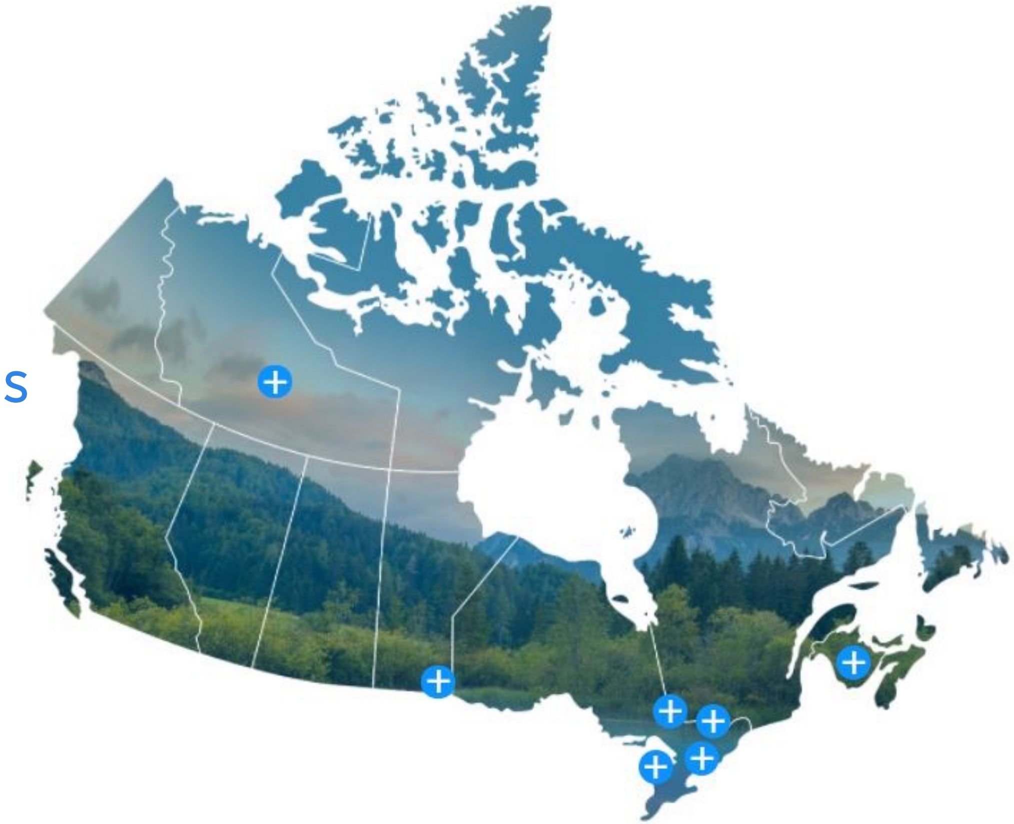
Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Investigations on **Small Modular Reactor** Emergency Preparedness and Response Planning Basis



Dave Hummel, Luke Lebel

7th NERIS Workshop
2023 October 9th, Dublin, Ireland

Outline

1. Nuclear Emergency Preparedness and Response in Canada
2. Emergency Planning Zone (EPZ) Framework Development – Research Project
3. Considerations for Operational Intervention Levels in Northern Canada
4. Summary

