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Title:

Auteur: Mohammadhossein Afsharipour
Author:

Date: 2023

Type: Mémoire ou thèse / Dissertation or Thesis

Référence: Afsharipour, M. (2023). Small Modular Reactors for Energy Transition in Northern Canada: Thermal Modeling and Some Geotechnical Considerations [Mémoire de maîtrise, Polytechnique Montréal]. PolyPublie. https://publications.polymtl.ca/57047/
Citation:

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Small Modular Reactors for Energy Transition in Northern Canada: Thermal Modeling and Some Geotechnical Considerations

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
Génie Civil

November 2023

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Ce mémoire intitulé :

Small Modular Reactors for Energy Transition in Northern Canada: Thermal Modeling and Some Geotechnical Considerations

présenté par **Mohammadhossein AFSHARIPOUR**
en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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RÉSUMÉ

Les collectivités nordiques éloignées du Canada font face à des défis énergétiques en raison de leur dépendance aux combustibles fossiles. Les petits réacteurs modulaires (PRM) sont prometteurs en tant que solution durable à ce problème, car ils peuvent réduire les émissions de gaz à effet de serre et promouvoir le développement durable. Cependant, les SMR nécessitent des paradigmes de conception structurelle et géotechnique spécifiques pour la mise en œuvre et l'exploitation dans les régions de pergélisol, qui sont affectées par le changement climatique et la dégradation du pergélisol.

Cette étude présente le potentiel des PRM pour la production d'énergie durable dans le contexte nordique. Nous donnons un aperçu des PRM et soulignons leur place dans la transition énergétique du Canada dans les régions nordiques. De plus, nous discutons des défis associés à la conception thermique et à la mise en œuvre des SMR dans les régions nordiques dans le context des changements climatiques. Notre étude présente deux études de cas concernant des sites hypothétiques de SMR à Salluit (QC) et à Inuvik (TN-O.) et prédit le profil de température du sol à la fin du 21e siècle. Cette étude contribue à la masse croissante de littérature sur les PRM dans les régions de pergélisol et souligne la nécessité de poursuivre la recherche et l'élaboration de politiques pour soutenir leur adoption. Pour présenter les idées et les résultats aux parties prenantes, les résultats de l'étude sont transposés dans le contexte de l'industrie 4.0. qui promeut l'application des modèles de réalité augmentée (AR) et de réalité virtuelle (VR) pour améliorer la présentation et la communication des concepts de recherche. Un processus détaillé étape par étape pour créer des représentations 3D des concepts, y compris la texturation, le mappage UV, l'animation et les techniques d'exportation et de publication, est présenté. À cette fin, deux puissants logiciels de modélisation et d'animation 3D, Autodesk Maya et Blender, sont utilisés. Dans Autodesk Maya, une représentation du changement de profondeur de la couche active suite au changement climatique est présentée, tandis que Blender est utilisé pour créer un modèle PRM minimal et son effet thermique sur le sol. Ces avatars, ainsi que plusieurs autres modèles pédagogiques, sont ensuite téléchargés sur Sketchfab, un site Web d'édition populaire prenant en charge les formats AR/VR. Nous explorons également la possibilité de créer un laboratoire virtuel d'ingénierie géotechnique, en soulignant les possibilités de transformation qu'il offre en termes d'expériences d'apprentissage pratiques et d'accessibilité pédagogique.

ABSTRACT

Remote northern communities in Canada face energy challenges due to their reliance on fossil fuels. Small modular reactors (SMRs) show promise as a sustainable solution to this issue, as they can reduce greenhouse gas emissions and promote sustainable development. However, SMRs require specific structural and geotechnical design paradigms for implementation and operation in permafrost regions, which are adversely affected by climate change and permafrost degradation.

This study presents the potential of SMRs for sustainable energy production in the northern context. We provide an overview of SMRs and highlight their position in Canada's energy transition in northern regions. Additionally, we discuss the challenges associated with the thermal design and implementation of SMRs in northern regions in the context of climate change. Our study presents two case studies, regarding hypothetical SMR sites at Salluit (QC) and Inuvik (NWT) and predicts the ground temperature profile at the end of the 21st century. This study contributes to the growing body of literature on SMRs in permafrost regions and highlights the need for further research and policy development to support their adoption. To present the ideas and results to stakeholders, the results of the study are brought to the Industry 4.0 context by developing an Augmented Reality (AR) and Virtual Reality (VR) platform to enhance the presentation and communication of research concepts. A detailed step-by-step process for creating 3D representations of the concepts, including texturing, UV mapping, animation, and export and publishing techniques, is introduced. For this purpose, two powerful 3D modeling and animation software programs, Autodesk Maya and Blender, are employed. In Autodesk Maya, a representation of the change in active layer depth as a result of climate change is presented, while Blender is utilized to create a minimal SMR model and its thermal effect on the ground. These avatars, along with several other pedagogical models, are then uploaded to Sketchfab, a popular publishing website that supports AR/VR formats. We also explore the potential for establishing a virtual laboratory for geotechnical engineering, highlighting the transformative possibilities it offers in terms of practical learning experiences and educational accessibility.

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CHAPTER 1 INTRODUCTION

1.1 Background

In 2021, Canada witnessed a notable 4.5% increase in its primary energy production, which reached a total of 21,753 petajoules [21]. Within this energy landscape, crude oil took the lead as the most prominent contributor, representing a substantial 49.8% of the overall primary energy production. In the second place, natural gas played a significant role, contributing 31.8% to energy production, while primary electricity held an 8.3% share. Moreover, the contribution of total coal and gas plant natural gas liquids amounted to 5.6% and 4.2%, respectively. This marked the 12th consecutive year in which crude oil held its position as the primary driver of Canada's energy production. Canada Energy Regulator (CER) describes the "Evolving Policies Scenario" as a future in which Canadians decrease their energy consumption and develop a greater reliance on lower-carbon energy sources [22]. Despite an overall reduction of 21% in total energy consumption, there would be a notable jump in electricity demand, marking a substantial 44% to 47% increase from 2021 to 2050 within this scenario [22, 23]. This shift shows a growing preference for electricity as an important component of Canada's evolving energy landscape, driven by a concerted effort to embrace more sustainable and environmentally friendly energy options. Canada has aligned itself with over 120 countries worldwide, including all other G7 nations (United Kingdom, United States, Germany, Italy, France, and Japan) in a collective commitment to achieve net-zero emissions by the year 2050 [24]. This global resolve reflects a profound international interest in reducing reliance on fossil fuels and an increasing emphasis on adopting clean alternative energy sources. In the northern regions of Canada, this imperative is particularly urgent, given that per capita energy consumption is nearly double the national average, largely attributable to the region's extended and harsh winters [25]. Furthermore, the existing energy infrastructure in these areas is nearing its operational limits and requires significant repair or replacement to accommodate Canada's evolving energy goals. Wind and solar energy sources offer environmentally friendly power generation with low greenhouse gas emissions. However, these technologies come with the challenge of storing excess energy produced during periods of surplus, such as during daytime when demand is relatively lower. Regardless of the specific storage methods employed, addressing this requirement adds to the overall cost of integrating wind and solar power into the energy grid. To align with ambitious net-zero emissions targets, numerous countries, such as Canada, are making substantial investments in small modular reactors (SMRs) [26]. SMRs present the potential for shorter construction timelines

and feature simpler and safer designs compared to conventional reactors, making them a key focus for achieving sustainable energy solutions.

1.2 Motivation

The introduction of SMRs as a solution for off-grid communities and businesses presents an intriguing option, but it raises certain unexplored concerns. One aspect that has received relatively little attention in the existing literature is the interaction between these reactors and permafrost, a critical consideration for many remote communities and mining operations situated in areas where the ground remains frozen. The deployment of a high-temperature underground reactor could potentially jeopardize the integrity of the underlying permafrost, leading to ground subsidence and posing hazards to the facility's structural stability.

Furthermore, it's essential to recognize that permafrost regions are already under threat due to the impacts of global warming. Canada is experiencing warming at an accelerated pace compared to the global average, with temperatures rising at over twice the global rate. Notably, the Canadian Arctic is undergoing warming at a rate approximately three times faster than the global average [27]. The alarming trends in rising ground surface temperatures have the potential to exert adverse effects on the stability of permafrost. This underscores the critical need to address the vulnerability of permafrost ecosystems in the face of escalating climate change.

To address these critical concerns, a comprehensive modeling and simulation approach is necessary. This study introduces a numerical model that examines the heat transfer considering the combined effects of SMRs and climate change. The goal is to illustrate the potential consequences of placing such a facility within permafrost-bearing ground. The study presents ground temperature profiles to shed light on the severity of this issue and to gauge the extent to which ground disturbance could intensify by the end of the current century. This research aims to provide valuable insights into the complex interplay between SMRs and permafrost, highlighting the importance of cautious planning and design in these contexts.

1.3 Thesis structure

Each chapter of the dissertation is outlined as follows :

Chapter 1 is the introduction of the thesis, which introduces the background and motivation of the research.

Chapter 2 is the section where the literature review of this thesis can be found.

Chapter 3 presents several numerical simulations, considering the effect of SMRs and climate change on the ground's thermal profile in two distinct Canadian locations : Salluit and Inuvik.

Chapter 4 introduces powerful 3D visualization platforms, Autodesk Maya and Blender, to present engineering structures such as SMRs and ideas in an Augmented Reality (AR) and Virtual Reality (VR) format.

Chapter 5 concludes the thesis and discusses contributions as well as future research plans.

CHAPTER 2 ARTICLE 1 : SMALL MODULAR REACTORS FOR ENERGY TRANSITION IN NORTHERN CANADA (LITERATURE REVIEW)

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Afsharipour M., Fatolahzadeh Gheysari A., Bouaanani N., Boudreault R., Maghoul P. *Small Geotechnical and Geological Engineering,* Journal, in Review (2023).
Submission date : 2023-12-21

Abstract

Remote northern communities in Canada face energy challenges due to their reliance on fossil fuels. Small modular reactors (SMRs) show promise as a sustainable solution to this issue, as they can reduce greenhouse gas emissions and promote sustainable development. However, SMRs require specific structural and geotechnical design paradigms for implementation and operation in permafrost regions, which are adversely affected by climate change and permafrost degradation. This study presents the potential of SMRs for sustainable energy production in the northern context. We provide an overview of SMRs and highligh their position in Canada's energy transition in northern regions. Additionally, we discuss the challenges associated with designing and implementing SMRs in northern regions. Our study contributes to the growing body of literature on SMRs in permafrost regions and highlights the need for further research and policy development to support their adoption.

2.1 Introduction

The Canadian energy market has a unique demand for electricity and heating, especially in remote and scarcely populated Northern regions. According to the International Energy Agency's World Energy Outlook, Canadians used over 300 gigajoules of energy per person in 2020, which is three times the world average and one of the highest per capita rates globally [28]. This places Canada among the most intense consumers of energy in the world. In terms of electricity consumption, Canada was the fourth-largest consumer on a per capita basis among G20 countries in 2020, with 16,698 kilowatt-hours (kWh) per person [29]. Canada's high per capita energy consumption can be attributed to several factors such as the presence of energy-intensive industries, high demand for heating and cooling due to cold temperatures,

low population density, and relatively affordable electricity prices compared to other G20 countries. Additionally, the size and climate of Canada, along with its reliance on energy-intensive natural resource production, contribute to higher energy needs.

According to Statistics Canada [21], Canada's energy consumption in 2021 increased by 2.8% to 8,167 petajoules. The industrial and transportation sectors saw the highest increase in energy consumption, followed by the agriculture sector. Energy consumption decreased in the residential, public administration, and commercial and other institutional sectors. Natural gas surpassed refined petroleum products as the main source of energy consumed in Canada for the second year in a row, followed by electricity. Ontario, Alberta, and Quebec accounted for the majority of energy consumed in Canada in 2021, with a combined share of total energy consumption of 74.6% [21]. Energy consumption increased in several regions in 2021 compared to 2020. The northern territories (Nunavut, Yukon, and the Northwest Territories) (+6.0%) saw the greatest increase, followed by Quebec (+4.6%), Alberta (+3.8%), Ontario (+2.3%), Saskatchewan (+1.9%), Prince Edward Island (+1.7%), British Columbia (+1.1%), and Nova Scotia (+0.7%). However, energy consumption decreased in Manitoba (-0.4%), Newfoundland and Labrador (-0.5%), and New Brunswick(-1.1%) in the same year [21]. A comparison of energy consumption by Canadian provinces and territories is presented in Figure 2.1.

The International Energy Agency's report suggests that Canada's power demand may fall below 300 gigajoules per person by 2030 due to policies aimed at improving energy efficiency, transitioning away from fossil fuels in the power grid, and promoting electric vehicles [28]. Figures 2.2 and 2.3 show that reduced energy demand is primarily due to emissions reduction measures and adopting low-carbon technologies. Achieving net-zero emissions by 2050, as stated by the Canada Energy Regulator, would result in a total drop in energy demand to approximately 10,000 PJ by that year (Figure 2.2). However, Canada's energy consumption would still be nearly three times the global average and one of the highest in the world. In contrast, a "Reference Scenario" assuming fewer emissions reduction efforts would lead to over 12,600 PJ in total energy demand [8, 30] (Figure 2.3).

In 2021, Canada's primary energy production increased by 4.5% to 21,753 petajoules. Crude oil accounted for the largest share of primary energy production at 49.8%, followed by natural gas (31.8%), primary electricity (8.3%), total coal (5.6%), and gas plant natural gas liquids (4.2%) [21]. Also, in 2021, Canada's energy exports increased by 5.3% to 14,011 petajoules. Within these exports, the country accounted for 79.2% of its crude oil production and 43.9% of its marketable natural gas. Energy imports increased by 2.5% to 3,681 petajoules as well, with crude oil and natural gas being the largest components. It is worth mentioning that Canada's energy landscape heavily relies on renewable sources, with over two-thirds of electricity

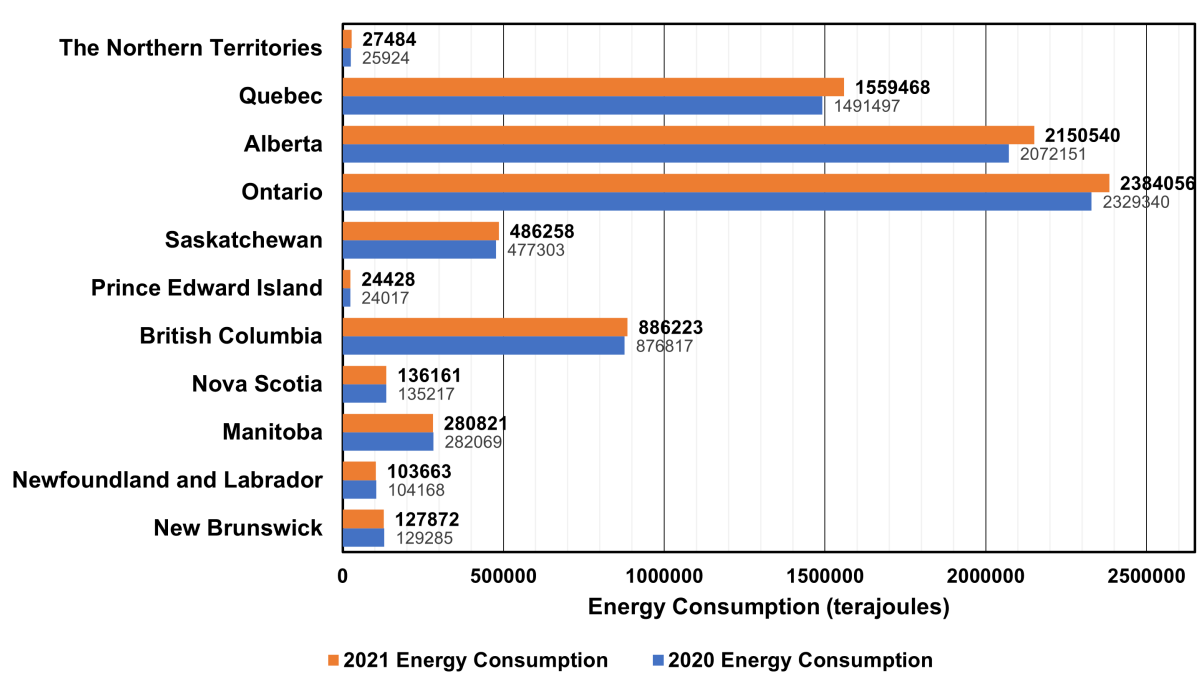


FIGURE 2.1 Total primary and secondary energy demand in Canada by territory. The northern territories (including Yukon, Nunavut and The Northwest Territories) have shown the largest proportional increase in demand compared to other provinces. Data is acquired from the Canadian Centre for Energy Information [7].

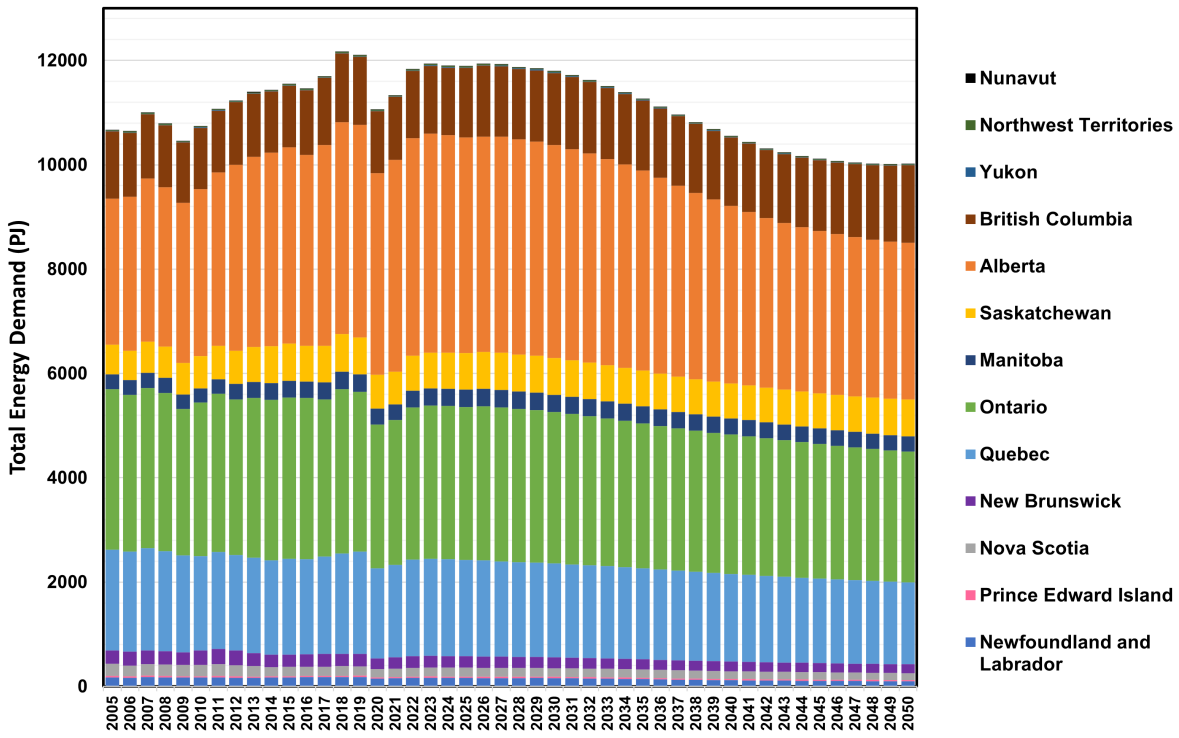


FIGURE 2.2 Total energy demand by region until the year 2050, in case Canada achieves its net-zero goal by the same year [8].

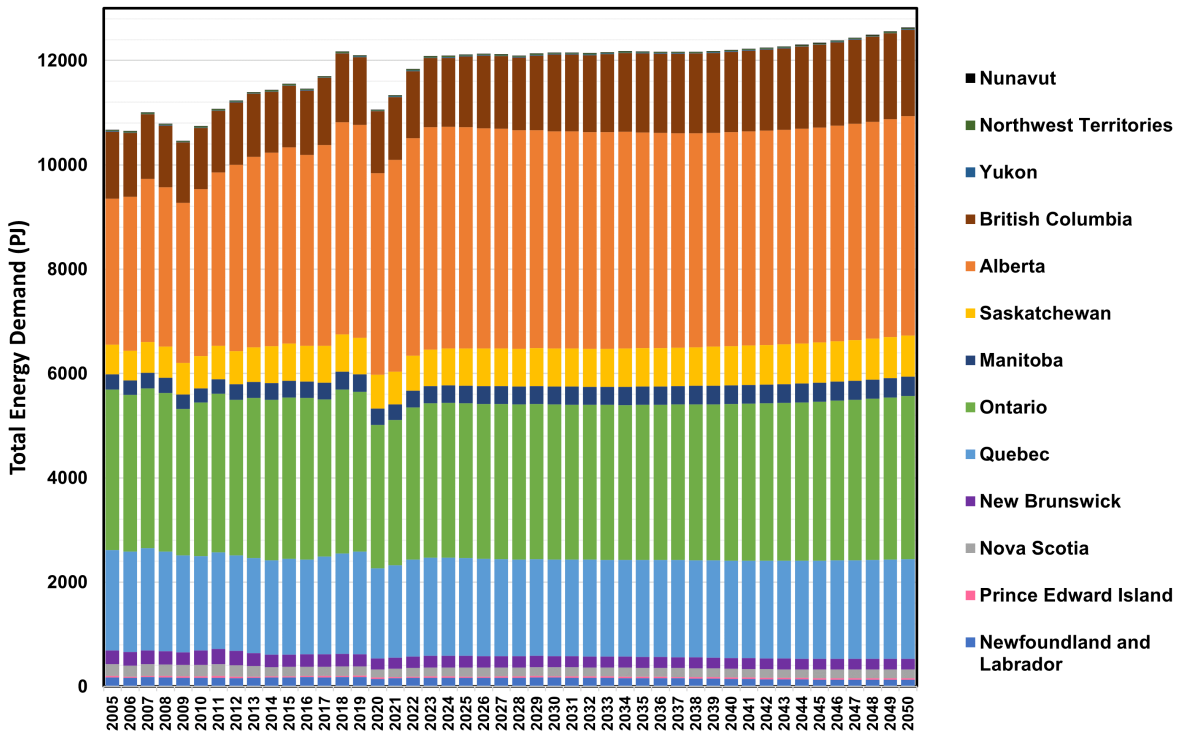


FIGURE 2.3 Total energy demand by region until the year 2050, in case Canada continues the current measures under the Reference Scenario [8].

generated from renewables in 2018 [31]. Hydroelectric power, accounting for 58% of electricity production, is the predominant contributor (Figure 2.4). Additionally, non-hydro renewables like wind and solar have shown significant growth in the past decade, with continued but slightly slower expansion projected in the medium term [31].

Canada's Energy Future 2021 report states that in the Evolving Policies Scenario, which represents a transition towards lower carbon emissions, low and non-emitting energy sources, including renewables, nuclear, and fossil fuels with carbon capture and storage (CCS), make up the majority of energy use in Canada. Unabated fossil fuel combustion (without CCS) is projected to decrease by 62% from 2021 to 2050 in this scenario [32].

Canada aims to achieve net-zero greenhouse gas emissions by 2050 and transition to a low-carbon economy. To meet these targets, a diverse clean energy portfolio, including resilient nuclear power, is essential. Nuclear energy can significantly contribute to Canada's energy transition and support economic development in northern regions. While renewable sources like solar, wind, and geothermal have limitations in capacity and reliability, making them not generally practical for long-term solutions in islanded, micro-grid communities, nuclear power offers a consistent and reliable energy supply. Despite progress in renewable energy, including hydroelectric power, there are challenges in expanding these sources to meet Canada's future energy needs [33]. The Canadian energy market may face increased electricity demand of around 200 TWh from 2025 to 2050 [32], and despite producing significant hydroelectric power, Canada may struggle to keep pace with this rising demand. Moreover, the geopolitical importance of Canada's Arctic underscores the need for a reliable energy source in remote areas.

Small Modular Reactors (SMRs) are proposed to address Canada's energy needs, particularly in the North [34]. This would be the beginning of a greater role for SMRs toward the Canadian energy goals. They are aimed to integrate in Canada's power plan and phase out coal and reduce natural gas emissions [35–37]. While renewables are vital, nuclear energy will serve as a stable base load for cleaner electricity. Beyond power generation, SMRs can electrify carbon-intensive sectors like mining and petroleum extraction [37].

In this paper, we aim to examine the potential role of SMRs in meeting the energy demands of Canada's remote and scarcely populated Northern regions, including the vulnerable Canadian Arctic. We will discuss the potential benefits and challenges of implementing SMRs in Canada's Northern regions, as well as their wider implications for the country's energy transition. The criteria for site selection as well as geotechnical and structural design will also be discussed.

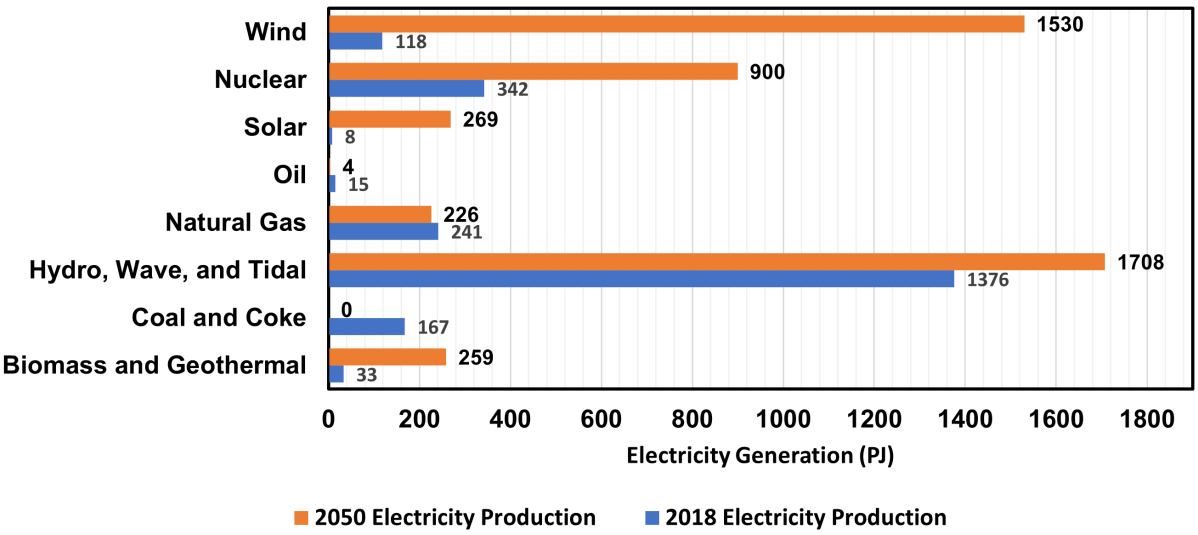


FIGURE 2.4 Electricity generation sources during 2018 compared to 2050 projection. According to the projection, significant development needs to occur in wind, solar, biomass and geothermal, and nuclear sectors [8].

2.2 Understanding Small Modular Reactors

According to the International Atomic Energy Agency (IAEA), SMRs are considered as advanced reactors that only have the capacity to generate electricity up to 300 MWe per module [38, 39]. This definition of smallness could vary as some organizations like the Canadian Nuclear Safety Commission (CNSC) put a threshold of 200 MWt power level to differentiate small reactors from conventional ones [40]. The term "Modular" in the context of nuclear power plants refers to the unit assembly of the Nuclear Steam Supply System (NSSS) that can be coupled to a power conversion system or process heat supply system to generate the desired energy product. This unit assembly can be made up of one or more sub-modules and can be combined with one or more modules to achieve the required power rating for the power plant [39]. The use of a smaller amount of fuel compared with large conventional nuclear power plants and the ability to incorporate passive safety systems, such as natural circulation, are why these low-power reactors are considered safer as well. Additionally, small reactors are simpler and more robust compared to larger ones, which makes them easier to manufacture and construct. There are certain applications and locations that can only support or require a small amount of power, such as small off-grid communities, industrial facilities, or areas with moderate or low power needs [41]. These reactors come equipped with advanced engineered features and can be set up as either a single or multi-module plant. Moreover, they are intended to be manufactured in factories and delivered to utility providers for installation based

on their needs. There are about 50 SMR designs and concepts globally, most of which are in various developmental stages and some are claimed as being near-term deployable. These are with varying designs and capacities to meet different requirements, including water-cooled reactors, high-temperature gas-cooled reactors, liquid-metal reactors, fast neutron spectrum sodium-cooled reactors, and molten salt reactors [42]. Since the production of SMRs has not yet been undertaken on a commercial scale in North America and Western Europe, the actual cost of producing these modules is yet to be determined. Due to the diverse range of SMR designs currently being considered, there may be significant variation in cost estimations [43].

SMRs also have the potential to produce steam for district heating, desalination, and industrial processes [44]. Other possible applications include hydrogen production and powering resource extraction processes such as steam-assisted gravity drainage for oil extraction (SAGD). Different SMRs capacities have applications in providing non-emitting heat and power to various sectors, including remote communities and off-grid mines, heavy industry plants, and oil sands facilities in the following numbers [45] :

— Remote communities and mines : 79 remote communities and 24 off-grid mines (average 1 MWe)
— High-temperature steam for heavy industry : 85 heavy industry (such as mining) locations (average 25-50 MWe)
— Oil sands : Generated steam and electricity could affect 96 facilities (average 210 MWe)
— Replacing conventional coal-fired power : 29 units at 17 facilities (average 343 MWe)

Larger SMRs producing around 300 MWe energy are ideal for on-grid electricity production, while very small SMRs (micro-reactors) producing less than 3 MWe energy per module excel in off-grid settings, replacing diesel generators at remote sites due to their portability [44, 46]. Additionally, industrial applications like heavy industry process steam, hydrogen production, mining, and oil extraction require high-temperature heat exceeding 500 °C, which favors non-water-cooled advanced SMRs that can operate at temperatures above 500 °C. All in all, each type of SMR possesses unique characteristics tailored to specific energy needs.

2.3 SMR Vendors in Canada : The Next Generation of Clean Energy Solutions

In the early 2000s, SMR vendors recognized the potential of deploying innovative demonstration units in Canada [44]. These vendors focus on non-water-cooled advanced reactors suitable for both off-grid and on-grid applications. Canada is an attractive location for such demonstrations due to the CNSC's readiness to regulate advanced reactors. Additionally, Canada possesses essential factors supporting SMR implementation [44] : governmental support

at provincial and federal levels, a robust nuclear industry, an extensive supply chain, advanced research infrastructure, a skilled workforce, diverse potential applications, and available prototype deployment sites that align with these efforts.

As of December 2019, the Canadian nuclear industry had attracted 20 SMR vendors, with 12 actively engaged in discussions with the CNSC [44] and 11 in the pre-licensing process 2.1. In Canada, provinces are responsible for electricity generation. Ontario and New Brunswick, relying on CANDU-type reactors, generate approximately 50% and 30% of their electricity from nuclear power, respectively. Notably, major utilities in Ontario (Ontario Power Generation and Bruce Power) and New Brunswick (New Brunswick Power) are exploring SMR technology for new nuclear builds. Furthermore, SaskPower in Saskatchewan and Qulliq Energy Corporation in Nunavut are also considering SMRs to address their energy needs [44].

2.3.1 Stable Salt Reactor (Moltex Energy)

The Stable Salt Reactor-Wasteburner (SSR-W) (Figure 2.5) is different from conventional reactors because it uses molten salt fuel instead of traditional solid fuel. This reactor, working in 575-625 °C temperature range, produces heat through a molten chloride salt stream which can be stored in a large thermal storage system at low cost, allowing it to operate as a low-cost peaking power plant rather than just a base-load plant. This facility consists of a 14 m height, 7 m diameter reactor placed in a 22,500 m^2 plant. Moltex was chosen by the Government of New Brunswick (NB) and NB Power to develop the SSR-W in Canada, with the aim of deploying the first reactor next to the Point Lepreau Nuclear Generating Station (Figure 2.6). The company plans to use used CANDU fuel stocks to produce fuel for the 300 MWe SSR-W (SSR-W300) [2].

Moltex Energy's GridReserve system allows for the storage of thermal energy generated by the Stable Salt Reactor and converts it to electrical energy for delivery to the grid during periods of high demand. This stored thermal energy can help supplement the inconsistent and inflexible nature of renewable energy sources. The GridReserve system comprises insulated tanks filled with a molten salt mixture made of sodium and potassium nitrates, similar to those used in concentrated solar power plants. Heat generated by the 300MW SSR-W300 can be stored in the system for approximately 8-10 hours at temperatures of around 550 °C. The fully welded, insulated, atmospheric, surface tanks have a normal operating temperature ranging from 270 °C to 565 °C. The tanks have auxiliary heaters to prevent salt temperatures from dropping below freezing (240°C) [49]. There are several issues associated with molten salt tanks :

— The distribution of high temperatures in the foundation of the tank can lead to severe

TABLE 2.1 Interested vendors and their proposed designs [1, 2]

Vendor	**Design**	**Coolant**	**Fuel type**	**Capacity (MWe)**	**Temperature range (°C)**
Moltex Energy	Stable Salt Reactor	Molten MgCl/NaCl	Molten Salt	300	575-625
GE-Hitachi Nuclear Energy	BWRX-300	boiling water	UO_2	270-290	270-288
Terrestrial Energy Inc.	IMSR400	Fluoride Fuel Salt	Molten Salt	200	620-700
SMR, LLC. (Holtec)	SMR-160	Pressurized Light Water	UO_2 pellet	160	243-321
ARC Nuclear Canada Inc.	ARC-100	Liquid Sodium	Metal fuel (U-Zr alloy)	100	355-510
X Energy, LLC	Xe-100	Helium	UCO	80	260-750
NuScale Power, LLC	NuScale Integral	Pressurized water	UO_2 pellet	77	249-316
Ultra Safe Nuclear Corporation	MMR-5 and MMR-10	Helium	FCM TRISO	5-10	300-630
Westinghouse Electric Company, LLC	eVinci Micro Reactor	Heat pipes	TRISO	Up to 5	650 [47]
U-Battery Canada Ltd.	U-Battery	Helium	TRISO	4	over 700 [48]
LeadCold Nuclear Inc.	SEALER	Molten Lead	UN	3	390-432 [10]

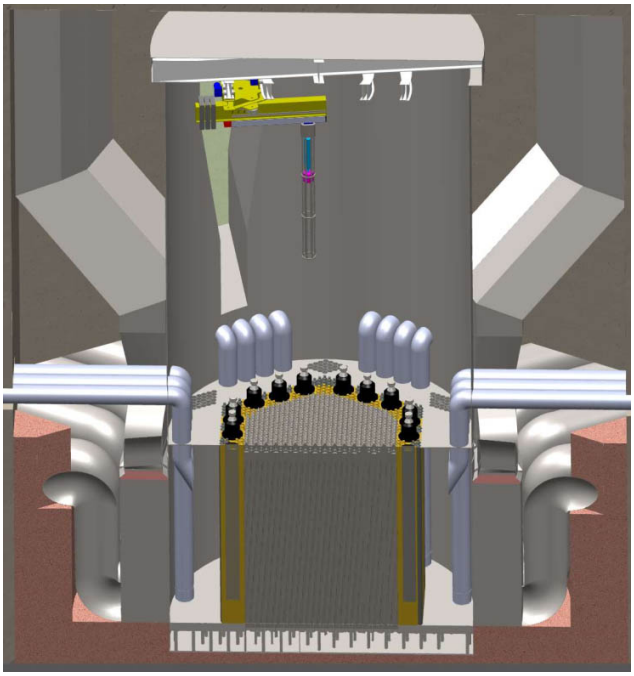


FIGURE 2.5 The Stable Salt Reactor-Wasteburner (SSR-W) by Moltex [2].

effects in the absence of a cooling system [50]. There is a certain need for foundation refrigeration to ensure natural soil temperatures do not exceed safe levels. This temperature level is determined around 60-70 °C by some sources [49]. The refrigeration can be passive or active [51], although active systems may be required considering the high heat levels generated by SMRs.

