly into the thyroid gland is prevented. However, the thyroid gland, like other organs in the body, may be exposed to radioactive iodine and other radionuclides from external exposure pathways. In the scenarios considered in this study, the inhalation pathway would dominate all other exposure pathways. As such, it was assumed for risk assessment purposes that the dose would be zero if KI pills were ingested.

Children were identified as a sensitive receptor in the human health risk assessment to address the potential thyroid cancer risk to children (see section 5.4.2). For the purposes of the study, the thyroid doses calculated by the MACCS2 code for an adult were multiplied by a factor of three to reflect the approximate difference (see annex 4) in the dose-per-unit exposure between a child and an adult (ICRP 1994 and 1995, Bailey et al. 1996, UNSCEAR 2014).

[8] DNGS-centered population values are total population by ring and sector, and are based on Canadian and U.S. census data from 2006 (see annex 2 for the 2006 population distribution table).

## 5.4 How dose translates to risk

Health effects from exposure to radiation have been generally divided into two categories: deterministic (e.g., tissue effects such as skin burns) and stochastic (e.g., cancer). Further, the way in which the risk of an adverse health effect can vary with radiation dose is described by a dose-response model. Many different dose-response models exist, and there is scientific evidence in support of each one. Deterministic effects are described by a threshold dose-response model. This means that the effect is very unlikely to occur until a given dose is exceeded. Stochastic effects are random in nature and are described by a relatively linear dose-response model (CNSC 2012).

**On what basis does the CNSC regulate radiation protection?**

The CNSC is mandated by the *Nuclear Safety and Control Act* to protect the health and safety of all Canadians. As part of its regulatory framework, the CNSC has established the *Radiation Protection Regulations* that set dose limits for workers and members of the public, and describes requirements for radiation protection programs, that include the requirement to keep doses as low as reasonably achievable (ALARA).

For radiation protection purposes, a dose-response model is used to describe how the risk of cancer varies with radiation exposure. This model is called the linear-non-threshold (LNT) model, which assumes that the risk of cancer is proportional to dose, with no threshold (all doses carry some risk). The LNT model has been repeatedly endorsed by international authoritative scientific advisory bodies as well as the CNSC, and remains the best model on which radiation protection regulations are based. The LNT model is not used to predict the incidence of radiation-related cancers at low doses. It is used to establish the regulatory framework, which includes setting appropriate dose limits.

### 5.4.1 Deterministic health effects

Deterministic effects are non-cancerous changes in cells and tissues. These adverse effects usually occur after a threshold dose is exceeded. The severity of health effects increases with the radiation dose received and in many cases appears quickly after exposure to radiation.

Examples of deterministic effects include radiation sickness (e.g., nausea, weakness, hair loss, skin burns or diminished organ function), teratogenic effects (e.g., mental retardation), cataracts, skin necrosis and reproductive dysfunctions including transitory or permanent infertility (NRC 2006, Hall 2000, ICRP 1991, UNSCEAR 1988).

For the scenarios examined in this study, no deterministic effects are predicted.

### 5.4.2 Stochastic health effects

Stochastic effects are radiation-induced health effects (such as cancer or heritable diseases) and the probability of their occurrence increases proportionally to the radiation dose received. In other words, the higher the dose, the higher the probability of occurrence. However, it is never certain – even for relatively high doses – that cancer or genetic damage will result. Heritable effects are genetic effects (i.e., DNA damage) that occur in one generation and are passed down to future generations. To date, these effects have not been observed in humans, only in experimental

animal studies (UNSCEAR 2001). Stochastic effects often show up years after exposure (generally 10–20 years after), they are believed to occur without a threshold dose, and their severity is independent of dose. Well known exceptions are leukemia and thyroid cancer, starting to appear two and five years after radiation exposure, respectively (UNSCEAR 2008). Cancer is more likely to develop in certain parts of the body (like the thyroid gland and bone marrow) depending on the radiosensitivity of each tissue or organ.

Radiosensitivity is the relative susceptibility of cells, tissues, and organs to the harmful effects of radiation. Ionizing radiation increases the risk of certain types of cancer more than others. In general, it has been found that actively dividing cells or those not fully mature are most at risk from radiation exposure. Therefore, actively dividing tissues, such as bone marrow, are the most radiosensitive (the law of Bergonié and Tribondeau) (Hall 2000). In addition, age is a factor that plays a role in the probability of some cancer development. Children's growing bodies, for example, are generally more sensitive to radiation than adults (UNSCEAR 2013). However, there are many additional factors such as genetic background and lifestyle characteristics that also need to be considered.

It is nearly impossible to attribute cancer to radiation exposures below approximately 100 mSv (UNSCEAR 2012). This is, in part, due to limitations of epidemiology studies at low doses due to the high number of cancers that occur in the absence of that exposure – these are referred to as baseline cancers. That is, it is often difficult to assess risk from low dose exposures because it requires a very large population to observe a radiation-related increase above the baseline number of cancers. In Canada, the baseline cancer incidence rate is high – two in five Canadians may develop cancer in their lifetime, masking the effect of cancers potentially attributable to a given radiation exposure. Further, there are other biological processes, such as hormesis, the adaptive response and the bystander effect that may impact the dose response relationship. These processes must be better understood and investigated to better understand the risk of cancer development at low doses.

The types of cancer considered in this assessment include:

- Thyroid cancer, which starts in the cells of the thyroid. The thyroid is a small gland that makes hormones that help control bodily functions including heart rate, blood pressure, body temperature and weight. The thyroid gland in children is particularly sensitive to radiation. For the purposes of the health risk assessment, a 30-year-old male was considered for the adult thyroid analysis and a 4-year-old girl was considered for the child thyroid analysis. These ages and sexes were selected to be representative of an adult and child population surrounding the accident site. Radiation-related thyroid cancer would start to appear approximately five years after exposure.
- Leukemia, a type of cancer that starts in blood stem cells (immature blood cells) in the bone marrow. Bone marrow is the soft, spongy material that fills the centre of most bones. There are several different types of leukemia. These are first grouped based on the type of blood stem cell they developed from, either myeloid cells or lymphoid cells. They are further grouped based on how quickly the leukemia progresses, regardless of radiation exposure. Acute leukemias progress quickly (within days or weeks) whereas chronic leukemias progress slowly (over months or years). For the purposes of this health risk assessment, leukemia is representative of all types of leukemia. Analysis was performed for a 30-year-old male, representative of an adult population surrounding the accident site. Radiation-related leukemia would start to appear approximately two years after exposure.

- "All cancers combined", which provides an overall risk value for a general idea of increased cancer risk. All cancers combined refers to the sum of many cancers. This category includes a number of cancers with varying degrees of radiosensitivity. For the purposes of this health risk assessment, an organ dose (or equivalent dose) is required for the analysis. The colon was chosen to represent the dose to all organs because it can illustrate changes in dose to deeper tissues that experience shielding from the more superficial tissues of the body, it is relatively centered in the body from a physiological perspective, it is a highly radiosensitive organ, and it is not sex-specific. Analysis was performed for a 30 year old male, representative of an adult population surrounding the hypothetical accident site. Radiation-related cancer (all cancers combined) would start to appear approximately 10 to 20 years after exposure.

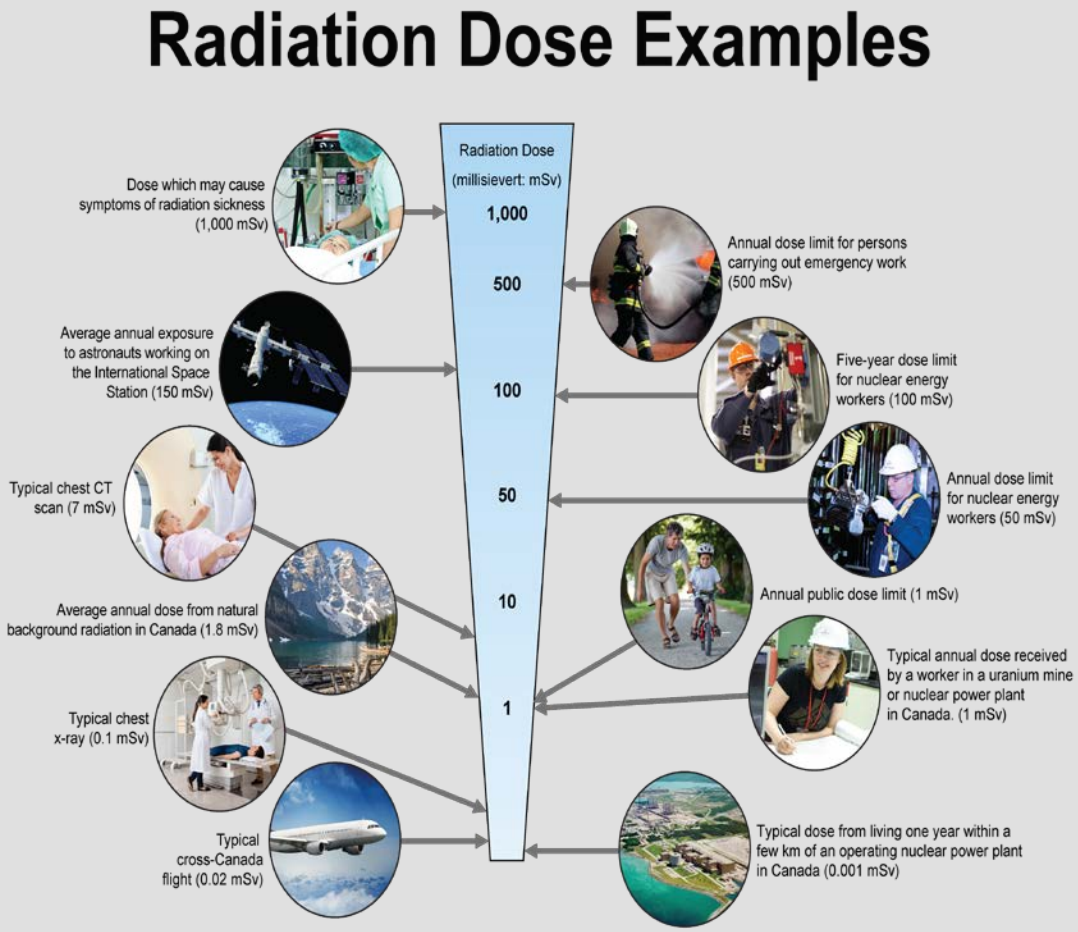
**Sources of radiation exposure for an average adult in Canada**

According to United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2008), the total annual dose from all sources, averaged over the population of the world, is 3.0 mSv. Over 80 percent of this dose comes from natural sources with about half of that from radon and radon decay products. In Canada, the total annual dose from natural background is 1.8 mSv.

Exposure to radiation occurs from several sources such as:

- natural background radiation (from the sun, earth and food)
- medical screening, diagnostic and therapeutic procedures (e.g., dental X-rays, CT scan and radiotherapy)
- air travel and airport security screening
- nuclear weapons testing fallout
- nuclear electricity generation
- occupations that entail increased exposure to man-made or naturally occurring radiation sources

**Canadian radiation dose examples:**



## 5.5 How health effects from the severe accident scenarios were determined

The linear-non-threshold (LNT) model is a prudent and useful approach for radiation protection purposes. The LNT model is, however, of limited use for determining individual risk. During an overexposure or accident scenario when individual dose, age and sex are known, a detailed methodology can be used to calculate risk. In this document, risk calculations were performed using the U.S.National Cancer Institute's radiation risk assessment tool known as "RadRAT"[9] (Berrington de Gonzalez et al. 2012). The risk models used by the risk calculator are broadly based on those developed by the Biological Effects of Ionizing Radiation (BEIR) VII committee for estimating lifetime risk for radiation-related cancer (NRC 2006). A linear dose-response model was used for all cancers combined and thyroid cancer, and a linear-quadratic risk model was used for leukemia.

RadRAT is publicly available online. An important consideration of this interactive online computer program is that it is meant for individuals with life-expectancy and cancer rates similar to the general population of the United States. The lifetime risk estimates are based on the incidence rates for the United States 2000-2005 population, combined with survival data (*United States Decennial Life Tables for 1999-2001*). As can been seen in table 5.1, the Canadian population, both nationally and separately for Ontario, is similar to the United States population for all solid cancers combined[10], thyroid cancer and leukemia across multiple age categories. For further details on regional variability, particularly with regards to the Durham Region as compared to the province of Ontario, the CNSC has published a report entitled *Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008 (The RADICON Study) Summary Report* on this topic (CNSC 2013b).

RadRAT estimates excess risk to 11 cancer sites using BEIR VII models (stomach, colon, liver, lung, breast, prostate, uterus, ovary, bladder, thyroid and leukemia) in addition to seven other cancer sites based on U.S. National Cancer Institute risk models developed after the publication of the BEIR VII report (oral cavity and pharynx, esophagus, rectum, gallbladder, pancreas, kidney, and central nervous system). Also considered in this tool is a "remainder organ category" that includes all other solid cancers other than the above mentioned 18 cancer sites modelled individually. Using this classification, results are presented for three groupings: all cancers combined, thyroid cancer and leukemia. One has to recognize that the first grouping of all cancers combined includes leukemia and thyroid cancer. In most cases the risks were assessed assuming an adult was exposed. However, the risk of childhood thyroid cancer was investigated further based on the experiences of Chernobyl and Fukushima that have shown childhood thyroid cancer to be a health outcome of concern.

The following information was required to perform the analysis using RadRAT: gender (male or female), year of birth (1984 or 2010, based on a 4-year-old or 30-year-old, age at exposure, respectively), year of exposure (2014), exposure rate (acute), organ (apply to all organs, thyroid or leukemia), type of distribution (fixed value) and dose in mGy (see tables in annex 3).

[9] The uncertainty intervals provided by RadRAT (upper and lower levels) take into account statistical uncertainties in the risk parameters and subjective uncertainties in a number of the assumptions. The calculator reports the mean risk and 90 percent uncertainty interval from the resulting distribution.
[10] Table 5.1 compares the incidence rate of all solid cancers combined which excludes leukemia. For the purposes of the risk assessment, all cancers combined included leukemia.

**Table 5.1: Incidence rates of selected cancers for the United States, Canada and Ontario**

| Annual incidence rates per 100,000 people | Select United States regional rates[1] | | | | Canadian national rates[2] | | | | Ontario provincial rates[2] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Age category (years)** | 0–19 | 20–49 | 50–64 | 65+ | 0–19 | 20–49 | 50–64 | 65+ | 0–19 | 20–49 | 50–64 | 65+ |
| **Solid cancers** | 24.7 | 268.9 | 1,738.5 | 4,148.4 | 24.9 | 236.5 | 1,594.8 | 3,972.5 | 25.4 | 251.1 | 1,598.7 | 3,827.9 |
| **Thyroid cancer** | 1.1 | 24.0 | 37.7 | 35.8 | 1.4 | 24.6 | 36.5 | 29.7 | 1.8 | 33.5 | 48.4 | 35.4 |
| **All leukemias** | 8.7 | 7.6 | 34.0 | 110.0 | 9.2 | 7.0 | 34.5 | 110.0 | 8.9 | 7.4 | 36.4 | 111.9 |

[1]Source: Howlader et al. 2013, [2] Source: Forman et al. 2013

RadRAT can be used to estimate risks from complex histories (e.g., multiple exposures) and acute or chronic doses lower than about 1 Gray (Gy)[11] for childhood exposures, or about 2 Gy for adult exposures.

The health effects presented for this risk assessment were the overall increased risk of cancer (all cancers combined), the increased risk of leukemia and the increased risk of thyroid cancer (for both adults and children). Uncertainty in calculations can be minimized by grouping all types of cancer together (all cancers combined).

The primary risk quantity described in this document is the excess future risk attributed to the radiation exposure from the emergency scenarios described from 2014 (or in this case the time of exposure) until the end of expected lifetime. To put this in context, the baseline future risk (the risk in the absence of the radiation exposure described) is also provided.

**Variation in background cancer rates**

Cancer incidence rates vary with age; with higher incidence rates generally occurring with increasing age (see table 5.1). Therefore, populations with a larger proportion of their age distribution in the higher age categories are likely to show higher rates of cancer incidence. In order to compare incidence rates between different populations, age-standardized incidence rates (ASIRs) must be considered. The calculation of ASIRs involves weighting the age-specific incidence rates to the age distribution of a standard population. Without the confounding factor of the age distribution of the population, the ASIRs can be compared to gain better insight into the natural variation of cancer incidence rates.

A previous CNSC report examined cancer incidence rates across Ontario, calculating the ASIRs for each of the 2006 Ontario census divisions, standardised to the 1991 Canadian population (CNSC 2013b). Based on these ASIRs, we can gain the following insight into the natural variation of the three cancer types considered in this study:

[11] 1 Gray = 1,000 mSv for the purposes of this health risk assessment

For all cancers combined, the ASIR for Ontario is 394.59 per 100,000. The ASIRs for the individual census divisions can vary from the provincial value by up to 14 percent.

For thyroid cancer, the ASIR for Ontario is 10.82 per 100,000. The ASIRs for the individual census divisions can vary from the provincial value by up to 70 percent.

For leukemia, the ASIR for Ontario is 11.76 per 100,000. The ASIRs for the individual census divisions can vary from the provincial value by up to 34 percent.

It is due to this large natural variation in cancer incidence rates that it is often not possible to measure very small increases in cancer incidence that could be caused by exposure to radiation.

Further information on cancer rates across Ontario can be found in the CNSC report *Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008* (the RADICON study) (CNSC 2013b).

### 5.6 Psychosocial effects

It is recognized from experience that nuclear accidents lead to psychosocial effects at both the individual and community level. Psychosocial effects could include fear, anxiety, a sense of loss of control, depression, and a feeling of hopelessness and distress (Sorensen et al. 1987). Disruption of lifestyles, increased stress, and negative effects to community well-being could occur in reaction to the accident and the subsequent need for taking protective actions. The uncertainty, perceptions of risk, physical and social displacement, and conflict associated with assignment of responsibility and decisions about when one should leave and when it is safe to return to the community that follow an accident all contribute to these psychosocial effects (Gregory and Satterfield 2002, Freudenburg 1993 and 1997, Barnes et al. 2002, Picou et al. 2004).

The severity and duration of these effects would likely be related to the nature of the protective actions (e.g., evacuation) implemented and the length of time the protective actions were in place, the amount of radiation released from the plant, the timing and quality of information provided to residents by the plant operator and regulatory authorities, and the degree of conflict and uncertainty experienced by families and communities during and following the emergency.

### 5.7 Non-human biota effects

Radiological dose effects to flora and fauna (e.g., mammals, birds, vegetation) are collectively known as non-human biota effects. An in-depth examination of this topic was done in the Darlington New Nuclear Power Plant Project EA. Given the similarity in some of the accident scenarios with this study, it was possible to examine the effects on non-human biota. In order to assess these effects, predicted doses were compared to international thresholds (e.g., UNSCEAR 2008).

**Keeping up with leading-edge science**

The CNSC stays up to date on the advances in the scientific basis for radiation protection and radiation risk through various means. Many CNSC staff actively participate in recognized international committees such as the United Nations Scientific Committee on the Effects of

Atomic Radiation, the International Organization for Standardization, the Information System on Occupational Exposure, and the Radiation Safety Standards Committee, to name a few. CNSC staff publish work in peer-reviewed scientific journals, and also keep informed through national and international working groups, professional affiliations, conference participation and review of external publications.

# 6. Results

This chapter summarizes the results of the study of consequences of a hypothetical severe nuclear accident.

## 6.1 Dose assessment

Tables 6.1 and 6.2 provide a summary of the whole body and thyroid dose results for adult individuals exposed for the first seven days up to a distance of 90 km from the plant. This includes information on the GLR scenarios and the sensitivity cases (fourfold increase in the radiological release) without consideration of protective actions. These centre-line doses are used for the purposes of decision making during the emergency. For a complete list of doses used for the human health risk assessment, including colon, bone marrow and thyroid dose (adult and child), see annex 3.

Trends for the centre-line doses for the first seven days after the hypothetical accidents include:

- doses would decrease rapidly with distance from the plant then tail off gradually at farther distances
- the scenario with the highest centre-line doses would be the short-term release scenario (24-01), whether the GLR or the sensitivity cases are considered – this scenario assumes a significant breach of containment after 24 hours
- the doses in the 24-24 scenario are lower than 24-01 scenario by over an order of magnitude across all distances, reflecting primarily the decay of noble gases as well as the effect of variable wind
- the 24-72 scenario results in the lowest doses of all scenarios considered, though the difference between it and 24-24 scenario is minimal

## 6.2 Emergency plan implementation

The GLR selected for this study is based on the CNSC safety goal of a large release, and was selected to examine human health consequences, with consideration of the emergency planning provisions of the Ontario PNERP. It is important to note that the Ontario PNERP is flexible in its structure and execution. Emergency planning zones, PALs, etc. are reference criteria; however, the execution of the plan considers a number of factors such as, but not limited to, local emergency response needs and capabilities, population, land characteristics, access routes, and jurisdictional boundaries. The results presented below do not account for this flexibility. Nonetheless, it is useful to examine how the PNERP reference criteria compare to the predicted doses from the various hypothetical scenarios.

From an emergency planning basis, tables 6.1 and 6.2 illustrate the results of three scenarios and two sensitivity cases, respectively, using PALs in conjunction with adult centre-line doses. To put these results in context, mSv values above the whole body doses and thyroid doses associated with the lower Ontario PNERP PALs for evacuation (10-mSv whole-body dose, 100-mSv thyroid dose) and sheltering (1-mSv whole-body dose, 10-mSv thyroid dose) have been bolded and italicized, respectively, for illustrative purposes. With respect to KI pill ingestion, mSv values above the thyroid blocking PAL of 50 mSv to the thyroid are denoted by an asterisk.

