Canadian SMR Roadmap

Technology Working Group Report

Prepared by: SMR Roadmap Technology working group

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Outline of Final Report

1. Introduction

In the fall of 2017, shortly after the government of Canada's launch of Generation Energy, a number of organizations came together to discuss whether SMRs might play a role in Canada for energy production and greenhouse gas reduction while contributing to innovation and economic development. A Steering Committee consisting of numerous provinces and utilities across Canada and chaired by Natural Resources Canada, convened to develop a roadmap that would lay out a path forward for the potential deployment of SMRs and associated supporting supply chain in Canada.

Several workshops across Canada were held to receive input on the potential opportunity relating to the three market applications:

- On-grid power
- Remote communities
- Heavy industry & mining

Five working groups or sub-committees were also formed to examine the specific details related to:

- Technology
- Regulatory Readiness
- Indigenous & Public Engagement
- Waste Management
- Economic & Finance

This report documents the findings of the Technology Working Group and as such provides details relating to technology review and considerations supporting the findings and conclusions of the overall Pan-Canadian SMR Road Study.

1.1 Technology Working Group Mandate and Membership

The mandate of the Technology Working Group (TWG) was to identify SMR technology categories that could meet stakeholder requirements regarding: size, energy output, technology readiness, deployment timelines, geographical considerations, and supply chain.

The TWG was comprised of experts from across the Canadian nuclear industry: Canadian Nuclear Laboratories (co-chair), New Brunswick Power (co-chair), Atomic Energy of Canada Limited, Bruce Power, Canadian Nuclear Safety Commission (observer), Alberta Energy, Natural Resources Canada, Ontario Power Generation, Province of Ontario Ministry of Energy, SaskPower, and Jerry Hopwood (industry consultant)

The key activities of the TWG were to:

- Analyze SMR technology categories against Canadian SMR end-user requirements, and
- Identify key gaps in research and development for preferred technology categories

To guide its work, the Working Group considered the following questions:

1. What are the user requirements for SMRs in Canada?
    - What are the characteristics of those applications that impact the required attributes of an SMR technology?
    - Identify similarities between the attributes for the different application categories
    - What are the future energy of needs of Canadians and what may be the future needs of nuclear energy technologies (e.g. more sustainable fuel types, recycling of fuel, transmutation of used fuel, etc.)? Are there desirable attributes that would not be ready for near-term deployment (e.g. 2030), but would be desired in the longer term (e.g. 2050)?
2. Are there technologies under development domestically or internationally that may be able to meet the requirements identified above?
3. What are the timelines and major milestones needed to support domestic SMR deployment and/or SMR manufacturing for international export?
4. What support or activities/programs are needed from key stakeholders: industry, private sector, public/government sector to facilitate the deployment of SMRs?
5. What changes will be needed to the front-end or back-end stages of the fuel cycle from those that currently exist in Canada, for the identified technologies and applications?
6. To what extent can Canada make use of other national or international activities?

There were four other working groups involved in this SMR roadmapping exercise:

- Economics and Finance Working Group (EFWG)
- Regulatory Readiness Working Group (RRWG)
- Indigenous and Public Engagement Working Group (IPEWG)
- Waste Management Working Group (WMWG)

This report by the TWG does not consider these topics, where these interact with the technology working group report the reader is directed towards the reports from those groups.

The Technology Working Group was made up of the following people and organizations:

Person	**Organization**
Bronwyn Hyland (Co-chair)	Canadian Nuclear Laboratories
Paul D Thompson (Co-chair)	New Brunswick Power
Martin Mader	Alberta Energy
Stephen Busby	Atomic Energy of Canada Ltd
Frank Saunders	Bruce Power
Jerry Hopwood	JMH Technology Consulting
Daniel Brady	Natural Resources Canada
Wilson Lam	Ontario Ministry of Energy, Northern Development and Mines

Chris Deir	Ontario Power Generation
Bret Kempel	SaskPower
Laura Andrews Daniel Duchesne Sean Belyea Melanie Rickard	Canadian Nuclear Safety Commission

1.2 Introduction to Some Key Concepts

1.2.1 Fast Reactors vs. Thermal Reactors

Nuclear fission reactors can be categorized in two major classes: thermal reactors and fast reactors. “Thermal” and “fast” relate to the speed of neutrons used to sustain the nuclear chain reaction. Thermal reactors use a medium, such as water or graphite, to “thermalize” or “moderate” neutrons, i.e. to slow neutrons down. Thermalized neutrons have a larger probability of splitting fissile atoms, and hence sustaining the chain reaction that is needed to produce power. Although there are a few fast reactors operating worldwide, thermal reactors constitute more than 97% of the currently active power reactor fleet. Nuclear reactors can be further categorized according to the neutron moderator used for slowing neutrons and the coolant used extract heat from the fuel.

Unlike thermal reactors, fast reactors do not contain a neutron moderator and achieve a sustained chain reaction on fast neutrons alone. The lower fission probability of fast neutrons and the desire to minimize the amount of moderating materials allow fast reactors to have much smaller core volumes for a given power. These factors also result in a tighter fuel lattice, and therefore higher fuel enrichments than thermal reactors, typically on the order of 20%. The necessity of low moderation also restricts the choice for coolant, and fast reactors are typically cooled by liquid metal. The core designs are typically heterogeneous, including several fuel types at different enrichments. Fast reactors typically include blanket regions either radially around the edge of the core, axially above/below the main fuel region, or both. Depending on the intended application of the reactor, the fuel in the blanket region may be composed of fertile material such as depleted uranium or thorium, which can be irradiated to produce new fissile material. The blanket region may also contain actinide-bearing fuel for the purposes of transmuting the long-lived isotopes from spent fuel. The blanket region is driven by a fissile, or “seed” region, which is typically enriched uranium or plutonium. The two main disadvantages of fast reactor technology are the higher fuel enrichments needed and material degradation caused by fast neutrons; in some designs a reflector may improve neutron economy and reduce irradiation damage to reactor components.

1.2.2 Passive and Inherent Safety

New designs implement knowledge gained from the previous generations, including the use of concepts of inherent and passive safety. Inherent safety is attained by the elimination of hazards through decisions made during the conceptual design phase. With thorough understanding of the physics phenomenon governing the operation of a particular reactor concept, nuclear reactors can be designed to preclude the possibility of certain accident scenarios. For example, a reactor designed with such that when the fuel heats up, the reactivity of the reactor decreases (via selection of material or core configuration) is inherently safe with respect to increasing temperature.

Passive safety is provided by engineered safety systems which do not rely on external action, signal, or influence. Passive safety systems are designed to use the natural phenomena or properties of materials to perform their intended function. Passively-activated shutdown systems, such as freeze plugs in molten salt reactor designs, are one example of a passive safety system. In an accident scenario it is desirable that any shutdown system designed to work in an emergency should activate with no human intervention. A further example is heat removal by natural circulation. During shutdown in an accident scenario it is not always possible to circulate the coolant with pumps to keep the fuel cooled. Decay heat can be removed by natural circulation instead [17]. In some non-water-cooled Generation IV reactor designs, such as gas-cooled reactors, the intrinsic passive safety features provide mitigation in the unlikely event of the loss of the gas coolant (typically helium). Firstly, the fuel temperature does not rise up rapidly, thus allowing sufficient time for operator intervention. Secondly, the peak fuel temperature rise in such severe accident is well under the maximum temperature for fuel damage, thus precluding a core melt accident.

1.2.3 Fuel Recycling and Advanced Fuel Cycles

Management of used nuclear fuel is a continuing concern for the nuclear industry. Recycling of used fuel has been proposed as an alternative to long-term disposal. Fuel cycles that recycle fuel are often termed advanced fuel cycles or closed fuel cycles. Several countries, such as France, Russia and China, already reprocess used fuel. Although there is more than one way to reprocess spent fuel (often dependant on the fuel type) all methods carry out similar steps [18].

The main reasons for spent fuel reprocessing are:

- Recovery of fissile material (e.g. plutonium and uranium) to be used for fresh fuel
- Reduction of the volume, heat, and/or radiotoxicity of high level waste. The parameter and the timeframe over which that parameter is targeted to be reduced is typically depended on the disposal scenario.

As new advanced reactors are conceived, closing the fuel cycle is increasingly being considered. Fast spectrum reactors can use what would have been previously considered spent fuel waste as a direct fuel source [20]. Work has been carried out demonstrating that used CANDU fuel can be burned in fast reactors [21.] Fast reactors can also be used to eliminate long lived minor actinides present in spent fuel, significantly reducing the inventory of nuclides which require long term disposal.

Certain non-fissile isotopes, termed fertile isotopes, can be transmuted by neutron irradiation into fissile isotopes. The two most abundant fertile isotopes are Th-232 and U-238, which form the basis of the thorium fuel cycle and the uranium-plutonium cycle, respectively.

The process of creating new fissile material from fertile isotopes is referred to as breeding. Reactors which operate on this process and produce more fissile material than they consume are called breeder reactors. In contrast, reactors which are used to eliminate certain isotopes, or burn, spent fuel, but do not produce additional new fissile isotopes, are called burner reactors.

Breeding and burning are collectively referred to as advanced fuel cycles. Although some thermal reactors (e.g. CANDU reactors and molten salt reactors) can take advantage of advanced fuel cycles, fast reactors are typically viewed as better suited to the purpose.

Recovery of fissile materials from used fuel is conventionally undertaken by an aqueous reprocessing process **Error! Reference source not found.**]to separate radioactive waste streams. Aqueous reprocessing involves the application of mechanical and chemical processing steps to separate, recover, purify, and convert the constituents in the used fuel for subsequent use or disposal. Major support systems include chemical recycle and waste handling solid, high level waste (HLW), low-level liquid waste (LLLW), and gaseous waste.

Alternate advanced fuel recycling processes include pyro-processing, which uses an electro-refiner process **Error! Reference source not found.**]. Electrorefining is very similar to electroplating. Used fuel attached to an anode is suspended in a chemical bath; electric current then dissolves the used fuel and plates out the uranium and other actinides on the cathode. These extracted elements are then sent to the cathode processor where the residual salt from the refining process is removed. Finally, the remaining actinides and uranium are cast into fresh fuel rods and the salt is recycled back into the electrorefiner.

2. Canadian SMR Applications

Three target applications for deployment of SMRs in Canada were explored in this roadmap activity:

- On-grid;
- Heavy industry, which was sub-divided into remote mineral extraction and oil sands applications; and
- Remote communities

The TWG has investigated the characteristics that SMRs would require for successful deployment in each of the three applications. This was done primarily through the three application workshops that were held over the course of this Roadmap activity, supplemented with additional literature reviews and interviews with industry experts. A general set of requirements has emerged that any SMR will need to meet, regardless of the target application. For each individual application type, specific requirements can be established, and are summarized in this section.

The overall scope of the potential market for each of the types of application has been reviewed, leading to the primary requirements of output range and possible fleet size.

The purpose of the technology roadmap portion, as laid out in this report, is to provide a route that enables stakeholders to develop the elements for successful SMR deployment. The TWG report does not define a formula for technology or design selection – that will be the responsibility of project proponents in the future. The Roadmap provides information on requirements to support effective choices of development and evaluation by the SMR stakeholder community.

2.1 General requirements

In many topic areas, the requirements for deployment are common between all application types. At this initial stage, requirements are not always laid out as detailed specifications, but as expectations for design. Compliance with requirements can be used in future as a method of individual design selection.

From the engagements through the three applications workshops that were held over the course of this roadmapping exercise, the TWG noted the following list of general technical requirements:

- Availability/technical readiness
- Fuel readiness (globally)
- Fabrication readiness (globally)
- Supply chain readiness
- Availability of codes & standards for fabrication
- Availability of computational tools, for design, verification and analysis
- Technology readiness (in context of deployment in Canada)
- R&D pedigree

- Domestic capability and expertise
- Existing safeguards approaches

This list excludes requirement related to:

- Economics, cost and financing, covered by the EFWG
- Regulatory and licensing: covered by the RRWG
- Public and Indigenous engagement: covered by the IPEWG
- Waste management: covered by the WMWG

In addition to these requirements, which are common to all applications, each of the three applications has additional unique requirements. These are explored in the following sections.

2.2 Requirements for On-Grid Deployment

The impact of clean electrification on the grid throughout Canada is currently not well known but may involve significant expansion of clean electricity services. This potential is becoming increasingly recognized, for example, through the Generation Energy discussion forum sponsored by the

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]. SMRs have the potential to play a significant role in transition to greater reliance on electrification as clean, non-emitting sources of electricity generation will be required; many energy demands today are currently met by fossil fuels. The transition to clean electricity, such as for transport, heating and cooling systems, and industrial processes will require more electricity, in addition to the replacement of Canada's remaining fleet of coal-powered units with non-GHG-emitting power supply. The existing fleet of coal powered units (subsequent to the Ontario coal shutdown), comprises approximately 10,300 MW of capacity. Canada's plan is to close all this capacity in the 2020s. As fossil-fuel use is reduced, the ability to supply intermediate loads is reduced. With greater potential to load-follow, SMRs may be suitable to meet this need. A detailed study is needed, to better understand the change in demand as clean electrification is introduced.

Overall requirements for on-grid deployment of SMR units will be set in detail by utilities, in specification documents, typically after discussion with potential design vendors. The key requirements identified by the TWG could be used to establish a given design's viability. It is noted that certain proposed short-term available designs are expected to meet these requirements, while other designs at an earlier stage of technology maturity could be developed in accordance with the requirements in the longer-term. Developments in electricity supply and demand indicate that there will be a potential need for short-term deployment, with in-service dates from 2025-30; this will require a high level of design completion and regulatory review today. There will continue to be deployment potential beyond 2030, and development of designs that establish further benefits for the longer-term should also be pursued (see 3.7).

- **Output range**: Scalable/modularized for different markets (50 MWe < Unit Size < ~300 MWe)
- **Economics**: For commercial scale applications; levelized electricity costs comparable to current nuclear plant designs (see EFWG report for further discussion); the enabling process of technology demonstration, FOAK deployment and on to NOAK deployment will need to be within the fiscal capacity of the SMR roadmap stakeholders.
- **Construction**: For fleet-scale construction (NOAK); Length of time between decision to launch the project to Commercial Operational Date (COD), <10 years
    - Minimal gap between Licence to Construct (LtC) and COD (< 5 yrs)
- **Operations**: Simplicity of operation, and organizational resilience to technology, pre-requisites to confidence in enabling a sustainable O&M organization for all locations
    - Capable of load following when integrated with renewables (support changes in electricity demand)
    - Capacity factor > 85% Load-following CF > 50% forced loss rate < 2%

- **Safety**: The baseline requirement is to meet the Canadian regulatory safety requirements with a demonstrated safety case (“Licensable in Canada”). In practice, to have confidence in a safety case that meets the highest public expectations, utilities anticipate that Gen-IV passive safety features will be a required element, to assure lower reliance on engineered systems, and confidence in a very low core damage or uncontrolled radioactive release probability.
    - Plant cooling for at least 7 days, without operator action for severe accidents
    - Fire & security resistance built into design
    - A safety-related requirement expected to be defined will be a minimum size of exclusion or emergency planning zone
    - Safeguards and security requirements must be met, including compliance with IAEA safeguards protocols; this means a requirement for characteristics that increase the proliferation resistance of the nuclear energy system, such as low attractiveness of the nuclear material in the system, inability of the operation of the facilities to undetected and undeclared use. To meet IAEA requirements, the system must be amenable to IAEA inspection, and the implantation of safeguards equipment.
- **Fuel**: Qualification of nuclear fuel is a lengthy process; a typical time for qualification is a decade. Therefore, near-term deployable SMRs (<2030) will require a pre-qualified fuel technology; a fuel design that has undergone irradiation testing for reactor use for early deployment; and evidence of fuel reliability for required duty over long-term operation.
    - Ability to credibly verify analysis of fuel within Canadian nuclear community
    - It is advantageous for enrichment to not exceed 20% to stay within known existing safety and security protocols
- **Supply Chain**: To be ready for commercial deployment, a qualified supply chain is necessary for all major or specialized components. An important benefit to Canada is the participation of domestic companies and facilities in supply; the TWG recommends that Canadian supply organizations are incentivized to invest in supply chain readiness (this is further discussed in Chapter 6).
- **Waste Management**: As a minimum, waste management requirements comparable to current fleet requirements, including available on-site dry storage of spent fuel available; Waste management easily integrated with existing waste management plans, e.g. NWMO low level waste depository and current strategy for fuel retrievable storage. Spent fuel management plans will need to be accepted by NWMO.
    - In addition, desirable characteristics that would be part of utility evaluation include:
    - “Zero emissions” during operation
    - Minimize/eliminate high level waste stream
    - Ability to burn/recycle CANDU spent fuel
    - Minimize low and intermediate level waste streams

- **Socio-Economic Benefits**: A commercial on-grid SMR deployment proposal would be evaluated by the owner/end-user on its own merits to provide clean, economical, reliable power and energy services. However, from a policy and government engagement point of view, the socio-economic benefits arising would be important in evaluating supporting programs. In evaluating technologies, governments and energy stakeholders would consider positive, measurable economic benefits (e.g. jobs, GDP); this is covered by the EFWG reporting.
    - Proportional benefits to Canada relative to risk/cost sharing (including supply chain, R&D, intellectual property (IP), value chain, etc.)
    - Support/complement uptake of variable/renewable generations
    - Support climate change initiatives
    - Export opportunities
    - Contribution of the design to non-power benefits such as medical isotope production

2.3 Remote Community Application

2.3.1 Description of the Canadian Remote Community Application

An off-grid community is defined as a permanent or long-term settlement with at least ten dwellings that is not currently connected to the North-American electrical grid nor the piped natural gas network **Error! Reference source not found.**]. The size and characteristics of the market have been identified and are detailed in Appendix A. To summarize, there are 319 remote communities in Canada **Error! Reference source not found.**]. There are off-grid communities in 10 of the 13 provinces and territories, (with the exceptions of Nova Scotia, New Brunswick, and Prince Edward Island). Almost all these communities have electricity supply by diesel generator, frequently with the associated issues of difficult and expensive fuel supply, difficulty in maintenance, and unreliability. The map below shows the locations of these communities.

Figure 1. A map showing the locations of remote communities in Canada **Error! Reference source not found.**]

The primary driver to deploy SMRs to these communities is to replace diesel power generators. Traditional drivers of cost competitiveness and carbon emissions are not as critical to this application, given the high expense of the existing supply. The underlying requirement is for the cost of power to be comparable or lower than the full (excluding subsidies) cost of diesel power.

2.3.2 Requirements for Remote Communities

The majority of remote communities have an electric power capacity of between 0.5 and 2 MWe. In some cases, there may be a potential to deliver district heating as a secondary energy service. The electricity demand profile varies between different communities but would not be a constant "baseload". Integration with demand management, energy storage, and planning for future demand growth, would be essential areas of technology study to identify how to effectively deploy SMRs. Such work should be carried out in cooperation with the communities themselves. The key would be a requirement for a high degree of reliability both for the SMR itself and for the overall energy system to the community. Designs that can potentially meet these requirements are at early stage of development, so fit into longer-term deployment; this is consistent with the need for longer-term, early-start efforts in siting, and community outreach, in parallel with technology and design development completion.

Most remote communities in Canada are Indigenous-based or have a significant Indigenous population. Deployment of any new power generation must respect the Indigenous way of life. Any such projects must ensure that historical lessons learned are incorporated and that there will not be any long-term legacy associated with the project for future generations. Canada's remote communities have, or seek, to have autonomy in managing their affairs. This means that there will be process requirements for SMR stakeholders, on deeper consultation and decision-making on infrastructure development. It also means that SMR technologies have characteristics that meet frequent community concerns, as raised in workshops and consultations. Important requirements for SMR technologies and for project deployment arising from community feedback include:

- **Project development:**
    - Respect Indigenous culture, knowledge and way of life
    - Incorporate community view and decision making
    - Communities may desire to have some partnership or ownership in the project
- **Technology:**
    - Community deployment cannot be "First of a Kind" (FoaK), must have been demonstrated elsewhere
    - Minimize environmental impact to land, water and wildlife from construction and operations -- essentially zero emissions from the facility
    - Prompt and complete removal of facility following end of commercial operations
    - No on-site storage of waste including fuel

It will be important to deliver maximum local community benefits from an SMR installation, for example, enabling local people to be employed in operations and maintenance (and using a project as a vehicle for farther-reaching employment for local community members); and considerations of possible combined heat and power applications, as district heating is a potential benefit.

Given the interest in using renewable technologies, there is a requirement for underlying technology development, to enable effective co-generation in micro-grids, between nuclear and other forms of generation, particularly intermittent generation such as wind and solar, adjusting to local demands.

An important consideration for deployments in remote communities is that the incoming technology must have been previously proven by operation in some application either commercial deployment or, at minimum, demonstration. This means, in practice, that a **demonstration project** as part of the deployment program may be an essential pre-requisite to provide the proof that the technology is ready for remote applications.

Additional factors to be considered for power SMR suitability for remote communities include:

- **Demand flexibility:** Electricity demands in a community may grow significantly between now and when SMRs are ready for deployment. The capacity of should be chosen considering future growth projections in energy demand.
- **Reliability:** High reliability is of particular importance, both for the SMR itself and for the overall energy system, including micro-grid, other energy sources and storage equipment: SMR design should achieve effectively no unplanned downtime, target design to achieve >90% capacity factor.
- **Minimal water usage:** Many remote communities have very limited water supplies, so SMR deployment should consider keeping water usage requirements to a minimum. For example use of the ambient air as the primary heat sink, minimizing make-up water requirements.
- **Ability to load follow:** The load following capabilities of a given SMR technology may have a significant effect on the maximum capacity that can be installed in a given community. These characteristics include minimum operating power level, and quick start-up capability. An SMR that is capable of operating at power levels that match the full range of demands of the community with capacity to spare would be well suited for deployment as a stand-alone unit.
- **Coupling to energy storage and alternative/renewable energy sources:** The installation of energy storage capacity would reduce the required installed SMR capacity. This would allow the SMRs to operate at a higher power level than needed to meet current demands, with the excess energy stored and used to meet power demands that exceed the SMR capacity. SMRs may be proposed for operation in conjunction with other energy sources, such as wind or solar.
- **District or electric heating systems**: The installation of SMRs could enable the installation of electric heating systems or district heating systems to replace or supplement current diesel fuelled systems. This may increase the electricity demand by a significant amount depending on the relative amount of diesel consumed for heating, typically increasing demand up to three times.
- **Safety Considerations:** the following key considerations emerged from the TWG deliberations and the Roadmap workshops:
    - Minimize safety risks through passive/inherent features
    - Complete walk-away, to the extent possible
    - Minimal plant boundary & emergency planning zone for flexible siting in a variety of locations
    - Remote monitoring and shutdown
    - Minimize use of toxic materials in design
    - Generation-IV passive and inherent safety
    - Fire and safety resistance built into design
    - Emergency planning must account for entire community

The following characteristics of remote communities will need to be considered in the development of any SMR technology intended for this application, and in the deployment of any SMR projects:

- Limited sea lift time for equipment to be brought in (3-4 months per year)
- Limited local skills for operations
- Communications with remote sites are limited (no internet connections are available, only satellite communications)
- The communities are fly-in only for much of the year

2.4 Requirements for Heavy Industry Applications

Industry applications that provide a potential demand for SMR energy include two main sub-groups: mineral mining, and oil sands operations. Individual operations will have differing energy needs, in terms of electrical supply capacity, and heat delivery in temperature and quality; however, many requirements are common for the range of possible applications in this sector.

2.4.1 Mineral Mining

SMRs could have a significant impact on the mineral mining and oil and gas industries. Presently, heat and energy needs for remote operations are predominantly met using diesel fuel or natural gas. As governments increasingly introduce policies to reduce greenhouse gas emissions, the reliance on these traditional fuels becomes more and more of a concern for these operations, due to the increased cost and uncertainty moving forward. SMRs may be able to replace diesel and natural gas generation by providing clean, reliable, safe, and comparably priced heat and energy for these remote operations.

In Canada, there are over 1000 operating mines, but only 32 operating or proposed off-grid mines that rely on diesel power generators, the remainder are connected to electricity grids. The total power demands for these operating and proposed off-grid mines in Canada is 658 MWe, with the minimum and maximum power requirements of 4 MWe and 125 MWe, respectively. The power requirements of 91% of these mines are between 5 MWe and 30 MWe.

Technical Considerations: Feedback to the Roadmap team from the mineral mining and oil sands sector has identified the following key expectations for SMR deployment in this sector. These considerations have been further reinforced from the SMR Deployment Feasibility Study sponsored by the Ontario Ministry of Energy and NRCan, from 2015.

- **Output**: Unit Sizing between 10 to 60 MWe, in most cases, 30 MWe limit.
- **Near zero emissions** (radioactive and other) during operation
- **Load following** -- response characteristics to varying industrial loads, needs further study as part of the roadmap.
- **Deployable** in the same timeline as the development of a new mining operation (siting, licensing, construction, commissioning)

- **Prompt and complete removal** of facility following end of commercial operations
- **Cost** of power to be competitive with existing fuel system
- Limited local skills for **operations**
- Deployable by **transport to site** by truck or ship
- Potential for **limited cooling water** options
- High **reliability**: target is “no” unplanned downtime; planned outages to match industrial facility outages to maximum extent
- **Refueling timeline** compatible with plant maintenance outages
- **Safety**:
    - Gen-IV passive and inherent safety
    - Walk-away safety: days without operator action for severe accidents
    - Fire and safety resistance built into design
    - Emergency Planning Zon**e** (EPZ) of the nuclear power plant must not extend further than that of the industrial operation
    - Emergency planning must account for site personnel

As noted, the Ontario SMR Feasibility Study **Error! Reference source not found.**], based on the considerations specific to Ontario, identified a more detailed base-case specification for SMR deployment to the mining industry, summarized here Table 1.

Table 1 SMR Considerations, Desired Features, and Baseline Criteria **Error! Reference source not found.**]

Categories	Consideration	Importance	Desired Feature	Baseline Criteria
Economics (Financing)	Capital Cost	Important	Low CAPEX $/kW compared to large NPP	≤ $5500/kW CAD
	EPC time		EPC time to be short	≤ 4 years
	First Concrete to Operation time		First concrete to operation time short	≤ 2 years
	Plant Footprint		Smallest physical plant footprint possible to reduce site size	≤ 1600 m2
Economics (Lifetime)	Cost of Electricity	Very Important	LCOE to be equal or less than alternative options (or large NPP)	≤ $0.11/kWh CAD
	Recoverable Materials and Costs		Reactor materials are reusable and redeployable at other sites	At least 50% of direct cost
	Reactor Capacity for Site		Acceptable size for site based on loading requirements	<3 MW for RC, <10 MW for RM
	Plant expected life		Appropriate for respective site	40 years for RC and 20 years for RM
Site Deployability	Transportation during construction	Important	Transportation and construction of modules without additional infrastructure need	Weight of largest module ≤100 t
	Prefabrication		Reactor module is prefabricated off-site and can be installed using local resources. Plant can be constructed using local resources.	Yes
	Site Specific Civil Considerations		Plant design is above ground	Yes
	Suitability to Northern Ontario Climate		Capability of start-up and operation in Northern Ontario climate design considered	Yes
	Decommissioning and end-of-life		Easy decommissioning of the facility	Yes
Reactor and Plant Design	Base load capability	Important	Base load power provider	at least 90% CF
	Load and frequency fluctuations		Load following capability	Yes
	Provenness Based on Operating Practices		Technology provenness demonstrated with operating practices	Yes
	Unit Standardization		NPP is based on standardized design (i.e. no changes from nth and (n+1)th unit, reactors at different sites, does not use	Yes
	Co-generation Capability		Co-generation capability is possible	Yes

Categories	Consideration	Importance	Desired Feature	Baseline Criteria
Operation	Operation Cycle	Somewhat Important	Long refueling frequency	≥ 5 years
	Refueling Methodology		Refueling time is short, simple	≤ 2 weeks
	Operator Requirements		The reactor requires no on-site or no operators.	Yes
	Simple Component Replacement		Modular component replacement	Yes
	Safety System Operation		Safety systems are simple to operate, incorporation of passive safety systems	Yes
Security	IAEA Safeguard Friendliness	Very Important	Designed to accommodate IAEA non-proliferation tools and protocols (space for monitors, accounting system, etc.)	Yes
	Security		Enhanced engineering security to reduce security staff on site	≤ 20 security staff
Safety	Safety System Proof	Very Important	All safety systems are proven with OPEX available	Yes
	External Event Safety		Designed to withstand seismic (natural and man-made), tsunami, fire, explosion, flooding, airplane crash, etc.	Yes
	Radiation Exposure Approach and Dosage		ALARA principle incorporated, Worker dose is less than 20 mSv/year, Public dose is less than 1 mSv/year	Yes
	Accident Frequencies		Severe core damage frequency	≤ 10^{-5}/year
	Shutdown Safety		Decay heat removal capability	Yes
Environmental	Environmental impacts (radioactive, chemical)	Very Important	Release of radioactive or chemical materials to the environment under regulatory limit	Zero effluent discharge
	Environmental impacts (water)		Consumes little or no water during operation	Yes
	High Level Radioactive Waste Production		Produces less high level radioactive waste than CANDU reactors.	17.9 g/MWh
	Waste Management and Storage		Secure on-site spent fuel storage for cooling	Yes

2.4.2 Oil & Gas

Canada has an estimated 1.5 trillion barrels of petroleum reserves. This is one of the largest hydrocarbon resources in the world and continues to be of uniquely powerful economic importance to Canada. Of these reserves, 97% are located in the Alberta oil sands. Currently there are two methods to access these resources, surface mining and in situ mining, which together account for one of the main uses of power in oil operations. Reducing the carbon emissions from the oil sands resource extraction process is seen as important to sustainability of this resource. For example, Suncor, the most prominent company active in oil sands extraction, has a public target to achieve a 30% reduction in emissions by 2030. This type of ambitious target would require major changes in technologies ("disruptive technologies"); the need for large capital commitments, and early action, is recognized.

Surface mining is suited for resources that are closer to ground level consisting of digging the resource out of the ground and transporting it to a processing facility to extract the bitumen. In situ mining, for resources that are further underground, uses a deep well to inject steam to liquefy the bitumen, which is then pumped to the surface. The second major consumer of power in oil operations is the upgrading facilities. These facilities produce hydrogen which is then used to upgrade the bitumen to synthetic crude. It should be noted that oil companies often have a large-scope vertically integrated organization. Downstream operations such as refining, also large single-point power and process heat consumers, may benefit in future from reliable GHG-free energy supply. The oil sands industry is strongly engaged in examining options for energy provision to its operations. With a technology-neutral stance, different technologies contributing to individual fractions of the total energy demand will be under consideration.

As detailed below, there is a large and growing energy demand from these facilities today, consisting of large volumes of process heat, along with electrical supply. While today's demand is met by fossil fuel facilities, there may be a case, based on economics, GHG reduction and air pollution reduction, to add a significant number of SMRs into the supply mix. The balance between process heat and electricity supply, and the specifications for the process heat, will vary with individual application. The type of energy requirement is significantly different between surface mining applications and in situ extraction. Surface mining requires large quantities of hot water, while in situ operations require high pressure steam supply. More than one SMR technology may be considered in matching energy supply to requirements. To align SMR design specifications to industry needs for individual facilities, further detailed studies to establish requirements should be undertaken as an early Roadmap step.