— The tank's thermal behavior and its related thermal expansion require careful attention, particularly with regard to the bottom plate, which is subject to significant stresses. Additionally, any irregularities or uneven temperature distribution may pose potential problems [49].

— In case of the formation of cracks on the lower molten salt storage tank surface, the molten salt can spill into the foundation, insulation layers, soil, and groundwater. This leakage raises environmental concerns [52].

2.3.2 BWRX-300 (GE-Hitachi Nuclear Energy)

This boiling water reactor with a 4 m diameter and 26 m height works in 270-288 °C temperature range (Figure 2.7). The intended uses of BWRX-300 range from producing base load electricity to providing load-following electricity in the range of 50 to 100% power. Other potential applications include district heating, synthetic fuel and hydrogen production, as

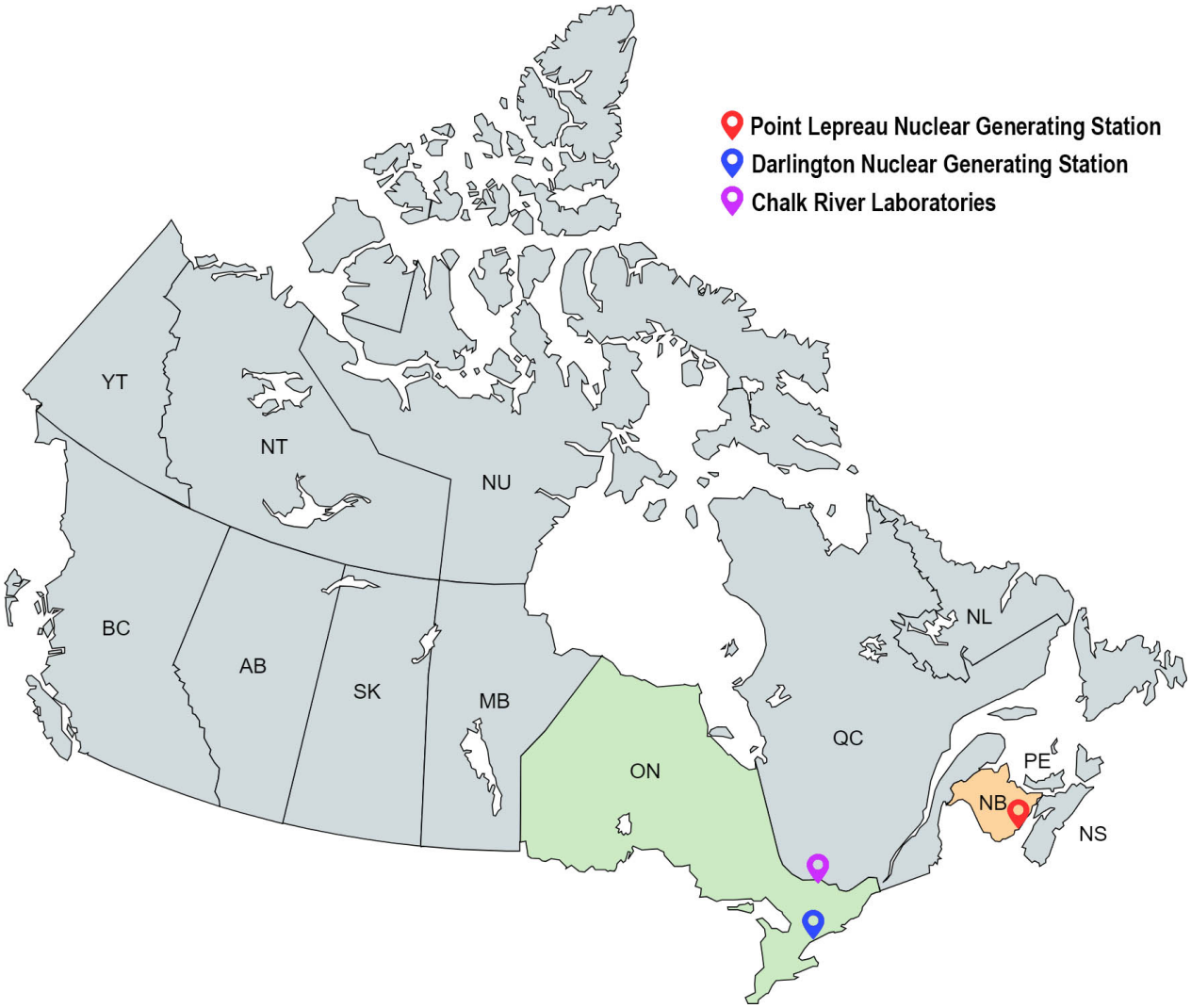


FIGURE 2.6 New Brunswick and Ontario are stepping forward to test and employ SMR technology. Point Lepreau Nuclear Generating Station in New Brunswick aims to deploy SSR-W. Darlington nuclear generating station in Ontario is considering BWRX-300, IMSR400, and Xe-100 designs for deployment. Ontario's Chalk River plans to host a MMR-5 or MMR-10 design [2, 9] as well as a SEALER demonstration unit [10].

well as other process heat applications [2]. The planned commercial operation of this design is in 2028 [2].

The BWRX-300 reference site is contained within a small footprint of 170 m by 280 m, which includes various facilities like the plant building, cooling tower, switch yard, warehouse, parking lot, and site office. The reactor building extends underground, where the primary containment vessel and reactor pressure vessel (RPV) are mostly located. This underground construction technique helps reduce the use of concrete [53]. To construct the BWRX-300, the site would require either a deep water pier for transportation via barge or heavy haul routes for land transportation. The heaviest component that would need to be transported to the site is the RPV, which weighs 485 tons. During normal operation, the maximum acceptable ambient air temperature and the maximum recommended inlet temperature for the main condenser/heat exchanger is 37.8 °C [53]. Ontario Power Generation's Darlington Nuclear Generating Station is evaluating three different designs for potential deployment, and this facility is one of them [54].

2.3.3 IMSR400 (Terrestrial Energy Inc.)

The Integral Molten Salt Reactor (IMSR) has an 18 m height and 4.1 m diameter and works in the very hot 620-700 °C temperature range (Figure 2.8). With a plant footprint of 45,000 m^2, IMSR is designed with an integral structure that includes a single vessel containing pumps, heat exchangers, and shutdown rods. The vessel is sealed, and the entire Core-unit is replaced after a period of about 7 years when its useful life is complete. The IMSR facility is intended for use in supplying electric power grids and providing industrial heat and power (no off-grid applications). Produced thermal energy could be conserved in molten salt tank systems as well, as described in the Moltex SSR-W design. The first IMSR plant in service is planned for 2031 [2]. The IMSR is considered to have a safe design against seismic hazards because of its compact and integral primary system that does not have pipes. Furthermore, the Core-unit is situated below grade in a silo and the buildings are of low profile, leading to a low center of gravity [55]. This facility is one of the three designs being considered for deployment at Ontario Power Generation's Darlington Nuclear Generating Station [56].

2.3.4 SMR-160 (SMR, LLC.)

Holtec International has created the SMR-160, a reactor of 15 m height and 3 m diameter working in 243-321 °C temperature range, which is primarily designed for producing electricity, with the option of co-generation equipment such as hydrogen generation, thermal energy storage, district heating, and seawater desalination (Figure 2.9). The SMR-160 is suitable for

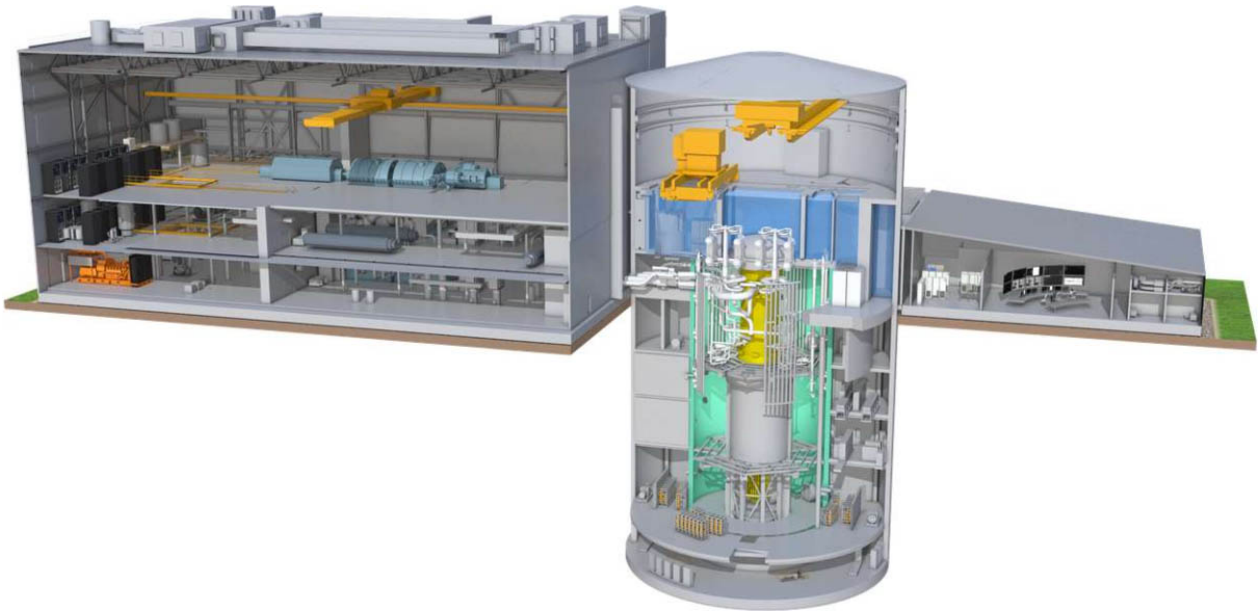


FIGURE 2.7 The BWRX-300 plant layout by GE-Hitachi Nuclear Energy [2].

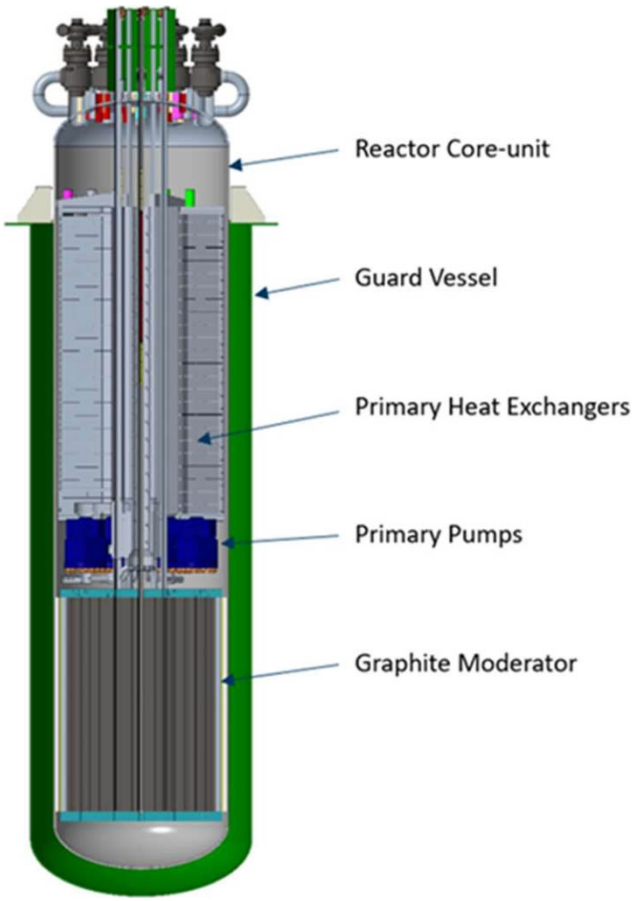


FIGURE 2.8 The IMSR400 by Terrestrial Energy Inc. [2].

locations with unstable power grids or off-grid use. It is expected to receive commercialization approval through a construction permit-based process in 2023 [2].

2.3.5 ARC-100 (ARC Nuclear Canada Inc.)

The Sodium-cooled ARC-100 works in 355-510 °C temperature range and places a 16.7 m height, 7.9 m diameter reactor in a 56,000 m^2 footprint power plant (Figure 2.10). The primary target market for the reactor is grid-scale electricity generation in developed countries. However, the reactor's ease of operation make it well-suited for meeting electricity needs in remote locations such as mines and smaller grid markets in developing countries that can accommodate up to 100 MW(e). Additionally, the reactor can be used for industrial heat, hydrogen production, and water desalination. Being one of the few reactors with a publicly available detailed waste management plan, it is stated that the spent fuel assemblies are stored outside the reactor vessel, and once they have cooled down, they are periodically removed and stored in dry-cask storage on-site. For long-term storage, the spent fuel will be stored in containers that meet the Nuclear Waste Management Organization's requirements for deep geological repositories [2]. The province of New Brunswick would likely be a potential client for this design [57], and the commencement of the first unit's operation is planned for 2029 [2].

2.3.6 Xe-100 (X Energy, LLC)

The gas-cooled Xe-100 consists of 4 reactor modules that have 16.4 m in height and 4.88 m in diameter. Their working temperature range is 260-750 °C, which makes them one of the highest temperature reactors on the list (Figure 2.11). Designed for a plant footprint of 340 m by 385 m, the start of construction is planned for 2025 [2]. One of the three options being evaluated for installation at Ontario Power Generation's Darlington Nuclear Generating Station is this particular facility [54].

2.3.7 NuScale Integral (NuScale Power, LLC)

The NuScale Integral is a pressurized-water reactor that uses light water for cooling (Figure 2.12). Its VOYGR SMR plants are designed to be scalable and can be tailored to fit customers' energy needs by adjusting the number of modules. This modular design enables flexible operations for load-following and non-electrical process heat applications. The reactor measures 17.7 m in height and 2.7 m in diameter, and its plant footprint takes 140,000 m^2, making it one of the most area-demanding options on the list. The reactor temperature range is 249-316 °C [2]. NuScale will provide manufacturing services related to the upper

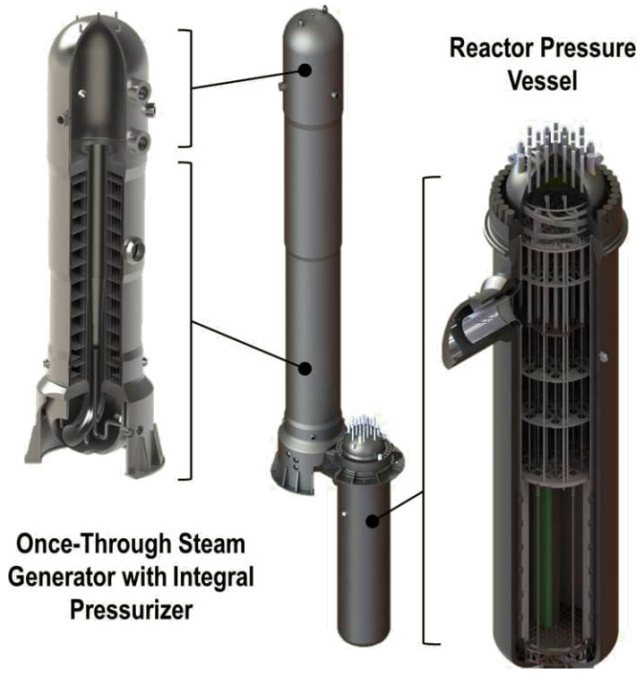


FIGURE 2.9 The SMR-160 by SMR, LLC. [2].

RPV, with the aim of supporting a Canadian deployment in 2028 [58].

2.3.8 MMR-5 and MMR-10 (Ultra Safe Nuclear Corporation)

These reactor models work in the temperature range of 300-630 °C and store thermal energy in molten salt tanks (Figure 2.13). They have a height of 13.25 m and a diameter of 3.5 m, and Helium is used as the coolant in their system. The design is to provide a safe, clean, and affordable source of power and heat to isolated mining operations, industries, and communities. The MMR system can also be scaled to meet energy demands by installing multiple units at the same location. The operation duration is estimated for 20 years, and by changing the cores once, 20 more years can be added. Using an MMR facility at Chalk River, Canada is currently undergoing a formal licensing process. Plant operation is planned to start in 2026 [2].

2.3.9 eVinci Micro Reactor (Westinghouse Electric Company, LLC)

The Westinghouse eVinci Micro Reactor has been designed to generate energy in remote or isolated areas by producing both electricity and process heat (Figure 2.14). Its unique feature is its portability as it can be transported in standard shipping containers. This makes it suitable for use in mining operations, remote communities, or critical infrastructure ins-

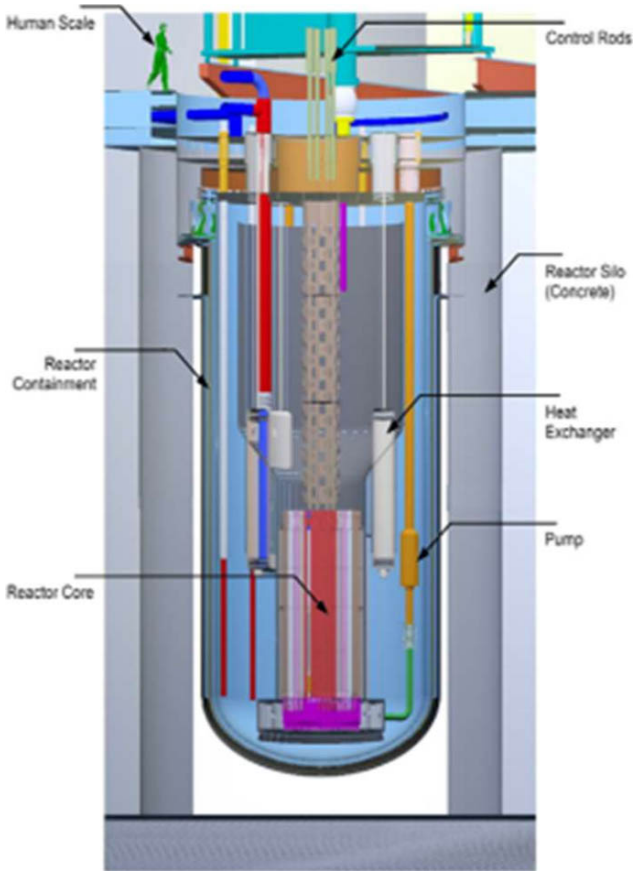


FIGURE 2.10 The ARC-100 by ARC Nuclear Canada Inc. [2].

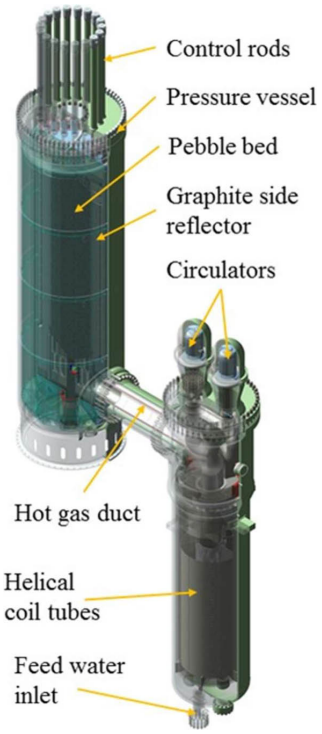


FIGURE 2.11 The Xe-100 by X Energy, LLC [2].

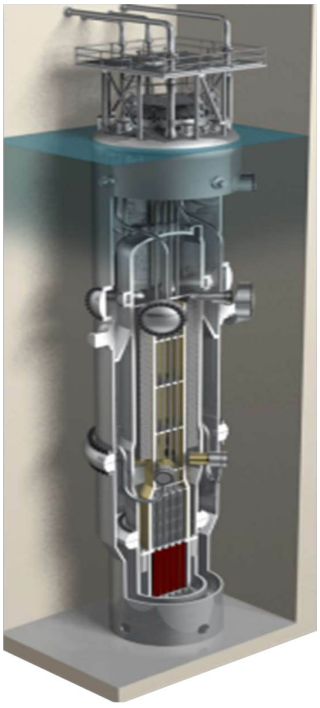


FIGURE 2.12 The NuScale Integral by NuScale Power, LLC [2].

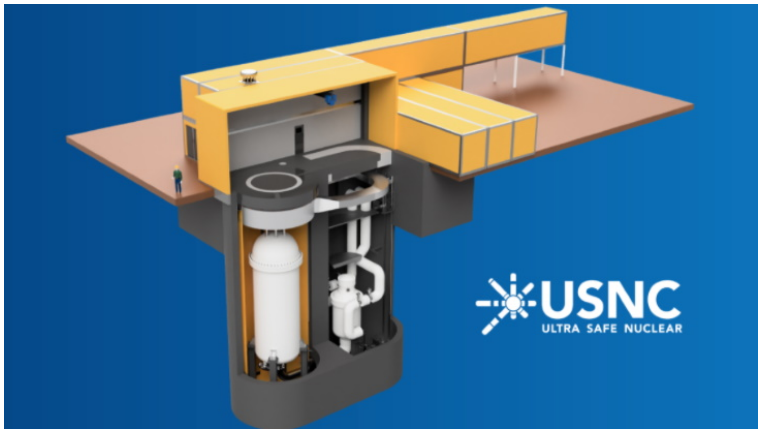


FIGURE 2.13 The MMR design by Ultra Safe Nuclear Corporation [2].

tallations. To facilitate logistics and minimize on-site construction, the eVinci Micro Reactor is designed to be mostly prefabricated in the factory and packaged into shipping containers for transport by air, water, or land to its final location. Once on site, the container can be installed and connected to the electrical grid or piping system as needed, with minimal additional construction required. The eVinci Micro Reactor can operate at full power for up to 3 years without the need for refueling. Once this time period is reached, the reactor will be disconnected and transported back to the factory in its original canister. At this point, it can either be refueled and redeployed or placed in long-term storage. eVinci Micro Reactor is still at the conceptual design level, and the first demonstration of this unit is planned for 2024 [2].

2.3.10 U-Battery (U-Battery Canada Ltd.)

The project was initiated by Urenco, a leading company in the nuclear industry, and the conceptual design was created by the Universities of Manchester in the UK and Delft in the Netherlands [59]. The size of the core reactor in this design is one of the smallest on the list, with only 5.5 m in height and 2.2 m in diameter (Figure 2.15). U-Battery is a versatile reactor that consists of a standardized reactor block including the primary Helium and secondary Nitrogen coolant circuits, as well as a spent fuel store. The reactor has various applications such as providing heat and power supply to remote regions, localized heat and/or power supply for existing industrial applications, and new applications such as hydrogen production. The rejected heat from the U-Battery primary applications could also be used for other purposes such as district heating and desalination. The RPV is designed to operate under a pressure of 40 bar at 300 °C, yet some sources state that its temperature would rise

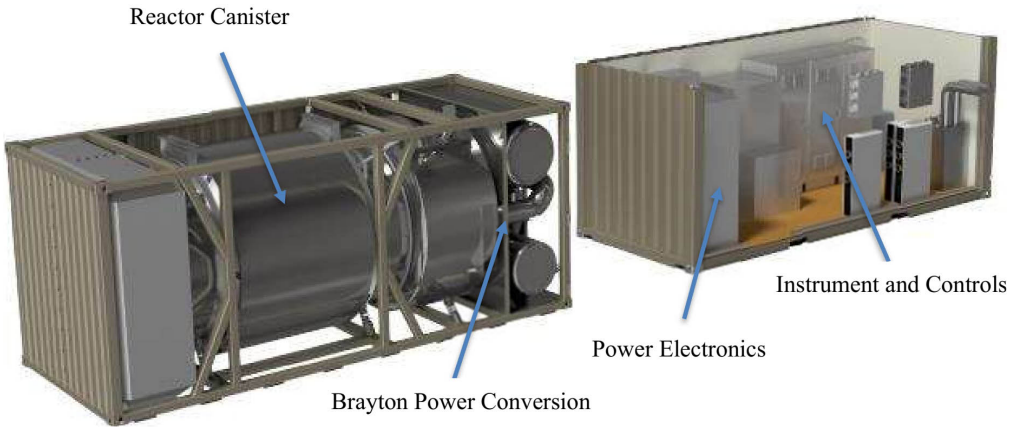


FIGURE 2.14 The eVinci Micro Reactor by Westinghouse Electric Company, LLC [2].

over 700 °C [48]. A first-of-a-kind U-Battery is planned to start operating in 2028 [2].

2.3.11 SEALER (LeadCold Nuclear Inc.)

SEALER is a fast reactor designed to operate on enriched UO_2 fuel and is capable of producing 3-10 MWe of electricity (Figure 3.1). The reactor, measuring 2.7 m in diameter and 6 m in height, works in 390-432 °C temperature range and uses lead as a coolant [10]. It is intended for commercial use in communities and mining operations situated in the Canadian Arctic, where there is no connection to the main power grid [60]. Approximately ten off-grid communities in Nunavut and the North-West Territories are considered to be of a size where a standalone SEALER unit can be a commercially feasible power source. In addition, using SEALER units at mining sites in the Arctic can be cost-effective as power accounts for a significant portion (30-50%) of the expenses associated with producing commodities. SEALER units can be installed at each site, resulting in reduced costs and making it possible to profitably process lower grade ores [10].

Landowners, stakeholders, and potential customers of LeadCold in the Arctic regions of Canada have shown interest in evaluating SEALER for power production. They believe that a demonstration plant is necessary for a meaningful assessment. LeadCold, in collaboration with Canadian Nuclear Laboratories (CNL), is currently evaluating the Chalk River site in Ontario as a possible location for this demonstration unit [10]. LeadCold is targeting off-grid communities in the Canadian Arctic with a power consumption of 2-10 MW as its initial market for the SEALER unit due to the uncertainty of starting a mining operation. Nine communities in Nunavut and one in the North-West Territories have been identified for the 3 MWe version of SEALER. For the mining industry, LeadCold plans to offer a solution of 2x10



FIGURE 2.15 U-Battery by U-Battery Canada Ltd. [2].

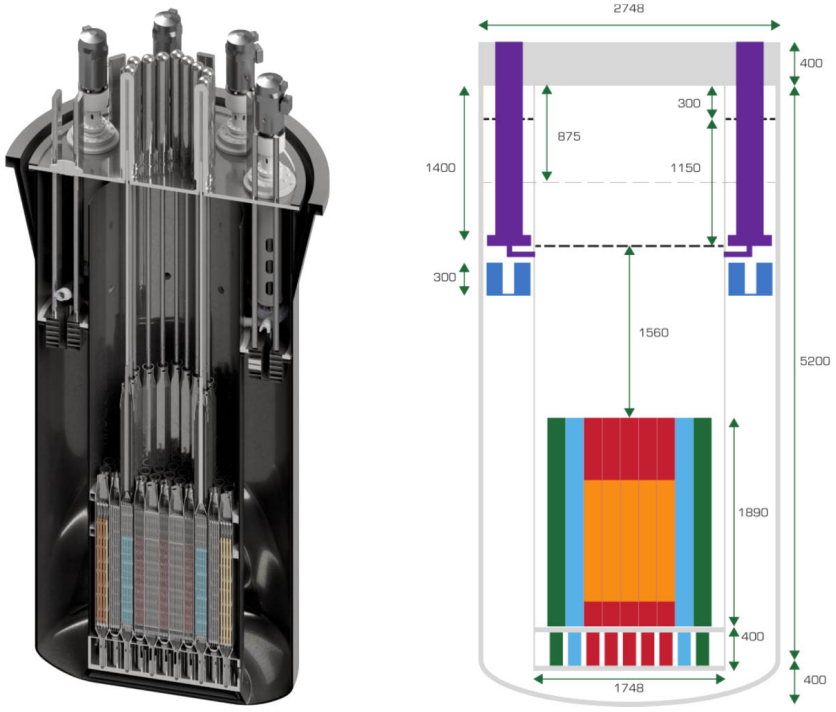


FIGURE 2.16 SEALER by LeadCold Nuclear Inc. [10, 11].

MWe units, as the typical requirement is for 20±5 MW electricity. The Canadian market for off-grid power production, including Yukon and northern Ontario, is estimated to require two new mines or about four SEALER units per year. It is expected that over a period of several decades, approximately 100 reactors will be deployed for commercial off-grid power production in Canada [10].

In terms of design, the maximum cladding temperature is ensured not to exceed 450 °C, while the core inlet temperature remains above 390 °C. By maintaining this narrow temperature range and utilizing effective corrosion barriers, it is feasible to extend the lifespan of the fuel cladding to 30 years [11, 60]. The heat generated by the reactor body is conveyed to the surrounding concrete pit and is eventually lost to the ground. In a study [11], assuming the surrounding of a SEALER reactor as an infinite heat sink, the pit wall temperature is assumed constant at 90°C.

2.4 A Perspective on Canada's Northern Regions

Canada's Northern regions,north of approximately 55° latitude, hold significant importance. The Northern territories, including Yukon, the Northwest Territories, and Nunavut, encompass approximately 40% of Canada's total area [13]. Yukon spans 472,345.44 square kilometers, the Northwest Territories encompass 1,127,711.92 square kilometers, and Nunavut covers approximately 2,093,190 square kilometers [61]. Moreover, northern areas in provinces like British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Newfoundland and Labrador, which extend beyond isolated permafrost limits, are part of Canada's northern circumpolar regions [12]. Together with the territories, these northern regions account for nearly two-thirds of Canada's landmass (Figure 2.17). The presence of permafrost serves as a natural demarcation between northern and southern Canada among various other indicators, marking the transition from subarctic boreal forests to the Arctic's tundra, permafrost, and desolate snowy landscapes. In this remote, sparsely populated area, communities are scattered, with most located in the territorial capitals.

Population growth in Canada's Northern regions varies among the territories. From 2016 to 2021, Yukon experienced the country's highest growth rate at 12.1% [61]. In contrast, the Northwest Territories saw a slight decline, from 41,786 to 41,070 residents [61]. Nunavut saw slower growth, with a 2.5% increase during the same period [61]. The growth rates are influenced by factors such as economic conditions, interprovincial migration, and the impacts of the pandemic.

The Canadian government considers the Arctic and Northern regions as essential to national

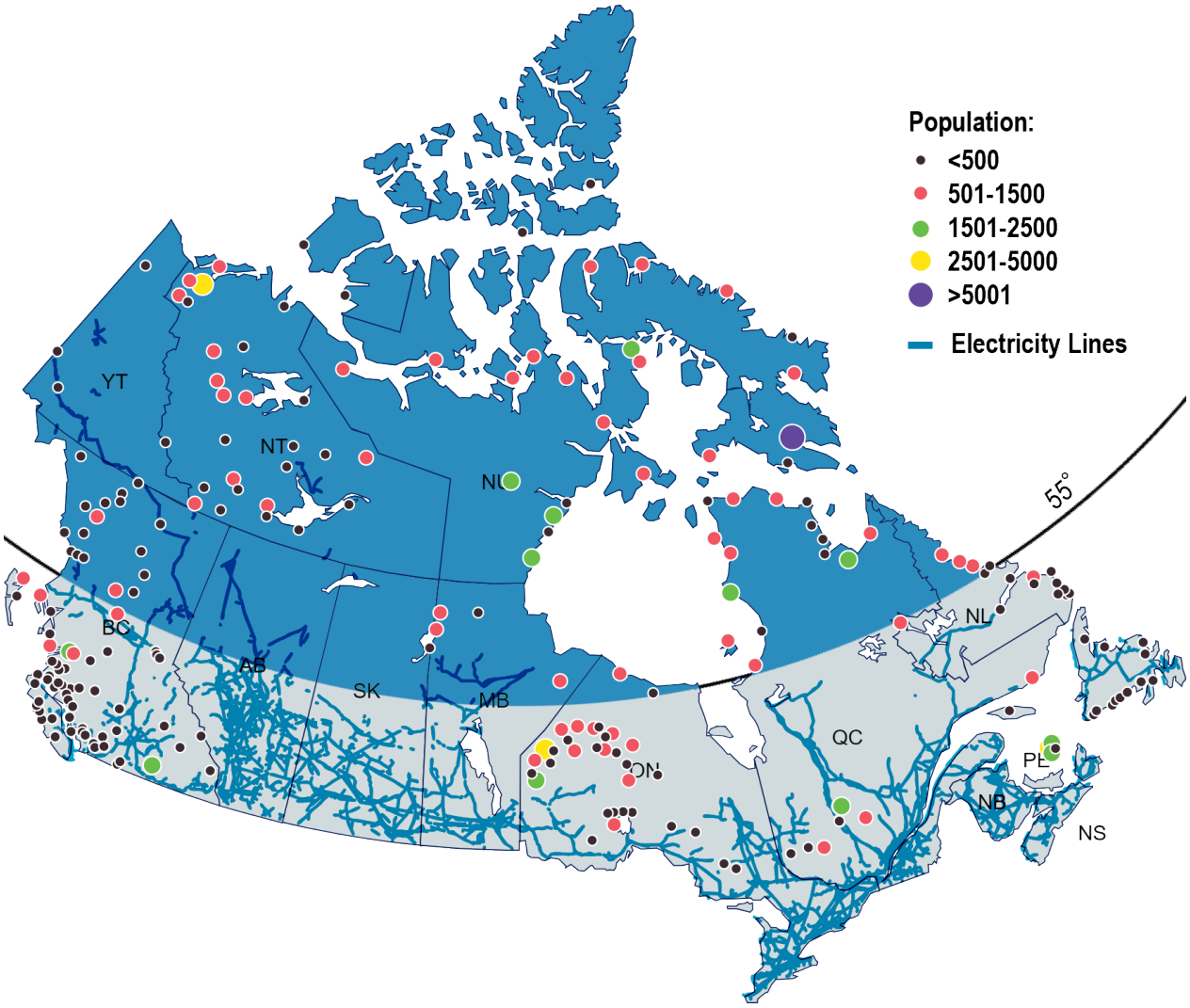


FIGURE 2.17 North circumpolar regions of Canada are defined as regions above 55° latitude [12]. The Canadian Arctic and Northern regions cover almost 60% of of the total area of Canada [9, 13]. There are 279 active remote communities that are not integrated into the North American electric grid, many of which reside in the northern regions. 239 of them heavily depend on diesel fuel for electricity generation and oil for heating. Approximately two-thirds of these remote communities are Indigenous [14].

identity, prosperity, security, and interests. Canada maintains a focus on sovereignty, security, development, environmental preservation, and relations with Indigenous peoples in the Arctic [62].