The distances identified for evacuation, sheltering and KI pill ingestion were then used to inform the dose inputs for the human health risk assessment as follows:

- in the event that at a given distance, the applicability of an evacuation or sheltering PAL differed (e.g., based on the dose, a different protective action decision could be made) between whole body and thyroid doses, the whole body PAL was chosen (i.e., 6 km distance in table 6.2)
- within the evacuated area, the doses were assumed to be zero – this is a modelling assumption of the study; however, it is recognized that in reality this may not always be the case (e.g., an evacuee could be exposed during the evacuation)
- within the sheltered area, doses were assumed to be reduced by only 20 percent
- for those areas sheltered within 12 km of the plant (for the purposes of this study, analogous to the Primary Zone), the thyroid doses were assumed to be zero when KI pill ingestion is applied – it is assumed that KI pills are available to residents in advance of the radiological exposure and that ingestion is done in the time frame prior to or immediately after exposure
- for those areas beyond 12 km in this study that exceeded the thyroid blocking PAL of 50 mSv to the thyroid, it was assumed that no KI pills were ingested

**Table 6.1: Adult centre-line dose values for whole body and thyroid relative to provincial nuclear emergency planning aspects (evacuation, sheltering, KI pill ingestion)[1] for the generic large release scenarios**

| Distance (km) from plant | Centre-line dose (mSv) for generic large release scenarios | | | | | |
|---|---|---|---|---|---|---|
| | 24-01 | | 24-24 | | 24-72 | |
| | Whole body | Thyroid | Whole body | Thyroid | Whole body | Thyroid |
| 1 | **324** | **5,470** | **25.40** | **431** | **21.30** | **357** |
| 3 | **78.60** | **1,210** | *4.50* | *70.70** | *3.72* | *59.40** |
| 6 | **33** | **479** | *1.75* | *26.70* | *1.44* | *22.10* |
| 12 | **12.70** | **179** | 0.67 | 9.82 | 0.56 | 8.21 |
| 20 | *5.69* | *77.40** | 0.31 | 4.40 | 0.25 | 3.59 |
| 28 | *4.09* | *57.20** | 0.18 | 2.49 | 0.15 | 2.03 |
| 36 | *1.90* | *25* | 0.13 | 1.75 | 0.10 | 1.42 |
| 50 | *1.06* | *13.9* | 0.07 | 0.95 | 0.06 | 0.74 |
| 70 | 0.51 | 6.76 | 0.04 | 0.52 | 0.03 | 0.41 |
| 90 | 0.39 | 5.23 | 0.03 | 0.39 | 0.02 | 0.30 |

[1]**Bold = greater than the lower PAL for evacuation;** *Italics = greater than the lower PAL for sheltering*
* = greater than the 50 mSv PAL for thyroid blocking

**Table 6.2: Adult centre-line dose values for whole body and thyroid relative to provincial nuclear emergency planning aspects (evacuation, sheltering, KI pill ingestion)[1] for sensitivity cases of generic large release x 4**

| Distance (km) from plant | Centre-line dose (mSv) for generic large release sensitivity cases | | | |
|---|---|---|---|---|
| | 24-24x4 | | 24-72x4 | |
| | Whole body | Thyroid | Whole body | Thyroid |
| 1 | **101.60** | **1724** | **85.20** | **1428** |
| 3 | **18** | **282.8** | **14.88** | **237.60** |
| 6 | *7* | **106.8*** | *5.76* | *88.4** |
| 12 | *2.68* | *39.28* | *2.24* | *32.84* |
| 20 | *1.24* | *17.6* | *1* | *14.36* |
| 28 | 0.72 | 9.96 | 0.6 | 8.12 |
| 36 | 0.52 | 7 | 0.4 | 5.68 |
| 50 | 0.28 | 3.8 | 0.24 | 2.96 |
| 70 | 0.16 | 2.08 | 0.12 | 1.64 |
| 90 | 0.12 | 1.56 | 0.08 | 1.2 |

[1]**Bold = greater than the lower PAL for evacuation;** *Italics = greater than the lower PAL for sheltering*
* = greater than the 50 mSV PAL for thyroid blocking

### 6.2.1 Emergency planning zones and evacuation protective action levels

Without the implementation of protective actions, in the 24-01 scenario, centre-line doses would exceed the upper evacuation PAL for whole body (100 mSv) up to 1 km from the plant. The lower-level evacuation PAL of 10 mSv would be exceeded up to a distance of approximately 12 km. As indicated earlier, the PNERP and its execution are inherently flexible. Depending on the circumstances, OFMEM could, for example, use a PAL that is above the lowest value of 10 mSv in the range, evacuate beyond the Primary Zone or implement other protective measures such as sheltering. It must be understood that PALs are expressed as a range so that decision making can be flexible given the unique challenges that any given emergency will present. For the purposes of the human health risk assessment (see section 6.3) for this scenario, evacuation out to 12 km (table 6.3) was assumed, with evacuated individuals receiving zero dose.

**Table 6.3: Distances up to which protective action levels in Ontario would be exceeded in the scenarios considered**

| Scenarios / sensitivity cases | Evacuation distance | | Sheltering distance | | Thyroid Blocking distance |
|---|---|---|---|---|---|
| | Upper PAL (100 mSv) [1] | Lower PAL (10 mSv) [1] | Upper PAL (10 mSv) [1] | Lower PAL (1 mSv) [1] | Thyroid PAL (> 50 mSv to Thyroid) [2] |
| 24-01 | 1 km | 12 km | 12 km | 50 km | 28 km |
| 24-24 | < 1 km | 1 km | 1 km | 6 km | 3 km |
| 24-72 | < 1 km | 1 km | 1 km | 6 km | 3 km |
| 24-24x4 | 1 km | 3 km | 3 km | 20 km | 6 km |
| 24-72x4 | < 1 km | 3 km | 3 km | 20 km | 6 km |

[1] whole body dose
[2] adult thyroid dose

With respect to the distance to be evacuated, the 24-24 and 24-72 scenarios and both sensitivity cases would result in evacuations only to distances that are within the Primary Zone (table 6.3) with those individuals receiving zero dose.

Overall, for all scenarios and sensitivity cases within this study, evacuations would be needed at distances that are up to or within the Primary Zone (analogous to 12 km in this study), using the most conservative criterion (i.e., 10 mSv lower PAL).

### 6.2.2 Sheltering protective action levels

The lower sheltering PAL value of 1 mSv whole body dose was chosen to identify up to what distance sheltering was applied (table 6.3). A 20-percent dose reduction was applied at these distances for the purposes of the human health risk assessment. It is recognized that in the event of an accident, depending on the circumstances, OFMEM could, for example, use a PAL above the lower 1-mSv limit. Based on this conservative lower limit, the maximum distance that could require sheltering was 50 km from the plant in the 24-01 scenario, corresponding to the Secondary Zone.

### 6.2.3 Thyroid blocking protective action level

Depending on the specifics of an actual accident, the thyroid blocking PAL could be implemented, for example, if there was a preponderance of iodine-131 in the source term, a radionuclide directly affecting the thyroid.

To inform the distances at which KI pill ingestion would be applied in the human health risk assessment, two criteria needed to be satisfied: (1) dose needed to be greater than the thyroid-blocking PAL of > 50 mSv to the adult thyroid, and (2) this dose exceedence had to occur at distances within the Primary Zone (analogous to 12 km or less for the purposes of this study).

With respect to the thyroid blocking PAL of > 50 mSv to the thyroid (table 6.3) using adult centre-line thyroid doses, the direction to take KI pills could be warranted in addition to sheltering (based on the lower 1-mSv sheltering PAL):

- for the 24-01 scenario, up to 28 km from the plant, which is beyond the Primary Zone
- for the 24-24 and 24-72 scenarios, up to 3 km, which is within the Primary Zone
- for the 24-24x4 and 24-72x4 scenarios, up to 6 km, which is within the Primary Zone

As described in the PNERP, for thyroid blocking, OPG is required to procure adequate quantities of KI pills for the Primary Zone population around the DNGS. Durham Region is responsible for the facilitation of the availability of KI for the Primary Zone institutions (e.g., schools, childcare centres, healthcare facilities), for emergency centres, and for members of the public who may wish to possess a supply in advance of an accident (e.g. designated pharmacies). The decision to administer KI is the responsibility of the Chief Medical Officer of Health for the province.

No credit for KI pill ingestion was taken in the 24-01 scenario since the distances for which it could be applied were beyond the Primary Zone (all those within the Primary Zone were evacuated). It was applied in the 24-24 and 24-72 scenarios and their respective sensitivity cases at distances within the Primary Zone that were above the thyroid blocking PAL of 50 mSv to the adult thyroid.

## 6.3 Human health risk assessment

For this study, a human health risk assessment is the process to estimate the nature and probability of adverse effects to humans who may be exposed to radionuclides released to the environment in the event of a nuclear accident. As described in chapter 5, the possible adverse effects on humans due to radiation exposure are tissue effects (deterministic effects) and stochastic effects (e.g., cancer). When considering the dose estimates once protective actions have been put in place, no threshold doses for deterministic effects were reached. Therefore, no deterministic effects are expected as a result of the scenarios considered in this study. For this reason, deterministic effects are not discussed further. Cancer risk has been quantitatively assessed considering protective actions.

### 6.3.1 Cancer risk assessment in the general population

Three types of cancer were chosen as indicators of the magnitude of risk for the hypothetical accident scenarios. It is important to note that if there was a real accident, doses would likely be modelled after the start of the accident but prior to a possible release of any radionuclides from the plant, to allow for implementation of protective actions. Post-release, doses would be calculated for individuals or groups of individuals based on more detailed information such as measurements of radionuclides in the environment combined with considerations for age, lifestyle characteristics and duration of exposure. In some cases doses would be measured more directly using personal dosimetry. Also, the risk would be assessed for various age groups and a greater number of cancers than were considered in this study. For the purpose of this assessment, an overview is provided to indicate the magnitude of risk rather than precise risk estimates.

For all three scenarios (24-01, 24-24, 24-72) and two sensitivity cases (24-24x4 and 24-72x4) considered, evacuation was determined based on the centre-line effective dose information and evacuation to the lower PAL was assumed. In the evacuated areas, this would result in no dose and therefore no additional cancer risk for those individuals. The scenario (24-01) and sensitivity case (24-24x4) that would have the highest increase in cancer risk have been chosen to demonstrate the results graphically for each type of cancer. In these graphs, the three distances chosen represent distances from the plant in areas that were not evacuated, and therefore differ between the scenarios.

All results have been reported as excess future risk above the baseline future risk. The excess future risk means the additional risk, over and above baseline risk that can be attributed directly to the radiation exposure from 2014 (the day of exposure) to the end of expected lifetime. The baseline future risk means the risk that would occur in the absence of radiation exposure associated with the accident from 2014 (the day of exposure) to the end of expected lifetime.

For the full list of cancer risk estimates across all scenarios and sensitivity cases, using average and centre-line doses, see annex 3.

### 6.3.2 All cancers combined

Regardless of the scenario under consideration, the equivalent dose to the colon, which was used to calculate the excess future risk of all cancers combined, would be too low to result in any detectable increased cancer risk. In other words, any cancers due directly to radiation exposure from the accident would be too few to distinguish from baseline cancers that would occur in the absence of radiation exposure from the accident.

| |
|---|
| The baseline risk of an individual developing any type of cancer (all cancers combined) is 49,114 chances in 100,000 or approximately 49 percent. |

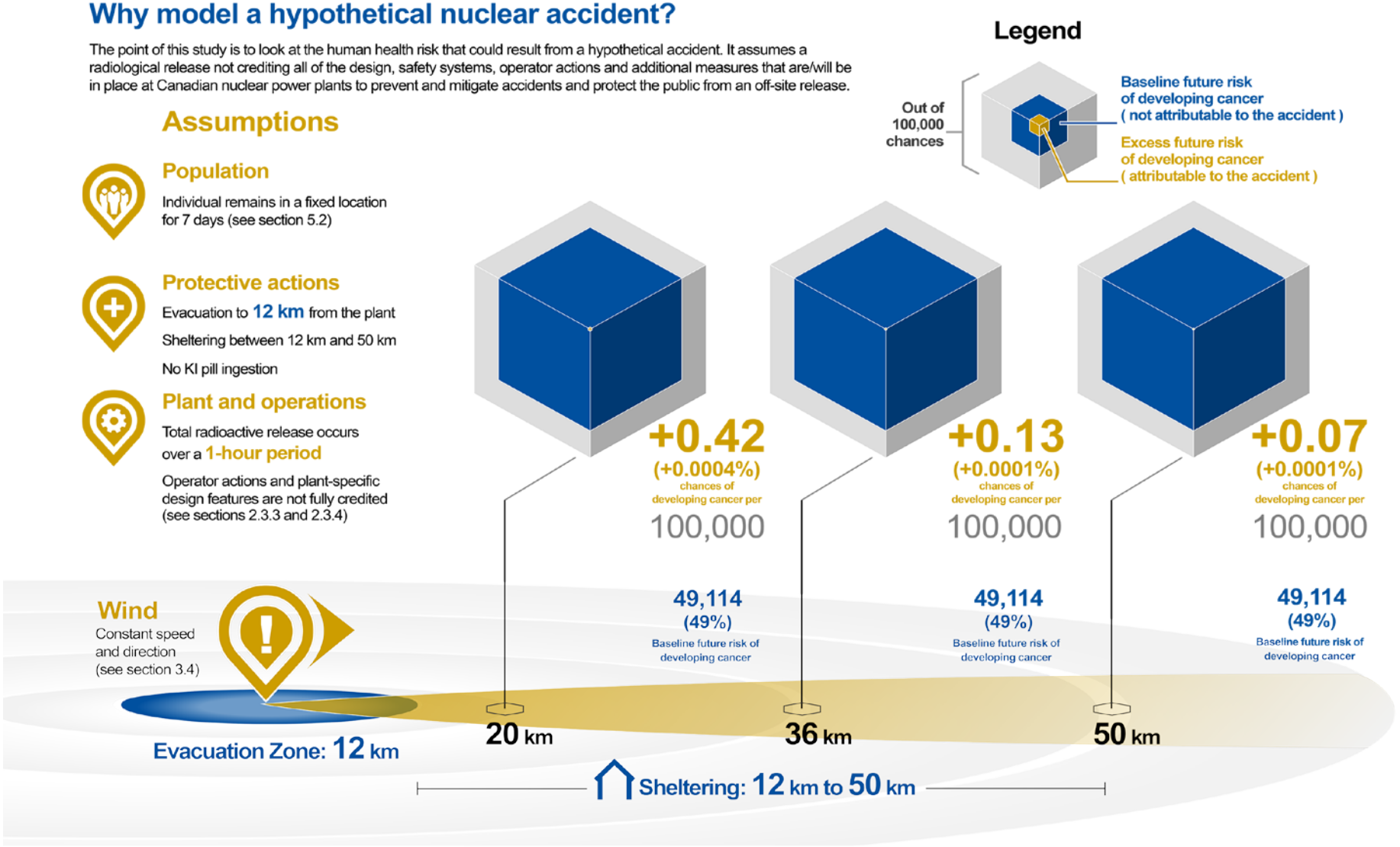
Figures 6.1 and 6.2 show the excess future risk of all cancers combined, at three distances from the plant for two scenarios. Both of these figures show how the risk would decrease sharply with distance from the plant.

- In the 24-01 scenario, at 20 km, the excess future risk would be an additional 0.42 chances in 100,000 (or approximately 0.0004 percent) of developing all cancers combined based on an average colon dose of 0.043 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after the radiation exposure occurred and would be in addition to the baseline future risk of 49,114 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 18.2 chances in 100,000 (for a centre-line colon dose of 1.86 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).
- In the 24-24x4 sensitivity case, at 6 km, the excess future risk would be an additional 4.9 chances in 100,000 (or approximately 0.005 percent) of developing all cancers combined based on an average colon dose of 0.5 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after the radiation exposure occurred and would be in addition to the baseline future risk of 49,114 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 20.3 chances in 100,000 (for a centre-line colon dose of 2.1 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).

The above mentioned risk values could be presented in several ways. Rather than looking at the impact of a radiation-related cancer on the total chances of developing cancer (baseline + radiation-related), one could compare these values directly to the baseline (radiation-related/baseline). For both scenarios (24-01 and 24-24x4), average and centre-line doses would increase the baseline of 49 percent by less than 0.01 percent. This increase is smaller than the variation in the age-standardized incidence rates (ASIRs) for “all cancers combined” across census divisions in Ontario which range from 337.04/100,000 to 450.98/100,000 and would not permit distinction between a radiation-related cancer and a baseline cancer.

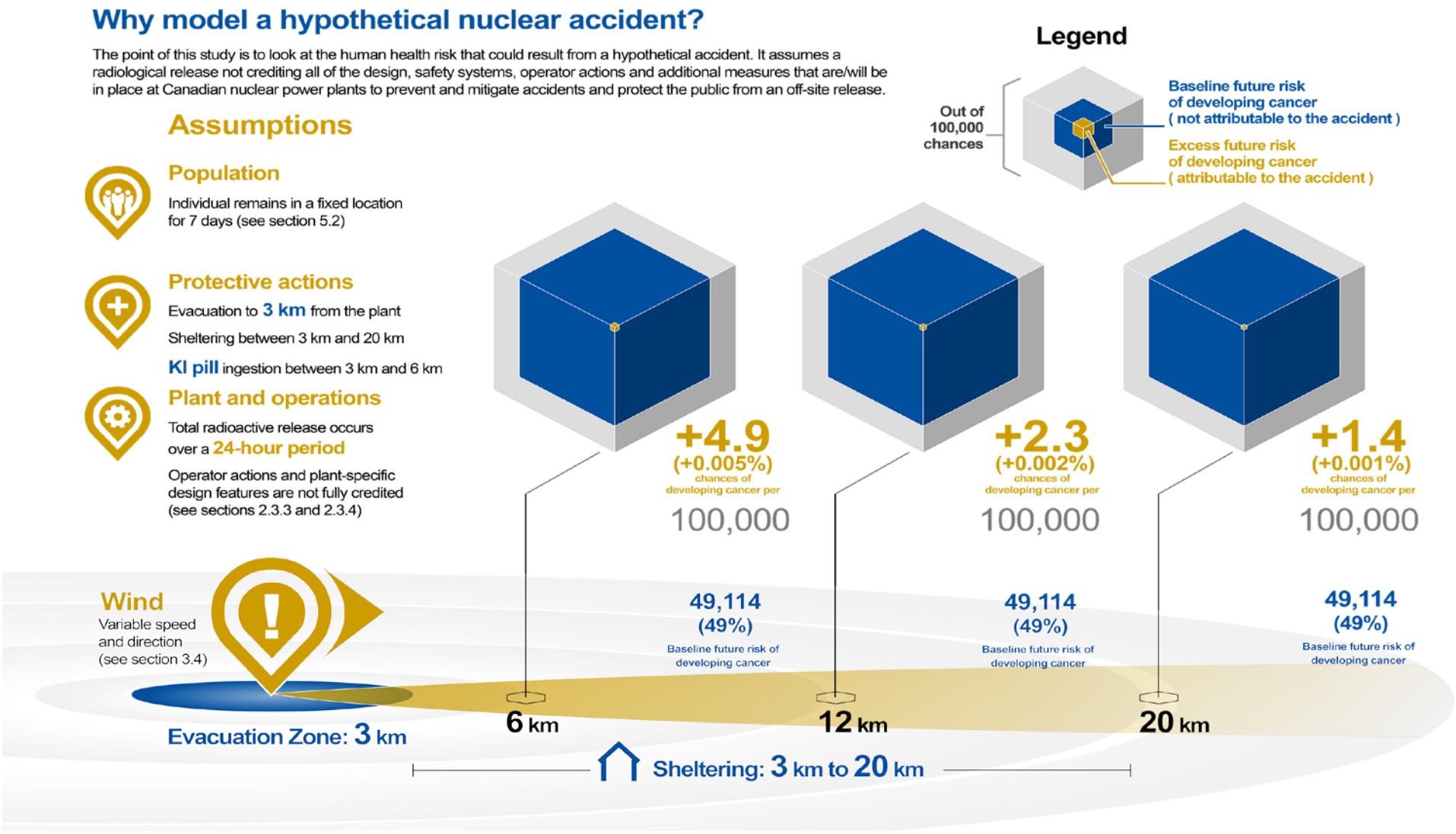
# Figure 6.1: Predicted impact on risk of developing cancer (all combined)

**24 hour hold-up, followed by a 1 hour release (24-01)**



# Figure 6.2: Predicted impact on risk of developing cancer (all combined)

**24 hour hold-up, followed by a 24 hour release, factor of 4 radiation increase (24-24x4)**



### 6.3.3 Leukemia

Regardless of the scenario under consideration, the equivalent dose to the bone marrow which was used to calculate the excess future risk of leukemia would be too low to result in any detectable increased cancer risk. In other words, any cases of leukemia due directly to radiation exposure from the accident would be too few to distinguish from baseline cases that would occur in the absence of radiation exposure from the accident.

The baseline risk of an individual developing any type of leukemia is 837 chances in 100,000 or approximately 0.84%.

