



Canadian White Paper on Accelerator Driven Systems (ADS) - Past, Present Status and the Future Benefits for Canada

153-129100-REPT-005718

Revision 0

Authored by:	Michael Gharghouri	2024/09/11
	Research Scientist	Date
Reviewed by:	Blair Bromley	2024/08/02
	Reactor Physicist	Date
Approved by:	Alexandre Trottier	2024/09/16
	Acting Manager, Computational Techniques	Date

Canadian White Paper on Accelerator Driven Systems (ADS) – Past Experience, Present Status and the Future
Benefits for Canada

153-129100-REPT-005718 Rev. 0

Page 1 of 67

This page is for Content Controls that apply to this document. If no Content Controls apply,
none will be listed.

Canadian White Paper on Accelerator Driven Systems (ADS) – Past Experience, Present Status and the Future
Benefits for Canada

153-129100-REPT-005718 Rev. 0

Page 2 of 67

Revision History

Rev. No.	Date	Details of Rev.	Authored By	Reviewed By	Approved By
0	2024/07/23	Issued as “Approved for Use”	M. A. Gharghouri	B. Bromley	A. Trottier
D1	2024/03/28	Issued for “Review and Comment”	M. A. Gharghouri	B. Bromley	

Table of Contents

Section	Page
1. Introduction – Overview of Document	9
2. What are Accelerators?	10
2.1 Introduction	10
2.2 Accelerator Characteristics	11
3. Accelerator-Based Systems.....	15
3.1 Introduction	15
3.2 Synchrotron Radiation Facilities	16
3.3 Accelerator-Based Neutron Sources and Neutron Scattering Facilities	17
4. Accelerator-Driven Sub-Critical Systems (ADS)	19
4.1 Introduction	19
4.2 Radioactive Waste	20
4.2.1 Some Facts	20
4.2.2 Radioactive Waste Hazardous?	21
4.2.2.1 Reprocessing of Slightly Utilized Nuclear Fuel.....	22
4.2.2.2 Disposal of Slightly Utilized Nuclear Fuel in a Deep Geological Repository	24
4.3 Breeding Fissile Nuclear Fuel	24
4.4 Thermal-Spectrum Reactors	25
4.5 Fast-Spectrum Reactors	26
4.6 ADS for Radioactive Waste Transmutation/Destruction and Fission-Based Nuclear Power Generation.....	28
5. Accelerator Systems to Support Fusion Energy Development	34
5.1 Use of Accelerators in Fusion Reactor Technology	35
5.2 Accelerator-Based Irradiation Facilities for Testing Materials for Future Fission and Fusion Reactors.....	36
6. An Alternative / Complementary Technology for ADS: The CANDU PT-HWR.....	37

7.	Summary and Conclusions.....	37
8.	Acronyms	40
9.	Acknowledgements.....	41
10.	References	42
Appendix A	Where Nuclear Energy Comes From.....	51
A.1	Nuclear Basics	51
A.2	Matter and Energy	52
A.3	Energy From Nuclear Fission.....	53
A.3.1	Neutron Capture	53
A.3.2	Radiative Capture.....	53
A.3.3	Decay, Half-Life, and Activity	54
A.3.4	Fission and Fission Products	56
A.3.5	Activation Products.....	56
A.3.6	Neutron Cross Sections.....	56
A.3.7	Fissionable, Fissile, and Fertile Nuclides	58
A.4	Conventional Nuclear Fission Energy Production.....	58
A.4.1	The Fission Chain Reaction	58
A.4.2	Criticality and Reactivity	60
A.4.3	Fuel Enrichment and Depleted Uranium	61
A.4.4	Prompt and Delayed Neutrons	61
A.4.5	Decay Heat	62
Appendix B	Deep Geological Repositories Around the World.....	63
Appendix C	Fusion Power Generation	64
C.1	Definition and Advantages of Fusion.....	64
C.2	Fusion Reactor Concepts	65

Tables

Table 1:	Main Functions of an Accelerator.....	12
----------	---------------------------------------	----

Table 2: General Characteristics of Accelerators.....	13
Table 3: Number of Light Sources per Country/Region.....	17
Table 4: Spallation Neutron Sources Around the World.	18
Table 5: Radiotoxic Nuclides in Spent Nuclear Fuel.	21
Table 6: ADS proposals past and present for fission power generation, breeding, and spent nuclear fuel transmutation. Institutional acronyms are included at the end of the table.	29
Table 7: Accelerator Requirements for Fission Power Generation and Radioactive Waste Transmutation.....	34
Table 8: Accelerator Characteristics for Fusion Energy Generation.....	36
Table 9: Decay reactions.	55
Table 10: Neutron cross sections.....	57
Table 11: Neutron Energies ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$)	58
Table 12: Status of some deep geological repositories.	63
Table 13: Past and current fusion power generation efforts.	66

Executive Summary

Around the world, significant resources are being invested by leading nuclear nations to develop and deploy accelerator-based systems for research and accelerator-driven sub-critical systems (ADS) for neutralizing radioactive waste, for making new nuclear fuel, and for producing clean energy.