Nowadays, energy sources in Canada's Northern regions, particularly the Northwest Territories, are predominantly fossil fuel-based due to their high energy density, transportability, reliability, and established technology [63–65]. In 2017, the total demand for refined petroleum products in the Northwest Territories was 6.2 Mb/d, with diesel accounting for 4.2 Mb/d and gasoline for 0.7 Mb/d [63]. About half of the diesel consumption was attributed to electricity generation in 2016. However, the lack of infrastructure, seasonal transportation restrictions, absence of pipelines, and a small and dispersed population pose challenges such as increased heating costs, limited energy supply, and reliance on distant sources [64].

Canada's future is interconnected with the development and well-being of its Northern regions. Canada aims to support sustainable economic growth in the North, identifying innovative trade and commercial opportunities that benefit Northerners [66]. Industries like mining, renewable energy, tourism, and natural resource exploration are pivotal in driving economic development in these regions. Climate change is presenting both challenges and opportunities in the Arctic and northern regions. Melting Arctic sea ice opens doors to increased economic activity and shipping routes. How Canada manages foreign activities, asserts control over its waters, and addresses jurisdictional and security concerns will define its future in the region. Sustainable development, environmental preservation, and strengthening ties with Indigenous communities are central to ensuring the long-term prosperity and stability of Canada's Northern regions.

Canada's Arctic policy and Northern economic development strongly depend on sustainable energy supply while striving for net-zero greenhouse gas emissions. With almost 300 remote communities (Figure 2.17) and energy-dependent resource industries, reliable power access is crucial for sustainability [67]. SMRs emerge as a prominent clean energy source for Northern regions.

2.4.1 Climate Change and Northern Regions

Climate change is a major 21st-century challenge with profound implications for northern Canada's long-term sustainability. Climate system Observations indicate that global mean near-surface air temperatures have recently increased unprecedentedly over the last two millennia. Over the last decade, a 1.5 °C warming over land has occured compared to the pre-industrial era . Global land precipitation has likely increased since the mid-20th century, and sea levels are rising at the fastest rate since the last three millennia [68].

The Arctic, encompassing nearly 40% of Canada's landmass, has warmed four times faster than global averages [69]. Widespread changes in the cryosphere, including sea ice, glaciers, ground ice, and snow coverage, have been observed. Arctic sea ice coverage is currently at its lowest in two centuries. Globally, September sea ice coverage decreased from 6.23 million km2 in 1979-1988 to 3.76 million km2 in 2010-2019 [68]. In Canada's northern waters, summer sea ice declined at 7.1% per decade since 1968 [70]. The loss of sea ice profoundly impacts northern Canada's socioeconomic prospects. Over the past three decades, activities like shipping, commercial fishing, and marine tourism in Canada's Arctic have nearly tripled, primarily due to global warming and declining sea ice [71]. Also, the northern Canada population is projected to increase by 10% by 2055 [72], implying rising energy and infrastructure demands.

Canada's Arctic and subarctic lands experienced severe climate changes in recent decades, which are expected to continue throughout the century. Nine of the ten warmest years in Canada have occurred during the last 25 years [70]. Climate models project increasing near-surface air temperatures across the country, particularly at higher latitudes, under both moderate and extreme emission pathways (Figure 2.18). The Canadian Regional Climate Model (CanRCM) anticipates mean annual air temperature changes of up to 6°C and 10°C by the end of the 21st century under RCP 4.5 and RCP 8.5 pathways, representing moderate and extreme climate change scenarios, respectively. Moreover, snow cover has already diminished by 5% to 10% per decade since 1981 and is projected to decline further according to CanRCM (Figure 2.19). The model also predicts an overall increase in annual precipitation across the country (Figure 2.20). The distribution of wind speed anomalies is presented in Figure 2.21. These projections are calculated as the difference between the average outcomes of projection simulations for the last decade (2091-2100) and the average data from the initial decade (2011-2020) under two different climate scenarios.

Permafrost thawing is considered as one of the most critical consequences of global warming in Canada's north. Defined as ground that remains at or below 0 °C for at least two consecutive years [73], permafrost underlies more than 15 percent of the northern hemisphere and about 50% of Canada's land [74]. Permafrost distribution generally follows a northward transition from sporadic patches at lower latitudes to extensive discontinuous formations at around 55° and continuous along the shores of Hudson Bay and the Arctic Ocean [18]. In terms of structure, permafrost may consist of pore ice and excess ground ice in various forms, such as relict, segregated ice, and ice wedges. [16] have developed a national-scale mapping of ground ice conditions in Canada (Figure 2.22).

The stability of permafrost is governed by the surface energy budget, i.e., the energy fluxes

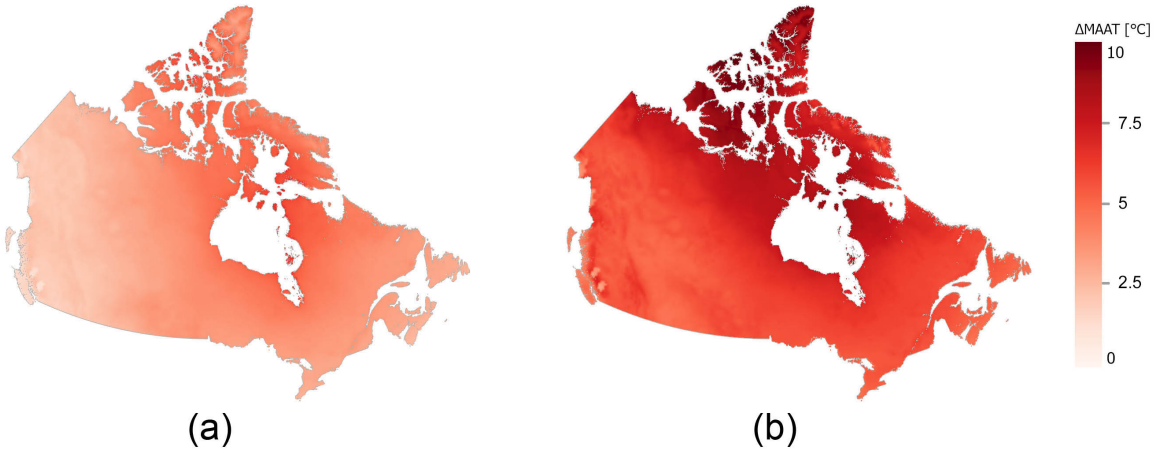


FIGURE 2.18 The distributions of near-surface air temperature anomalies for RCP4.5 (a) and RCP8.5 (b) climate change scenarios [15].

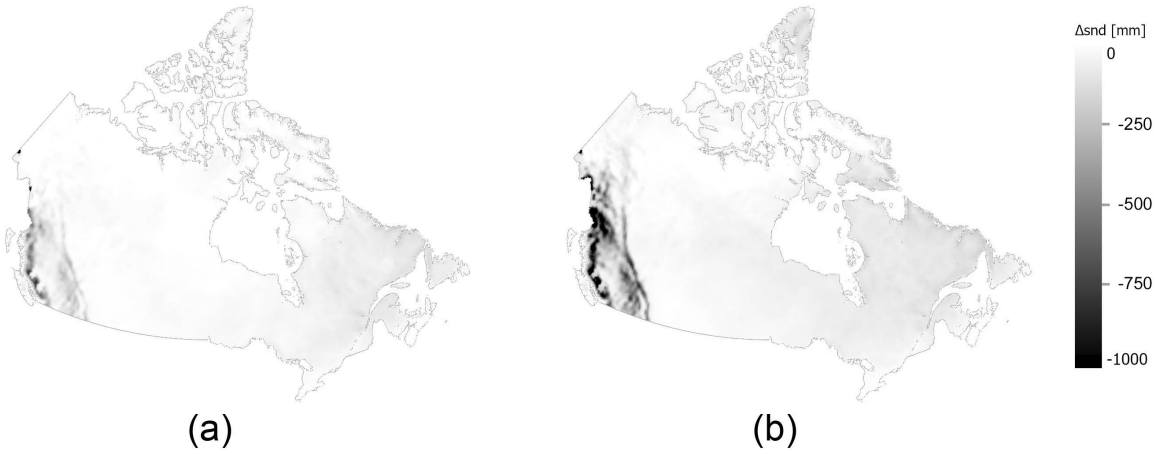


FIGURE 2.19 The distributions of snow cover anomalies for RCP4.5 (a) and RCP8.5 (b) climate change scenarios [15].

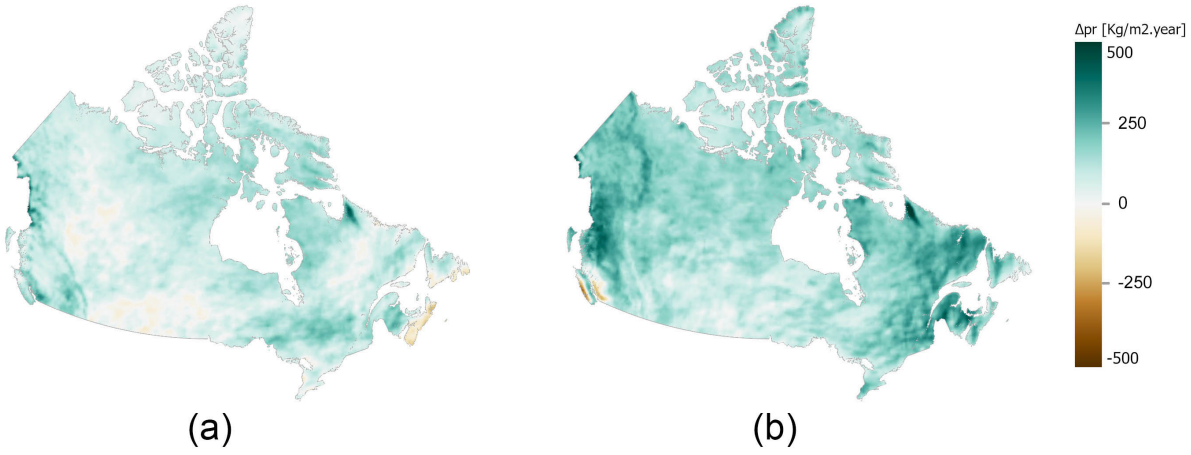


FIGURE 2.20 The distributions of precipitation anomalies for RCP4.5 (a) and RCP8.5 (b) climate change scenarios [15].

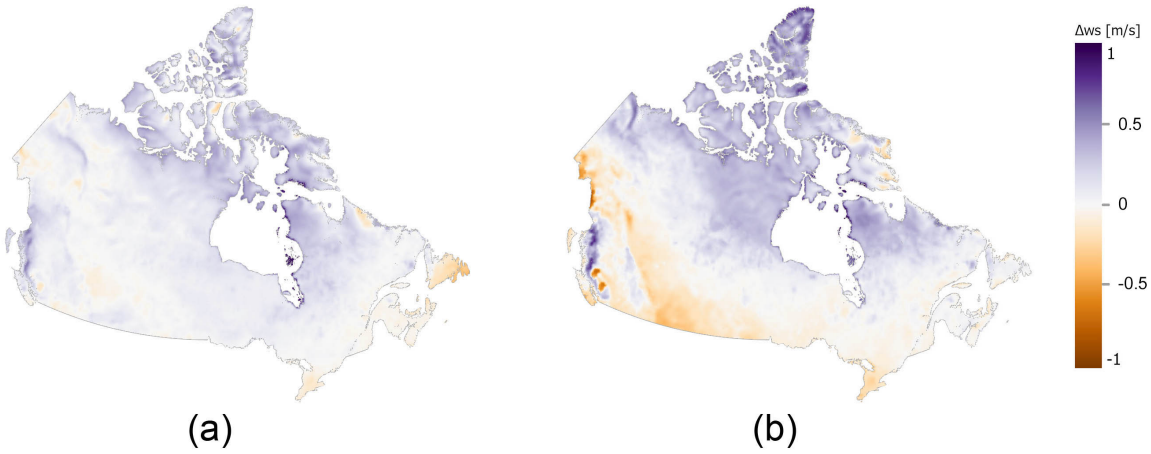


FIGURE 2.21 The distributions of wind speed anomalies for RCP4.5 (a) and RCP8.5 (b) climate change scenarios [15].

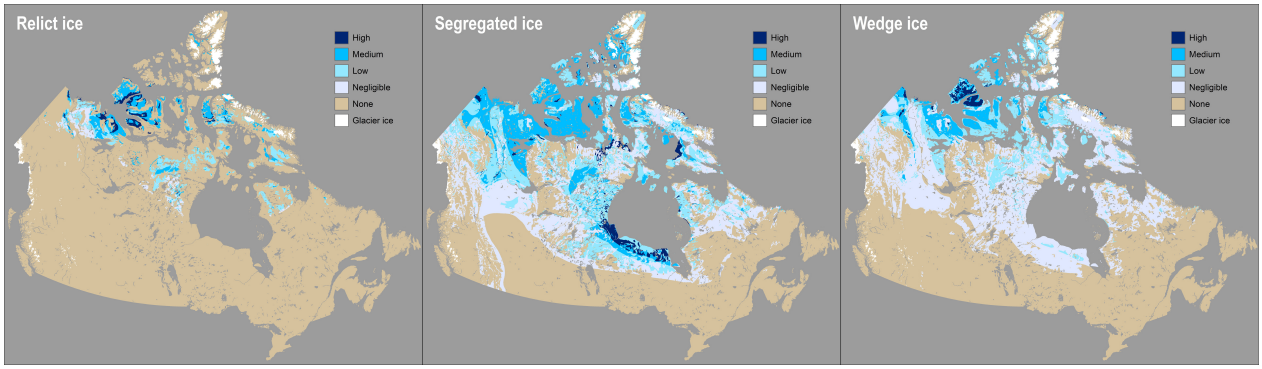


FIGURE 2.22 Relict, segregated and wedge ice formations across Canada, presented by [16].

between the ground and outer space, including the atmosphere. The surface energy budget has several components, including solar and terrestrial radiation and other factors, such as wind speed, albedo, vegetation, and snow cover. The resultant of the surface energy budget, ground surface temperature, is often used as a rough indicator of permafrost stability. Long-term prediction of ground surface temperatures at several major communities in Northern Canada using a data-driven approach indicates a warming up to 2.90–4.44 °C by 2100 under RCP 4.5 and RCP 8.5 scenarios, respectively (Figure 2.23) [17, 75]. The location of these communities and the type of permafrost associated with each location is shown in Figure 2.24.

The warming of permafrost is associated with the loss of mechanical strength in soil, which results in a wide range of geohazards that puts the overlaying infrastructure at risk. The geohazards range from slow-paced deformations, a.k.a. creep, to coastal erosion and sudden landslides, known as retrogressive thaw slumps (RTS), which have become more common in northern Canada. Between 1984 and 2015, a 60-fold increase RTSs has been observed, as more than 4000 were initiated across Banks Island in the Northwest Territories [76].

Moreover, man-made alterations to the surface energy budget are known to destabilize permafrost. Construction-related activities, such as deforestation and devegetation, water ponding, snow accumulation, and alteration of ground slope and wind regime at the ground surface, can increase ground temperature and induce permafrost thaw [77–79]. Several passive cooling methods, including high-albedo surfacing, sun sheds, air convection embankments, air ducts, heat drains and thermosyphons, have been proposed for pipelines and transportation infrastructure [80,81]. In the case of SMRs, the heat loss from the underground envelope may surpass the thermal capacity of passive cooling methods and may require active cooling or pre-thawing of the existing permafrost prior to construction to mitigate ground subsidence during the lifecycle of the unit.

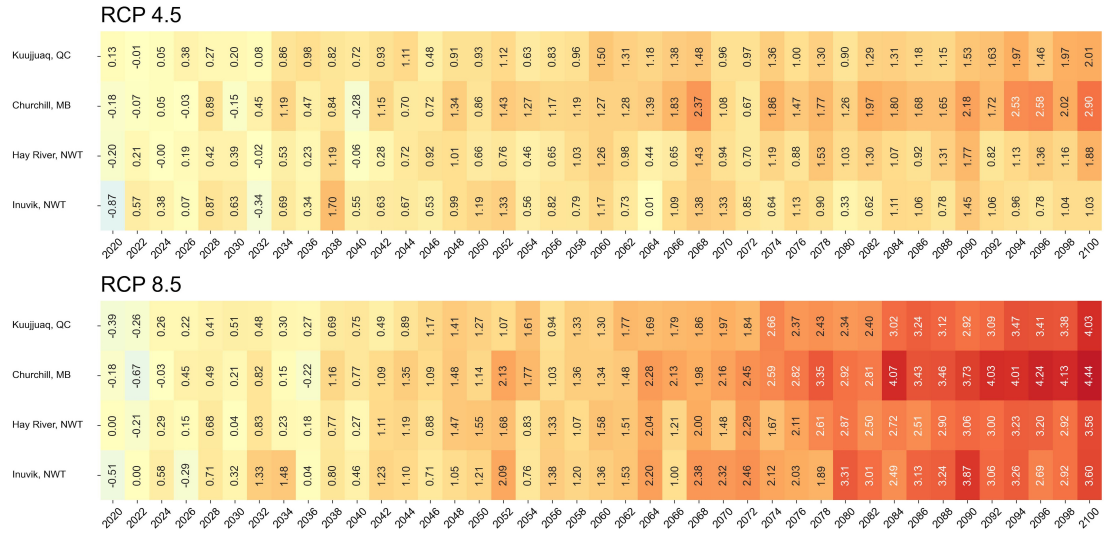


FIGURE 2.23 Mean annual ground surface temperature anomalies (2010-2020 baseline period) projected at major northern communities under the RCP 4.5 and RCP 8.5 climate change scenarios [17].

2.5 Pros and Cons of SMR Technology in Northern Canada : Environmental and Economic Considerations

Employing SMRs in Canada's northern territories offers several advantages [43], including sustainable energy supply, reduced fossil fuel consumption, greenhouse gas emissions, lower unemployment rates, and the potential for exporting SMR technology. However, there are notable challenges to adopting SMRs. Economic concerns arise due to the potentially high operation and maintenance costs compared to energy output in remote communities and mines. Additionally, deploying SMRs in northern mines may raise local concerns about reactor safety, radioactive waste management, and perceived health and environmental impacts.

SMRs can also pose ecological and human health risks in northern or arctic regions since the environmental guidelines for Canadian nuclear facilities are mostly based on designs that apply to temperate climate regions [82]. For instance, a significant portion of SMR-generated heat is dissipated to the environment. SMRs must be located more than 1 km away from communities and cannot contribute to district heating. Efforts are underway by the Standards Council of Canada (SCC) to develop and promote climate-resilient standards for northern infrastructure design, management and operation [83]. Although the IAEA offers some data and parameters for northern regions [84], specific parameters for SMR design in northern regions are lacking. Experimental data are needed to verify and validate numerical models simulating SMR behavior in northern environments. Additionally, SMRs using unconventional

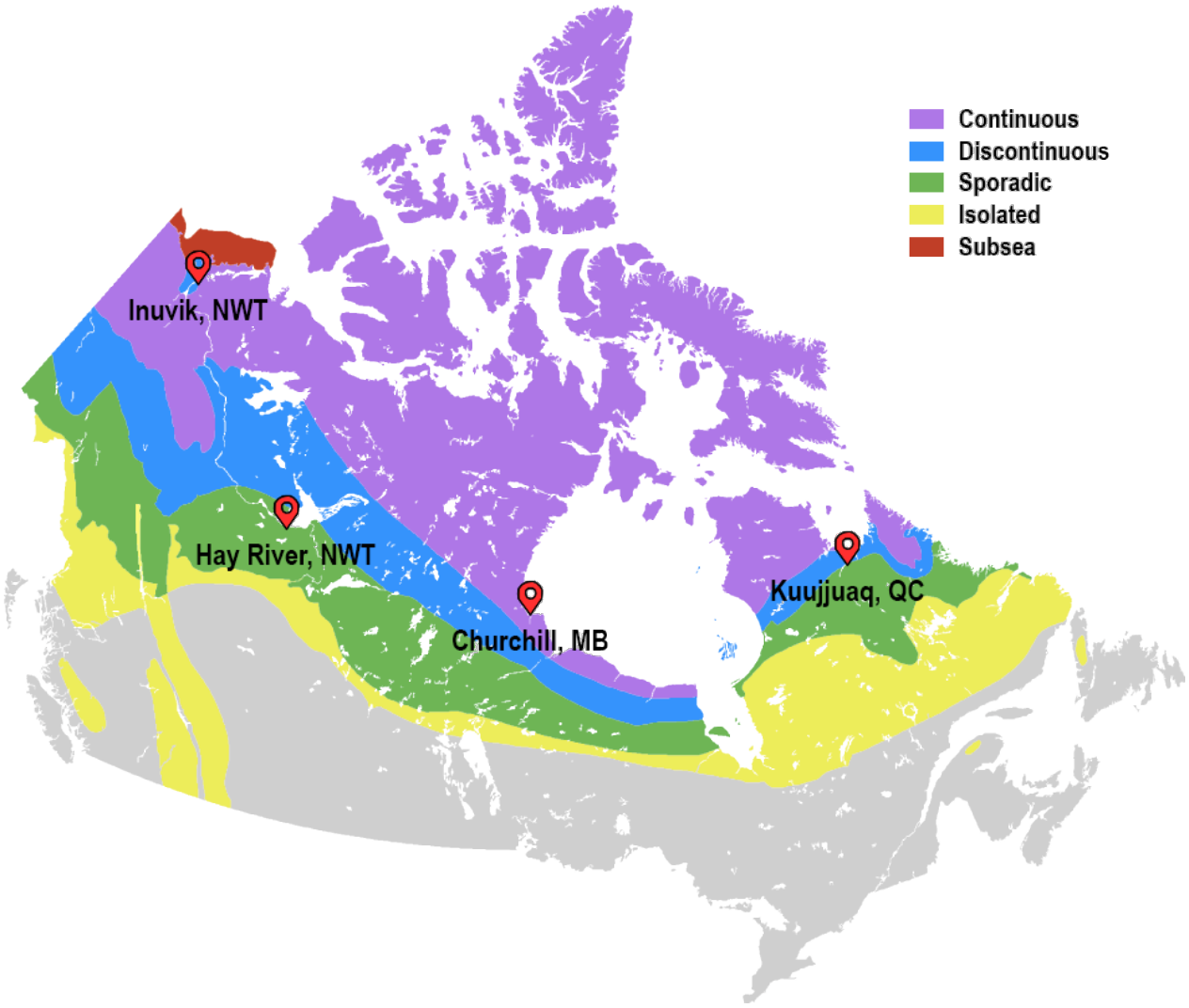


FIGURE 2.24 The location of selected major communities for ground surface temperature projection on a permafrost distribution map. The permafrost distribution map is a modified version of Permafrost Atlas of Canada, 5th edition [18] presented by B. O'Neill et al (2019) [16].

fuel and coolant mixtures may generate poorly-understood emissions and waste. Uranium-fueled SMRs produce familiar byproducts, but gas-cooled, molten salt, sodium-cooled, and lead-cooled SMRs could yield different activation products, some of which may be highly mobile in the environment or accumulate in the food chain. Addressing these concerns requires specific guidelines considering northern geoenvironmental conditions [82].

2.6 Finding the Perfect Spot : How to Choose the Best Location for SMRs

For deploying SMRs, thorough assessments of necessity and feasibility are crucial. Site selection is a critical step considering natural conditions, land use, geotechnical characteristics, soil conditions, public acceptance, environmental impacts, climate change, and geohazards [42]. This process significantly influences construction costs, environmental health, public safety, and long-term success.

To regulate SMRs, CNSC categorizes all reactor facilities, including SMRs, as Class IA nuclear facilities under the Class I Nuclear Facilities Regulations, applying the same regulations as traditional reactor facilities [85]. This approach allows for the use of traditional nuclear power plants (NPPs) site selection studies as references for SMR site selection, considering four major group factors : natural conditions, socio-economic factors, environmental impact, and safety concerns [42]. CNSC evaluates potential NPP sites through site surveys and detailed assessments to minimize negative environmental impacts and ensure safe operation within defined parameters. They also aim to identify mitigation strategies to reduce risks to national security, public safety, and the environment if the site is chosen for the NPP [86]. According to CNSC, key parameters for evaluating new reactor facility sites include :

- General criteria : population density and growth, technical basis for the safety and security of the reactor, radiological or conventional effects, storage and transport, chemical or thermal releases.
- Atmospheric and meteorological considerations : wind speed and direction, air temperature, precipitation, humidity, atmospheric pressure.
- Evaluation of natural external events : climate change, meteorological hazards, surface water hazards, groundwater hazards, geotechnical hazards, seismic and geological hazards, biological hazards, natural fire hazards.
- Evaluation of external, non-malevolent, human-induced events : aircraft crashes and other transportation hazards, fires and explosions, chemical and radiological hazards, electromagnetic interference hazards.

In the following sections, a different categorization is made according to the literature.

2.6.1 Natural conditions

When selecting NPP sites, safety criteria include natural factors like earthquakes, temperature, precipitation, flooding, and volcanism. These encompass geographical and geological aspects, as well as meteorological conditions. Geographical and geological considerations involve avoiding tectonically active zones with seismic disturbances, such as faults, fractures, and crustal movements. Additionally, factors like the availability of cooling water, subsurface material characteristics, bedrock depth and type, topography, slope, and location (coastal or inland) are vital for site selection. Meteorological factors such as wind speed, humidity, atmospheric stability, and extreme events, alongside temperature and rainfall, also play a significant role in NPP siting [42].

In the context of climate change and spatiotemporal characteristics of permafrost regions, it is crucial to take into account climate nonstationarity in the site selection and not only rely on historic and recorded data. Also, the geomechanical response of permafrost foundations to structural and climate loadings is of great importance. A thorough permafrost characterization through extensive field surveys and advanced laboratory geotechnical testing is required for the soil-structure design of SMR structures. This should include not only mechanical responses but also the effect of temperature change close to the freezing point, frost susceptibility, and seepage on the thermo-hydro-mechanical behavior of permafrost geomaterials.

2.6.2 Socio-economic factors

It is important to consider socioeconomic factors when selecting a site for SMR deployment, including factors such as public support, population density, construction costs, transmission expenses, and transportation expenses [42]. Engaging with local communities is essential for gaining social acceptance and addressing any concerns or potential impacts, especially in the context of northern development. This includes conducting thorough public consultations, providing transparent information, and addressing the socioeconomic needs and aspirations of the local community.

2.6.3 Environmental impacts

The compatibility of SMRs with the environment is a crucial factor that must be taken into account during site selection. This involves assessing the potential radiological and non-radiological impacts on the surrounding environment, including human health, terrestrial and aquatic ecosystems, and natural reserves [42].

SMRs require a significant amount of water for cooling purposes, which can have an impact

on local water resources [87]. The site selection should consider the availability of water resources and the potential impact on local water quality and quantity. Moreover, SMRs emit small amounts of greenhouse gases and other pollutants during operation, which can have an impact on local air quality [87]. The site selection should consider the potential impact on local air quality and the surrounding environment.

SMRs generate radioactive waste, which requires careful management to minimize the impact on the environment and public health [87]. The site selection should consider the availability of suitable waste management facilities and the potential impact on the surrounding environment. This is of great importance in the context of permafrost regions since even conventional landfill management in northern regions affected by permafrost degradation is a challenging task.

The site selection should consider the potential impact on local biodiversity and ecosystems [87]. The site should be chosen in a way that minimizes the impact on natural habitats and preserves the local biodiversity.

2.6.4 Safety concerns

The primary safety objective for SMRs can be viewed from two perspectives : (1) safeguarding individuals, the public, and the environment against harmful radiation effects ; and (2) safeguarding SMRs from being potentially dangerous facilities [42].

The site selection should consider the availability of emergency response resources and the ability of the local community to respond to a potential accident, e.g. community resilience. The local community should be involved in the emergency planning process to ensure that they are prepared to respond to any potential incidents.

2.7 Conclusion and Policy Implications

SMRs will play a vital role in Canada's ambitious energy transition strategy. They can provide sustainable clean energy supply for northern development and contribute to the sovereignty, security, development, and relations with Indigenous peoples in the Arctic. In spite of this great potential, there are several uncertainties regarding the best design, adaptation, and implementation of SMRs in the Canadian unique climate. For instance, it is of great importance to assess the structural integrity of SMRs subject to climate nonstationarity and environmental loading. Such considerations are crucial in the structural and geotechnical design of SMR structures as well as their maintenance [88]. This is even more critical in regions that are more vulnerable to adverse effects of climate change such as northern regions and coastal

lines.

In terms of structural and geotechnical design considerations, a key factor is that a substantial part of the reactor unit itself can be partially or fully embedded in the ground. As presented in Section 2.3, SMRs work at very high-temperature ranges and the underground reactors will dissipate significant heat to the surrounding soils. The dissipation of heat from SMRs to the ground is an important consideration for their installation. While specific information regarding heat dissipation from SMRs to the ground is not readily available in the literature, it can be inferred that managing heat transfer and its impact on the surrounding environment, particularly in permafrost regions, is a significant concern. The heat generated by SMRs can potentially contribute to permafrost thawing, which can have detrimental effects on the stability of the ground and infrastructure [89]. Hence, it is crucial to assess and mitigate the impact of heat dissipation on permafrost conditions during the site selection and design process [90]. The interaction between the reactor unit and surrounding soil/rock, especially with accelerating climate change in northern regions, can raise issues for the structural integrity of SMRs and soil stability. For example, the ground's strength and stiffness may be significantly reduced due to thermal disturbance of the permafrost, resulting in structural settlement and stability problems. The ensuing damage will potentially shorten the lifespan of the infrastructure and increase maintenance costs, leading to significant operational and financial risks. It may also cause adverse environmental impacts and safety concerns from the public. The thermal stability of the ground should be guaranteed during the design and operation of SMRs. Local permafrost conditions must be assessed and adequately protected around the structural foundations of the SMR facility when constructing an SMR on/or in permafrost soils or bedrock. Different strategies such as ground freezing [91] and pre-thawing and ground improvement techniques should be studied in advance.

Studies have been conducted on the external heat transfer capabilities of submerged SMR containment structures, particularly in relation to seawater natural convection and fluid dynamics [92]. These studies focus on the heat transfer features induced by the heating of the reactor containment, which can provide insights into the management of heat dissipation from SMRs. As mentioned earlier, the availability of water resources for cooling purposes is one of the important considerations for site selection for SMRs. According to the World Nuclear Association [93], 45% of nuclear plants use the sea for once-through cooling, while 26% use cooling towers. According to Energy Services Group International [94], Russia's SMRs are water-cooled reactors that require active cooling. However, in the Arctic and northern regions, using Arctic ocean water for cooling SMRs may not be feasible due to the low temperatures of the water. As mentioned previously, the use of water for cooling purposes can have environmental impacts, such as thermal pollution and the potential for harm to

aquatic life. Additionally, the use of water for cooling purposes may not be feasible in areas with limited water resources. As such, the best strategies for cooling purposes should be adopted in the Arctic and northern regions for permafrost and environmental protection.

Changing climatic conditions may degrade the permafrost's physical and mechanical properties over and above the changes caused by the thermomechanical interaction between the SMR and surrounding soils. As our climate changes (non-stationarity), the demands or loads arising from weather conditions change over time (e.g., changing precipitation patterns). Because of these changing climatic patterns, erratic changes in ambient and ground temperature may occur resulting in detrimental transformations in the permafrost properties both spatially and temporally. Civil engineers traditionally rely on the stationarity of climatic conditions to design and deliver safe, reliable, and durable civil infrastructure, assuming the constancy of historical climatic conditions to predict infrastructure behavior. Thus, climate change-induced variations in loads (demands) and capacities, combined with permafrost degradation create additional challenges to the structural design of SMRs. The lack of appropriate provisions for the incorporation of future weather and climate information into the design, operation, and management of infrastructure remains a significant barrier to systematically improving the climate resilience and structural integrity of civil infrastructure, particularly SMRs. It is necessary to characterize the spatial and temporal variation and alternation of permafrost caused by the thermomechanical soil-structure interaction between an SMR and surrounding permafrost. At the same time, it is necessary to incorporate the changing permafrost properties and the SMR-permafrost interaction caused by climate change in the civil engineering design and asset management of SMRs to ensure structural integrity, safety, and serviceability.