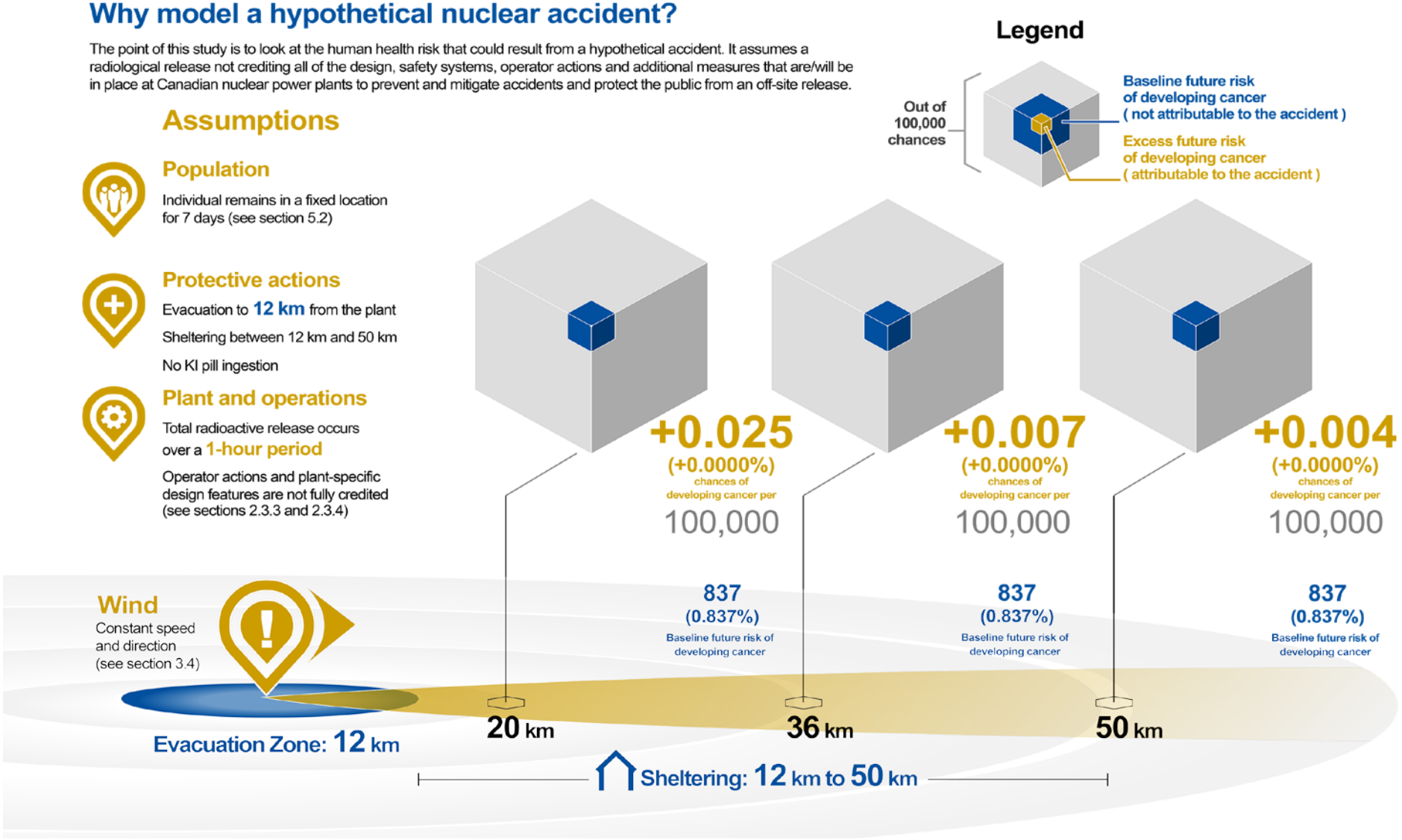
Figures 6.3 and 6.4 show the excess future risk of leukemia, at three distances from the plant for the two scenarios. Both of these figures show how the risk would decrease sharply with distance from the plant.

- In the 24-01 scenario, at 20 km, the excess future risk would be an additional 0.025 chances in 100,000 (or approximately 0 percent) of developing leukemia based on an average bone marrow dose of 0.03 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 837 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 1.1 chances in 100,000 (for a centre-line bone marrow dose of 1.3 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).
- In the 24-24x4 sensitivity case, at 6 km, the excess future risk would be an additional 0.25 chances in 100,000 (or approximately 0.0003 percent) of developing leukemia based on an average bone marrow dose 0.3 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 837 chances in 100,000 because of genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 1.1 chance in 100,000 (for a centre-line bone marrow dose of 1.2 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).

As mentioned above, risk values can be presented in several ways. Rather than looking at the impact of a radiation-related cancer on the total chances of developing leukemia (baseline + radiation-related), one could compare these values directly to the baseline (radiation-related/baseline). For both scenarios (24-01 and 24-24x4), average and centre-line doses would increase the baseline of 0.84 percent by less than 0.1 percent. This increase is smaller than the variation in the ASIRs for leukemias across census divisions in Ontario, which range from 7.91/100,000 to 15.75/100,000 and would not permit distinction between a radiation-related cancer and a baseline cancer.

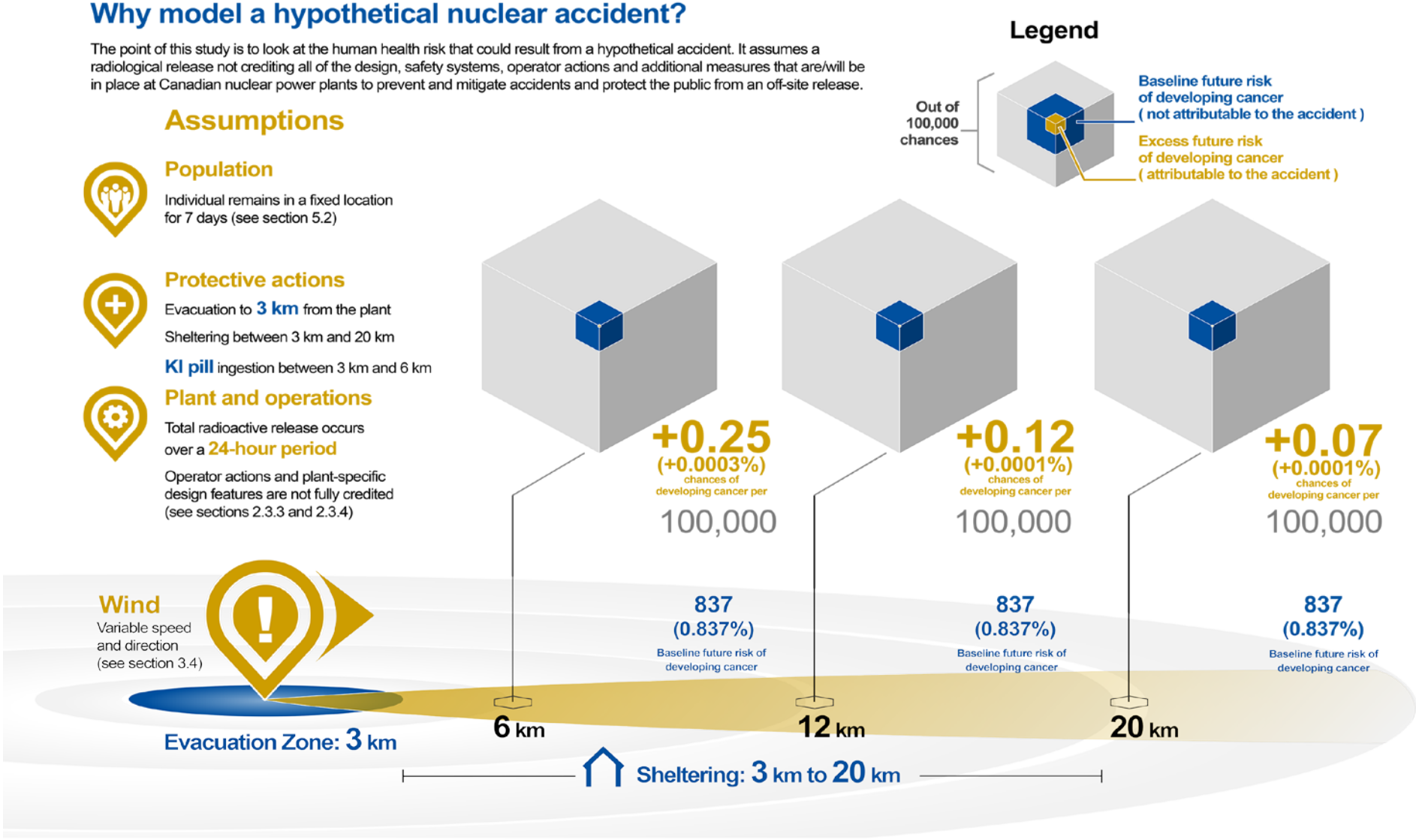
# Figure 6.3: Predicted impact on risk of developing leukemia

**24 hour hold-up, followed by a 1 hour release (24-01)**



# Figure 6.4: Predicted Impact on risk of developing leukemia

**24 hour hold-up, followed by a 24 hour release, factor of 4 radiation increase (24-24x4)**



### 6.3.4 Adult thyroid cancer

Regardless of the scenario under consideration, the equivalent dose to the adult thyroid which was used to calculate the excess future risk of thyroid cancer would be too low to result in any detectable increased risk. In other words, any cases of thyroid cancer due directly to radiation exposure from the accident would be too few to distinguish from baseline cases that would occur in the absence of radiation exposure from the accident.

The baseline risk of an individual developing thyroid cancer as an adult is 366 chances in 100,000 or approximately 0.37 percent.

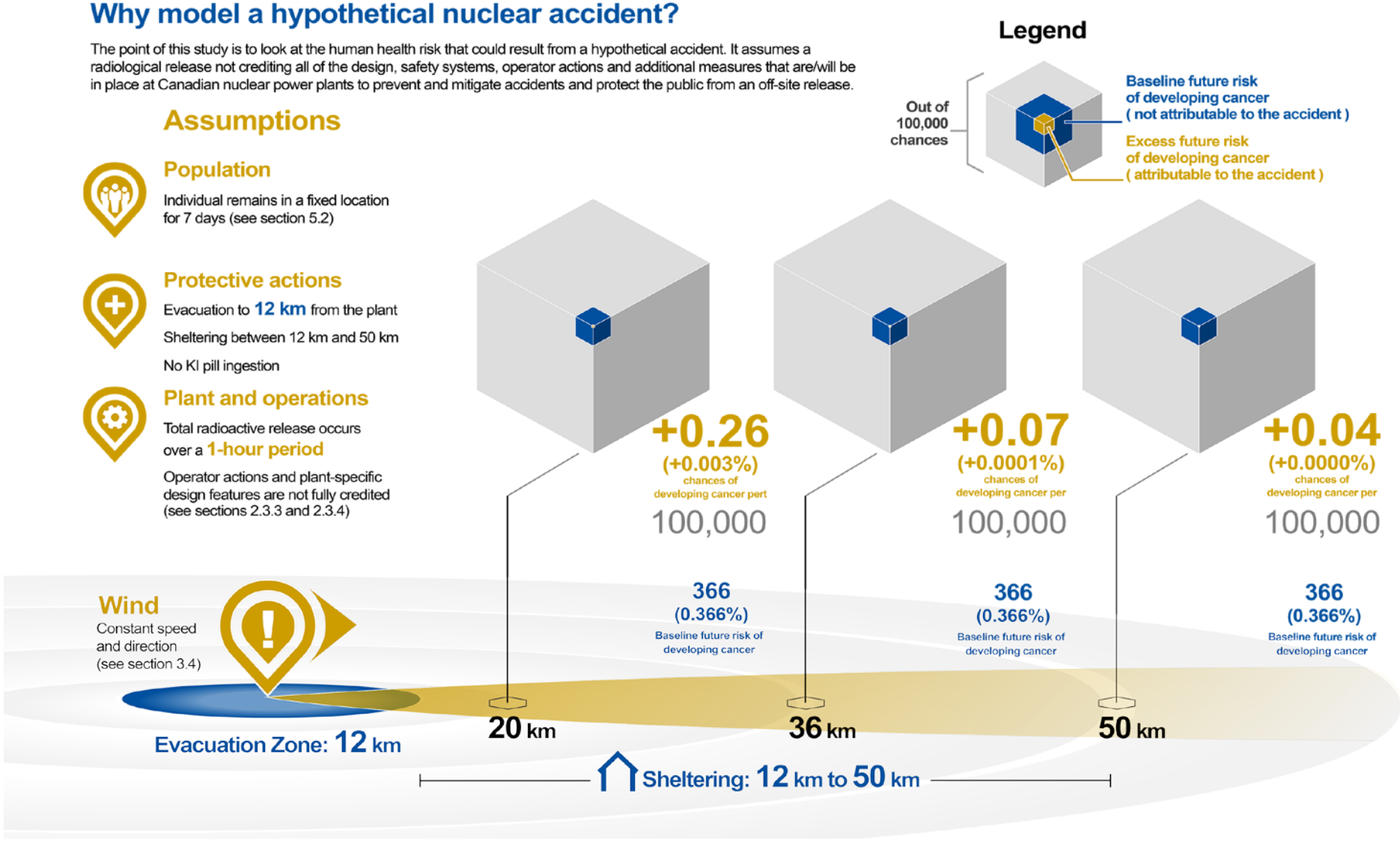
Figures 6.5 and 6.6 show the excess future risk of thyroid cancer, at three distances from the plant for the two scenarios. Both of these figures show how the risk would decrease sharply with distance from the plant.

- In the 24-01 scenario, at 20 km, the excess future risk would be an additional 0.26 chances in 100,000 (or approximately 0.0003 percent) of developing thyroid cancer as an adult based on an average thyroid dose of 1.59 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 366 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 13.2 chances in 100,000 (for a centre-line thyroid dose of 61.92 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).
- In the 24-24x4 sensitivity case, between 3 and 6 km, there would be no excess future risk of developing thyroid cancer as an adult because KI pill ingestion was applied resulting in zero dose to the thyroid – it is assumed that KI pills are available to residents in advance of the radiological exposure and that ingestion takes place in the time frame prior to or immediately after exposure.
- In the 24-24x4 sensitivity case, at 12 km, the excess future risk would be an additional 1.7 chances in 100,000 (or approximately 0.002 percent) of developing thyroid cancer as an adult based on an average thyroid dose of 10.24 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 366 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 6 chances in 100,000 (for a centre-line thyroid dose of 31.4 mSv indicative of the risk to a potentially maximally exposed person) (annex 3).

As mentioned above, risk values can be presented in several ways. Rather than looking at the impact of a radiation-related cancer on the total chance of developing adult thyroid cancer (baseline + radiation-related), one could compare these values directly to the baseline (radiation-related/baseline). For both scenarios (24-01 and 24-24x4), average and centre-line doses would increase the baseline of 0.37 percent by less than 4 percent. This increase would not permit distinction between a radiation-related cancer and a baseline cancer. In Ontario the age-standardized incidence rates (ASIRs) for thyroid cancer vary from 3.28/100,000 to 17.82/100,000 across census divisions.

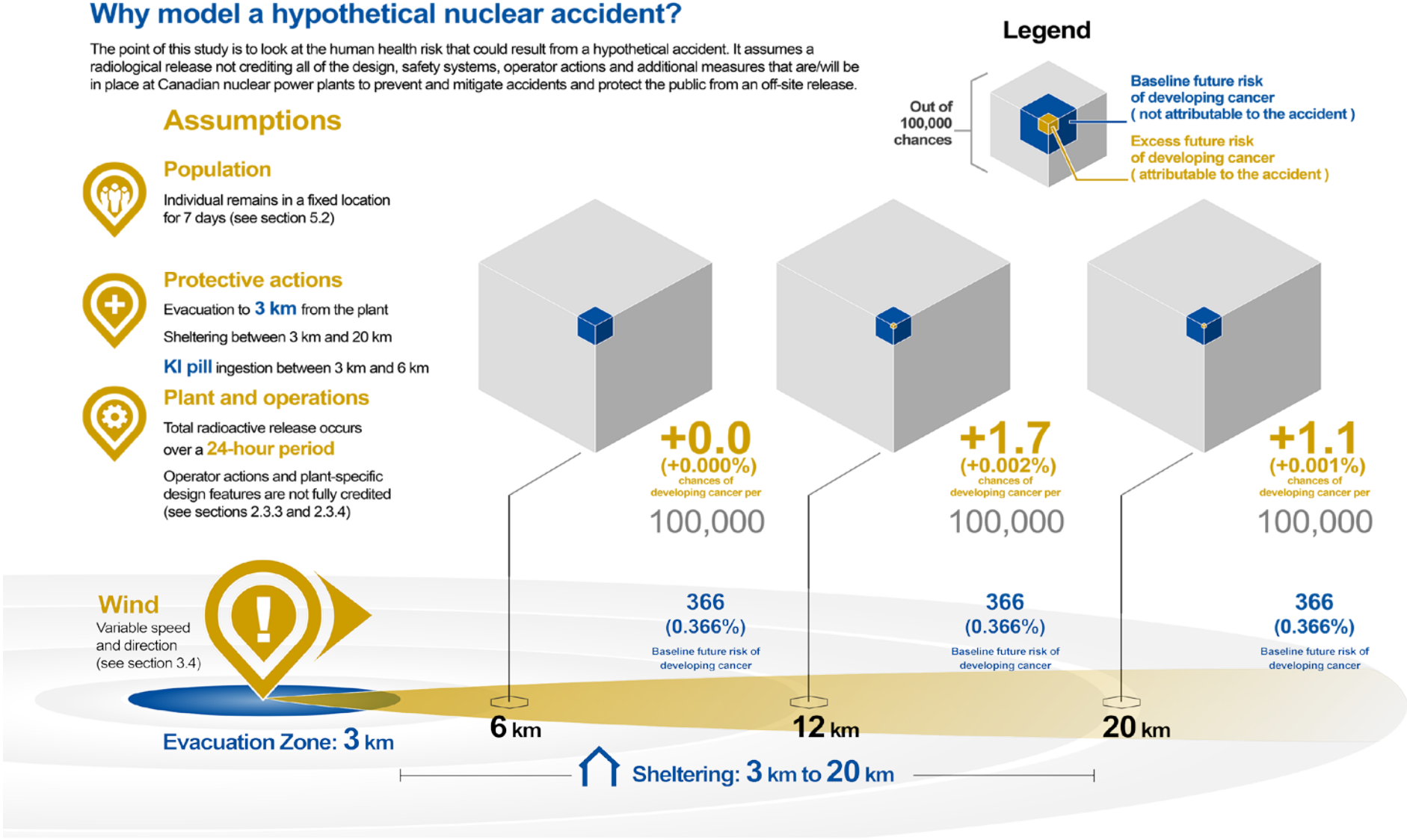
# Figure 6.5: Predicted impact on risk of developing adult thyroid cancer

**24 hour hold-up, followed by a 1 hour release (24-01)**



# Figure 6.6: Predicted impact on risk of developing adult thyroid cancer

**24 hour hold-up, followed by a 24 hour release, factor of 4 radiation increase (24-24x4)**



### 6.3.5 Childhood thyroid cancer

Childhood thyroid cancer is the only health effect in this study where an excess future risk could be detected above baseline risk. The dose to the child's thyroid is elevated in all five scenarios, and based on average doses distinction between an excess cancer and a baseline cancer is more likely for the two sensitivity cases than the three generic large release scenarios.

The baseline risk of a child developing childhood thyroid cancer is 1,078 chances in 100,000 or approximately 1 percent.

Figures 6.7 and 6.8 show the excess future risk of thyroid cancer, at three distances from the plant for the two scenarios. Both of these figures show how the risk would decrease sharply with distance from the plant.

- In the 24-01 scenario, at 20 km, the excess future risk would be an additional 41 chances in 100,000 (or 0.041 percent) of developing childhood thyroid cancer based on an average thyroid dose of 4.8 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 1,078 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 2,260 chances in 100,000 (for a centre-line thyroid dose of 185.8 mSv indicative of the risk to a potentially maximally exposed child) (annex 3).
- In the 24-24x4 sensitivity case, between 3 and 6 km, there would be no excess future risk of developing thyroid cancer as a child because KI pill ingestion was applied (based on adult thyroid doses) resulting in zero dose to the thyroid – it is assumed that KI pills are available to residents in advance of the radiological exposure and that ingestion is done in the time frame prior to or immediately after exposure.
- In the 24-24x4 sensitivity case, at 12 km, the excess future risk would be an additional 301 chances in 100,000 (or approximately 0.3 percent) of developing childhood thyroid cancer based on an average thyroid dose of 31 mSv. This risk is based on someone who was sheltered. This risk would be incurred over the remaining lifetime after radiation exposure and would be in addition to the baseline future risk of 1,078 chances in 100,000 due to genetic and other factors. The excess future risk could range from zero (for a minimum dose of approximately 0 mSv) to 1,120 chances in 100,000 (for a centre-line thyroid dose of 94.3 mSv indicative of the risk to a potentially maximally exposed child) (annex 3).

As mentioned above, risk values can be presented in several ways. Rather than looking at the impact of a radiation-related cancer on the total chances of developing childhood thyroid cancer (baseline + radiation-related), one could compare these values directly to the baseline (radiation-related/baseline). Average doses for the 24-01 and 24-24x4 scenarios would increase the baseline risk by approximately 4 percent and 16.5 percent respectively. These increases may be too low to distinguish from baseline cases. Centre-line doses for the 24-01 and 24-24x4 scenarios would increase the baseline risk by 210 percent and 40 percent respectively. These increases could likely be attributed to the radiation exposure from the accident.