Surface extraction

Currently, seven oil sands surface mining projects operating in Canada **Error! Reference source not found.**], produced an average of 1,162,000 barrel per day (bbl/d) of raw bitumen in 2015. According to the Canadian Association of Petroleum Producers (CAPP), the production of crude bitumen from surface oil sands extraction in Canada will grow by a further 420 000 bbl/d between the years 2015 and 2025, **Error! Reference source not found.**]. Surface mining requires 6.9 kWth to produce 1 bbl/d of bitumen **Error! Reference source not found.**]. This means that a total of 10.9GWth of installed capacity will be required to achieve the forecasted production of 1 586 000 bbl/d in 2025 **Error! Reference source not found.**]. An estimate of the number of SMR facilities needed to meet these energy requirements, using a typical electrical output of SMRs of 300 MWe and assuming thermal-electric efficiency of 30% gives 11 SMRs with a capacity of 300 MWe to meet overall 2025 energy requirements. Typically, the energy breakdown for a surface mining operation would be in the range of 10% electrical power, 70% heat, and 10% transportation energy.

The choice of whether to build a SMR power plant will be project specific and will likely take into consideration the remaining lifetime of the project and the age of the existing power plants; an investment in an SMR may be most advantageous for new projects where the future project life is longest.

In situ extraction

There are currently 31 oil sands in situ extraction projects operating in Canada **Error! Reference source not found.**] that produced on average 1 365 000 bbl/d of raw bitumen in 2015 and 55 projects that have been approved but are not yet operational with a total capacity of 1 834 800 bbl/d **Error! Reference source not found.**]. By the year 2025, the bitumen production is forecasted to reach 1 914 000 bbl/d. In situ projects require significant process heat, in the form of high pressure steam. Pressure requirements vary with facility and can be up to 7-8MPa. The energy breakdown is in the range of 10% electrical power, 90% process heat. A typical in situ extraction project requires 12.71 kWth to produce 1 bbl/d of raw bitumen [5]. This study also states that in situ extraction projects are typically installed in phases, each of which adds no more than 70 000 bbl/d of capacity. Assuming 30% thermal-electric efficiency, this corresponds to a 267 MWe (890 MWth) SMR, 28 of which would be required to meet all of the power requirements for in situ projects in Canada in the year 2025.

Hydrogen production and upgrading facilities

There are currently five oil sands upgrading facilities operating in Canada with a total processing capacity (2015) of 1 330 000 bbl/d of raw bitumen **Error! Reference source not found.**]. The power requirements are not publicly available for all five facilities. While the production of raw bitumen is expected to grow, it is not clear whether upgrading capacity will see similar growth. The installation of more upgrading capacity will depend on the price of the upgraded product, synthetic crude, relative to that of diluted bitumen. The increasing sale of diluted bitumen to refineries indicates that it is currently uneconomical to install new upgrading facilities in Canada. If these market conditions persist then it is likely that no new upgrading capacity will be installed. Conversely, a persistently high premium for synthetic crude will likely lead to the installation of more upgrading capacity to keep pace with bitumen production. In this latter case, SMRs may be installed to power the upgrading facilities, with a total capacity that should be no less than the bitumen production for the corresponding year: 3 500 000 bbl/d in 2025.

The upgrading processes require between 2.25 and 10.65 kWth heat input, and around 4 kg of hydrogen, to process 1 bbl/d of raw bitumen **Error! Reference source not found.**]. Requirements for hydrogen production depend on the process. Steam methane reforming, a commonly used method, requires 2.2 kWth **Error! Reference source not found.**] to produce 4 kg of hydrogen per day. Based on this, the total power required to produce hydrogen and upgrade 3 500 000 bbl/d, is between 15.5 and 44.9 GWth. This is equivalent to between 16 and 45 SMRs with 300 MWe equivalent electric power and 30% efficiency.

Industry Requirements:

Based on feedback from industry, technical expectations for this application for a suitable SMR design are based on the needs for an industry where production, economic benefit, and risk management, are emphasized. For example, the design should not only be proven, but would need a well-qualified and experienced supply chain to minimize delivery risk; deployment projects should have minimal schedule and cost risk; and operating reliability should be high, and highly confident. Additional technical requirements include:

- Near zero emissions
- Reliable fuel supply chain
- Cost certainty for fuel and operations
- Varied heat and energy requirements; 10 to 300 MWe with 100 to 3000 MWth as overall facility demands (could be met by multiple SMR units).
- High temperature, high quality steam production
- Load/steam following ability— while facilities normally require continuous energy supply in base load, the ability to shutdown and startup on demand for facility maintenance shutdowns, and to respond to load rejection from unplanned outages, is necessary
- Expected life >50 years for mining; the application life can be less for in situ operations (ability to move unit after local operations completed, would be an asset)
- >90% capacity factor; limits to planned outage requirements (try to match to industrial load maintenance outages)
- Extended outages no greater in frequency and not longer than normal turn-around maintenance cycle
- Operational in 2030
- Development timeline less than 5 years
- Limited cooling water resources – SMR usage comparable to oil/gas options
- Safety Requirements: As per general and other industrial applications. In keeping with mining applications: target minimal exclusion zone for flexible siting.
- Flexibility of transport: ship, rail, or truck; greater restrictions may apply in Northern jurisdictions (limits to weight, dimensions for major components)
- Shorter license process for fleet with NoaK units; for first deployment, must have a confident licensing case to enable short project schedule
- Develop benefits for fleet deployment: Streamline licensing process for fleet deployment of standard units; centralized maintenance support, operational monitoring; streamlined supply chain and spare parts provision
- Create technology programs to enhance Indigenous partnerships and knowledge, and local community participation in employment
- Waste: Limit transportation of waste, to the extent possible, and minimize onsite storage (both time and volume)

2.5 Technology Features that May Impact Public Acceptance

Technology features affecting public acceptance are noted here, as input to the discussion of this topic by the IPE WG.

The general acceptance of nuclear technology by both the general public and Indigenous communities is essential from a social licence and an environmental assessment approval point of view. Both aspects are embedded firmly into the licensing/siting process. The proposed Impact Assessment Act (Bill C-69) makes this subject particularly important. This aspect will be explored further in the report by the Regulatory Readiness Working Group.

The following points are of particular interest both from a potential impact on the local community or environment, and more broadly from a philosophical viewpoint on support for nuclear power.

The following discussion compares these areas with the current generation of CANDU reactors, which themselves have been shown to have no significant adverse environmental impact during many decades of operation.

Virtually all the SMR technologies represent an improvement from today's nuclear fleets in the areas of nuclear safety, reduced environmental emissions, ability to complement renewables, and some aspects of radioactive waste. SMRs are generally equal in terms of conventional environmental footprint. From this viewpoint, the candidate SMR designs offer a strong safety and environmental case. However, as with other new technologies, public confidence will need to be earned through a strong and credible demonstration of the SMR features, and through outreach activities to bridge from the technology practitioners to the public stakeholders For example, where a technology employs "inherent safety" features that renders large release of radioactivity virtually negligible probability, host communities will want to be able to see, and understand, credible experimental and design information that proves this. From this point of view, SMR designs may be held to a higher standard of certainty than the current fleet, where years of operating experience represent a form of credibility.

Some designs, such as fast spectrum SMR reactors, have the additional benefit of a potential to close the fuel cycle (thus producing a lower volume of high level radioactive waste). Some of these concepts, termed fast burners, even have the extra significant benefit to employ used CANDU bundles as a fuel source to potentially reduce the amount of existing high level radioactive waste in Canada. Other concepts, termed fast breeders, have the potential to produce more fissile content than in the initial fuel, and recycle the fuel, enabling a highly sustainable fuel cycle and near-endless power source.

These points are explained more fully below.

Nuclear Safety
Nuclear safety has long been one of the largest, if not the largest, public concern against nuclear power. Noting the excellent safety record of CANDU reactors, several significant nuclear accidents have taken place around the world. Chernobyl and Fukushima are the two most recent high-profile accidents that have left an indelible black mark on the industry. The nuclear industry has learned from these accidents and incorporates those lessons in current operation, and in the design of future reactors. All SMR technologies have a much higher degree of passive safety built into the design, and in some cases, include inherent safety features which are superior to the multiple engineered barrier approach

currently used. SMRs explicitly consider beyond design basis events in the early design stage, have at least one order of magnitude lower risk, and are much less reliant on human interaction. Most do not require evacuation of the community immediately surrounding the station even for severe accidents.

An important current technology advancement is the development of accident-tolerant fuel. This will improve safety margins, for the short-term available designs, and may be recognized as a safety benefit.

While the potential for improved safety appears sound, it will be important that this be rigorously demonstrated. The foundational work will be done during the design phase and will be a key aspect to be reviewed as part of the regulatory process. The regulatory process in Canada is well recognized, respected, open and transparent.

Radioactive Waste

As SMRs have a higher degree of passive safety and many have inherent safety features, which translates into fewer systems and components, with correspondingly lower requirements for maintenance and lower production of operational wastes. For thermal spectrum designs, the amount of high level radioactive waste (spent fuel) produced will be similar on a MW basis to current reactors. However, fast spectrum reactors operating with a closed fuel cycle will produce a significantly lower volume high level radioactive waste, and certain fast burner reactors can reduce the existing inventory of spent CANDU fuel. This is an important factor for future long-term sustainability. Canada has a technically sound approach to spent fuel disposal, employing adaptive phase management for its planned deep geological repository, and has placed great importance and effort on Indigenous and public engagement. However, current experiences demonstrate the challenges of the environmental assessment (EA) process for the less significant low- and intermediate-level waste repositories. The ongoing EAs for these facilities have been extremely difficult, time consuming, and have not yet secured any clear outcome. The seven generations perspective of Indigenous peoples makes the hundreds of thousands of years storage of high level waste a potential concern. If reprocessing facilities are collocated at reactor sites, it simplifies the transport of spent fuel. Nonetheless, if fast reactors are to be adopted in Canada, there will be a need for public dialogue around either around the use and transport of enriched fuel, and or fuel reprocessing, recognizing this is done routinely in some countries.

For remote communities in particular, a strong concern has been expressed in having the complete facility dismantled and removed at the end of the operating life, returning the site and surroundings to conventional use. This will need to be built in to both design and deployment. Similarly, transportation of operating wastes, including fuel transportation, must be shown to have negligible risk or environmental impact.

Conventional Environmental Footprint

The environmental footprint of SMRs, including fish entrapment, fish impingement, is expected to be similar to current reactors on a per MW basis.

Environmental Emissions and Spills

Nuclear related environmental emissions are expected to be lower than the current CANDU designs due to the lower amount of tritium being produced. Other releases are expected to be roughly the same. The non-nuclear emissions are expected to be similar to the current fleet of reactors, recognizing the key environmental benefit of near zero greenhouse gas emission for all nuclear power plants.

Ability to Complement Renewables
Unlike today's CANDU fleet, SMRs can load follow and thus will be able to complement intermittent renewable forms of energy. This means SMRs are not in competition with renewable energy sources. Rather, SMRs can enable the introduction of these sources, and can replace natural gas plants that currently perform the role of back-stopping renewables.

Summary
The following characteristics of SMRs may influence public perception in positive and negative ways:

- + Like today's CANDU reactors, all SMRs offer the key environmental benefit of near zero greenhouse gas emission. This is a strong positive point.
- + All SMRs will offer improved nuclear safety, which is one of the biggest public concerns.
- + All SMRs can complement intermittent renewable forms of energy, due to the load following capability
- + Fast spectrum and more particularly the fast burner reactor designs significantly reduce the volume of very long term radioactive spent fuel.
- – Thermal spectrum reactors, will face the same concerns related to acceptance of the strategy for long term storage of high level radioactive spent fuel (waste) as the current fleet of reactors until the final disposal repository is in place.
- – Storage of larger volumes of waste on the smaller SMR sites will be an issue for public acceptance. Since the date for the final repository is not yet confirmed an interim centralized solution is required.

2.6 Schedule and Technology Readiness Requirements

The readiness for use of the many proposed designs ranges from a simple conceptual design to designs that are sufficient for submission for regulatory approval. At least one North American small pressurized water design plans to start construction at a US site by the mid-2020s. Other small PWR designs would be available in the next 5 – 10 years if the development plans are accurate. Advanced reactor designs which include both thermal and fast flux reactors are not far behind. There remain some first of a kind technical issues to be verified prior to design finalization and licensing but design schedules suggest these will be completed in the relatively near future for at least some of the designs and that several reactor designs will be available for licensing and deployment within 10 years.

There are also international designs that are in service or where construction is in progress, but it is not clear that these would satisfy Canadian requirements or be easily licensed in Canada.

Small electrical grid size reactors are overall the most advanced in design and are likely to be the first to be deployed. The reasons for this are:

- The designs and operation are similar to current reactors, so it will be easier for utilities to adapt to these new reactors.
- Confidence from operators is relatively high with these types of design.

- The electrical output is similar in size to existing carbon emitting electrical generation plants and the need for replacement power is current.
- These designs will fit into the current grid architecture without significant changes or costs.

Heavy industry applications are likely to be near the same time line as grid applications but will be slightly longer in implementation due to the off grid and remote applications. Some reactor designs will be suitable for both applications.

Remote northern communities represent the most radical change in design and operation from the current reactor fleets as well as the most challenging terrain in which to construct a facility. It will also be a unique application from a licensing and environmental assessment perspective which will likely lead to a protracted review for the first deployment. As a result, the first reactor deployed in a northern community is will likely be longer than the 10-year time frame, but the time line will be much faster once the first is operational.

2.7 Findings and Recommendations

Overall technology requirements for SMR deployment in each individual application type can be identified, covering the total energy demands, the range of unit size, and the safety and environmental expectations in particular. Economic requirements will need to be met and are covered by the EFWG. A later report section discusses the ability for SMR designs to meet, or to be developed to meet, the requirements.

The overall scope of the potential market for each of the types of application has been reviewed, leading to the most immediate requirement: output range and possible fleet size.

Finding: The current generation of nuclear power plants continues to provide a significant source of clean energy to Canada. However, relative to current operating technologies, SMRs offer the promise of major additional potential benefits:

- Smaller upfront capital costs per project (by more than an order of magnitude) and shorter delivery timing, allowing more accessible financing and project delivery
- Flexibility to be deployed in a wider range of situations, enabling a broader role in GHG-free energy delivery
- Designs which have a built-in, inherent, level of safety protection, independent of engineered systems with the possibility for faster licensing and a new social license relationship with public and stakeholder groups
- In the longer-term, the opportunity to recycle fuel, and to introduce fuel cycles that radically reduce the complexity of spent fuel management

Finding: SMR technologies can add major value in all three application areas (on-grid, off-grid, industry).

Recommendation: to establish the demand for deployment and the timing of the demand, further detail is needed. Further work to define requirements and desirable characteristics in more detail should be an early roadmap action.

Finding: Wide-scale clean electrification will impact electricity demand and distribution. SMRs have the potential to play a significant role in clean electrification. The impact of clean electrification and the role of SMRs needs to be better understood to clearly establish SMR requirements.

Recommendation: Commission a study regarding the future of electricity demand due to clean electrification. This study would consider the role of SMRs in meeting that need, and SMRs in conjunction with other renewable energy sources and energy storage.

Finding: Developments in electricity supply and demand indicate that there will be a potential need for short-term deployment, with in-service dates from 2025-30; this will require a high level of design completion and regulatory review today. SMR deployment potential will continue to be beyond 2030.

Recommendation: development of designs that establish further benefits for the longer-term, beyond 2030, should also be pursued (see 2.5).

Finding: Heavy industry applications are likely to be near the same time line as grid applications but will be slightly longer in implementation due to the off-grid and remote nature of these applications.

Finding: Deployment in remote communities is most likely further in the future than the other two applications, greater than 10 years.

Finding: An important consideration for deployments in remote communities is that the incoming technology must have been previously proven. This means, in practice, that a demonstration project may be an essential pre-requisite to provide the proof that the technology is ready for remote applications.

Finding: For the oil sands industrial applications, because of the diversity of energy-type requirements, more than one SMR technology may be considered in matching supply to requirements.

Recommendation: Future studies should be undertaken to examine which SMR technology could meet the widest set of heavy industry requirements and market needs.

Recommendation: To align SMR design specifications to industry needs for individual facilities, including output size and heat supply requirements, further detailed requirements studies should be undertaken as an early action. Develop tools to model full interfaces between SMR and external energy demands, and local grid/community infrastructure.

Finding: Some features of SMR technologies may impact public acceptance, such as nuclear safety, waste production and the capability to recycle and burn spent fuel, environmental impact, and ability to complement renewables. The potential for these characteristics to impact acceptance should be taken into consideration in future technology selection.

Recommendation: A centralized interim waste storage facility should be established to allow timely shipment of waste from small reactor sites until permanent facilities are available.

3. Technology Development and Deployment

3.1 SMR Technology Development Process

Over the last few decades, the commercial development and evolution of power reactors has followed a path based on small scale changes to a limited set of technologies; light water reactors consisting of either Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), or Pressurized Heavy Water Reactors (PHWRs). In recent years, the pre-commercial development of other reactor design types has accelerated, in particular for SMR designs. The steps needed to develop these designs to the commercial project-ready state will follow a common sequence, well established over the history of reactor design development since the start of nuclear technology; for each technology type, and for each individual design, the stage of development and the scope, effort and risk involved in achieving project-readiness, vary considerably.

In the first two decades of the nuclear age, from the 1950s to 1960s, a wide variety of nuclear design concepts were investigated; this includes the technology approaches being considered for SMR designs today. In some cases (e.g. gas-cooled reactors; sodium fast reactors), commercial-scale plants and plant fleets were built. This means that today's SMR design propositions can rely on a certain level of previous research and development knowledge gained in previous decades. Given that, in most cases, the full development cycle to commercial applications did not occur and given changes in the social and regulatory environment since the early days, there is a significant development stage to be completed for designs other than more direct spin-offs of today's water reactor technology.

3.1.1 Development process and steps

For any new or innovative nuclear reactor, the design and development process steps would follow a staged sequence of: concept definition and development; formal design and development; detailed pre-project design and approvals. The stages expand rapidly in scope, effort and cost from concept definition to pre-project; conversely, the impact on project competitiveness via economics, time-to-market, delivery risk, etc., is highest at the initial stage. Completion of stages and milestones is a trigger to further investment funding and can be the trigger to increased participation via customers, owner/operators, or co-operation with government programs.

Today's development approach typically follows a stage-gate process, whereby a go/no-go decision ("gate") to proceed further occurs at the conclusion of each stage, or at milestone points within each stage. Some SMR vendor designs (example: NuScale) are well down this development path, into the pre-project stage. Other vendor designs are still working through the concept development stage. An outline of major elements in each stage is given below.

a) Concept development stage: the initial informal stage of ideation, considering concept options and leading to a concept definition. A design team may examine the potential for a particular baseline technology (e.g. molten salt, gas cooling etc.), and identify the pros and cons of a particular configuration within that category (e.g. fuel type, fast vs thermal spectrum, etc.). The choice of concept would be based on the advantages and challenges of design options; the level of existing experience and foundational information; the required scope of future development versus organizational capacity; the degree of challenge to obtain regulatory approvals; and the concept fit to the intended market and its requirements. The key outcome at this stage would be an initial design/development plan along with a design concept description, and prospectus documents to outline to future investors and customers the target product. This stage is largely carried out by a small vendor product development team, along with selected experts from R&D organizations, academia, industry specialists, etc.

b) Formal design and development stage: This stage would involve a structured process to carry out and verify the design, with parallel applied R&D to provide necessary data and confirm design choices (e.g. materials tests to confirm design life achieved). A formal quality assurance program would now be applied across all work. Work would be completed to develop foundations of the licensing case and n^{th} unit cost estimate at early stage. Initial steps of formal regulatory review would be carried out. The design would be advanced through a formal requirements-setting process, to allow preliminary specifications for major components to be developed for supply chain input. Fuel design and supply approach would be established. The design would require a defined approach to decommissioning and waste management, as part of review with the regulatory authority. Security, and non-proliferation concepts would undergo reviews including IAEA oversight. At this stage, the vendor team will work in co-operation with selected partner organizations through defined scope distribution and will be formally engaged with own/operator and regulatory groups.

   Note: An essential part of this stage is developing confirmation that the design can be developed to meet regulatory requirements. Each country has its own sovereign regulatory system; but the principles that are used in regulatory review have become well-established as international norms. The diagram below, Figure 2, shows the process. Regulatory review proceeds at the same time as operational reviews to confirm the design will meet general operational requirements such as reliability, capacity factor, design life, flexibility of operation, fuel cost and availability etc. The operational review also needs to establish confidence from the viewpoint of the owner-operator, and eventual licensee, that regulatory requirements will be met. Both regulatory and operational reviews of the safety basis will consider topics that cover the overall scope of design, namely:

   - Fuel qualification;
   - Instrumentation and control;
   - Materials and analysis;
   - Core heat removal;
   - Accident sequence and analysis and probabilistic safety analysis;
   - Analytical codes and methods;
   - Structural analysis.

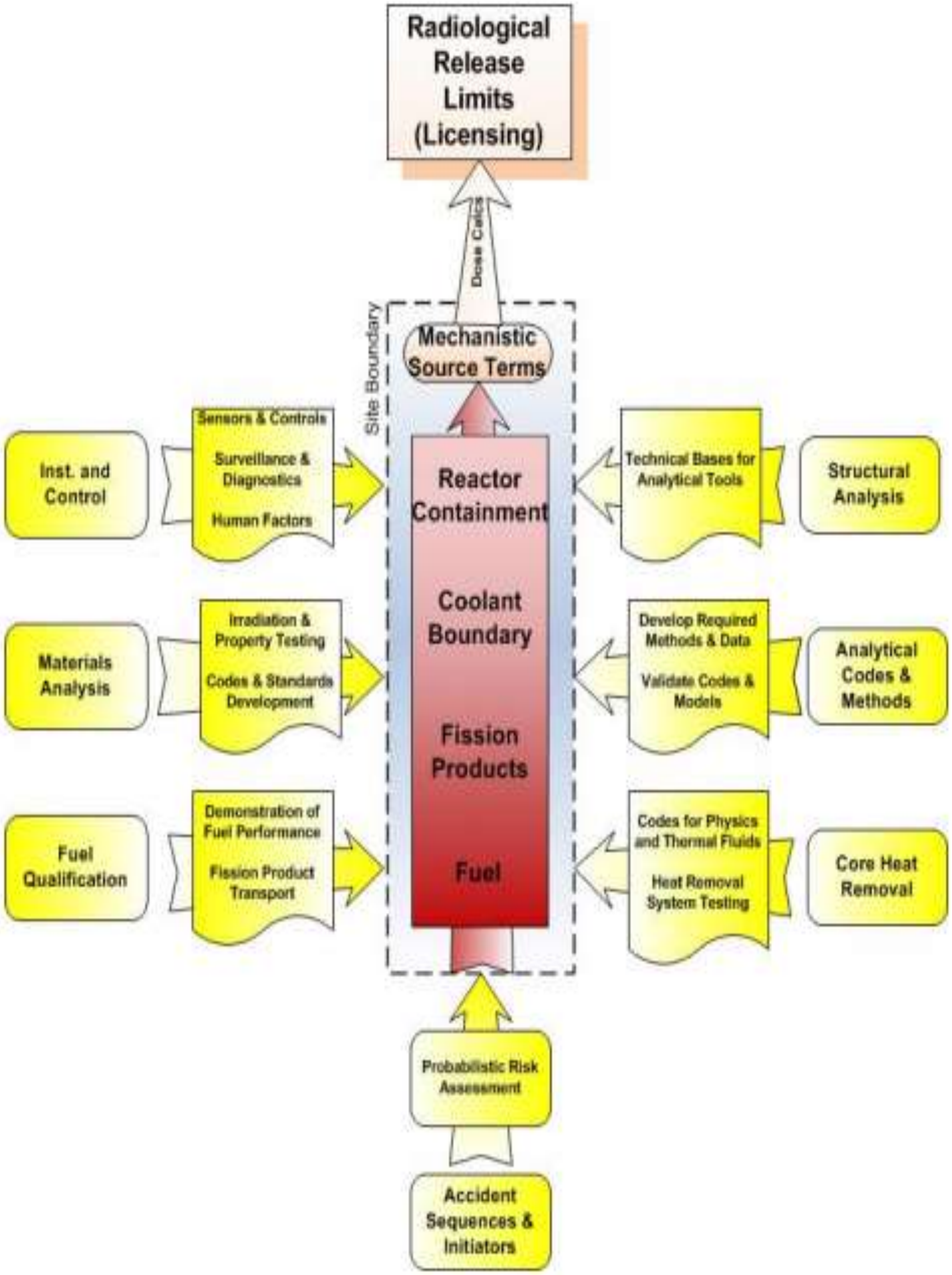

Figure 2 R & D elements important in plant safety and licensing reviews **Error! Reference source not found.**]

c) Detailed pre-project design and development stage: This stage centres on the completion of all design documents, supporting experimental information, licensing submissions and procurement information required to go ahead with a construction project. Formal safety case preparation will include a series of discussion stages with the regulator to establish the required safety case scope. This will include independent verification of safety claims (including tools, models). The designers will work with operating specialists (ideally with the prospective owner/operator organization) to get confirmation of the operations and maintenance model, to confirm reliability and operating life assurance. Development of an investment-level cost estimate is completed, including supply-chain quotes, fuel supply quotes. At this stage, the vendor organization is formally engaged with all stakeholders to an eventual build project, including customer, operator, supply chain, fuel supply, waste management and regulatory.

Each stage of the development process proceeds in parallel with business development by the vendor organization, closely informed by development by both potential customers and/or owner operators, and in the light of government policy and strategy. In practice, continuous collaboration, up to the point of partnership, between vendor and other stakeholders is effective in aligning design development to the market needs. Feedback from stakeholder engagement is a vital part of the stage-gate go/no-go reviews.

In parallel with the vendor's own development program, common R&D activities will be underway worldwide that add to the foundational knowledge base underlying the design. The vendor will need to carry out development reflecting awareness of common R&D outcomes (e.g. investigations into material properties and ageing) from outside its own program.

3.1.2 Factory Manufacturing: Paradigm Shift

Modularization and manufacture in a factory is a dramatic change from how nuclear reactors are constructed, at the site location, today. This infers a corresponding large change to the supply chain.

Factory manufacturing and assembly of SMR modules, or of a complete reactor facility offers major potential advantages over the traditional on-site assembly approach to reactor build projects. Maximizing factory use offers much greater efficiency in labour effort; enhance quality control, ability to reduce schedule; and the opportunities to benefit from standardization and repeat production. SMRs are being designed with the intent of taking advantage of this.

Factory manufacturing and assembly is more practical for SMRs compared to traditional large NPP designs. For smaller outputs, individual components become smaller, allowing a greater proportion of work to be done within factory dimensions. In addition, the auxiliary systems and sub-systems are simpler, and SMR scale will allow benefits of a greater degree of pre-operational testing in the factory, under more controlled and efficient conditions. By taking advantage of recent advances in manufacturing technology, and by working with manufacturing innovators and R&D institutes, SMR designs can be best placed to adapt designs, components and materials to take advantage of factory-build.

Such factory-build benefits are a vital part of the potential economic advantage for SMRs, which must be achieved to counter their economy-of-scale disadvantage. This is particularly so for vSMR designs applicable to remote community applications. Assessments of economic competitiveness often rely on assumptions about factory-build benefits.

To achieve the benefits of factory-build will require development of new capability by manufacturing organizations and will also require technology development to enable efficient manufacturing and assembly. A typical example would be the development of welding techniques for new materials in innovative SMR designs. To enable efficient manufacturing at fleet level would require demonstration and proof-testing of technologies, e.g. demonstration of seismic resistance, ability to meet design life, etc.

This means that development and demonstration of manufacturing technologies will need to proceed in parallel with design development and material and other testing. It will be important to encourage design and R&D organizations to work together with manufacturing and project delivery organizations, and to provide incentives[1] for supply chain organizations to participate in the SMR development activity from the earliest stage.

3.2 Deployment of an SMR Project

Deployment of a small modular reactor draws many parallels to the process of deploying a larger grid scale nuclear power plant and has many of the same primary risks, namely: timeliness of regulatory approvals, extended delays in construction due to changes in design leading to increased costs due to accruing interest, and loss of confidence from key stakeholder and decision makers.

Regardless, there are three major types of project deployment models which can be followed for either grid scale NPPs or SMRs:

1. Government owned utility with self-financing:
2. Independent power producer with a guaranteed power purchase agreement from an end user
3. Government backed contract for public power provided by non-government owned companies

The focus in this section on how these deployment models influence the operating model, as well as the development of the technology. This is discussed in more detail in the following subsections.

3.2.1 On Grid Project

Currently this is the predominant method for nuclear usage in Canada: large, 500+ MWe nuclear units owned by provincially controlled entities under regulated cost recovery. The long-term liabilities associated with the nuclear facility (waste, fuel and decommissioning) are all borne by the utility (and/or the province). These existing units, and any future ones including SMR technology, would be included within long term provincial power planning. The province would direct the provincially owned agencies to establish a procurement process to allow one of the existing incumbent utilities to assume the role of constructing and operating any new build nuclear facility.

In this scenario, it is very unlikely that any significant risk will be borne by the province or the utility in the development of any technology: the procurement process would set out rigid end user requirements, with technology risk to be borne by the selected vendor consortium under the oversight of a qualified nuclear utility.

Under this model, it is very difficult for new players to enter, given the very strong position of the incumbent utilities and the interrelations with the provincial planning agencies. As well, the potential

[1] The level and type of incentives is addressed by the Economics and Finance Working Group.

opportunities are very limited, with potential deployment opportunities in the single digits across Canada for the foreseeable future. A very strong business case will need to be present to enable a provincial program to engage directly with the technology development given the generally high risk associated with a grid scale project that will likely have overnight capital costs in the order of billions of dollars, leading to decisions based on lower technology risk (high proven-ness) and the ability the vendor to provide accountability for EPC activities, none of which favours first movers and FOAK projects. Another key factor is the overhead burden inherent any operating nuclear facility whether it is one or dozens of units and regardless as to the type of technologies in use. This overhead can be substantial and is generally a fixed burden not greatly influence by the number of MWe being produced, making the overall economics of a fleet improved if these overhead costs can be spread over more and more MWe of any type.

This planning process is also not conducive to coordination between provinces given the different timelines, political conditions and financial abilities of each province. That said, as adverse to FOAK projects a utility may be, they are equally or more concerned about being the OOAK – Only Of A Kind. A paramount tenet of current nuclear operations is sharing or best practices, operating experience and peer reviews. None of these things can be accomplished if the operator is running the only example of its technology. A utility that is unwilling to be the FOAK is inherently also unwilling to be the OOAK, leading to procurement decisions of technology that has already been built or has been selected by another qualified nuclear operator and the project is well underway.