It is worth reminding that the requirements for geotechnical and structural design for sensitive infrastructure such as SMR facilities are unique. For instance, considering climate extreme events such as extreme heat, extreme precipitation, climate-induced landslides and retrogressive thaw slumps, with intensity and frequency surpassing the recorded historical data, as well as considering the earthquake load uncertainties is necessary to design a system that is highly robust and resilient. Accounting for extreme events and accidents associated with very low probability is crucial for these sensitive systems, unlike conventional structural systems. Design of such sensitive infrastructure due to its socioeconomic importance must consider both fail-safe and safe-to-fail design concepts ensuring safety, serviceability, robustness, and resilience. Therefore, estimating the loads considering non-stationarity is important, particularly in the current scenario of a rapidly changing climate with an increasing frequency of extreme events. The whole spectrum of extreme loads, including earthquakes, must be considered in the geotechnical and structural design of nuclear facilities and reac-

tor buildings, and in the analysis of containment [95]. According to the Canadian Seismic Hazard Model, Canada's north has a relative hazard of low/moderate to high (Figure 2.25). The seismic hazard provided by the Geological Survey of Canada and up-to-date engineering seismology tools should be used to select and scale hazard-consistent multi-component (3D) input ground motion recordings for each selected site. The dynamic nonlinear soil-foundation-structure interaction and seismic site effects must be also analyzed at the local and basin scales [96, 97]. In particular, basin-scale seismic site effects in permafrost regions have not been extensively studied in the literature. These are of great importance in the robust and resilient design of SMR structures. Seismic isolation might be required [98, 99], but relevant studies and guidelines applicable to SMRs in northern climates are lacking. The vibration effects of fluid in the pools during seismic excitation, i.e. fluid-structure interaction, must also be considered [100, 101]. Seismic fragility evaluations based on Probabilistic Seismic Hazard Analysis (PSHA) can be conducted to further assess SMR resilience to earthquakes [102,103], including post-earthquake safe operation.

Last but not least, it is worth mentioning that emergency preparedness and community resilience are crucial considerations for the installation of SMRs in Canada's North. Educating the northern communities about SMRs and what to do in the event of an emergency is crucial for effective emergency preparedness [104]. This includes providing information on evacuation procedures, sheltering in place, and other protective actions. SMR plants should have contingency plans in place to respond to potential emergencies, such as natural disasters, equipment failures, or security threats [105]. These plans should include procedures for communication, evacuation, and emergency response.

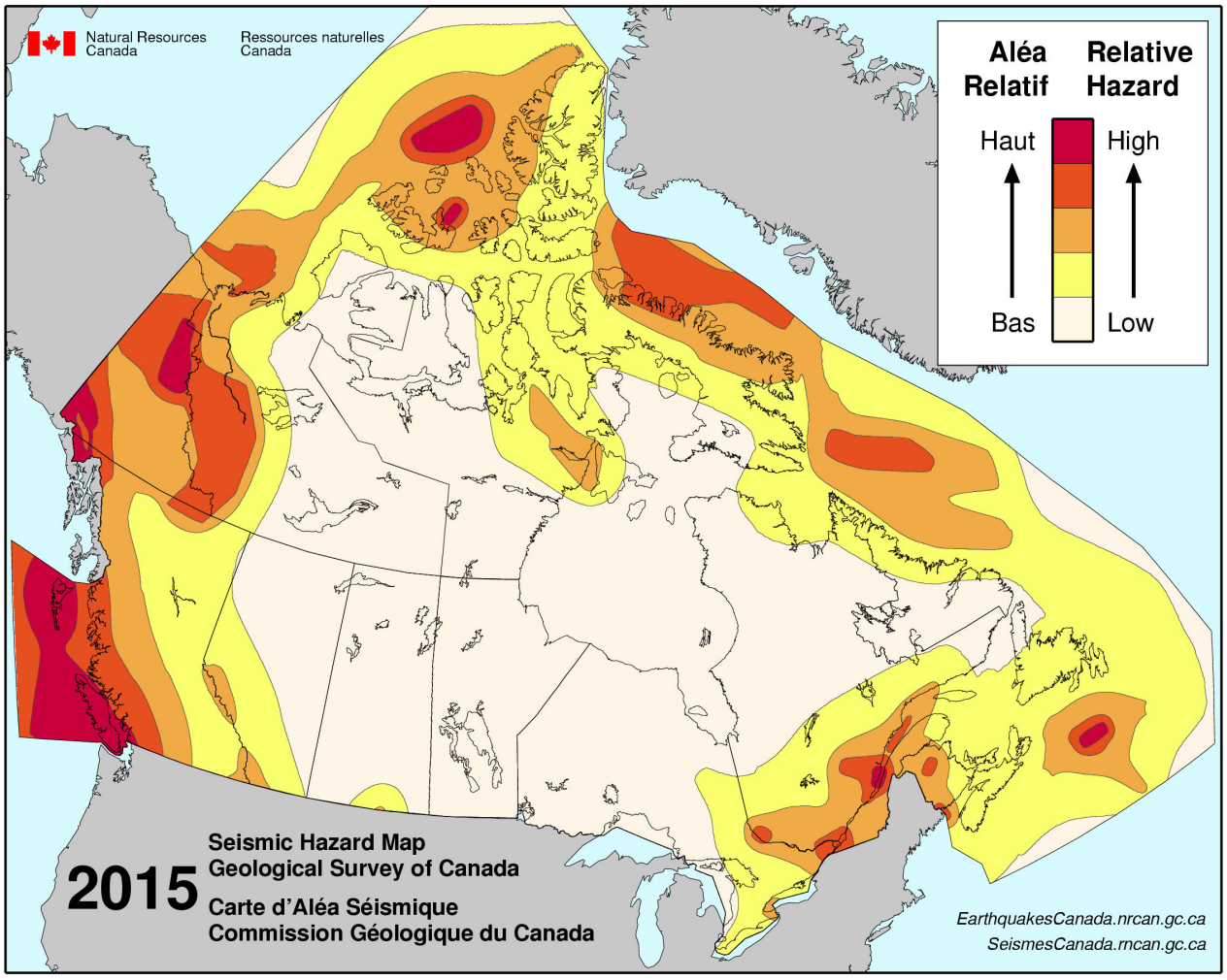


FIGURE 2.25 The simplified seismic hazard map for Canada [19]

CHAPTER 3 ARTICLE 2 : THERMAL MODELING OF SMALL MODULAR REACTORS IN PERMAFROST REGIONS SUBJECT TO CLIMATE NON-STATIONARITY

This chapter is reproduced, with modifications, from,

Afsharipour M. Gheysari A., Bouaanani N, Boudreault R., Maghoul P. *Thermal Modeling of Small Modular Reactors in Permafrost Regions Subject to Climate Non-stationarity*, Journal of Cold Regions Engineering, in Review (2023).
Submission date : 2023-10-31

Abstract

Small Modular Reactors (SMRs) are an alternative for clean energy solutions in Canada's remote northern communities thanks to their safety, flexibility, and reduced capital requirements. Currently, these communities are heavily reliant on fossil fuels, and the transition to cleaner energy sources, such as SMRs, becomes imperative for Canada to achieve its ambitious net-zero emissions target by 2050. However, applying SMR technology in permafrost regions affected by climate change presents unique challenges. The degradation of permafrost can lead to significant deformations and settlements, which can result in increased maintenance expenses and reduced structural resilience of SMR infrastructure. In this paper, we studied the combined effect of climate nonstationarity in terms of ground surface temperature and heat dissipation through SMR reactor cores in two distinct Canadian locations : Salluit in Quebec, and Inuvik in the Northwest Territories. It was shown that these combined effects can make serious changes to the ground thermal conditions for a radius of 15 m to 20 m within a radius of 15 to 20 meters around the reactor core. The change in the ground thermal conditions poses a threat to the integrity of the permafrost table. The implementation of mitigation strategies is imperative to maintain the structural integrity of the nuclear infrastructure in permafrost regions.

3.1 Introduction

Reliable energy is a necessity for the sustainability of communities. In Canada, there are approximately 300 remote communities and resource-driven businesses, such as mining operations, that depend on locally generated heating and electricity [67, 106]. The energy requirements for these communities and commercial ventures can vary significantly, ranging from

a few hundred kilowatts to tens of megawatts. Presently, many of these communities and businesses rely on fossil fuel-based power generation to meet their electricity and hot water needs [67]. However, a majority of the existing power generation plants have either reached their intended lifespan or are approaching it within the next decade. Moreover, Canada is aiming toward a net-zero emission goal along with 120 other nations, including all other G7 countries (United Kingdom, United States, Germany, Italy, France, and Japan) [24]. Consequently, efforts are underway to reduce dependence on fossil fuel generators. Given that the electricity demand across Canada is likely to see a jump of 47% from 2021 to 2050, alternative clean approaches to producing power need to be considered.

3.1.1 SMRs : Potential Solutions to Canada's Energy Demand

In response to the demanding Canadian energy market, Small Modular Reactors (SMRs) are being presented as a promising new technology with a wide range of environmental, social, and economic benefits [107]. As the International Atomic Energy (IAEA) describes, SMRs are advanced reactors in which the capacity to produce energy does not exceed 300 MWe [38]. They are considered by their promoters to be safer, more flexible, and less costly when compared to traditional large-scale nuclear power plants [107]. This makes SMR technology a viable option to consider for replacing carbon-emitting power generators across Canadian remote communities. SMRs offer various benefits to these remote areas, including the generation of electrical power and the provision of heat for district heating and small-scale industrial processes. As of December 2019, 12 different SMR vendors were in negotiations with the Canadian Nuclear Safety Commission (CNSC) at various phases of licensing [44]. This shows that SMRs are being considered as serious candidates to play a part in Canada's arctic energy landscape, however, there is a lack of design recommendations and geotechnical investigation for installing such infrastructure in the Canadian remote locations.

3.1.2 Permafrost, SMRs, and Climate Non-Stationarity

Permafrost degradation is one of the adverse consequences of climate warming in northern Canada. Permafrost, defined as ground that maintains a temperature at or below 0 °C for a duration of at least two consecutive years [73], encompasses more than 15 percent of the northern hemisphere and spans roughly half of Canada's landmass [74]. The geographical distribution of permafrost typically follows a northward trend, commencing with isolated patches at lower latitudes and progressing to more extensive formations as one approaches the 55° latitude mark. It attains continuity along the shores of Hudson Bay and the Arctic Ocean [18]. Permafrost can comprise pore ice as well as different manifestations of excess

ground ice, including relict ice, segregated ice, and ice wedges [108].

The stability of permafrost is linked to the surface energy budget, which consists of the exchange of energy between the ground and the surrounding environment. This budget comprises numerous constituents, including but not limited to solar and terrestrial radiation, wind speed, albedo, vegetation cover, and snow cover. Ground surface temperature, an outcome directly influenced by the surface energy budget, frequently serves as a general indicator for permafrost stability [108]. Projections indicate that the surface energy budget will exhibit an escalating trend due to the influence of global warming under different climate projection scenarios. Long-term forecasts for Canada, in particular, point to a warming trajectory ranging roughly from 2.90 to 4.44 °C by the year 2100 under the RCP 4.5 or RCP 8.5 climate scenarios, respectively [17, 75].

By constructing the SMRs on the surface or below the ground, the combined effect of such climate non-stationarity and heat dissipation through the SMR reactor core could seriously disturb the surrounding ground's thermal regime and permafrost table. Therefore, maintaining the permafrost integrity against this thermal disturbance is of paramount importance. To ensure the stability of the SMR foundation, it is essential to comprehend the heat transfer mechanisms and assess how various factors influence the local permafrost conditions. This includes a thorough analysis of ground temperature and its distribution with depth, which, in turn, aids in determining the mechanical properties of the permafrost ground [6].

3.1.3 SEALER : One of the SMR Candidates in Canada

SEALER is an SMR design created by the Swedish company LeadCold. This compact reactor has the capacity to generate electricity ranging from 3 to 10 MWe, measuring 2.7 meters in diameter and 6 meters in height. Operating within a temperature range of 390-432 °C, SEALER employs lead as its coolant [10]. Its application is targeting communities and mining operations located in the Canadian Arctic, which lack connectivity to the main power grid [60]. SEALER units are considered viable power sources for several off-grid communities in Nunavut and the North-West Territories due to their size and energy needs. Furthermore, deploying SEALER units at Arctic mining sites is cost-effective, bringing about reduced operational costs and the profitable processing of lower-grade ores [10].

The heat produced by the SEALER core is transferred to the adjacent concrete pit, and over time, it dissipates into the surrounding ground. In a preliminary investigation, it is assumed that the area around a SEALER reactor serves as an effectively limitless heat sink, maintaining the pit wall temperature at a constant 90°C [11].

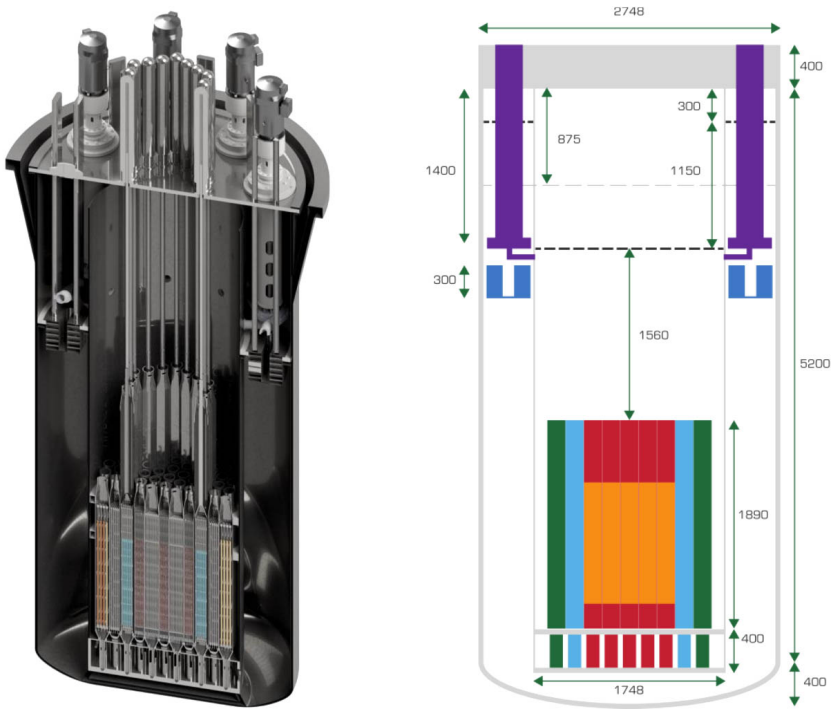


FIGURE 3.1 SEALER by LeadCold Nuclear Inc. [10, 11].

In this paper, we will apply a heat transfer model on two sites in Canada's north to study the effect of climate non-stationarity and heat dissipation from a SEALER reactor core on permafrost thermal conditions until the end of the century. The model takes into account heat conduction within permafrost soil and considers the in-situ phase change of pore water. To project the climate conditions up to the end of the 21st century, an AI-driven approach is utilized, and this climate projection is incorporated into the model as a temperature boundary condition. The simulations are conducted using an axisymmetric Finite Element (FE) model, with the assumption that a SEALER reactor will start operating at both sites in January 2025.

3.2 Methodology

3.2.1 Case Studies

Two case studies on different locations are considered in this study. The first site is located near the village of Salluit, Quebec and the second site is near Inuvik, Northwest Territories (Figure 3.2).

The site features, including the stratigraphy of the soil along with physical and thermal

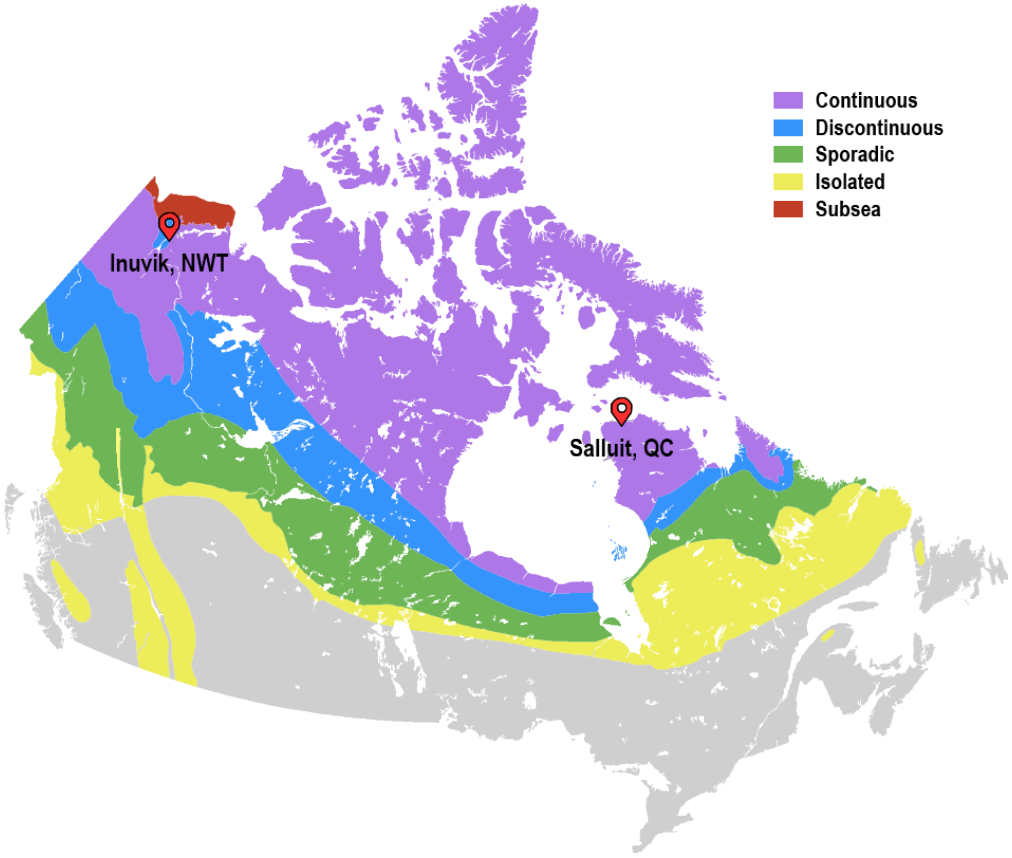


FIGURE 3.2 The selected locations for this study on a permafrost distribution map. The permafrost distribution map is a modified version of Permafrost Atlas of Canada, 5th edition [18].

properties of the layers for Salluit and Inuvik locations, are obtained from from the available literature [3, 4]. A representation of both sites is presented in Figure 3.3. Thermal properties associated with each layer for Salluit are also presented in Table 3.1, along with Inuvik thermal properties in Table 3.2.

An additional component, concrete, is added to both geometries which is used to model the pit around the reactor core. The thickness of the concrete pit is assumed to be 1 m. The properties of concrete are shown in Table 3.3.

3.2.2 Governing equations

In this study, frozen soil is considered a three-phase porous medium composed of solid skeleton, pore water, and pore ice. The equation governing the transient conductive heat transfer in such a medium, accounting for the impact of pore-water phase change, is expressed as follows :

$$\left(\rho C_p - L_f \rho_i \frac{\partial \theta_i}{\partial T}\right) \frac{\partial T}{\partial t} + \nabla . \mathbf{q} = Q \tag{3.1}$$

in which $(\rho C_p - L_f \rho_i \frac{\partial \theta_i}{\partial T})$ is the apparent volumetric heat capacity. L_f is the latent heat of fusion per unit mass of water (approximately $3.33 \times 10^5 [J/kg]$), ρ_i is the density of ice and $\theta_i = \Theta_{tot} - \theta_w$ is the volumetric fraction of pore ice by knowing that Θ_{tot} is the total water content and θ_w is the unfrozen water content. ρC_p is the volumetric heat capacity of the soil which can be estimated by the sum of the volumetric heat capacity of each constituent of a saturated freezing soil (solid skeleton, water, and ice) multiplied by its volumetric fraction as described below :

$$(\rho C_p) = \rho_w C_w \theta_w + \rho_i C_i \theta_i + \rho_s C_s \theta_s \tag{3.2}$$

The heat conduction flux, denoted as $\mathbf{q}$ (W/m^2), can be described using Fourier's law as follows :

$$\mathbf{q} = -k \nabla T \tag{3.3}$$

where k $(W/m.K)$ is the thermal conductivity of the medium :

$$k = k_w \theta_w + k_i \theta_i + k_s \theta_s \tag{3.4}$$

The total water content (Θ_{tot}) in this study is assumed to be constant, and in-situ phase change takes effect as a function of temperature, turning a fraction of the total water content into ice. An empirical relationship is employed in this model to establish a connection between

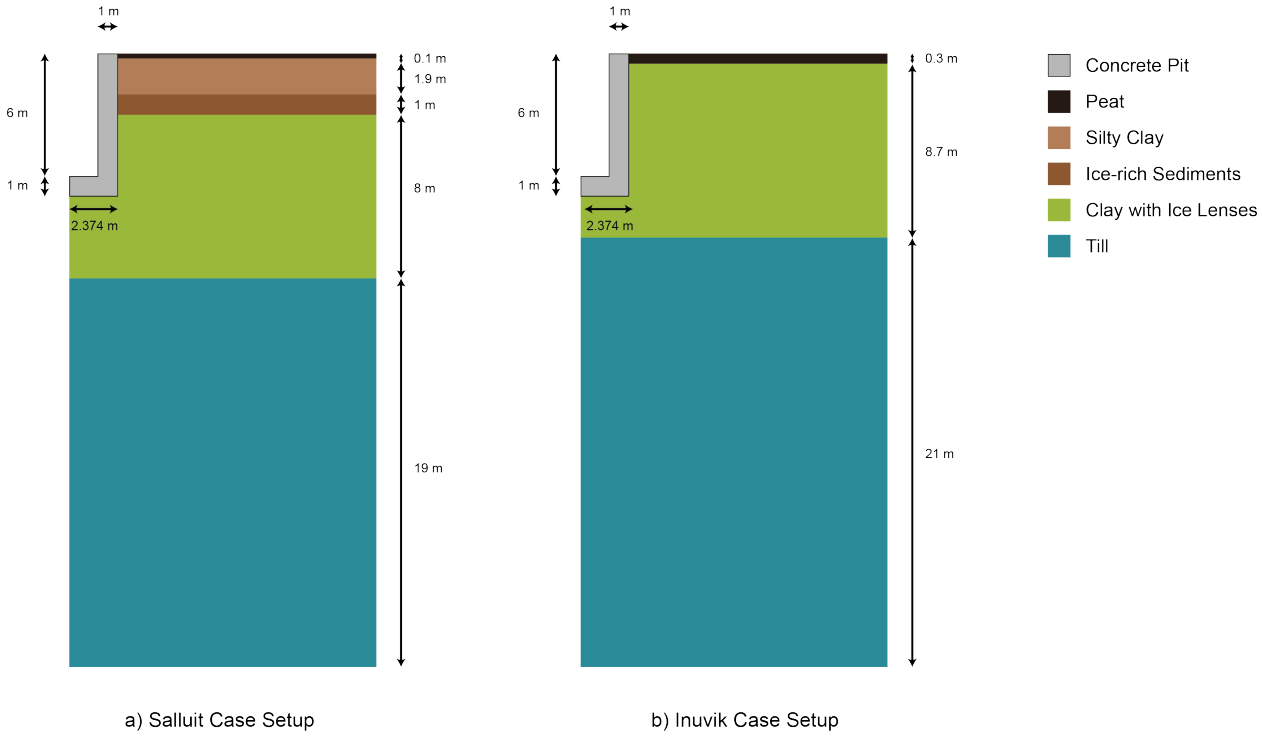


FIGURE 3.3 Salluit site setup and stratigraphy (a) [3]. Inuvik site and stratigraphy (b) is also presented [4].

TABLE 3.1 Properties of the different layers for Salluit case study, from [3]. Missing data is assumed with respect to [4,5]

Layer	**Unfrozen Heat Capacity** $(kJ/m^3.K)$	**Frozen Heat Capacity** $(kJ/m^3.K)$	**Unfrozen Thermal Conductivity** $(W/m.K)$	**Frozen Thermal Conductivity** $(W/m.K)$	**Bulk Density** (kg/m^3)
Peat	3600	3000	0.52	1.10	1000
Silty clay	2000	1700	4.57	4.63	1260
Ice rich sediments	3000	1990	1.27	1.50	1430
Clay with ice lenses	3125	1891	1.10	1.21	1600
Till	1840	1620	1.85	2.12	2085

TABLE 3.2 Properties of the different layers for Inuvik case study, from [4]. Missing data is assumed with respect to [3, 5]

Layer	**Unfrozen Heat Capacity** $(kJ/m^3.K)$	**Frozen Heat Capacity** $(kJ/m^3.K)$	**Unfrozen Thermal Conductivity** $(W/m.K)$	**Frozen Thermal Conductivity** $(W/m.K)$	**Bulk Density** (kg/m^3)
Peat	3750	3000	0.52	0.98	1000
Clay with ice lenses	3125	1891	1.10	1.21	1600
Till	1840	1620	1.85	2.14	1850

the unfrozen water content and the temperature within freezing soil [109] :

$$\theta_w = \theta_{wr} + (\theta_{w0} - \theta_{wr})e^{(a(T-T_0))} \tag{3.5}$$

in which θ_{wr} is the residual unfrozen water content assumed to be 0.05 in this study and $a[1/^\circ C]$ is a parameter that controls the curvature, taken here 0.16 [109].

TABLE 3.3 Concrete properties [6])

Component	**Density** (kg/m^3)	**Heat Capacity** $(J/kg.K)$	**Thermal Conductivity** $(W/m.K)$
Concrete	1920	840	1.4

Initial Conditions

The initial ground temperature for the Salluit site is given for 2017-2018 [3]. The temperature profile provides data up to 13.5 m depth, and the rest of the profile is assumed to remain constant from 13.5 m to 30 m depth (Figure 3.4). This assumption is made in comparison with the deepest presented temperature profiles of a nearby site, where the profile remains mostly constant up to a depth of 27 m (Figure 3.5). For Inuvik, the initial temperature profile is adapted from "Inuvik Airport 01TC02" site, situated in north of Inuvik [110], and the values are shown in Figure 3.6. The same assumption of the constant temperature profile is applied in the case of Inuvik as well. However, no neighboring site was found to confirm this hypothesis. Since the initial ground temperature profile did not extend throughout the entire depth of both model domains, a preliminary 5-year warm-up phase was incorporated before the primary study period in both cases. This warm-up phase was necessary to ensure that the ground reached a stable equilibrium state. To verify the simulations, a comparison of the measured ground temperature profile and the simulation results at the end of the warm-up phase is presented. The temperature profiles at the end of the warm-up phase serve as initial conditions for the model itself.

Boundary Conditions : Implementing Climate Non-Stationarity

A schematic of the boundary conditions of both models is presented in Figure 3.7. To incorporate the effects of climate change, an AI-driven projection of ground surface temperature is integrated into each model as the boundary condition at the ground surface [75]. The method introduces an innovative data-driven approach utilizing Long Short-Term Memory

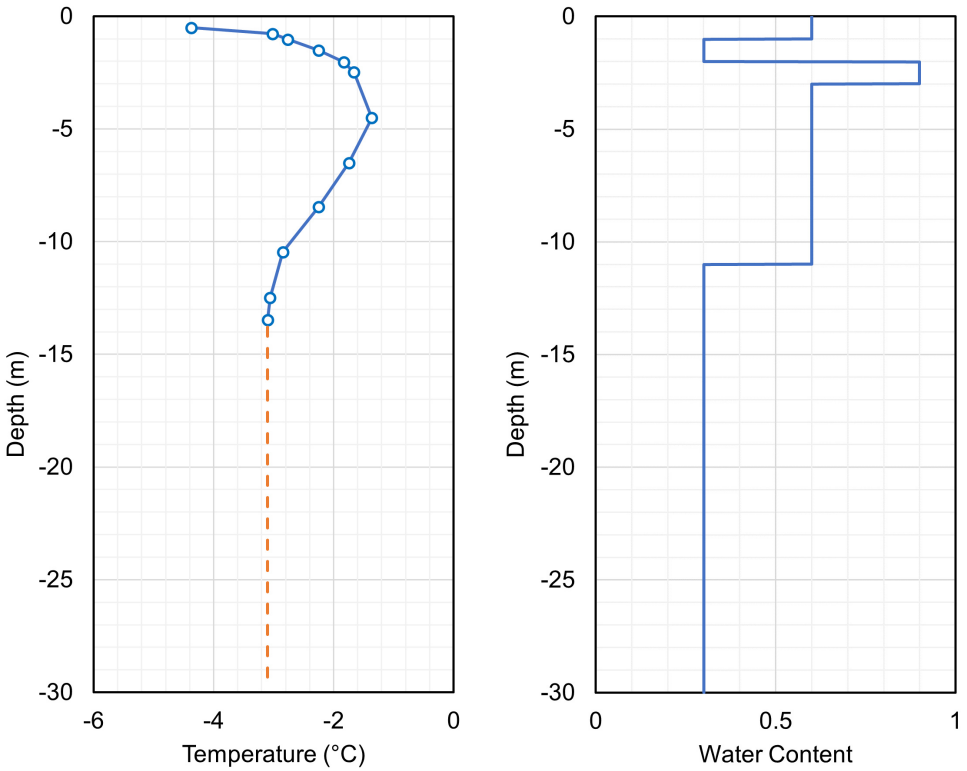


FIGURE 3.4 Salluit initial conditions [3]. The ground temperature profile is assumed to stay constant (orange dashed line).

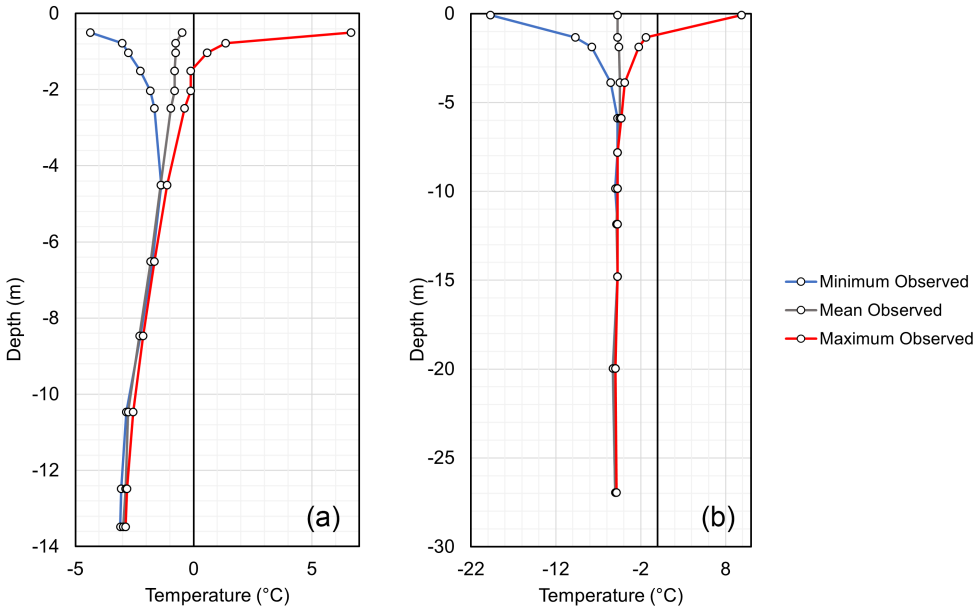


FIGURE 3.5 FP4 site (a) is considered in this article for the SMR location [3]. The deepest borehole temperature data is presented for FP2 site (b), containing temperature data up to 27 m depth. Comparing to this nearby site, the temperature profile is assumed constant from 13.5 m to 30 m.

(LSTM) networks for predicting ground surface temperatures based on meteorological variables. Their proposed framework for data-driven forecasting comprises three main stages : training, testing, and projection. The LSTM network is trained and tested using two subsets of a labeled dataset, which encompasses meteorological variables like air temperature and ground surface temperature, both of which were recorded at a specific site. This data-driven approach offers the advantage of generating predictions over extended timeframes under diverse climate scenarios or through ensemble modeling. Temperature data for Salluit (latitude 62.2 and longitude -75.6) includes daily records from January 2018 through December 2099 for two distinct climate scenarios : RCP4.5 and RCP8.5 (Figure 3.8). Similarly, temperature data for Inuvik, situated at latitude 68.3 and longitude 133.5, spans the same time frame and climate warming scenarios (Figure 3.8).

To account for the geothermal gradient effect, the bottom boundary of the models is set to $q = 0.032W/m^2$ [111, 112]. The left and right boundaries of the models were assigned adiabatic conditions, implying no heat flow. The models are axisymmetric geometries, with the axial symmetry defined on the left boundary of each model. It is assumed that the SMR would start working in January 2025. Therefore, the test consists of three main periods : a period of warm-up to stabilize the ground temperature profiles ; the period between January

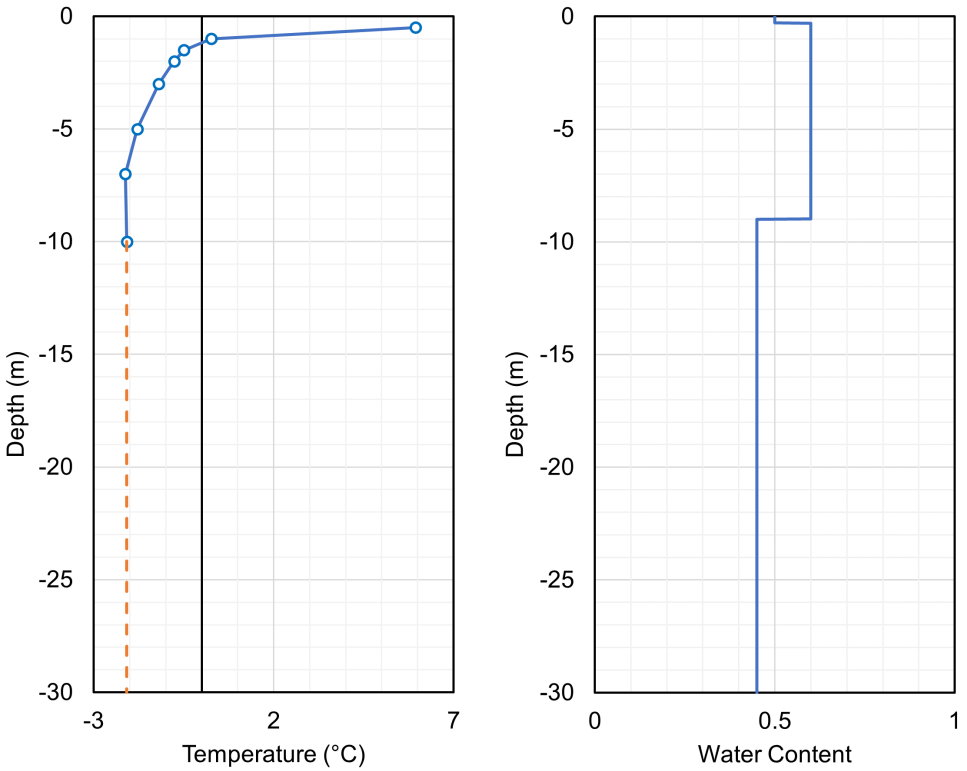


FIGURE 3.6 Inuvik initial conditions [4, 20]. The ground temperature profile is assumed to stay constant (orange dashed line).