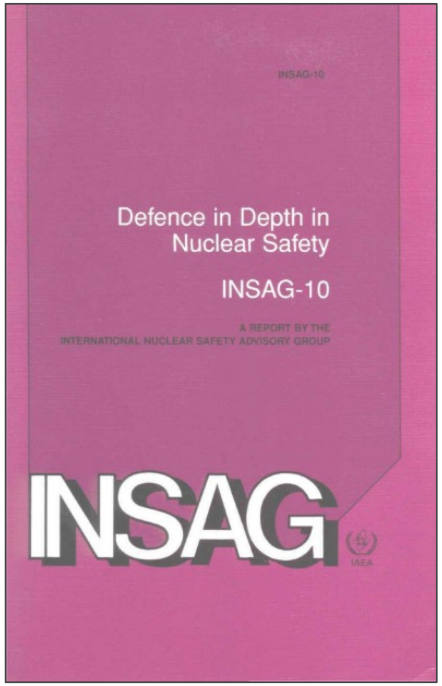
Chalk River Labs (CRL) site in 2015

BACKGROUND

Nuclear Emergency Preparedness and Response (EPR) in **Canada**

Defence in Depth in Nuclear Safety

Level	Objective	Essential Means
1	Prevention of abnormal operation and failures	Conservative design with high quality in construction and operation
2	Control of abnormal operation and detection of failures	Control, limiting, and protection systems and other surveillance features
3	Control of accidents within the design basis	Engineered safety systems and accident procedures
4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complimentary measures and accident management
5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response



https://www.iaea.org/publications/4716/defence-in-depth-in-nuclear-safety

Emergency Planning Zone (**EPZ**)

Definition

"…**the regions encapsulating the advanced planning areas** [for prompt or urgent response areas] and the planning distances [designated during the response as a result of evolving accidents]. Advanced emergency planning should be conducted in order **to avoid or minimize severe deterministic effects, reasonably reduce stochastic effects and mitigate consequences of the accident at its source**."

SMR Regulators' Forum, referencing IAEA General Safety Requirements No. GSR Part 7

EPR **Planning Basis** Components

CSA N1600:21 *General Requirements for Nuclear Emergency Management Programs*

I. **The basis for protective action decision making**

e.g. Health Canada's generic criteria and operational intervention levels (OILs)

II. **The type of radiological hazard**

Selected from the possible **reactor facility accidents** and the associated radionuclide releases (source terms)

III. **Effects of accident on public health and safety (dose)**

Environmental dispersion and dose consequence assessments using the source terms as input

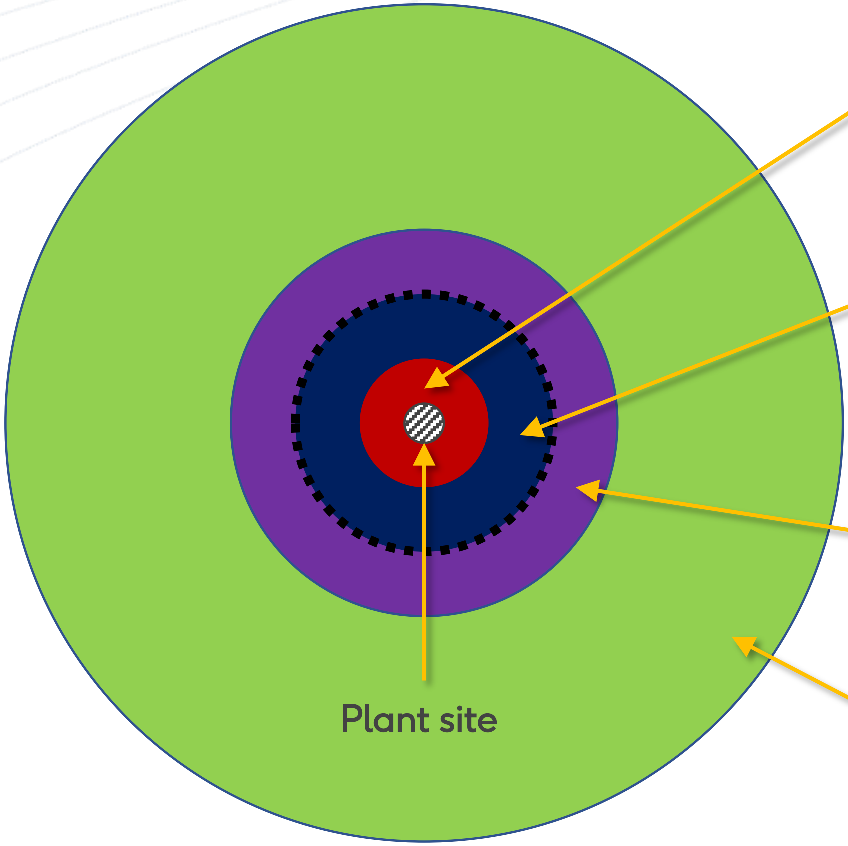
IV. **Extent of accident consequences (geographical distance)**