Since the likely operator is an experienced nuclear utility, the new unit will likely share many of the management systems, infrastructure and processes already established by that operator. This reduces the need for a utility to have more than one unit of the same type under its own fleet to enable spreading of the overhead burden of nuclear operations, if the unit has comparable units in operation elsewhere where information and experiences can be shared under existing international alliances (e.g. WANO, INPO, IAEA).

A utility that is willing to be a FOAK inherently needs to accept the risk of being the OOAK as well. However, if in accepting the FOAK project, and if other utilities are also under programs for nuclear expansion, this allows those utilities to consider using similar technology as the FOAK and reducing the chances of an OOAK project.

3.2.2 Resource Project

A project to support the development of a resource (e.g. an ore mine, oil sands project or processing facility) is likely to have two primary characteristics: 1) cost/cost certainty of power is of primary importance and 2) ownership of a nuclear facility is unlikely to be considered. A resource project is in itself a very high-risk proposition requiring development lead times, significant environmental and regulatory approval hurdles and economics dictated by sometimes volatile global commodity prices. Taking on the challenges of owning and/or operating a nuclear facility which may have different approval process and timelines is unlikely to be something that would be an acceptable risk to the business model. To be successful nuclear projects will need to as separate from the mining project as possible including a complete separation of the environmental assessment: linking the two projects as one under any form of assessment process are anticipated to be a non-starter for the project. It is unlikely any resource company would take the risk of a nuclear portion of a project, which is a simple support role in the overall scheme, with the risk of derailing the resource facility, which is the primary purpose.

Since this type of nuclear deployment is unlikely to part of any long-term energy plan produced by government agencies as the power produced is likely for a single end user, cost of power is critical. The nuclear project development will have full responsibility for all aspects of the project and it does not necessarily need to be driven by a nuclear utility. However, the engagement of an experienced nuclear operator in the project to mitigate licensing and operations risk would likely be an important factor in the financing of the project. If the nuclear utility is not part of the ownership group of the nuclear asset, their role of operator under Canadian regulations will likely be limited to the direct operations role of the facility with no long term liability for waste disposal, spent fuel management and decommissioning of the asset at end of life; all of these duties fall on the owner of the asset as their full accountability. As discussed by the Waste Management Working Group, the primary waste disposal facilities in Canada are fully funded by the existing nuclear utilities: access to and/or cost for access to these disposal facilities is uncertain at this time. To be successful, these IPP-type projects will need assurances that they will have access to suitable long-term master and spent fuel disposal facilities at known costs which support the long-term viability of the project.

If the nuclear utility is part of the ownership group, this implies that utility is willing to take on a large part of the long-term liabilities as part of its interest in the project. It is likely the utility will want this contribution recognized as a form of “in kind”, as it can be a substantial part of the overall levelized cost of power from the facility.

Government policy with regards to nuclear and energy in general needs to be formulated such that certainty can be assured for project to proceed. This can be done in the form of contractual clauses with the government as signatory to ensure a change of regulation does not harmfully impact an ongoing project.

As has been identified by the Regulatory Readiness Working Group, the largest risk to any potential nuclear project is the currently proposed Impact Assessment Act (Bill C-69). The potential for an extended, indeterminate and uncertain assessment process for a power project which is likely to be less than 100MWe is probably to be too much of a burden for financial markets to withstand.

3.2.3 Off Grid Project

In many areas of Canada, power is provided to a self-contained grid that does not have a main connection to a larger, more robust grid. This is very typical in Canada’s Nunavut territory and to a lesser extent the Northwest Territories, where smaller, community-based power distribution is the norm, with the bulk of the power provided using diesel generation. The realities of the north come into play very quickly and must be applied in any deployment model for a nuclear project:

- The generation units are generally small, less than 1 MWe each
- There is minimal technical support available in the community to fix major issues. Local staff are limited to duties more in line with caretaking than maintenance.
- Construction and major activities are limited to periods when heavy equipment can be transported to the site, generally a few months when the ocean is not frozen

- Very high reliability is of paramount importance: loss of power in the winter can be a life or death scenario
- Access to and communications with the power station is generally slow (high speed internet is not available) or completely disrupted for extended periods

The model used for operations of a large on-grid nuclear facility in the south is simply not viable for this application. The smaller units needed for northern applications do not allow for large, specialized staffing models and ready access to high skilled technical personal is unlikely. To support deployment, the economies of scale need to be replaced with the economies of fleet, and a model more similar to how diesel power is brought in needs to be considered:

- Common nuclear technology
- Centralized, preplanned maintenance and outages
- Reliance on the OEM for ongoing support
- Centralized training and spare parts storage
- High reliability or complete power back up of the facility for end user needs

It is evident that this is may be best accomplished by a single operating company working in conjunction with a chosen technology vendor on a long-term commitment with assurances of longevity. To be successful, the cost of power needs to be equal to or less than the cost of displaced diesel, accounting for the cost of the fuel only. The high reliability constraint makes it unlikely that diesel generators will ever be completely replaced by any current envisioned technology, as the diesel asset will always be called on to serve as a backup.

The concept of a joint project between an experienced nuclear operator, that can absorb the incremental costs of operations of a fleet of 1MWe units into their overall nuclear management systems, working with a technology provider willing to provide long term support and financial backing to the technology may be viable. The issue of long term waste management and spent fuel disposal can be accommodated using the nuclear operators existing infrastructure and plans, and the relatively low capital costs can potentially be financed between the operator and the technology provider given a PPA with the end user.

Again, the potential for Bill C-69 to increase timelines and uncertainty may make the project unviable, to a much greater degree than in other deployment models.

From a technology point of view, there are many areas than need additional support. The type of technology likely to be deployed in the North is at a lower technical readiness level than those for grid and resource applications. Power conversation system, permafrost, remote monitoring, security, transport, and advanced construction are a few areas that need support specific to applications to the North over and above the challenges a technology vendor will face in developing the actual nuclear product. Direct government involvement in the demonstration and deployment of SMRs would greatly accelerate the deployment of nuclear technology into the north. Given the level of subsidies that are currently provided for diesel generation, a business case to justify this investment seems readily available.[2]

3.2.4 Canadian Example of Fleet Deployment: Slowpoke Reactors

The SLOWPOKE reactor is a small 20 kWth research reactor developed in the late 1960's as a simple inherently safe reactor for university and laboratory purposes. While designed, built, operated as a non-power research reactor, there are many aspects and experiences of the reactor that may be applicable to modern efforts in SMR development and deployment: fleet management, fleet licensing, centralized nuclear maintenance, inherent passive safety by design, unattended operation, shipment of complete irradiated cores in a single flask, and decommissioning without a decommissioning license:

"Fleet Management": The SLOWPOKE fleet spanned nine reactors located in five different provinces and one in Jamaica; four reactors remain operational. Each reactor installation was kept as identical as possible, with only minor modifications depending on facility location/size, and different reactor features (e.g., number of irradiation sites). The reactors were sold by a central agency (AECL), which ensured consistency in the installations, procedures, and operations. Initially, AECL also provided training and certification for reactor operators, but that function is now held by the facilities.

"Fleet Licensing": While each facility is separately licensed, the licenses are very similar for each facility. Furthermore, the license periods are aligned such that hearings can be conducted in unison and facilities can work together for licensing requirements and challenges. For example, the current licenses are all effective 2013 to 2023, and reviews and hearings are conducted together, as applicable.

"Centralized Nuclear Maintenance": One aspect of inherent safety of the reactor included an inability of the operator/owner to access the core, or to perform any type of nuclear maintenance activity. Therefore, all nuclear maintenance staff and tooling were provided by a separate entity. By centralizing nuclear maintenance staff and tooling, the facilities themselves did not require such skills or equipment, and therefore are trained in routine operation only. Auxiliary reactor systems (ion exchange, power, control systems, irradiation systems, etc.) are maintained/upgraded as required by facility staff. The tools and services did not remain with the same entity, but transferred ownership several times: AECL 1970-1987, Nordion 1987-1998, AECL 1998-2014, CNL 2014-present. The ownership transfer may be relevant for SMR deployment, as it demonstrates that different entities could continue to provide maintenance support, should the initial fabricator exit the business post-SMR deployment.

"Inherent passive safety by design": The reactor was designed to be as small and simple as possible, while still meeting the requirements of an effective neutron source; this principle applies particularly to vSMRs attempting to be as simple and safe as possible, while still generating useful amounts of power. This principle led to a simple inherent safety around limited excess reactivity (can only be changed by

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[2] The business case for very small SMRs (vSMR) has been established recently with the recent release of the US Nuclear Energy Institute's (NEI) new Roadmap, which already indicates that vSMRs are well suited to remote off-grid locations. These reactors can eliminate the need for constant, costly diesel fuel supply. NEI new roadmap outlines what is needed to make the project a reality within a decade. Reference: Nuclear Energy Institute, "Road Map for the Deployment of Micro-Reactors for U.S. Department of Defense Domestic Installations, October 4, 2018, available at https://www.nei.org/resources/reports-briefs/road-map-micro-reactors-defense-department

the centralized nuclear maintenance group) and a negative coefficient of reactivity (reactor becomes sub-critical as temperature increases). The inherent passive safety means the reactor control system is not considered a safety system (an unusual feature in the reactor world), and the reactor can also be operated unattended.

"Unattended Operation": The reactors are currently licensed for unattended operation for up to 24 hours[3]. For most facilities the high hazard area radiation alarms are routed to a centralised security centre, with instructions for security staff to contact the reactor operators should an alarm activate. The centralised security is not in place solely for the reactor, but part of overall security for the university or lab complex that includes the reactor.

"Shipment of Cores": The SLOWPOKE reactor core consists of a cage with ~200-300 fuel elements peened in place[4]. During commissioning, the fuel elements are shipped in a single shipment and the cage shipped separately. The fuel is then loaded and peened into the cage at the reactor facility until commissioning is complete. The core is then never altered, and instead additional beryllium shims added every 2-4 years to compensate burnup effects, until a maximum burnup is achieved after ~20-30 years. At this point, the reactor can be decommissioned or refuelled; either process entails removal of the core (as a single unit) and placement in a dedicated flask. The complete core is then shipped in its flask to its final destination. The flask (known as the F-257) was custom built specifically to contain complete spent SLOWPOKE-2 cores for shipment, including the ability to be loaded under water at the facility in the existing reactor pool (i.e., no additional shielding or facilities required). There were significant capital costs in designing, building, certifying the flask, but once certified, maintenance and operational costs are minimal.

"Decommissioning without License to Decommission": Historically, SLOWPOKE-2 reactor decommissioning required a License to Decommission, followed by a License to Abandon once all activities complete. However, a new precedent was set in Alberta, whereby decommissioning activities occurred under the Operating License (most activities are nuclear maintenance and fall under the Operating License envelope) and once complete, a License to Abandon will be issued (a License to Decommission was never required/issued).

3.2.5 Potential Non-Terrestrial Deployment Methodologies

Most remote communities are located adjacent to a major body of water. This may enable alternate methods of deploying SMRs to these communities, and the potential for such power plants to be transported and operated on floating platforms.

As previously noted there are over 150 proposed designs for SMRs worldwide reflecting a wide spectrum of possible nuclear reactor technologies. Small nuclear reactors of various designs have existed from the beginning of nuclear technology and were in fact often the prototypes or testing platforms for larger reactor designs. Likewise, several deployment methodologies beyond terrestrial

[3] There is some variation in requirements between the different facilities.
[4] LEU cores have ~200 elements, and HEU cores ~300 elements.

build have been tested and utilized over the last 75 years including marine propulsion reactors used in vessels of several navies for decades and deployable reactors mounted on floating platforms.

Although never built due to changing economic conditions, in the mid-1970s a licence was approved in the US to build an Offshore Power System (Westinghouse) with 8 nuclear units off the east coast. Recently Both China and Russia have deployed small reactors using floating mobile platforms. Work is likewise underway in North America to study the potential deployment of SMRs through a floating or offshore pile mounted platforms. In this concept the platform would be built in a shipyard, the reactor inserted and floated to the deployment site, fueled and operated at the site and when no longer required defueled and moved to another site or decommissioned at a shipyard. This approach has significant potential as a means of deploying SMR technology in coastal areas, in areas where terrestrial builds are difficult or when power requirements are more temporary in nature such as natural resource extraction.

Offshore platforms can be designed to accommodate many SMR designs.

3.3 Key Findings and Recommendations

Finding: nuclear reactors have been deployed historically in non-terrestrial applications. Several jurisdictions are pursuing non-terrestrial deployment of SMRs currently. This approach has significant potential as a means of deploying SMR technology in coastal areas, in areas where terrestrial builds are difficult or when power requirements are more temporary in nature such as natural resource extraction.

Recommendation: Commission a study to perform a comparison of land-based vs. floating SMRs for remote community applications, to include economic, logistical, and regulatory aspects.

Finding: Modularization and manufacture in a factory is a dramatic change from how nuclear reactors are constructed, at the site location, today. This infers a corresponding large change to the supply chain.

Finding: development of new capability by manufacturing organizations will be required and will also require technology development to enable efficient manufacturing and assembly.

Finding: Efficient manufacturing at fleet level will require demonstration and proof-testing of technologies.

Finding: There is an overhead burden inherent any operating nuclear facility regardless of the number of units, the size of the units, and the type of technologies. Therefore, the need for of a fleet approach increases with smaller output SMR units, as there is an increased need to spread the costs of operations across multiple units.

Finding: Engagement of an experienced nuclear operator in any nuclear projects for industry applications will be required to mitigate licensing and operations risk and will likely be an important factor in the financing of the project.

Finding: The operational model used current large on-grid plants is not viable for the remote community application. The smaller units needed for northern applications do not allow for large, specialized staffing models, and ready access to high skilled technical personal is unlikely. To support deployment, the economies of scale need to be replaced with the economies of fleet.

Finding: Remote applications should consider deployment via a joint project between an experienced nuclear operator, that can absorb the incremental costs of operations of a fleet of 1MWe units into their overall nuclear management systems, working with a technology provider willing to provide long term support and financial backing to the technology.

4. Overview of SMR Technologies and Benefits

4.1 Methodology

The TWG compiled a list of SMR technologies under development worldwide today and identified 104 SMR technologies. These 104 technologies were then classified into six broader technology categories to facilitate description and analysis, and to avoid discussions of any particular designs. Coolant type was selected as the method of categorization. The six SMR technology categories are:

1. Water cooled reactors
2. High temperature gas cooled reactors
3. Sodium cooled reactors
4. Lead cooled reactors
5. Molten salt reactors
6. Heat pipe reactors

A summary of various characteristics of these reactor technologies is given in Table 2. A general description along with some high-level examples of advantages and disadvantages of each technology is provided in the following sections.

As the reactor fuel is a key element of any reactor design, and often dominates the technology development timeline due to the length of time and challenges associated with fuel qualification, Section 4.3 gives a brief overview of some of the fuel types being considered for use in the various SMR technologies.

Table 2 Summary of each reactor type. [15], [23], [30, [34], [43], [45], [67], [75]

Parameter	Heat Pipe	LWR/iPWR	HTGR	MSR	LFR	SFR
Coolant	Molten metal (e.g. sodium, potassium)	Light Water	Helium	Molten fluoride or chloride[1] salt	Lead or lead-bismuth eutectic	Sodium
Moderation	None	Light Water	Graphite	Graphite, zirconium hydride or none	None	None
Size Range	≤ 15 MWe	≥ 30 MWe	≥ 4 MWe	≥ 100 MWe	≥ 5 MWe	≥ 100 MWe, some smaller designs do exist in the 10-50MWe range
Fuel Type	Metal, Ceramics (oxides, nitrides, carbides)	Ceramics (oxides, silicides)	TRISO particles in (typically graphite) matrix	Liquid salt[2], TRISO	Ceramics (oxides or nitrides)	Ceramics (oxides), Metallic
Fuel	Pu, Enr.U	Enr.U, MOX	Enr.U-Pu, MOX, U-Th, Th-Pu	Enr.U, U-Pu/Th, Th	Enr.U, U-Pu	Enr.U, MOX, U-Pu[3]
Enrichment	4% - <20%	4% - <20%	LEU - <20%	Low, 19.9%	10%-19.5%	4% - <20%
Burnup	30-70 GWd/t	45-70 GWd/t	80-200 GWd/t	>150 GWd/t [~70 GWd/t if TRISO]	35-60 GWd/t	80 GWd/t
Coolant Temperature	355-600 °C	260-330 °C	750-1000 °C	700 °C	450-550 °C[4]	>500 °C
Pressure	Approximately atmospheric	15 MPa	5-10 MPa	Approximately atmospheric	Approximately atmospheric	Approximately atmospheric
Neutron Spectrum	Fast or epithermal	Thermal	Thermal	Thermal or fast	Fast	Fast
# under construction / operating	0 / 1	27 / 363 [2/0 for iPWR]	1 / 2	0/0	0/0	0 / 8
# operated historically	0	90 [0 iPWR]	5	1	18	14
Passive Safety	Moderate	Moderate to High	Low	High	Moderate	Moderate
Ability to use advanced and recycled fuel	Yes	Limited	Yes	Yes	Yes	Yes

[1] Chloride salt cooled reactor concepts are typically larger and outside of the SMR power range.

[2] Moltex Energy's Stable Salt Reactor uses liquid salt within in a fuel pin [15].

[3] Some fast spectrum U-238 breeder reactors have been proposed but none in a SMR form factor and as such will not be discussed here [47].

[4] Some proposed design may operate at higher temperatures around 800°C to allow for cogeneration applications [45].

4.2 Overview of the SMR Technologies

4.2.1 Water-Cooled Reactors

Light Water Reactors

Light Water Reactors (LWR) comprise a large portion of the world's nuclear energy capacity and are an example of a well-tested technology. Active for over 50 years, as well as being the most common reactor type, there is extensive experience with LWR operations and technology risks have been reduced significantly. A summary of the properties of LWRs is shown in Table 2.

A Light Water Reactor uses liquid light water as both coolant and neutron moderator. As shown in Figure 3, the reactor core is housed inside a pressure vessel, which maintains the water at a high pressure, required to prevent the water from boiling. Cool water enters the reactor vessel, passes through the fuel assemblies, where it is heated, and then exits the vessel. This heated water then passes through a steam generator, where the heat is transferred into the secondary system, producing pressurized steam, which in turn is used to power the turbine and generate electricity [22].

The high neutron absorbing materials used in PWRs, such as light water and stainless steel, necessitate the use of enriched uranium as fuel. Enrichment levels as well as fuel burnup have increased with time.

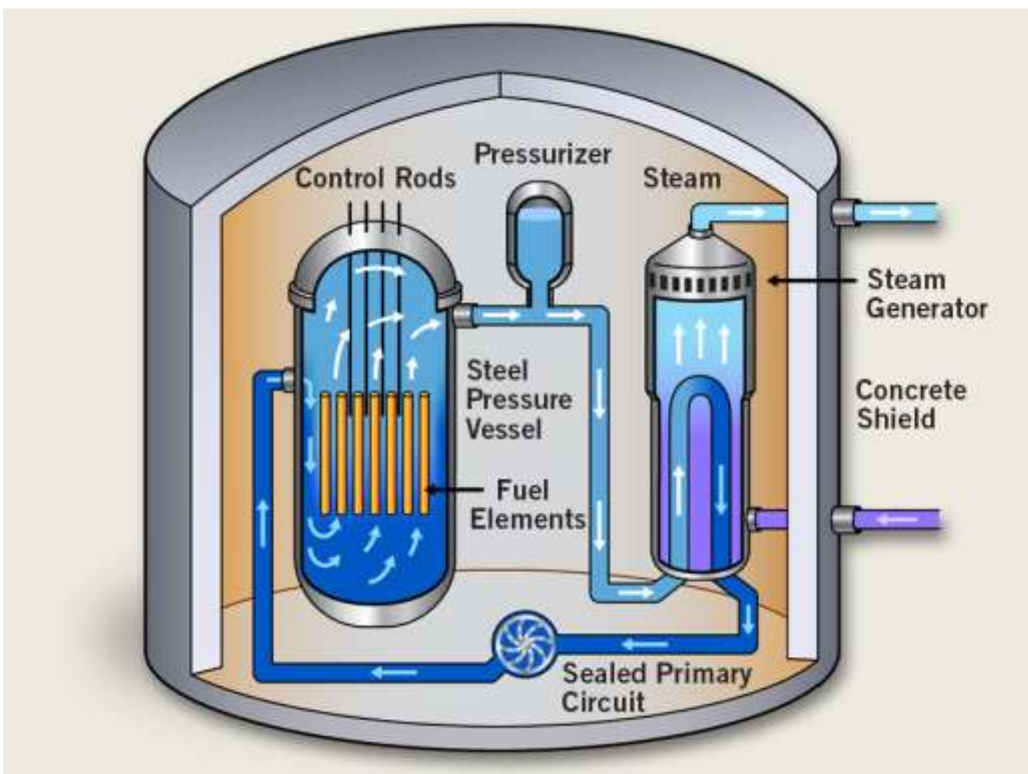

Figure 3 Schematic diagram of a pressurized water reactor **Error! Reference source not found.**

Advantages

- Lots of OPEX

- Well-established supply chain
- Currently available technology

Disadvantages

- Pressurized, need for a large pressure vessel
- Active safety systems
- Limited potential for modular, factory construction

Integral Pressurized Water Reactors

Integral pressurized water reactors (iPWR) are a variant of LWRs in which all the major primary pressure components such as the steam generator, the pressuriser, and the heat transport pumps are contained within the reactor pressure vessel (RPV), thus eliminating the piping that would be required for connecting these components. A schematic of the proposed NuScale, an iPWR, is shown in Figure 4, demonstrating the designed operation. Passive safety is increased because of the integrated design, by removing large diameter piping between systems typically used for PWRs Currently one iPWR has completed construction, the RITM-200 (50 MWe), which operates on Russian nuclear ice breakers. The Argentinean CAREM-25 (27 MWe), has also begun construction [26].

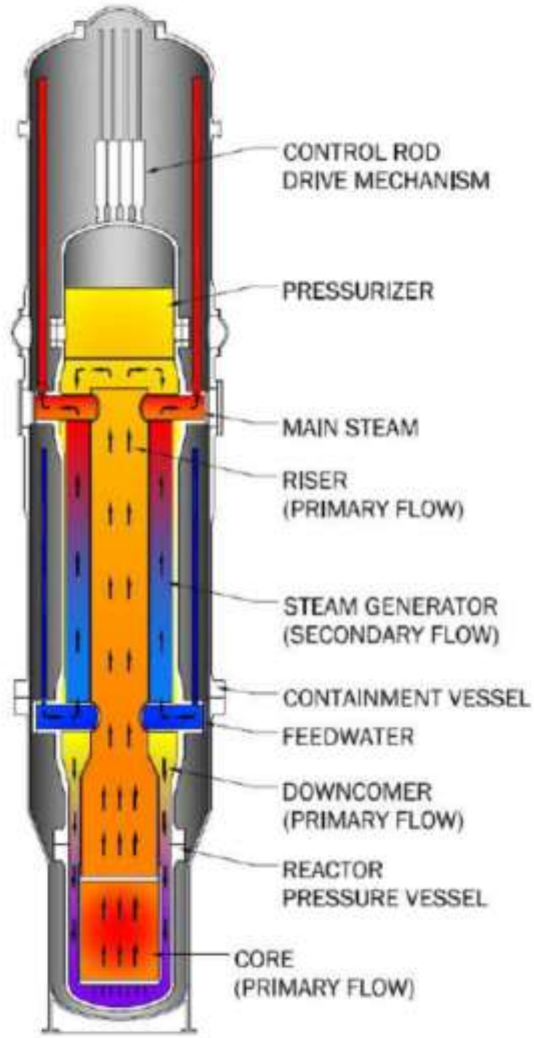

Figure 4 NuScale power module [27]

Advantages (relative to standard PWRs)

- More compact reactor containment [27].
- Greater potential for factory manufacturing [15].
- Elimination of Loss of Coolant Accidents (LOCA) related to heat transport piping [27].

Disadvantages (relative to standard PWRs)

- Increased waste volume per unit of reactor energy [28]
- Lower fuel burnup causing increases fuel cost [15]
- Pressurized system
- Maintenance and inspection of in-core components more difficult once integrated [29].

4.2.2 High Temperature Gas-Cooled Reactors

The High Temperature Gas-Cooled Reactor (HTGR), a variant of which is the Generation IV Very High Temperature Reactor (VHTR), is a reactor design that is graphite moderated and helium cooled [30]. There are currently two different types HTGR designs: the prismatic block core or the pebble-bed core [30]. Both designs use millimeter-size TRISO fuel particles embedded in compacts, typically composed of graphite, that are formed into cylindrical (prismatic) or spherical (pebble) geometries. The TRISO particles typically have an enriched UO_2 or UCO fuel kernel at their centre [30]. The HTGR concept can, in principle, also support advanced fuel cycles and fuels other than enriched uranium [30]. A summary of the properties for a typical HTGR can be found in Table 2.

Advantages

- The TRISO particle encapsulates all radioactive nuclides generated during reactor operation [22], effectively sequestering them from the environment.
- The TRISO fuel form is capable of withstanding extremely high temperatures (up to 1600 °C [30]) without failing or releasing radioactive material.
- HTGRs have low power density, meaning that for a given power output, they are physically larger than other concepts. Additionally, increases in temperature result in a large decrease in power. These factors grant HTGRs significant inherent safety.

Disadvantages

- The low power density and larger size also increases the capital cost and size of facility [15].
- Graphite is combustible in air at temperatures greater than 400 °C, which is lower than the operating temperature of this reactor [32].
- Graphite dust creates a potential contamination challenge

4.2.3 Sodium-Cooled Fast Reactor

Sodium Fast Reactors (SFRs), may operate using oxide or metallic fuels and are cooled by liquid sodium metal. The reactor operates at near atmospheric pressure, providing a safety advantage [33]. Sodium coolant can also operate at a higher temperature, resulting in a higher thermal efficiency for the power plant. However, a major drawback is the violent hydrogen-producing chemical reaction of sodium with water. This necessitates an additional heat exchange loop, and mandates extra care in the fabrication of the steam generator. Sodium also reacts exothermically with air, which has been a problem with early prototypes (MONJU, Superphénix) [34]. However, this technology has been operated in several instances, including the experimental reactor Rapsodie, the prototype Phénix and the full-scale prototype Superphénix reactors in France. This history of operation shows that this technology is available [34].

Advantages

- High thermal conductivity (with metal fuels), allows better transfer of heat from fuel [35].
- Passively cooled by natural circulation in the event of an accident or shutdown [35].
- Can maintain heat transfer at low flow rates, including at natural circulation [35].
- Depending on the design, negative reactivity coefficients.

Disadvantages

- Prototypes have demonstrated a propensity for leaks in the sodium circuit to develop, usually around the steam generators. This has occurred in multiple reactors across various times in their operation [34].
- Sodium is a reactive element and will react with both air and water [34].
- Large cores could have positive sodium void reactivity worth, placing an additional challenge on shutdown systems [33].
- To use natural circulation for coolant, limits must be put on the reactors physical size [35].

4.2.4 Lead-Cooled Fast Reactor

Lead-cooled fast reactors (LFR) share many design similarities with other liquid metal cooled concepts (e.g. SFRs), except that they are cooled by molten lead or a lead-bismuth eutectic. A summary of the properties of small modular LFRs can be seen in Table 2. Many proposed LFR designs are integral units with small footprints targeted at small remote communities or developing nations [15].

Advantages:

- Atmospheric operating pressures with low risk of over pressure due to the high boiling point of the lead coolant [42].
- In smaller reactors, the lead coolant also allows for circulation via natural convection during an accident scenario [38].
- Compared to other metal cooled reactors such as SFRs, lead cooled reactors have the advantage of being relativity non-reactive with air or water, simplifying containment [42].
- LFRs are also able to use recycled fuel and, by using uranium-plutonium mixed oxide fuels, may be capable of operating in a closed cycle [15].
- Small physical size

Disadvantages:

- The corrosive nature of molten lead around 500 °C in contact with structural materials necessitates some form of mitigation strategy [36].
- High mass of lead presents challenges, for example in the transportation of the core and added strain on structures and components [41].
- Lead has a high melting point, and is liquid during reactor operations, but solid at room temperature. This creates operational challenges and the need to prevent lead solidifying during reactor shut-down [44].
- Lead-bismuth designs also suffer from the relative rarity of bismuth, increasing cost as well as the production of polonium from neutron interactions with bismuth [43].

4.2.5 Molten Salt Reactors

There are broadly three types of Molten Salt Reactor (MSR) concepts [46]:

- Liquid fuel, dissolved into liquid coolant (e.g. MSR Experiment at Oak Ridge, Terrestrial Energy)

- Liquid fuel in tubes, separated from liquid coolant (e.g. Moltex Energy)
- Solid fuel, separated from liquid coolant (e.g. Fluoride Salt High Temperature Reactor, Kairos)

In all three cases, the heat exchange medium is a liquid salt, typically a fluoride or chloride of lithium, beryllium, sodium, or potassium. Near term applications focus on those with solid fuel with the potential for lessons learned to be applied to future liquid fueled designs [15]. Many MSR designs operate at high coolant temperatures of approximately 700 °C, to allow for process heat to be used in various applications [46]. In concepts with liquid fuel, gaseous fission products can be bubbled off and removed while operating at full power. Some concepts further advocate online reprocessing of liquid fuel to remove dissolved fission products or useful isotopes.

A summary of typical properties of small modular SMR concepts is shown in Table 2.

Advantages

- A typical inherent safety feature of MSR concepts is a strong negative temperature coefficient of reactivity (i.e. an increase in temperature results in a large decrease in power) [48].
- Near-atmospheric pressure of the primary coolant loop salt simplifies containment and construction [48].
- Liquid fuel allows the possibility of removal of some online fission products and of incremental fuel make up, allowing very high fuel utilization [49].
- Some liquid fuel designs can be used for breeding using a thorium salt seed blanket or used to burn spent LWR fuel, allowing for a more sustainable fuel cycle [49].
- High temperature allows for increased power production efficiency and possible process heat applications [15].

Disadvantages

- Molten salts are corrosive, introducing structural material challenges or need for stringent chemistry control [48].
- Tritium production in lithium salts possess a problem for many designs. This may be mitigated by using lithium enriched in ^{7}Li [15], but the technology for this is not currently widespread. Chemistry control, to prevent migration of tritium out of the coolant, may also be required.
- Removal of fission products creates and additional waste stream requiring management.
- Reduced defense in depth due to lack of fuel matrix and fuel cladding [51].
- Molten salt fuels will require cooling and further processing prior to disposal, and there is no such process currently in place.