**Thyroid cancer in children**

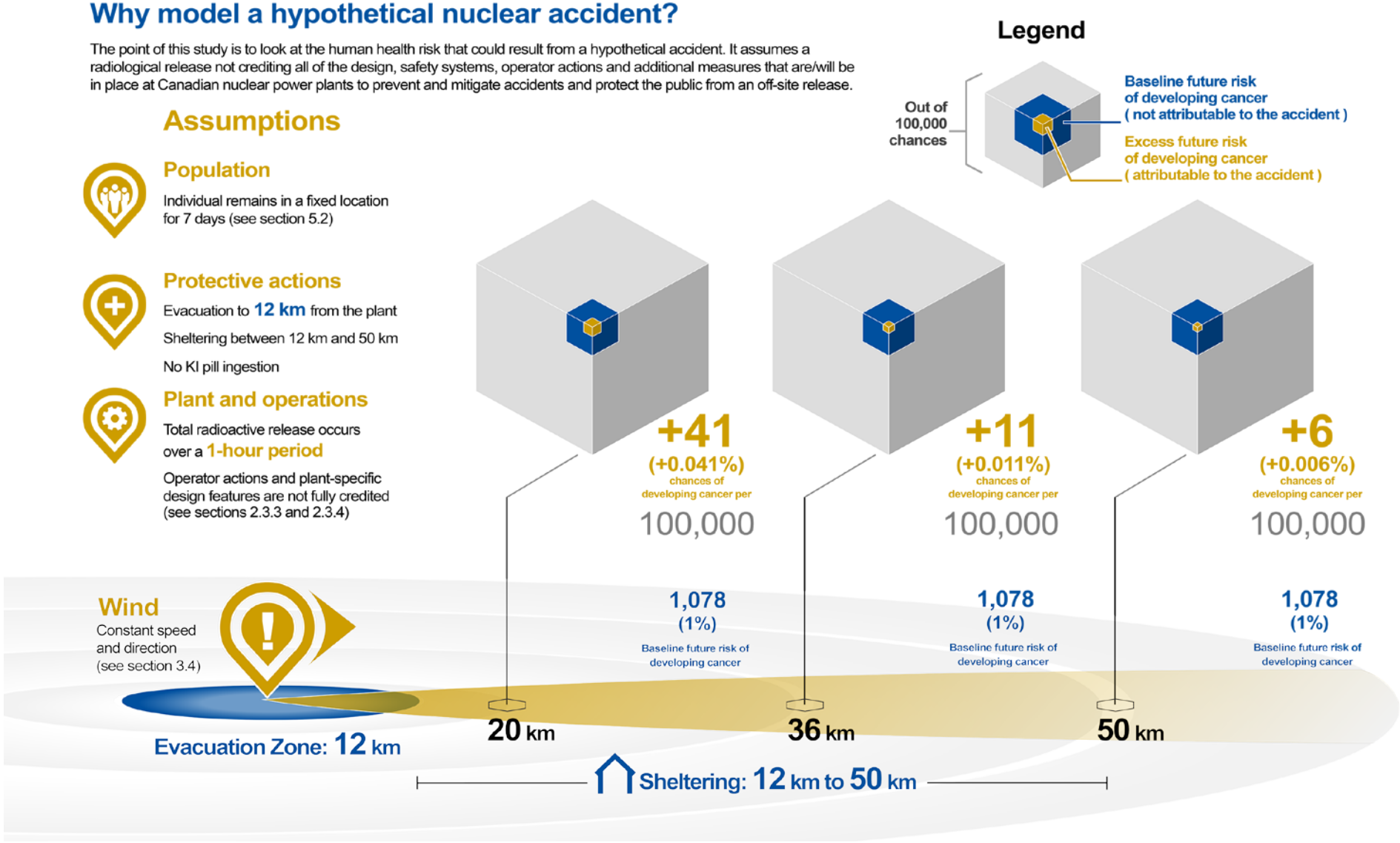
In general, thyroid cancer is rare for all age categories. The lifetime probability of developing thyroid cancer in Canada (for all ages) was 0.5 percent for males and 1.7 percent for females in 2009 (Canadian Cancer Society 2014). Thyroid cancer is particularly rare in children; the incidence rate of thyroid cancer generally increases with age. As indicated in table 5.1, in Ontario the annual incidence rate per 100,000 people for thyroid cancer is 1.8 for the age category 0–19 and is 117.3 for all other age categories (20–49, 60–64, 65+) combined (Forman et al. 2013).

Despite the low incidence rate, thyroid cancer in children is still an important adverse health outcome to examine in this study. Children have been shown to be more sensitive to radiation-induced thyroid cancer than adults. This may be due to the smaller size of the thyroid gland in children in comparison to adults, differences in metabolism, or other modifying factors.

Although the results of this study indicate what appears to be a large increase in the risk of incidence of thyroid cancer in children, this would not equate to a large increase in the actual number of thyroid cancers. With rare cancers any additional risk appears to be a large increase above the baseline.

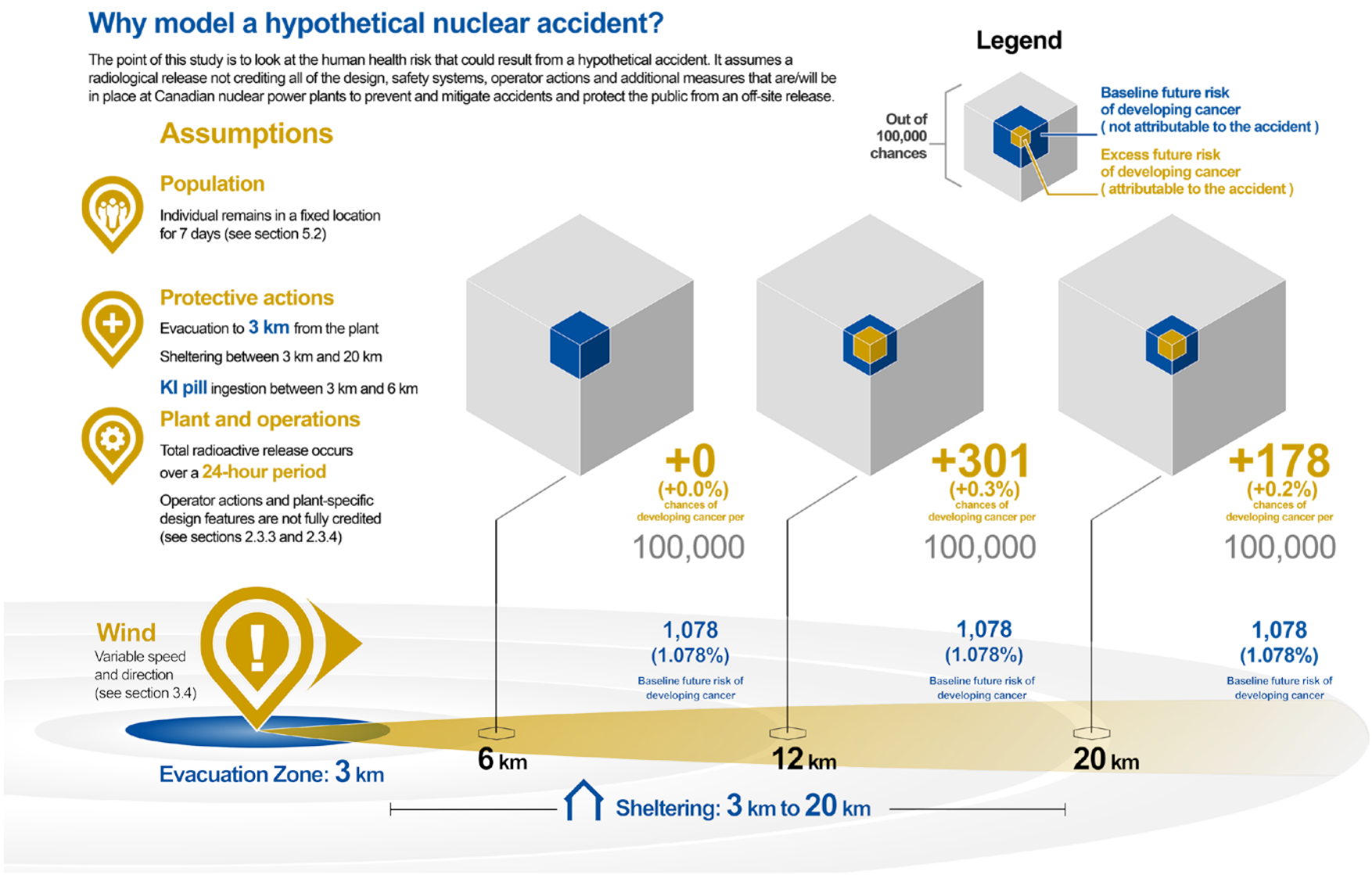
# Figure 6.7: Predicted impact on risk of developing childhood thyroid cancer

**24 hour hold-up, followed by a 1 hour release (24-01)**



# Figure 6.8: Predicted impact on risk of developing childhood thyroid cancer

**24 hour hold-up, followed by a 24 hour release, factor of 4 radiation increase (24-24x4)**



Given the excess future risk values presented above for childhood thyroid cancer for the 24-01 and 24-24x4 scenarios, an overview of the dose and resulting excess future risk for select distances from the plant are presented in tables 6.4 to 6.8. These tables provide an indication of how the doses and risks would vary across the different scenarios and sensitivity cases considered for this study. Of note, there would be little difference in the risk between the three GLR scenarios when looking at average doses for similar distances from the plant (e.g., at 20 km). Further, the risks associated with the three GLR scenarios would be considerably lower than it is for the sensitivity cases where the source term is increased fourfold. For the sensitivity cases, the 24-24x4 would have higher risks than the 24-72x4. Further insights on these findings can be found in section 7.

**Table 6.4: Excess future risk of developing childhood thyroid cancer (in 100,000) over and above the baseline future risk of 1,078 chances in 100,000 for the 24-01 scenario**

| Distance (km) from plant | Average dose (mSv) | Excess future risk based on average dose (chances in 100,000) | Centre-line dose (mSv) | Excess future risk based on centre-line dose (chances in 100,000) |
|---|---|---|---|---|
| 20 | 5 | 41 | 186 | 2,260 |
| 36 | 1 | 11 | 60 | 666 |
| 50 | 1 | 6 | 33 | 332 |

**Table 6.5: Excess future risk of developing childhood thyroid cancer (in 100,000) over and above the baseline future risk of 1,078 chances in 100,000 for the 24-24 scenario**

| Distance (km) from plant | Average dose (mSv) | Excess future risk based on average dose (chances in 100,000) | Centre-line Dose (mSv) | Excess future risk based on centre-line dose (chances in 100,000) |
|---|---|---|---|---|
| 6 | 17 | 150 | 64 | 720 |
| 12 | 10 | 82 | 30 | 287 |
| 20 | 6 | 52 | 13 | 114 |

**Table 6.6: Excess future risk of developing childhood thyroid cancer (in 100,000) over and above the baseline future risk of 1,078 chances in 100,000 for the 24-72 scenario**

| Distance (km) from plant | Average dose (mSv) | Excess future risk based on average dose (chances in 100,000) | Centre-line Dose (mSv) | Excess future risk based on centre-line dose (chances in 100,000) |
|---|---|---|---|---|
| 6 | 14 | 123 | 53 | 575 |
| 12 | 7 | 57 | 25 | 233 |
| 20 | 5 | 41 | 11 | 93 |

**Table 6.7: Excess future risk of developing childhood thyroid cancer (in 100,000) over and above the baseline future risk of 1,078 chances in 100,000 for the 24-24x4 sensitivity case**

| Distance (km) from plant | Average dose (mSv) | Excess future risk based on average dose (chances in 100,000) | Centre-line dose (mSv) | Excess future risk based on centre-line dose (chances in 100,000) |
|---|---|---|---|---|
| 6 | 0 | 0 | 0 | 0 |
| 12 | 31 | 301 | 94 | 1,120 |
| 20 | 20 | 178 | 42 | 438 |

**Table 6.8: Excess future risk of developing childhood thyroid cancer (in 100,000) over and above the baseline future risk of 1,078 chances in 100,000 for the 24-72x4 sensitivity case**

| Distance (km) from plant | Average dose (mSv) | Excess future risk based on average dose (chances in 100,000) | Centre-line dose (mSv) | Excess future risk based on centre-line dose (chances in 100,000) |
|---|---|---|---|---|
| 6 | 0 | 0 | 0 | 0 |
| 12 | 21 | 195 | 79 | 914 |
| 20 | 15 | 135 | 35 | 345 |

### 6.3.6 Uncertainties for the health risk assessment

The methodology chosen for the health risk assessment was based on standard international practice, and any calculation of lifetime radiation-induced risk carries large uncertainties (UNSCEAR 2008, NRC 2006). To minimize uncertainties in risk estimates, more detailed information is required to analyze lifetime risk from the accident scenarios considered for this study. For example, members of the population would continue to be exposed to radionuclides in the environment resulting from the hypothetical accident for years to come; however, these exposures were not considered in the health risk assessment. Chronic radiation exposure over a protracted period of time would necessitate more complicated assumptions about dose distribution and more complicated models with larger uncertainties. For this reason, the health risk assessment was performed for the first seven days after the accident.

**Timeframes for dose assessment**

The time frame modelled in this assessment was the first seven days after a release from a hypothetical nuclear accident. This is identified as the early phase in the MACCS2 code, and is also the timeframe recommended by various jurisdictions (international, national, provincial) for the implementation of urgent protective actions. Although it is likely that the population would also be exposed to radiation after the first seven days, this would depend greatly on the protective actions taken. Assuming that protective actions such as evacuation would remain in place for much of the first year, the dose received in the first seven days could make up the bulk of the dose (or even the entirety of the dose) received in that time frame.

To look further at potential lifetime doses we can examine the experience with previous nuclear accidents. For example, in their 2013 report, the WHO examined the ratio of

lifetime dose to 1-year dose for both the Fukushima and Chernobyl nuclear accidents. In both cases the doses were considerably less for all subsequent years following the first year, largely due to the decay of short-lived radioisotopes. For Chernobyl the ratio of lifetime dose to 1-year dose was projected to be 3, based on data collected during the 20 years following the accident. Taking into consideration the differences between the Chernobyl and Fukushima accidents, the WHO considered it reasonable to assume that for Fukushima the ratio of lifetime dose to 1-year dose would be 2 (WHO 2013).

The above provides some context of the magnitude of the 1-year or lifetime doses that could occur as a result of the hypothetical nuclear accident described in this study. It is not possible to estimate precisely what these doses would be, as this would depend greatly on longer-term decisions, such as the return of people to contaminated areas. This is a complex decision making process which involves consideration of numerous factors, not only radiological considerations. However, it is expected that authorities would take protective actions during the recovery period that are aligned with international recommendations and would ensure that doses do not exceed 1–20 mSv per year.

A list of key assumptions made in this health risk assessment is presented in annex 4. The implication of these assumptions (or choices) as well as the potential effect on the results are discussed. The main factors that could influence the radiation-related excess risk of cancer include sex, age at exposure, time since exposure and attained age (UNSCEAR 2008).

Generally speaking, risk estimates are of considerable value in characterizing the health impact on a population after a radiation exposure. It is important to keep in mind the health status of the population. Different populations could be impacted differently from the same exposure.

**Chernobyl and Fukushima – Health effects from radiation exposure**

Health effects from Chernobyl[1]:

- The only health effect detected in members of the public has been 5,127 childhood thyroid cancers (largely due to the ingestion of radioactive milk). To date, 15 of those children have died because of their radiation-related thyroid cancer.
- One hundred and thirty four workers suffered from acute radiation syndrome, 28 of whom died within four months of the accident.
- There is no scientific evidence of increases in overall cancer incidence or mortality rates, or in rates of non-malignant disorders related to radiation exposure from this accident.
- The incidence of leukemia in the general population does not appear to be elevated.
- There has been no clear evidence of any measurable increases in adverse health effects in countries outside of Belarus, the Russian Federation and Ukraine.

Health effects from Fukushima[2]:

- None of the seven reported deaths among emergency workers is attributable to radiation exposure (they died of other causes).
- No radiation-related deaths or acute diseases have been observed among members of the Japanese public exposed to radiation from the accident.
- An increased incidence in cancer is unlikely to be observed in the future because of the combined effects of the size of population exposed and low exposures.

- If a radiation-induced cancer would occur, it would be nearly impossible to distinguish it from a cancer that would occur in the absence of radiation exposure. It is highly likely that the 70% increased relative risk of thyroid cancer reported for children will go undetected since the initial predicted doses are much higher than measured doses.

[1] See UNSCEAR 2008 (Volume II)
[2] See UNSCEAR 2014 (Volume I), WHO 2012, WHO 2013

### 6.4 Psychosocial effects

Research on communities and individuals in the vicinity of previous actual nuclear accidents (such as Three Mile Island in the USA in 1979, Chernobyl in Ukraine in 1986, Tokaimura in Japan in 1999, and Fukushima in Japan in 2011) has consistently found that such accidents have short and long-term effects on the mental health and well-being of those in the vicinity of the accident site and on their communities (Norris et al. 2002, Bromet et al. 2011, World Health Organization 2002, Havenaar et al. 2003 ). A nuclear accident would likely cause fear of exposure to radiation; uncertainty about the appropriate actions to take to protect oneself, other family members, and one's home and belongings, including pets; and anxiety and stress in those living in the vicinity of the plant (Baum et al. 1983, Dohrenwend 1983, Dohrenwend et al. 1981). The more severe the accident and the longer the accident continues, the greater the fear, anxiety, and stress would be. These effects would likely impact mothers who fear their children would be at risk of exposure to radiation and therefore to potential future health consequences (Greve et al. 2007) and for plant employees, first responders, and clean-up workers who are on the site during the emergency (Bromet et al. 2011, Fabrikant 1983). The effects would also be progressively worse if the accident results in a recommendation or order to shelter or to evacuate. Effects on social cohesion and well-being would be long-lasting if there are concerns about persistent contamination from radioactivity or other hazardous materials (Edelstein 1988, Gregory and Satterfield 2002, Gregory and Mendelsohn 1993). Clear epidemiological evidence of radiation-dose related risks of psychosocial effects is lacking and would not allow estimation of projected risks. The most likely explanation for lacking evidence is difficulty in studying the wide spectrum of psychosocial conditions.

Because accidents occur unexpectedly, information about what has happened and what is going to happen is likely to be incomplete, contradictory, and subject to multiple revisions over time. Although emergency preparedness and communication planning provide an essential pathway for coordinating and disseminating emergency information, official communiques will be competing with media coverage and social network communications in providing information to area residents about the accident, risks, and recommended actions (Rubin et al. 2012, Houts and Cleary 2010, Hasaegawa 2013). For example, one issue that arose out of Fukushima was the reliability and accuracy of the information being communicated via social media (e.g., Friedman 2011). This will increase the uncertainty and anxiety of residents trying to evaluate the information and make decisions about protective measures such as taking KI pills, sheltering, or evacuating. It is likely that this uncertainty and anxiety will be most acute for the relatively small number of people present within the Contiguous Zone (1–3 km from the site), and only slightly less acute for those in the Primary Zone (0–10 km from the site). It is likely that residents within these zones will be immediately concerned about their, and their family and friends' health, safety, and well-being. The "invisible" nature of radioactive contamination and residents' unfamiliarity with the nature and progression of accidents at nuclear facilities is likely to increase their sense of dread, anxiety, and fear (Edelstein 1988, Gregory and Mendelsohn 1993, Page et al. 2006). If this information indicates a worsening accident, or is perceived as revealing lack of

knowledge or trustworthiness by those responsible for controlling the accident, mobilizing the emergency response, or advising the public, the stress, anger, and frustration levels of residents are likely to increase (Sorensen et al. 1987, Richardson et al. 1987, Norris et al. 2002, Freudenburg 1997, Gregory and Mendelsohn 1993). Ineffective communication and/or coordination of measures to protect the populations at risk will have a similar consequence. These effects are likely to extend to residents in the Secondary Zone, who are likely to be less familiar with the plant and associated emergency plans, if they feel they are not receiving the information or assistance they need in a timely way.

A need to implement sheltering or evacuation, which is more likely for those in the Contiguous and Primary Zones, as discussed in section 6.2, will raise the level of fear and increase residents' sense of loss of control, anxiety, and stress. This is likely to leave a subset of the population with post-traumatic stress disorder, depression, and a sense of hopelessness and alienation that will affect their sense of health and well-being (Sorensen et al. 1987, Houts et al. 2010, LaJoie et al. 2010). A potential need to evacuate will add to concerns about personal and family health and safety; the security of property; economic expenses and lost wages; and the duration of exclusion from home, business, and community. An extended evacuation, which would disrupt social relationships, increase economic costs, and create a sense of dislocation, is likely to be particularly difficult for children and those with limited resources (GAO 2013, Hasegawa 2013, Bellamy and Hierholzer 2012, Lai et al. 2013). Heightened stress levels and health concerns may persist for many years after the accident, particularly among mothers of children (Bromet et al. 2011, Houts et al. 2010, Gray et al. 2004, Hussain et al. 2011). This highlights the importance of science-based decision making in emergency response.

An accident that results in an offsite release of radioactive material is likely to affect the reputation, sense of place, and image of the community or region. Residents of communities that have been contaminated by hazardous materials, including radioactive materials, may feel themselves and their community to be stigmatized and isolated, with their social well-being reduced (Venables et al. 2012, Mix and Shriver 2007, Kahneman and Krueger 2006, Bush et al. 2001). In addition, efforts to establish responsibility and compensation for damages suffered from accidents involving hazardous materials are likely to create additional stress and uncertainty, increase conflicts, and reduce trust and confidence in the company and governmental institutions for residents of communities involved in these negotiations (Freudenburg 1993 and 1997, Mix and Shriver 2007, Picou et al. 2004).

The severity and duration of these effects would likely be related to the length of time the protective actions were in place, the amount of radiation released from the plant, the information provided to residents by the plant operator and regulatory authorities, and the length of time individuals were prevented from returning to their homes, communities, and daily activities. In general, these effects decline relatively rapidly over time for most of the affected population, once they are able to return to their normal life patterns (Williams and Drury 2009, Tucker 1995).

Clear, credible and regular communication from responsible parties before, during and after the emergency would help to minimize these effects as would transparent decisions (e.g., based on health-based limits and other factors) for the return of residents to their homes and daily lives.

## 6.5 Effects to non-human biota

This study also considered the potential effects on non-human biota exposed to radiation in the event of a hypothetical severe nuclear accident. Using the analysis done in the Darlington New

Nuclear Power Plant Project EA, where this topic was examined in detail, comparisons across similar accident scenarios (24-72) were possible to examine the effects on non-human biota in this study.

The results indicate that at 1 km, the Darlington New Nuclear Power Plant Project accident release was far below the acute reference dose (1,000 mGy) for all non-human biota. At these low levels, no acute effects on individual non-human biota or observable effects on populations would be identified at 1 km from the accident release point, and would further be expected to diminish rapidly at greater distances away from the plant. Given these results, and the similarity of dose projections at 1 km for both the Darlington New Nuclear Power Plant Project EA and this study, the same conclusion can be derived for the 24-72 scenario and related sensitivity case (24-72x4 scenario). For the remainder of the study scenarios/ sensitivity case, though not directly comparable, it would be expected that doses to non-human biota would be below the 1,000-mGy acute reference dose.

Details can be found in annex 5.

# 7. Study insights

## 7.1 Assumptions and context

This study was undertaken to address the Commission's direction to CNSC staff to undertake an assessment of health and environmental consequences of severe nuclear accident scenarios.

This study relied on the following key assumptions:

- assumed releases – without full credit taken for plant-specific design features and operator actions
- an individual not evacuated remains in a fixed location for a period of seven days during exposure to radiation
- use of modelling to project doses
- use of constant wind (speed and direction) for the 24-01 scenario and variable wind for the remainder of the scenarios

While insights around issues concerning emergency planning and health impacts can be drawn, the study assumptions must always be kept in mind.

## 7.2 Protective actions

The decision to implement protective actions in response to a nuclear accident in Ontario resides with the Office of the Fire Marshall and Emergency Management (OFMEM). The benefit of a protective action must be weighed against the potential risk of the action. A number of factors are considered in such a decision.