Extrapolation based on the results of items II. and III., used to define the EPZ

Most novel component for SMRs and advanced reactors

Types of **EPZ** in Canada

CSA N1600:21 *General Requirements for Nuclear Emergency Management Programs*



Automatic Action Zone (AAZ): Area surrounding the plant where pre-planned actions are taken by default upon declaration of a general emergency. Aim to prevent deterministic health effects.
(IAEA analog is precautionary action zone, PAZ)

Detailed Planning Zone (DPZ): Area where pre-planned actions are taken as needed based on known conditions, modeling, and environmental monitoring. Aim to reduce stochastic health effects.
(IAEA analog is urgent action zone, UPZ)

Limit of "EPZ" per IAEA definition

Contingency Planning Zone (CPZ): Area with contingency planning & arrangements to allow protective actions to be extended past DPZ as needed. Aim to reduce chance of exposure.
(IAEA analog is extended planning distance, EPD)

Ingestion Planning Zone (IPZ): Area where arrangements are made to protect the food chain and restrict the distribution of potentially contaminated products.
(IAEA analog is ingestion and commodities planning distance, ICPD)

EPR **Planning Basis** Components

Reactor facility accidents

- Events are typically selected from plant deterministic safety analysis and level 2 probabilistic safety assessment (PSA).
- Design basis accidents (DBA) are the starting point for detailed planning, but the off-site consequences are likely minimal. The extent of the EPZ is typically dictated by beyond design basis accidents (BDBA) where some safety systems are impaired.

Important questions for SMRs:

1. Which accident sequences should be part of the planning basis, and which should be ***practically eliminated***[1]?
2. What is necessary to satisfy Level 5 of ***defense in depth***?
3. What are the ***authorities with jurisdiction*** (emergency management organizations) going to accept?

[1] **practically eliminated**: physically impossible or extremely unlikely with a high degree of confidence

PRESENT WORK

EPZ Framework Development – Research Project

IAEA **Coordinated Research Project** (CRP) on SMR EPZ

Development of Approaches, Methodologies, and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Deployment (CRP I31029)

- Three original objectives:
  1. Formulate criteria on the events and technical aspects to be considered for EPZ sizing.
  2. Develop approaches and methodologies that relate SMR safety features to the extent of offsite arrangements needed.
  3. Provide suitable technical basis for EPR.
- Initiated 2018 February, formally extended to 2021 August, now being wrapped-up by writing summary technical document (TECDOC).
- International participation

  Argentina, **Canada (CNL)**, China, Finland, Indonesia, Israel, Japan, Netherlands, Pakistan, Republic of Korea, Saudi Arabia, Tunisia, United Kingdom, United States of America
- Our observation (as a participant) was that the **technical criteria to identify or select events were not fully addressed** in the CRP.

First research coordination meeting, Vienna 2018 May

Second research coordination meeting, Beijing 2019 May

Motivation

EPZ Framework Development – Research Project

- Off-site EPR requirements that are **commensurate with risk** is an area of emphasis for many SMR stakeholders ("appropriately sized EPZs").
- General and widely accepted methodology for *practically eliminating* situations from the EPR planning basis is desirable, but not likely forthcoming.
- Public health studies[1,2,3,4] following the Fukushima and Chernobyl accidents have shown that over-prescription of protective actions can have net-negative health consequences.

[1] I. Waddington et al., "J-Value Assessment of Relocations Measures Following the Nuclear Power Plant Accidents at Chernobyl and Fukushima Daiichi," *Process Safety and Environmental Protection*, No. 112, pp. 16-49, 2017.

[2] John E. Ten Hoeve and Mark Z. Jacobson, "Worldwide Health Effects of the Fukushima Daiichi Nuclear Accident," *Energy & Environmental Science*, no. 5, pp. 8743-8757, 2012.

[3] A. Hasegawa et al., "Health Effects of Radiation and Other Health Problems in the Aftermath of Nuclear Accidents, with an Emphasis on Fukushima," *The Lancet*, vol. 386, pp. 479-488, 2015.