4.2.6 Heat-Pipe Reactors

Heat pipe reactors have been proposed for applications where small amounts of highly reliable power are needed, such as space applications and for remote communities or mines. Heat pipe reactor concepts in the MWe-power range proposed for terrestrial applications go back to the 1980s [55]. In these reactors, solid fuel and heat pipes are embedded in a solid metal block structure. The heat generated in the active fuel region is deposited along the evaporator section of the heat pipes, which are used to transport heat from the core to the power conversion unit without a need for additional mechanical components such as pumps and valves, resulting in increased reliability. The main difference between a heat pipe reactor and other reactors is that the coolant, typically sodium or potassium, is contained inside a heat pipe rather than being in direct contact with the fuel elements or fuel bundles. A heat pipe is a closed tube or a pipe containing a working liquid that transfers heat from a heat source (reactor core) to a heat sink (power conversion unit) through mechanisms of evaporation and condensation [52]. A summary of the properties of heat pipe reactors are shown in Table 2. General reactor reliability and safety is maintained due to the large number of heat pipes, where a loss of one or several heat pipes would not necessarily result in an unsafe condition.

Heat pipe reactors typically operate on either the fast or epithermal spectrum and are only suitable for very small power levels (typically less than 15 MWe). In March 2018, NASA demonstrated KRUSTY, a very small heat-pipe reactor with a power level in the order of a kilowatt [54]. This reactor was designed, built, and tested following the initial project launch in 2015. More recently, ANL [56] and INL have proposed various heat pipe reactor concepts in the MWe range. The ANL concept is being commercialised by Westinghouse [57].

Advantages

- High reliability due to the reduced number of components and systems, with minimal moving parts.
- Potentially lower maintenance costs; refuel period of five to ten years, or more,
- Similar to other sodium-cooled fast reactors, heat pipe concepts are expected to be inherently safe due to the strongly negative temperature coefficient of reactivity [52].
- Small footprint due to low power level may allow the complete plant to be transported by a truck, resulting in drastically reduced site installation time.

Disadvantages [59]

- Typical working fluids used in heat pipes, sodium and potassium, react with air and water.
- Lack of OPEX.
- Only suitable for small power outputs, up to around $15MW_e$.

4.3 New Fuel Types

The current fleet of light and heavy water reactors uses ceramic uranium dioxide fuel. Many advanced reactor designs are considering other fuel types, as well as accident tolerant fuels. Several advanced fuel concepts are discussed below:

Accident tolerant fuels

Accident tolerant fuels (ATF) have recently gained prominence following the Fukushima accident. While the term typically refers to fuels intended for use in the current generation of light water reactors, ATF can be broadly defined as any fuel which can withstand a loss of coolant scenario for a longer period than conventional fuel.

Metal fuel

Metallic fuel was one of the first concepts to be tested in early reactors. While heavy metals in general conduct heat more readily than ceramic oxides, they have much lower melting points (e.g. the melting point of uranium metal is 1,132 °C, while that of uranium oxide is 2,865 °C). This restricts their usage from a safety perspective. Metal fuel is particularly well suited to fast reactors, however, due to its higher density of fissile atoms and the lack of moderating influence from oxygen.

Uranium Silicide

Interest in silicide fuels (such as U_3Si_2 and USi_2) has recently increased due to their higher uranium density and advantageous thermophysical properties. Although the melting point (1,665 °C) of uranium silicide is lower than that of uranium oxide, it has a higher thermal conductivity and heat capacity, both of which increase with temperature. This results in lower fuel centerline temperatures in nominal and accident conditions. They are typically paired with advanced cladding materials, such as SiC or FeCrAl, which carry a neutronic penalty and are not suitable for use with conventional oxide fuels. Silicide fuels have poorer oxidation resistance than other fuel types, and an engineering solution to this issue is an ongoing area of research.

Uranium Nitride

Like silicide compounds, the uranium density, thermal conductivity, heat capacity and thermal expansion coefficient of uranium nitride (UN) are higher than that of UO_2 and further increase with temperature. One of the disadvantages of UN is that ^{14}N has a high probability for absorbing neutrons, and that this process produces radioactive ^{14}C. UN fuel might therefore require the use of nitrogen highly enriched in ^{15}N, to alleviate these issues.

Also like silicide is the low oxidation resistance of UN fuels. UN powders oxidize in air and UN pellets decompose in hot water. Exposure of UN to high temperature water leads to the formation of ammonia. Addition of USi_x or “alloying” UN with ZrN, CrN or AlN nitride compounds might increase the oxidation resistance of UN fuel.

Irradiation studies of UN fuel were performed for space nuclear power applications using different cladding alloys, cladding temperatures, burnups, fuel densities, UN grain sizes and stoichiometries [18]. Overall, the results showed that the low-density UN fuel tends to restructure and form center voids. UN dissociates in the hot regions (fuel centerline) and reformates in the cold regions (cladding walls). Chemical interactions between fuel, fission products, liners, and cladding occur during irradiation. In contrast, high density (>95 %TD) UN fuel displays rather mild changes in microstructure. Classical fission gas bubbles form and migrate to the grain boundaries with increasing burnup. High density UN operating at moderate temperatures has low swelling, low fission gas release (i.e., Xe, Kr), no fission product interaction, and the potential of operating to high burnups.

Uranium Carbide

Uranium Carbide (UC) is another high density ceramic fuel concept which has higher thermal conductivity and higher heavy metal density than UO_2. UC fuels present several challenges, however. UC is a hard, brittle material and is subject to thermal stress cracking when operated at high heat ratings. UC reacts rapidly with water as the temperature increases forming UO_2, hydrogen and hydrocarbons.

Another fuel option is Uranium oxycarbide, which is a mixture of UO_2, UC_2, and UC often denoted by UCO. It is intended as an alternative to uranium dioxide for use in TRISO fuels (discussed in the following section), as lower oxygen content will result in reduced production of CO gas and thereby reduce the pressure within the fuel particle.

TRISO Fuel

Tristructural-isotropic (TRISO) fuel is a concept where fuel rods or spheres are composed of many micro-particles encapsulated, typically in a graphite matrix. The micro-particles are a multi-layered fuel form with a kernel composed of UO_2 or UCO at the centre, as seen in Figure 5. TRISO fuel has potentially superior safety characteristics relative to other fuels due to its multiple barriers to fission product dispersion, high mechanical stability, and good thermal conductivity. It can also withstand relatively high temperatures without failure, making it particularly well suited for high temperature gas cooled reactors. However, the low fissile density caused by the presence of multiple barriers must be compensated by the fuel and core designs.

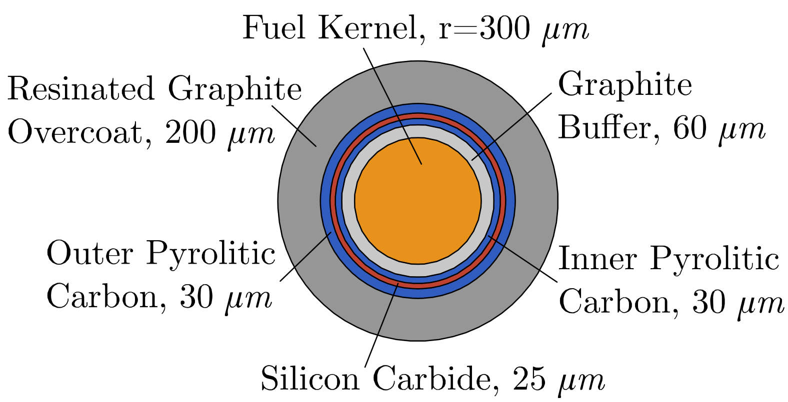

Figure 5 Cross-sectional view of a typical TRISO particle concept.

Thermal conductivities of irradiated and un-irradiated TRISO are higher than standard UO_2 fuel. Overall, FCM fuel presents the following challenges:

- Excessive reactivity in fresh fuel due to high enrichment and reduced self-shielding, which in turn requires very high burnable absorber loadings;
- Shortened residence time in the core, which may result in an economic penalty associated with shortened cycles; and
- Higher volumetric heat generation rates in the fuel kernels with reduced volume of fuel meat.

Molten salt fuels

In most molten salt reactor concepts, the fuel and coolant are a single fluid where the fissile material has been dissolved into a liquid salt. The salt is typically a mixture of the fluorides of lithium, sodium, potassium, and/or beryllium (such as FLiBe or FLiNaK), although sodium chloride has also been proposed in some larger reactor concepts. The fuel in these cases is itself also a fluoride (such as UF_4 or ThF_4). The largest advantage of molten salt fuels is that they cannot melt down, as they are already molten. The liquid form also allows the bubbling of certain gaseous fission products out of the fuel, granting significant neutronics and waste management advantages. Molten salts are, however, corrosive to most metals, presenting a challenge when designing reactor components and piping.

4.4 General benefits from all SMR technologies

The following benefits are provided from SMRs regardless of the specific technology, although the magnitude and extent of the benefits could be somewhat technology specific:

- Greater passive safety relative to Generation-III reactors
- Reduced safety risk due to the use of integral components in the primary heat transport system
- Modular design that can be factory built and transported by truck or rail (it is noted that this might be difficult for some physically larger-size reactors)
- Lower initial capital cost relative to current larger GW-class reactors. This is important as it means it could be easier to finance and find investors.
- A source of abundant, reliable, GHG-free energy that can be used for power generation or to electrify the transportation industry. The later can produce far deeper GHG reductions and could potentially be an enabler for technology growth in the transportation sector.
- Most can load follow much better than the current generation of reactors allowing them to be base load and to complement intermittent renewable energy sources.

Additional benefits are linked to the current level of readiness of the technology. Two perspectives on technology readiness are shown in Figures 6 and 7. While in some cases these reactors use technologies that are well-developed and well understood, new configurations or variations on a design will result in a lower technology readiness.

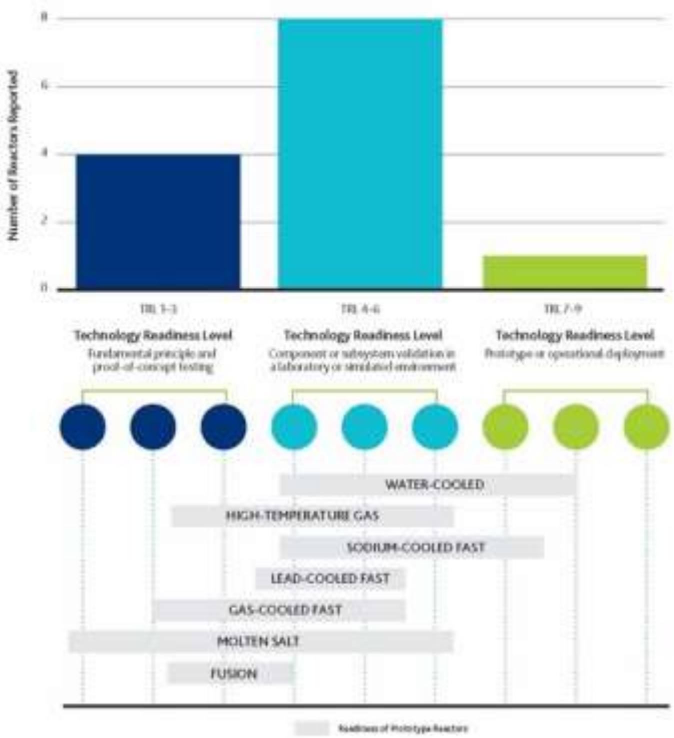

Figure 6 Technology readiness levels as reported by technology developers through CNL's Request for Expression of Interest **Error! Reference source not found.**]

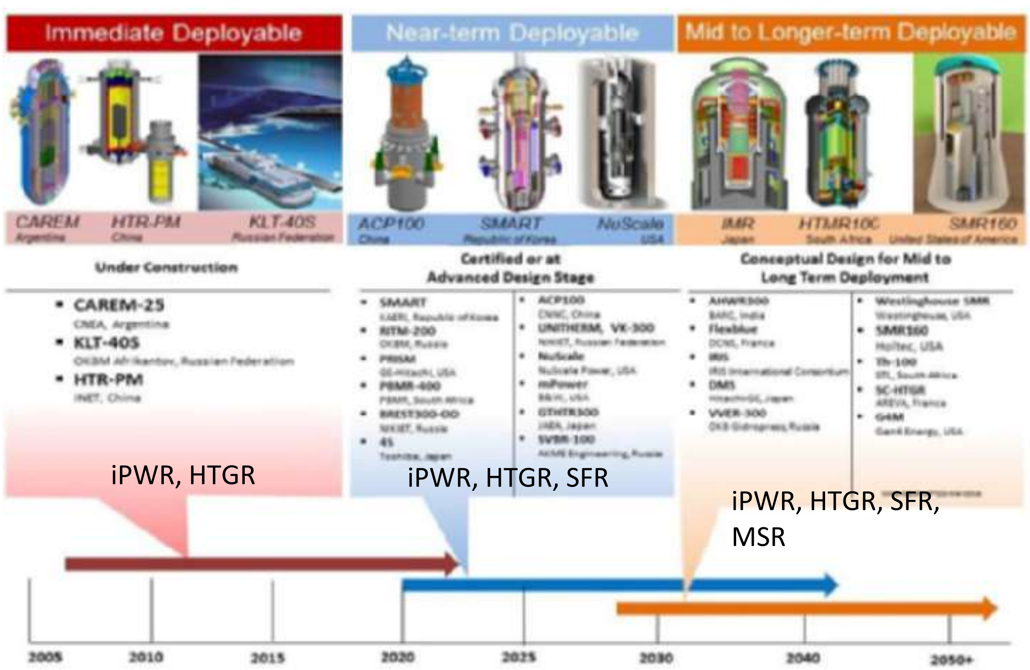

Figure 7 Estimated timeline of deployment for on-grid applications **Error! Reference source not found.**]

4.4.1 Higher Technological Readiness Designs

The water-cooled and high temperature gas reactors have the features identified above and are at a more advanced stage of development. These technologies more likely for early deployment (or lower risk on the timeline) and less investment would be required for their deployment. However, as these designs were progressed by other countries, there may be less opportunity for Canada to develop intellectual property (IP), provide leadership in R&D, or provide technology-related supply chain for export market, compared to the lower TRL technologies. It should be noted that high temperature reactors can produce high temperature steam which could also be used for co-generation applications and thus may also be applicable for heavy industry application and offer an alternative to electrolysis for hydrogen generation for use in the transportation industry.

While higher TRL technologies have fewer opportunities for the Canadian supply chain to participate, there still may be some. One recent potential opportunity is the announcement by NuScale **Error! Reference source not found.**] that BWXT will manufacture their modules. BWXT has considerable presence in Canada, and it is likely that some of that iPWR technology may be located in Canada.

4.4.2 Lower Technological Readiness Designs

Sodium fast reactors, lead fast reactors and molten salt reactors are almost a mirror image to the TRL risks and opportunities as shown in Figure 8. Since there is more development, the timelines either are longer or there is a higher risk to early deployment, and the investment required to get to deployment is higher. On the other hand, because they are less development, there is substantially greater opportunity for Canada for innovation, R&D, and supply chain, including the potential for export opportunity and all the benefits that come with it. Canada would be viewed as a country of choice for suppliers of SMR technology by some countries because of our reputation which includes well developed and respected regulator and national laboratory and our strong track record on safety design and operation with CANDU reactors.

These lower TRL designs also fall into the category of advanced reactors. The fast reactors also have inherently safe characteristics and either allow for the reprocessing of their spent fuel. Some fast reactors can also be burners, which can reduce the current stock pile of spent CANDU fuel. Like HTGR designs, some of the lower TRL designs such as sodium cooled and molten salt reactors which like the HTGR reactors could also be used for co-generation applications and thus may also be applicable for heavy industry application and offer an alternative to electrolysis for hydrogen generation for use in the transportation industry.

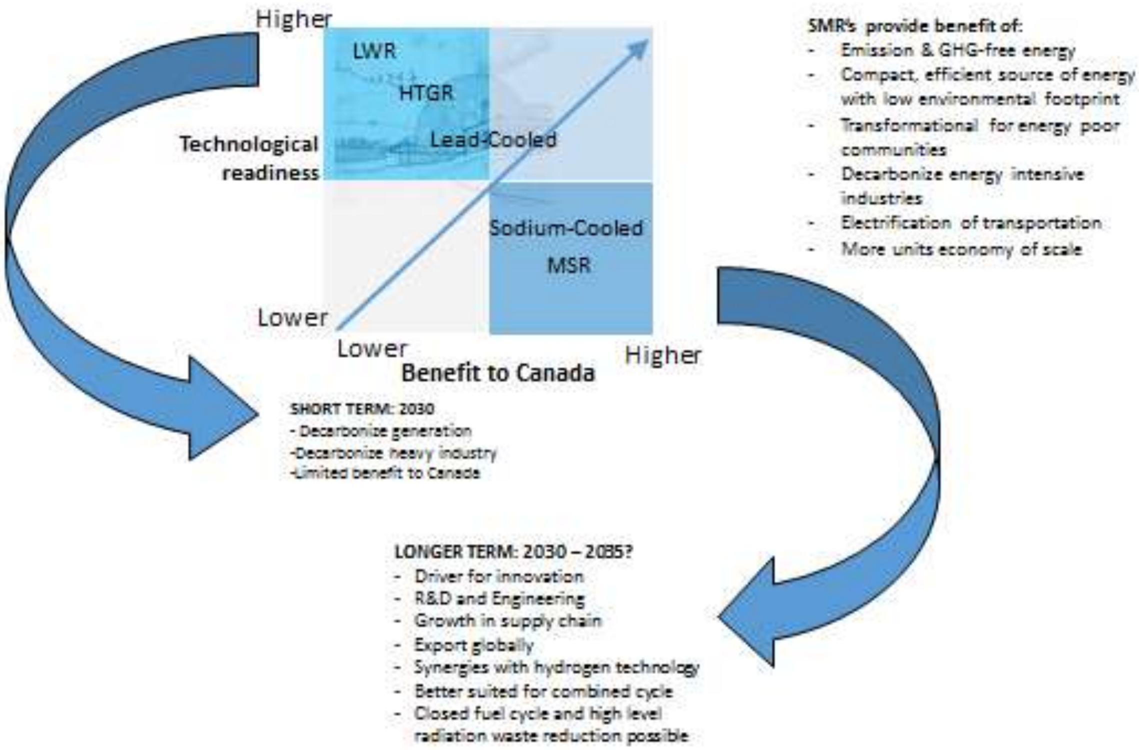

Figure 8 Potential benefit to Canada for technologies of varying technology readiness

4.5 Cross-Cutting Enabling Technologies

The term 'enabling technology' is used in a broad sense; for example, it could denote the technology of a particular system, structure or component as well as a combination of design approaches used to ensure inherent or passive safety features or high economic competitiveness of a certain SMR design **Error! Reference source not found.**]. In general, these are technologies that would enable the development and deployment of any SMR technology, i.e. they are not design or technology dependent. Computational simulation technologies, instrumentation & controls, data sets for validation of nuclear power plant performance and safety, and strategic programs necessary for ensuring safe operation and maintenance may also fall under this definition.

Enabling technologies and strategic programs are expected to result in substantial impact in reducing deployment risk and cost for SMR fleet operation & maintenance. Worldwide efforts are underway to date to both define the strategy and identify the most promising enabling innovations that are critical to SMR deployment success.

Examples of cross-cutting enabling technologies **Error! Reference source not found.**]

- **Dry Cooling**: Dry cooling allows the installation of SMRs at locations with scarce water supplies. Some thermodynamic heat-power conversion cycles are much better suited to transferring heat to air than others, as opposed to traditional steam cycles. Some coolants have much more favorable temperature-matching characteristics when combined with air cooling. Supercritical carbon dioxide (sCO2) is one of multiple examples.

- **Load Following and Energy Storage**: Load following should be considered, especially for markets that have varying energy needs and large renewable integration. Although it is possible to a certain extent, it is not ideal to load follow by changing reactor power to match the power need of the grid. Some nuclear plants follow load by dumping excess steam to condensers while maintaining normal power level, but this practice wastes otherwise useful heat. An alternate and more efficient approach is to employ energy storage systems as a buffer between the electrical generator and the load, such as parallel power generators on a reactor, where one provides baseload and the second stores energy and responds to transient conditions. These systems can respond to power changes very rapidly (on the order of ½ second), which would allow the reactor to respond much more slowly and still provide a system with fast load following capability.
- **High Thermal Efficiency**: Most power plants today use steam Rankine power conversion cycles that is suitable for steam temperatures typical of water-cooled nuclear reactors. Although the thermal efficiency of Rankine power conversion cycle increases with increased steam temperature, thermal efficiency of Brayton cycle increases more rapidly, making it attractive at higher temperatures where advanced reactors operate at. The sCO2 Brayton cycle power conversion technology, for example, is maturing to be a more compact and less complex alternative to the steam Rankine cycle.
- **Walkaway Secure**: The SMR plant should be designed to be secure to the point that no adversary actions can be taken to place the public at risk during an emergency that requires the plant personnel to evacuate for safety reasons. This requires **advanced barriers that are at least equal in security hardness to that of the reactor containment**. Examples would include a reactor that is completely enclosed, possibly in a sealed container underground. Such reactor would be inaccessible without especially large equipment that is not available and would be easily detected as it approaches the reactor site.
- **Small Emergency Planning Zone**: As part of the design process, an emergency planning zone (EPZ) should be as small as possible. Utilizing **a dose/distance approach**, it may be possible to show that SMRs could have an EPZ that is coincident with the site boundary. Utilizing **stochastic techniques** that are used in other areas, such as fire protection, design of an appropriate EPZ may avoid unnecessary conservatisms that are inherent in the current process, while still meeting all safety requirements.
- **Low-Uncertainty and Short Manufacturing Lead Times**: Many potential customers may be discouraged from ordering an SMR if the time to deliver it is too long or if the delivery time is highly uncertain. Therefore, developing a **highly reliable**, **highly efficient modular advanced manufacturing process as enabling technology** is important.
- **Walkaway Safe**: Some current water-cooled reactors claim to have been designed to be walkaway safe. However, safety is strongly coupled with other key reactor characteristics. It must be considered concurrently with **security, safeguards, and operations**.

- **Material-related technologies**: There are many material technologies that could improve multiple technologies. An example is the qualification of Silicon Carbide (SiC) core materials, including structural fuel materials. High temperature materials offer the potential to enhance safety margins. They provide valuable heat storage time for passive cooling features to work, and paths for the heat to get out.
- **Inspection and testing technologies:** to performing testing and inspection of advanced fuels, and for inspection of reactor vessel and fuel structural integrity.
- **Modeling and simulation** is essential to the development process. An important foundation for this is good knowledge base for material properties (physical, chemical, and nuclear) used for modeling and simulation. The use of software structured around state variables in the time domain to more accurately visualize time and amplitude response of the systems. Frequency domain simulations can then be made to better analyze components for fatigue.

  Recent advances in massively parallel systems, **advanced computational methods** employing multi-physics modeling with neutronics-thermalhydraulic coupled codes, and validation and verification should form the cornerstone of computational modeling for innovative, more efficient, secure, environmentally-benign, and reliable energy systems.
- **Diversion Risk Modeling** - For instance, Sandia National Laboratory and the Japan Atomic Energy Agency (JAEA) developed a demonstration for an **Advanced Transparency Framework** which relies solely in the **real-time analysis of intrinsic process data to report changes in diversion risk during facility operations**. The application can extract and format system data from an automated physical training model, conduct secure transmissions of the data to a remote location for analysis, integrate and optimize plant design and declared activities into diversion risk calculations, and calculate diversion risk. This type of technology offers great potential for the safe and secure deployment of SMRs that operate autonomously and monitored remotely.
- An **independent remote monitoring capability** to announce incipient unusual conditions that may require observation, and possibly reduce power or shut down the reactor for unplanned maintenance, is an important enabling technology.
- **Advanced robust, in-core sensors** would improve the visualization of axial and radial burnup, and with adequate control rod operation, allow for (a) a better use of the fuel and (b) longer times without refueling**.**
- An integrated diagnostic platform would be useful for fuel or component material irradiation and qualification, as well as for fuel irradiation.
- For reliable and economic long-term operation of Small Modular Reactors (SMR), it is imperative that continuous **in situ monitoring of critical equipment** must be developed and incorporated in the reactor design phase. This capability is attractive for **remote deployment of SMRs with longer fuel cycle duration** and for **minimizing forced outages**, thus enhancing the utilization of these power generating systems in small electric grid environments. These technologies contribute to **smart condition-based maintenance,**

reduced human resources, remote monitoring of reactor components, and autonomous operation.

For instance, on-line monitoring of SMR components, using electrical signature analysis (ESA), could be applied to an experimental flow loop in SMR. Monitoring electrical signatures of critical components could help in diagnosing anomalies in these components and thereby facilitate their timely maintenance. This would reduce maintenance costs and forced outages. Remote monitoring technologies would also reduce human resources. Because most of the critical components are internal to the vessel and thus inaccessible during normal operation, remote monitoring via electrical signal analysis provides a means for monitoring their performance.

There are significant reactor innovations in the Pan-Canadian nuclear industry and research sectors underpinning the O & M excellence of CANDU technologies for the past 40 years. These remarkable innovations can be further developed and extended to support cross-cutting enabling technologies for SMR deployment worldwide.

4.5.1 Cross-Cutting Enabling Technologies Development for SMRs in Canada

Currently, there are no specific programs for cross-cutting enabling technologies in preparation for SMR deployment in Canada, hence there are clearly technology gaps that are not being actively addressed, in comparison with other international programs.

However, Canada has a mature nuclear science, technology and innovation ecosystem, based on the example of CANDU technologies:

- Mature industry that has already experienced process of developing OEM technology with the CANDU reactor and has the capability to repeat this success for SMR;
- There are high quality university and trade school-educated workforce including technicians, scientists, and engineers in the nuclear sector to support the CANDU technologies;
- Requisite nuclear infrastructure with advanced research centres, universities research network such as UNENE and Canadian industry facilities and special R & D groups such as CANDU Owners Group (COG).

Appendix B lists numerous cross-cutting enabling technologies developed for CANDU reactors. Guided by a Pan-Canadian SMR Roadmap vision, these innovations can be further developed and extended to support cross-cutting enabling technologies for SMR deployment domestically and internationally, as outlined in Appendix B.

A possible strategy for developing or pursuing cross-cutting enabling technologies to support SMR deployment in Canada is as follows:

1. SMR technology development in on-grid, off-grid, industrial market applications consider the technology readiness level, as discussed in Section 4.4.2. These action plans may involve multiple technologies with various technology risks and corresponding benefits to Canada.

2. As multi-market-focused SMR technology development proceeds, the innovations listed in Appendix B.4 should be reviewed: where Canada has a unique advantage to excel in specific identified areas of cross-cutting technologies in targeted market applications, leverage and exploit the existing innovations to expand further development, in collaboration with others and SMR vendors. For example, grid-based SMR will require inspection technologies and enhanced in situ monitoring of critical component, off-grid applications may be enabled by security and surveillance enhancement by drones, and online monitoring systems may provide enhanced risk-informed operation to multiple SMR technologies and to multiple applications.
3. Development and testing of cross-cutting technologies should be considered as part of any SMR demonstration projects. This will be dependent on the specific project, and its mission, suitability for such testing, and the willingness of the project proponents and financiers to host such programs.
    a. The established of Pan-Canadian cross-cutting technology R & D development framework will provide the secondary tier support for developing the enabling technologies in support of the demonstration reactors such as those mentioned in Section 4.5, e.g.: walk-away safety; walk-away-secure; small emergency planning zone; inspection and testing technologies; modeling and simulation; diversion risk modeling; remote monitoring capabilities, continuous in situ monitoring of critical equipment, etc.
    b. The proposed cross-cutting technology R&D framework should be coordinated with any national SMR development and capability program, see Section 6.2. This portion of that program could be modelled after similar programs underway in the US Department of Energy, e.g. Advanced Research Program Agency – Energy (ARPA-E, see Appendix B.2) and Nuclear Energy Enabling Technologies (NEET, see Appendix B.3).

4.6 Findings & Recommendations

Finding: SMRs offer great potential benefits including: greater inherent and passive safety and reduced safety risks, modular design that can be factory built and transported by truck or rail, potential for lower initial capital cost, a source of abundant, reliable, GHG-free energy, and better ability to complement and integrate with intermittent renewable energy sources.

Finding: Additional benefits to Canada, such as development of supply chain, economic benefits and jobs, competitiveness, and driving an RD&I economy, from SMRs are linked to the current level of readiness of the technology.

Recommendation: The additional benefits of SMRs should be considered in technology selection and in providing support and investments in technologies, especially those by federal, provincial and territorial governments.

Finding: Cross-cutting enabling technologies are critically important in ensuring inherent or passive safety features and economic competitiveness of SMRs.

Recommendation: collaborative capability building and R&D programs (further discussed in Section 6.2) should include actions and development of cross-cutting technologies, such as those mentioned in Section 4.5. There have also been significant reactor innovations in the Canadian nuclear industry and research sectors that should be investigate and could be further developed and extended to enable SMR technologies.

Finding: A comprehensive program covering both short-term applications of relatively well-developed technology (e.g. LWRs) and technologies that have significant technology development still to be carried out would enable Canada to realize greater benefits of SMR deployment.

Finding: Taking a passive approach "sit back, wait and see" approach to advanced SMR technologies will not lead to the full benefits for Canada – developments will not be optimized to our requirements, and the industrial benefits will go elsewhere

Finding: For emerging technologies the amount of intellectual property (IP) produced so far is a small fraction of the final amount of IP (design, verification and licensing, manufacture, build, operate, decommission, waste management) that will be needed and used. Therefore, if Canada invests in technology development, and is producing valuable IP, and should share in the benefits.

Finding: It is notable that the potential benefits increase as the scope of development moves from shorter to longer term; a long-term vision for SMRs in Canada offers far-reaching benefits – reliable on-grid power free from GHGs; ability for heavy industries to operate with drastically reduced GHG emissions; and delivery of reliable power that ends energy poverty in northern and other remote communities.

Finding: Some SMR technologies, particularly for on-grid applications, are near to deployment readiness. In these cases, the ability to complete the pre-project steps of capacity-building, regulatory framework definition and design review, and technology risk review is a pre-requisite. In other cases, particularly for industrial and remote applications, a more extensive, and longer time-frame development program is needed. To gain the benefits of recycled and low-waste fuels, a longer-term sustained program commitment is needed

5. SMR Technology Gaps With Respect to Applications

Over 150 SMR designs are currently proposed or under development worldwide. Some SMR technologies could potentially be utilized in all applications, while others, although not necessarily restricted to a single application, are judged to be more appropriate to a particular application. Likewise, some designs have additional benefits not exclusive to the application environment which will need to be considered in evaluating a design for any specific application. Below we have attempted to outline, at a high level, the gaps in each technology in general, and gaps that exist in applying each technology to each of the three applications, without intending to eliminate the potential for any design to be used elsewhere.

The development of this section included consideration of the technologies on the TWG's SMR listing (Section 4.1). The TWG also consulted literature, documents from SMR developers, and applied expert knowledge from the TWG members. In identifying gaps, TWG considered limitations of the technology itself to meet the requirements identified, and the knowledge gaps in terms of technology provenness to meet the requirements.

The requirements that will be discussed for each of the SMR technology types are listed in Table 3. Further descriptions of these requirements are discussed in Chapter 2.