Overall, for all scenarios and sensitivity cases examined in this study, the emergency planning zones even for the most stringent criteria (i.e., 10-mSv lower PAL) in the PNERP would generally be adequate with respect to carrying out evacuation within those zones to effectively reduce the risks. In a real incident, a number of factors would be considered by the OFMEM on whether to evacuate to a distance corresponding to the lower PAL or another higher value, and is accommodated in the inherent flexibility in the execution of the PNERP.

As a sensitivity analysis in the human health risk assessment, the higher PALs for both evacuation and sheltering were considered (see annex 6). Briefly, by choosing a higher dose PAL value to initiate both evacuation and sheltering, a larger number of people would receive more radiation dose and therefore would be at a higher risk of developing cancer over time. However, non-radiological risks could be subsequently decreased by implementing shelter in place and KI pill ingestion instead of implementing evacuation. The evacuation process itself can pose risks (e.g., traffic accidents), and as previously described may be associated with psychosocial effects including anxiety and stress caused by the displacement from home and community. In addition, the prevailing meteorological conditions and their impact on the movement of the plume is an important determining factor in responding to a nuclear emergency (e.g., whether to evacuate as well as the route chosen to carry out the evacuation).

To illustrate this discussion, in the 24-01 scenario, application of the lower end of the PAL called for evacuation of the entire Primary Zone (up to 12 km). Using the upper end of the PAL, a minimal evacuation (1 km) would be required. As a result, the people living in the area of 1–12 km would receive a dose, whereas they previously received no dose. Given the alternative protective actions that could be implemented (such as KI pill ingestion between 1 and 6 km) and

the small excess future risk (presented in annex 6), authorities could decide that sheltering is a better option than evacuating. This logic is applied to all five scenarios in annex 6.

In summary, decision making with respect to a nuclear emergency situation involves many factors that need to be considered when weighing the benefit of a protective action against the potential risk of the action.

### 7.3 Human health effects

For the various scenarios and related sensitivity cases examined in this study, it would be nearly impossible to distinguish an excess future cancer (caused by the radiation released from the accident) for all cancers combined, leukemia, and adult thyroid cancer from a baseline future cancer (caused by something other than the radiation released from the accident). The exception is that of childhood thyroid cancer.

Though an excess future risk of childhood thyroid cancer was found across all scenarios, the greatest risks, based on average doses, would be associated with the two sensitivity cases (24-24x4 and 24-72x4). In these scenarios, excess future risk (e.g., 301 and 195 chances in 100,000, at a distance of 12 km) would be a small fraction of expected baseline future risk –1,078 chances in 100,000.

Thyroid cancer in children is very rare. The lifetime probability of developing thyroid cancer in Canada (for all ages) was 0.5 percent for males and 1.7 percent for females in 2009 (Canadian Cancer Society 2014). Thyroid cancer is also often treatable. Five-year survival rates among Canadians diagnosed with thyroid cancer is currently 98 percent.

Modelling of doses using consequence assessment tools/models often leads to overestimates, largely due to conservative assumptions built into the models. These assumptions relate to the assumed magnitude and release behaviour of the radionuclides, weather conditions and assumptions related to dosimetric parameters (such as the underestimation of the protection afforded by sheltering). In Fukushima for example, dose modelling was carried out for members of the public that when verified by direct measurements, proved to be overestimates (UNSCEAR 2014; Kamada et al. 2012; Tokonami et al. 2012; Kim et al. 2013; Matsuda et al. 2013). Thyroid monitoring was carried out in over 1,000 children in the most affected areas in March of 2011 and the resulting doses were 2-5 times less than UNSCEAR's estimates of settlement-average absorbed doses to the thyroid from internal exposure (UNSCEAR 2014).

It is important to note that although modelling often results in an overestimation of the dose, it serves an important purpose in informing decision makers early on of the overall magnitude of an accident before detailed information is available.

It is important to keep in mind that cancer is a stochastic disease and although an individual's risk may have increased due to an additional radiation exposure, there is no guarantee that they would develop the disease. For example, not all individual smokers develop lung cancer; however, a person who does smoke is at a greater risk of developing lung cancer.

### 7.4 Emergency planning and human health considerations

In order to be effective, KI pills must be taken before or shortly after the time of exposure. Normally, 1 or 2 doses are provided with the understanding that 2 doses would be protective for up to 48 hours after exposure (1 dose for 24 hours) (source: World Health Organization). In most

situations, 1 or 2 doses would be sufficient since evacuation would likely have been accomplished within this timeframe. If evacuation cannot be completed within this timeframe, additional dosages could be recommended; this flexibility is captured in the PNERP. In all cases, people would be directed to follow instructions from their local emergency response team and/or medical health advisor.

Given the excess future risk of childhood thyroid cancer found in this study, it may be important to examine the nature of protective actions and the levels they are set at regarding thyroid doses (e.g., thyroid blocking PAL of > 50 mSv) with respect to emergency planning in Ontario.

During an emergency, it is possible that not all residents will be able to take a dose of KI when directed by local authorities. For this reason, table 7.1 shows how the dose and resulting risk could vary with time of ingestion relative to exposure to the plume. If taken prior to the time of exposure or within one hour of exposure, KI is essentially 100 percent effective and blocks all uptake of radioactive iodine by the thyroid resulting in no dose (for adults or children) and, therefore there would be no additional excess future risk above the baseline future risk of developing thyroid cancer. The baseline future risk of developing thyroid cancer for adults and children is 366 and 1,078 chances in 100,000, respectively. If KI is taken 2 hours after exposure, the dose to the thyroid would be reduced by 80 percent resulting in a small excess future risk above baseline of 0.729 and 116 chances in 100,000 for adults and children, respectively. If KI is taken 3 hours after exposure, the dose to the thyroid would be reduced by 60 percent resulting in an excess future risk above baseline of 1.46 and 257 chances in 100,000 for adults and children, respectively. If for any reason, KI is not taken, the risk to adults would remain very small while the excess future risk for children (764 chances in 100,000) would be 70 percent above baseline (1,078 chances in 100,000). This table, while it considers for illustrative purposes the worst case scenario evaluated in this study, clearly demonstrates the need to ensure distribution of KI pills beforehand and for clear communication on KI use (e.g., timing of ingestion).

**Table 7.1: Example of KI effectiveness in reducing thyroid dose and the resulting risk for both adults and children living at 6 km who were sheltered for the 24-24x4 sensitivity case**

| Effectiveness of KI[1] | Mean adult thyroid dose as a result of KI ingestion (mSv) | Excess future risk of developing adult thyroid Cancer (chances in 100,000) | Mean child thyroid dose as a result of KI ingestion (mSv) | Excess future risk of developing childhood thyroid cancer (chances in 100,000) |
|---|---|---|---|---|
| 100 percent if taken prior to or within 1 hour of exposure beginning | 0 | 0 | 0 | 0 |
| 80 percent if taken 2 hours after exposure begins | 4.5 | 0.729 | 13.4 | 116 |
| 60 percent if taken 3 hours after exposure begins | 9.0 | 1.46 | 26.8 | 257 |
| 0 percent if not taken | 22.5 | 3.98 | 67 | 764 |

[1] source: NRC 2004

Both the effectiveness and the potential adverse side effects associated with KI pill ingestion are informed by previous experience. For example, as a result of the Chernobyl accident, over 17 million doses of KI were administered in Poland, including 10 million to children. No treatment-related fatalities occurred and there were only two serious allergic reactions, both of which were successfully treated (Nauman and Wolff, 1993).

The use of KI pills was minimal in the case of Fukushima as evacuation and sheltering effectively minimized the excess risk for child thyroid cancer. The assessments indicate that the rates of child thyroid cancer in Japan will not be detected above baseline rates (UNSCEAR 2014).

In the event of an actual accident with this level of predicted risk, decision makers could mitigate this risk through the administration of KI pills as discussed above at distances greater than applied in this study or by evacuating those areas most likely to be affected

## 7.5 Risk acceptability

In order to meaningfully assess the significance of the estimated excess cancer risks from the modelled hypothetical accident scenarios, it is important to look at them in the context of risk acceptability.

Various risk assessment and management frameworks for non-threshold chemical carcinogens have been developed in various countries, including Canada, as well as by international organizations such as the World Health Organization (WHO), the International Chemical Safety Program (ICSP), the International Labour Organization and the United Nations Environment Programme. Health Canada (2009a, 2009b) considers an incremental lifetime cancer risk of 1 in 100,000 ($10^{-5}$) to be "essentially negligible". Australia, Canada, the Netherlands, WHO and ICSP, among others, have identified target risk levels for different types of risk management decisions in the range of $10^{-5}$ and $10^{-4}$. Under these internationally accepted risk management frameworks, some of the highest excess cancer risks estimated in this study would be considered to be "essentially negligible" while others fall within the target risk levels ($10^{-5}$ and $10^{-4}$) for which the need for risk management actions are assessed on a case by case basis.

The maximum plausible excess cancer risk (based on centre-line dose) for the four cancer types investigated across all scenarios in this study would range as follows:

- all cancers combined: $9.96 \times 10^{-5}$ to $2.03 \times 10^{-4}$
- leukemia: $4.8 \times 10^{-6}$ to $1.07 \times 10^{-5}$
- adult thyroid cancer: $3.01 \times 10^{-5}$ to $1.32 \times 10^{-4}$
- childhood thyroid cancer: $5.74 \times 10^{-3}$ to $2.26 \times 10^{-2}$

Annex 7 further presents the various combinations of hypothetical accident scenarios and cancer types within each of the "risk bands" discussed above. For all combinations with risks > $10^{-4}$, the provisions in the PNERP and its flexibility would effectively reduce these risks. For example, for the 24-01 scenario, evacuation up to a maximum of 28 km would effectively reduce the excess risk of "all cancers combined" to within the $10^{-5}$ and $10^{-4}$ target risk levels. The excess risk (based on centre-line dose) of childhood thyroid cancer estimated for all scenarios and of adult thyroid cancer for the 24-01 scenario could effectively be mitigated through the timely administration of KI pills.

Taking into consideration the low probability of an actual severe accident, existing safety features, the even lower probability of a multi-unit accident (in this study, a fourfold increase in the source term), and the fact that the post-Fukushima safety enhancements would further reduce the likelihood of such severe accidents by a factor of 10 or more, overall the risks estimated in this study of the potential health consequences of a hypothetical severe nuclear accident would be considered acceptable. From a risk management perspective as described above, many means exist to control, mitigate and manage the risks, with due consideration to the likelihood of the accident occurring.

Further, as described in annex 7, the radiation protection framework recommended by the ICRP and endorsed by others, recommends that doses to members of the public (e.g., non-occupational doses) during emergency situations be kept below a reference level of 20–100 mSv (effective dose). The estimated residual colon doses (surrogate for effective doses) after the application of protective actions are all less than the lower end of this range and in that regard, can be regarded as acceptable.

## 7.6 Conclusions and recommendations

In this study, where hypothetical severe nuclear accident scenarios were assessed for consequences, there would be no detectable excess risk related to all cancers combined, leukemia and adult thyroid cancer. The only result attributable to the hypothetical accident would be an excess risk of childhood thyroid cancer, largely for the sensitivity cases examined in this study where the GLR source term was increased fourfold. The excess future risk (based on average dose) would be an additional 0.3 percent in developing childhood thyroid cancer (from an approximately 1 percent baseline future risk to a total risk of approximately 1.3 percent) at 12 km from the DNGS for the worst-case scenario.

Canadian nuclear power plants are safe. Following the Fukushima accident, the CNSC Task Force recommendations further strengthened each layer of defence built into the Canadian nuclear power plant design and licensing philosophy to ensure that the likelihood of accidents with serious radiological consequences is extremely low, with an emphasis on severe accidents. In this study, had all of the plant-specific design features, operator actions and other Task Force recommendations been fully credited/realized, the likelihood of a severe accident would have been lowered and the release of radioactive material considered would have been significantly reduced. It means that a severe accident would be extremely unlikely to arise or practically eliminated.

For emergency planning, the planning zones established under the PNERP would be adequate to address the evacuation related to the scenarios and sensitivity cases examined in this study. In response to the CNSC Task Force recommendations, improvements are being implemented to enhance emergency plans and capabilities to respond effectively in a severe event or multi-unit accident. This includes alignment of the PNERP thyroid blocking PAL with provincial, federal and international guidance, and the review of measures in place around KI pill stocking and distribution strategies. The PNERP is inherently flexible to deal with specific circumstances around an accident and the surrounding environment.

Furthermore, the evidence that has emerged from studies conducted after Chernobyl and Fukushima indicates that the preliminary modelled doses (e.g., used for decisions on evacuation and predictions of potential cancer risks) were higher than the doses obtained after the fact from direct measurements (e.g., environmental contamination, personal dosimetry). For example, excess cancer incidence is unlikely to be observed due to the Fukushima accident in the future

because of the combined effects of the size of population exposed and the very low exposures. If an excess cancer (due to the radiation from the accident) would occur, it would be nearly impossible to distinguish it from a baseline cancer (a cancer that would occur in the absence of radiation exposure from the accident). These findings are important as the doses from direct monitoring at Fukushima are comparable to the estimated doses of this study.

The above paragraphs point to study conservatisms in the progression of the accident (i.e., assumed releases) and in the human health risk assessment (i.e., modelled doses rather than measured). These conservative assumptions had to be made to allow for an examination of results beyond the accepted beyond-design-basis accident for the Darlington Nuclear Generating Station EA. Despite these conservatisms, the results show an excess cancer risk would only occur for one type of cancer (childhood thyroid cancer) out of the four examined. This is not unexpected given the radiosensitivity of a child's thyroid gland and is consistent with what actually happened following the Chernobyl accident.

Consideration of sensitive receptors in emergency planning is an integral part of federal (e.g., *Canadian Guidelines for Intervention during a Nuclear Emergency* (Health Canada 2003)) and provincial (e.g., *Potassium Iodide (KI) Guidelines* (Ontario Ministry of Health and Long-Term Care 2014) emergency decision making.

To conclude, though this study is conservative in nature, its findings would suggest that sensitive receptors (i.e., children) continue to be an important consideration in emergency planning; for example, in thyroid-related aspects of emergency planning such as protective action levels and plans for KI pill distribution (e.g., how, when, where). In addition, given the conservative assumptions in this study, more precision around risk estimates for thyroid cancer in children may be needed in support of any related emergency planning analyses.

From a risk acceptability perspective, the ability of the PNERP to effectively reduce the health risk, combined with the very low likelihood associated with severe nuclear accidents given Fukushima enhancements (i.e., such an event will be practically eliminated), allows these risks to be effectively managed to an acceptable level in alignment with international risk frameworks.

# Glossary

**absorbed dose**
The amount of energy deposited in a substance (e.g., human tissue), measured in a unit called the gray (Gy). A dose of 1 gray is equivalent to 1 unit of energy (joule) deposited in 1 kilogram of a substance.

**age at exposure**
Age at which ionizing radiation exposure occurs.

**as low as reasonably achievable (ALARA)**
An optimization tool in radiation protection used to keep individual, workplace and public dose limits as low as reasonably achievable, social and economic factors being taken into account. ALARA is not a dose limit; it is a practice that aims to keep dose levels as far as possible below regulatory limits.

**attained age**
Synonym of age at risk for a disease (e.g., the risk to develop cancer in general increases as people get older).

**average dose**
The average dose for a given distance range (i.e., ring) corresponds to the calculated average population dose over all the sample results divided by the population in that distance range. The average population dose is based on the variation of dose away from the plume centre line (i.e.,“off-centre-line doses”).

**baseline cancer rate (or baseline cancer)**
The cancer rate that would occur in the absence of (in the case this study) radiation exposure from the hypothetical severe nuclear accident. Baseline cancer is due to genetic and other factors, other than radiation exposure from the hypothetical severe nuclear accident.

**baseline future risk (or baseline risk)**
The risk that would occur in the absence of radiation exposure from the hypothetical accident from 2014 to the end of expected lifetime.beyond-design-basis accident

**beyond-design-basis accident**
An accident less frequent than a design-basis accident. A beyond-design-basis accident may or may not involve core degradation.

**cancer incidence**
Newly diagnosed cases of cancer

**centre-line dose**
Dose based on conservative, ground-level releases and calculated at the vertical and horizontal centre line of the plume and representative of the highest mean anticipated individual dose in any sector at a given distance from the reactor.

**design-basis accident**
Accident conditions for which a reactor facility is designed according to established design criteria, and for which the damage to the fuel and the release of radioactive material are kept within authorized limits.

**deterministic effect**
Changes in cells and tissues that are certain to occur after an acute dose of radiation (in excess of a threshold value of at least 1,000 mSv), below which the radiation effect is not detected. The severity of health effects – such as skin reddening, burns and hair loss – increases with the radiation dose received.

**deterministic safety analysis**
An analysis of nuclear reactor facility responses to an event, which is performed using predetermined rules and assumptions (e.g., those concerning the initial operational state, availability and performance of the systems and operator actions). Deterministic analysis can use either conservative or best-estimate methods.

**deoxyribonucleic acid (DNA)**
The molecular compound in the nucleus of a cell that forms the blueprint for the structure and function of the cell.

**dose**
When ionizing radiation penetrates the human body or an object it deposits energy. The energy absorbed by tissue from exposure to ionizing radiation is called a dose. Radiation dose quantities are described in three ways: absorbed, equivalent, and effective.

**dosimetry**
A scientific subspecialty in radiation protection and medical physics that focuses on calculating the internal and external doses from ionizing radiation.

**effective dose**
A measure of dose designed to reflect the amount of radiation detriment. The effective dose is obtained by multiplying the equivalent dose of each tissue or organ by an appropriate tissue weighting factor and summing the products. The unit of measurement is the sievert (Sv). Often referred to as the whole body effective dose.

**energy**
A physical quantity that describes the amount of work that can be performed by a given force, subject to a conservation law. Different forms of energy include kinetic, potential, thermal, gravitational, sound, light, elastic and electromagnetic.

**equivalent dose**
A measure of the dose to a tissue or organ designed to reflect the amount of harm caused to the tissue or organ. The equivalent dose is obtained by multiplying the absorbed dose by a “radiation weighting factor" to allow for the biological effectiveness of the various types of radiation in causing harm to tissue. The unit of measurement is the sievert (Sv). In the text of this study the thyroid dose, colon dose and bone marrow dose are all equivalent doses.

**excess future risk (or excess risk)**
The additional risk, over and above baseline risk that can be attributed directly to the radiation exposure from the hypothetical accident from 2014 (the day of exposure) to the end of expected lifetime.

**genetic effects**
The result of exposure to a substance, ionizing radiation for example, that causes damage to the genes of germinal cells, (i.e., sperm or egg).

**gray**
The SI (International System of Units) unit of absorbed radiation dose. It is defined as the absorption of 1 joule of radiation energy by 1 kilogram of matter (or tissue).

**heat sink**
A system or component that provides a path for heat-transfer from a source, such as heat generated in the fuel, to a large heat absorbing medium, such as water.

**heat transport system (primary)**
That system of components that permit the transfer of heat from the fuel in the reactor to the steam generators or other heat exchangers employing secondary cooling.

**ionizing radiation**
A form of radiation that is capable of adding or removing electrons as it passes through matter (such as air, water, or living tissue). Examples are alpha particles, gamma rays, X-rays and neutrons.

**linear-non-threshold (LNT) model**
A risk model used internationally by most health agencies and nuclear regulators to set dose limits for workers and members of the public. The LNT model assumes a direct and proportional relationship between radiation exposure and cancer risk with all radiation doses.

**practically eliminated**
The possibility of certain conditions occurring being physically impossible or with a high level of confidence to be extremely unlikely to arise.

**radiation**
Energy travelling through space in the form of waves or particles. There are two main types of radiation, ionizing and non-ionizing. All references to radiation in this study are to ionizing radiation.

**risk assessment**
A tool or a process for estimating the potential for adverse health effects that could result from the presence of contaminants at a site. A typical radiation risk assessment is made up of four parts:

- problem identification
  - gather information on the hazard (radiological contaminant) and baseline conditions
- dose-response evaluation
  - identify what effects could be expected and how those effects can vary with dose
- dose (exposure) assessment
  - assess doses through modelling or direct measurement
- risk characterization and acceptability
  - determine the probability of an adverse outcome

**safety and control areas**
Technical topics used by the CNSC to assess, review, verify and report on regulatory requirements and performance across all regulated facilities and activities.

**severe accident**
An accident more severe than a design-basis accident, and involving significant core degradation or significant fuel degradation in the spent fuel pool (also called the irradiated fuel pool).

**severe accident management program**
A program that establishes:

- the actions to be taken to prevent severe damage to the reactor core, to mitigate the consequences of the core damage (should it occur), and to achieve a safe, stable state of the reactor over the long term
- the preparatory measures necessary for implementation of such actions

**sievert (Sv)**
The SI unit of absorbed radiation dose in living organisms modified by radiation type and tissue weighting factors. The sievert is the unit of dose measuring the "equivalent dose" and "effective dose". It replaces the classical radiation unit rem. Multiples of sievert used in practice include millisievert (mSv) and microsievert (μSv).

**steam generator**
A heat exchanger that transfers heat from the heavy water coolant to ordinary water. The ordinary water boils, producing steam to drive the turbine. The steam generator tubes separate the reactor coolant from the rest of the power-generating system.

**stochastic effects**
A term used to group radiation-induced health effects (such as cancer or inheritable diseases) which have a statistical risk. For these diseases, the probability of their occurrence increases proportionally to the radiation dose received: the higher the dose, the higher the probability of occurrence. However, at no time, even for high doses, is it certain that cancer or genetic damage will result.

**time since exposure**
Period of time between exposure to ionizing radiation and the occurrence of an effect.

**total station blackout**
Occurs when all power sources used to cool the reactors, including on site power, off site power, standby and emergency generators, are unavailable.

**wind (constant versus variable)**
For the purposes of the study, the MACCS2 code treated the 1-hour release duration for the 24-01 scenario as one segment for modelling purposes and therefore, wind direction and speed were assumed to be constant over the entire time period due to the relatively short duration of the release. The wind direction and speed was varied over time for the other two scenarios (24-24 and 24-72). For modelling purposes, the 24-24 scenario is divided into 4 equal segments of 6 hours each and the 24-72 scenario is divided into 4 equal segments of 18 hours each.