[4] A. Ohtsuru et al., "Nuclear Disasters and Health: Lessons Learned, Challenges, and Proposals," *The Lancet*, vol. 386, pp. 489-497, 2015.

Probabilistic Safety Assessment (PSA)

Also called Probabilistic **Risk** Assessment (PRA)

- Structured means to answer three basic questions:
  1. What can go wrong?
  2. How likely is it that it goes wrong?
  3. What are the consequences when it does go wrong?
- Traditionally defined levels of PSA:

  Level 1 PSA: identifies sequences that lead to severe core damage / fuel failures

  Level 2 PSA: identifies sequences that lead to releases from containment to the environment

Example requirements from REGDOC-2.5.2 *Design of Reactor Facilities*

Core damage frequency $<10^{-5}$ per reactor year

Small release frequency $<10^{-5}$ per reactor year $>10^{15}$ Bq ^{131}I, or requires temporary evacuation

Large release frequency $<10^{-6}$ per reactor year $>10^{14}$ Bq ^{137}Cs, or requires long-term relocation

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Level 3 PSA: analyses distribution of radionuclides in the environment and the **effect on public health**

*not a licensing requirement in Canada

Hypothesis

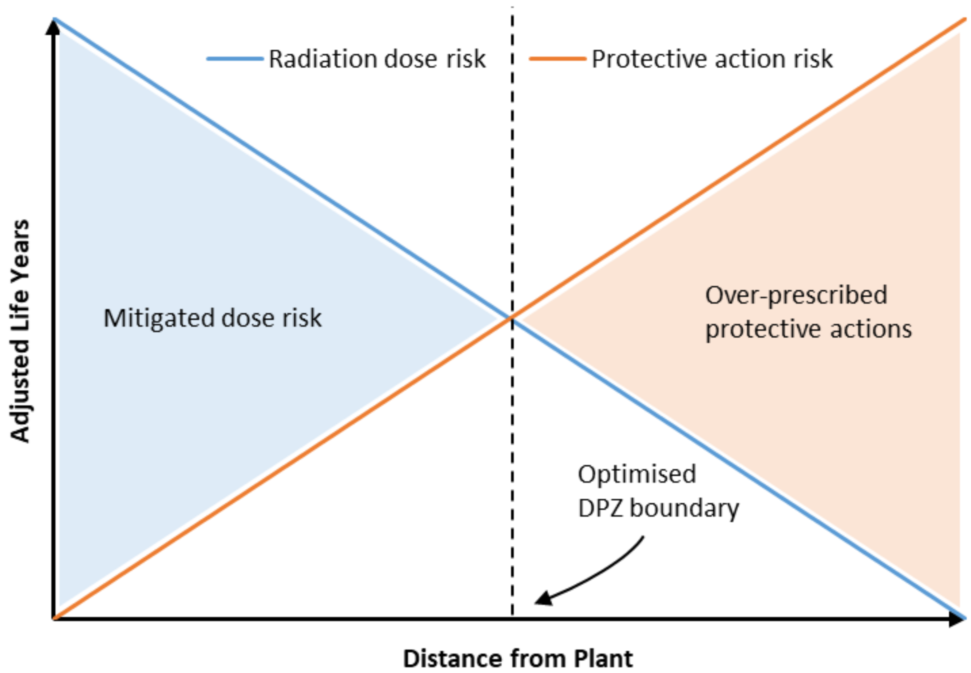
EPZ Framework Development – Research Project

- A risk-informed framework for SMR EPZs will likely resemble Level 3 PSA / PRA
- Fundamental to Health Canada's guidance is the concept of **optimisation of protection**: *"…the achievement of a positive net benefit if a protective action is implemented."*
- Parallel research on mixed-hazard emergencies has identified **adjusted life years** (e.g., **health-** [HALY], **quality-** [QALY], **disability-** [DALY], etc.) as a metric for optimizing protective actions.
- Level 3 PSA results can be quantified in adjusted life years (e.g. HALY, QALY, DALY, etc.) based on radiation doses.
- This work postulates that the risks (negative health consequences) also associated with protective actions can be expressed in units of adjusted life years.