Table 3. SMR Requirements

<table>
<tr><th colspan="4">General Requirements, For all Applications</th></tr>
<tr><td colspan="4">Availability/technical readiness
Fuel readiness (globally)
Fabrication readiness (globally)
Supply chain readiness
Availability of computational tools, for design, verification and analysis
Waste management readiness, in the Canadian context
Technology readiness (in context of deployment in Canada)
R&D pedigree
Availability of codes & standards for fabrication
Domestic capability and expertise
Existing safeguards approaches
Regulatory readiness</td></tr>
<tr><th colspan="4">Application-Specific Requirements</th></tr>
<tr><th>On-Grid</th><th>Mining</th><th>Oil & Gas</th><th>Remote Communities</th></tr>
<tr><td>Power output
Compatibility with closed fuel cycles</td><td>Power output
Temperature
Ease of Transport
Simplicity of Operation
Limited cooling water option
Refuelling outages concurrent with mine</td><td>Power output
Temperature
Refuelling outages concurrent with facility
Limited cooling water</td><td>Power output
Ease of Transport
Simplicity of Operation</td></tr>
</table>

5.1 Light Water Reactors

5.1.1 LWR: General Requirements

Availability/technical readiness *Current Status:* This is the nearest-term available technology. Some research and development is required for new designs, which incorporate substantial changes to current reactor and plant designs. Overall, there exists a high degree of proven-ness based on existing LWR technology. This technology is one of the oldest and most tested reactor designs. Internationally, 363 of the 444 operating reactors (82%) are LWRs. This provides a wealth of experience and experimental data from which future work can draw [24].

Fuel readiness (globally) *Current Status*: The LWR fuel supply chain is well-established, and this fuel can be purchased as a commodity. In addition, there are many programs worldwide, especially in the US, to develop new fuels that have higher tolerance in accident scenarios. *Medium Term*: A pilot program is required to test deployment of new accident tolerant fuel designs. *Long Term*: Enrichment and fuel fabrication capabilities in Canada must be established to improve the value-added aspects of LWR fuel.

Fabrication readiness (globally) *Current Status:* High, with few components that are unable to be manufactured. *Medium Term*: Specialized forging capabilities are required to support manufacturing of high temperature/high pressure vessels. *Long Term*: Application of LWR technology to beyond grid applications would require increased tolerances in temperature and pressure used for nuclear applications to allow production of higher quality heat/steam.

Supply chain readiness *Current Status:* Excepting the unavailability of enriched fuel, the existing supply chain of the Canadian nuclear industry is sufficient to support the deployment of light water reactors. *Medium Term:* Domestic enrichment capability must be developed such that high assay low enriched uranium is available at commercial scales.

Availability of codes & standards for fabrication *Medium Term*: Advanced materials must be added to ASME Section II to support high temperature/high pressure applications.

Availability of computational tools, for design, verification and analysis *Current Status*: Multiple computational tools exist and are in current use. Additional functionality is ongoing to increase the predictive ability of the tools, and to reduce the need for expensive experimental programs.

Waste management readiness, in the Canadian context: *Current Status*: LWR spent fuel waste containers must be certified for disposal in the NWMO DGR. *Medium Term*: A domestic supply of waste containers could be established.

Technology readiness (in context of deployment in Canada): *Current status*: LWR technology is ready for deployment, there are no anticipated issues. *Medium Term*: New technology needs to be developed in order to perform measurements (Heat, pressure, etc.) within iPWR vessels. This technology must be able to fit within the vessel (reduced space due to integration) and must be able to measure specific parameters [60].

R&D pedigree *Current Status:* High pedigree, established R&D programs exist in many countries. Integration with US based owners groups (PWROG and BWROG) would likely be required for OPEX.

Domestic capability and expertise *Current Status:* Although Canada has experience with water reactors, most it has been with heavy water reactors. Canadian experience with light water reactors has been gained primarily with NRX and SLOWPOKE. Current capabilities and expertise would likely be easily adaptable to LWRs. Experiments have also been carried out in Canada on testing integral CANDU reactors using test loops [68]; the experience from these tests may be applicable to integral LWRs.

Existing safeguards approaches[5] *Current Status:* LWRs are currently under safeguards in many jurisdictions worldwide.

Regulatory readiness *Current Status:* No major issues anticipated. Any regulations in the current framework that are geared to heavy water-based reactors may also be applicable to LWRs. In addition, this technology is regulated worldwide, so there is a large body of knowledge and expertise for the Canadian regulator to draw on through its networks.

Examples of technology gaps for iPWR:

- New technology needs to be developed to perform measurements (Heat, pressure, ect.) within the iPWR vessel. This technology must be able to fit within the vessel (reduced space due to integration) and must be able to measure specific parameters [60].

5.1.2 LWR: On-Grid Power Generation

Power output *Current Status:* Designs in the required power output range exist.

Compatibility with closed fuel cycles *Current Status:* Moderate compatibility. A partially-closed fuel cycle with some recycle of plutonium is deployed in several countries (e.g. France, the UK, Japan, Russia, China and India). While some studies have been done to investigate the potential to transmute higher minor actinides in LWRs, as thermal neutron spectrum reactors they are less suitable to this purpose than other technologies.

5.1.3 LWR: Heavy Industries

Power output (Mining) *Current Status:* While most commercial plants today employ large reactors, designs do exist that are in the range of required power output for this application.

Power output (Oil & Gas) *Current Status:* Designs in the required power output range exist.

Temperature *Current Status:* Designs are lower temperature and do not meet the high temperature requirements for some oil sands applications without additional secondary processes to further heat the water. *Medium Term*: Higher temperature and pressure designs, such as the supercritical water-cooled reactor could be explored and developed.

Limited Cooling Water *Current Status:* Current LWR designs depend on a source of cooling water for emergencies and occasionally as the condenser.

[5] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report.

Predictable and Infrequent Refuelling Outages *Current Status:* LWRs are refuelled at regular intervals, and the extensive OPEX gained in the past decades has drastically reduced the length of refuelling outages.

5.1.4 LWR: Remote Communities

Power output *Current Status:* While LWRs in the power range for this application have been developed and operated in the past, they have been primarily for research purposes and marine propulsion [50]. Design adaptations are possible for this technology, and a few companies have begun to explore this possibility. Floating nuclear power plants are also under consideration for this purpose, see Section **Error! Reference source not found.**. However, it is noted that the output of those designs exceeds the needs of most of Canada's remote communities.

Ease of Transport *Current Status:* Light water reactors are currently typically assembled on site. Efforts at improving modularization are underway. *Medium Term*: Additional research and development is required to improve modularity and pre-fabrication capabilities for LWRs.

Simplicity of Operation *Current Status:* Existing plants are large and have complex operations. *Medium Term*: Plants must be simplified, and operations streamlined to allow LWRs to be applicable to this market.

5.2 Sodium Cooled Fast Reactors

5.2.1 SFR: General Requirements

Availability/technical readiness *Current Status:* Not currently available for deployment, but with concerted effort, could be available in the near future. *Medium Term*: Successful demonstration and deployment of a prototype is needed to provide key data and OPEX prior to commercial deployment. R&D activities are required to enable use of advanced fuel cycles.

Fuel readiness (globally) *Current Status:* Expertise with metallic SFR fuel is available internationally but is limited compared to conventional fuels. Some historic data are available, but additional fuel qualification is needed, and fuel fabrication facilities must be developed. Use of oxide fuel could speed readiness. *Medium Term*: Qualified fuel must be made available at commercial scales. Advanced fuels must be developed to close the fuel cycle. *Long Term:* Availability of advanced metallic fuel and reprocessing capability at commercial scales.

Fabrication readiness (globally) *Current Status:* Sodium fast reactors have been constructed in several countries, and some are currently operational. There is no Canadian experience in fabricating components for metal-cooled reactors. *Medium Term:* Knowledge sharing from international partners and construction of fabrication facilities.

Supply chain readiness *Current Status:* Enrichment capabilities required for production of SFR fuel are not currently available in Canada. There is currently also no supply chain for many of the components required for construction or operation of an SFR. Part of the existing supply chain for heavy water reactors may also be applicable for SFRs. *Medium Term:* Domestic manufacturing facilities or capabilities for necessary parts and components, and/or import agreements with international partners must be established. Domestic enrichment capability must be developed such that high assay low enriched uranium is available at commercial scales.

Availability of computational tools, for design, verification and analysis *Current Status:* Multiple computational codes are available which are capable of modelling SFRs, but these require qualification. Verification and validation must be performed to fully qualify codes. *Medium Term*: Codes must be qualified, and their development and improvement must be an ongoing activity. *Long Term*: Development and improvement of codes should be an ongoing activity.

Waste management readiness, in the Canadian context *Current Status:* It is likely that current waste management capabilities are sufficient for some SFR waste. *Medium Term:* Dedicated waste management solutions must be developed. *Long Term*: Waste management solutions must be tested and in use.

Technology readiness (in context of deployment in Canada) *Current Status:* SFRs are a demonstrated technology internationally, but there is no practical Canadian experience with the construction or operation of these reactors.

R&D pedigree *Current Status:* Though there is a very limited history of research in Canada, sodium fast reactors have been investigated internationally since the 1950s. Several experimental facilities and test reactors have been constructed and operated, most notably in the US, France, Japan, and Russia. Current SFRs are also operating in Russia, Japan, India, and China.

Domestic capability and expertise *Current Status:* Canada does not have previous experience in building fast neutron reactors. *Medium Term:* International collaborations and concerted funding of domestic research will improve Canadian S&T capabilities with SFRs.

Existing safeguards approaches[6] *Current Status:* Sodium cooled fast reactors represent a challenge to current safeguard techniques which rely mainly on containment and surveillance (C/S) and item accountancy. For an SFR, because the coolant is not transparent, handling must be remote, and the spent fuel is enclosed in cans after reactor exit, item accountancy is difficult to achieve as individual item identification via markings is not possible after the fresh fuel has been introduced into the system, and current techniques, such as Cerenkov viewing detectors, are unable to distinguish spent fuel from dummy assemblies in the spent fuel bay. Currently, the safeguards approach for such reactors relies mainly on "Continuity of Knowledge" approaches, where the movement of fresh and spent fuel into and out of the facility as a whole is monitored by detectors at key points. The inherent problem with such an approach lies in the difficulty in recovering knowledge if the continuity is lost, potentially putting the facility out of compliance for long terms. Thus, robust reverification methods must be developed for such an occurrence, in particular for the loss of CoK of the canned spent fuel. *Medium Term:* There are several very promising techniques for item accountancy, and reverification available in the medium term for SFR safeguards. There exist "under sodium viewers", using ultrasonics, which have been demonstrated as capable of item serial number identification under reactor conditions. These could be applied during the canning process, for example, to allow a mass balance between the fresh and spent

[6] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report

fuel bays. Tomographic techniques using penetrating radiation have shown the ability to image canned fuel assemblies, thus preventing such scenarios as pin diversion, and may also be applied as a reverification method. This would require significant local infrastructure however.

Examples of technology gaps:

- When sodium absorbs a neutron, it is transmuted to radioactive isotope ^{24}Na, thereby making the coolant radioactive. This presents a major problem whenever any component in the reactor requires maintenance. A solution is required to avoid the isotope (which has a half-life of 15 hours) or shield against it during maintenance [15].
- Methods need to be adopted that can detect leaks into or out of sodium channels. These methods, if internal, must be able to maintain operation at high temperatures[35].

5.2.2 SFR: On-Grid Power Generation

Power output *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Compatibility with closed fuel cycles *Current Status:* There is potential for usage of SFRs with closed fuel cycles. *Medium Term:* Possible with concerted effort and investment. *Long Term*: Commercial scale operation with closed fuel cycle.

5.2.3 SFR: Heavy Industries

Power output (Mining) *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Power output (Oil & Gas) *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Temperature *Current Status:* At a typical coolant temperature of 500 °C, SFRs may be able to meet some of the temperature requirements of this application. Additional energy may be needed from the electricity production to further increase temperatures.

Limited Cooling Water *Current Status:* As sodium is highly reactive with water, a source of cooling water is not required for the primary loop. Some SFR concepts use cooling water in their secondary heat exchange loop.

Predictable and Infrequent Refuelling Outages *Current Status:* SFRs are refuelled at regular intervals. Refuelling intervals may be longer at earlier stages of deployment. *Medium Term:* With sufficient OPEX, refuelling outages can be streamlined and shortened.

5.2.4 SFR: Remote Communities

Power output *Current Status:* Concepts have been proposed in the higher end of the required power output range. R&D, engineering and design work would be required to develop concepts for this application. *Medium Term:* Preparation of detailed designs with the required power output.

Ease of Transport *Current Status:* Sodium fast reactors have compact cores, and sodium is a low-density metal. A fuelled core could be transported by truck to the installation site, although criticality and security issues would need to be considered.

Simplicity of Operation *Current Status:* Sodium fast reactors are expected to be able to operate for long periods with relatively little operator action, relative to today's large nuclear power plants. *Medium Term*: Further work is required to better understand and further optimize SFR refuelling operations. As refuelling reactors is a complex task, long refuelling frequency is a characteristic that aids in simplifying operation.

5.3 Lead Cooled Fast Reactors

5.3.1 LFR: General Requirements

Availability/technical readiness *Current Status:* Not feasible for deployment in Canada at present. A demonstration in Canada is needed to provide key data and OPEX prior to commercial deployment. *Medium Term*: Successful demonstration and deployment of a prototype. R&D activities are required to enable use of advanced fuel cycles. *Long Term*: Commercial deployment of power reactors with advanced fuel cycles.

Fuel readiness (globally) *Current Status:* Expertise with metallic LFR fuel is available internationally but is limited compared to conventional fuels. Some historic data are available, but additional fuel qualification is needed, and fuel fabrication facilities must be developed. Use of oxide fuel could speed readiness. *Medium Term*: Availability of qualified fuel. Develop advanced fuels to close the fuel cycle. *Long Term:* Availability of advanced metallic fuel and reprocessing capability at commercial scales.

Fabrication readiness (globally) *Current Status:* Lead fast reactors have been constructed in several countries, and some are currently operational. There is no Canadian experience in fabricating components for metal-cooled reactors. *Medium Term:* Knowledge sharing from international partners and construction of fabrication facilities is required. Lead is corrosive to structural materials such as steel at higher temperatures, techniques must be developed to mitigate this [36][69].

Supply chain readiness *Current Status:* There is currently no supply chain for many of the components required for construction or operation of an LFR. Part of the existing supply chain for heavy water reactors may also be applicable for LFRs. Canada has extensive capabilities in the production of refined lead, both from mining and recycling. The existing lead production industry would be able to support the additional demand from the construction of LFRs. *Medium Term:* Domestic manufacturing facilities or capabilities for necessary parts and components, and/or import agreements with international partners must be established. Domestic enrichment capability must be developed such that high assay low enriched uranium is available at commercial scales.

Availability of codes & standards for fabrication. *Medium Term:* Due to high density and large volume of lead, mechanical loads on the structure during operation can be considerable. This is especially important when designing seismic isolation systems [41].

Availability of computational tools, for design, verification and analysis *Current Status:* Multiple computational codes are available which are capable of modelling LFRs, but these require qualification. Current modelling and simulation techniques are not verified or validated for advanced coolants, leading to a gap in adequately modelling lead behaviour during operation [44]. *Medium Term*: Existing codes must be verified and validated for LFRs. Development and improvement of codes is an ongoing activity. *Long Term*: Development and improvement of codes is an ongoing activity.

Waste management readiness, in the Canadian context *Current Status:* It is likely that current waste management capabilities are sufficient for LFR waste. *Medium Term:* Waste management solutions expected to be ready. *Long Term*: Waste management solutions expected to be ready and in use.

Technology readiness (in context of deployment in Canada) *Current Status:* LFRs are a demonstrated technology internationally, but there is no practical Canadian experience with the construction or operation of these reactors. *Medium Term:* Effects of a possible steam generator leak into the primary lead coolant and subsequent primary coolant pressurisation could pose a threat to safety and needs additional research[70].

R&D pedigree *Current Status:* Though there is a very limited history of research in Canada, lead fast reactors have been investigated internationally, particularly in Russia, since the 1960s. Much of the global expertise was gained in the Soviet naval program, which ran 15 lead-bismuth reactors for a total of 80 reactor-years [69]. Though lessons learned from these reactors are not readily available, there has recently been extensive research conducted in Belgium, Sweden, and the US. In particular, Europe undertook research into lead cooled reactors under the European Lead SYstem (ELSY) which identified some key features and challenges in LFRs [71].

Domestic capability and expertise *Current Status:* Canadian R&D experience with LFR is minimal. *Medium Term:* International collaborations and concerted funding of domestic research will improve Canadian S&T capabilities with LFRs.

Existing safeguards approaches Existing safeguards approaches[7] *Current Status:* Lead cooled fast reactors represent a challenge to current safeguard techniques that are mainly based on containment and surveillance (C/S) and item accountancy. The challenges for LFRs are qualitatively similar to that posed by SFRs. Specifically, item accountancy based on serial numbers will be more difficult for assemblies immersed in lead and identification of spent fuel via Cerenkov viewing detectors will not be possible. No LFRs are currently under safeguards, but the safeguards approach in the short term will likely be similar to how SFRs are currently monitored - an approach based on “Continuity of Knowledge”, where the movement of fresh and spent fuel into and out of the facility as a whole is monitored by detectors at key points. The inherent problem with such an approach lies in the difficulty in recovering knowledge if the continuity is lost, potentially putting the facility out of compliance for long terms.

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[7] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report

Thus, robust reverification methods must be developed for such an occurrence. Since spent fuel bays with water coolant are likely to be impractical because of criticality concerns, canning of spent fuel is likely here (as well as for SFRs). This leads to item identification difficulties here as well, as for SFR canned spent fuel, but in the case of the loss of CoK for the spent fuel of an LFR reverification will be even more difficult since lead will shield identifying gammas and x-ray probes for tomography. *Long Term:* Unlike the "under sodium viewer" already proven for the SFR, no comparable ultrasonic technique has been demonstrated for lead, but the principle remains valid and development of such a system is a possibility. Tomographic techniques based on muon scattering may be able to isolate uranium from lead sufficiently for an in-can image to be reconstructed, but this will require development of the method and significant infrastructure. The slowness of this method mitigates it being used routinely.

Examples of technology gaps:

- Strategies to prevent freezing anywhere in loop to prevent damage to structural systems during shutdown, maintenance, refuelling, or accident scenarios. This poses a threat to keeping other parts of the reactor sufficiently cooled [41].
- Lead is corrosive to structural materials such as steel at higher temperatures, techniques must be developed to mitigate this [36], [69].
- Due to high density and large volume of lead, mechanical loads on the structure during operation can be considerable. This is especially important when designing seismic isolation systems [41].
- Lead is opaque, unlike most reactor coolants, necessitating the development of new inspection methods [41].
- Current modeling and simulation techniques are not verified or validated for advanced coolants, this leads to a modeling gap in its behaviour [44].
- Effects of a possible steam generator leak into the primary lead coolant and subsequent primary coolant pressurisation could pose a threat to safety and needs additional research. [70]

5.3.2 LFR: On-Grid Power Generation

<u>Power output</u> *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

<u>Compatibility with closed fuel cycles</u> *Current Status:* There is potential for usage of LFRs with closed fuel cycles. *Medium Term:* Possible with concerted effort and investment. *Long Term*: Commercial scale operation with closed fuel cycle.

5.3.3 LFR: Heavy Industries

<u>Power output (Mining)</u> *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

<u>Power output (Oil & Gas)</u> *Current Status:* Though no concepts are currently proposed at the required power range, gigawatt-scale LFRs are possible.

Temperature *Current Status:* At a typical coolant temperature of 550 °C, LFRs may be able to meet some of the temperature requirements of this application. Additional energy may be needed from the electricity production to further increase temperatures. *Medium Term:* With the development of more advanced structural materials, the outlet temperature for LFRs could be pushed to as high as 800 °C.

Limited Cooling Water *Current Status:* Lead cooled reactors have low need for thermal discharge, and the cooling water requirement should be minimal.

Predictable and Infrequent Refuelling Outages *Current Status:* Lead-cooled fast reactors can operate for long periods, up to ten years, without refuelling. Outages are predictable, and the timing can be controlled to some extent. Since refuelling outages are infrequent, their duration is expected to be relatively long.

5.3.4 LFR: Remote Communities

Power output *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Ease of Transport *Current Status:* Although the LFR core itself is quite compact, the large amount of lead shielding required results in a large reactor vessel. Lead is a very dense metal, and transportation of large amounts of coolant and shielding presents a transportation challenge.

Simplicity of Operation *Current Status:* Lead cooled fast reactors are expected to be able to operate for long periods with relatively little operator action. Some proposed concepts only require slow withdrawal of control rods over the life of the fuel, which can be performed by a semi-automated process. *Medium Term*: Further work is required to better understand and further optimize LFR refuelling operations. As refuelling reactors is a complex task, long refuelling frequency is a characteristic that aids in simple operation.

5.4 Molten Salt Reactors

5.4.1 MSR: General Requirements

Availability/technical readiness *Current Status*: Data from R&D activities are required prior to demonstration, as well as R&D activities to enable use of reprocessing and advanced fuel cycles. *Medium Term*: A demonstration in Canada is needed to provide key data and OPEX prior to commercial deployment.

Fuel readiness (globally) *Current Status:* Expertise with salt fuel is rare and available historic data are very limited. Some MSR concepts propose using solid fuels, which are better understood and have more operational and fabrication data available. Depending on the choice, a fuel qualification path must be selected, and the process must be initiated to enable deployment in the medium term. *Medium Term*: Availability of qualified fuel following concerted investment and effort. Fuel is deployed in a demonstration to provide additional data and OPEX. *Medium Term:* Availability of advanced fuel and reprocessing capability at commercial scales.

Fabrication readiness (globally) *To be assessed*.

Supply chain readiness *Current Status:* While some progress has been made in developing structural materials resistant to molten salt corrosion more research must be done to increase resistance at higher temperatures and reduce vulnerability to embrittlement under high neutron flux [50], however some designs are less susceptible. *Medium Term:* Facilities capable of large scale production of reactor-grade Hastelloy-N metal and FLiNaK or FLiBe salt are required. Domestic manufacturing facilities or capabilities for necessary parts and components, and/or import agreements with international partners must be established. Domestic enrichment capability must be developed such that high assay low enriched uranium is available at commercial scales, or reprocessing demonstrated.
Availability of computational tools, for design, verification and analysis *Current Status:* Significant code development activities required. Upon availability of codes, verification and validation activities are required. *Medium Term*: Codes are available, but additional data may be required due to gaps identified during verification and validation. Development and improvement of codes is an ongoing activity. *Long Term*: Development and improvement of codes is an ongoing activity.

Waste management readiness, in the Canadian context *Current Status:* There are large gaps in understanding of the waste management requirements of salt fuels and coolants. *Medium Term:* Management of MSR wastes possible with concerted effort and investment. *Long Term*: Waste management programme for MSR wastes expected to be ready. It should be recognized however that some designs close the fuel cycle and thus simplify the issue related to high level waste.

Technology readiness (in context of deployment in Canada) *Current Status:* Molten salt reactors require further research and development, particularly on reactor materials. *Medium Term:* A demonstration reactor should be built and operated.

R&D pedigree *Current Status:* MSR technology was developed in the 1950s in the USA by Oak Ridge National Lab, culminating in the construction of the MSRE [74]. More recently, China has claimed to have made progress with their liquid fluoride thorium reactor, to be completed development by 2024 [36]. Programs are underway at Canadian Nuclear Laboratories and several universities, such as the University of New Brunswick and the University of Ontario Institute of Technology to develop domestic capability in molten salt reactors.

Domestic capability and expertise *Current Status:* Canadian experience with MSR technology is minimal. Terrestrial Energy's integral MSR has completed pre-licencing Phase 1 Vender Design Review by the CNSC [45] and Moltex Energy SSR-W Phase 1 Vendor Design Review is in progress. *Medium Term:* Funding of research projects and the construction of experimental facilities is required to build domestic expertise with MSR technology.

Existing safeguards approaches[8] *Current Status:* No safeguard model for an MSR currently exists for those designs in which the fuel and coolant are one in the same. However, the problems of safeguarding such a facility, such as the existence of material unaccounted for (MUF) are similar to those which exist for a reprocessing facility, and the recent backfitting of safeguards to the Rokkasho reprocessing facility in Japan indicates that they are not insurmountable. Much of the safeguarding is done by well-tried C/S (containment and surveillance) approaches (e.g. cameras, inspections, portals)

[8] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report

but reverification is almost certainly a more frequent occurrence, necessitating the development of neutron and gamma detectors for determining the fissile content (and burnup) of fissile bearing liquid in pipes, containers etc. Such a requirement requires safeguards to be implemented “by design” – the dimensions of such pipes and containers must be suitable to the instrumentation so that self-shielding of the interior is not a problem. Also, a complicated movement of fuel around the facility, which would exist in the case where it is removed from the reactor, reprocessed, and returned, requires safeguards by design so that the number of required cameras and portals is minimized. Once through designs, without reprocessing, may be simpler to implement in the short term. *Medium Term:* Liquid fuel may require new approaches to safeguards to developed [73]. One such approach is the idea of process monitoring, in which the operation of the reactor is modeled independently against its verified inputs and outputs and secure reactor monitoring information.

Examples of technology gaps:

- While some progress has been made in developing structural materials resistant to molten salt corrosion more research must be done to increase resistance at higher temperatures and reduce vulnerability to embrittlement under high neutron flux [50].
- Pyroprocessing for online reprocessing of liquid fueled MSRs has not been tested at scale and still requires research [50].
- Depending on the selection of salt, methods of tritium control within MSRs must be investigated and methods to prevent its migration within the reactor determined [72]
- Graphite deformation in two fluid breeder MSRs has the potential to cause mixing and requires further research [36].
- Liquid fuel requires new approaches to safeguards that must be developed [73].

5.4.2 MSR: On-Grid Power Generation

<u>Power output</u> *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

<u>Compatibility with closed fuel cycles</u> *Current Status:* There is potential for MSRs on closed fuel cycles, but this requires an R&D demonstration.

5.4.3 MSR: Heavy Industries

<u>Power output (Mining)</u> *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

<u>Power output (Oil & Gas)</u> *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

<u>Temperature</u> *Current Status:* The outlet temperature of a typical MSR concept is between 600 °C and 700 °C, within the range to meet some of the temperature requirements of this application. Additional energy may be needed from the electricity production to further increase temperatures. *Medium Term:* The development of metals that are resistant to corrosion when in contact with higher temperature salts may enable operation of an MSR at higher temperatures.

Limited Cooling Water *Current Status:* Molten salt reactor concepts typically propose a salt as the medium for the secondary heat exchange loop and would therefore not require external cooling water. There are some SMR concepts, however, which do require external cooling water and would therefore not be suited to this application.

Predictable and Infrequent Refuelling Outages *Current Status:* MSR concepts generally require relatively frequent refuelling operations. However, since MSRs are refuelled while operating at power, an outage would not be required, and industrial operations would not be hindered.

5.4.4 MSR: Remote Communities

Power output *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Ease of Transport *Current Status:* Although the presence of graphite moderator increases the physical dimensions of the MSR core, a reactor with the capacity required for remote communities can be transported by truck. Since the core is not sealed, it is not transported in a fuelled state. Furthermore, the lack of fuel in the vessel means that the external shield can be transported separately as well.

Simplicity of Operation *Current Status:* The operation of molten salt reactors is expected to be relatively complex and require specialized expertise. *Medium Term*: Work is required to simplify MSR operation and reduce the level of operator expertise required. Further work is required to better understand and further optimize MSR refuelling operations. As refuelling reactors is a complex task, long refuelling frequency is a characteristic that aids in simple operation.

5.5 High Temperature Gas Cooled Reactors

5.5.1 HTGR: General Requirements

Availability/technical readiness *Current Status:* Partial readiness of technology for demonstration. HTGR projects are currently in progress internationally and research reactors of both varieties have been demonstrated (i.e. prismatic block variety by HTTR in Japan, pebble bed by HTR-10 in China). Integration of HTGRs into advanced power conversion and deployment models needs to be proven. *Medium Term:* Investigation of advanced high burnup fuels to extend operating life of battery style designs in remote applications. *Long Term*:

Fuel readiness (globally) *Current Status:* Marginal. There is currently one commercial source of TRISO fuel in China, but the majority of production capacity is already claimed. American production is possible in the short term, given sufficient demand. There is limited capacity to accommodate grid-scale deployment. *Medium Term:* A source of high assay low enriched uranium in TRISO form is needed to support extended operation of SMRs in remote applications without compromising power production. Ability to create fuel compacts from TRISO particles would bring value added prospects.

Fabrication readiness (globally) Current *Status:* Structurally, the majority of an HTGR core is composed of graphite, which is a well understood material. Fabrication of hexagonal graphite blocks with precise borehole locations on a large scale requires a facility with high quality control and low tolerances. *Long*

Term: Advanced heat exchanger technology must be developed to enable greater heat transfer from primary side to secondary side.

Supply chain readiness *Current Status:* There are multiple graphite mines in Canada, and the industry has recently experienced significant growth. Production is relatively small compared to China, but the existing mining operations should be able to support construction of HTGRs. With the exit of the United States government from the commercial helium industry, supplies may be limited in the future. There are significant exploration efforts underway in Saskatchewan, which may yield a domestic source for HTGR coolant, though demand is expected to be high. *Medium Term:* Domestic manufacturing facilities or capabilities for necessary parts and components, and/or import agreements with international partners must be established. Domestic enrichment capability must be developed such that high assay low enriched uranium is available at commercial scales. *Long Term*: The security of helium supply based on rates of depletion must be understood.

Availability of codes & standards for fabrication *Current Status:* An alternative process under existing regulations must be followed to allow licensing. *Medium Term:* ASME section V must be accepted as the design code of construction for nuclear facilities.

Availability of computational tools, for design, verification and analysis *Current Status:* Multiple analytical tools have been developed and are available. Substantial verification and validation activities are required to support licensing. *Medium Term:* Development of tools needed to support operation of HTGRs by utilities across multiple deployment models.

Waste management readiness, in the Canadian context *Current Status:* Certification of spent fuel containers and establishment of domestic supply.

Technology readiness (in context of deployment in Canada) *Current Status:* Development of integrated power conversion options to allow use of high quality energy for additional application beyond Rankine cycle electric production. *Long Term*: The establishment of high-assay low enriched uranium TRSO fuel compact manufacturing capabilities in Canada.

R&D pedigree *Current Status:* Canada does not have experience with building or operating any HTGRs. However, there is substantial experience with HTGR concepts internationally. Both Japan and China currently have operational HTGRs. The UK, Germany, and the United States have prior operational HTGR experience, but do not currently have operating reactors [48]. Development of domestic expertise in TRISO fuel development is needed to support both utility customers and regulatory capabilities. Knowledge gained through Canada's involvement with the Generation IV VHTR project [65], particularly with high temperature materials, may be useful for development of an HTGR.

Domestic capability and expertise *Current Status:* Canada does not have experience with building or operating any HTGRs. Knowledge gained through Canada's involvement with the Generation IV VHTR project [65], particularly with high temperature materials, may be useful for development of an HTGR.