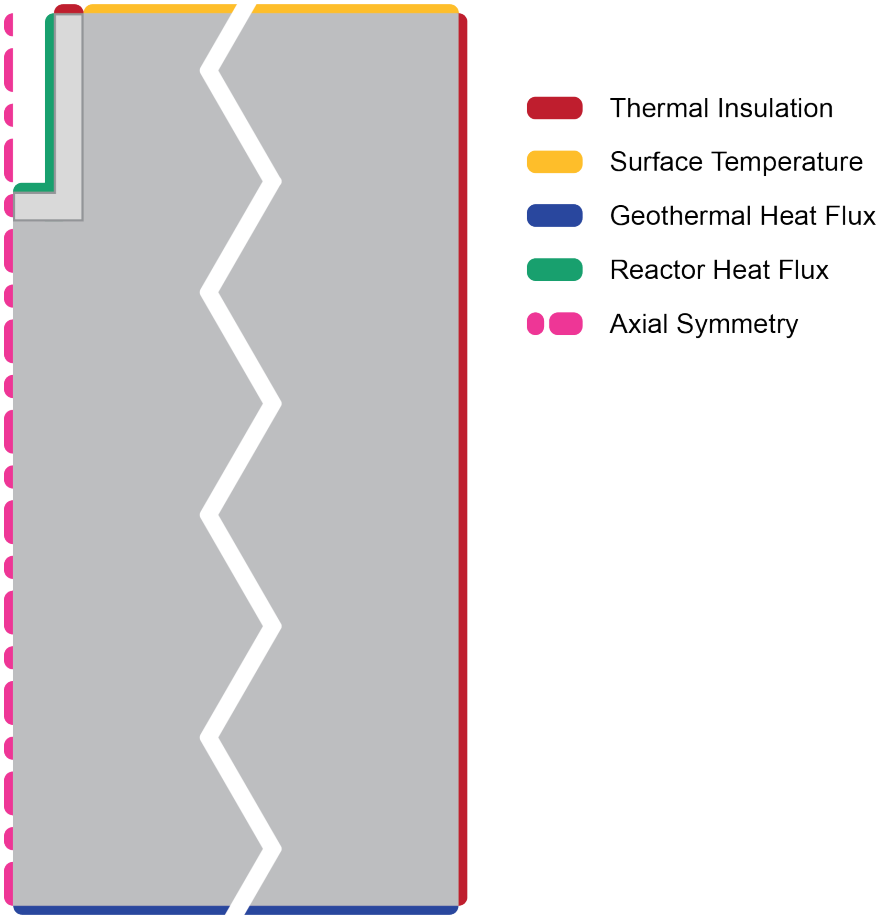


FIGURE 3.7 Boundary conditions for Salluit. The properties of the boundaries are the same for Inuvik.

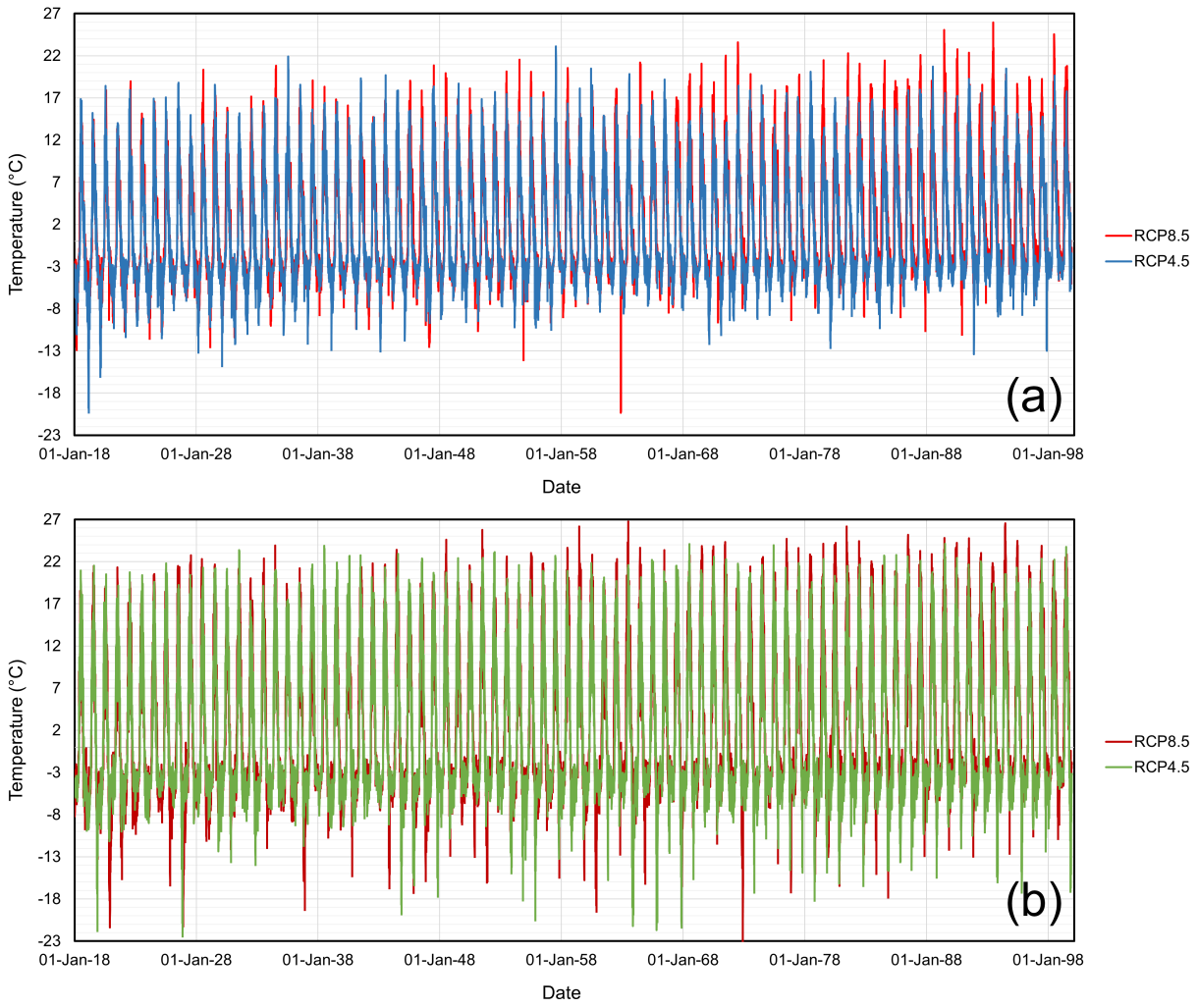


FIGURE 3.8 Salluit (a) and Inuvik (b) daily surface temperature projection data from January 2018 to December 2099 for two climate projection scenarios : RCP 4.5 and RCP 8.5. These values are applied to the top boundary of the respective simulations.

2018 to December 2024 in which the ground is only affected by climate non-stationarity ; and the period between January 2025 and December 2099 during which the inner boundaries of the concrete (heat dissipation) are assigned a convective heat flux of $q = 28(90°C - T)$ [113], implying the operation of the SMR reactor.

3.2.3 Numercial setup

The simulations were conducted in COMSOL v6.0, and the mesh and 3D representation of the models are illustrated in Figure 3.9. The mesh in this model is a custome quadrilateral build under extra fine settings. When the settings are set to extremely fine, one could obtain higher resolution graphs, but at the cost of a significant computation time with the same key results. Hence, the extra fine settings are used as a result of a sensitivity analysis.

For the tests, the radius of the model is set to 50 m to make sure that the effect of the thermal disturbance by the reactor would not reach the boundaries. Figure 3.10 shows the ground temperature profiles in December 2099 for these tests, which are set to only highlight temperatures above $0°C$. According to these results, it is evident that the reactor, considering the described setup, would affect a radius of around 15 m to 20 m in the time span of the simulation, depending on the location and climate scenario. Therefore, the radius of the models is kept at 50 m.

In total, eight simulation models were created, with four models for each location (Salluit and Inuvik). For each location, two climate scenarios were considered : RCP 4.5 and RCP 8.5. Within each scenario, two cases were examined : one with the deployment of an SMR and another without it. To capture the effect of temperature fluctuations, the models are run in daily time-steps, corresponding to the available daily temperature projection data.

Since the initial ground temperature profiles for both locations were measured from 2017 to 2018, the warm-up cycle must incorporate a suitable surface temperature measurement input within a close time period. Centre for Northern Studies (CEN) based at Laval University has published several ground temperature data sets for Salluit [114]. The average ground temperature data from the Salluit SILA 2 (SALSIL2) site was selected for this study because it provided temperature measurements closer to the surface compared to other available data. The temperature data from this source was accessible up until mid-2017. For the warm-up phase of the model, we utilized temperature data from a depth of 5 cm, covering the period from 2016 to 2017, as input for the ground surface temperature. After 10 cycles, no significant change was observed and a comparison between the initial ground temperature profile and the resulting temperature profile from the warm-up cycle was conducted. The monthly surface temperature data for Inuvik Airport is available in the literature from August

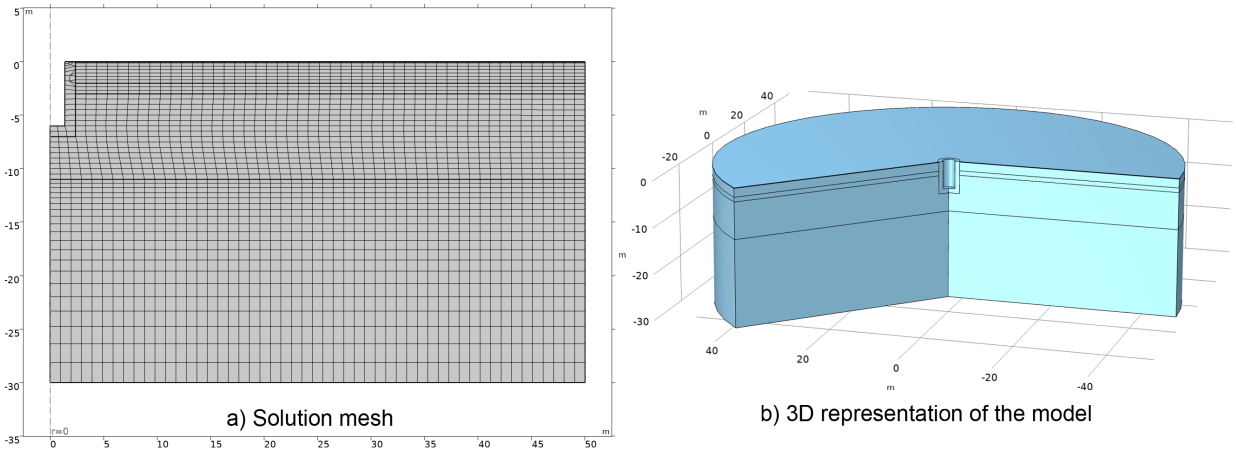


FIGURE 3.9 Mesh (a) and geometry (b) of the simulations. The model is an axisymmetric setting and would translate into a 3D model.

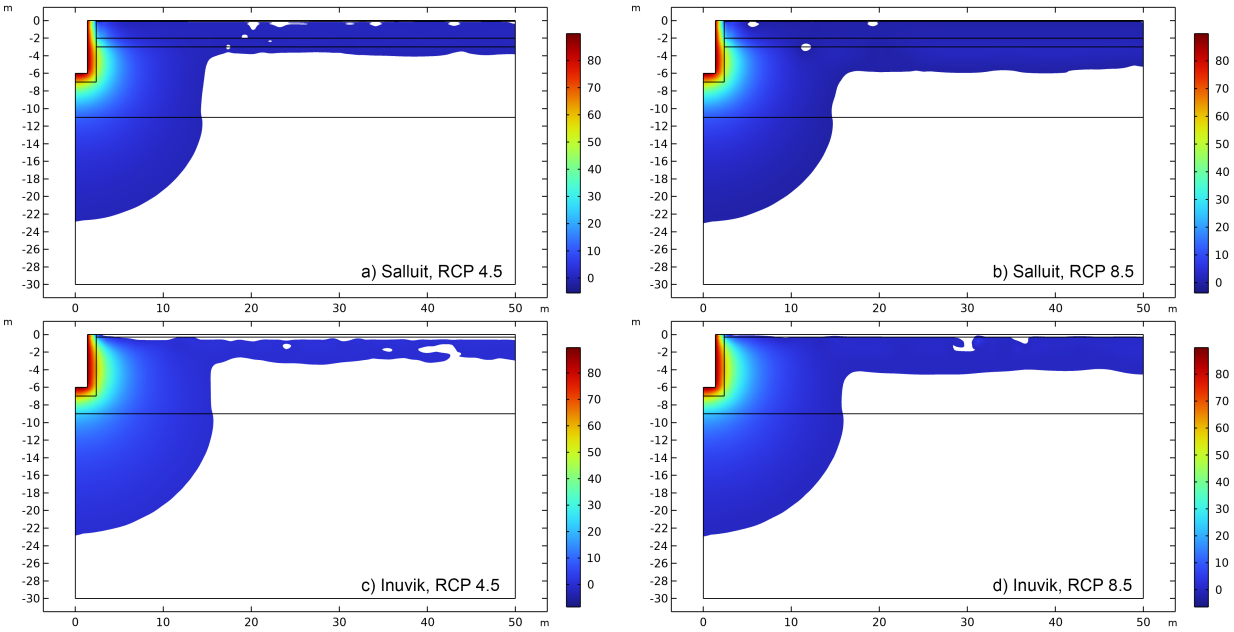


FIGURE 3.10 Ground temperature profiles on December 2099. In these graphs, only temperatures above $0°C$ are highlighted. Depending on the location and climate projection scenario, the thermal disturbance is seen around 15 m to 20 m away from the reactor core.The model is run in daily timesteps, and the detailed graphs showing comparable monthly ground temperature profiles are presented in the Results and Discussion section.

2016 to July 2017 [110], and the measurements are used for the Inuvik case 10-cycle warm-up. The comparison between measured ground temperature data and the simulation results at the end of the warm-up phase for both cases is presented in Figure 3.11.

3.3 Results and Discussion

In this section, the ground temperature profiles are presented at different distances from the reactor core, and compared to the case that no SMR is installed. To minimize numerical errors and create smoother charts, the results are averaged on a monthly basis over a 5-year long period. The main time periods of interest are :

- January 2020 to December 2024 : the thermal regime just before the installation of the SMR (Period 1)
- January 2050 to December 2054 : the thermal regime in the middle of the 21st century (Period 2)
- January 2095 to December 2099 : the thermal regime at the end of the 21st century (Period 3)

3.3.1 Salluit temperature profiles

Figure 3.12 shows the average monthly temperature profile for Salluit during the three desired time periods under two climate scenarios, RCP 4.5 and RCP 8.5, without implementing any SMR. The active layer refers to the layer above permafrost that undergoes seasonal freeze-thaw cycles. As can be seen from the results for Period 1 (Figure 3.12a and Figure 3.12d), which are averaged monthly data from January 2020 to December 2024, the depth of the active layer stays around 1.20 m in both climate scenarios. At the end of the century (Period 3) (Figure 3.12c and Figure 3.12f), the permafrost active layer is lowered down to 3.26 m under the RCP 4.5 and 5.24 m under the RCP 8.5 scenario, suggesting a permafrost degradation of 2.06 m to 4.04 m depending on the climate projection. This depth does not consider the effect of heat dissipation from the SMR reactor core and is only the effect of climate change on the ground thermal conditions.

Figure 3.13 shows the monthly average temperature of Period 2 and Period 3 for both climate scenarios 5.0 m away from the reactor core. As expected, the effect of the reactor is very significant at this distance, thickening the active layer by 16.10 m until the mid-century and to 21.39 m depth until the end of the 21st century in the more optimistic scenario, namely RCP 4.5. For RCP 8.5, the values are 16.16 m and 21.54 m, respectively. The difference made by the climate non-stationarity is from 6 to 15 centimeters, implying that when getting

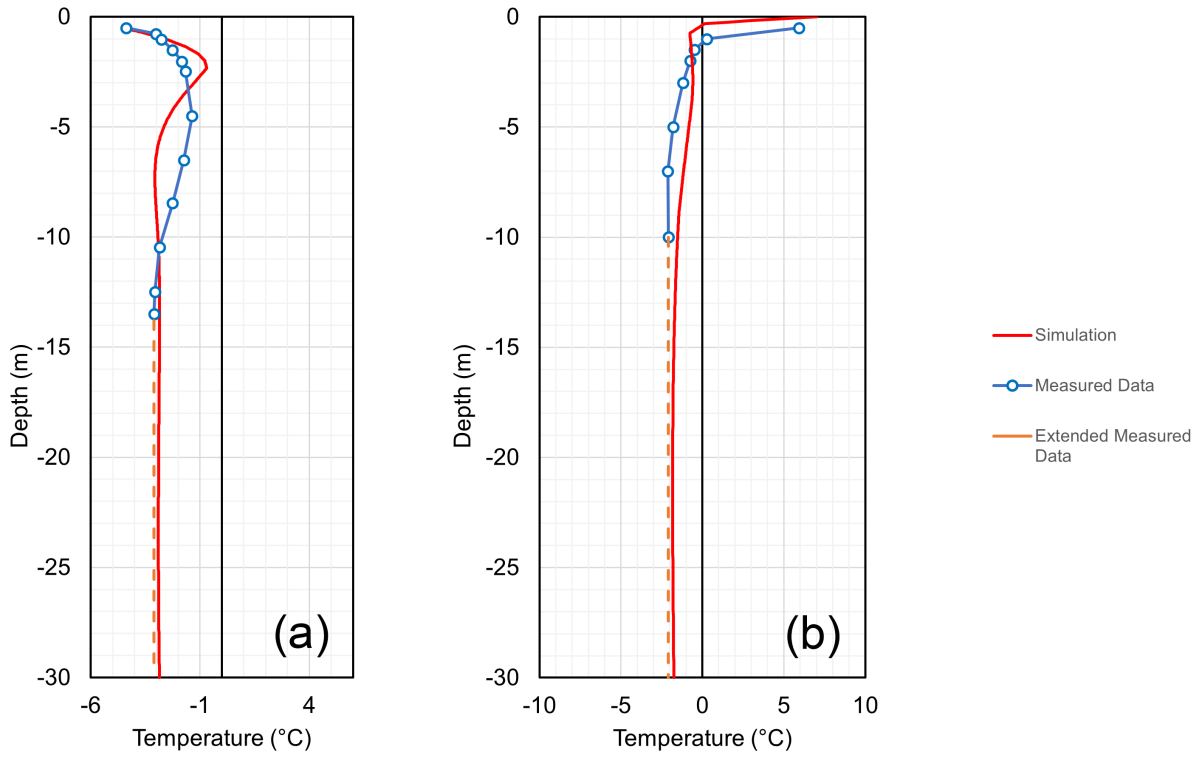


FIGURE 3.11 Comparison between measured data and simulation results at the end of the warm-up cycle for Salluit (a) and Inuvik (b). The difference between measured data and the simulation data can be attributed to the stratigraphy properties, which might not be exactly the same between the ground temperature measurement locations and stratigraphy presentation locations.

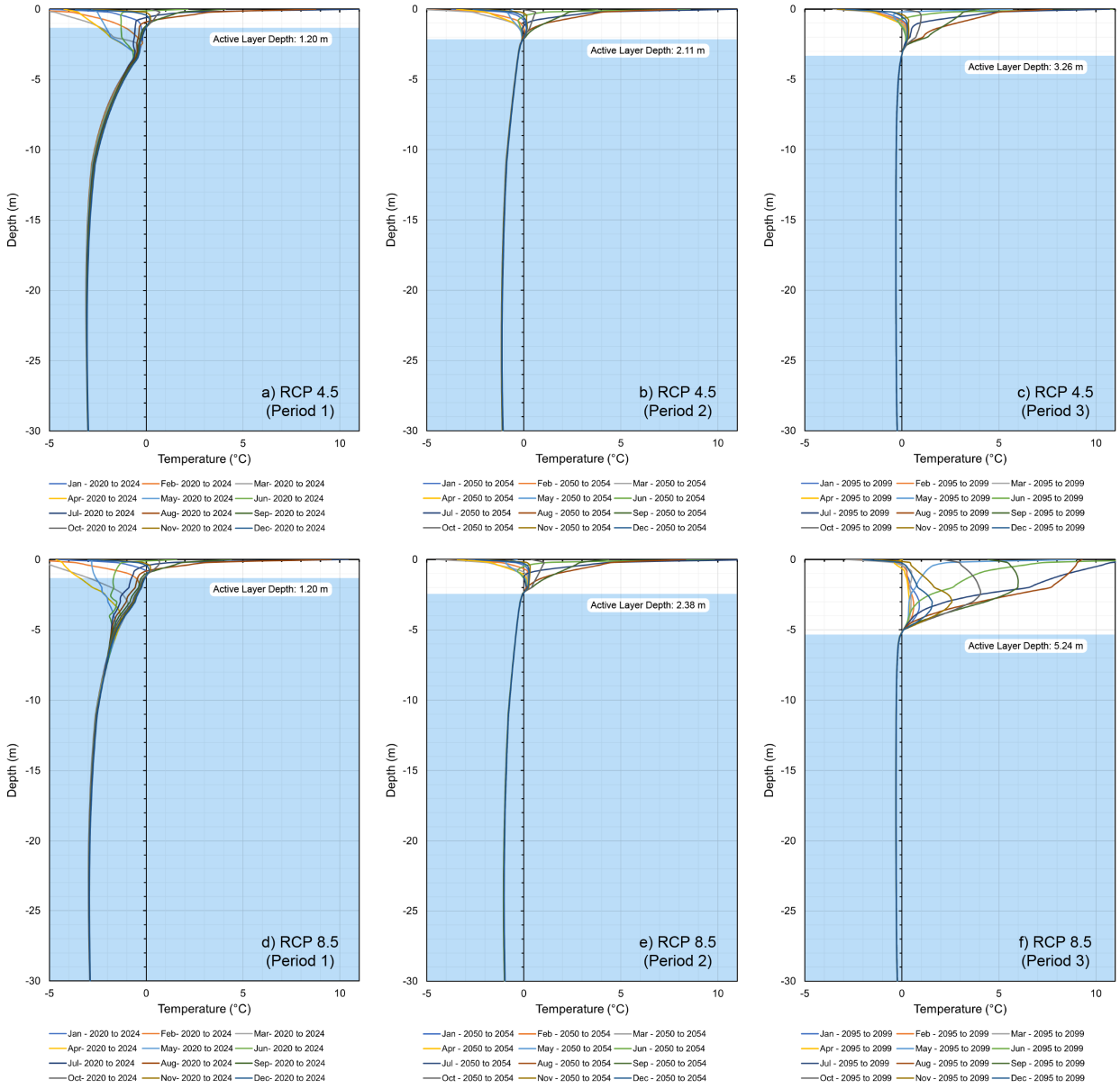


FIGURE 3.12 Ground thermal regime in the absence of SMR in Salluit. There are three main time periods of interest : Period 1 from January 2020 to December 2024 (a, d), Period 2 from January 2050 to December 2054 (b, e), and Period 3 from January 2095 to December 2099 (c, f). The thermal regime for two climate change scenarios is presented : RCP 4.5 (a, b, c) and RCP 8.5 (d, e, f). The depth of the active layer in both scenarios stays around 1.20 m during Period 1 (a,d), but gradually increases until the end of the century. In RCP 4.5, the depth increases to 2.11 m in the mid-century (b) and reaches 3.26 m until the end of the century (c). In RCP 8.5 the change is more significant, reaching to 2.38 m until the mod-century (e) and 5.24 m until the end of the century (f).

close to the reactor, the core's heat loss is the predominant factor in disturbing the ground's thermal regime.

Moving further away from the reactor, at a 10 m distance, the ground temperature graphs are illustrated in Figure 3.14, predicting the active layer as thick as 10.15 m and 18.63 m for RCP 4.5 during Period 2 and Period 3, respectively. The results for RCP 8.5 are 10.33 m and 18.85 m, respectively. The effect of the reactor is still predominant at this distance.

If a 15 m distance from the reactor core is taken into account, as can be seen in Figures 3.15, the ground temperature profiles would be very similar to the ground without an SMR installed, as shown in Figures 3.12. As previously shown in Figure 3.10, the thermal disturbance caused by the SMR does not dissipate as far as 15 m in the Salluit case. The rest of the model's width generates the same profile with a negligible difference from the case where no reactor is active. This can be proved by the ground thermal profile as illustrated in Figure 3.16, showing the profiles 20 m away from the reactor core.

3.3.2 Inuvik temperature profiles

For Inuvik, the results are presented in Figures 3.17. During Period 1, the thickness of the active layer is 0.97 m and 1.02 m for RCP 4.5 and RCP 8.5, respectively. By the end of the century, this thickness increases to 2.25 m and 3.52 m for the aforementioned scenarios.

When the SMR is implemented in the Inuvik case, 5.0 m away from the reactor, the ground temperature profiles look like Figure 3.18. The effect of the reactor is predominant in this region, thickening the active layer depth to 16.70 m until the mid-century and 21.51 m until the end of the century in the more optimistic climate scenario. For RCP 8.5, the results are 16.73 m and 21.55 m during Period 2 and Period 3, respectively.

Moving further away from the reactor, at the distance of 10.0 m, the ground temperature profiles are presented in Figure 3.19. At this distance, although the effect of the reactor is not as severe as it was at the 5.0 m radius, it is still the predominant factor when compared to the case under only climate non-stationarity. The depth of the permafrost table is 12.59 m during Period 2 and 18.86 m during Period 3 for RCP 4.5. These values for RCP 8.5 are 12.61 m and 18.92 m, respectively.

At a distance of 15.0 m, the temperature profiles in the mid-century, as shown in Figure 3.20, start to look more like the profiles without any reactor implemented. When compared with Figure 3.10, we can realize that at this distance, the effect of the reactor starts to fade away. According to the temperature profiles, the active layer stands at 1.90 m during Period 2 and 11.50 m during Period 3 for RCP 4.5. This shows that until the mid-century, the effect of the

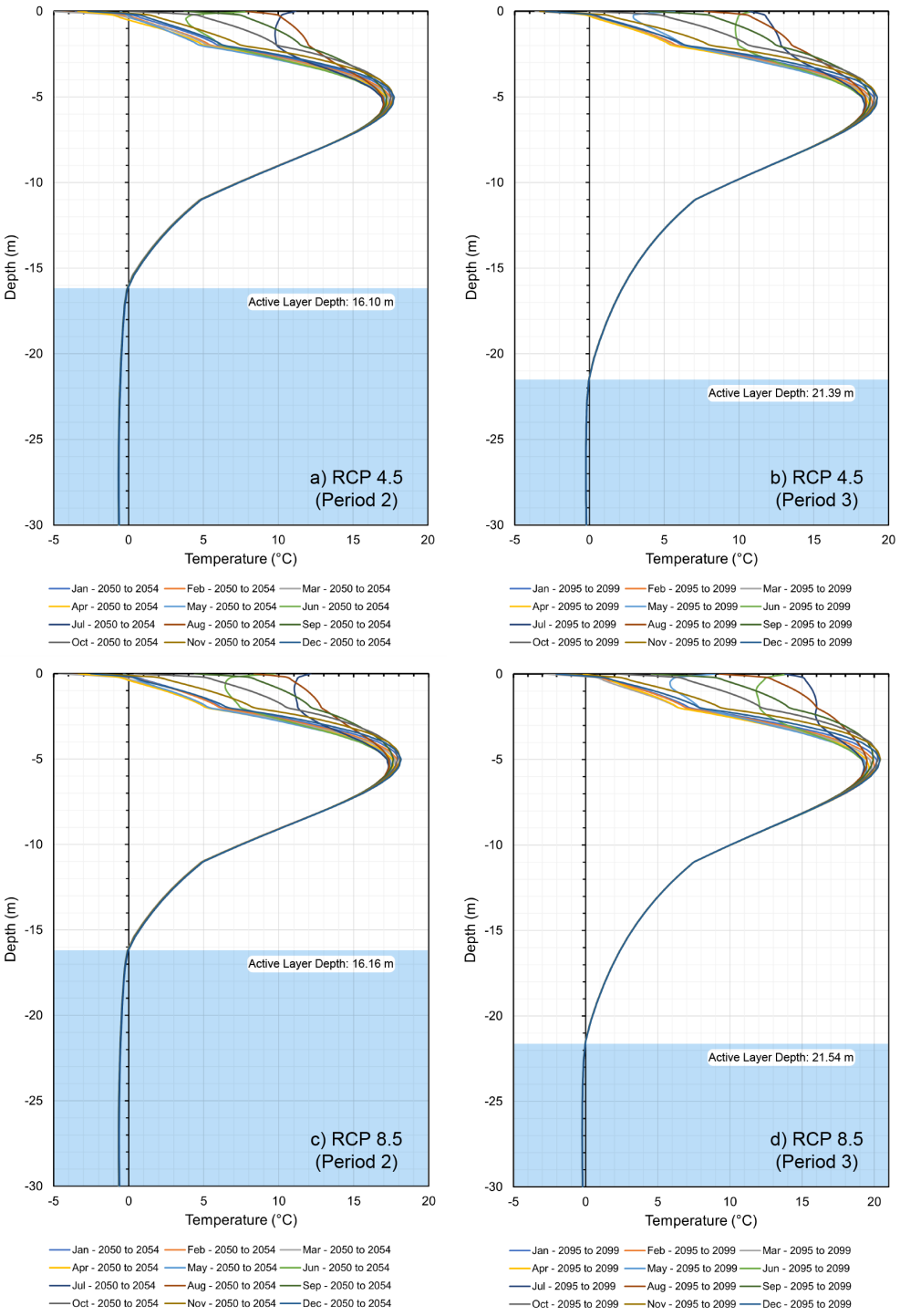


FIGURE 3.13 Ground thermal regime during Period 2 (mid-century) and Period 3 (end-century) for Salluit, 5.0 m away from the reactor core. In RCP 4.5 climate scenario, the active layer reaches 16.10 m in Period 2 (a) and 21.39 m in Period 3 (b). In RCP 8.5, the depths are 16.16 m during Period 2 (c) and 21.54 m during Period 3 (d).

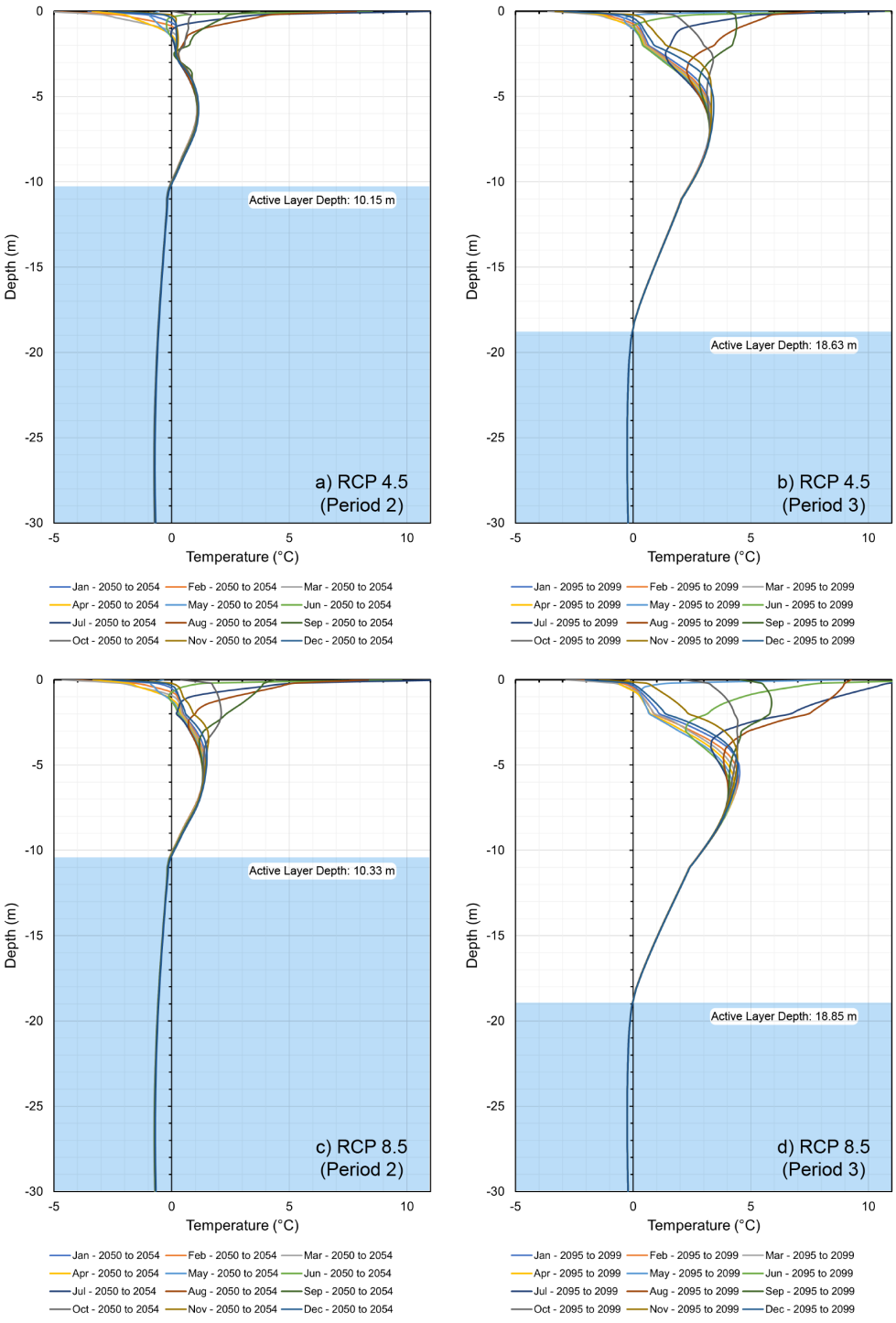


FIGURE 3.14 The ground thermal conditions for Salluit, located 10.0 m from the reactor core, in Period 2 (a,c) and Period 3 (b,d). Under the RCP 4.5 climate scenario, the active layer depth reaches 10.15 m in Period 2 (a) and 18.63 m in Period 3 (b). In the RCP 8.5 scenario, the depths are 10.33 m during Period 2 (c) and 18.85 m during Period 3 (d).