Proposed Method

EPZ Framework Development – Research Project

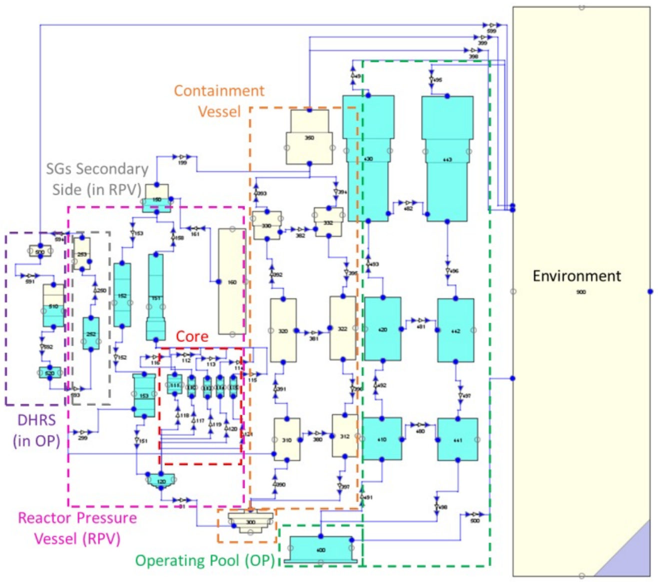
- Where radiation dose risks from plant accidents are in the same units as the risks of protective actions, there must be a definite threshold where protective actions are unwarranted based on **optimisation of protection**.
- If that threshold in space (distance) for a particular event is within the site boundary, the event could be reasonably eliminated from the off-site EPR planning basis.
- Risk thresholds in space are proposed as the basis for the geographical extent of **AAZ** (deterministic health effects) and **DPZ** (stochastic health effects).



Proof-of-Concept Case Study (In-Progress)

EPZ Framework Development – Research Project

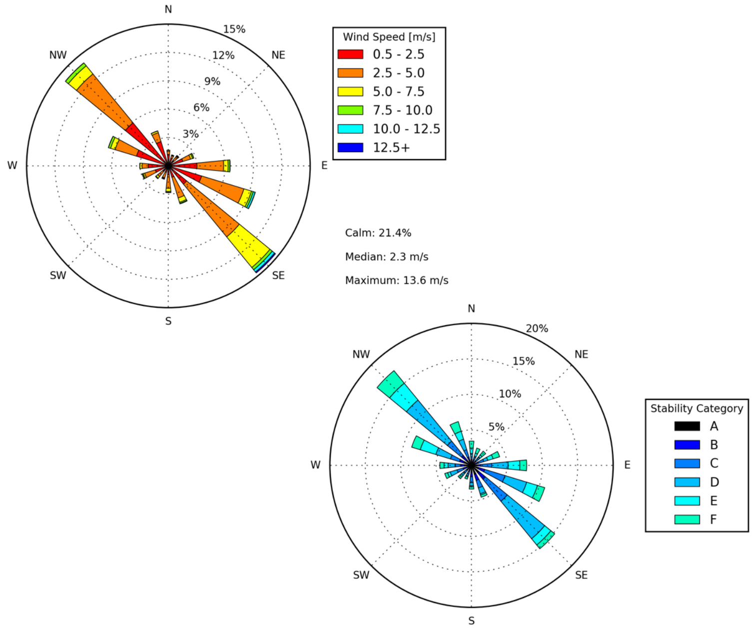
- Quantifying the negative health consequences of protective actions (stable-iodine thyroid blocking, evacuation, sheltering, temporary relocation) as DALY still to be completed – the biggest challenge.