Existing safeguards approaches[9] *Current Status:* HDR10 (China) and HTTR (Japan) are working examples of research reactors using these technologies (pebble and prismatic rod respectively), so safeguards have been demonstrated with current techniques. Reactors with very many small fuel assemblies offer a particular challenge to safeguards based on C/S (containment and surveillance) and item accountancy. Both the hexagonal prismatic design and the pebble design potentially involve hundreds of thousands of individual fuel assemblies (potentially grouped into graphite blocks in the prismatic design) each with a very small amount of fuel. In this case, individual fuel assembly identification and tracking is may be unworkable and the fuel flow into and out of the reactor will require statistical sampling methods to be adopted. The IAEA has accepted in principle accepted this necessity and there already exists an IAEA agreement on inventory monitoring outside of physical marking/counting of fuel assemblies. .

Examples of technology gaps:

- Air and moisture ingress, or leakage, into the RPV which can cause problems within the reactor ranging from: hydrolysis of fuel particles to variations in coolant pressure. Occurrence of this is determined by the operating conditions: Temperature of components, gas flow rates, pressure within the system. Therefore, systems need to be put in place that prevent any ingress or that can make detections of any ingress [61].
- Management of and preventing the production of graphite dust. This is more of an issue for pebble bed reactors than prismatic where seismic activity can cause shifting in fuel pellets[62].
- Should the TRISO coating become compromised, there are no mechanisms in place to prevent the escape of fission products from the UO_2 particles into the primary circuit [63].
- Graphite shrinkage due to irradiation and thermal expansion over the life of the reactor will result in interstitial gaps between fuel blocks in prismatic HTGRs [64]. This may result in a reduction in capability to effectively cool the fuel.

5.5.2 HTGR: On-Grid Power Generation

Power output Current *Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Compatibility with closed fuel cycles *Current Status:* At the current stage of development, HTGRs are mostly focused on once through cycles. *Medium Term:* Research into extracting and reprocessing fuel kernels from TRISO particles on a large scale is required. *Long Term*: There is potential for closed cycles, particularly with thorium-based fuels, if reprocessing technology is well understood.

5.5.3 HTGR: Heavy Industries

Power output (Mining) *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

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[9] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report

Power output (Oil & Gas) *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Temperature *Current Status:* As their name implies, HTGRs operate at high temperatures, with an outlet temperature up to 1000 °C, and are particularly well suited for high temperature applications. The Japanese HTTR research reactor was developed with the specific purpose of hydrogen generation using its high coolant outlet temperature.

Limited Cooling Water *Current Status:* Though some HTGR concepts do require cooling water, it is possible to operate these reactors with gas coolants on both the primary and secondary loops.

Predictable and Infrequent Refuelling Outages *Current Status:* HTGRs can operate for long periods, up to ten years, without refuelling. Outages are predictable, and the timing can be controlled to some extent. Since refuelling outages are infrequent, their duration is expected to be relatively long.

5.5.4 HTGR: Remote Communities

Power output *Current Status:* Concepts have been proposed in the required power output range. *Medium Term:* Preparation of detailed designs with the required power output.

Ease of Transport *Current Status:* The HTGR core is relatively large and is mostly composed of graphite. Transportation can be somewhat simplified by transportation of prismatic blocks or fuel pebbles separately from the reactor vessel.

Simplicity of Operation *Current Status:* Some HTGR concepts are proposed to be operated partially remotely, with using local operators performing routine control and specialists executing complex procedures remotely. *Medium Term*: Further work is required to better understand and further optimize HTGR refuelling operations. As refuelling reactors is a complex task, long refuelling frequency is a characteristic that aids in simple operation.

5.6 Heat Pipe Reactors

5.6.1 Heat Pipe: General Requirements

Availability/technical readiness *Current Status:* Not available for deployment at present. A very small kilowatt reactor is built and tested (March 2018) by NASA for space applications but scaling it up to the MWe power level will require significant effort. *Medium Term:* Because of its small size (typically smaller than 15 MWe), it is feasible to build and test a full-scale non-nuclear version of the reactor that can accelerate the licencing process significantly. *Long Term*: No significant technical risk is seen for long term deployment. If economic competitiveness is demonstrated, heat pipe reactors have significant potential for multi-unit off-grid installations.

Fuel readiness (globally) *Current Status:* High assay low enriched UO2 can be a low-risk first fuel for heat pipe reactors. High assay low enriched uranium (HA LEU) cannot be currently procured commercially. *Medium Term:* Enriching uranium for HALEU can be readily done, but the political environment has to change to allow the development of such facilities. *Long Term*: Higher density fuels, such as Uranium

Nitride or Uranium Carbide can be good candidates to replace UO2 at lower fuel enrichment levels. More OPEX will be needed for the deployment of these fuels.

Fabrication readiness (globally) *Current* New components and instrumentation not used in current reactors may be used, such as heat pipes, core monoblock and control drums. However, no significant difficulties are anticipated to quickly develop fabrication methods in existing facilities. *Medium Term:* to be commercially viable, hundreds (and thousands) of heat pipe reactors will have to be deployed. This will necessitate special facilities that can handle continuous production lines. Although technically low risk, building such facilities will require significant up-front capital. *Long Term*: Because of small size of these reactors, 3D printing may be a viable option for specialised components that can reduce the fabrication cost (as well as the cost of replacement components). A complete 3D printing of a very small unit can be a game changer.

Supply chain readiness *Current Status:* Enrichment capabilities required for production of HA LEU fuel is not currently available in Canada. New components and instrumentation not used in current reactors may have to be qualified. The operating temperature of heat pipe reactors is greater than 500 °C, which is outside the OPEX of existing nuclear reactors. *Medium Term:* A policy decision is needed to enable enrichment past 5% in Canada. Suppliers are expected to meet the high temperature operational requirements.

Availability of codes & standards for fabrication *Current:* There are no existing codes and standards for heat pipe reactors. *Medium Term:* Because heat pipe reactors are not pressurised, developing design codes and standards would be straightforward. More R&D will likely be required for heat pipe materials and other in-core components that will be subject to high fast neutron flux fields. *Long Term*: codes and standards will be further refined with increasing OPEX.

Availability of computational tools, for design, verification and analysis *Current Status:* Existing computational tools should be sufficient to model heat pipe reactors. AECL performed such calculations in the late 1980s as part of AECL's Nuclear Battery program. *Medium Term:* Existing tools may have to be refined.

Waste management readiness, in the Canadian context *Current Status:* Existing waste management capabilities and practices are expected to be sufficient for heat pipe reactor waste.

Technology readiness (in context of deployment in Canada) *Current Status:* There is very little experience with heat pipe reactors, which consists of the recent Kilopower reactor testing by NASA. *Medium Term:* Individual components in heat pipe reactors have reasonably high technology readiness, but system level technology readiness is not well advanced. However, the technology is suitable for integrated tests that should help move the technology readiness level quickly.

R&D pedigree *Current Status:* In March 2018, NASA operated the first heat pipe reactor: KRUSTY. This is a very small heat-pipe reactor with a power level in the order of a kilowatt. ORNL and INL are developing MW-level heat pipe reactor concepts. In Canada, AECL worked on a heat pipe reactor concept in the 1980s called Nuclear Battery. Although it has been more than 25 years since that work was halted, a significant number of documents exists on reactor physics and heat pipe technology (including building and testing of heat pipes with potassium coolant).

Domestic capability and expertise *Current Status:* Canada (AECL) worked on a heat pipe reactor concept in the 1980s called Nuclear Battery. Although it has been more than 25 years since that work was halted, a significant number of documents exists on reactor physics and heat pipe technology (including building and testing of heat pipes with Potassium coolant). CNL has initiated S&T projects on heat pipe technology.

Existing safeguards approaches[10] *Current Status:* No current heat-pipe reactors exist under safeguards. This type of technology is most suitable for very small reactors which would likely be of a sealed core design. Safeguards would then depend on verification technologies for the presence of fissile material, but principally on traditional containment and surveillance, in this case, seals.

Examples of technology gaps:

- Qualification and understanding degradation mechanisms of components new to nuclear reactors: heat pipes, core monoblock and rotating control drums.
- Transportation of the entire reactor unit is new. The components have to be shown to have arrived at the installation site in acceptable condition.
- Heat pipe reactor mechanical design is quite different than that in existing reactors. Hence, new inspection or monitoring techniques may have to be developed to demonstrate the fitness for service. For example, all heat pipes may have to be monitored as they are part of the safety system.

5.6.2 Heat Pipe: On-Grid Requirements

Power output *Current Status:* Practical power range for heat pipe reactors is <15 MWe. Hence, they are unlikely to be economically feasible for on-grid operations where alternate power sources exist. May be suitable for micro-grids at remote locations where the cost of electricity is high.

Compatibility with closed fuel cycles: *Current Status:* Fast spectrum heat pipe reactors may be suitable for closed fuel cycles, depending on the fuel types used. However, studies would need to be performed on the economics of such operations, given the small volumes of fuel involved and the need for a centralized facility to reprocess and refabricate the fuel.

5.6.3 Heat Pipe: Heavy Industries

Power output (Mining) Heat pipe reactors can be a good option for mines. With multiple unit installations a variety of power outputs can be obtained satisfying that the maintenance requirements of the heat pipe units are minimal.

Power output (Oil & Gas) Power requirement for oil and gas may be typically greater than 250 MW, which may be better served with technologies that scale up to this power level.

[10] Some high-level comments on the current status and potential challenges to safeguarding the six SMR technologies are presented here. A more thorough discussion on safeguards and non-proliferation of SMRs can be found in the RRWG report.

Temperature The operating temperature of heat pipe reactors is determined by the boiling temperature of the heap pipe coolant (typically sodium or potassium), which is in the order of 700C or higher. Hence, the secondary side steam temperature can be selected to be close to 700C or lower.

Limited Cooling Water Safety systems do not rely on water and the ultimate heat sink is ambient air. Power conversion systems can be selected to use air cooling instead of water. Hence, the design can accommodate installations with limited water resources.

Predictable and Infrequent Refuelling Outages Heat pipe reactor concepts were originally developed for remote locations with very high reliability. Past experience with heat pipes show excellent reliability, but very little to no OPEX exists at reactor conditions.

5.6.4 Heat Pipe: Remote Communities

Power output The power range of heat pipe reactors is ideal for remote communities.

Ease of Transport The small power level directly results in a compact reactor design that is easy to transport. If regulatory issues are resolved, transportation by truck, barge and train is feasible.

Simplicity of Operation This would be a function of the reactor design and the features developed by the technology developer. For very small units such as those suitable for remote communities, it makes sense that the reactor is designed to be fully autonomous with remote monitoring by the reactor operator.

5.7 Key Findings and Recommendations

A major finding and recommendation of this chapter is the need for one or more demonstration SMRs. This is discussed more fully in Section 5.7.1.

Finding: There are several types of new reactor designs being proposed. Some utilize well established technology in new and novel ways and therefore do not require substantial future investment in R&D of reactor systems. However, a substantial number of designs utilize unique reactor systems which require additional investment in R&D over the next several years in various aspects of design such as materials research.

Recommendation: A mechanism be put in place to direct funding to these R&D areas for the next 10 years.

Recommendation: As an initial step to aid in future SMR technology selection and deployment:

a) Identify today's state of the art:
    i. Compile a directory of Canadian initiatives supporting SMR development
    ii. Compile a directory of Canadian University programs, facilities and individual expert availability in SMR topics)
    iii. Document and summarize major world initiatives in SMR development
b) Identify Canadian role in international technology development

i. Pan-Canadian assessment to identify Canadian information needs, niche capabilities, and opportunities for co-operation with international organizations

Finding: SMR technologies have key technology gaps that require data and development of operating experience prior to licence applications and commercial deployment. These gaps vary among technologies, but include: fuel, materials, verification and validation of computer modelling codes, operation at higher temperatures than are available in current codes and standards, demonstration of passive or inherent safety functions.

Finding: Develop capabilities, knowledge and expertise in Canada in advanced SMR technologies. Since Canada is new to such technologies, establish international collaborations to fast-track capability development.

Finding: Modelling and simulation toolsets, along with associated nuclear data and code qualification will be needed to deploy new nuclear technologies in Canada. Domestic capability to use these toolsets will also need to be developed.

Recommendation: the SMR development and capability-building program include scope on modelling and simulation toolset development, qualification and training.

Finding: Except for LWRs, most SMR technology types lack significant available operating experience. A demonstration SMR would enable generation of some operating experience prior to commercial deployment.

Finding: Many of the SMR technologies under consideration require fuels with less (and in some cases no) operating experience compared to current generation reactors, and with additional innovative features not yet fully tested. Fuel qualification, and in some cases completion of fuel development and testing, will be required in the lead up to SMR deployment.

Finding: A fuel qualification program is required. This could be done through an incremental fuel qualification program in a demonstration reactor.

Finding: Many, if not most, of the SMR technologies using high assay low enriched uranium (HA LEU) fuel. There is currently no available source of HA for the deployment of these technologies in Canada.

Recommendation: Studies be undertaken to identify and subsequently pursue sources of HA LEU.

Recommendation: Canadian efforts in pursuit of HA LEU be coordinated with similar efforts in the United States.

Recommendation: The federal government should provide policy direction regarding reprocessing of spent fuel/enrichment.

Recommendation: Over the longer-term, Canada should review and consider developing domestic enrichment capabilities, including for HA LEU.

Finding: many of the SMR technologies use fuel types other than the uranium dioxide fuel form in use in nuclear power reactors in Canada today.

Recommendation: Canada build knowledge and expertise in non-uranium dioxide fuel forms, such as metallic, TRISO, and nitride fuels. This should include fabrication, performance, and post-irradiation examination of the fuels. This could be considered as a area of research and capability building under a coordinated capacity building and development program, see Section 6.2.

Finding: LWRs, SFRs, LFRs, MSRs and HTGRs could all be suitable for on-grid applications. However, of these, LWRs are the only technology type that are ready to deploy today. With some concerted effort and investment, it may be possible to speed the deployment of the other SMR technologies.

Finding: Deployment of any on-grid SMR technology would result in benefits to Canada in terms of a supply of clean energy. Technologies with lower technology readiness offer greater potential benefits to Canada. Benefits include: greater role for the supply chain, potential for increase of RD&I in Canada, potential to develop and deploy other fuel cycle infrastructure, such as fuel manufacture and back-end recycling technologies. However, the advantages to the Canadian supply chain need to be balanced against lower readiness technologies being longer to market, and therefore carrying a greater associated risk of missing a global market.

Recommendation: For mid-to-large size SMRs, focus effort on those that have the potential for growth in RD&I in Canada and a role for the Canadian supply chain. Provide programs to enable the faster development of these lower-TRL technologies.

Finding: Investment and concerted, focused effort is required to accelerate the development of the lower readiness technologies to enable deployment in the early 2030 timeframe that is required by the on-grid market.

Recommendation: Provide ongoing Canadian support for evaluating suitability of analysis/modeling tools, and for troubleshooting issues at plants throughout their operating lives

Finding: As many of these SMR technologies have operated at some scale in the world previously, there is some basis for safeguards for most technologies. However, the applicability of current typical safeguards techniques varies across the technologies, and some new technologies or approaches may be needed, especially for liquid fuelled reactors.

Recommendation: Studies be undertaken regarding safeguards of new SMR technologies, in cooperation with national and international regulatory bodies, according to current practice.

Recommendation: New safeguard technologies, for example, detection in new coolants, be undertaken as part of a coordinated capacity building and development program, see Section 6.2.

5.7.1 Demonstration Initiatives

Generally speaking, en route to full-scale implementation, evolution of *any* complex technology involves the building and operation of a demonstration unit in a relevant environment. This classic progression certainly has merit when it comes to new nuclear technologies, and indeed has been applied in Canada, where the Nuclear Power Demonstration (NPD) and Douglas Point reactors were constructed and operated as pre-cursors to the existing fleet of CANDU reactors.

When it comes to SMRs, the relative newness and/or unprovenness of most of the designs indicates that a demonstration unit would also be beneficial before the large-scale introduction of a fleet of reactors could realistically be contemplated. This is certainly true for designs that are lower on the technology readiness level. Technologies that are considered more “market-ready” today (e.g. those based on conventional LWRs) or have operated in other countries (e.g. high temperature gas, sodium fast reactors) may have sufficient operating experience that a lead project could proceed in Canada. However, even in these cases, a demo unit or facility could be warranted to, if nothing else, illustrate the effectiveness of a given project-delivery model – a stated expectation by some potential end users and/or investors who do not want a first-of-a-kind nuclear project.

Beyond the obvious objectives of proving a given technology and collecting adequate operating experience, to obtain maximum benefit for Canada and achieve so-called “first mover advantage”, the following require consideration when contemplating a demo unit or first-of-a-kind commercial plant:

1. **The Canadian nuclear industry is poised to address the risks associated with new technologies and project delivery that could be a barrier to SMR implementation and private-sector investment**

   The large nuclear projects worldwide that are currently delayed or stalled (e.g. Flamanville in France, Okiluoto in Finland, Vogtle in South Carolina) can broadly be described as failures in project management, and not problems with the technology (LWRs have operated efficiently and safely for decades). Issues with these large projects have included an unprepared supply chain; poorly estimated FOAK engineering and construction costs; and, poor recognition of licensing requirements. These same challenges could certainly exist for SMRs. A demo unit or first-of-a-kind commercial SMR in Canada would address these potential barriers to investment head on by adequately preparing the Canadian supply chain for SMR delivery models prior to large-scale introduction; enabling vendors to properly accounting for FOAK uncertainties in engineering and construction; and, preparing potential SMR operators to engage the CNSC early and throughout the design/construction process (e.g. vendor design reviews).

   The Canadian government can enable SMR development and deployment through the support of an SMR demonstration project. This could be done in partnership with the private sector.

2. **Established nuclear sites in Canada are willing hosts for an SMR demonstration plant,**

   One of the main challenges identified in the report on the “Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario” **Error! Reference source not found.**] was the scarcity of cost-effective technology-demonstration sites. Within Canada, both the Canadian Nuclear Laboratories and New Brunswick Power (NBP) have signalled their interest in hosting an SMR (or SMRs). Both locations have associated infrastructure and nuclear programs, which are essential components of siting and licensing a nuclear project. Moreover, both locations have communities that, on average, are accepting of nuclear power, which may be a differentiator for first plants given the importance of public consultation in Canadian regulatory processes. Importantly, the CNL and NBP stated aspirations are complementary, not competing. CNL’s stated goal is to host demonstration unit(s) in the immediate to short term; whereas NBP are more interested in a first-of-a-kind commercial on-grid plant sometime in the 2030 timeframe. CNL, as the Canada’s national nuclear laboratory, is also capable of performing any enabling R&D that NBP that might be required for the technologies that NBP is most interested in pursuing, namely Sodium fast and molten salt reactors.

3. **A Canadian SMR project would enable proof of cross-cutting technologies**

   The demonstration projects can be structured to enable proof-testing and demonstration of individual cross-cutting technologies and organizational strategies. Some examples include: remote operation instrumentation and control (I&C) features; monitoring to establish compact exclusion zones; safeguards and security technologies; and, waste handling for innovative fuels and coolants. A demo project could also be structured to illustrate the role of SMRs in an integrated grid with renewables, where the efficacy and identified benefits of load following could be shown.

Finding: One or more demonstration reactors are required to provide data to fill key technology gaps, such as: fuel, materials, verification and validation of computer modelling codes, higher temperatures than are available in current codes and standards, demonstration of passive or inherent safety functions.

Recommendation: One or more demonstration reactors be constructed at a site, or sites, that is suitable for performing research and development activities associated with the demonstration, such as at Canadian Nuclear Laboratories, or another licensed site.

6. Roles, Responsibilities and Gaps for SMR Technology Development and Deployment

Addressing Canada's clean energy needs will present some unique roles and requirements for SMRs. So, to achieve successful SMR deployment, a pan-Canadian program to address Canada-specific gaps is necessary, as a complement to individual development programs by vendors and other SMR stakeholder organizations. In addition, Canadian organizations have the opportunity to play significant roles in development for specific designs and technologies, as summarized in section 6 above. Gaps to be addressed to achieve project or fleet readiness for SMRs include:

- Technology gaps specific to individual designs
- Technology gaps common to designs within a technology type
- Technology gaps in cross-cutting technologies or common underlying technologies
- Technology gaps relating to the specific applications for SMRs in Canada
- Technology gaps in the organizational and policy frameworks and infrastructure to support SMR deployment
- Potential opportunities (e.g. ability to recycle existing spent fuel) that require further research to bring to fruition

Technology development from any of the competing options would be helped by **enabling programs** to build capacity in people, knowledge and capability. This would include professional expertise, facilities, tools, regulatory and other frameworks, and linkages with programs overseas. This should also be aimed at providing outreach to communicate the technology to stakeholders and listen to their feedback. Overall, enabling programs would develop a foundational basis to support other actions addressing specific gaps:

- Generic knowledge basis
- People skills, experience
- Facilities and tools to provide independent confirmation/review of vendor claims
- Research into common challenges to develop Canadian approach (e.g. challenges due to extreme climate, remote locations etc.)
- Basis for technology outreach to stakeholders

The SMR Roadmap can identify pathways that will benefit Canada, the provinces and territories, and Canadian organizations, to address significant gaps in developing the SMR role. This will need to be done using careful prioritization, depending on the fit of the development to national benefits; on work planned and underway by the technology suppliers themselves, by other stakeholders in Canada; and also work under way and planned in other countries that are contributors to individual or common SMR development.

Filling the readiness gaps also helps stakeholders in decision-making. For governments, owner-operators, end-users: the choices of which technology to adopt; timing; and definition of the technology application; will all be based on accessing the fullest level of knowledge at the point when decisions are required.

The SMR Roadmap is based on a vision of multiple SMRs employed in a range of applications, to provide safe, reliable, environmentally-friendly power to meet vital needs for Canadians. To progress to the delivery of this vision, several elements need to be in place. From the Technology viewpoint, key elements are summarized here. Many activities are already in progress towards putting these elements in place. The TWG report develops recommendations to complete and add to these activities so that a comprehensive foundation exists to achieve the roadmap vision. The needs and progress to date vary with the three major SMR applications, and these are noted separately below.

- Institutional frameworks
- Cohesive development programs
- Demonstration initiatives
- Capacity-building
- Confidence in rigorous, timely licensing via regulatory review
- Pan-Canadian co-operation that enables fleet approach
- First-mover leadership
- Supply-chain participation
- Effective outreach
- Financing confidence (see EFWG Report)
- Waste management and disposal

The aspects related to licensing, Indigenous and public engagement, economics and financing, and waste management are not further discussed here, as they are addressed by the other Working Groups.

6.1 Institutional frameworks

Well-established for grid-scale SMR deployment; experience in using the frameworks, and adapting them as needed, will be more necessary for industrial and remote community applications.

- Stable policy regime: Building of a consensus among levels of government
- Regulatory framework: CNSC framework (already in place) has been applied in practice and added to as needed. International cooperation on regulatory requirements is further strengthened
- Experience with Impact Assessment. The new Impact Assessment process is well-understood and can be applied to development of multiple replication units and projects of smaller scale

- Energy pricing regime. A predictable regime is in place that enables consistency across Canada, and accounts for the benefits of GHG-free generation and generation reliability and flexibility

6.2 Integrated Capability Building and Development Program

One of the first steps towards a significant SMR deployment, is the buildup of expertise and knowledge among the Canadian nuclear community. This will be required in all respects but particularly in the engineering and related skills required to design, license, construct and operate innovative designs. Building up expertise that can be adapted to different technologies would apply to all SMR applications: on-grid, industrial applications and remote communities. The build-up of capabilities (e.g. human resources, facilities and equipment, and organizational competencies) would be a contributor to the specific development activities needed to address technology gaps.

For certain technologies (such as grid-scale LWR designs), major development activities are largely complete, or based on strong existing technology base. For smaller-scale and innovative SMR designs, the steps to complete the capability building and development and verification of the designs, and to carry out licensing assessments, will require significant activities.

- Foundational expertise: Add university engineering courses addressing SMR science and technology; expand SMR-specific university secondments to R&D, design and operating organizations; launch university R&D projects and research chair programs that address SMR topics; build cooperative links between Canadian universities and international organizations (e.g. OECD-NEA, IAEA) and university networks to engage with other SMR initiatives.
- Active expertise: SMR nuclear stakeholders begin assigning staff to SMR initiatives with a training component, to build up in-house expertise – designers; R&D institutes; operators; regulator. Stakeholders work with university sector to define and implement cohesive capacity-building approach.

A well-coordinated and integrated development program is needed to perform foundational research in support of capability development and deployment of SMRs in new applications and regions. The coordinated and integrated approach will allow for all levels of development to drive towards the goal of a well-establish SMR market in Canada, Figure 9. Basic R&D and cross-cutting R&D activities will support SMR demonstration project(s), which in turn lead to early commercialization of a few SMR technologies, leading to a successful SMR commercialization. This platform could take the form of a Pan-Canadian Centre of Excellence Network.

Figure 9 Coordinated and integrated technology development and capability building program

This approach would:

- Allow capability and expertise to be developed early in the regions of intended deployment
- Create strong links with the university sector will result in expertise available when needed
- Engage and provide benefits to the whole range of SMR stakeholders including: universities, national lab, federal government, interested provincial and territorial government, as well as industry and utilities.
- Develop strong links with the application industries (mining, oil and gas) to improve the potential for update by those industries
- Include governance and oversight by industry and utility partners to ensure that the solution and technologies generated through the R&D projects a greater chance of uptake deployment in the field
- Include industrial and utilities as funding partners, therefore requiring less investment by government, and enabling greater leverage of any investments by governments, providing better value
- Be pan-Canadian, with focus centres across Canada, centred in the regions where SMRs would be deployed for the three applications. This approach will benefit many regions across Canada, maritime provinces, central Canada, the prairie provinces, and the North.
- Pursue not just the traditional R&D, also place foci on engagement and training. This will enable deployment of the developed technologies, as the communities and stakeholders will be understood, and enabled/engaged throughout the development of the technology, not just at the end when deployment is sought. This area of the development program would be developed in alignment with the findings and recommendations from the Indigenous and Public Engagement Working Group.

A preliminary concept for this integrated development program is to pursue five focus areas, to be phased in over time as this program develops, supported by a foundational knowledge and capacity building area.

1. Clean Energy Systems

- How SMRs integrate with other clean energy technologies, such as wind, solar, and energy storage
- Technology and economic aspects
- Includes the demonstration of hybrid systems, e.g. wind/solar/energy storage in conjunction with one or more demonstration SMRs
- Possible headquarter at CNL

2. Mining Applications
    - Early focus on the business cases for SMRs at various mining situations.
    - Other enablers of SMR deployment at mines
    - Build relationships with mining universities and mining companies
    - Possibly headquarter in Sudbury
3. Oil & Gas Sector Applications
    - Focus on SMR applications to the oil sands, enabling technologies including hydrogen upgrading, extraction, business cases and technology selection
    - Perform studies with universities with oil & gas-related programs, explore possibility to leverage R&D programs of oil and gas companies
    - Possible headquarter in Alberta
4. Remote Communities
    - Provide neutral information on nuclear technologies
    - Start building some nuclear-related knowledge in the North. This does not have to be SMR-related, any projects that have a nuclear science aspect could be considered, as a way to build some nuclear knowledge and capabilities.
    - Technologies to enable deployment of SMRs, but that would also potentially enable other infrastructure. E.g. remote monitoring/sensing, construction in permafrost.
    - Possible partners: Aurora Research Institute (Inuvik, NWT), Nunavut Research Institute (Iqaluit, NU), Yukon Research Institute (Whitehorse, YK), the Northern Engineering Centre at Ecole Polytechique; and an organization specializing in communication/education that can help develop communications materials.
5. Advanced Technologies
    - Longer-term R&D focus, including concept development and proof-of-concept testing towards closing the fuel cycle
    - Possible joint headquarters in New Brunswick and Chalk River
6. Foundational Knowledge and Capacity-Building
    - University network collaboration with research institutes and industry to develop foundational knowledge and explore early-stage (low-TRL) initiatives, and leverage activities via coordinated education and training, to develop human expertise, facilities and tools

The work conducted as part of this integrated development program would fit under three foundational themes:

1. SMR Science and Technology

    a. Include "hard science" work on SMR technologies – materials, coolants, fuels, etc.
    b. R&D and engineering
2. Public and Indigenous Engagement
3. Human Resource Development

6.2.1 Manufacturing Technology Development and Readiness

The application of efficient manufacturing technology is a key to the economic competitiveness for SMRs. For any SMR design, the ability to manufacture and assemble the reactor in a factory setting is an important advantage, due to the much greater efficiencies enabled by factory facilities. However, gaps remain to be addressed before this can be confidently achieved.

- Factory assembly of a full reactor system has not been the norm for civil nuclear projects. Most or all assembly functions have been carried out on-site – a very expensive approach given the logistical difficulties and high labour costs involved. Most recently, designs such as the AP-1000 have focussed on a greater degree of factory module assembly. However, the results have not yet established the successful reductions in time and cost that are ultimately achievable. Because the benefits of factory assembly are so crucial for SMRs, it is necessary for the designers, construction organizations and manufacturing leaders to work together to develop and demonstrate how factory assembly can be used to reduce schedule and cost.
- SMRs use innovation in both materials (e.g. new alloys needed for alternative coolant conditions) and in configurations such as new pressure boundary definitions. This means that innovative techniques for manufacturing will be needed, e.g. in welding techniques, in component fabrication.
- As new and emerging designs, SMRs are best placed to benefit by applying innovations in overall manufacturing technology. New approaches to structural materials, new applications to deal with the more extreme conditions in Canada's northern communities, approaches to benefit from a fleet model by replication manufacturing, all have potential benefits, but will need development in the manufacturing sector.
- For one particular aspect – fuel supply – manufacturing development may be particularly important. Some SMR designs require innovative fuel approaches, and for fleet deployment, a highly reliable fuel route is essential. Fuel manufacturing development and demonstration will be essential to establishing commercial deployment.
- Development of manufacturing technology represents an opportunity for Canadian industry. While most SMR designs are originating outside Canada, for all but the most thoroughly-established designs, the supply chain is not fully established. For deployment in Canada, there is a strong logistical advantage in delivering equipment or modules from Canadian facilities, so there is benefit in incentivizing Canadian organizations to address manufacturing technology development challenges.

6.3 First-Mover Leadership

In addition to the development of a Canadian industry Canada has an international reputation that could help make it a preferred supplier in many jurisdictions. The opportunity to establish an enterprise with significant development and fabrication capability deployed in Canada is time sensitive as others are looking to the same opportunity. We have significant advantages if we are willing to move forward decisively. Deployment of first of a kind technology and deployment of the early units when several may be required before the fleet can truly support the overheads and allow the enterprise to be economically viable is a significant hurdle to be overcome. To encourage the first movers, some form of risk sharing is essential. Government will need to play a role in the more advanced technologies by enabling design, engineering and licensing completion through R&D support programs. Financial support is covered by EFWG report. Again, less first-mover technology leadership for on-grid established technologies such as integral SMRs will be needed.

6.4 Supply Chain Participation

At one extreme, a scenario where all project equipment is procured from offshore supply-chain is possible. However, this severely limits the associated benefits to Canada, and limits the ability to deliver a fleet solution. Encouraging domestic supply chain readiness and fit-for-role will enable economic and job benefits. This will require capability-building (staff knowledge, expertise), manufacturing knowledge and tooling investments.