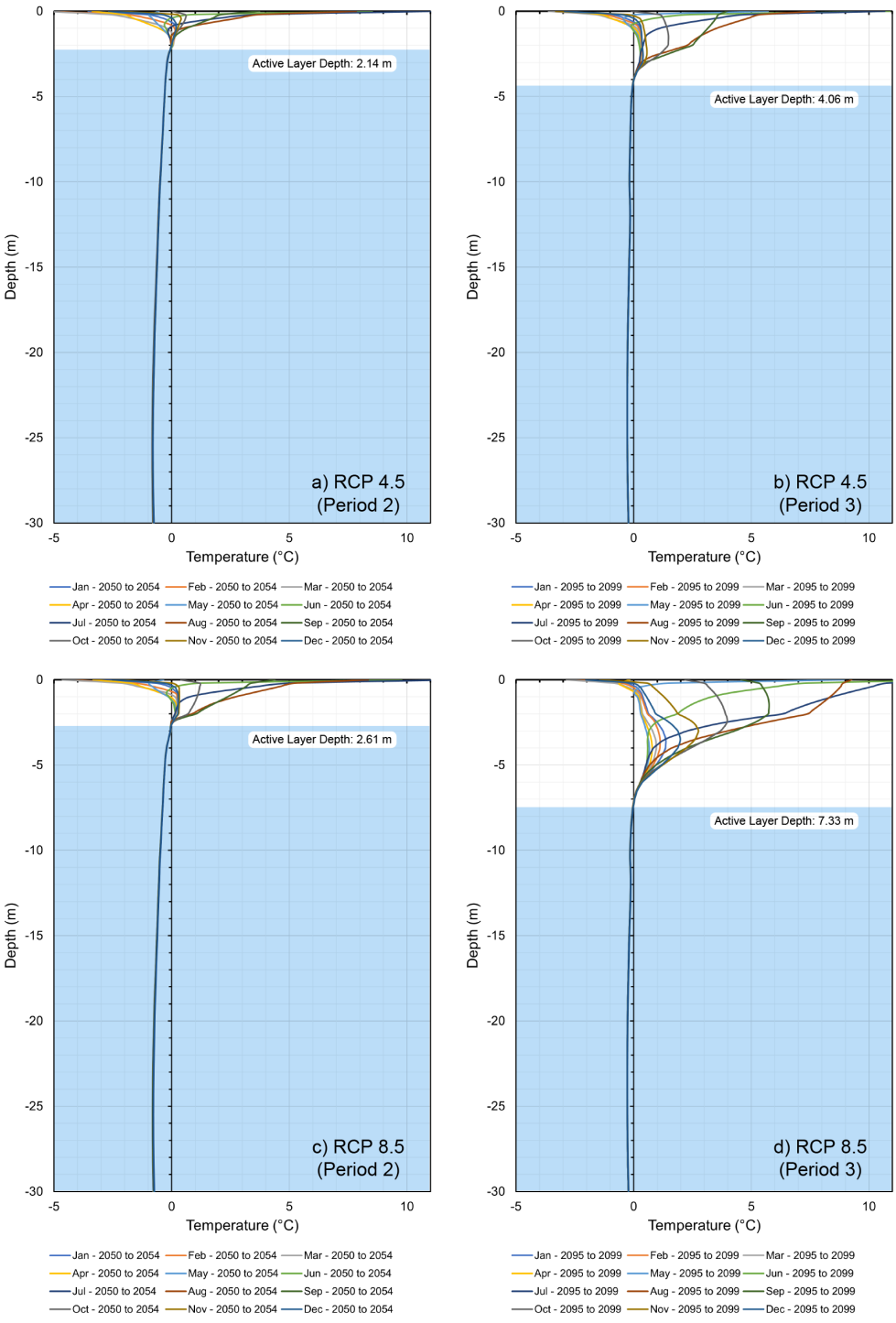


FIGURE 3.15 The ground temperature profiles for Salluit, positioned at a distance of 15.0 meters from the reactor core. In the RCP 4.5 climate scenario, the active layer depth extends to 2.14 m in Period 2 (a) and reaches 4.06 m in Period 3 (b). In the RCP 8.5 scenario, the depths are 2.61 m during Period 2 (c) and 7.33 m during Period 3 (d).

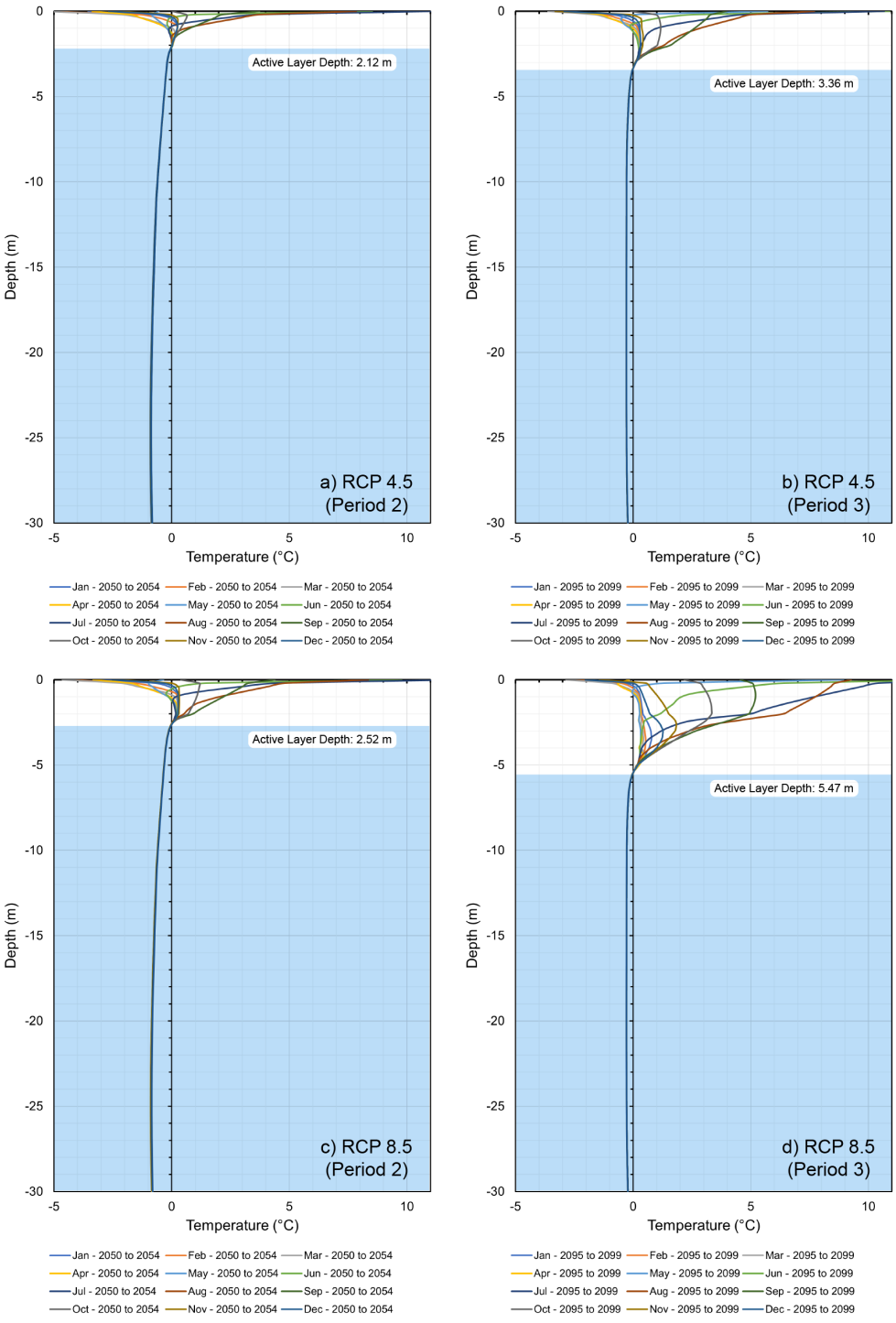


FIGURE 3.16 The ground temperature profiles for Salluit, situated 20.0 m away from the reactor core. Under the RCP 4.5 climate scenario, the active layer depth reaches 2.12 meters in Period 2 (a) and expands to 3.36 m in Period 3 (b). In the RCP 8.5 scenario, the depths measure 2.52 m during Period 2 (c) and increase to 5.47 m during Period 3 (d).

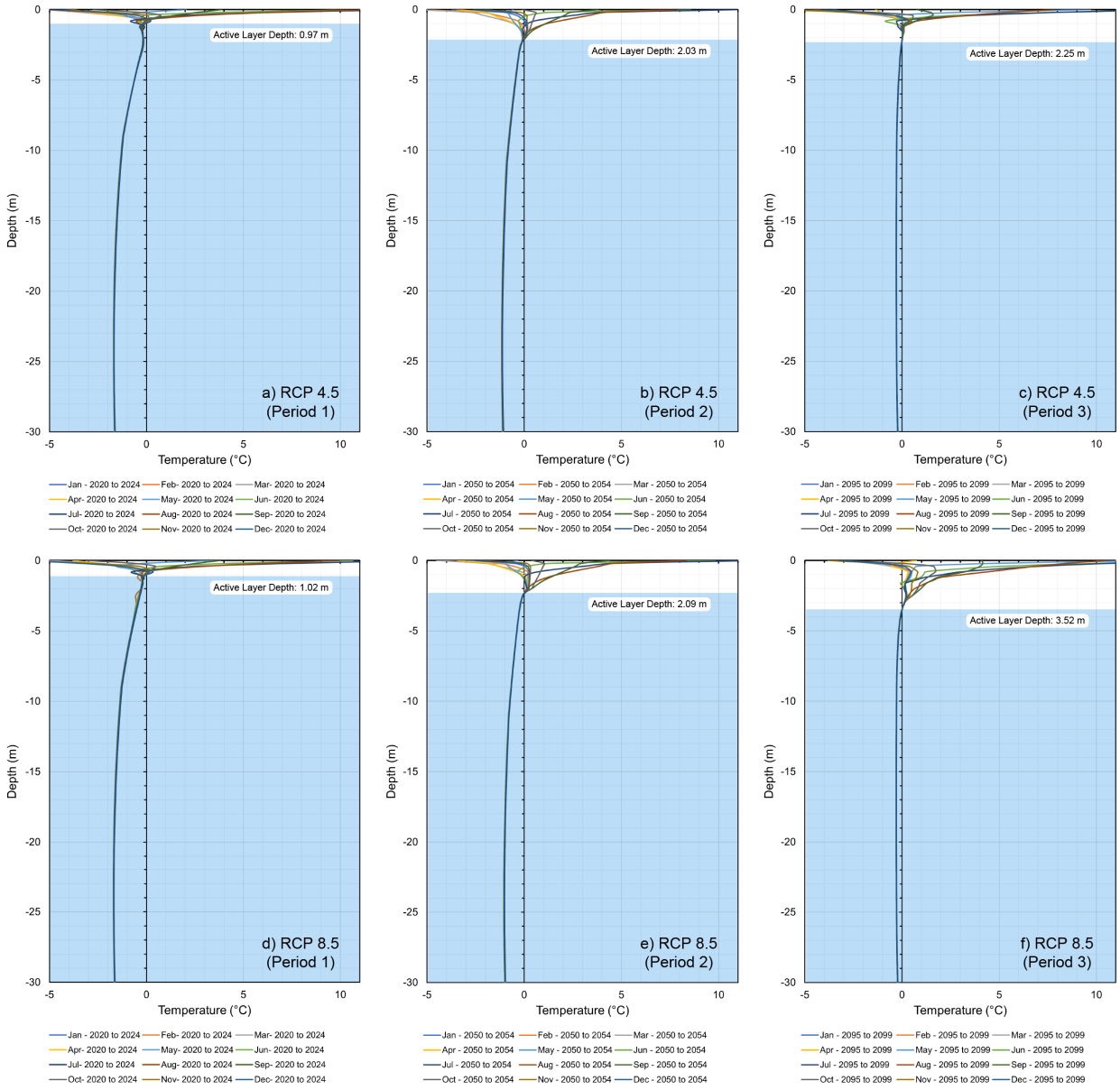


FIGURE 3.17 The ground's thermal condition in the absence of SMR in Inuvik is presented across three time periods : Period 1 spanning from January 2020 to December 2024 (a, d), Period 2 covering January 2050 to December 2054 (b, e), and Period 3 encompassing January 2095 to December 2099 (c, f). During Period 1, the active layer depth remains at 0.97 m in RCP 4.5 (a) and 1.0 m in RCP 8.5 (d), but gradually deepens over the course of the century. In RCP 4.5, it increases to 2.3 m by mid-century (b) and extends to 2.25 m by the century's end (c). In RCP 8.5, the change is more substantial, with depths of 2.09 m by mid-century (e) and 3.25 m by the century's end (f).

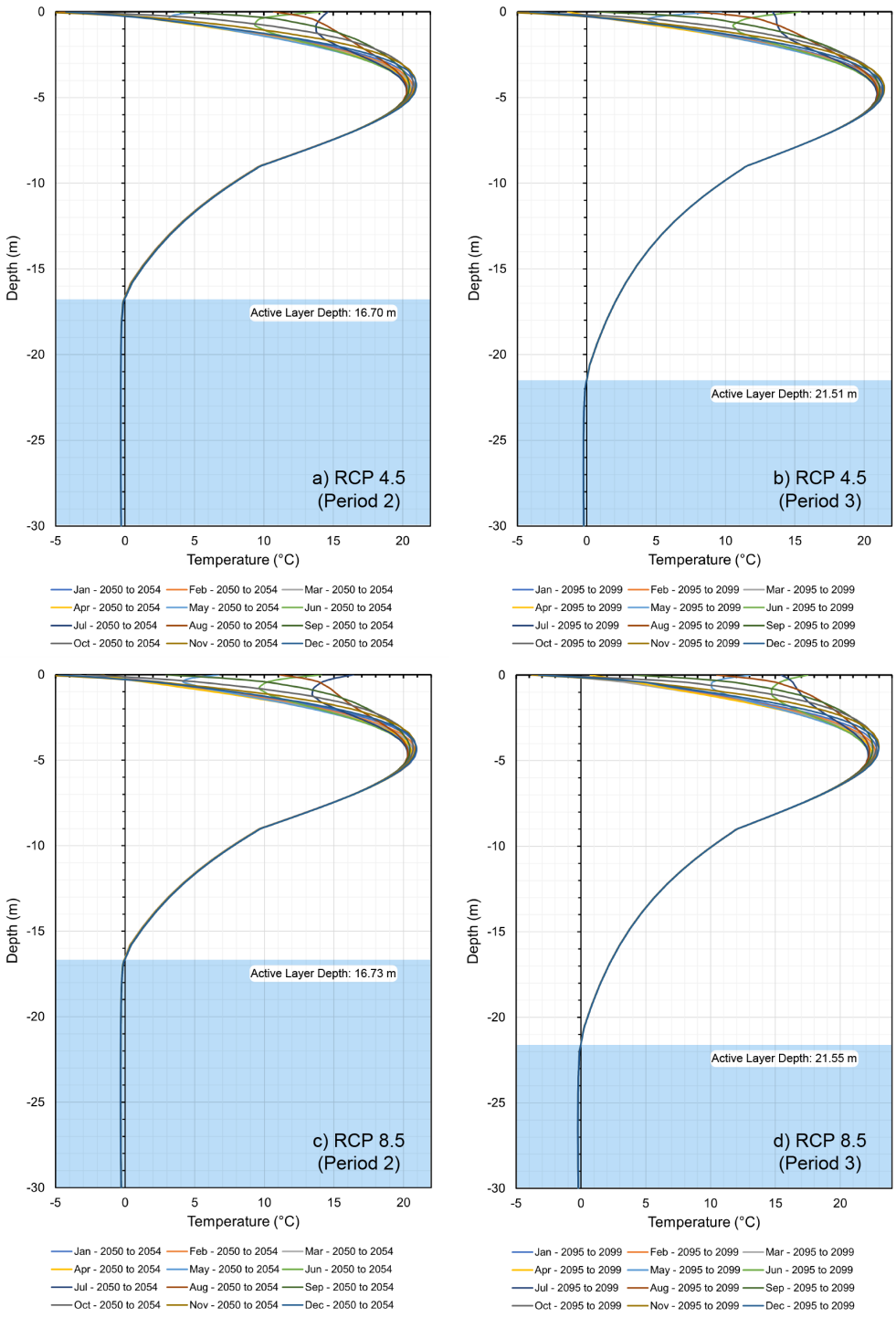


FIGURE 3.18 The ground temperature profiles for Inuvik at a distance of 5.0 meters from the reactor core. In the RCP 4.5 climate scenario, the active layer depth reaches 16.70 m in Period 2 (a) and progressively deepens to 21.51 m in Period 3 (b). When considering the RCP 8.5 scenario, the depths measure 16.73 m during Period 2 (c) and increase to 21.55 m in Period 3 (d).

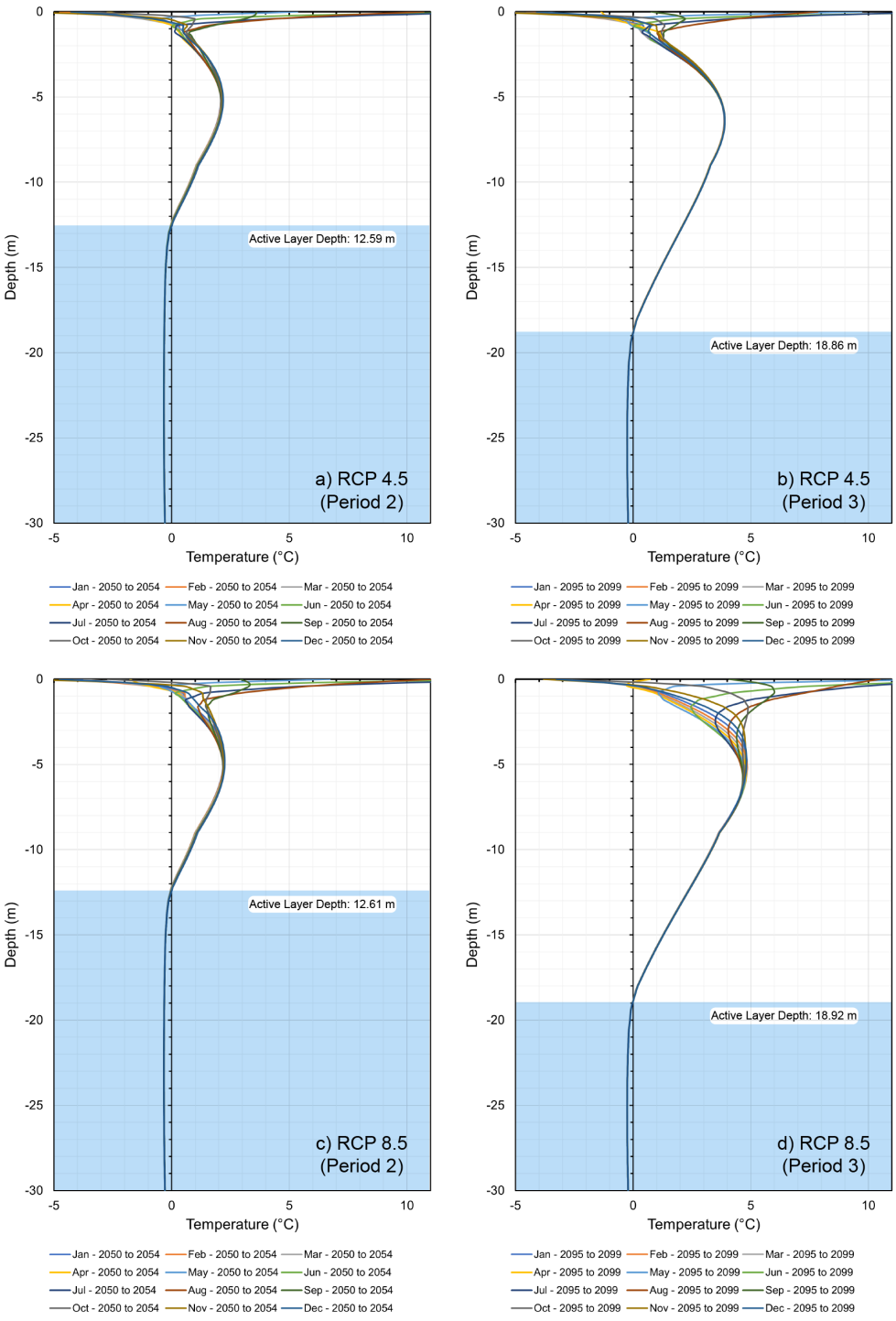


FIGURE 3.19 The ground temperature characteristics for Inuvik, positioned 10.0 m away from the reactor core. In the RCP 4.5 climate scenario, the active layer depth extends to 12.59 m in Period 2 (a) and steadily increases to 18.86 m in Period 3 (b). Under the RCP 8.5 scenario, the depths measure 12.61 m during Period 2 (c) and expand to 18.92 m in Period 3 (d).

reactor had not yet reached this far. The respective values are 1.95 m and 11.95 m for RCP 8.5. At a 20.0 m distance from the reactor core, the effect of the reactor on the permafrost table is negligible, as shown in Figure 3.21.

3.4 Conclusion

This study focused on examining the coupled effect of heat dissipation from an SMR reactor core and climate nonstationarity on the ground thermal conditions and permafrost degradation. Two distinct case studies, namely Salluit (QC) and Inuvik (NWT), and their ground temperature profiles are presented during three time periods of interest : Period 1 from January 2020 to December 2024, Period 2 from January 2050 to December 2054, and Period 3 from January 2095 to December 2099. SEALER reactor developed by LeadCold is chosen as the SMR case for these location since it is one of the possible SMR options to be implemented in the Canadian remote communities. In the case where the concrete pit around a SEALER reactor maintains a temperature of $90°C$, it was calculated that the active layer's thickness in a distance of 5.0 m could increase up to 21.54 m in Salluit and 21.55 m in Inuvik. The thermal destabilization in both regions can be seen up to approximately 15.0 m to 20.0 m distance from the reactor core. The ground temperature profiles were presented at 5.0 m, 10.0 m, 15.0 m, and 20.0 m away from the reactor core. Climate non-stationarity has the main contribution in ground temperature disturbance as we go further away from the reactor, and the effect of the climate change showed from 3.26 m to 5.24 m depth of thaw for Salluit and 2.25 m to 3.52 m depth of thaw for Inuvik. The increase in thaw depth as a result of the climate change is alarming, and the difference made by the presence of a hot reactor poses the risk of uneven settlement and creep large deformation of the foundation at the SMR site. To address this issue, a potential solution could involve implementing refrigeration facilities and thermo-suphon technology to regulate the reactor's temperature or pre-thawing permafrost foundation prior to construction. Additionally, the use of advanced insulation materials surrounding the reactor can help mitigate heat transfer and prevent detrimental effects on the frozen soil layers. Further investigation is necessary to explore the impact of coupled heat and mass transfer and assess various thermal mitigation techniques for the SMR reactor.

3.5 Acknowledgements

The authors acknowledge the financial support of the Polytechnique Montreal startup program, the Centre d'études interuniversitaire des structures sous charges extrêmes (CEISCE) of the Fonds de Recherche du Québec Nature et technologies as well as the NSERC-CNSC

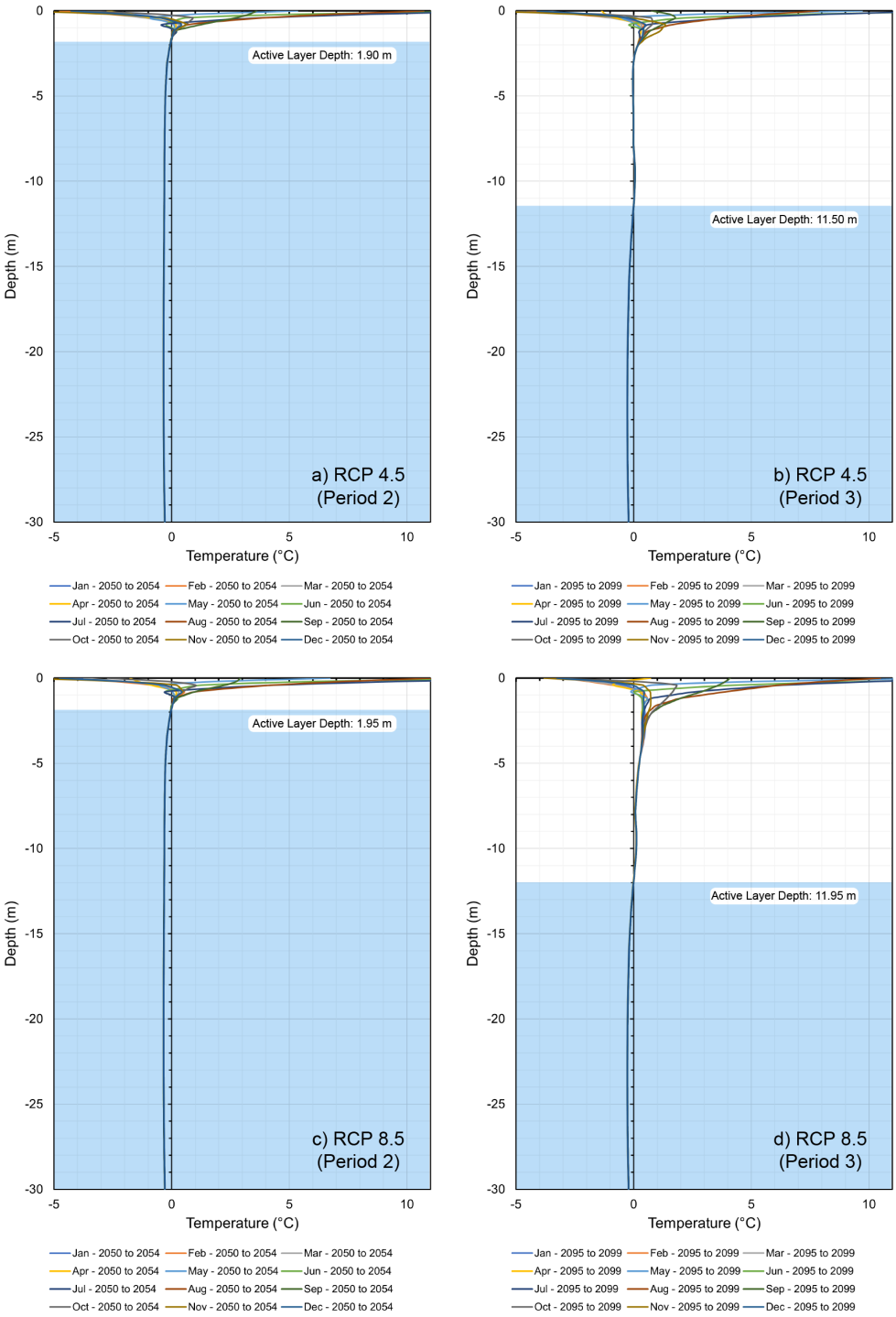


FIGURE 3.20 The ground temperature profiles for Inuvik, situated at a distance of 15.0 meters from the reactor core. In the RCP 4.5 climate scenario, the active layer depth reaches 1.90 m in Period 2 (a) which shows that the effect of the reactor has not yet reached this distance by mid-century. At the end of the centyry, the active layer deepens to 11.50 m in Period 3 (b). When considering the RCP 8.5 scenario, the depths measure 1.95 m during Period 2 (c) and increase to 11.95 meters in Period 3 (d).

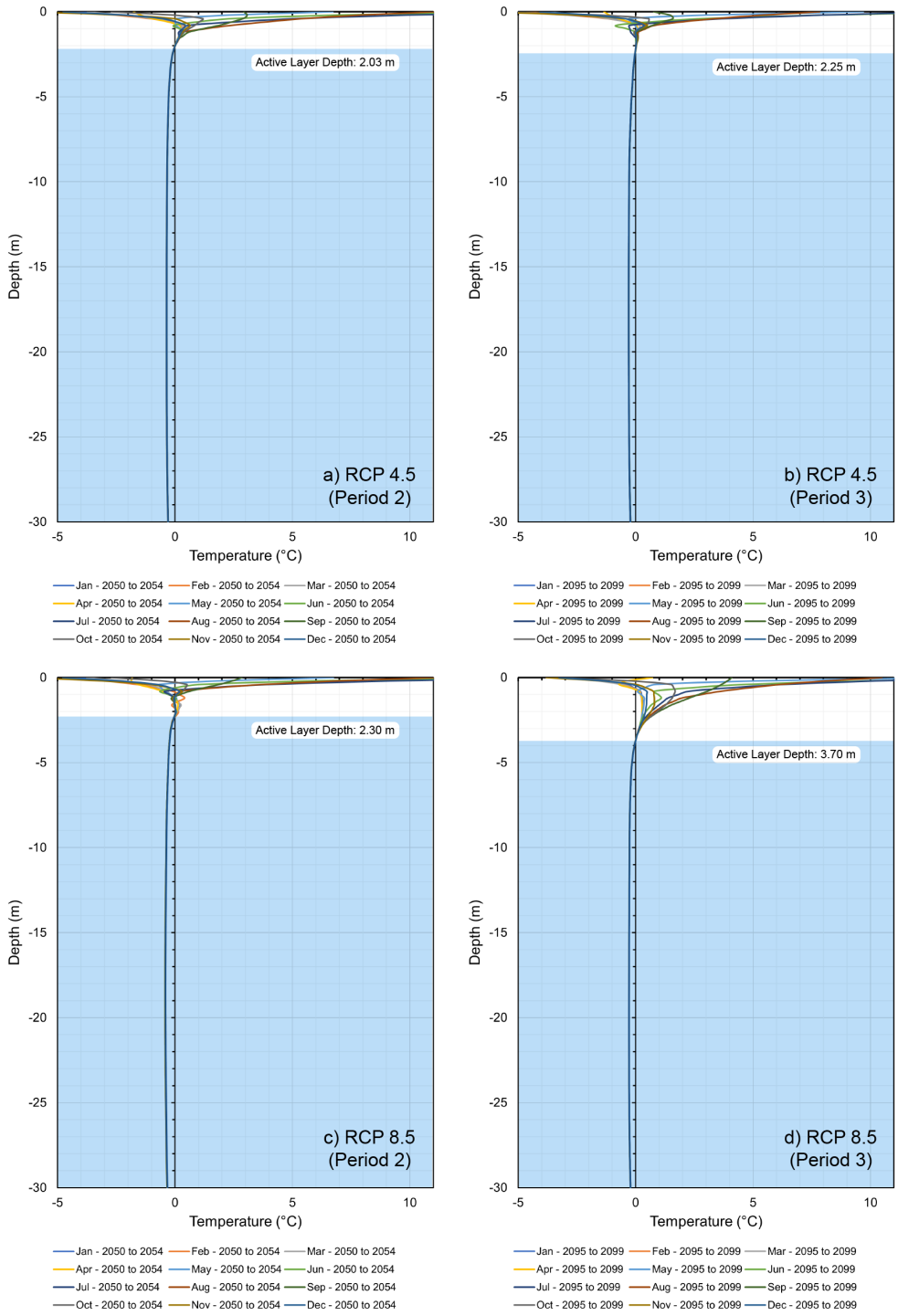


FIGURE 3.21 The ground temperature profiles for Inuvik, positioned at a distance of 20.0 m from the reactor core. In the RCP 4.5 climate scenario, the active layer depth reaches 2.03 meters in Period 2 (a). By the end of the century, the active layer deepens to 2.25 m in Period 3 (b). When considering the RCP 8.5 scenario, the depths measure 2.30 m during Period 2 (c) and increase to 3.70 m in Period 3 (d).

Small Modular Reactors Research Grant Initiative.

CHAPTER 4 ARTICLE 3 : TOWARDS EDUCATION 4.0 IN GEOTECHNICAL ENGINEERING USING A VIRTUAL REALITY/AUGMENTED REALITY VISUALIZATION PLATFORM

This chapter is reproduced, with modifications, from,

Afsharipour M. and Maghoul P., *Towards Education 4.0 in Geotechnical Engineering Using a Virtual Reality/Augmented Reality Visualization Platform*, Geotechnical and Geological Engineering (2023).
Submission date : 2023-08-01
Publication date : 2023-12-21

Abstract

Education 4.0 can play a significant role in the future of geotechnical engineering education. It can provide personalized and equitable learning experiences and be used to develop skills for the fourth industrial revolution in geotechnical engineering. In this paper, we explore the application of Augmented Reality (AR) and Virtual Reality (VR) models, as part of Education 4.0, to enhance the presentation and communication of soil mechanics concepts. A detailed step-by-step process for creating 3D representations of geotechnical concepts, including texturing, UV mapping, animation, and export and publishing techniques, is introduced. For this purpose, two powerful 3D modeling and animation software programs, Autodesk Maya and Blender, are employed to develop geotechnical avatars in a soil mechanics laboratory. In Autodesk Maya, a detailed representation of the soil phase diagram is presented, while Blender is utilized to create a Consolidated Undrained (CU) triaxial laboratory experiment. The geotechnical testing avatars are then uploaded to Sketchfab, a popular publishing website that supports AR/VR formats. We also explore the potential for establishing a virtual laboratory for geotechnical engineering, highlighting the transformative possibilities it offers in terms of practical learning experiences and educational accessibility.

4.1 Introduction

Virtual environments and the real world exist as two distinct concepts, with the former involving complete immersion in a synthetic world that may or may not replicate real-world characteristics. On the other hand, the strictly real-world environment adheres to the laws of physics. Rather than considering them as opposites, it is more practical to view them as

positioned at opposite ends of a continuum [115]. Within this continuum, a Mixed Reality (MR) environment emerges, where real-world and virtual objects coexist and are presented simultaneously on a single display. This generic setting allows for different combinations of the real and virtual worlds, leading to the development of concepts such as amplified reality, augmented reality, mediated reality, augmented virtuality, and virtualized reality [116]. Among these concepts, Augmented Reality (AR) stands out as a particularly prominent and widely recognized technology, allowing users to view the real world while superimposing virtual objects onto it or combining them with the real environment [117]. The capability of AR to bridge the gap between abstract concepts and real-world progress is achieved by overlaying digital designs onto the physical environment. Unlike 2D plans and projections, which keep design and reality separate, AR brings them together, enriching the user's perception and understanding [118].