A particle accelerator, usually referred to simply as an accelerator, is an electrical device for generating a beam of fast-moving (up to ~400 million m/s) electrically charged ions, electrons, or other subatomic particles. Initially developed as a research tool for studying the structure of nuclei, the nature of nuclear forces, and the properties of elements not found in nature, accelerators now impact our daily lives. Tens of thousands of low-energy and medium-energy accelerators are used every day around the world in industry, medicine, and research.

Accelerator-based systems for generating X-rays (light sources) and neutron beams (spallation neutron sources) have been deployed successfully in Canada, the United States, the United Kingdom, Europe, China, Japan, and many other nations. These light sources and spallation neutron sources are mature technologies which can be deployed with little risk and with well-quantified costs and operational requirements. In addition to providing the necessary particle beams, the high-performance accelerators which underpin these facilities are used as test beds for new accelerator technologies.

With the shutdown of the National Research Universal (NRU) multi-purpose research reactor at the Chalk River Laboratories in 2018, Canada, a Tier 1 nuclear nation, has no large-scale facility for neutron irradiation and testing of nuclear materials and fuels. Currently, within Canada, only the modest capabilities offered by the McMaster University Nuclear Reactor (MNR) and the Queen's University Reactor Materials Testing Laboratory (RMTL) are available.

Canadian investment in an accelerator-based spallation neutron source could provide both irradiation facilities and neutron beams for research. Such capabilities would complement the irradiated materials characterization methods offered by the Advanced Nuclear Materials Research Centre (ANMRC) under construction at the Chalk River Laboratories. A dedicated spallation neutron source could also complement the Canadian Light Source at the University of Saskatchewan, which is currently undergoing significant upgrades to ensure that it continues to offer world-class performance.

A key application of accelerator-driven sub-critical systems (ADS) is the transmutation and destruction of various forms of radioactive waste, including long-lived fission products and minor actinides extracted from slightly utilized nuclear fuel (SUNF)¹. In this application, radioactive waste produced from the operation of conventional nuclear reactors would be “neutralized”, solving a long-term liability issue and addressing a long-term public concern.

¹ Fuel from a nuclear fission reactor is often referred to as spent nuclear fuel (SNF). However, the term “slightly utilized nuclear fuel (SUNF)” is perhaps more appropriate since most of the energy content of the fuel is not extracted when it is burned in a reactor. If the appropriate technology were available, SUNF would be a resource rather than a liability.

While significant progress has been made over the last 70 years on the development of ADS technology within the international community, significant additional effort and investment will be needed over the next 10 to 30 years to bring large-scale ADS applications to fruition and commercialization.

Other ADS applications include producing certain medical and industrial radioisotopes, breeding new fissile fuel, and generating power. In this context, ADS would augment and complement conventional and advanced nuclear reactors to ensure long-term nuclear energy sustainability.

To enable the commercialization of ADS, at least as dedicated national facilities, significant improvements in accelerator power and reliability will be required. Extensive research into the characteristics of thermal-spectrum and fast-spectrum sub-critical reactors, and their coupling with accelerator-based neutron sources will also be needed. Finally, it will also be necessary to develop and scale up safe and economically viable methods for reprocessing and recycling irradiation target materials and fuels. Many international proposals for ADS assume that such reprocessing methods will be available. Ambitious research programs have been launched worldwide to meet these many challenges.

From the Canadian perspective, one potential cost-effective short-term option for providing a variety of capabilities is a single high-performance particle accelerator coupled to multiple spallation target stations, each tailored to a specific application. This approach, which has been pursued at the ISIS facility in the United Kingdom and at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) in the United States, is compatible with a multi-year staged modular approach for managing costs and risks. The main requirement would be planning to identify the appropriate accelerator performance specifications and to ensure an optimal layout of the target stations and support buildings. Such a facility could complement or augment the use of a multi-purpose research reactor. In planning such a facility, the considerable experience available at the TRI-University Meson Facility (TRIUMF) in British Columbia would be a significant asset.