CNL's model of a generic SMR created with the MELCOR code (for source term calculation)

	A	B	C	D	E	F	G
1		SBO	DHRS	SG Feed	OP Break	Cont Brea	**Prob**
2	Case 1_A	1.00E-03	5.00E-03	0.1	1	1	**5.00E-07**
3	Case 1_B	1.00E-03	1	0.1	1	1	**1.00E-04**
4	Case 1_C	1.00E-03	2.00E-02	0.1	1	1	**2.00E-06**
5	Case 1_D	1.00E-03	1.00E-02	0.1	1	1	**1.00E-06**
6	Case 1_E	1.00E-03	5.00E-03	0.22	1	1	**1.10E-06**
7	Case 1_F	1.00E-03	5.00E-03	0.35	1	1	**1.75E-06**
8	Case 1_G	1.00E-03	5.00E-03	0.55	1	1	**2.75E-06**
9	Case 1_H	1.00E-03	5.00E-03	0.17	1	1	**8.50E-07**
10	Case 1_I	1.00E-03	5.00E-03	0.27	1	1	**1.35E-06**
11	Case 1_J	1.00E-03	5.00E-03	0.37	1	1	**1.85E-06**
12	Case 2_A	1.00E-03	5.00E-03	0.1	1.00E-04	1	**5.00E-11**
13	Case 2_B	1.00E-03	1	0.1	1.00E-04	1	**1.00E-08**
14	Case 2_C	1.00E-03	2.00E-02	0.1	1.00E-04	1	**2.00E-10**
15	Case 2_D	1.00E-03	1.00E-02	0.1	1.00E-04	1	**1.00E-10**
16	Case 2_E	1.00E-03	5.00E-03	0.1	5.00E-04	1	**2.50E-10**
17	Case 2_F	1.00E-03	1	0.1	5.00E-04	1	**5.00E-08**
18	Case 2_G	1.00E-03	2.00E-02	0.1	5.00E-04	1	**1.00E-09**
19	Case 2_H	1.00E-03	1.00E-02	0.1	5.00E-04	1	**5.00E-10**
20	Case 2_I	1.00E-03	5.00E-03	0.1	2.00E-03	1	**1.00E-09**
21	Case 2_J	1.00E-03	1	0.1	2.00E-03	1	**2.00E-07**
22	Case 2_K	1.00E-03	2.00E-02	0.1	2.00E-03	1	**4.00E-09**
23	Case 2_L	1.00E-03	1.00E-02	0.1	2.00E-03	1	**2.00E-09**
24	Case 3_A	1.00E-03	5.00E-03	0.1	1	0.01	**5.00E-09**
25	Case 3_B	1.00E-03	1	0.1	1	0.01	**1.00E-06**
26	Case 3_C	1.00E-03	2.00E-02	0.1	1	0.01	**2.00E-08**
27	Case 3_D	1.00E-03	1.00E-02	0.1	1	0.01	**1.00E-08**
28	Case 3_E	1.00E-03	5.00E-03	0.17	1	0.01	**8.50E-09**
29	Case 3_F	1.00E-03	5.00E-03	0.27	1	0.01	**1.35E-08**
30	Case 3_G	1.00E-03	5.00E-03	0.37	1	0.01	**1.85E-08**
31	Case 3_H	1.00E-03	5.00E-03	0.1	1	0.05	**2.50E-08**
32	Case 3_I	1.00E-03	1	0.1	1	0.05	**5.00E-06**
33	Case 3_J	1.00E-03	2.00E-02	0.1	1	0.05	**1.00E-07**
34	Case 3_K	1.00E-03	1.00E-02	0.1	1	0.05	**5.00E-08**
35	Case 3_L	1.00E-03	5.00E-03	0.17	1	0.05	**4.25E-08**
36	Case 3_M	1.00E-03	5.00E-03	0.27	1	0.05	**6.75E-08**
37	Case 3_N	1.00E-03	5.00E-03	0.37	1	0.05	**9.25E-08**