The field of AR technology has made significant progress over the years. In their late 90s study, Feiner et al. [119] described their mobile AR system as a see-through head-mounted display powered by a computer placed in the user's backpack, in addition to a hand-held computer and stylus. However, with the advancements in technology, the current landscape of AR has expanded considerably. Today, not only do we have more light and sophisticated head-worn AR devices, but most mobile phones and tablets are also equipped with advanced capabilities to display AR models in the surrounding environment using their built-in cameras. This accessibility to AR through widely available devices opens up new possibilities for users to experience and interact with augmented content seamlessly. The future holds promise for a new generation of lighter, smaller, and more affordable AR/VR headsets that will feature enhanced processing power and higher-resolution scanners. This future indeed appears to be within reach, with major companies like Apple investing in ambitious projects like Apple Vision Pro. These advancements have already helped geologists and engineers collect data in the field and process it seamlessly in the office, transforming the way they work [120]. Hence, they are encouraged to capitalize on these advancements by developing and utilizing AR/VR software to enhance their fieldwork, office tasks, training, and communication. Embracing these technologies can lead to significant improvements in the efficiency and effectiveness of their work processes.

Education 1.0 reflects traditional, teacher-centric methods, primarily lecture-based and reliant on standardized assessments. The introduction of the internet and collaborative tools resulted in a shift toward Education 2.0 (interactive learning). Education 3.0 built on this by emphasizing personalized learning experiences, leveraging social media and adaptive technologies [121]. Education 4.0 embraces the Fourth Industrial Revolution, incorporating smart technologies and fostering collaboration between education and industry. The integration of

AR/VR models into education promotes time and place independent learning, learning flexibility, and visualized education, which are key elements in the transition towards Education 4.0, which emphasizes the integration of technology to enhance learning outcomes and equip students with the skills necessary for the modern workforce [122]. In the context of Education 4.0, aligned with the technology-driven fourth industrial revolution, AR/VR tools can be utilized as valuable resources within the classroom setting [123], having a positive impact on the scientific and technical attitudes of students who engage with them [124]. AR/VR representation of concepts will continue to play an important role when moving towards Education 5.0, as the emphasis on flexibility and dynamic approaches in education, combined with technology-enhanced training, will continue to make these tools crucial components of the learning process [125].

The purpose of this study is to use the available software to create AR/VR models for engineering concepts presented in this thesis. This platform can be used as a pillar towards education 4.0 and 5.0 in geotechnical engineering. Furthermore, several AR/VR models are developed for graduate research dissemination. The aim is to develop an immersive demonstration experience by presenting the concepts as engaging and dynamic 3D models. This can help the audience explore and experiment with geotechnical concepts in a virtual environment. Such AR/VR demonstrations contribute to the effective presentation of geotechnical engineering ideas, which also offer a novel approach to introducing complex concepts in a more accessible, equitable, and engaging manner.

4.2 AR/VR models : A way to introduce engineering concepts

There are significant advantages, both pedagogically and professionally, to incorporating AR/VR technology into education curricula and research dissemination. This is especially true when considering the improved learning and equitable experiences it can provide. AR/VR models can play a significant role in pedagogy by effectively introducing complex and technical concepts to individuals who have little or no prior knowledge in the field. AR/VR applications in education have yielded successful results in facilitating the grasp of engineering ideas for undergraduate engineering students [126]. According to a survey-based study, even advanced users such as engineers and architects show a preference for AR demonstrations over traditional methods such as 3D models on a personal computer (PC) and 2D plans on paper [118]. The study indicates that AR presentations are not only more understandable but also more usable for these professionals. Additionally, AR/VR technologies have been introduced as a way to enhance the communication of geological, geotechnical, and geoenvironmental information and complex scenarios to stakeholders, particularly for those who may

not possess the expertise to comprehend complex engineering drawings [118, 127, 128]. This would provide users with more dynamic and interactive experiences, freeing them from traditional paper or screen-bound methods. Others suggest that AR/VR demonstrations could also facilitate engineering design reviews by introducing interactivity that is not available on a conventional desktop workspace [129]. Furthermore, VR experience can be used as a flexible training tool for hazardous occupations [130, 131]. In the field of geotechnical engineering, researchers employed cutting-edge VR/MR technology to equip users in the field with virtual tools for real outcrop mapping, including virtual compasses and virtual tape measures [120]. Additionally, they devised holographic mapping procedures for office-based mapping of virtual rock outcrops. Research groups have also employed AR/VR technology in various engineering endeavors, including projects focused on open pit mining and investigating landslides [127]. With the use of Microsoft's HoloLens2 holographic glasses and their own developed Clirio software platform, Janeras et al. [127] have obtained mostly positive reviews from academics and students who had reviewed their geo-visualizations. They suggest that by using MR applications, professionals can overcome the simplification of the 3D real world to 2D plan and section views to improve the communication of project data to stakeholders, liberating users from paper or screen-bound experiences by offering natural and intuitive interactions with the data being presented. MR applications allow the interrogation of large amounts of information, especially underground, walking inside the 3D model as if you were in a "see-through" world.

The development of an AR/VR application can be demanding in terms of time and resources, hindering its widespread adoption in education [132]. However, the increasing demand for AR/VR technology holds promise for overcoming this obstacle and the development of more user-friendly applications. This trend is expected to simplify the implementation of AR/VR in educational settings. In the field of civil and geotechnical engineering, the utilization of this technology emerges as a potential solution to address the challenges associated with these disciplines, such as high risks, costs, and lengthy laboratory experiments [126, 133]. As institutions prioritize the safety of students, it becomes imperative to ensure that laboratory experiments are conducted in a secure and protected manner. In this context, the integration of this technology brings about the creation of simulated environments that not only enhance the learning experience but also provide a safe and controlled platform for students to engage in practical exercises. Additionally, the availability of infrastructure at institutions, including equipment, space, and budget, can impose limitations on the amount of laboratory time allocated to students. As a result, institutions with insufficient resources may encounter significant constraints when it comes to providing extensive laboratory opportunities [126]. The integration of AR/VR demonstrations can serve as a solution to this challenge as well. By

utilizing AR/VR, institutions can offer immersive and interactive experiences that simulate real-world laboratory settings, providing students with valuable learning opportunities even in resource-constrained environments.

The advantages of employing AR/VR in education extend beyond the university or institution and have a positive impact on students' (self-)learning experiences, cognitive abilities, enthusiasm, and pedagogical outcomes [132, 134]. With the increased use of Artificial Intelligence (AI) tools such as ChatGPT nowadays, the role of instructors has to shift from traditional lecturing to more collaborative and interactive training [135]. By providing such interactive experiences, AR/VR helps students actively engage in the learning process by immersing them in a virtual environment and allowing for virtual interaction with 3D models. This approach provides an active learning experience that encourages students to enhance the knowledge they have gained in the classroom through the virtual environment [126]. Not every AR/VR demonstration would lead to creating such an experience since the design quality of the interface and material plays a critical role in determining the effectiveness of AR/VR learning experiences and eliciting positive feedback from students. It is also worth emphasizing the importance of story-telling and instructor-student interaction in the learning experience of students. Teaching the basic concepts of soil mechanics using AR/VR, such as the behavior of different types of soils under different triaxial loading conditions, should be accompanied by a story describing the complex physics of geomaterials. Given the self-directed nature of AR/VR learning, where students actively engage with the technology, the design quality directly impacts their overall learning outcomes. When the interface and material are well-designed, students perceive the platform more positively, leading to enhanced engagement and knowledge acquisition [132]. In practice, over 100 colleges and universities throughout China have developed 119 virtual simulation experimental teaching projects for civil engineering courses using VR technology [133]. Their virtual developments cover a wide range of courses ranging from basic to professional, and the implementation of each project has successfully resolved the issues associated with high risk, high costs, and long cycles of traditional experimental courses. Furthermore, VR technology stimulated students' interest in learning, boosted their participation, and achieved positive teaching outcomes [133].

All in all, using AR/VR technology as a learning model holds great promise for the future of engineering education, as it can present information in a more engaging and dynamic way while also motivating students to pursue their academic goals. Even prior to the COVID-19 pandemic, education was already experiencing a digital revolution that was reshaping its methodologies. The pandemic has accelerated this transformation, leading to a significant shift towards hybrid or phygital (physical-digital) learning models [136]. However, there is still work to be done in terms of finding the most effective method of introducing such learning

models into the classroom, as current literature on the subject lacks clear guidance in this area [137].

4.3 From Concept to Creation : Building AR/VR demonstrations

The development of an AR/VR model to demonstrate engineering concepts involves several key steps. The process behind creating 3D models will be discussed in this section, with the aim of providing useful information for students and researchers creating AR/VR demonstrations in the field of geotechnical engineering and other engineering disciplines. In general, we can assume the following steps for creating AR/VR demonstrations :

- The first step is to conduct thorough research and planning. This involves identifying the learning objectives of the model, understanding the core physical concepts of the model, and deciding on the features and functionalities of the AR/VR demonstration. A team of educators, geotechnical experts, and 3D modeling professionals can work together to develop the research and planning phase.
- The second step is to create a concept design of the AR/VR models. This includes deciding on the layout, user interface and experience, and the overall look and feel of the output. The concept design phase can be done using sketching or prototyping tools.
- The next step is to provide the content for the AR/VR environment. This includes creating 3D models of tests, simulations, equipment, and other objects relevant to the subject being studied. There are several software tools and platforms for AR/VR development such as Unity, Unreal Engine, ARCore, ARKit, Microsoft Mixed Reality Toolkit, Blender, Autodesk Maya, Oculus SDK, and so on. The content development phase can involve subject experts and educators working together to ensure the accuracy and relevancy of the content.
- After the content is developed, the next step is to integrate it into an AR/VR environment. The integration and finalization can be done using online platforms such as Sketchfab or gaming engines such as Unity. The integration phase involves combining the 3D models, creating a user interface to create a seamless experience for users, and programming to an extent.

In this paper, we have used Autodesk Maya and Blender, which are powerful 3D modeling software to create high-quality AR/VR models. In the following section, we will present, as an example, two platforms used to develop 3D models for geotechnical applications.

4.4 Entering the virtual world : modeling and animating using Maya

Autodesk Maya is a powerful 3D modeling software that allows users to create realistic models and special effects. With its animation tools, users can bring their creations to life with natural movements and expressions [138]. Autodesk offers students and educators the opportunity to access their products and services for free. Eligible users can receive a one-year educational license that can be renewed as long as they remain eligible [139]. This educational access provides students and educators with access to a range of Autodesk products, including Autodesk Maya. In this section, a demonstrative model of permafrost thaw as a result of climate change is built step by step, consisting of two separate columns of soil representing two different climate projection scenarios RCP 4.5 and RCP 8.5.

4.4.1 3D modelling with Maya

Maya's modeling tools make it easy to shape 3D objects and scenes with precision and ease. For our modeling, we start with the basic polygons available in the software, as they appear in Figure 4.1 (Create > Polygon Primitives).

The visualization of the ground thermal regime can take effect by a primitive cylinder polygon, representing a column of soil. When the user taps on the "Cylinder" option (Figure 4.1), a default cylinder polygon will be created in the 3D Viewport. Navigating the 3D modeling space in Maya can be initially confusing, and as a result, an introduction to the various navigation tools can be beneficial. By default, every added shape is positioned in the center, and numerous operations can be performed on each shape. Table 4.1 containing the different navigation and transformation tools, along with their corresponding keyboard shortcuts, is available for reference.

Table 4.1 Default navigation and transformation tools in Maya

Function	**Command**
Camera Move	Alt + Middle Mouse Button
Camera Rotate	Alt + Left Mouse Button
Camera Zoom	Alt + Right Mouse Button
Object Center	"F" on Keyboard
Object Select	"Q" on Keyboard
Object Move	"W" on Keyboard
Object Rotate	"E" on Keyboard
Object Scale	"R" on Keyboard

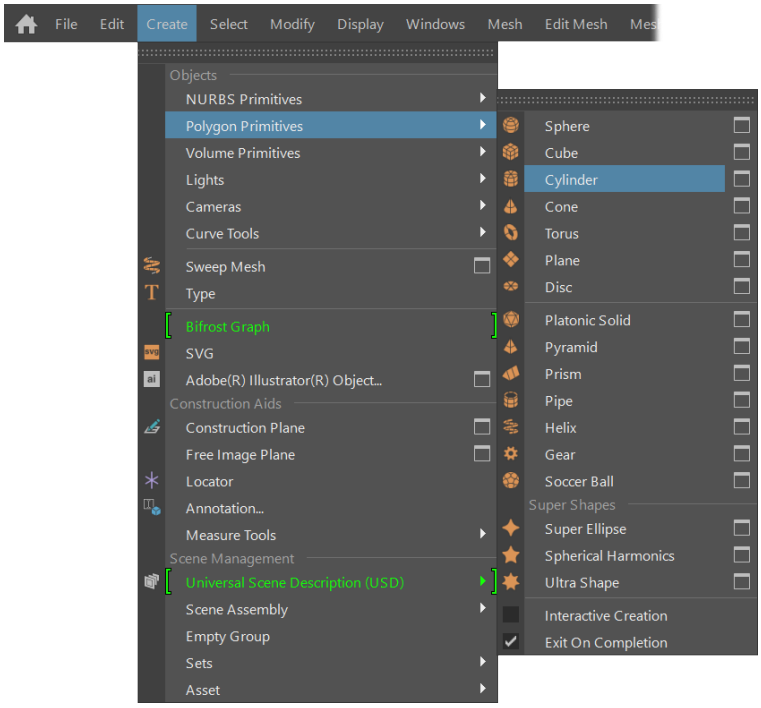


FIGURE 4.1 By selecting "Create > Polygon Primitives", the user can choose between numerous default polygons including sphere, cube, cylinder, etc.

The object attributes can be set manually through "Attribute Editor" window (Windows > General Editors > Attribute Editor). After adjusting the coordinates and assigning the desired attributes to the column of soil, we can enrich the model by adding some elements to the surface. In our model, we have added a random height map to the top of the model to make a terrain-like appearance, a house using a combination of the basic shapes previously introduced, and some elements downloaded from online sources. For this study, a free maple tree design from the Sketchfab website is added to the ground surface to make it more realistic. Additionally, a car is also added to the model from the available designs on this website. The list of elements added to the model from Sketchfab is available in Table 4.2.

TABLE 4.2 Sketchfab free samples integrated in the model

Element	**License**	**Source**
Car	CC Attribution	`skfb.ly/6UryD`
Maple Tree	CC Attribution	`skfb.ly/oGyJw`

4.4.2 Texturing and UV mapping

In order to achieve the objective of creating AR/VR models that are engaging, presentable, and realistic, it is necessary to incorporate colors and textures into the 3D models. To accomplish this, one can access the texturing environment in Maya by selecting "Windows > Rendering Editors > Hypershade". Within the "Hypershade" window, different types of textures can be defined and assigned to different parts of the model. These textures can either be created entirely within the software or obtained from online sources. In this paper, the AmbientCG website is used for textures. This website provides high-quality textures up to 8K under the Creative Commons CC0 1.0 Universal License, meaning near limitless freedom to use the materials, models, and other assets. For the ground cylinder, three different textures including grass, soil, and rock were obtained. The different parts of the house also include several textures which are addressed in Table 4.3.

Table 4.3 Textures used in Autodesk Maya model

Texture	**License**	**Source**
Asphalt	CC0	`ambientCG.com/a/Asphalt023S`
Ground - Grass	CC0	`ambientCG.com/a/Grass001`
Ground - Rock	CC0	`ambientCG.com/a/Rock041`
Ground - Soil	CC0	`ambientCG.com/a/Ground048`
House - Door	CC0	`ambientCG.com/a/Wood013`
House - Roof	CC0	`ambientCG.com/a/RoofingTiles001`
House - Wall	CC0	`ambientCG.com/a/Bricks060`

The textures associated with the house were implemented directly, but the ground texture was a more complex since one single geometry needed to have three textures implemented into it. After editing the three color textures and exporting them into one single texture file (Figure 4.2), we can assign the color texture to the ground cylinder.

From time to time, the user might notice that some textures may not properly be placed on the 3D model in the initial attempt. In this situation, UV mapping is needed which is the process of assigning a 2D texture map to the surface of a 3D object. In Autodesk Maya, UV mapping involves defining a 2D coordinate system on the surface of a 3D object, which determines how textures and images will be applied to the object's surface. Maya does that by unwrapping the 3D model's surface into a 2D plane, available through "UV > UV Editor". In this menu, each face of the 3D model can be manipulated like a flat image and adjusted to the right orientation and size of the texture, so that the model can appear more realistic

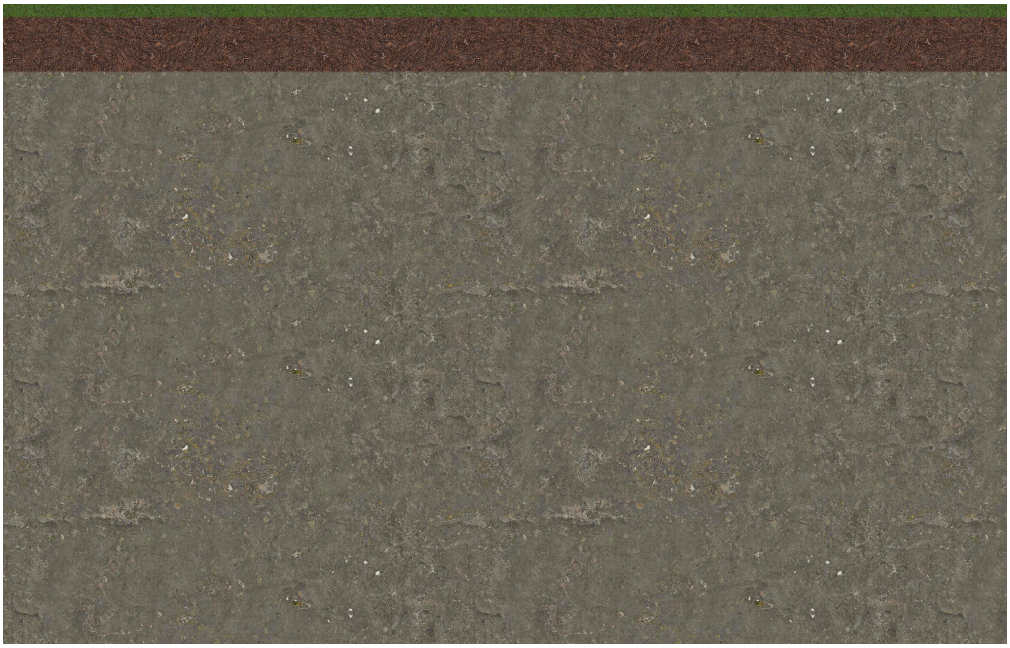


FIGURE 4.2 For the ground cylinder, three different textures are combined into a single image.

and detailed when rendered in AR/VR applications. A visual explanation of UV mapping and its necessity is presented in Figure 4.3.

Textures downloaded from AmbientCG are also accompanied with normal and roughness maps. Normal maps and roughness maps are two types of texture maps that can be used to enhance the appearance of a 3D model's surface without actually modifying the geometry of the mesh. A normal map is a type of texture map that encodes surface normals in the RGB channels of an image [140]. By applying a normal map to a 3D model's surface, it can create the illusion of surface details and depth that are not actually present in the mesh. This can give the model a more realistic and textured appearance. Roughness maps, on the other hand, control the roughness or smoothness of a surface. A roughness map typically encodes the surface's roughness information in gray scale, with black areas indicating a completely smooth surface, and white areas indicating a completely rough surface. Applying a roughness map to a surface can help create a more natural material appearance by controlling the way that light interacts with the surface. By using normal maps and roughness maps, developers can create highly detailed and realistic models without needing to add additional geometry to the mesh. The normal and roughness textures associated with the created color texture are presented in Figure 4.4. An ensemble of the surface elements is also shown in Figure 4.5.

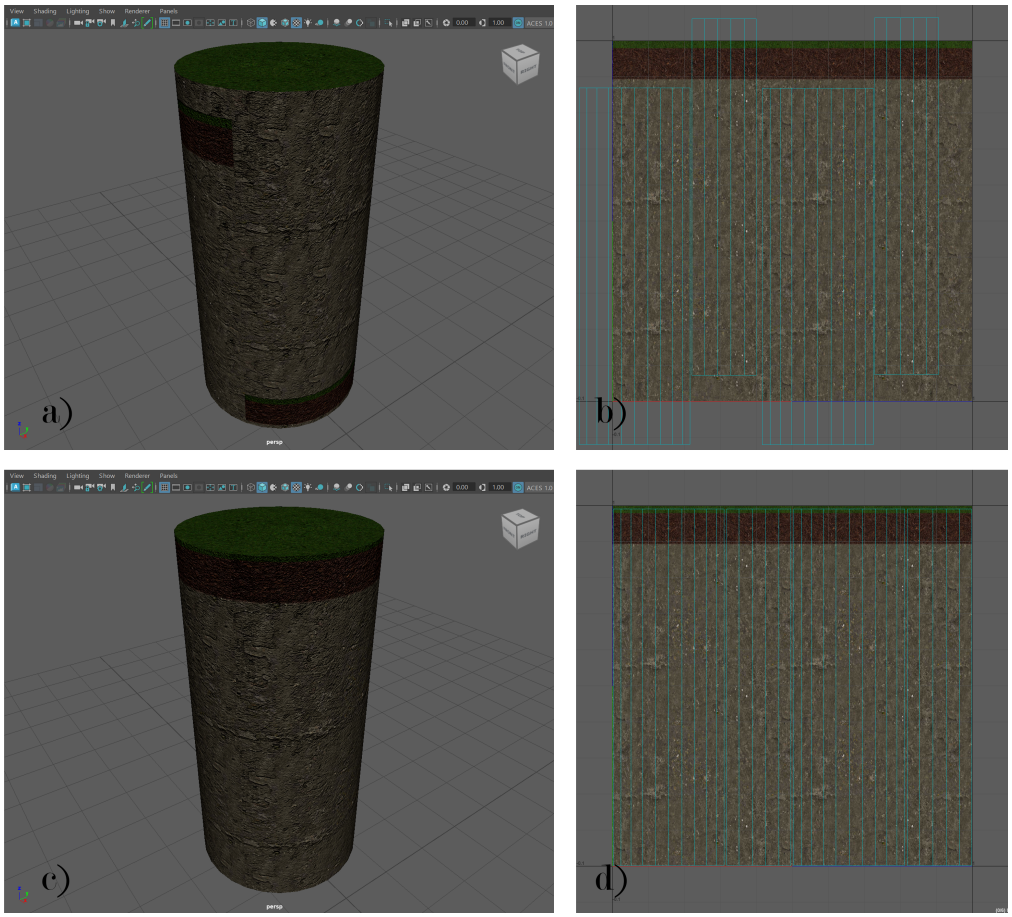


FIGURE 4.3 The first attempt for adding texture to a material might not always be successful (a). The reason is that in the first attempt, Maya would try to unwrap the faces of the 3D model on the texture by itself (b) which may not be what we have in mind. In order to get a nicely textured ground cylinder (c), we need to assign the faces manually through UV mapping (d).

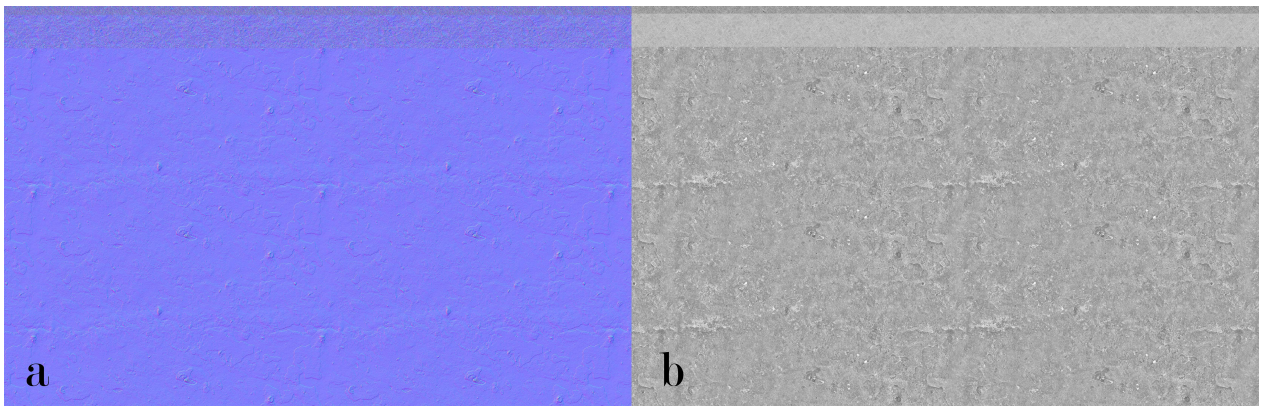


FIGURE 4.4 a) Normal and b) Roughness textures for the ground cylinder.



FIGURE 4.5 Surface elements of the model in Autodesk Maya

4.4.3 Animating and export

Autodesk Maya provides the ability to animate static 3D creations. To animate 3D models in Autodesk Maya, keyframes need to be created. These are specific points in time where the position, rotation, and scale of the model are set. The object to be animated can be selected, and the keyframe for the frame to be animated can be set on the timeline. Once the keyframes have been set, the model can be animated by adjusting its position, rotation, and scale at different points in time, resulting in a fluid animation. After a basic animation has been created, it can be refined by adjusting the timing and easing of the animation curves (Windows > Animation Editors > Graph Editor). Tools are provided by Maya to adjust the timing and smoothing of the animation curves, allowing for a more polished and refined animation. The animation for this study consists of semi-transparent cylinders with blue and red lighting, representing above and below-freezing temperature regions of the ground at different time steps. By obtaining simulation results from a numerical model (as discussed in the previous chapter) and visualizing it in the form of AR/VR models, they can be effectively presented to a general audience and stakeholders, providing them insight into the effect of global warming on northern infrastructure in different climate projection scenarios (Figure 4.6).

Once the modeling and animating process is concluded, the result should be exported in order to share with the audience. FBX is a popular exporting format in Autodesk Maya, which is widely compatible with other 3D modeling software and publishing websites like Sketchfab.

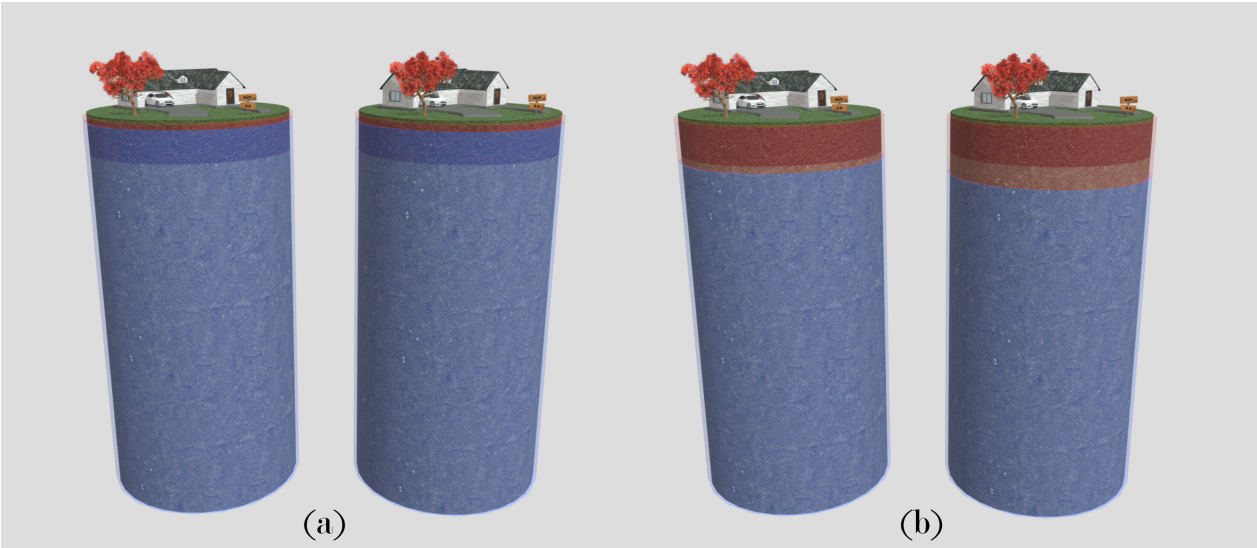


FIGURE 4.6 Animation stages in Maya.

It is a versatile format that supports embedded textures and animations, making it easy to share 3D models with other users. FBX can handle complex geometries, animations, and materials, which makes it ideal for game development, virtual reality, and other real-time applications. In addition, FBX files are relatively small, which makes them easy to upload and download from the internet. Exporting FBX models from Autodesk Maya involves several steps that need to be followed. Once the model is ready to be exported, it should be selected in Maya's viewport. The Export dialog box should then be opened (File > Export Selected). In the Export dialog box, the FBX format should be selected from the list of available file formats. Various settings related to the export process, such as geometry, animation, and materials, can be configured in the FBX export options. It is especially important to enable animations and textures in the export file. To do this, FBX export options window, select "File Type Specific Options > Include > Animation" and "File Type Specific Options > Include > Embed Media". After configuring the export settings, the model can be exported as an FBX file by clicking Export. Finally, it is important to open the exported file in another program to verify that the export was successful and that the animations and textures look correct.

4.5 Exploring more possibilities : modeling and animating using Blender

Another suitable tool for creating 3D models for engineering is Blender. Blender is a free and open-source 3D creation software that can be used for a variety of applications such as 3D modeling, animation, rendering, compositing, motion tracking, and video editing. Blender is

specifically suitable for creating 3D demonstrative designs in engineering as it is a powerful 3D modeling and animation software that gives the user plenty of options to control the model dimensions and assign physics and attributions through "Modifiers". Additionally, Blender has a robust community of users who create add-ons and plugins that can extend its functionality even further. In this section, a demonstrative model of the effect of a Small Modular Reactor (SMR) as well as climate warming on the ground temperature profile is presented. The model consists of a column of soil affected by the combined effect of a SMR device and climate warming, along with a minimal reactor building.

3D modelling with Blender

Much like Autodesk Maya, Blender offers basic initial 3D shapes that come in handy when creating engineering models. In the Layout tab, by selecting "Add > Mesh", the user can select among some pre-defined objects. To open the "Add" menu, the user can press the keyboard shortcut "Shift+A" as well (Figure 4.7).

While Blender and Maya have similar navigation and transformation tools, the specific shortcuts and commands used to access those tools can differ between the two software programs. This could be a challenge for users who are used to working with one software and need to transition to the other. However, Blender does offer the ability to customize the keyboard shortcuts to match Maya's, which can help make the transition easier for users who are already familiar with Maya's shortcuts. The default navigation and transformation tools for Blender are mentioned in Table 4.4.

TABLE 4.4 Default navigation and transformation tools in Blender

Function	**Command**
Camera Move	Shift + Middle Mouse Button
Camera Rotate	Middle Mouse Button
Camera Zoom	Ctrl + Middle Mouse Button
Object Center	"." on NumPad
Object Select	"W" on Keyboard
Object Move	"G" on Keyboard
Object Rotate	"R" on Keyboard
Object Scale	"S" on Keyboard

The axi-symmetric nature of this model and the positioning of the reactor at the center of the model requires a more complex geometry rather than a simple cylinder as the previous

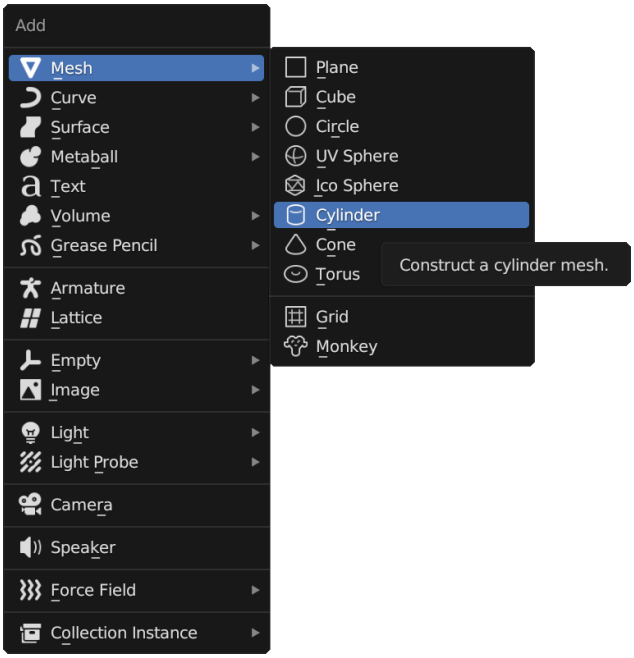


FIGURE 4.7 Pre-defined objects in Blender, accessible through Layout > Add > Mesh or simply Shift+A > Mesh

example. The first step towards achieving this is to create a default cylinder mesh and assign the dimensions as per the desired specifications. Once the basic geometry is in place, the next step is to slice the model to make the middle sections visible. To incorporate surface elements into the model, a conceptual reactor building is designed. This addition serves to contextualize the ground surface and provide a visual cue to its location, as well as add an additional layer of realism to the model. After adding a new cylinder mesh in Blender and setting the model dimensions (press N on keyboard to set the dimensions manually), we can slice the cylinder in the "Edit Mode" (press Tab on the keyboard to enter the edit mode) using the knife tool (Figure 4.8).

By using the same procedure, a minimal reactor building is added on the surface, consisting of a wall and a dome part. In addition, the concrete pit containing the reactor core is designed as well. A national Canadian flag is also added to this model as a surface element, with the help of Blender's "Cloth Simulation" feature. Since the flag is constantly moving in the wind, it would be one of the most engaging elements of the model for users in VR mode.