# Acronyms

| | |
|---|---|
| ALARA | as low as reasonably achievable |
| ASIRs | age-standardized incidence rates |
| BEIR | Biological Effects of Ionizing Radiation |
| Bq | becquerel |
| CFVS | containment filtered venting system |
| CNSC | Canadian Nuclear Safety Commission |
| DNGS | Darlington Nuclear Generating Station |
| EA | environmental assessment |
| EME | emergency mitigating equipment |
| GLR | generic large release |
| Gy | gray (unit) |
| ICRP | International Commission on Radiological Protection |
| ICSP | International Chemical Safety Program |
| KI | potassium iodide |
| LNT | linear-non-threshold |
| MAACS2 | Melcore Accident Consequences Code System |
| MAAP | modular accident analysis program |
| mGy | milligray |
| mSv | millisievert |
| NRC | Nuclear Regulatory Commission (U.S.) |
| OFMEM | Office of the Fire Marshall and Emergency Management |
| OPG | Ontario Power Generation |
| PAL | protective action level |
| PAR | passive autocatalytic recombiner |

| | |
|---|---|
| PNERP | Ontario Provincial Nuclear Emergency Response Plan |
| SI | International System of Units |
| Sv | sievert (unit) |
| UNSCEAR | United Nations Scientific Committee on the Effects of Atomic Radiation |
| WHO | World Health Organization |

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# Annex 1: Estimated radionuclide releases and core inventory

**Table A1.1: Estimated radionuclide releases for the hypothetical nuclear accidents considered in this study and for previous nuclear accidents**

| Isotope | Fission product releases (becquerels) | | | |
|---|---|---|---|---|
| | GLR (24-24) | GLRx4 (24-24) | Chernobyl | Fukushima |
| **Ba-140** | 8.14E+11 | 3.26E+12 | 2.50E+17 | 3.10E+15 |
| **Cs-134** | 3.21E+13 | 1.29E+14 | 5.90E+16 | 1.80E+16 |
| **Cs-137** | 1.02E+14 | 4.08E+14 | 8.20E+16 | 1.50E+16 |
| **Ce-141** | 2.40E+11 | 9.58E+11 | 2.00E+17 | 1.80E+13 |
| **Ce-144** | 8.17E+10 | 3.27E+11 | 1.70E+18 | 1.20E+13 |
| **I-131** | 3.93E+15 | 1.57E+16 | 1.50E+18 | 1.60E+17 |
| **I-132** | 5.80E+11 | 2.32E+12 | 2.10E+18 | 1.30E+13 |
| **I-133** | 2.79E+15 | 1.12E+16 | 3.00E+18 | 4.20E+16 |
| **I-135** | 2.50E+14 | 9.98E+14 | N/A | 2.30E+15 |
| **Ru-103** | 1.00E+15 | 4.00E+15 | 2.30E+17 | 7.50E+09 |
| **Ru-106** | 1.14E+14 | 4.55E+14 | 5.00E+16 | 2.10E+09 |
| **Xe-133** | 1.99E+18 | 7.95E+18 | 6.00E+18 | 1.10E+19 |

## Table A1.2: Equilibrium Core Inventory of Isotopes Included in Dose Calculation (Unless Otherwise Indicated)

| Isotope | Parent | MACCS2 Group | Half-Life (s) | Core Inv. (Bq) |
|---|---|---|---|---|
| **Co-58** | None | 6 | 6.12E+06 | 1.00E+00* |
| **Co-60** | None | 6 | 1.66E+08 | 1.00E+00* |
| **Kr-85** | None | 1 | 3.39E+08 | 6.28 E+15 |
| **Kr-85M** | None | 1 | 1.61E+04 | 7.57 E+17 |
| **Kr-87** | None | 1 | 4.56E+03 | 1.51 E+18 |
| **Kr-88** | None | 1 | 1.01E+04 | 2.10 E+18 |
| **Rb-86** | None | 3 | 1.61E+06 | 7.21 E+14 |
| **Sr-89** | None | 5 | 4.49E+06 | 2.92 E+18 |
| **Sr-90** | None | 5 | 8.87E+08 | 5.17 E+16 |
| **Sr-91** | None | 5 | 3.41E+04 | 3.65 E+18 |
| **Sr-92** | None | 5 | 9.76E+03 | 3.87 E+18 |
| **Y-90** | Sr-90 | 7 | 2.31E+05 | 5.41 E+16 |
| **Y-91** | Sr-91 | 7 | 5.08E+06 | 3.60 E+18 |
| **Y-92** | Sr-92 | 7 | 1.27E+04 | 3.91 E+18 |
| **Y-93** | None | 7 | 3.64E+04 | 2.96 E+18 |
| **Zr-95** | None | 7 | 5.66E+06 | 4.49 E+18 |
| **Zr-97** | None | 7 | 6.05E+04 | 4.74 E+18 |
| **Nb-95** | Zr-95 | 7 | 3.03E+06 | 3.90 E+18 |
| **Mo-99** | None | 6 | 2.38E+05 | 5.41 E+18 |
| **Tc-99M** | Mo-99 | 6 | 2.17E+04 | 4.76 E+18 |
| **Ru-103** | None | 6 | 3.42E+06 | 4.06 E+18 |
| **Ru-105** | None | 6 | 1.60E+04 | 2.91 E+18 |
| **Ru-106** | None | 6 | 3.19E+07 | 4.57 E+17 |
| **Rh-105** | Ru-105 | 6 | 1.28E+05 | 2.53 E+18 |
| **Sb-127** | None | 4 | 3.28E+05 | 2.58 E+17 |
| **Sb-129** | None | 4 | 1.56E+04 | 9.60 E+17 |
| **Te-127** | Sb-127 | 4 | 3.37E+04 | 2.39 E+17 |
| **Te-127M** | None | 4 | 9.42E+06 | 2.57 E+16 |
| **Te-129** | Sb-129 | 4 | 4.20E+03 | 9.04 E+17 |
| **Te-129M** | None | 4 | 2.89E+06 | 1.73 E+17 |
| **Te-131M** | None | 4 | 1.08E+05 | 6.11 E+17 |
| **Te-132** | None | 4 | 2.81E+05 | 4.19 E+18 |
| **I-131** | Te- | 2 | 6.95E+05 | 2.94 E+18 |
| **I-132** | Te-132 | 2 | 8.23E+03 | 4.37 E+18 |
| **I-133** | None | 2 | 7.49E+04 | 5.95 E+18 |
| **I-134** | None | 2 | 3.16E+03 | 6.63 E+18 |
| **I-135** | None | 2 | 2.37E+04 | 5.65 E+18 |
| **Xe-133** | I-133 | 1 | 4.57E+05 | 5.88 E+18 |
| **Xe-135** | I-135 | 1 | 3.30E+04 | 5.63 E+17 |
| **Cs-134** | None | 3 | 6.50E+07 | 2.12 E+16 |
| **Cs-136** | None | 3 | 1.12E+06 | 4.07 E+16 |
| **Cs-137** | None | 3 | 9.50E+08 | 6.71 E+16 |
| **Ba-139** | None | 9 | 4.99E+03 | 5.27 E+18 |
| **Ba-140** | None | 9 | 1.11E+06 | 5.26 E+18 |
| **La-140** | Ba-140 | 7 | 1.45E+05 | 5.32 E+18 |
| **La-141** | None | 7 | 1.42E+04 | 4.86 E+18 |
| **La-142** | None | 7 | 5.72E+03 | 4.74 E+18 |
| **Ce-141** | La-141 | 8 | 2.81E+06 | 4.78 E+18 |
| **Ce-143** | None | 8 | 1.19E+05 | 4.52 E+18 |
| **Ce-144** | None | 8 | 2.46E+07 | 1.59 E+18 |
| **Pr-143** | Ce-143 | 7 | 1.17E+06 | 4.54 E+18 |
| **Nd-147** | None | 7 | 9.50E+05 | 1.85 E+18 |
| **Np-239** | None | 8 | 2.03E+05 | 7.80E+19** |
| **Pu-238** | Cm-242 | 8 | 2.77E+09 | 8.26E+13** |
| **Pu-239** | None | 8 | 7.59E+11 | 5.57E+14** |
| **Pu-240** | Cm-244 | 8 | 2.06E+11 | 5.22E+14** |
| **Pu-241** | None | 8 | 4.54E+08 | 4.21E+16** |

| Isotope | Parent | MACCS2 Group | Half-Life (s) | Core Inv. (Bq) |
|---|---|---|---|---|
| **Am-241** | None | 7 | 1.36E+10 | 9.24E+12** |
| **Cm-242** | None | 7 | 1.41E+07 | 1.13E+15** |
| **Cm-244** | None | 7 | 5.71E+08 | 5.05E+12** |

*Structural steel activation products set to arbitrary low value due to very low quantities of steel in CANDU core

**Actinides not included in dose calculations due to extremely low volatility

## Annex 2: Modelling structure for wind and population-based considerations

**Figure A2.1:** Polar coordinate grid – features 10 concentric rings, 16 radial sectors corresponding to compass directions, resulting in 160 ring sectors. Population (see table below) is known for each ring sector. Example population value identified in red below is mapped to the table.

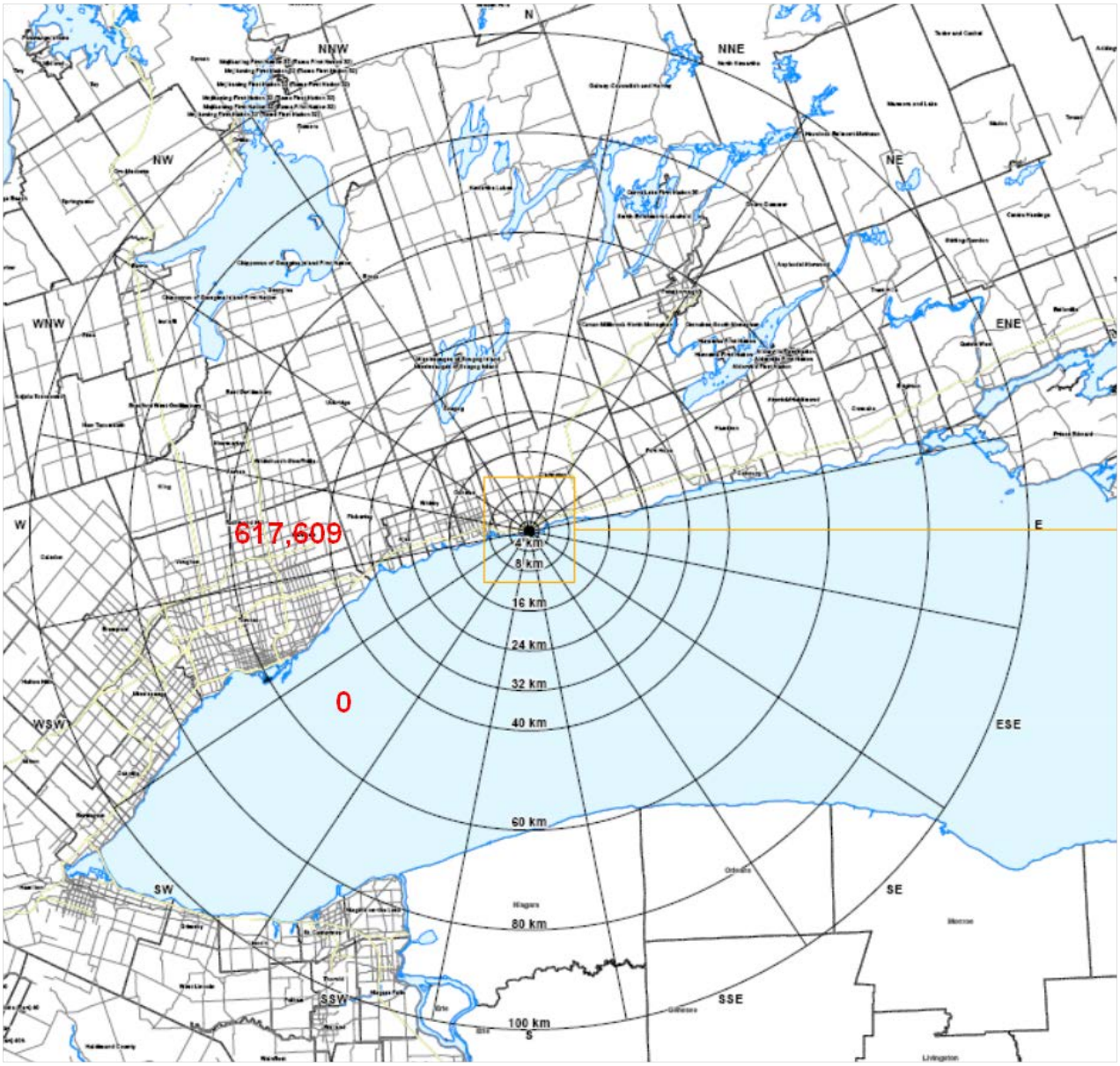

**Table A2.1: 2006 population distributions around the Darlington nuclear power plant site [1, 2]**

| Wind sector[3] | Radial distance (km) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0-2 | 2-4 | 4-8 | 8-16 | 16-24 | 24-32 | 32-40 | 40-60 | 60-80 | 80-100 |
| N | 9 | 1139 | 723 | 1691 | 654 | 1107 | 3850 | 27561 | 16096 | 6815 |
| NNE | 17 | 4339 | 15238 | 2015 | 833 | 1963 | 2671 | 77660 | 26414 | 5651 |
| NE | - | 1918 | 8605 | 1907 | 1170 | 1453 | 3976 | 16536 | 9460 | 16027 |
| ENE | - | 294 | 1190 | 8719 | 1305 | 1055 | 15111 | 29547 | 12229 | 51210 |
| E | - | 11 | - | 57 | 51 | - | - | - | - | 3013 |
| ESE | - | - | - | - | - | - | - | - | - | - |
| SE | - | - | - | - | - | - | - | - | 5096 | 65225 |
| SSE | - | - | - | - | - | - | - | - | 22613 | 51249 |
| S | - | - | - | - | - | - | - | - | 52931 | 298419 |
| SSW | - | - | - | - | - | - | - | - | 21621 | 335317 |
| SW | - | - | - | - | - | - | - | - | - | 61696 |
| WSW | - | 10 | - | 3556 | 11105 | 24385 | 102683 | 1340350 | 1245165 | 1040379 |
| W | - | 121 | 3392 | 61620 | 81829 | 98036 | 44888 | **617609** | 276782 | 140369 |
| WNW | - | 35 | 15937 | 84830 | 34812 | 2154 | 2541 | 47550 | 158926 | 77510 |
| NW | 9 | 50 | 5633 | 8202 | 2466 | 8877 | 5690 | 18372 | 19818 | 154428 |
| NNW | 9 | 44 | 495 | 1874 | 1788 | 2642 | 6638 | 10142 | 11745 | 10555 |
| Total | 44 | 7961 | 51213 | 174471 | 136013 | 141672 | 188048 | 2185327 | 1878896 | 2317863 |

[1] Source: 2006 Canadian and U.S. census data

[2] Red highlighted ring sector corresponds to the highlighted ring sector in the polar coordinate grid in this annex

[3] N = north, E = east, S = south, W = west

# Annex 3: Cancer risks considering evacuation, sheltering and thyroid-blocking protective actions

**Table A3.1: 24-01 - Excess future risk of developing all cancers combined**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 3 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 6 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 12 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 20 | 49,114 (48,246; 49,997) | 4.32E-02 | 0.422 (0.2; 0.76) | 1.86E+00 | 18.2 (8.79; 32.5) |
| 28 | 49,114 (48,246; 49,997) | 2.77E-02 | 0.270 (0.13; 0.48) | 1.31E+00 | 12.8 (6.19; 22.9) |
| 36 | 49,114 (48,246; 49,997) | 1.28E-02 | 0.125 (0.06; 0.22) | 6.30E-01 | 6.15 (2.97; 11) |
| 50 | 49,114 (48,246; 49,997) | 7.25E-03 | 0.070 (0.03; 0.13) | 3.50E-01 | 3.42 (1.65; 6.12) |
| 70 | 49,114 (48,246; 49,997) | 4.20E-03 | 0.041 (0.02; 0.07) | 2.13E-01 | 2.05 (0.99; 3.67) |
| 90 | 49,114 (48,246; 49,997) | 2.45E-03 | 0.024 (0.01; 0.04) | 1.56E-01 | 1.56 (0.75; 2.8) |

**Table A3.2: 24-01 - Excess future risk of developing leukemia**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 3 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 6 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 12 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 20 | 837 (803; 872) | 2.86E-02 | 0.025 (0.0084; 0.0514) | 1.26E+00 | 1.09 (0.37; 2.27) |
| 28 | 837 (803; 872) | 1.78E-02 | 0.015 (0.0052; 0.0320) | 8.48E-01 | 0.734 (0.25; 1.53) |
| 36 | 837 (803; 872) | 8.48E-03 | 0.007 (0.0025; 0.0153) | 4.27E-01 | 0.371 (0.126; 0.773) |
| 50 | 837 (803; 872) | 4.87E-03 | 0.004 (0.0014; 0.0088) | 2.36E-01 | 0.207 (0.070; 0.432) |
| 70 | 837 (803; 872) | 2.86E-03 | 0.003 (0.0009; 0.0052) | 1.45E-01 | 0.129 (0.044; 0.27) |
| 90 | 837 (803; 872) | 1.59E-03 | 0.001 (0.0005; 0.0029) | 1.03E-01 | 0.0863 (0.029; 0.18) |

**Table A3.3: 24-01 - Excess future risk of developing adult thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 3 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 6 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 12 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 20 | 366 (344; 389) | 1.59E+00 | 0.26 (0.055; 0.669) | 6.19E+01 | 13.2 (3.49; 30.6) |
| 28 | 366 (344; 389) | 1.04E+00 | 0.17 (0.036; 0.437) | 4.58E+01 | 9.18 (2.4; 22.10) |
| 36 | 366 (344; 389) | 4.46E-01 | 0.07 (0.016; 0.188) | 2.00E+01 | 3.47 (0.84; 9.01) |
| 50 | 366 (344; 389) | 2.42E-01 | 0.04 (0.0008; 0.102) | 1.11E+01 | 1.82 (0.4; 4.67) |
| 70 | 366 (344; 389) | 1.35E-01 | 0.02 (0.005; 0.057) | 6.76E+00 | 1.10 (0.24; 2.84) |
| 90 | 366 (344; 389) | 8.54E-02 | 0.01 (0.003; 0.036) | 5.23E+00 | 0.85 (0.18; 2.20) |

**Table A3.4: 24-01 - Excess future risk of developing childhood thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 3 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 6 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 12 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 20 | 1,078 (1,038; 1,119) | 4.78E+00 | 40.6 (9; 69) | 1.86E+02 | 2,260 (603; 5,440) |
| 28 | 1,078 (1,038; 1,119) | 3.12E+00 | 26.5 (6; 69) | 1.37E+02 | 1,660 (436; 4,020) |
| 36 | 1,078 (1,038; 1,119) | 1.34E+00 | 11.4 (2.5; 29.5) | 6.00E+01 | 666 (178; 1,550) |
| 50 | 1,078 (1,038; 1,119) | 7.27E-01 | 6.2 (1.4; 16) | 3.34E+01 | 332 (88; 840) |
| 70 | 1,078 (1,038; 1,119) | 4.05E-01 | 3.4 (0.8; 8.9) | 2.03E+01 | 185 (46; 473) |
| 90 | 1,078 (1,038; 1,119) | 2.56E-01 | 2.2 (0.5; 5.7) | 1.57E+01 | 138 (34; 364) |

**Table A3.5: 24-24 - Excess future risk of developing all cancers combined**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 3 | 49,114 (48,246; 49,997) | 3.50E-01 | 3.410 (1.65; 6.11) | 1.30E+00 | 12.7 (6.14; 22.7) |
| 6 | 49,114 (48,246; 49,997) | 1.26E-01 | 1.230 (0.59; 2.19) | 5.20E-01 | 5.08 (2.45; 9.09) |
| 12 | 49,114 (48,246; 49,997) | 7.2E-02 | 0.705 (0.34; 1.26) | 2.58E-01 | 2.54 (1.23; 4.54) |
| 20 | 49,114 (48,246; 49,997) | 4.5E-02 | 0.442 (0.21; 0.79) | 1.22E-01 | 1.17 (0.57; 2.10) |
| 28 | 49,114 (48,246; 49,997) | 2.9E-02 | 0.286 (0.14; 0.51) | 6.96E-02 | 0.68 (0.33; 1.22) |
| 36 | 49,114 (48,246; 49,997) | 1.6E-02 | 0.151 (0.07; 0.27) | 4.99E-02 | 0.49 (0.24; 0.87) |
| 50 | 49,114 (48,246; 49,997) | 9.00E-03 | 0.086 (0.04; 0.15) | 2.76E-02 | 0.29 (0.14; 0.52) |
| 70 | 49,114 (48,246; 49,997) | 5.00E-03 | 0.052 (0.03; 0.09) | 1.55E-02 | 0.20 (0.09; 0.35) |
| 90 | 49,114 (48,246; 49,997) | 3.00E-03 | 0.025 (0.01; 0.05) | 1.15E-02 | 0.1 (0.05; 0.18) |

**Table A3.6: 24-24 - Excess future risk of developing leukemia**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 3 | 837 (803; 872) | 2.01E-01 | 0.173 (0.0589; 0.3610) | 7.43E-01 | 0.639 (0.217; 1.330) |
| 6 | 837 (803; 872) | 7.3E-02 | 0.063 (0.0215; 0.132) | 3.10E-01 | 0.268 (0.091; 0.557) |
| 12 | 837 (803; 872) | 4.2E-02 | 0.036 (0.0124; 0.0759) | 1.58E-01 | 0.138 (0.047; 0.288) |
| 20 | 837 (803; 872) | 2.6E-02 | 0.023 (0.0077; 0.0471) | 7.60E-02 | 0.069 (0.024; 0.144) |
| 28 | 837 (803; 872) | 1.7E-02 | 0.015 (0.0051; 0.0313) | 4.36E-02 | 0.035 (0.012; 0.072) |
| 36 | 837 (803; 872) | 9.00E-03 | 0.008 (0.0028; 0.0169) | 3.14E-02 | 0.026 (0.009; 0.054) |
| 50 | 837 (803; 872) | 5.00E-03 | 0.005 (0.00161; 0.0099) | 1.75E-02 | 0.017 (0.006; 0.036) |
| 70 | 837 (803; 872) | 3.00E-03 | 0.003 (0.00094; 0.0058) | 9.97E-03 | 0.009 (0.003; 0.018) |
| 90 | 837 (803; 872) | 2.00E-03 | 0.001 (0.0005; 0.0031) | 7.38E-03 | 0.006 (0.002; 0.013) |