In evaluating ADS for radioactive waste transmutation/destruction and power generation for Canada, the following considerations must be kept in mind:

1. The Canadian nuclear industry has a strong safety record, such that the often-stated advantage that an ADS is inherently safer than a critical reactor can be credibly challenged. Thus, perceived safety should not be considered a necessary or driving factor for the construction of an ADS in Canada.
2. Canada has limited recent experience in reprocessing and recycling fuel from commercial nuclear power reactors due to:
 - a. the relatively low concentration of fissile uranium and plutonium nuclides in CANDU® slightly utilized nuclear fuel (SUNF) compared with light water reactor SUNF,

- b. the costs of reprocessing, which have consistently proven to be higher than initially estimated all over the world, even under ideal conditions of strong government support, and
 - c. the production of multiple partially-understood solid, gaseous, and liquid waste streams rather than a single well-understood solid waste stream.
3. Canada's current, conventional, mainstream power reactor technology, the CANDU® (CANada Deuterium Uranium) reactor, a pressure-tube heavy water reactor (PT-HWR), is a highly capable and flexible system with great potential. With modest modifications, it is anticipated that the CANDU® reactor could be adapted to perform several of the applications for which ADS are considered ideal. The CANDU® platform offers a multitude of possible fuel cycles: it is possible to burn plutonium and minor actinides (with reprocessing) and also, potentially, to develop a thorium-based fuel cycle. Thus, it may be advantageous to further develop advanced CANDU® reactors and fuel cycles, possibly through collaborations with other countries which also operate CANDU® reactors. ADS for radioactive waste transmutation could thus complement and augment conventional nuclear reactors.
4. Thanks to careful community engagement, the Canadian Nuclear Waste Management Organization (NWMO) has made very good progress toward siting and developing a deep geological repository (DGR), which, at the international level, is considered a viable option for radioactive waste management. If the slightly utilized nuclear fuel placed in a DGR is easily retrievable, at least until the DGR is finally sealed, it may be possible for Canada to take advantage of new developments in ADS and advanced reactor technologies to recycle and reprocess the stored fuel for the benefit of Canada.

1. Introduction – Overview of Document

This document provides an overview of accelerator-driven sub-critical systems (ADS), with the goal of informing decisions on new and ongoing Canadian investment in these technologies. This document could, for example, inform a future “*Canadian ADS Roadmap*”, in the same spirit as the recently published Canadian roadmap for small modular reactors (SMRs) [1]. The intended audience includes:

1. government policymakers, advisors, and analysts,
2. government agencies,
3. industry,
4. research laboratories and institutions, and
5. academia and universities.

Over the past several decades, there has been significant investment in ADS R&D worldwide. Canada has been active in this field by developing and maintaining expertise in designing and building accelerators and in building accelerator-based systems for research.

The document is organized as follows.

1. Section 2 provides a brief introduction to accelerators, including their component subsystems and their performance characteristics, with the goal of providing sufficient background for non-experts to consume the literature and web resources on accelerators.
2. Section 3 focuses on current applications of accelerators and accelerator-based systems. Ubiquitous everyday accelerator applications that impact our daily lives as well as established accelerator-based systems for research are also covered.
3. Section 4 reviews ADS under active development for applications in radioactive waste management and nuclear power generation.
4. Section 5 reviews the application of accelerator technology to fusion energy development.
5. Section 6 provides a review of applications where the CANDU® reactor (a PT-HWR) may be considered an alternative or a complement to ADS.
6. Section 7 provides a summary and conclusions to help identify paths to pursue as Canada works to increase its nuclear power generation capacity, while addressing long-term concerns about nuclear energy sustainability, and minimizing long-term liabilities associated with radioactive waste and radioactive minor actinides found in slightly utilized nuclear fuel (SUNF)².

² Fuel from a nuclear fission reactor is often referred to as spent nuclear fuel (SNF). However, the term “slightly utilized nuclear fuel (SUNF)” is perhaps more appropriate since most of the energy content of the fuel is not extracted when it is burned in a reactor. If the appropriate technology were available, SUNF would be a resource rather than a liability.