Artificial level 2 PSA results for the generic SMR created for the case study



Weather data measured at CRL – hypothetical site of generic SMR

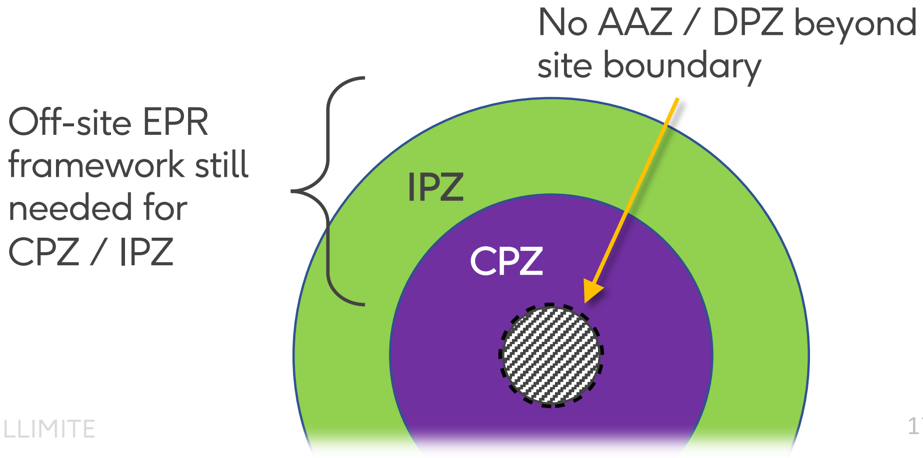
PRESENT WORK

Considerations for **Operational Intervention Levels** in Northern Canada

Reactive vs Proactive Protective Actions

Situations with Minimal-Extent EPZ

- A risk-informed approach may justify no automatic action zone (AAZ) or detailed planning zone (DPZ) outside the site boundary (“**site-boundary EPZ**,” “**no off-site EPZ**,” “**no EPZ**,” etc.), but offsite EPR is a fundamental part of defense in depth.
- **Proactive** protective actions will likely **not** be taken automatically.
  - i.e., actions taken automatically after the declaration of a general emergency, or in response to model projections.
- Protective actions will likely be implemented **reactively** based on **field measurements**.
- **Operational intervention levels** (OILs) are a framework for expanding or confirming the use of protective actions according to field measurements.
- Minimal-extent EPZ may require:
  1. A robust radiological monitoring system.
  2. OILs fine-tuned for both the reactor technology and environment.
  3. Centralized response teams covering multiple sites, and capabilities for a specified response period (firefighter model).

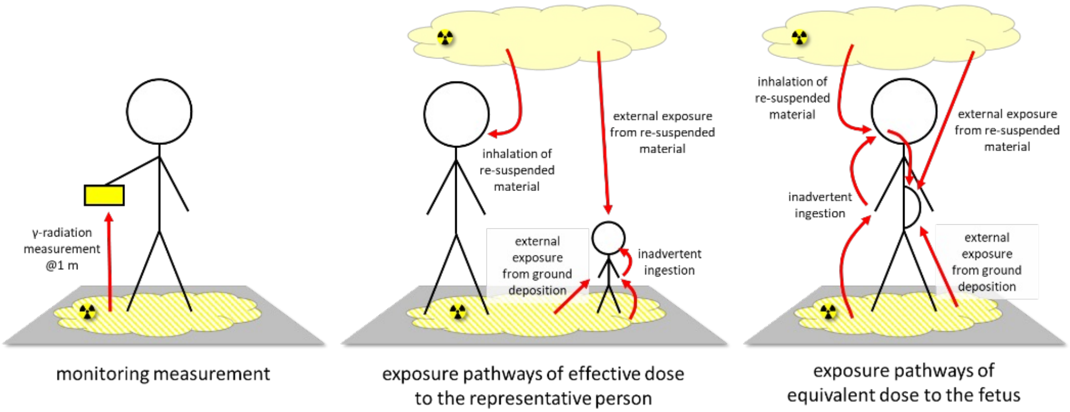


SMR OILs for Northern Canada

Two-Part Study in Progress

- OILs allow for the prompt implementation of response actions based on **monitoring results** that are **readily available** during a nuclear emergency.
  - Used to quickly infer whether doses are projected to exceed allowable limits.
- First part of the study devoted to evaluating radionuclide mixes from SMRs likely to be deployed:
  - High-temperature gas reactors (e.g., for industrial uses) and heat pipe microreactors (e.g., for remote communities or mines).
  - Benchmarked vs contemporary OILs (based on light water-cooled reactors).
- Second part devoted to environmental transport parameters and food consumption behaviours.
  - Prototypical of either boreal forest or arctic (winter conditions, alternative types of local food sources).