**Table A3.7: 24-24 - Excess future risk of developing adult thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 3 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 6 | 366 (344; 389) | 5.62E+00 | 0.91 (0.196; 2.360) | 2.14E+01 | 3.75 (0.91; 9.62) |
| 12 | 366 (344; 389) | 3.20E+00 | 0.52 (0.111; 1.340) | 9.82E+00 | 1.60 (0.35; 4.12) |
| 20 | 366 (344; 389) | 2.04E+00 | 0.33 (0.071; 0.857) | 4.40E+00 | 0.71 (0.15; 1.85) |
| 28 | 366 (344; 389) | 1.26E+00 | 0.20 (0.044; 0.529) | 2.49E+00 | 0.40 (0.09; 1.05) |
| 36 | 366 (344; 389) | 6.5E-01 | 0.11 (0.023; 0.273) | 1.75E+00 | 0.28 (0.06; 0.74) |
| 50 | 366 (344; 389) | 3.5E-01 | 0.06 (0.012; 0.146) | 9.47E-01 | 0.15 (0.03; 0.4) |
| 70 | 366 (344; 389) | 2.1E-01 | 0.03 (0.007; 0.088) | 5.24E-01 | 0.08 (0.02; 0.22) |
| 90 | 366 (344; 389) | 9.00E-02 | 0.02 (0.003; 0.040) | 3.87E-01 | 0.06 (0.01; 0.16) |

**Table A3.8: 24-24 - Excess future risk of developing childhood thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 3 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 6 | 1,078 (1,038; 1,119) | 1.69E+01 | 150.0 (37; 392) | 6.41E+01 | 720 (194; 1,700) |
| 12 | 1,078 (1,038; 1,119) | 9.6E+00 | 82.1 (18; 211) | 2.95E+01 | 287 (71; 741) |
| 20 | 1,078 (1,038; 1,119) | 6.1E+00 | 52.1 (12; 135) | 1.32E+01 | 114 (27; 290) |
| 28 | 1,078 (1,038; 1,119) | 3.8E+00 | 32.1 (7; 83) | 7.47E+00 | 64 (14; 165) |
| 36 | 1,078 (1,038; 1,119) | 1.9E+00 | 16.6 (4; 43) | 5.25E+00 | 45 (10; 116) |
| 50 | 1,078 (1,038; 1,119) | 1.0E+00 | 8.8 (2; 23) | 2.84E+00 | 24 (5; 63) |
| 70 | 1,078 (1,038; 1,119) | 6.00E-01 | 5.3 (1; 14) | 1.57E+00 | 13 (3; 35) |
| 90 | 1,078 (1,038; 1,119) | 3.00E-01 | 2.4 (0.5; 6.2) | 1.16E+00 | 10 (2; 26) |

**Table A3.9: 24-72 - Excess future risk of developing all cancers combined**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 3 | 49,114 (48,246; 49,997) | 3.00E-01 | 2.96 (1.43; 5.30) | 1.02E+00 | 9.96 (4.82; 17.80) |
| 6 | 49,114 (48,246; 49,997) | 1.00E-01 | 0.96 (0.46; 1.72) | 4.07E-01 | 4.00 (1.93; 7.16) |
| 12 | 49,114 (48,246; 49,997) | 5.00E-02 | 0.47 (0.23; 0.85) | 2.04E-01 | 1.95 (0.94; 3.49) |
| 20 | 49,114 (48,246; 49,997) | 3.00E-02 | 0.34 (0.16; 0.60) | 9.53E-02 | 0.98 (0.47; 1.75) |
| 28 | 49,114 (48,246; 49,997) | 3.00E-02 | 0.25 (0.12; 0.44) | 5.49E-02 | 0.49 (0.24; 0.87) |
| 36 | 49,114 (48,246; 49,997) | 1.00E-02 | 0.14 (0.07; 0.25) | 3.95E-02 | 0.39 (0.19; 0.70) |
| 50 | 49,114 (48,246; 49,997) | 1.00E-02 | 0.08 (0.04; 0.15) | 2.16E-02 | 0.20 (0.09; 0.35) |
| 70 | 49,114 (48,246; 49,997) | 1.00E-02 | 0.06 (0.03; 0.10 | 1.21E-02 | 0.12 (0.06; 0.21) |
| 90 | 49,114 (48,246; 49,997) | 0 | 0.02 (0.01; 0.04) | 8.81E-03 | 0.09 (0.04; 0.16) |

**Table A3.10: 24-72 - Excess future risk of developing leukemia**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average bone marrow dose to a 30 year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line bone marrow dose to a 30 year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 3 | 837 (803; 872) | 1.58E-01 | 0.137 (0.0464; 0.2850) | 5.47E-01 | 0.475 (0.161; 0.989) |
| 6 | 837 (803; 872) | 5.3E-02 | 0.046 (0.0156; 0.0955) | 2.27E-01 | 0.198 (0.068; 0.414) |
| 12 | 837 (803; 872) | 2.7E-02 | 0.024 (0.0080; 0.0491) | 1.18E-01 | 0.104 (0.035; 0.216) |
| 20 | 837 (803; 872) | 1.9E-02 | 0.016 (0.0056; 0.0342) | 5.74E-02 | 0.052 (0.018; 0.108) |
| 28 | 837 (803; 872) | 1.4E-02 | 0.012 (0.0041; 0.0250) | 3.34E-02 | 0.026 (0.009; 0.054) |
| 36 | 837 (803; 872) | 8.00E-03 | 0.007 (0.0023; 0.0143) | 2.42E-02 | 0.021 (0.007; 0.043) |
| 50 | 837 (803; 872) | 5.00E-03 | 0.004 (0.0015; 0.0091) | 1.36E-02 | 0.012 (0.004; 0.025) |
| 70 | 837 (803; 872) | 3.00E-03 | 0.003 (0.0010; 0.0059) | 7.75E-03 | 0.007 (0.002; 0.014) |
| 90 | 837 (803; 872) | 1.00E-03 | 0.001 (0.0004; 0.0026) | 5.61E-03 | 0.005 (0.002; 0.011) |

**Table A3.11: 24-72 - Excess future risk of developing adult thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 3 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 6 | 366 (344; 389) | 4.70E+00 | 0.76 (0.164; 1.970) | 1.77E+01 | 3.01 (0.73; 7.95) |
| 12 | 366 (344; 389) | 2.21E+00 | 0.36 (0.077; 0.928) | 8.21E+00 | 1.33 (0.29; 3.44) |
| 20 | 366 (344; 389) | 1.60E+00 | 0.26 (0.056; 0.672) | 3.59E+00 | 0.58 (0.13; 1.51) |
| 28 | 366 (344; 389) | 1.16E+00 | 0.19 (0.040; 0.487) | 2.03E+00 | 0.33 (0.07; 0.85) |
| 36 | 366 (344; 389) | 6.2E-01 | 0.10 (0.022; 0.259) | 1.42E+00 | 0.23 (0.05; 0.60) |
| 50 | 366 (344; 389) | 3.5E-01 | 0.06 (0.012; 0.147) | 7.42E-01 | 0.12 (0.03; 0.31) |
| 70 | 366 (344; 389) | 2.4E-01 | 0.04 (0.008; 0.100) | 4.09E-01 | 0.07 (0.01; 0.17) |
| 90 | 366 (344; 389) | 8.00E-02 | 0.01 (0.003; 0.035) | 2.97E-01 | 0.05 (0.01; 0.13) |

**Table A3.12: 24-72 - Excess future risk of developing childhood thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 3 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 6 | 1,078 (1,038; 1,119) | 14.1E+00 | 123.0 (28.6; 311) | 5.30E+01 | 575 (153; 1,330) |
| 12 | 1,078 (1,038; 1,119) | 6.6E+00 | 56.5 (12.4; 146) | 2.46E+01 | 233 (58; 615) |
| 20 | 1,078 (1,038; 1,119) | 4.8E+00 | 40.8 (9.0; 106) | 1.08E+01 | 92 (20; 237) |
| 28 | 1,078 (1,038; 1,119) | 3.5E+00 | 29.6 (6.5; 76.7) | 6.09E+00 | 52 (11; 134) |
| 36 | 1,078 (1,038; 1,119) | 1.9E+00 | 15.7 (3.4; 40.8) | 4.26E+00 | 36 (8; 94) |
| 50 | 1,078 (1,038; 1,119) | 1.1E+00 | 8.9 (2.0; 23.2) | 2.23E+00 | 19 (4; 49) |
| 70 | 1,078 (1,038; 1,119) | 7.00E-01 | 6.0 (1.3; 15.7) | 1.23E+00 | 10 (2; 27) |
| 90 | 1,078 (1,038; 1,119) | 2.00E-01 | 2.1 (0.5; 5.5) | 8.91E-01 | 7 (2; 20) |

**Table A3.13: 24-24x4 - Excess future risk of developing all cancers combined**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 3 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 6 | 49,114 (48,246; 49,997) | 5.00E-01 | 4.88 (2.36; 8.74) | 2.08E+00 | 20.3 (9.8; 36.4) |
| 12 | 49,114 (48,246; 49,997) | 2.3E-01 | 2.25 (1.08; 4.02) | 8.26E-01 | 8.1 (3.9; 14.5) |
| 20 | 49,114 (48,246; 49,997) | 1.4E-01 | 1.37 (0.66; 2.45) | 3.90E-01 | 3.8 (1.8; 6.8) |
| 28 | 49,114 (48,246; 49,997) | 1.2E-01 | 1.17 (0.57; 2.10) | 2.78E-01 | 2.7 (1.3; 4.9) |
| 36 | 49,114 (48,246; 49,997) | 6.00E-02 | 0.59 (0.28; 1.05) | 2.00E-01 | 2.0 (0.9; 3.5) |
| 50 | 49,114 (48,246; 49,997) | 4.00E-02 | 0.39 (0.19; 0.70) | 1.10E-01 | 1.1 (0.5; 1.9) |
| 70 | 49,114 (48,246; 49,997) | 2.00E-02 | 0.20 (0.09; 0.35) | 6.20E-02 | 0.6 (0.3; 1.1) |
| 90 | 49,114 (48,246; 49,997) | 1.00E-02 | 0.10 (0.05; 0.18) | 4.60E-02 | 0.5 (0.2; 0.9) |

**Table A3.14: 24-24x4 - Excess future risk of developing leukemia**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 3 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 6 | 837 (803; 872) | 2.94E-01 | 0.250 (0.085; 0.521) | 1.24E+00 | 1.07 (0.36; 2.23) |
| 12 | 837 (803; 872) | 1.35E-01 | 0.121 (0.041; 0.252) | 5.06E-01 | 0.44 (0.15; 0.92) |
| 20 | 837 (803; 872) | 8.4E-02 | 0.069 (0.024; 0.144) | 2.43E-01 | 0.21 (0.07; 0.43) |
| 28 | 837 (803; 872) | 7.00E-02 | 0.060 (0.021; 0.126) | 1.74E-01 | 0.15 (0.05; 0.31) |
| 36 | 837 (803; 872) | 3.7E-02 | 0.035 (0.012; 0.072) | 1.26E-01 | 0.11 (0.04; 0.23) |
| 50 | 837 (803; 872) | 2.2E-02 | 0.017 (0.006; 0.036) | 7.00E-02 | 0.06 (0.02; 0.13) |
| 70 | 837 (803; 872) | 1.3E-02 | 0.009 (0.003; 0.018) | 3.99E-02 | 0.03 (0.01; 0.07) |
| 90 | 837 (803; 872) | 7.00E-03 | 0.006 (0.002; 0.013) | 2.95E-02 | 0.03 (0.01; 0.05) |

**Table A3.15: 24-24x4 - Excess future risk of developing adult thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 3 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 6 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 12 | 366 (344; 389) | 1.025E+01 | 1.67 (0.37; 4.30) | 3.14E+01 | 5.9 (1.5; 15.2) |
| 20 | 366 (344; 389) | 6.53E+00 | 1.06 (0.23; 2.74) | 1.41E+01 | 2.3 (0.5; 6.0) |
| 28 | 366 (344; 389) | 5.04E+00 | 0.82 (0.18; 2.12) | 9.96E+00 | 1.6 (0.4; 4.2) |
| 36 | 366 (344; 389) | 2.60E+00 | 0.42 (0.09; 1.09) | 7.00E+00 | 1.1 (0.3; 2.9) |
| 50 | 366 (344; 389) | 1.39E+00 | 0.23 (0.05; 0.58) | 3.79E+00 | 0.6 (0.1; 1.6) |
| 70 | 366 (344; 389) | 8.4E-01 | 0.14 (0.03; 0.35) | 2.10E+00 | 0.3 (0.1; 0.9) |
| 90 | 366 (344; 389) | 3.8E-01 | 0.06 (0.01;0.16) | 1.55E+00 | 0.3 (0.1; 0.7) |

**Table A3.16: 24-24x4 - Excess future risk of developing childhood thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 3 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 6 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 12 | 1,078 (1,038; 1,119) | 3.1E+01 | 301 (75; 773) | 9.43E+01 | 1,120 (298; 2,680) |
| 20 | 1,078 (1,038; 1,119) | 2.00E+01 | 178 (44; 456) | 4.22E+01 | 438 (119; 1,060) |
| 28 | 1,078 (1,038; 1,119) | 1.5E+01 | 132 (32; 349) | 2.99E+01 | 292 (72; 751) |
| 36 | 1,078 (1,038; 1,119) | 8.00E+00 | 66 (15; 172) | 2.10E+01 | 193 (47; 490) |
| 50 | 1,078 (1,038; 1,119) | 4.00E+00 | 35 (8; 92) | 1.14E+01 | 98 (22; 250) |
| 70 | 1,078 (1,038; 1,119) | 3.00E+00 | 21 (5; 55) | 6.29E+00 | 54 (12; 139) |
| 90 | 1,078 (1,038; 1,119) | 1.00E+00 | 10 (2; 25) | 4.64E+00 | 40 (9; 102) |

**Table A3.17: 24-72x4 - Excess future risk of developing all cancers combined**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line colon dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 3 | 49,114 (48,246; 49,997) | 0 | 0 | 0 | 0 |
| 6 | 49,114 (48,246; 49,997) | 3.9E-01 | 3.81 (1.84; 6.81) | 1.63E+00 | 15.9 (7.7; 28.5) |
| 12 | 49,114 (48,246; 49,997) | 1.6E-01 | 1.56 (0.75; 2.80) | 6.53E-01 | 6.4 (3.1; 11.4) |
| 20 | 49,114 (48,246; 49,997) | 1.1E-01 | 1.07 (0.52; 1.92) | 3.05E-01 | 2.9 (1.4; 5.2) |
| 28 | 49,114 (48,246; 49,997) | 1.00E-01 | 0.98 (0.47; 1.75) | 2.20E-01 | 2.2 (1.0; 3.8) |
| 36 | 49,114 (48,246; 49,997) | 6.00E-02 | 0.59 (0.28; 1.05) | 1.58E-01 | 1.6 (0.8; 2.8) |
| 50 | 49,114 (48,246; 49,997) | 3.00E-02 | 0.29 (0.14; 0.52) | 8.64E-02 | 0.9 (0.4; 1.6) |
| 70 | 49,114 (48,246; 49,997) | 2.00E-02 | 0.20 (0.09; 0.35) | 4.84E-02 | 0.5 (0.2; 0.9) |
| 90 | 49,114 (48,246; 49,997) | 1.00E-02 | 0.10 (0.05; 0.18) | 3.52E-02 | 0.4 (0.2; 0.7) |

**Table A3.18: 24-72x4 - Excess future risk of developing leukemia**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line bone marrow dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 3 | 837 (803; 872) | 0 | 0 | 0 | 0 |
| 6 | 837 (803; 872) | 2.12E-01 | 0.181 (0.062; 0.378) | 9.09E-01 | 0.786 (0.267; 1.640) |
| 12 | 837 (803; 872) | 8.7E-02 | 0.078 (0.026; 0.162) | 3.78E-01 | 0.328 (0.111; 0.683) |
| 20 | 837 (803; 872) | 6.1E-02 | 0.052 (0.018; 0.108) | 1.84E-01 | 0.155 (0.053; 0.324) |
| 28 | 837 (803; 872) | 5.6E-02 | 0.048 (0.016; 0.101) | 1.34E-01 | 0.112 (0.038; 0.234) |
| 36 | 837 (803; 872) | 3.2E-02 | 0.028 (0.009; 0.058) | 9.68E-02 | 0.086 (0.029; 0.180) |
| 50 | 837 (803; 872) | 2.00E-02 | 0.017 (0.006; 0.036) | 5.44E-02 | 0.043 (0.015; 0.090) |
| 70 | 837 (803; 872) | 1.3E-02 | 0.011 (0.004; 0.023) | 3.10E-02 | 0.026 (0.009; 0.054) |
| 90 | 837 (803; 872) | 6.00E-03 | 0.005 (0.002; 0.011) | 2.24E-02 | 0.017 (0.006; 0.036) |

**Table A3.19: 24-72x4 - Excess future risk of developing adult thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 30-year-old male (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 3 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 6 | 366 (344; 389) | 0 | 0 | 0 | 0 |
| 12 | 366 (344; 389) | 7.1E+00 | 1.2 (0.2; 3.0) | 2.63E+01 | 4.78 (1.17; 12.60) |
| 20 | 366 (344; 389) | 5.1E+00 | 0.8 (0.2; 2.2) | 1.15E+01 | 1.88 (0.41; 4.82) |
| 28 | 366 (344; 389) | 4.6E+00 | 0.8 (0.2; 2.0) | 8.12E+00 | 1.32 (0.29; 3.40) |
| 36 | 366 (344; 389) | 2.5E+00 | 0.4 (0.1; 1.0) | 5.68E+00 | 0.92 (0.20; 2.38) |
| 50 | 366 (344; 389) | 1.4E+00 | 0.2 (0.05; 0.6) | 2.97E+00 | 0.48 (0.10; 1.25) |
| 70 | 366 (344; 389) | 9.00E-01 | 0.2 (0.03; 0.4) | 1.64E+00 | 0.27 (0.06; 0.69) |
| 90 | 366 (344; 389) | 3.00E-01 | 0.1 (0.01; 0.1) | 1.19E+00 | 0.19 (0.04; 0.50) |

**Table A3.20: 24-72x4 - Excess future risk of developing childhood thyroid cancer**

| Distance (km) from plant | Baseline future risk (mean) as chances in 100,000 (90% confidence intervals) | Average thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on average dose as chances in 100,000 (90% confidence intervals) | Centre-line thyroid dose to a 4-year-old female (mSv) | Excess future risk (mean) based on centre-line dose as chances in 100,000 (90% confidence intervals) |
|---|---|---|---|---|---|
| 1 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 3 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 6 | 1,078 (1,038; 1,119) | 0 | 0 | 0 | 0 |
| 12 | 1,078 (1,038; 1,119) | 2.1E+01 | 195 (48; 496) | 7.78E+01 | 915 (242; 2,130) |
| 20 | 1,078 (1,038; 1,119) | 1.5E+01 | 135 (33; 356) | 3.45E+01 | 345 (91; 867) |
| 28 | 1,078 (1,038; 1,119) | 1.4E+01 | 121 (28; 306) | 2.44E+01 | 230 (57; 608) |
| 36 | 1,078 (1,038; 1,119) | 7.00E+00 | 63 (14; 163) | 1.70E+01 | 151 (37; 396) |
| 50 | 1,078 (1,038; 1,119) | 4.00E+00 | 36 (8; 93) | 8.90E+00 | 76 (17; 196) |
| 70 | 1,078 (1,038; 1,119) | 3.00E+00 | 24 (5; 63) | 4.91E+00 | 42 (9; 108) |
| 90 | 1,078 (1,038; 1,119) | 1.00E+00 | 8 (2; 22) | 3.56E+00 | 30 (7; 79) |

# Annex 4: Key assumptions in the human health risk assessment

**Table A4.1: Key assumptions in the human health risk assessment**

| Assumption | Implication | Effect on results |
|---|---|---|
| **The adult population near the accident site has the same cancer incidence rates as the United States population between 2000 and 2005** | The communities surrounding the DNGS were shown to have similar but slightly elevated cancer rates compared to the province of Ontario (Lane et al. 2013) and were not attributable to the operation of the station. As shown in table 5.1, Ontario cancer incidence rates are comparable to the United States. | No significant effect on estimates of excess future risk or baseline future risk in this study. |
| **The child population near the hypothetical accident site have the same thyroid cancer incidence rates as children in the United States between 2000 and 2005** | As shown in table 5.1, children in the United States and in Canada aged 0–19 have similar thyroid cancer incidence rates.<br><br>Children in the United States and in Canada aged 0–4 also have similar thyroid cancer incidence rates (Forman et al. 2013). | No significant effect on risk estimates. |
| **A 30-year-old male represents the adult population surrounding the hypothetical accident site** | Women and children are more radiosensitive than males (UNSCEAR 2013). | Underestimates the dose and the risk to women and children for all cancers combined and leukemia. However, child thyroid dose was investigated further because the experiences of Chernobyl and Fukushima have shown that childhood thyroid cancer is the most sensitive indicator with regards to health effects observed in the population. |
| **A 4-year-old female represents all children surrounding the hypothetical accident site (children were only considered for thyroid cancer)** | The risk of thyroid cancer is not very different between male and female children. | No significant effect on risk estimates. |

| Assumption | Implication | Effect on results |
|---|---|---|
| **Child dose to the thyroid is equal to three times that of an adult dose from a similar exposure** | Many radionuclides contribute to the thyroid dose such as I-131, I-132, I-133, I-135, Cs-134 and Cs-137.<br><br>A ratio of the dose coefficients for the committed effective dose to the thyroid for a child (a 1-year-old infant) versus an adult was determined to be approximately 2.3, which was rounded up to 3. This evaluation took into account all key contributing radionuclides from the source term and their relative contribution in terms of activity. | Small overestimation of the dose and the risk. |
| **Colon dose was used to calculate the increased risk for all cancers combined** | It is international practice to use the colon dose as a representative organ for the whole body. | More precise risk estimate.<br>The uncertainty in risk estimates for individual types of cancer are generally greater than combining all cancers (UNSCEAR 2008). |
| **Cancer risk at high doses and high dose rates is somewhat higher than low doses and low dose rates** | Accounted for by applying a reduction factor when projecting risks derived from high dose and dose rate epidemiological data. This adjustment factor is referred to as the dose and dose rate effectiveness factor (DDREF). | Introduces uncertainty in any risk estimates there is a significant amount of uncertainty in the value of the DDREF. |
| **The use of an average population weighted dose and dose for a maximally exposed individual** | The population weighted average dose was used to generate an excess future risk value. This value is indicative of the risk that would occur in most weather conditions. | The average dose would underestimate the risk to the most exposed individual. For that reason, a centre-line dose has also been used in risk predictions to represent a surrogate for the “maximally exposed person”. The centre-line dose value has been used in previous EAs for this purpose. |
| **KI pill ingestion was credited as 100-percent effective, resulting in zero dose to the thyroid** | The internal (inhalation) pathway for radioiodines is the dominant pathway in the early days after an accident for which KI pills effectively protect the thyroid gland from radioactive iodine uptake. However, the thyroid gland may be exposed to radioactive iodine and other radionuclides from other | Underestimation of zero risk when KI pill ingestion is credited; however, the contribution from external pathways is anticipated to be small. |

| Assumption | Implication | Effect on results |
|---|---|---|
| | exposure pathways such as external exposure to the radioactive plume in the air and radioactive material deposited on the ground. | |

# Annex 5: Effects to non-human biota

This study also considered the potential effects on non-human biota exposed to radiation in the event of a hypothetical severe nuclear accident. Given the airborne pathway of the hypothetical release, considerations were given to the effects to terrestrial-based biota, such as mammals which are more radiosensitive compared to aquatic biota such as fish (UNSCEAR 2013). For waterborne emissions, two pathways can be assumed possible: direct fallout of radionuclides into water from the airborne pathway; or contaminated liquid leaking from the plant onto the ground and flowing into the lake adjacent to the plant. Though this study did not examine these pathways, the Pickering B Refurbishment and Continued Operation EA (CNSC 2008) did examine a bounding aquatic release from a postulated nuclear accident. Estimated doses to non-human biota were predicted to be below UNSCEAR (1996) guidelines.