For innovative designs, where an experienced supply-chain does not yet exist, the investments required would be greater, but the potential for business, including export business, will be correspondingly greater. This means that supply-chain capacity-building will need to be closely coupled with the process of technology selection.

6.5 National and International Activities that can be Leveraged

For the leading individual SMR technologies (see Section 4.2) more work has been done outside Canada so far, than within Canada. This means:

- The Canadian industry needs to engage with independent institutions overseas that are active in the SMR field, to benefit from their insights and access information.
- International engagement would enable expansion of common work programs that can benefit many of the gap areas, for example: capacity-building, evaluation tools and models, regulatory reviews, and waste management.
- It is viewed as beneficial for Canada to build these collaborations, rather than delivering all the required enabling steps alone.

There are many programs underway around the world that are developing cross-cutting technologies that have potential applications for SMRs. A few examples of international programs and possible collaboration opportunities are:

- The OECD (Organization for Economic Cooperation and Development) Nuclear Energy Agency (NEA) has initiated the Nuclear Education, Skills and Technology (NEST) program as a model for greater student/researcher cross-cutting experience.
- The UK has a strong industry government program supporting SMR development, as part of the national nuclear “Sector Deal”. This includes cross-cutting technology support through the National Nuclear Laboratory in conjunction with universities and research institutes such as the Advanced Nuclear Manufacturing Research Centre. Canada has an opportunity to develop liaison at different levels; government-to-government; university network-to-network; NNL—to-CNL; regulator-to-regulator. Some of this is already happening, but an umbrella agreement would benefit all.
- USA Department of Energy (DOE) programs: Taking leadership in the development of SMR, the US DOE announced up to $20 million of funding for projects to identify and develop innovative technologies for lower cost and safer advanced nuclear reactors, under the Advanced Research Projects Agency-Energy (ARPA-E) initiative. Further, The US DOE announced in 2015 the Gateway for Accelerated Innovation in Nuclear (GAIN) program, to make DOE’s facilities, scientists, laboratories, and knowledge more accessible to entrepreneurs and scientists working on advanced nuclear technologies. The Nuclear Energy Enabling Technologies (NEET) program, which operates under GAIN, sponsors R&D and strategic infrastructure investments to develop crosscutting nuclear technologies. Canada can encourage liaison with US programs and turn specific initiatives into communal programs. The Canada-US Implementing Arrangement (IA) – provides an opportunity for Canadian laboratories to collaborate with US DOE laboratories in areas of mutual interest including SMRs which exists under the current Canada-US IA Action Plan.
- The IAEA (International Atomic Energy Agency) has an active SMR information exchange program, covering comprehensive status reporting and regular conferences, workshops and fora. The IAEA also promotes common standards and infrastructure models, which provide enabling frameworks for advanced technologies such as SMR’s. Since 2005, IAEA has prepared a number of state-of-the-art reports with member states in connection with the cross-cutting enabling technologies for SMRs, and regularly convenes forums for member country institutions active in the SMR field. Canada can use IAEA activities to build relationships with other countries’ activities (e.g. UNENE is exploring becoming an information clearing house for university R&D on SMRs).
- The COG SMR Technology Forum: The CANDU Owners Group established the SMR Technology Forum (SMRTF) in 2017 with the mandate to identify key issues and to promote harmonized policies. This may include developing technical positions on the regulatory framework, fuel cycle, siting and supply chain for deployment of SMRs for both on and off-grid applications. The SMRTF aims to provide value to the development of SMRs in Canada, through a harmonized approach, both domestically and internationally, to SMR deployment.

6.5.1 Innovation Superclusters Initiative

Recently, the federal government awarded $950 million over five years to five innovation 'superclusters', which are matched by private sector's contributions. Two of these superclusters are aimed at developments that will support SMRs among other innovations.

Based in Ontario, the Advanced Manufacturing Supercluster will build up next-generation manufacturing capabilities, incorporating technologies like advanced robotics and 3D printing. By focusing on training and technology adoption, this supercluster will help make the words "Made in Canada" synonymous with "innovative" and "value added."

Based in Quebec, the AI-Powered Supply Chains Supercluster (SCALE.AI) will bring the retail, manufacturing, transportation, infrastructure, and information and communications technology sectors together to build intelligent supply chains through artificial intelligence and robotics. This supercluster will help Canadian small and medium-sized businesses scale up and help ensure Canada is a globally competitive export leader.

Strategically, the Advanced Manufacturing Supercluster and AI-Powered Supply Chains Supercluster represent huge Canadian strength in cross-cutting enabling technologies in Advanced Manufacturing and Artificial Intelligence, which are critical for developing SMR cross-cutting Enabling Technologies.

These two supercluster initiatives may provide an opportunity to develop important capacities and capabilities. A coordinated and integrated SMR development and capability program (section 6.2) should consider participation in or collaboration with these superclusters.

6.5.2 Generation IV International Forum

Of particular interest and opportunity is the Generation IV International Forum (GIF). The GIF is a multinational effort, in which Canada participates, to undertake collaboratively research to develop the next generation ("Generation IV") of nuclear energy systems. The six nuclear energy systems being pursued by GIF are: Gas-cooled Fast Reactor (GFR), Supercritical Water-cooled Reactor (SCWR), Very High Temperature Reactor (VHTR), Lead-cooled Fast Reactor (LFR) and Molten Salt Reactor (MSR). The six reactor systems feature increased safety, improved economics for electricity production and new products such as hydrogen for transportation applications, reduced nuclear wastes for disposal, and increased proliferation resistance.

To support and contribute to this aim, the GIF has 3 main working groups: Economics Modeling Working Group (EMWG), Proliferation Resistance & Physical Protection Working Group (PRPPWG), and Risk & Safety Working Group.

The EMWG is working towards the creation of an Integrated Nuclear Energy Economics Model to provide a robust tool for economic optimization during the viability and performance phases of the Generation IV project. The innovative nuclear systems considered within Generation IV require new tools for their economic assessment. The current economic models were not designed to compare alternative nuclear technologies or systems but rather to compare nuclear energy with fossil alternatives. An Integrated Nuclear Energy Model is central to credible economic evaluation of Generation IV systems. It is intended to be a living document, updated successively to: further refine the different cost models; broaden the coverage to energy products other than electricity, including hydrogen; and include an analysis of the economic impacts of plant size and modularity.

The goal of the Proliferation Resistance and Physical Protection Working group is to ensure that Generation IV systems increase the assurance that they are very unattractive, provide the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

A principal focus of the Generation IV Risk and Safety Working Group is the development and demonstration of an integrated methodology to evaluate and document the safety of Generation IV nuclear systems. Generation IV nuclear energy systems will aim to excel in safety and reliability, to have a low likelihood and degree of reactor core damage, and to eliminate the need for offsite emergency response. Since 2008, this working group has been carrying out risk assessments and safety assessments of the various Generation IV systems and concepts, as well as studying the methodology itself.

Canada currently participates in the SCWR systems, three working groups, and the hydrogen production project. There is great opportunity to revisit and re-align Canada's participation to better align Canada's Canadian industry needs based upon SMR technologies that best align to Canadian conditions.

6.6 Roles and Responsibilities

SMR development has many characteristics of the start-up of a new industry. Given the potential value to Canada, a government role in addressing gaps, alongside the roles of other stakeholders, is necessary and appropriate, to bring the SMR enterprise to the commercial stage. Each participant in the SMR enterprise has a valued and distinct role. Because the campaign to successful SMR deployment is a wide-ranging effort which requires all the roles to be acted on, it is essential for the stakeholders to work as a well-coordinated partnership, in particular between governments and other stakeholders. The technology elements of the Roadmap identify roles and activities within this partnership context. Many stakeholders are already taking individual actions that will be positive elements of this collaborative initiative:

Vendors/Technology Developers: Ultimately, vendors are responsible for presenting evidence their designs are complete, fully supported and with sufficient proven-ness to proceed to project. Vendors are responsible for preparing the safety case delivered by the facility licensee to the regulator, for demonstrating design reliability and life assurance, and for taking on contractual responsibilities. The vendors will work with regulators to understand the requirements for the safety case; with research institutes and academia to complete the assembly of supporting information. Vendors also depend on the common infrastructure of the nuclear community as a basis for knowledge, resources, and organizational framework.

Owner-operators: The owner-operator role is to satisfy themselves of the SMR design readiness to proceed to contract. They are responsible for defining the overall project and plant requirements to meet end-user needs, and for establishing plant economic viability. The owner-operator will act as the intelligent customer and will build up the internal expertise to provide design, licensing and project oversight as the ultimate licensee to the regulator.

End-users: End users define the ultimate application and establish the interfaces between the SMR project and surrounding environment. For example, end users will identify the range of energy applications, such as industrial or district heating in addition to electricity supply. End users also participate in policy formation, in defining the broader role that an SMR project or program plays in both industrial development and environmental protection. This means that end-users also need to become educated consumers, and able to evaluate and oversee projects.

Supply chain: Supply-chain readiness will be an essential component in build-project success. Supply chain companies will invest time and resources in familiarizing themselves with SMR technologies and qualifying themselves as suppliers of innovative components and materials. Canadian supply chain organizations may also need to identify their roles within and international supply environment, and where appropriate, build collaborations and develop technologies in international partnerships.

Academia: Academia provide an essential education and training role. They would ensure that students and researchers can address SMR technology topics to develop relevant skills. In addition, universities can carry out early-stage research to address knowledge gaps in an economical and nimble way.

Research Institutions: Research institutions need to be able to anticipate the needs for research, development and demonstration activities, and ensure that facilities, tools and people are ready for the needed development work. National institutions, such as Canadian Nuclear Laboratories, with unique facilities and capabilities will be asked to play leadership roles in technology development.

Regulators: With the exception of the CNSC, who already has established frameworks, the other government arms need to establish frameworks and procedures to evaluate and approve projects, both at the research, the demonstration and the commercial stage. This requires the ability to carry out independent assessments, again needing a build-up of qualified specialists, and access to independent simulation and evaluation tools.

Governments: Governments play an enabling role, in several ways:

- Providing policy direction and public support. Industry is very alert to government direction and priorities. Signals of government support provide clarity to enable industry to move forward with confidence
- Enabling frameworks: Governments ensure that appropriate regulations and organizational capabilities are in place to allow SMR development and deployment
- Co-ordination between federal, provincial and territorial governments: given the distribution of government responsibilities, governments work together to ensure a consistent position to the SMR community
- International co-operation: SMR development and commercialization activities are underway in a number of leading nuclear countries; government-to-government co-operation will ensure the effective flow of information, and co-ordination between different national SMR initiatives
- Pre-commercial support: Application of government resources to the early-stage and demo-stage R&D will be crucial in creating project-ready SMR applications that meet Canadian needs in a commercially viable way.

6.7 Findings and Recommendations

Finding: To succeed, all sectors of the nuclear community will have a role to play, from designer/engineering to operators, regulators, researchers and academia, complemented by government, in a partnership approach.

Recommendation: Establish a well-coordinated and integrated development program, such as an SMR Centres of Excellence Network, which brings together industry, government support, R&D institutions and academia to carry out both focussed development and capacity-building. A potential concept for this development program is further discussed in Section 7.2, including focus areas and foundational themes.

Recommendation: Establish capacity building infrastructure (e.g. through industry-university centres of excellence) including university courses, student assignments to R&D centres, participation by university and industry personnel in R&D programs

FINDING: Development of manufacturing technology represents an opportunity for Canadian industry. For deployment in Canada, there is a strong logistical advantage in delivering equipment or modules from Canadian facilities, so there is benefit in incentivizing Canadian organizations to address manufacturing technology development challenges.

FINDING: While most SMR designs are originating outside Canada, for all but the most thoroughly-established designs, the supply chain is not fully established. Especially for innovative designs, where an experienced supply-chain does not yet exist, the investments required would be greater, but the potential for business, including export business, will be correspondingly greater.

Recommendation: As part of the SMR development activity, Canadian supply organizations to be incentivized to invest in design development support, and to establish supply chain readiness for deployment.

Recommendation: Supply-chain capacity-building will need to be closely coupled with the process of technology selection.

Recommendation: Undertake a supply chain initiative to identify competitive roles in manufacturing and construction of leading SMR technologies and designs.

Recommendation: the federal government act as a first mover, deploying the FOAK SMR to federal installations, such as remote military bases. This would provide a clean, reliable supply of energy at those locations, while demonstrating many aspects of deploying these technologies, such as the deployment model, logistics, licensing, operation in the field, waste management, prompt decommissioning, etc.

Finding: Canada is in a unique position with regard to SMR technology. Although the majority of contending designs are developed outside Canada, and much baseline technology development has been and is being carried on overseas, Canada is in the forefront of considerations for SMR use. The first-mover opportunity for SMR technology demonstration/development window for Canada’s active participation is now. Once Canada’s leadership in SMRs is demonstrated, other non-nuclear energy countries seeking potential SMR deployment will come to Canada for advice, export, and/or technology collaborations.

Finding: Canada has certain specific advantages and opportunities that can be pursued to provide enabling steps towards the evaluation and introduction of SMR technologies:

- Demand: Because of our wide-spread geography, both smaller communities and many resource industries, can uniquely benefit from suitably-sized SMR applications with potential fleet scale.
- Comprehensive nuclear capability: Canada's nuclear community has expertise in all aspects of nuclear technology;
- The current initiatives at CNL and in New Brunswick to assess potential SMR designs for demonstration projects is an important enabling step.

7. Findings

This section compiles the findings of the TWG that are identified elsewhere in this document and is divided into two parts. The first is key findings, which represent the most significant major findings that the TWG has raised to the SMR Roadmap Steering Committee and the final Roadmap report. Also included are secondary findings, which the TWG feels are important and should be take into consideration in the development of an SMR industry in Canada.

7.1 Key Findings

The key findings of the TWG are:

This is real and this is now: SMRs are under development today around the world. Development has progressed to the point where these technologies are near to deployment. Many countries have recognized the potential and are making significant investments in SMRs, including the UK, the US, China and Russia. Canada has many differentiating capabilities, such as robust flexible regulatory framework, world-class laboratories, and multiple market applications. But the window of opportunity to capitalize on this emergent technology is dwindling.

Applicable technologies: There are SMR technologies under development that have designs that meet the requirements of each of the three applications. Also, there are real projects ready to move forward today in Canada, with applications across multiple markets, as evidenced by the response to CNL's recent Invitation to site SMR Demonstration Projects. Some SMR technologies that may be suitable for multiple applications, but more than one technology may be required to enable deployment to all three applications. Selecting a technology for multiple applications may lead to economies of fleet in production and operations.

R&D and capability gaps: Canada's national nuclear laboratory and nuclear university capabilities are world class, we have the experience and facilities to do be a world leader in SMR technologies. However, there are new areas of activity that will be needed to pursue these new technologies. These areas are within reach. Most of the SMR designs utilize unique reactor systems which require additional investment in R&D over the next several years to address key technology gaps, generate data, build capacity and develop operating experience prior to licence applications and commercial deployment. An ongoing domestic R&D program will also be needed to support emergent issues during the operation of the SMR fleet. Two key things are needed to address these gaps:

- One or more demonstration reactors are required to provide data to fill key technology gaps and generate operating experience for designs proposing new reactor systems.
- A well-integrated and coordinated capability-building and R&D program, such as a Centre of Excellence Network, would best enable a structured R&D program to achieve the ultimate goal of wide deployment of SMRs in Canada.

Technology benefits: Not all of the technologies under development today offer the same possibilities for benefits to Canada. The TWG surveyed over 100 SMR technologies and found that some lower readiness technologies or those with supply/manufacture chains that are not yet fully set may offer greater potential benefits to Canada through first-mover leadership. However, the advantages of having a completely Canadian supply chain needs to be balanced against lower readiness technologies being longer to market, and therefore carrying a greater associated risk of missing a global market. Benefits beyond simply a clean, reliable energy supply, such as: development of supply chain, economic benefits and jobs, competitiveness, and driving a research, development and innovation economy can be significant and therefore should be considered. SMRs will require ongoing support will be needed throughout the lifecycle and establishing these capabilities in Canada during the development phase will allow Canada to maintain its status as a Tier One nuclear nation, and not have to procure these services off-shore. An additional potential benefit that should be explored further is that many advanced SMR technologies enable alternative pathways for spent fuel management other than long-term disposal in a deep geological repository. These technologies may enable closing the fuel cycle, and potentially to reduce current waste inventories.

Fleet approach: The development of a common fleet is the logical end state goal that will logically evolve from the initial movers of SMR technology as they look to integrate new technology into their existing fleets. Technology decisions will most likely be based on either existing knowledge of the design principles because of similarity with previous operating units or in the case of new designs the existence of demonstration units or similar commercial deployments, with first movers likely setting a path for other operators to follow. The need for of a fleet approach increases with smaller output SMR units, as there is an increased need to spread the costs of operations across multiple units. Deployment of the first unit will likely be done with an understanding that there will be more units of the same type owned/operated by the same entity. Utilities will make every effort to use existing processes and people toward SMR deployment, even across different applications, to maximize the use of existing support while developing the additional unique support needed for new technology.

New fuels: China and Russia currently have the most advanced programs in the development of the fuel types that would be used in most SMR designs. Most SMR technologies use a grade of low enriched uranium fuel and fuel forms that are not currently commercially deployed in Canada; a commercial fuel supply will need to be established to deploy SMRs beyond an initial demonstration unit. Canada should work with like-minded countries, notably the US, to ensure a secure commercial long-term SMR fuel supply.

Supply chain: SMRs represent a paradigm shift in manufacturing/construction and deployment of nuclear reactors. Canada has a robust supply chain due in large part to Ontario's $26B investments in refurbishments. This is in stark contrast to other nations, such as the UK and US, where supply chains have declined. However, some re-tooling will be needed to pivot to meet SMR supply chain demands, but Canada's supply chain is well-positioned to do so. Coordination between industry, federal and provincial governments, laboratories and academia will be required to execute this pivot. While most SMR designs originate from outside Canada, for all but the most established designs, the supply chain is not fully established. Especially for innovative designs, where an experienced supply chain does not yet exist, the investments required would be greater, but the potential for business, including export business, will be correspondingly greater. Opportunities for value-added services, for example fuel enrichment and manufacture should be considered.

7.2 Secondary Findings

The secondary findings of the TWG broken down by area are:

7.2.1 Overall

Finding: Wide-scale clean electrification will impact electricity demand and distribution. SMRs have the potential to play a significant role in clean electrification. The impact of clean electrification and the role of SMRs needs to be better understood.

Finding: Developments in electricity supply and demand indicate that there will be a potential need for short-term deployment, with in-service dates from 2025-30; this will require a high level of design completion and regulatory review today. SMR deployment potential will continue to be beyond 2030.

Finding: Longer-term potential benefits include the decarbonisation of the transport industry. SMRs can enable this through greater electrification, including integration with energy storage and/or hydrogen production.

Finding: SMR technologies can add major value in all three application areas (on-grid, off-grid, industry).

Finding: Heavy industry applications are likely to be near the same time line as grid applications but will be slightly longer in implementation due to the off-grid and remote nature of these applications.

Finding: Deployment in remote communities is most likely further in the future than the other two applications, greater than 10 years.

Finding: Investment and concerted, focused effort is required to accelerate the development of the lower readiness technologies to enable deployment in the early 2030 timeframe that is required by the on-grid market.

Finding: There is an overhead burden inherent any operating nuclear facility regardless of the number of units, the size of the units, and the type of technologies. Therefore, the need for of a fleet approach increases with smaller output SMR units, as there is an increased need to spread the costs of operations across multiple units.

Finding: To succeed, all sectors of the nuclear community will have a role to play, from designer/engineering to operators, regulators, researchers and academia, complemented by government, in a partnership approach.

Finding: A comprehensive program covering <u>both</u> short-term applications of relatively well-developed technology (e.g. LWRs) <u>and</u> technologies that have significant technology development still to be carried out would enable Canada to realize greater benefits of SMR deployment.

Finding: Taking a passive approach “sit back, wait and see” approach to advanced SMR technologies will not lead to the full benefits for Canada – developments will not be optimized to our requirements, and the industrial benefits will go elsewhere

Finding: It is notable that the potential benefits increase as the scope of development moves from shorter to longer term; a long-term vision for SMRs in Canada offers far-reaching benefits – reliable on-grid power free from GHGs; ability for heavy industries to operate with drastically reduced GHG emissions; and delivery of reliable power that ends energy poverty in northern and other remote communities.

Finding: Canada is in a unique position with regard to SMR technology. Although the majority of contending designs are developed outside Canada, and much baseline technology development has been and is being carried on overseas, Canada is in the forefront of considerations for SMR use. The first-mover opportunity for SMR technology demonstration/development window for Canada's active participation is now. Once Canada's leadership in SMRs is demonstrated, other non-nuclear energy countries seeking potential SMR deployment will come to Canada for advice, export, and/or technology collaborations.

7.2.2 Technology applications

Finding: The current generation of nuclear power plants continues to provide a significant source of clean energy to Canada. However, relative to current operating technologies, SMRs offer the promise of major additional potential benefits:

- Smaller upfront capital costs per project (by more than an order of magnitude) and shorter delivery timing, allowing more accessible financing and project delivery
- Flexibility to be deployed in a wider range of situations, enabling a broader role in GHG-free energy delivery
- Designs which have a built-in, inherent, level of safety protection, independent of engineered systems with the possibility for faster licensing and a new social license relationship with public and stakeholder groups
- In the longer-term, the opportunity to recycle fuel, and to introduce fuel cycles that radically reduce the complexity of spent fuel management

Finding: SMRs offer great potential benefits including: greater inherent and passive safety and reduced safety risks, modular design that can be factory built and transported by truck or rail, potential for lower initial capital cost, a source of abundant, reliable, GHG-free energy, and better ability to complement and integrate with intermittent renewable energy sources.

Finding: There are several types of new reactor designs being proposed. Some utilize well established technology in new and novel ways and therefore do not require substantial future investment in R&D of reactor systems. However, a substantial number of designs utilize unique reactor systems which require additional investment in R&D over the next several years in various aspects of design such as materials research.

Finding: Nuclear reactors have been deployed historically in non-terrestrial applications. Several jurisdictions are pursuing non-terrestrial deployment of SMRs currently. This approach has significant potential as a means of deploying SMR technology in coastal areas, in areas where terrestrial builds are difficult or when power requirements are more temporary in nature such as natural resource extraction.

Finding: Cross-cutting enabling technologies are critically important in ensuring inherent or passive safety features and economic competitiveness of SMRs.

Finding: For emerging technologies the amount of intellectual property (IP) produced so far is a small fraction of the final amount of IP (design, verification and licensing, manufacture, build, operate, decommission, waste management) that will be needed and used. Therefore, if Canada invests in technology development, and is producing valuable IP, and should share in the benefits.

Finding: SMR technologies have key technology gaps that require data and development of operating experience prior to licence applications and commercial deployment. These gaps vary among technologies, but include: fuel, materials, verification and validation of computer modelling codes, operation at higher temperatures than are available in current codes and standards, demonstration of passive or inherent safety functions.

Finding: Capabilities, knowledge and expertise in Canada in advanced SMR technologies are needed. Since Canada is new to such technologies, establishing international collaborations should be pursued to fast-track capability development.

7.2.3 Commercial and Supply Chain

Finding: SMR technologies offer many design options and features as well as a variety of deployment options and are at various states of readiness from currently available to available several years into the future. All offer major advantages in the effort to reduce carbon emissions but also have the potential to bring significant economic opportunities to Canada. The economic opportunities are many but based on our review the TWG has grouped the opportunities into three major areas as below:

- National and international Operations: In some cases, the primary design and fabrication work would be concentrated outside of Canada. In this case some of the fabrication benefits and most of the construction benefits would likely accrue to Canada through contract negotiation. Operations in Canada and potentially internationally would be a major opportunity for Canada if we moved quickly to secure the market.
- Fabrication and Operations: Some designs are nearing design completion but have not yet established a fabrication base. Moving quickly to establish a partnership on theses designs could allow, in addition to the items discussed in the first bullet, a primary fabrication base to be established in Canada for both national and international deployment.
- Design, Fabrication, Operations: Some designs which are still in an earlier stage of development but have significant potential could with the right development effort offer a complete made in Canada advantage. In this case, in addition to the items discussed in the 2 bullets above, the R&D effort would also largely accrue in Canada. The ability to licence and export the technology internationally would also offer economic opportunity to Canada.

All the above offer significant economic advantage to Canada in addition to the opportunity to deploy low carbon energy sources. The probability of success and the financial risk incurred is different for each option. The options are not necessarily mutually exclusive and based on the technology solutions choosing an immediate and a longer-term option may offer the maximum opportunity.

Finding: Opportunities for value-added services, e.g. fuel enrichment/manufacture, depends on the potential export market and the global buy-in/achievement of a broader decarbonisation/electrification vision.

Finding: Additional benefits to Canada, such as development of supply chain, economic benefits and jobs, competitiveness, and driving an RD&I economy, from SMRs are linked to the current level of readiness of the technology.

Finding: While most SMR designs are originating outside Canada, for all but the most thoroughly-established designs, the supply chain is not fully established. Especially for innovative designs, where an experienced supply-chain does not yet exist, the investments required would be greater, but the potential for business, including export business, will be correspondingly greater.

7.2.4 Demonstration and Deployment Approach

Finding: There are SMR technologies that are suitable for multiple applications. Selecting a technology for multiple applications may lead to economies.

Finding: Modularization and manufacture in a factory is a dramatic change from how nuclear reactors are constructed, at the site location, today. This infers a corresponding large change to the supply chain.

Finding: development of new capability by manufacturing organizations will be required and will also require technology development to enable efficient manufacturing and assembly.

Finding: Efficient manufacturing at fleet level will require demonstration and proof-testing of technologies.

Finding: Development of manufacturing technology represents an opportunity for Canadian industry. For deployment in Canada, there is a strong logistical advantage in delivering equipment or modules from Canadian facilities, so there is benefit in incentivizing Canadian organizations to address manufacturing technology development challenges.

Finding: Some SMR technologies, particularly for on-grid applications, are near to deployment readiness. In these cases, the ability to complete the pre-project steps of capacity-building, regulatory framework definition and design review, and technology risk review is a pre-requisite. In other cases, particularly for industrial and remote applications, a more extensive, and longer time-frame development program is needed. To gain the benefits of recycled and low-waste fuels, a longer-term sustained program commitment is needed.

Finding: Canada has certain specific advantages and opportunities that can be pursued to provide enabling steps towards the evaluation and introduction of SMR technologies:

- Demand: Because of our wide-spread geography, both smaller communities and many resource industries, can uniquely benefit from suitably-sized SMR applications with potential fleet scale.
- Comprehensive nuclear capability: Canada's nuclear community has expertise in all aspects of nuclear technology;

- The current initiatives at CNL and in New Brunswick to assess potential SMR designs for demonstration projects is an important enabling step.

Finding: Except for LWRs, most SMR technology types lack significant available operating experience. A demonstration SMR would enable generation of some operating experience prior to commercial deployment.

7.2.5 Fuel and Fuel Cycle Considerations

Finding: Many of the SMR technologies use fuel types other than the uranium dioxide fuel form in use in nuclear power reactors in Canada today.

Finding: Advanced SMR technologies enable alternative pathways for spent fuel management other than long-term disposal in a deep geological repository. These technologies are well-suited to closing the fuel cycle, and potentially to reduce current high-level waste inventories.

Finding: Many of the SMR technologies under consideration require fuels with less (and in some cases no) operating experience compared to current generation reactors, and with additional innovative features not yet fully tested. Fuel qualification, and in some cases completion of fuel development and testing, will be required in the lead up to SMR deployment.

Finding: A fuel qualification program is required. This could be done through an incremental fuel qualification program in a demonstration reactor.

Finding: Many, if not most, of the SMR technologies using high assay low enriched uranium (HA LEU) fuel. There is currently no available source of HA for the deployment of these technologies in Canada.

7.2.6 Safety and Evaluation Considerations

Finding: Engagement of an experienced nuclear operator in any nuclear projects for industry applications will be required to mitigate licensing and operations risk and will likely be an important factor in the financing of the project.

Finding: Modelling and simulation toolsets, along with associated nuclear data and code qualification will be needed to deploy new nuclear technologies in Canada. Domestic capability to use these toolsets will also need to be developed.

Finding: Some features of SMR technologies may impact public acceptance, such as nuclear safety, waste production and the capability to recycle and burn spent fuel, environmental impact, and ability to complement renewables. The potential for these characteristics to impact acceptance should be taken into consideration in future technology selection.

7.2.7 On-grid Applications

Finding: LWRs, SFRs, LFRs, MSRs and HTGRs could all be suitable for on-grid applications. Of these, LWRs are likely the nearest to deployment today. With some concerted effort and investment, it may be possible to speed the deployment of the other SMR technologies.

Finding: Deployment of any on-grid SMR technology would result in benefits to Canada in terms of a supply of clean energy. Technologies with lower technology readiness offer greater potential benefits to Canada. Benefits include: greater role for the supply chain, potential for increase of RD&I in Canada, potential to develop and deploy other fuel cycle infrastructure, such as fuel manufacture and back-end recycling technologies. However, the advantages to the Canadian supply chain need to be balanced against lower readiness technologies being longer to market, and therefore carrying a greater associated risk of missing a global market.

Finding: As many of these SMR technologies have operated at some scale in the world previously, there is some basis for safeguards for most technologies. However, the applicability of current typical safeguards techniques varies across the technologies, and some new technologies or approaches may be needed, especially for liquid fuelled reactors.

7.2.8 Remote Communities

Finding: An important consideration for deployments in remote communities is that the incoming technology must have been previously proven. This means, in practice, that a demonstration project may be an essential pre-requisite to provide the proof that the technology is ready for remote applications.

Finding: The operational model used current large on-grid plants is not viable for the remote community application. The smaller units needed for northern applications do not allow for large, specialized staffing models, and ready access to high skilled technical personal is unlikely. To support deployment, the economies of scale need to be replaced with the economies of fleet.

Finding: Remote applications should consider deployment via a joint project between an experienced nuclear operator, that can absorb the incremental costs of operations of a fleet of 1MWe units into their overall nuclear management systems, working with a technology provider willing to provide long term support and financial backing to the technology.

7.2.9 Heavy Industry Applications

Finding: For the oil sands industrial applications, because of the diversity of energy-type requirements, more than one SMR technology may be considered in matching supply to requirements.

8. Recommendations

This section compiles the recommendations of the TWG that are identified elsewhere in this document and is divided into two parts. The first is key recommendation, which represent the most significant major recommendations that the TWG has raised to the SMR Roadmap Steering Committee and the final Roadmap report. Also included are secondary recommendations and actions, which the TWG feels are important and should be take into consideration in the development of an SMR industry in Canada.