4.5.1 Texturing and UV mapping

After creating the different desired elements, texturing and UV mapping processes are similar to Autodesk Maya. In order to create a new material in Blender, the user can use the

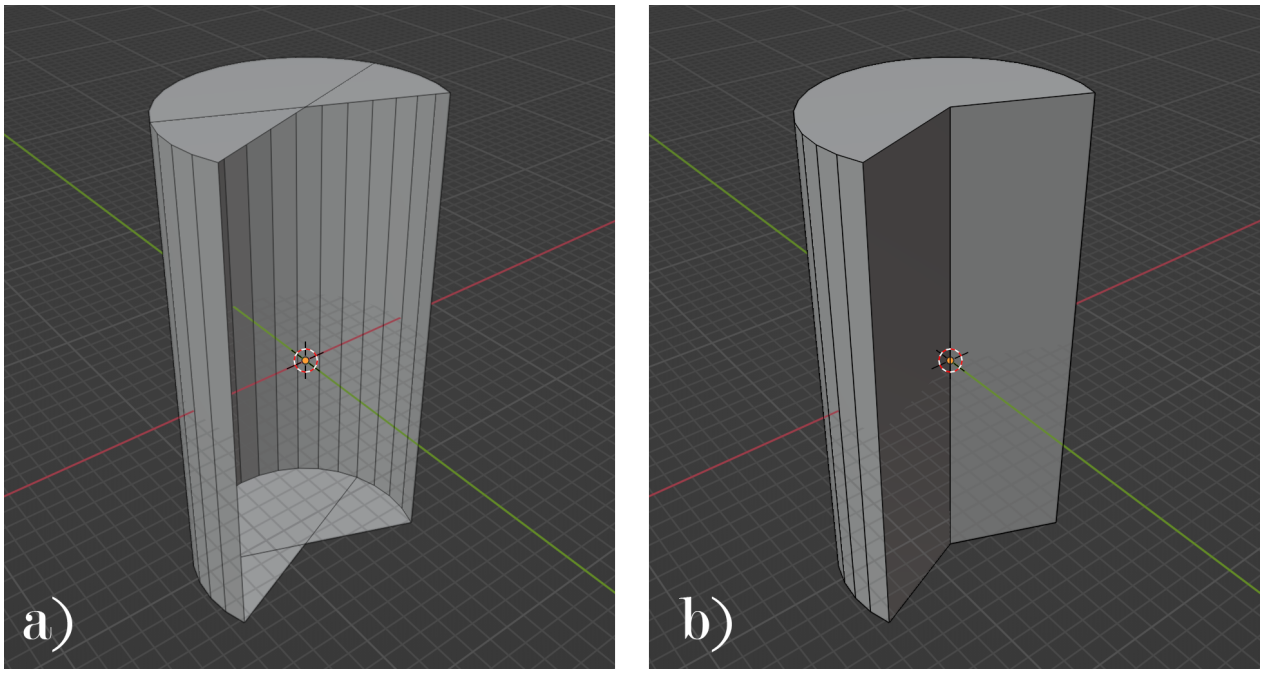


FIGURE 4.8 After cutting the cylinder on both bases using knife tool (to access the knife tool, press K on the keyboard while in "Edit Mode"), the undesirable faces can be deleted (a). Then, using the fill command (F on the keyboard), faces are placed between edges and the sliced cylinder is patched up (b).

"Shader Editor" window (Shift+F3). By selecting each part of the model, new material can be assigned. Blender's node-based editor, called the "Shader Editor" or "Compositor", allows the user to create material networks using texture nodes. This provides more control over how textures are applied and blended together (Figure 4.9). A list of different textures and their sources is provided in Table 4.5.

Table 4.5 Textures used in Blender model

Texture	**License**	**Source**
Canadian Flag	CC0	Government of Canada website [141]
Concrete pit	CC0	`ambientCG.com/a/Concrete042A`
Flagpole	CC0	`ambientCG.com/a/Metal044A`
Ground - Depth	CC0	Figure 4.10
Reactor - Dome	CC0	`ambientCG.com/a/Concrete034`
Reactor - Wall	CC0	`ambientCG.com/a/Concrete014`
Surface - Core top	CC0	`ambientCG.com/a/MetalPlates017B`
Surface - Grass	CC0	`ambientCG.com/a/Grass001`
Surface - Unit floor	CC0	`ambientCG.com/a/DiamondPlate001`

In this model, the SMR is embedded in the ground. However, no different 3D body is designed for the reactor core itself. Hence, a demonstration of the reactor has to be added to the ground texture to imply the existence of the facility. In their study, Wallenius et al [142] have presented a detailed cross-section of the SEALER reactor developed by LeadCold, and the same high-quality orthographic demonstration (without details) can be found on the internet [143]. After alteration of the reactor's orthographic view and its integration in the ground texture, the ground texture would look like Figure 4.10.

Another texturing challenge is the ground surface since in this model, the surface consists of three different parts, namely reactor core top, unit floor, and grass. Using image editing software, the different textures are re-sized and put together as Figure 4.11. Finally, a demonstration of textured model elements is presented Figure 4.12.

4.5.2 Animating and export

To animate an object in Blender, the desired stages of the animation need to be keyframed. Firstly, the object is selected in the 3D Viewport, and the desired frame is chosen from the Timeline window. Then, the object's properties in that frame are fixed by pressing the "I" key on the keyboard, which triggers the insertion of a keyframe. By selecting another frame and

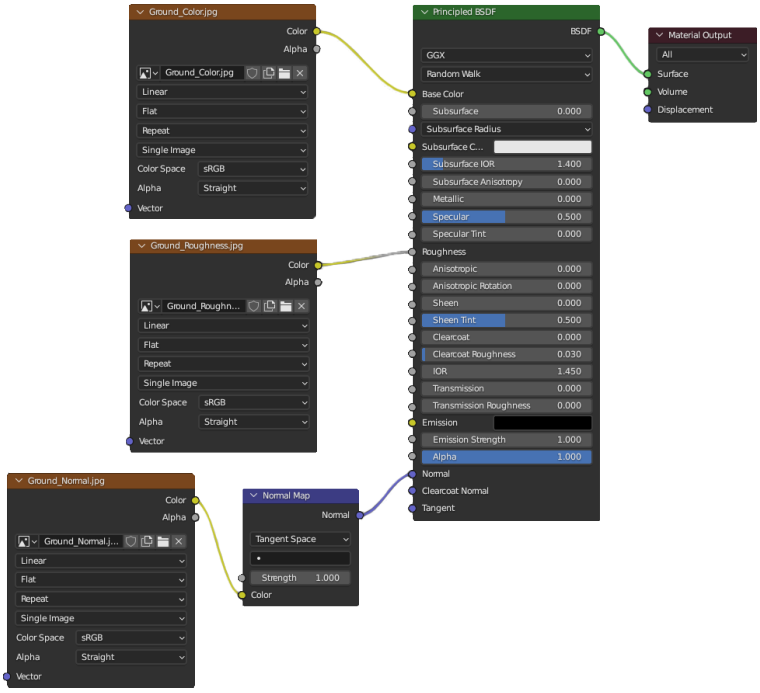


FIGURE 4.9 Blender's node-based editor for texturing the ground column. As previous, only color, roughness, and normal maps are used. However, many other attributes can be assigned to the model to make it more and more realistic.

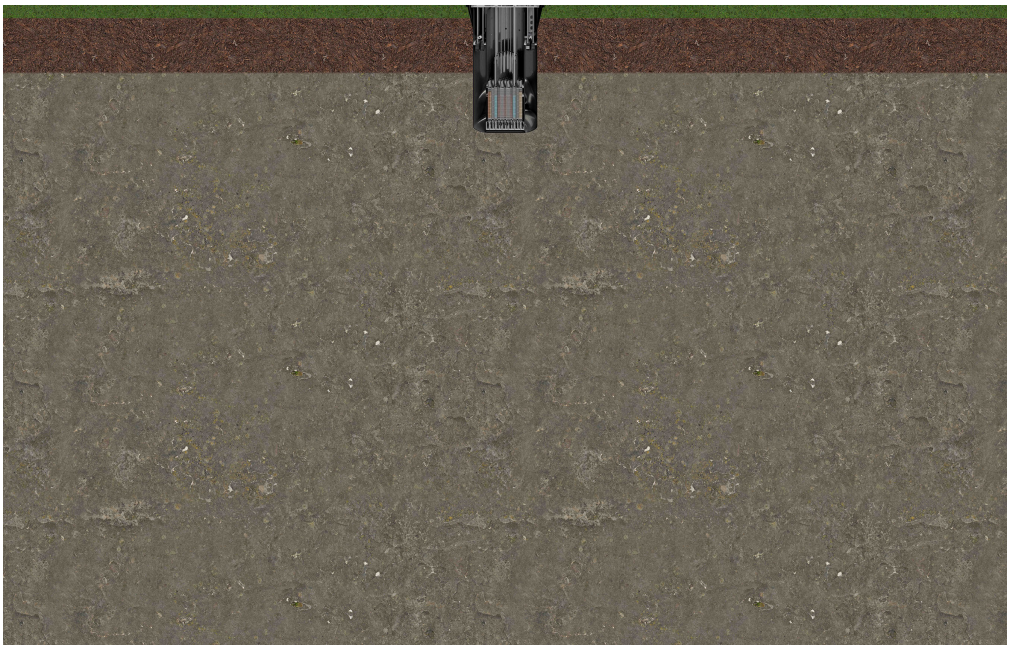


FIGURE 4.10 The ground color texture after adding the SEALER reactor.

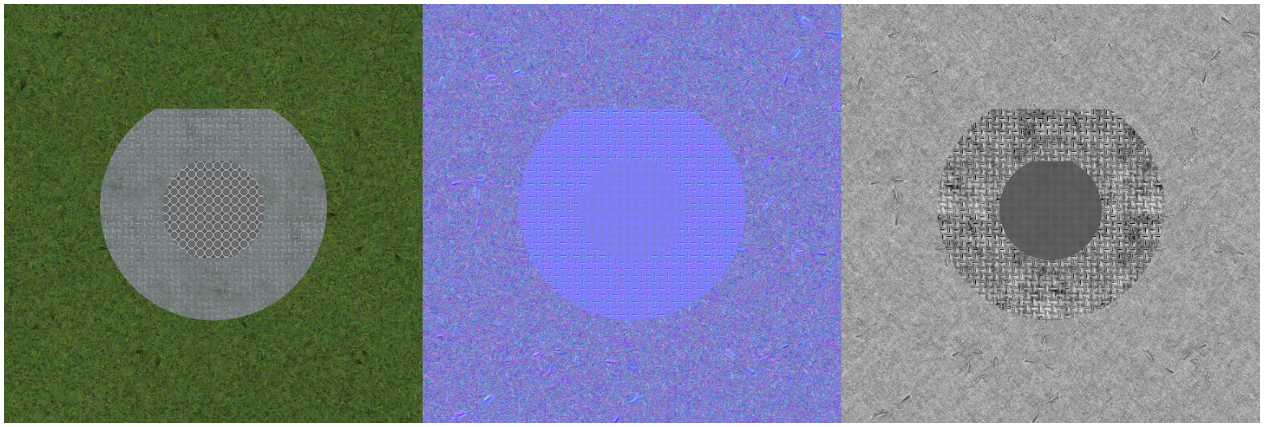


FIGURE 4.11 Different surface textures edited, re-sized and put together.



FIGURE 4.12 Textured model elements in Blender

inserting a new keyframe with different properties, such as changes in location, rotation, or scale, a smooth transition is created between the two keyframes. By adding a sufficient number of steps and keyframes, the 3D models can be brought to life. The Graph Editor window in Blender, much like Autodesk Maya, provides a comprehensive overview of the keyframes and transitions in the form of graphs, allowing the user to analyze and refine the animation. By adjusting and fine-tuning the position of the keyframes and manipulating the transition curve, the user can precisely control the timing and smoothness of transitions between keyframes. This process allows for precise control and manipulation of objects, resulting in dynamic and engaging animations. In this model, semi-transparent blue and red regions are created around the ground cylinder to represent above and below the pore-water freezing point. As time passes, high temperature propagates more and more into the ground, resulting in permafrost thaw. The final animated model is presented in Figure 4.13.

4.5.3 Sketchfab : A possible publishing platform

Sketchfab is a popular online platform that serves as a hub for publishing and discovering 3D content. It provides a user-friendly interface for creators to showcase their 3D models and animations to a wide audience. With a large community of users and a vast collection of models, Sketchfab offers an ideal platform for sharing and promoting 3D models. It also provides additional features and tools to enhance the presentation of 3D content, including annotations, material editing, and post-processing filters. The platform supports interactive viewing, allowing users to rotate, zoom, and explore models from different angles. Furthermore, Sketchfab offers embedding options, allowing the user to showcase 3D models on websites, blogs, or social media platforms. Sketchfab has good integration with Blender, providing support for native .blend format. Hence, the created model can directly be uploaded to Sketchfab without any exporting measures.

4.6 Results and Discussion

After the finalization process, the models created in both Maya and Blender are uploaded to Sketchfab. For Blender models, there is no need to export the model separately as Sketchfab supports the .blend format directly. However, for Maya models, they are exported as FBX files before uploading to Sketchfab. The access links to the models can be found in Table 4.6.

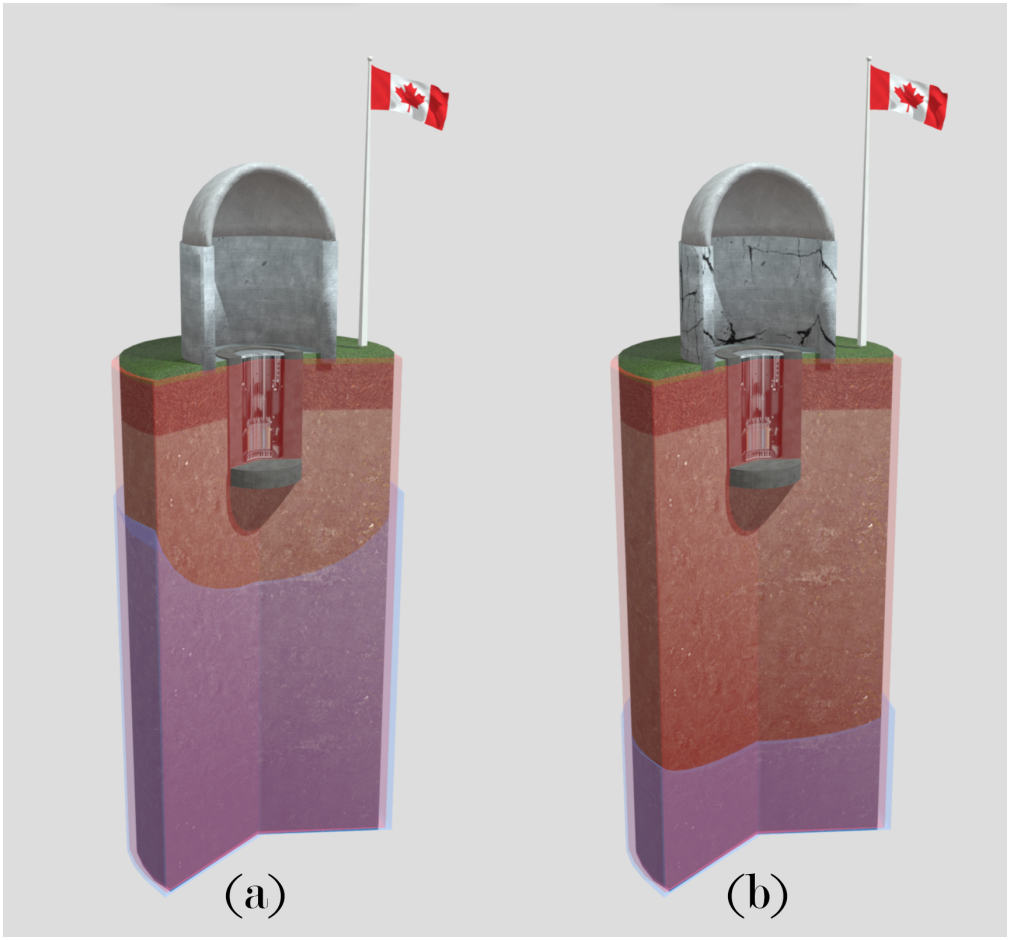


FIGURE 4.13 Animation stages in Blender.

TABLE 4.6 Created models in this thesis on Sketchfab

Model	**URL**
Climate Change (Maya)	`skfb.ly/oIr9w`
SMR (Blender)	`skfb.ly/oIrwz`

After uploading the models to Sketchfab, they are supported in both AR and VR formats, as demonstrated in Figure 4.14. The flexibility of supporting different formats enhances the accessibility and usability of the models, allowing users to choose their preferred mode of interaction.

4.6.1 Toward an AR/VR soil mechanics laboratory

As mentioned earlier, the application of AR/VR models has proven to be beneficial in presenting various concepts to students, particularly in laboratory practices. In order to establish a strong foundation in geotechnical understanding, it is crucial to develop a deep comprehension of the subject matter. Therefore, several pedagogic models were created using a combination of Autodesk Maya and Blender, following the procedure outlined previously. Once the models are finalized, they are all uploaded to Sketchfab, undergoing some post-processing stages such as shading, lighting, annotation, etc. The models are made available for free download, allowing anyone to access and utilize them for educational purposes or other applications. A list of created models and their access links is provided in Table 4.7.

TABLE 4.7 Virtual soil mechanics laboratory models on Sketchfab

Model	**URL**	**DOI**
Direct shear test (dense sand)	`skfb.ly/oHEKn`	10.5281/zenodo.8120962
Direct shear test (loose sand)	`skfb.ly/oHEED`	10.5281/zenodo.8121012
Hydrometer test	`skfb.ly/oHrMI`	10.5281/zenodo.8121092
Soil components	`skfb.ly/oHVGG`	10.5281/zenodo.8120943
Triaxial test (CD loading)	`skfb.ly/oHR87`	10.5281/zenodo.8121114
Triaxial test (CU loading)	`skfb.ly/oHEJU`	10.5281/zenodo.8121125
Triaxial test (Mohr-Coulomb failure criterion)	`skfb.ly/oHEFR`	10.5281/zenodo.8121128

To make the models more accessible and compatible with different software and devices, they are automatically converted by Sketchfab into various formats such as glTF, GLB, and USDZ.

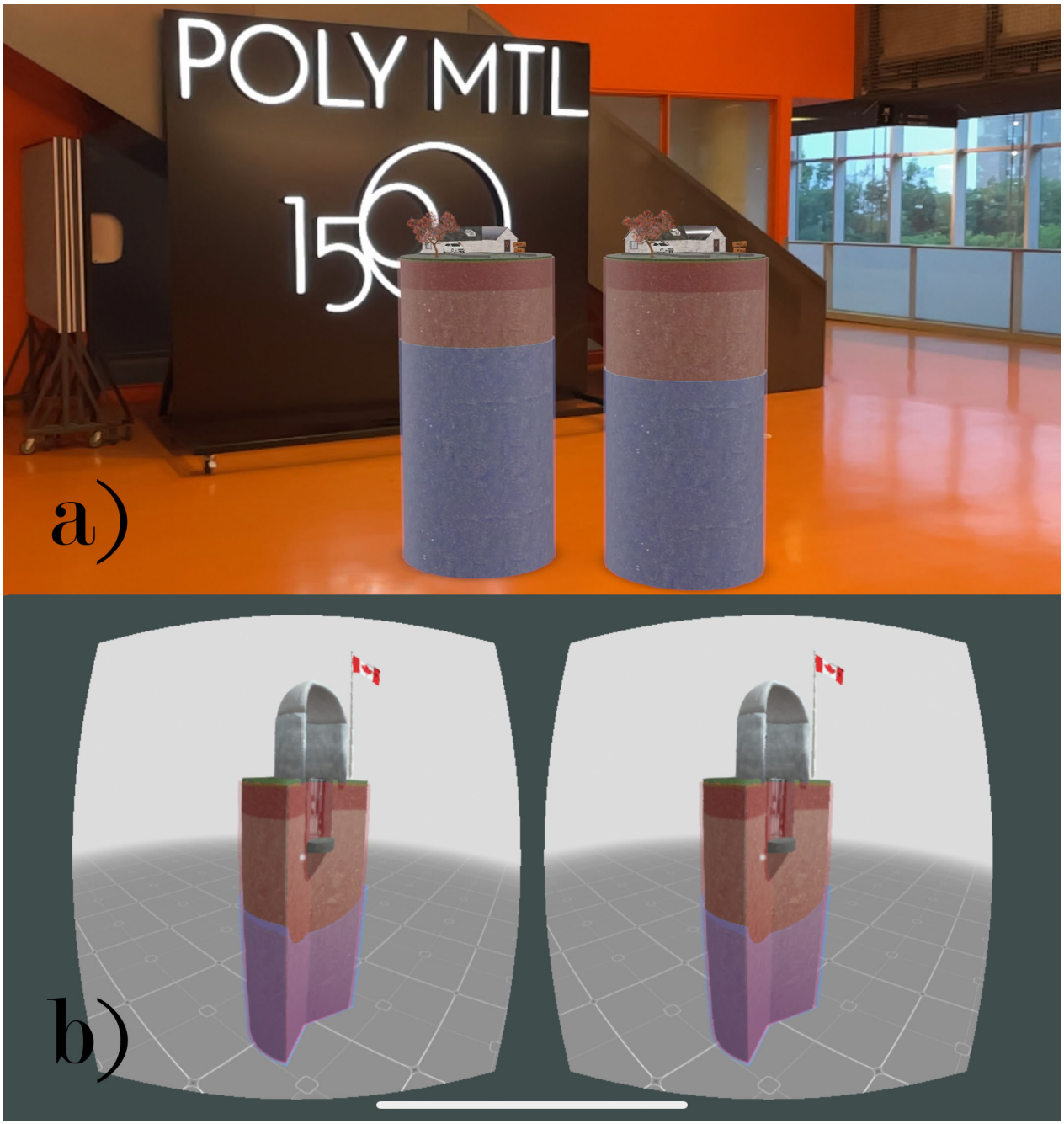


FIGURE 4.14 Finalized models are uploaded to Sketchfab. The "Climate Change" model is viewed in AR (a) and the "SMR" model in VR mode (b). The links to the models are accessible through Table 4.7.

The USDZ format is specifically designed for AR applications on iOS devices [144]. Devices running on iOS 12 and up can view 3D models in AR directly from Safari or other compatible apps, without the need for additional software or plugins (Figure 4.15). Sketchfab viewer also supports VR mode. With the use of VR headsets and tools such as Google Cardboard, users can view the models in a VR environment as well by turning their smartphones into VR headsets (Figure 4.15).

4.6.2 Challenges and Opportunities in Enhancing Realism and Physics in AR/VR Models

The created models can be further enhanced to look and feel real. Both Autodesk Maya and Blender empower users to introduce physical properties like gravity, cloth movement, and fluid dynamics into their virtual creations. For instance, in geotechnical labs, it is possible to simulate the mechanical response of the sample, such as simulating the cracking of a rigid sample or modeling the intricate interactions between soil particles during a triaxial test. This would add a layer of realism to the virtual experience. However, several challenges appear when incorporating physics into AR/VR models. The primary hurdle is mastering the appropriate physics. Configuring the environment and navigating through numerous properties to achieve the desired effects is a complicated and time consuming task. Moreover, while realistic effects such as cracking, cloth simulation, and fluid dynamics elevate the authenticity of AR/VR models, they come at a cost. These effects demand substantial computational resources and result in large file sizes, mainly because achieving an acceptable realistic result requires very fine mesh details. Furthermore, there is the matter of publishing these advanced models. Presently, accessible platforms like Sketchfab exhibit limitations in supporting these physics-based effects, and limitations become more significant for AR format support. An additional approach to consider for making the models more accurate is the adoption of dynamic textures, which could serve as an alternative to the static ones used in this study. In the current procedure explained in this thesis, there is no direct way to introduce the exact numerical results in an AR/VR model, and the models serve just as demonstrative prototypes for engineering concepts. Another limitation lies in the animation nature, which only allows for rotation, movement, and size changing effects (no alteration of the mesh). Utilizing widely accessible software employing Finite Element Method, it becomes possible to simulate the mechanical behavior of a test sample, such as the complex propagation of heat inside the ground, while recording the results of these simulations in dynamic formats like .gif or .mp4. This approach presents the opportunity to create highly precise AR/VR models that integrate accurate FEM data. However, an existing limitation lies in the lack of support for dynamic textures on current publishing platforms. Nevertheless, with the current

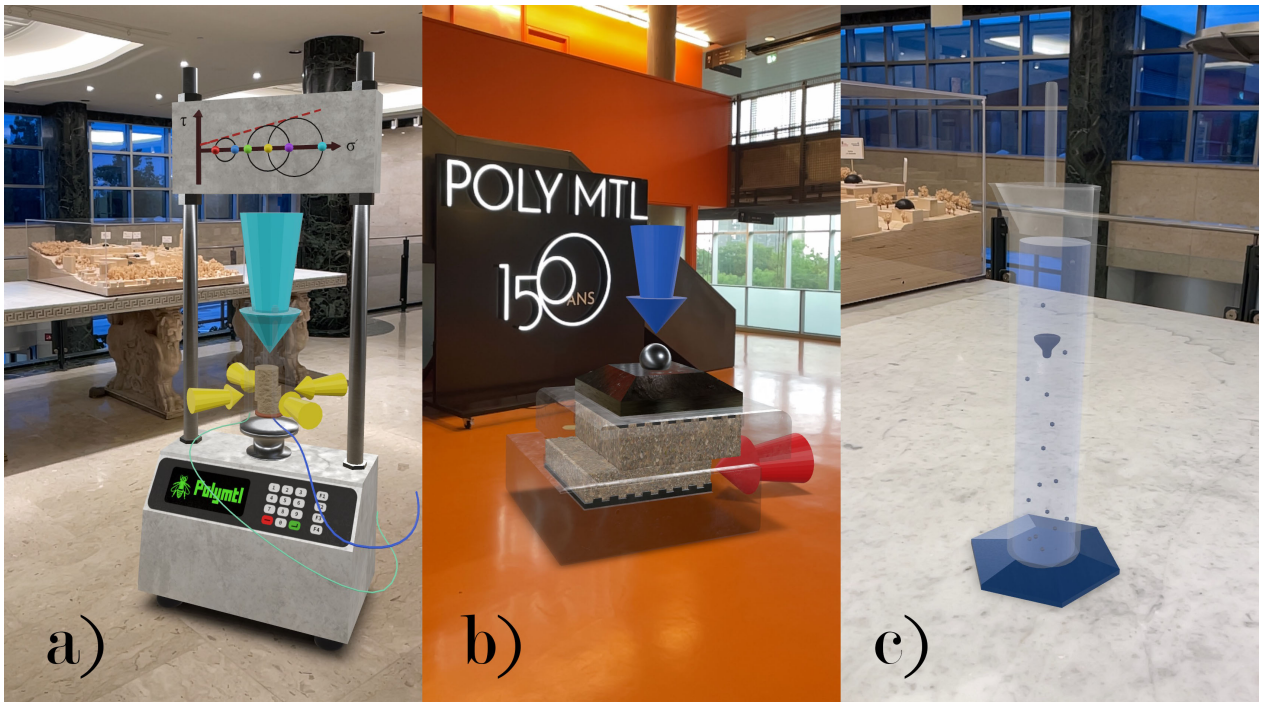


FIGURE 4.15 Some tests and procedures of soil mechanics laboratory in AR mode : triaxial test (a), direct shear test (b), and hydrometer test (c).

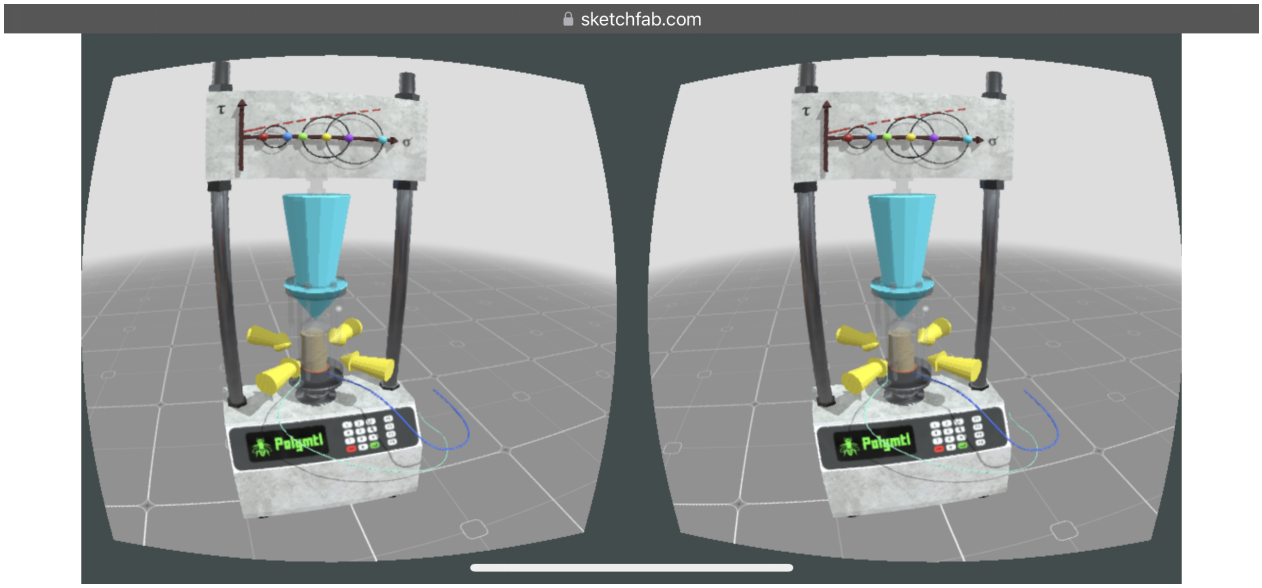


FIGURE 4.16 Triaxial test (Mohr-Coulomb failure criterion) model in VR format on Sketchfab.

trend of advances in technology, the future appears promising and these existing barriers will gradually dissipate. This would open the door to vast opportunities for delivering high-quality educational experiences, bringing the quality of Computer-Generated Imagery (CGI) to classrooms and laboratories.

4.7 Conclusions

In this paper, we present the application of emerging AR/VR technology in geotechnical engineering. The aim is to pave the way toward education 4.0 and 5.0 in geotechnical engineering, promoting time and place independent learning, learning flexibility, and visualized education. The presented ideas in the thesis were visualized, and several geotechnical concept avatars such as the phase diagram and CU triaxial test, created by using Autodesk Maya and Blender respectively, are presented to provide a base for engineers to start building their own 3D models. The links to the models and some other demonstrations (direct shear test for both dense and loose sands, hydrometer test, CD triaxial test, and Mohr-Columb failure criteria) are provided through Sketchfab website, which supports AR/VR view of the created 3D models in various formats.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

This thesis studies the critical role that Small Modular Reactors (SMRs) play in Canada's ambitious energy transition strategy. A thorough literature review has been presented regarding the role of SMRs as key players in the Canadian energy landscape, and the current vendors being considered for the SMR market and their proposed designs are presented.

Despite the promise brought about by SMRs, uncertainties persist regarding their optimal design, adaptation, and implementation in Canada's unique climate. A significant portion of the reactor unit can be partially or fully embedded in the ground, and considering that SMRs operate at high-temperature ranges, they could release substantial heat into the surrounding soil. While specific data on SMR heat dissipation to the ground is limited in the literature, it is reasonable to assume that managing heat transfer and its consequences on the environment, particularly in permafrost regions, is a significant concern. The heat generated by SMRs may contribute to permafrost thawing, posing risks to ground stability and infrastructure integrity. Consequently, it is essential to evaluate and mitigate the impact of heat dissipation on permafrost conditions during site selection and design.

On the other hand, the accelerating climate change is already threatening permafrost regions, and the thermal interaction between SMRs and the surrounding soils can add up to the problem at hand. Unlike traditional civil engineering practices which typically rely on the stability of climate conditions, the presented thesis has taken on a non-stationary climate approach, taking into consideration the changes in surface temperature trends projected until the end of 21st century.

This study aimed to evaluate the combined impact of SMRs and climate non-stationarity on permafrost conditions. The research focused on the intertwined effects of heat dissipation from a SMR reactor core and changing climate patterns on ground temperature and permafrost degradation. Two distinct locations, Salluit (QC) and Inuvik (NWT), were selected for in-depth case studies. The study investigated ground temperature profiles over three key time periods : Period 1 (January 2020 to December 2024), Period 2 (January 2050 to December 2054), and Period 3 (January 2095 to December 2099). The chosen SMR case for this analysis was the SEALER reactor developed by LeadCold, as it is a potential SMR option for implementation in Canada's remote communities. The research findings indicated that maintaining the concrete pit surrounding a SEALER reactor at $90°C$ could lead to a significant increase in the active layer's thickness at a distance of 5.0 meters, reaching up to 21.54 meters in Salluit and 21.55 meters in Inuvik. The thermal instability in both regions

was observed up to distances of approximately 15.0 to 20.0 meters from the reactor core. It was apparent that climate non-stationarity played a substantial role in ground temperature disturbances as one moved farther from the reactor. The impact of climate change resulted in permafrost thaw depths ranging from 3.26 meters to 5.24 meters for Salluit and 2.25 meters to 3.52 meters for Inuvik. The increase in thaw depth attributed to climate change was concerning, and the presence of a hot reactor introduced the risk of uneven settlement and significant foundation deformation at the SMR site.

To address this challenge, potential solutions could involve the implementation of cooling systems and thermo-syphon technology to control the reactor's temperature or pre-thawing of the permafrost foundation before construction. Additionally, the utilization of advanced insulation materials around the reactor could help mitigate heat transfer and prevent detrimental effects on the frozen soil layers.

Further research is required to explore the combined heat and mass transfer effects and assess various thermal mitigation techniques for SMR reactors. As vendors progress through subsequent development and licensing phases, more details about their reactor designs will be available to the public, and researchers will gain richer insights for their assessments. This study serves as a foundational step, paving the way for more sophisticated investigations suited to various reactor types proposed by vendors. This thesis and future publications in this domain hold the potential to guide policymakers toward a better perspective on the promises, and risks associated with these structures. A clearer roadmap for achieving the 2050 net-zero emission goal can thus be crafted, and geo-technical guidlines for implementing SMRs in the arctics can be developed.

To visualize the concepts introduced in this dissertation, two 3D computer graphics applications were introduced to provide a step-by-step guide on creating 3D models and showcasing them in augmented reality (AR) and virtual reality (VR) formats. This approach was extended to embrace the paradigms of Education/Industry 4.0 and 5.0, integrating engineering AR/VR demonstrations for soil mechanics laboratories. The generated models were equipped with accessible URLs and DOIs to ensure that they are readily available to a wide audience for educational purposes and potential future improvements. The AR/VR platform represents the future for conveying complex engineering ideas and concepts. They have aspired to lay the groundwork for other enthusiastic researchers to become acquainted with this domain and commence presenting their innovative ideas using these cutting-edge formats.

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