In calculating the radiological dose effects of a severe accident on non-human biota, the Darlington New Nuclear Power Plant Project EA, selected representative affected species as receptors, including small and large mammals, birds, earthworms and vegetation (OPG 2009b). The assessment of potential effects on non-human biota is generally referred to as an "ecological risk assessment". The Darlington New Nuclear Power Plant Project ecological risk assessment calculated the extent to which non-human biota would be affected by the release of radiation from a large release nuclear accident.

The evaluation of potential non-human biota effects from a large accident release, as assessed in the Darlington New Nuclear Power Plant Project EA, is comparable to aspects of this study as follows:

- both studies considered an event with a 24 hour holdup followed by a 72 hour release
- both assumed variable wind conditions over the 72 hours
- the doses for both studies are scaled based on the same fixed value for cesium-137, recognizing that there are some differences in the source terms attributed to the differences in reactor designs considered

As such, for the purpose of this assessment, the characteristics of the 24-72 scenarios and the predicted radiation releases were considered quite similar at 1 km (the area with the highest dose).
The similarities in characteristics of the Darlington New Nuclear Power Plant Project EA and this study means the effects documented in the Darlington New Nuclear Power Plant Project EA can be used to provide insights into non-human biota effects that would be expected with this study.

In the Darlington New Nuclear Power Plant Project EA, average values were calculated for each non-human biota receptor for the early phase of the accident releases, to predict a dose to various species at 1 km. The Darlington New Nuclear Power Plant Project EA benchmarked the predicted doses against values that have been established in international literature based on observations over many years. The generic threshold that is accepted for an acute effect to be observable on a population of non-human biota is 1 gray (1,000 milligrays [mGy]). The 1-gray dose was considered to be the threshold value for an acute effect during the early phase of the accident (UNSCEAR 2008).

The results indicate that at 1 km, the Darlington New Nuclear Power Plant Project accident release was far below the acute reference dose for all non-human biota, with actual 7-day exposure doses calculated at 1.5 mGy (~7 percent of the whole body human dose of 21 mSv). At these low levels, no acute effects on individual non-human biota or observable effects on populations would be identified at 1 km from the accident release point, and would further be expected to diminish rapidly at greater distances away from the plant. Given these results, and the similarity of dose projections at 1 km for both the Darlington New Nuclear Power Plant Project EA and this study, the same conclusion can be derived for the GLR in this study. Using this 7-percent ratio and applying it to the 24-72 scenario and related sensitivity case (24-

72x4 scenario) in this study with variable wind, doses of 1.49 mGy and 5.96 mGy are derived for non-human biota at 1 km from the accidental release point, respectively; well below the 1,000-mGy threshold.

Although no equivalent case is available in the Darlington New Nuclear Power Plant Project EA, this study suggests the largest short-term dose to non-human biota may be associated with the 24-01 scenario. In this case, the human whole-body dose estimate at 1 km was 354 mSv. Though not directly comparable, it would be expected that doses to non-human biota would be below the 1,000 mGy acute reference dose.

Non-acute (i.e., longer-term) effects of radiation on non-human biota is an area of ongoing research. Recent international findings have indicated that changes to certain terrestrial organisms, in particular mammals cannot be ruled out, but their significance for population integrity of those organisms is unclear. Any radiation effects would be restricted to the area where the deposition of radioactive material was greatest; beyond that area, the potential for effects on biota would be insignificant (UNSCEAR 2013).

# Annex 6: Sensitivity analysis using different protective action level values

Results are shown for kilometre distances where dose and risk values differ between the upper and lower choice of protective action levels (PALs).

**Table A6.1: 24-01 - All cancers combined; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average colon dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 4.4E-01 | 2.05 | 4.25 | 7.60 |
| 6 | 1.7E-01 | 0.82 | 1.70 | 3.04 |
| 12 | 8.00E-02 | 0.38 | 0.79 | 1.42 |
| 20 | 5.00E-02 | 0.26 | 0.53 | 0.94 |
| 28 | 3.00E-02 | 0.17 | 0.34 | 0.61 |
| 36 | 2.00E-02 | 0.08 | 0.16 | 0.28 |
| 50 | 1.00E-02 | 0.04 | 0.09 | 0.16 |

- evacuated

**Table A6.2: 24-01 - Leukemia; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average bone marrow dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 2.78E-01 | 0.082 | 0.240 | 0.500 |
| 6 | 1.12E-01 | 0.033 | 0.097 | 0.201 |
| 12 | 5.1E-02 | 0.015 | 0.044 | 0.092 |
| 20 | 3.6E-02 | 0.011 | 0.031 | 0.065 |
| 28 | 2.2E-02 | 0.006 | 0.019 | 0.040 |
| 36 | 1.1E-02 | 0.003 | 0.009 | 0.020 |
| 50 | 6.00E-03 | 0.002 | 0.005 | 0.011 |

- evacuated

**Table A6.3: 24-01 - Adult thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 |
| 20 | 1.99E+00 | 0.07 | 0.32 | 0.84 |
| 28 | 1.3E+00 | 0.05 | 0.21 | 0.55 |
| 36 | 5.6E-01 | 0.02 | 0.09 | 0.24 |
| 50 | 3.00E-01 | 0.01 | 0.05 | 0.13 |

- evacuated
0 value indicates KI pills ingested

**Table A6.4: 24-01 - Child thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average child dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 |
| 20 | 6.00E+00 | 11 | 51 | 132 |
| 28 | 6.00E+00 | 7 | 33 | 86 |
| 36 | 2.00E+00 | 3 | 14 | 38 |
| 50 | 1.00E+00 | 2 | 8 | 20 |

- evacuated
0 value indicates KI pills ingested

**Table A6.5: 24-24 - All cancers combined; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average colon dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 1.2E+00 | 5.9 | 12.1 | 21.7 |
| 3 | 4.00E-01 | 2.1 | 4.3 | 7.6 |
| 6 | 2.00E-01 | 0.7 | 1.5 | 2.7 |

**Table A6.6: 24-24 - Leukemia; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average bone marrow dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 6.6E-01 | 0.19 | 0.57 | 1.19 |
| 3 | 2.5E-01 | 0.07 | 0.22 | 0.45 |
| 6 | 9.00E-02 | 0.03 | 0.08 | 0.17 |

**Table A6.7: 24-24 - Adult thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 7.00E+00 | 0.2 | 1.1 | 3.0 |

0 value indicates KI pills ingested

**Table A6.8: 24-24 - Child thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 1.7E+01 | 37 | 150 | 393 |

0 value indicates KI pills ingested

**Table A6.9: 24-72 - All cancers combined; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average colon dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 1.1E+00 | 5.1 | 10.5 | 18.7 |
| 3 | 4.00E-01 | 1.8 | 3.7 | 6.6 |
| 6 | 1.00E-01 | 0.6 | 1.2 | 2.1 |

**Table A6.10: 24-72 - Leukemia; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average bone marrow dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 5.3E-01 | 0.16 | 0.46 | 0.95 |
| 3 | 2.00E-01 | 0.06 | 0.17 | 0.36 |
| 6 | 7.00E-02 | 0.02 | 0.06 | 0.12 |

**Table A6.11: 24-72 - Adult thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 5.9E+00 | 0.2 | 1.0 | 2.5 |

0 value indicates KI pills ingested

**Table A6.12: 24-72 - Child thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 1.8E+01 | 39 | 157 | 409 |

0 value indicates KI pills ingested

**Table A6.13: 24-24x4 - All cancers combined; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average colon dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 1.4E+00 | 6.6 | 13.7 | 24.5 |
| 6 | 6.00E-01 | 3.0 | 6.2 | 11.0 |
| 12 | 3.00E-01 | 1.4 | 2.8 | 5.1 |
| 20 | 2.00E-01 | 0.8 | 1.8 | 3.2 |

- evacuated
0 value indicates KI pills ingested

**Table A6.14: 24-24x4 - Leukemia; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average bone marrow dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 8.00E-01 | 0.24 | 0.69 | 1.44 |
| 6 | 3.7E-01 | 0.11 | 0.32 | 0.66 |
| 12 | 1.7E-01 | 0.05 | 0.15 | 0.30 |
| 20 | 1.00E-01 | 0.03 | 0.09 | 0.19 |

- evacuated

**Table A6.15: 24-24x4 - Adult thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 1.28E+01 | 0.5 | 2.1 | 5.4 |
| 20 | 8.2E+00 | 0.3 | 1.3 | 3.4 |

- evacuated
0 value indicates KI pills ingested

**Table A6.16: 24-24x4 - Child thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | - | - | - | - |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 3.8E+01 | 101 | 387 | 956 |
| 20 | 2.4E+01 | 56 | 226 | 598 |

- evacuated
0 value indicates KI pills ingested

**Table A6.17: 24-72x4 - All cancers combined; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average colon dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 4.3E+00 | 20.4 | 41.9 | 75.0 |
| 3 | 1.2E+00 | 5.7 | 11.8 | 21.1 |
| 6 | 5.00E-01 | 2.3 | 4.8 | 8.6 |
| 12 | 2.00E-01 | 0.9 | 1.9 | 3.3 |
| 20 | 1.00E-01 | 0.7 | 1.4 | 2.5 |

**Table A6.18: 24-72x4 - Leukemia; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average bone marrow dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 2.12E+00 | 0.62 | 1.83 | 3.81 |
| 3 | 6.3E-01 | 0.19 | 0.55 | 1.14 |
| 6 | 2.7E-01 | 0.08 | 0.23 | 0.48 |
| 12 | 1.1E-01 | 0.03 | 0.09 | 0.20 |
| 20 | 8.00E-02 | 0.02 | 0.07 | 0.14 |

**Table A6.19: 24-72x4 - Adult thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 8.8E+00 | 0.3 | 1.4 | 3.7 |
| 20 | 6.4E+00 | 0.2 | 1.0 | 2.7 |

0 value indicates KI pills ingested

**Table A6.20: 24-72x4 - Child thyroid; 100 mSv evacuation, 10 mSv sheltering; excess future risk based on average dose**

| Distance (km) from plant | Average thyroid dose (mSv) | Excess future risk (lower 90% confidence interval) | Excess future risk (mean) | Excess future risk (upper 90% confidence interval) |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 12 | 2.7E+01 | 63 | 253 | 664 |
| 20 | 1.9E+01 | 43 | 174 | 447 |

0 value indicates KI pills ingested

# Annex 7: Risk management bands for estimated cancer risks from hypothetical severe nuclear accident scenarios

Multiple frameworks for the assessment and management of health risks associated with exposures to contaminants have been developed worldwide.

In general, the Canadian Nuclear Safety Commission (CNSC) follows the radiation protection framework established by the International Commission on Radiological Protection (ICRP). This framework provides guidance when the contaminants in question are radiological.

The ICRP's most recent recommendations rely on protection strategies that depend on the type of exposure situation. These exposure situations have been broadly categorized into three types:

- In planned exposure situations, individual dose limits exist to protect members of the public and nuclear energy workers. .
- In emergency situations, reference levels are relied upon. These are levels of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur and below which optimization of protection should be implemented. [12]
- In existing exposure situations, reference levels are also relied upon. An existing exposure situation is one where the exposure already exists when a decision regarding control must be made. The period following an emergency situation is an example of an existing exposure situation.

The ICRP has recommended dose limits or reference levels for the three situations referred to above for both occupational and public exposures. For emergency situations, the recommended reference level for members of the public is 20–100 mSv. Further, other organizations such as the International Atomic Energy Agency have based intervention guidelines (for use in emergencies) that are in line with the ICRP recommended reference levels. Many national governments or other organizations responsible for setting guidelines are also revisiting their own intervention guidelines in the light of these relatively new international recommendations and experience gained from Fukushima. The upper bound of the reference level of 100 mSv could be interpreted to be the dose – and associated risk- above which could be deemed to be unacceptable.

The ICRP framework is deliberately not prescriptive. It allows for many options, optimization strategies and judgment with regards to radiation protection and relies on regulators or other organizations to implement the recommendations in a manner appropriate to each country. In Canada, many of the recommendations of the ICRP have become enshrined in law via the *Canadian Nuclear Safety and Control Act* and the *Radiation Protection Regulations*, etc. As described earlier, in Canada, organizations such as Health Canada and Ontario have set dose-based protective actions for the protection of the public.

Many jurisdictions have attempted to quantify radiological risk using other frameworks for the assessment and management of health risks associated with radiological contaminants. Notably, in 1998, the Atomic Energy Control Board (now the CNSC) and Health Canada published a document titled *Assessment and Management of Cancer Risks from Radiological and Chemical Hazards*, in which "the similarities, disparities and inconsistencies between the levels of risk considered *acceptable* for regulating ionizing radiation and those considered *acceptable* for regulating chemical and microbiological hazards"

[12] *The Radiation Protection Regulations* are undergoing revisions. These revisions include the proposed addition of reference levels with regards to the control of emergency situations.

were examined. As stated in this report, the risk assessment frameworks for ionizing radiation and genotoxic chemicals are well developed and generally similar in principle. Both can affect DNA and depend upon the establishment of dose-response relationships, and prudently assume linearity with no threshold dose (the LNT model). Estimated risks are then compared to risk management bands. In Canada (e.g., Health Canada) and internationally (e.g. ICSP), an incremental life time cancer risk of $10^{-5}$ (1 in 100,000) is considered an essentially negligible risk. In these frameworks, risk management options should be considered when risk estimates fall within the $10^{-3}$ to $10^{-5}$ band of risk. The higher risk target of $10^{-3}$ (1 in 1,000) is used in occupational settings and was therefore not used in this study. To inform possible risk management decisions within the context of this study, centre-line dose values were used to represent a maximum plausible cancer risk estimate.

The risk band $10^{-5}$ to $10^{-4}$ (1 in 100,000 to 1 in 10,000) is used as an input into risk management decisions on a case-by-case basis. Factors such as size of the affected population, feasibility and effectiveness of available mitigation options as well as cost vs risk reduction benefits are also taken into consideration. Another important consideration is the probability of occurrence of the situation that would lead to an exposure. For example, in dealing with a contaminated site the contamination exists and therefore the probability of occurrence is one. In the current study, the very low probability of the hypothetical accident ($\sim 1 \times 10^{-7}$) that is the basis for the dose and risk estimates (and even lower probability of a multi-unit accident – in this study, a fourfold increase in the source term) is an important consideration as is the fact that the post-Fukushima safety enhancements, including EME, would further reduce the probability of occurrence of a severe accident by a factor of about 10 and also mitigate the release (leading to lower dose and risk estimates).

Tables A7.1 to A7.3 present the maximum plausible cancer risks (based on centre-line doses) estimated in this study by risk management risk bands. For cancer risks greater than $10^{-4}$, distances where mitigation or risk management (beyond those considered in the study) could be needed to reduce the risk to within the range of $10^{-5}$ to $10^{-4}$ are noted.

**Table A7.1: Hypothetical accident scenarios that would lead to essentially negligible risk estimates ($\leq 10^{-5}$)**

| Type of cancer | Cancer risk estimate using centre-line dose | Accident scenario |
|---|---|---|
| Leukemia | $\leq 0.64 \times 10^{-5}$ | 24-24 |
| Leukemia | $\leq 0.48 \times 10^{-5}$ | 24-72 |
| Leukemia | $\leq 0.79 \times 10^{-5}$ | 24-72x4 |

**Table A7.2: Hypothetical accident scenarios that would lead to risk estimates within the > $10^{-5}$ to ≤ $10^{-4}$ risk management band. Given the extremely low probability of the hypothetical severe accident (~ 1 x $10^{-7}$), mitigation options could be considered on a case-by-case basis[1, 2]**

| Type of cancer | Cancer risk estimate using centre-line dose | Accident scenario |
|---|---|---|
| Leukemia | ≤ 1.09 x $10^{-5}$ | 24-01 |
| Adult thyroid | ≤ 3.75 x $10^{-5}$ | 24-24 |
| Adult thyroid | ≤ 3.01 x $10^{-5}$ | 24-72 |
| Leukemia | ≤ 1.07 x $10^{-5}$ | 24-24x4 |
| Adult thyroid | ≤ 5.9 x $10^{-5}$ | 24-24x4 |
| Adult thyroid | ≤ 4.78 x $10^{-5}$ | 24-72x4 |

[1]Implementation of the post-Fukushima safety enhancements, including emergency mitigating equipment (EME), would reduce the probability of occurrence of a severe accident by a factor of about 10.
[2]Implementation of the post-Fukushima safety enhancements, including EME, would mitigate the release and consequently reduce both dose and risk.

**Table A7.3: Hypothetical accident scenarios that would lead to risk estimates > $10^{-4}$ and potential emergency protective actions that could mitigate the estimated risks[1, 2]**

| Type of cancer | Cancer risk estimate using centre-line Dose | Accident scenario | Options for mitigation[3, 4] |
|---|---|---|---|
| All cancers combined | ≤ 1.82 x $10^{-4}$ | 24-01 | Evacuation up to 28 km |
| Adult thyroid | ≤ 1.32 x $10^{-4}$ | 24-01 | KI pill ingestion up to 20 km |
| Childhood thyroid | ≤ 22.6 x $10^{-3}$ | 24-01 | KI pill ingestion > 90 km |
| All cancers combined | ≤ 1.27 x $10^{-4}$ | 24-24 | Evacuation up to 3 km |
| Childhood thyroid | ≤ 7.2 x $10^{-3}$ | 24-24 | KI pill ingestion up to 90 km |
| All cancers combined | ≤ 9.96 x $10^{-5}$ | 24-72 | Evacuation up to 3 km |
| Childhood thyroid | ≤ 5.74 x $10^{-3}$ | 24-72 | KI pill ingestion up to 70 km |
| All cancers combined | ≤ 2.03 x $10^{-4}$ | 24-24x4 | Evacuation up to 6 km |
| Childhood thyroid | ≤ 11.2 x $10^{-3}$ | 24-24x4 | KI pill ingestion > 90 km |
| All cancers combined | ≤ 1.59 x $10^{-4}$ | 24-72x4 | Evacuation up to 6 km |
| Childhood thyroid | ≤ 9.14 x $10^{-3}$ | 24-72x4 | KI pill ingestion > 90 km |

[1]Implementation of the post-Fukushima safety enhancements, including EME would reduce the probability of occurrence of a severe accident by a factor of about 10.
[2]Implementation of the post-Fukushima safety enhancements, including EME, would mitigate the release and consequently reduce both dose and risk.
[3] Sheltering could be implemented at distances beyond those credited in this study in combination with KI pill ingestion.
[4] Distances identified apply to risk estimates > $10^{-4}$.

A risk band framework is one way risk managers can gain insights on the appropriate actions to take in the early phase of an emergency. The current study evaluated the excess future risk of developing cancer after an exposure lasting 7 days and thus the options for mitigation discussed in tables A7.1 to A7.3 reflect the same time period of 7 days, which is internationally accepted as the early phase of the emergency.

In all likelihood, exposures could persist for years to come, albeit getting smaller every year due to radiological decay, weathering and other factors (i.e., self-help protection strategies). As a result of lessons learned from different types of emergencies (radiological and non-radiological), the science behind risk management is quickly evolving. In order to minimize uncertainty, risk should be considered over a lifetime rather than in seven days or even annually. Although undergoing review, ICRP publications 109 and 111 (P109*: Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations* and P111: *Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency*), both state that, members of the public should not receive a dose greater than 100 mSv acutely or in one year due to a nuclear emergency. Forthcoming international guidance is expected to support this statement.

The radiation protection framework is flexible and can rely on multiple methods for ensuring public safety, be it risk bands, dose values or limits, protective action strategies (combinations of different protective actions), optimization and judgment.