8.1 Key Recommendations

The Technology Working Group makes the following key recommendations:

1. *Recommendation:* One or more demonstration reactors utilizing new designs that offer significant advantages be constructed at an existing licenced site. Additional benefits and efficiencies would be realized if the demonstrations are sited at a location with the required capabilities to perform the R&D activities associated with the demonstration, and the challenges expected with FOAK technology. The federal government should support efforts to site demonstration SMRs on federal lands, and Canadian Nuclear Laboratories' sites (owned by Atomic Energy of Canada Limited) are ideal candidate locations.
   Who: federal, provincial and territorial governments provide financial support towards SMR demonstrations; utilities provide operation support; national laboratories establish a provide a site and R&D support; universities and academia provide R&D support
   When: demonstration projects should be initiated as soon as possible
2. *Recommendation:* Establish a well-coordinated and integrated development program, linked to the SMR demonstration program, such as an SMR Centres of Excellence Network, which brings together industry, government support, R&D institutions and academia to carry out focussed research, development and capacity-building to support commercial deployment and continued operation of the commercial units.
   Who:

   AECL, CNL with the federal government: provide a lead organizational role and governance structure that ensures equitable access to R&D funds.
   Nuclear utilities: provide financial support, participate in the governance, and provide direction
   UNENE: key founding partner, execute R&D projects and capacity-building
   Universities and academic institutions: execute R&D projects and capacity-building
   Other R&D organizations: execute R&D activities based on agreed funding proposals
   CNL: execute R&D projects, provide access to experts and facilities
   Provincial and territorial governments: provide financial support, option to participate in the governance
   Potential end-user industries, such as mining and oil sands: participate in R&D projects and capacity building for projects related to their industry; options to provide financial support, participate in the governance, and provide direction
   Supply chain: participation to enhance the uptake of technologies developed under the

program; commercialize technologies
Other government laboratories (such as CANMET): execute R&D projects, provide access to experts and facilities

When: Initiate the organization and establish a framework, governance structure and founding partners in the next 6 months.

3. *Recommendation:* Recognizing that the potential additional benefits to Canada (e.g. development of supply chain, economic benefits and jobs, competitiveness, and driving an RD&I economy) of SMRs cross a wide spectrum of technologies and readiness, and that the additional benefits are, in general, potentially greater for lower readiness technologies, understanding the risks associated with being longer to market. The technology readiness level and the speed to market should both be considered as criteria and balanced when providing support and investments to technologies, especially those by federal, provincial and territorial governments.
Who: federal, provincial, territorial government, and any other organization providing support or investments in SMRs.
When: immediately, and continual, as selection and funding/support continues to be provided to SMR development and deployment

4. *Recommendation:* Canada work with like-minded countries, notably the US, to ensure a secure commercial long-term SMR fuel supply. In addition, the federal government should provide policy direction regarding reprocessing of spent fuel and enrichment of uranium to meet SMR requirements. Over the longer-term, Canada should review and consider developing domestic enrichment capabilities to support LEU fuel for SMRs going forward.
Who: Federal government: engage with like-minded nations. CNL, utilities, domestic nuclear fuel industry: partner in the pursuit of secure fuel supply as needed. Regulator: provide input and guidance as needed. Federal government, provide direction regarding domestic reprocessing and enrichment (medium term, over the next 2-5 years).
When: Initiate in the next 6 months.

8.2 Secondary Recommendations and Actions

Canada can benefit from Roadmap technology programs to fill both common and specific gaps. It is important at this stage, that pan-Canadian programming does not attempt to prematurely “pick winners” from the various technologies on offer. The eventual selection of SMR technologies and designs for commercial application, will be carried out by the conventional processes of commercial evaluation by the owner/operators and end-users. However, the Roadmap can identify key enabling development activities for major technologies to be addressed.

The first step in the pan-Canadian technology development is a status assessment, to expand on the above technology gap summary in a state-of-the-art report. This report can indicate: a broad timeline for each technology category; the main gaps to be addressed; the work world-wide that is underway to address the gaps; and the beneficial work that could be undertaken in Canada as part of this effort. This report would complement business development efforts to establish the Canadian development and deployment role for each technology.

The TWG makes the following secondary recommendations:

Recommendation: To establish the demand for deployment and the timing of the demand, further detail is needed. Further work to define requirements and desirable characteristics in more detail should be an early roadmap action.

Recommendation: Commission a study regarding the future of electricity demand due to clean electrification. This study would consider the role of SMRs in meeting that need, and SMRs in conjunction with other renewable energy sources and energy storage.

Recommendation: Development of designs that establish further benefits for the longer-term, beyond 2030, should also be pursued (see 2.5).

Recommendation: Future studies should be undertaken to examine which SMR technology could meet the widest set of heavy industry requirements and market needs.

Recommendation: To align SMR design specifications to industry needs for individual facilities, including output size and heat supply requirements, further detailed requirements studies should be undertaken as an early action. Develop tools to model full interfaces between SMR and external energy demands, and local grid/community infrastructure.

Recommendation: Commission a study to perform a comparison of land-based vs. floating SMRs for remote community applications, to include economic, logistical, and regulatory aspects.

Recommendation: As an initial step to aid in future SMR technology selection and deployment:

a) Identify today's state of the art:
    i. Compile a directory of Canadian initiatives supporting SMR development
    ii. Compile a directory of Canadian University programs, facilities and individual expert availability in SMR topics)
    iii. Document and summarize major world initiatives in SMR development
b) Identify Canadian role in international technology development
    i. Pan-Canadian assessment to identify Canadian information needs, niche capabilities, and opportunities for co-operation with international organizations

Recommendation: A mechanism be put in place to direct funding to these R&D areas for the next 10 years.

Recommendation: Establish a well-coordinated and integrated development program, such as an SMR Centres of Excellence Network, which brings together industry, government support, R&D institutions and academia to carry out both focussed development and capacity-building. A potential concept for this development program is further discussed in Section 7.2, including focus areas and foundational themes.

Activities to consider under the SMR capability program:

- Focus efforts on technologies that provide a greater benefit to Canada
- Consider funding studies to better understand the evolving environment and technologies, e.g.:

- Impact of clean electrification, and the role of SMRs to enable
- Non-land based NPPs
- Closed fuel cycles / advanced fuels
- Technologies to enable remote deployment, e.g. remote monitoring & operation
- Fuel availability studies, e.g. securing a supply of HA LEU
- Perform specific case studies of deployment of SMRs in remote communities
- Identify Canadian role in international technology development, develop international collaborations on SMR technology development
- Advanced fuel knowledge and capabilities (R&D and manufacturing capabilities)
- Power conversion in northern climates for and integration into production of synthetic hydrocarbons and hydrogen reduction in carbon usage
- Study breakthrough technologies for enrichment and reprocessing

Recommendation: Establish capacity building infrastructure (e.g. through industry-university centres of excellence) including university courses, student assignments to R&D centres, participation by university and industry personnel in R&D programs.

Recommendation: the SMR development and capability-building program include scope on modelling and simulation toolset development, qualification and training.

Recommendation: Collaborative capability building and R&D programs (further discussed in Section 6.2) should include actions and development of cross-cutting technologies, such as those mentioned in Section 4.5. There have also been significant reactor innovations in the Canadian nuclear industry and research sectors that should be investigate and could be further developed and extended to enable SMR technologies.

Recommendation: Studies be undertaken to identify and subsequently pursue sources of HA LEU.

Recommendation: Canadian efforts in pursuit of HA LEU be coordinated with similar efforts in the United States.

Recommendation: The federal government should provide policy direction regarding reprocessing of spent fuel/enrichment.

Recommendation: Over the longer-term, Canada should review and consider developing domestic enrichment capabilities, including for HA LEU.

Recommendation: Canada build knowledge and expertise in non-uranium dioxide fuel forms, such as metallic, TRISO, and nitride fuels. This should include fabrication, performance, and post-irradiation examination of the fuels. This could be considered as an area of research and capability building under a coordinated capacity building and development program, see Section 6.2.

Recommendation: The additional benefits of SMRs should be considered in technology selection and in providing support and investments in technologies, especially those by federal, provincial and territorial governments.

Recommendation: For mid-to-large size SMRs, focus effort on those that have the potential for growth in RD&I in Canada and a role for the Canadian supply chain. Provide programs to enable the faster development of these lower-TRL technologies.

Recommendation: Provide ongoing Canadian support for evaluating suitability of analysis/modeling tools, and for troubleshooting issues at plants throughout their operating lives.

Recommendation: Studies be undertaken regarding safeguards of new SMR technologies, in cooperation with national and international regulatory bodies, according to current practice.

Recommendation: New safeguard technologies, for example detection in new coolants, be undertaken as part of a coordinated capacity building and development program, see Section 6.2.

Recommendation: As part of the SMR development activity, Canadian supply organizations to be incentivized to invest in design development support, and to establish supply chain readiness for deployment.

Recommendation: Supply-chain capacity-building will need to be closely coupled with the process of technology selection.

Recommendation: Undertake a supply chain initiative to identify competitive roles in manufacturing and construction of leading SMR technologies and designs.

Recommendation: The federal government act as a first mover, deploying the FOAK SMR to federal installations, such as remote military bases. This would provide a clean, reliable supply of energy at those locations, while demonstrating many aspects of deploying these technologies, such as the deployment model, logistics, licensing, operation in the field, waste management, prompt decommissioning, etc.

Recommendation: Explore the opportunities that alternative pathways may offer for spent fuel management enabled by deployment of advanced SMR technologies.

8.2.1 Recommendations for On-Grid Applications:

- Utilities/owner-operators will evaluate technology options available for short-term deployment
- The nuclear community contributes to studies of the value and practical steps to expanding electricity production into areas of the energy supply currently dominated by fossil fuels, e.g. transportation, building heating etc.
- Federal government provides policy support for role of clean electricity and nuclear contribution
- Some technologies have notable potential for on-grid deployment but require further development before initial projects can be pursued:

    - Utilities/owner-operators to maintain active participation in overall industry development efforts and provide independent evaluation capability

8.2.2 Recommendations for Heavy Industry Applications

- Federal government provide site opportunity for heavy industry-capable SMR demonstration, e.g. an AECL site
- Develop focussed R&D program on high temperature SMRs to provide process heat as well as electricity, including study of reactor-infrastructure integration
- Work in partnership with heavy industry representatives to ensure needs are addressed in demonstration project
- Joint heavy industry/nuclear sector feasibility study of proposed SMR technologies potentially suitable for heavy industry, to identify/verify technologies and R&D required before commercial
- Develop fleet model ready for implementation, including supply chain qualification for short-listed technologies
- Industry evaluation of R&D progress to identify risk reduction and prepare for commercial deployment

8.2.3 Recommendations for Remote Community Applications

- Canadian government: evaluate potential contribution from SMR energy delivery to Canada remote sites (e.g. military sites); carry out feasibility study of SMR energy delivery to reduce operating site costs and reduce GHG footprint from remote government operations – if supported, government consider acting as lead customer for a FOAK remote site SMR
- Fund and carry out intensive outreach program to understand remote community individual needs and expectations, (e.g. per NWMO example)
- Fed/Territorial Government-led feasibility study of proposed SMR technologies potentially suitable for remote application, to identify/verify technologies and required R&D
- Define remote-community application requirements to be included in relevant demonstration projects
- Define fleet approach to SMR deployment for Canada’s northern and remote communities
- Demonstrate integration of SMR with renewable energy and other uses of process heat
- Fund and develop cross-cutting enabling technology solutions to challenges for remote siting, e.g. remote/automated operation, security assurance, waste removal and transportation
- Develop supply chain for full scope of fleet delivery

- Prepare detailed generic project model including delivery to site and full life-cycle out to decommissioned, “green-field” site

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10. Appendix A: Remote Community Energy Demand and Distribution of Power Capacity

There are 319 remote communities in Canada [2][11]. There are off-grid communities in 10 of the 13 provinces and territories, as shown in Figure 1, with the three exceptional provinces being Nova Scotia, New Brunswick, and Prince Edward Island. Table 2 shows the number of such communities by province and territory, and their primary source of electricity. Most power plants, 96%, that serve off-grid communities in Canada consume fossil fuels, with the remaining 4% using hydro-power. The communities that rely primarily on hydro-generated electricity also host a diesel power plant as a supplement to, or a backup for, the hydro-power plants. Of the 280 communities with active records in [2], 197 rely primarily on a local power plant that burns diesel fuel with a total nation-wide installed capacity of 337 MWe.

[11] Of the 319 communities, there are partial data for 297 communities. While 211 communities are listed as primarily relying on fossil fuel (FF), only 186 communities have a listed power plant capacity in [2].

Figure 10. A map showing the locations of remote communities in Canada [6]

Table 2. Fossil Fuel Generation in Off-grid Communities in Canada by Province (Active Records Only)

	Number of Communities					
Province / Territory	Total Number	Primary Diesel generation	Connected to Local Grid	Primary Renewable generation	Hybrid Diesel / Renewable	Other Primary Fossil Fuel
Alberta	2	1	1	0	0	0
British Columbia	75	57	6	4	1	0
Manitoba	7	7	0	0	0	0
New Brunswick	0	0	0	0	0	0
Newfoundland and Labrador	29	26	1	0	1	0
Northwest Territories	37	21	8	4	0	2
Nova Scotia	0	0	0	0	0	0
Nunavut	25	25	0	0	0	0
Ontario	38	31	0	0	1	0
Prince Edward Island	0	0	0	0	0	0
Québec	45	24	20	1	0	0
Saskatchewan	1	1	0	0	0	0
Yukon	21	4	16	0	0	1
Total	**280**	**197**	**52**	**9**	**3**	**3**

The current power generation capacity of off-grid communities is shown in Figure 2. The majority of remote communities have an electric power capacity of between 0.1 and 2 MWe.

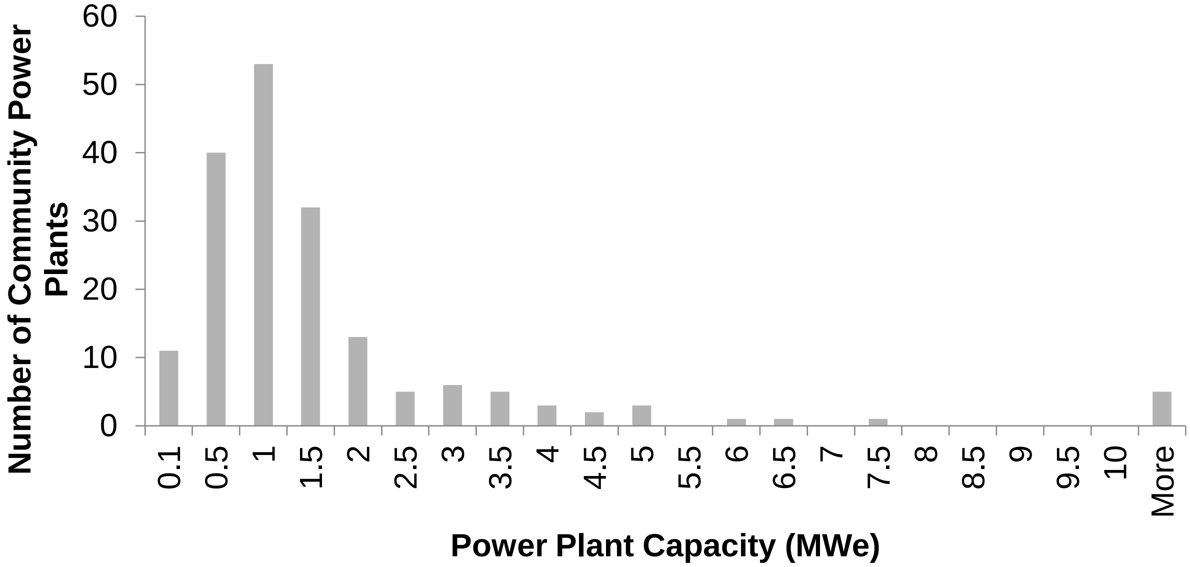

Figure 2. Histogram of current power plant capacity in Canadian off-grid communities

Since the total capacity of SMRs that may be installed in a community would depend on the peak and average electricity demand it would be informative to look at the relationship between installed capacity and demand data. On average, the installed capacity was more than double the peak power demands and quadruple the average annual power demands for those communities for which demand data was available. This excess capacity serves as backup and as a margin for future growth in peak demand. Assuming that it would be 10 years before an SMR is installed at a given community for which the current installed capacity is double that of peak demand, that the capacity of the SMR matches that of the current installed capacity, and that the SMR will operate for 30 years, then this SMR could support up to 1.7% average annual growth in peak demand and up to 3.5% average annual growth in total energy demands over its lifetime. It is also possible to install a smaller SMR that still exceeds current peak demand, and add another SMR if demand increases.

The relationship between installed capacity and the demand varies significantly across different communities. With peak and average demand data for 45 and 169 communities, respectively, the standard deviation of the ratio of installed capacity to peak and average demand is 0.9 and 3.0, respectively. This reinforces the need for community-specific assessments to gain a more accurate overall market assessment.

There are many factors to be considered regarding what power generating capacity of SMRs would be suitable for a given community including:

- *Demand*: Electricity demands in a community may grow significantly between now and when SMRs are ready for deployment. The capacity of the SMRs installed in a community should be chosen taking into account future growth projections in energy demand over a planning horizon.
- *Ability to load follow*: The load following capabilities of a given SMR technology may have a significant effect on the maximum capacity that can be installed in a given community. These characteristics include minimum operating power level, and quick start-up capability. A SMR

that is capable of operating at power levels that match the full range of demands of the community with capacity to spare would be well suited for deployment as a stand-alone unit. If the power demands of a community fall below the minimum power level of a SMR then multiple smaller SMRs would need to be installed, each with a quick start-up capability.

- *Coupling to energy storage*: The installation of energy storage capacity would reduce the required installed SMR capacity. This would allow the SMRs to operate at a higher power level than needed to meet current demands, with the excess energy stored and used to meet power demands that exceed the SMR capacity. The optimal combination of SMR and energy storage capacity would depend on the daily and seasonal demand characteristics of the community, and on the efficiency of the storage technology.
- *Integration with renewable energy source*s: Increased penetration of renewable power generators and energy storage capacity into this market by the time of SMR deployment would reduce the potential installed capacity for SMRs.

*District or electric heating system*s: The installation of SMRs could enable the installation of electric heating systems or district heating systems to replace or supplement current diesel fuelled systems. This may increase the electricity demand by a significant amount depending on the relative amount of diesel consumed for heating. For example, in 2011 the three territories in Canada consumed 2.9 times the amount of diesel for heating as was consumed for electricity [7]. A community that consumes 1 and 2.9 units of diesel for electricity (30% efficiency) and heating (90% efficiency), respectively, will increase its electricity demand by a factor of almost 10 if all heating is provided electrically. Alternatively, a community may have a district heating system in place that could draw thermal power from the SMRs. Such a system would likely require less thermal power than the equivalent electric power required for heating.

11. Appendix B: Examples of Cross-Cutting Technology Programs

B.1 International Atomic Energy Agency

The International Atomic Energy Agency ahs documented several cross cutting enabling technologies:

- Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating **Lessons Learned from the Fukushima Daiichi Accident**, IAEA-TECDOC-1752
- Advances in Small Modular Reactor Technology Development 2014
- Progress in Methodologies for the Assessment of **Passive Safety System Reliability** in Advanced Reactor, IAEA-TECDOC-1752
- Options to **Enhance Proliferation Resistance** of Innovative Small and Medium Sized Reactors, IAEA NE Series Report NP-T-1.11
- Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors, IAEA NE Series Report NP-T-3.7
- Status of SMR Designs 2012
- Small Reactors without On-site Refuelling: **Neutronic Characteristics, Emergency Planning and Development Scenarios**, Final Report of an IAEA Coordinated Research Project, IAEA TECDOC 1652 (2010)
- Design **Features to Achieve Defence in Depth** in Small and Medium Sized Reactors (SMRs), IAEA Nuclear Energy Series NP-T-2.2 (2009)
- Status of Small Reactor Designs **Without On-Site Refuelling**, IAEA-TECDOC-1536 (2007)
- Status of Innovative Small and Medium Sized Reactor Designs 2005, Reactors with Conventional Refuelling Schemes, IAEA TECDOC 1485 (2006)
- Advanced Nuclear Plant **Design Options to Cope with External Events**, IAEA TECDOC 1487 (2006)
- Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches, and **R&D Trends**, IAEA TECDOC 1451 (2005)

B.2 Advanced Research Program Agency-Energy Program[12]

The Advanced Research Projects Agency-Energy (ARPA-E) is an US DOE program which advances high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E projects have the potential to radically improve US economic security, national security, and environmental well-being. ARPA-E empowers energy researchers in the United States with funding, technical assistance, and market readiness.

[12] Source: https://arpa-e.energy.gov/?q=faq/general-questions

ARPA-E's Modelling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER) programme will focus on new, innovative enabling technologies aiming to help achieve "walkaway" safe and secure operation, extremely low construction capital costs, and dramatically shorter construction and commissioning times for the next generation of nuclear power plants.

MEITNER projects are developing technologies that will accelerate fabrication and testing, making construction cheaper, while integrating high levels of automation and built-in safety measures across the plant to reduce operational costs.

The ARPA-E projects involve enabling technologies such as robotics, sophisticated sensing, model-based fault detection, and secure networks to enable substantially autonomous controls that could reduce operational costs as well as contributing to a high degree of passive safety,

The funding opportunity will encourage interdisciplinary collaboration between scientists, engineers and practitioners from different organisations, scientific fields and technology sectors, to form diverse and experienced project teams. Such collaborations will be able to facilitate scientific and technological discoveries that a single group alone would **not** be able to achieve.

Advanced modelling and simulation tools will be used to improve and validate MEITNER programme projects and project teams will have access to subject matter experts from nuclear and non-nuclear disciplines.

An ARPA-E-provided resource team will coordinate sub-teams for modelling and simulation, techno-economic analysis, and subject matter expertise. Project teams will leverage these resources for modelling and simulation support, advanced technical information, design assistance, and information on the state of the art in relevant areas.

B.3 The US DOE Nuclear Energy Enabling Technologies (NEET) Program[13]

The Crosscutting Technology Development (CTD) subprogram is an US DOE program, which competitively awards innovative R&D to US industry, US universities, and national laboratories to develop innovative solutions to crosscutting nuclear energy technology challenges, with a focus on resolving US industry nuclear technology development issues and fill critical gaps.

The CTD subprogram focuses on innovative research that directly supports and enables the development of new, next generation reactor designs and fuel cycle technologies. CTD provides the technologies needed to maintain the current fleet of nuclear reactors and the innovative technology needed to support the development of advanced reactors which will increase the domestic nuclear reactor pipeline. CTD is coordinated with the DOE-Nuclear Energy’s other R&D programs to ensure that developed technologies and capabilities are part of an integrated investment strategy aimed at improving safety, reliability, and economics of U. nuclear technologies.

GAIN (Gateway for Accelerated Innovation for Nuclear) operates under the NEET program[14]. One of GAIN’s programs is to provide vouchers to help entrepreneurs perform work with or at national laboratories.

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[13] Source: https://www.energy.gov/ne/nuclear-energy-enabling-technologies/neet-mission

[14] Source: https://www.thirdway.org/memo/advanced-nuclear-appropriations

NEET will develop cross-cutting enabling technologies that directly support and complement the Department of Energy, Office of Nuclear Energy's (DOE-NE) advanced reactor and fuel cycle concepts, focusing on innovative research that offers the promise of dramatically improved performance.

NEET will coordinate research efforts on common issues and challenges that confront the DOE-NE R&D programs (Light Water Reactor Sustainability Next Generation Nuclear Plant, Advanced Reactor Technologies, and Small Modular Reactors) to advance technology development and deployment.

The NEET Program consists of the following Crosscutting Technology Development, which is broken into five subprograms:

- **Reactor Materials**
- **Advanced Sensors and Instrumentation**
- **Advanced Methods for Manufacturing**
- **Proliferation and Terrorism Risk Assessment**
- **Nuclear Energy Advanced Modeling Simulation**
- **Energy Innovation Hub for Modeling and Simulation**
- **Nuclear Science User Facilities**

Details of the subprograms can be found in the embedded hyperlinks above.

B.4 Nuclear Innovations developed by the Canadian nuclear industry

The Canadian nuclear utilities, research laboratories, and the nuclear industries at large have developed many innovation in support of CANDU's 40 years of operation and maintenance. This section provides an overview of some samples of these innovations and their potential application to SMRs.

Table 4 CANDU Reactor enabling technologies and their potential application to SMRs[15]

Enabling Technologies in existence for CANDU Technologies	Potential Applications to SMRs
1. Advanced Non – Destructive Examination (NDE) Steam Generator tubes Inspection and Monitoring; Phased Array Turbine Blade Scanner System to check for turbine blade defects in balance of plants.	• Ultrasonic testing uses high-frequency sound energy and ultrasonic waves, which can help identify tube-wall thickness, detect fractures

[15] References:
Ontario Power Generation, "OPG's Inspection and Reactor Innovation", Pickering, ON, 2017, available at: https://inside.rotman.utoronto.ca/gbc1new/files/2017/02/IRI-Technologies-2017.pdf
Canadian Nuclear Safety Commission, "Supplementary Information Presentation from Bruce Power Inc. In the matter of Bruce Power Inc. – Bruce A and B Nuclear Generating Station", CMD 18-H4.1A, Edocs: 5476542, March 7, 2018. Available at https://nuclearsafety.gc.ca/eng/the-commission/hearings/cmd/pdf/CMD18/CMD18-H41A-Presentation-from-Bruce-Power-Licence-Renewal-for-Bruce-A-and-B-NGS.pdf
Hanover Post, "Ontario's Nuclear Innovation Institute to be established in Bruce County", May 31, 2018
Canadian Nuclear Laboratories, "CNL opens National Innovation Centre for Cybersecurity", online http://www.cnl.ca/en/home/news-and-publications/news-releases/2018/cnl-opens-national-innovation-centre-for-cybersecu.aspx. Accessed October 4, 2018.

	or corrosion in the material, and measure the flow rate of the water running inside a pipe; • Eddy-Current testing uses specialized probes to detect defects such as erosion, cracking or even loose parts.
2. Laser Scanning and Mapping Determines the elongation of the fuel channels in the reactor over time. Using cameras, laser profiling and a scanning electron microscope, the crack flaw length, width depth and root radius are found.	• Laser technology can be used to map the profile of complex structures, such as the reactor face, to accurately predict operating lifespan.
3. Automation and Robotics Full circumferential inspection of feeder pipe welds, representing a worldwide first and breaking new ground in ultrasound technology. Heat Transfer Equipment Department (HTED) - uses robotic NDT technology to perform inspections on heat exchangers and steam generators.	• Matrix Inspection Technique (MIT) and Heat Transfer Equipment Department (HTED) can be applied for SMR components, using robotic NDT technology to perform remote inspections on heat exchangers and steam generators.
4. Concrete/Rebar Inspections Tools using Radar, Ultrasonics Ground Penetrating Radar: searches for voids, cracks, delaminations and thickness in concrete; ultrasonic wave used to measure the quality and strength of concrete.	• Similar inspection tools can be used to inspect containment structure of SMR installation.
5. Radiography and X Ray Challenges are brought on by MIC (Microbiological Corrosion) and FAC (Flow Assisted Corrosion). Digital radiography is an invaluable engineering tool for diagnosing required repair or replacement areas in piping systems. New technologies such as Pulsed X-Ray (PXR) and Small Controlled Radiography (SCAR) allow for a much smaller exclusion zone, increasing the margin of safety and efficiency of the system.	• Similar tools can be used to detect FAC in SMR components.
6. Unmanned Aerial Vehicles (UAVs) UAVs used to inspect Darlington's vacuum building, and now continues to inspect OPG's nuclear sites and hydroelectric stations (e.g. ice booms on Niagara River); OPG's fleet of UAVs are equipped with sensitive sensors and cameras capable of HD imagery, thermo-graphing capabilities, and high-resolution 3D images	• Remote monitoring and surveillance tool for SMRs in remote locations, providing real-time data for site security forces.

7. Programmatic Approach, Knowledge and Data Mining on Asset Management and Major Component Replacement The condition of plant systems, structures and components is managed through the asset management program. Data is monitored; the condition of various systems, structures and components is analyzed; future performance is predicted; and necessary maintenance/replacement activities are planned. Major Component Replacement activities are a subset of asset management work that encompasses those activities that require greater than a six month unit outage.	• Similar knowledge and skillset for Asset Management and Major Component Replacement can be applied for SMR fleet.
8. State of the Art Data Acquisition for Reactor Inspection Maintenance System One of a kind innovation in safe, efficient fuel channel inspection Circumferential Wet Scrape Tool (CWSET)– obtains fuel channel samples to determine hydrogen levels inherent in the metal Brims Advanced Non-Destructive Examination Tool (BRANDE) – performs ultrasonic inspection in a wet de-fueled channel.	• Apply similar state of the art Data Acquisition tool for SMR Reactor Inspection & Maintenance.
9. Enhanced Safety Monitoring – Real Time Severe Core Damage Risk Monitor Probabilistic Safety Assessments utilized to enhance safety through work planning: Equipment out of service assessment tool: Risk Monitor helps in work planning process to assess on-going risk on a real time basis. Allows work planners to shift work on safety related equipment to minimize risk	• On-line Risk Monitor can be further developed to help enhanced safety monitoring for SMR operation and maintenance.
10. Emergency Data Transmission System DLAN - Emergency data transmission system developed and implemented: Timely, reliable, accurate data Robust and operable in all design basis and beyond design scenarios Independent of local grid Digital transfer of same data to all stakeholders Digital storage of data remote from the site	• Similar Emergency Data Transmission System can be further developed applied for Emergency Management Planning for SMR installation.
11. Ontario Nuclear Innovation Institute Bruce Power and Bruce County are establishing the Ontario Nuclear Innovation Institute in Southampton as an international centre of excellence for applied research and training.	• The Ontario Nuclear Innovation Institute will also evaluate applications for new nuclear technologies including Small Modular Reactor (SMRs), which will be an essential component to future carbon free electricity needs.

With over 30 nuclear companies opening offices and other facilities regionally in the past two years, Bruce Power and the County of Bruce will harness this strong foundation by establishing a hub for nuclear innovation through applied research and training. The key focus areas of the Institute will include: Artificial intelligence and cyber security; Medical and industrial isotopes; Health and environmental excellence in the Lake Huron and Georgian Bay areas; Indigenous economic development, and; Nuclear sector operational excellence (OPEX).	
National Innovation Centre for Cybersecurity Canadian Nuclear Laboratories (CNL) opened its National Innovation Centre for Cybersecurity at Knowledge Park in Fredericton, NB, in May 2018. This brand new, multi-million-dollar research facility represents a major addition to Canada's national cyber security capabilities. The new centre will provide CNL with the ability to simulate an operating facility in its entirety, then introduce almost any variable a researcher chooses. This will allow CNL to test how the security systems of entire operations respond to anything from a full scale cyber-attack, to a simple software upgrade. With this capability, CNL can help customers find vulnerabilities in their security systems before they become an issue, and without having to disrupt the operation of their facility.	• Cyber security will be an ongoing concern for anything using a digital components, systems and tools. This will impact all new nuclear projects, including SMRs • Cyber security is a key aspect which is incorporated across the entire lifecycle of the SMR, from design through construction and operation to decommissioning • It will of special focus for technologies that wish to incorporate any remote monitoring, sensing or operation functionality