Example terrain of northern Canada



Monitoring measurement and exposure pathways for the ground contamination scenario for OIL1$_\gamma$ and OIL2$_\gamma$

Summary

Summary

Take-Aways

- Off-site EPR is still a key part of defence in depth, even when the EPZ is sized commensurate with risk.
- CNL is investigating a novel framework for determining the necessary size of the EPZ (AAZ and DPZ).
- Off-site monitoring and appropriate OILs may be critical when no proactive protective actions are planned.
- Existing OILs need to be re-examined for new technologies and environments.

Chalk River Labs (CRL) site in 2015

This study is funded by **Atomic Energy of Canada Limited**, under the auspices of the Federal Nuclear Science and Technology Program.

The research was conducted at the Canadian Nuclear Laboratories under project *Development in NPP Emergency Dose Assessment, Protection Strategy Optimization, and Disaster Informatics* by staff within the Nuclear Safety Experiments Branch (Advanced Reactors Directorate) and the Nuclear Response and Analysis branch (Safety and Security Directorate).

Thank you. Merci.

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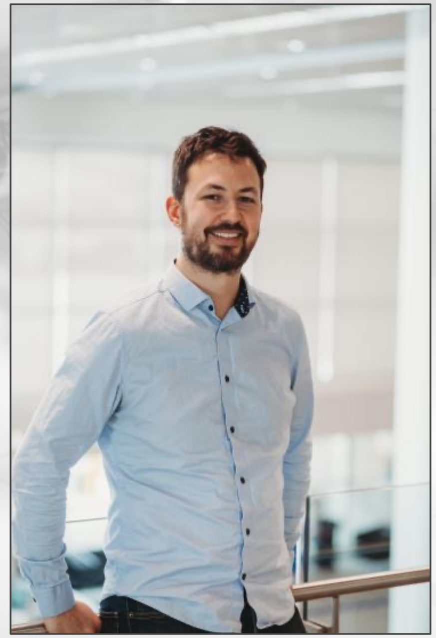

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Basis for Protective Action Decision Making

Generic Criteria and Operational Intervention Levels for Nuclear Emergency Planning and Response

- Generic criteria are the projected dose thresholds used to trigger emergency protective actions and should be independent of reactor type.
- Operational intervention levels (OILs) are thresholds for field measurements that, if exceeded, imply that generic criteria are likely to be exceeded.
  - Mainly used to confirm protective actions or extend them beyond what are taken automatically.
  - Depend on the radionuclide mix and could be substantially different for SMRs with different fuel types.

Table: Canadian Protective Action Generic Criteria (Health Canada)

	Protective Action	Generic Criteria
Exposure Control	Stable iodine thyroid blocking	**50 mSv** in first 7 days
	Evacuation	**100 mSv** in first 7 days
	Sheltering	**10 mSv** in 2 days
	Temporary relocation	**100 mSv** in first year; or **100 mSv** for full period of in utero development
Ingestion Control	Restriction of distribution and ingestion of potentially contaminated drinking water, milk and other foods	**3 mSv/y** or **1 mSv/y** depending on category

International Atomic Energy Agency Definitions

IAEA GSR Part 7 *Preparedness and Response for a Nuclear or Radiological Emergency*

Table: Summary of Emergency Preparedness Categories

Category	Description
I	Facilities, like nuclear power plants, for which on-site events are postulated that could give rise to severe deterministic health effects off the site that would warrant precautionary actions, urgent protective actions, or early protective actions.
II	Facilities, like some research reactors, for which on-site events are postulated that could give rise to doses warranting urgent or early protective actions, but excluding those facilities for which postulated events could lead to severe deterministic health effects.
III	Facilities, like industrial irradiation facilities or hospitals, for which no on-site events are postulated that would warrant urgent or early protective actions off-site.
IV	Activities that could give rise to a nuclear or radiological emergency warranting protective actions in an unforeseen location, e.g. during transport of nuclear material, or from the theft of a dangerous source and use in a radiological dispersal device. Also includes the detection of elevated radiation from an unknown source, the identification of clinical symptoms of radiation exposure, and a transnational emergency that is not within EPC V.
V	Areas that are within the emergency planning zone or emergency planning distance of a EPC I or EPC II facility located in another State.