2. What are Accelerators?

2.1 Introduction

A particle accelerator, usually referred to simply as an accelerator, is an electrical device for generating a beam of fast-moving (high-energy) electrically charged ions, electrons, or other subatomic particles. Initially developed as a research tool for studying the structure of nuclei, the nature of nuclear forces, and the properties of elements not found in nature, accelerators now impact our daily lives: tens of thousands of low-energy and medium-energy accelerators are used every day around the world in industry, medicine, and research [2].

A partial list of common accelerator applications is as follows:

1. Production of semiconductors for computer chips (ion implantation).
2. Fabrication of a wide variety of products such as heart valves, tires, plastic wrap for food, molds for plastic components, aircraft engine components (joining, machining, heat-treating, surface hardening, polymer cross-linking).
3. Sterilization of biological materials: medical instruments, food, water.
4. Production of medical radioisotopes.
5. Radiation cancer therapy.
6. Industrial radiography for inspection of critical structural components.
7. Treatment of industrial waste.
8. Radiocarbon dating.
9. Neutron generation for research.
10. X-ray generation for research and medicine.
11. Materials irradiation for investigating the effects of radiation on material structure and performance.

An accelerator-based system or an accelerator-driven sub-critical system (ADS) requires a beam of particles to perform its task, but the high-energy particles themselves are not the end goal. Currently, there are only three broad classes of accelerator-based systems and accelerator-ADS:

1. Accelerator-based systems for generating high-energy X-rays or neutrons:
 - a. Production of medical isotopes.
 - b. Production of neutrons and high-energy X-rays for research.
2. Accelerator-based systems for fusion energy research:
 - a. Accelerated charged particles are used to heat a plasma or drive a fusion reactor.
 - b. Accelerated charged particles which approximate the conditions in a fusion reactor are used to bombard and test materials for fusion reactor components.
3. Accelerator-driven sub-critical systems (ADS) in which neutron sources or X-rays are used to drive a sub-critical fission reactor:
 - a. Transmutation / destruction of radioactive isotopes, typically found in slightly utilized nuclear fuel (spent fuel from nuclear reactors). Such isotopes may include various minor actinides (such as isotopes of Neptunium, Americium, Curium), long-

- lived fission products (such as isotopes of Technetium, Iodine, and Zirconium), or neutron activation products. Neutrons or high-energy X-rays may be used to cause transmutation or destruction. In this way, the ADS “*neutralizes*” radioactive waste to mitigate or remove the associated long-term liability.
- b. Production of fissile nuclear isotopes (such as isotopes of plutonium and uranium) by bombardment of fertile nuclear isotopes (such as isotopes of uranium and thorium) with neutrons. Historically, this process has been referred as “electro-breeding”.
 - c. Production of power (like a conventional fission reactor) by bombarding nuclear fuel assemblies in a sub-critical nuclear reactor with neutrons. Such systems are considered safer than conventional nuclear reactors because the sub-critical reactor automatically shuts down when the accelerator is turned off. No control rods are needed.
 - d. In some cases, depending on the design of the ADS, two or more applications (medical isotope production, generation of neutrons/X-rays for research, transmutation, fissile breeding, power generation) may be achieved in the same system.

2.2 Accelerator Characteristics

Accelerators come in many varieties, each optimized for a particular application. The three functions of an accelerator are listed and described in Table 1. Accelerators range in size and complexity from small and compact off-the-shelf systems to large national and international facilities supported by a dedicated workforce. The ubiquity of accelerators is such that many components can be readily purchased from a variety of suppliers around the world.

The characteristics that must be considered when purchasing, manufacturing/building, or designing an accelerator for a given application are listed and discussed in Table 2.

Table 1: Main Functions of an Accelerator.

Function	Comments
Supply charged particles	The type of source depends on the type of charged particle desired.
Accelerate particles	Several systems, which are often used in combination, are available: 1) High-voltage transformer (~200 kV maximum) 2) Van de Graaff generator (~20 MV maximum) 3) Oscillating magnetic field: a static magnetic field cannot increase the speed of a particle, but an oscillating magnetic field induces an oscillating electric field which can. 4) Radiofrequency (RF) cavity: • When a charged particle enters an RF cavity, it experiences an electric field that alternates in polarity at the resonant frequency of the cavity. As the particle travels through the cavity, it gains energy from the electric field which causes the particle to gain speed. The maximum accelerating voltage which can be applied by an RF cavity is ~2 MV. Higher voltages are achieved by combining multiple cavities in series, or by having particles traverse the same cavity multiple times as they go around a ring, picking up energy at each passage. • An RF cavity fabricated from a normal conductor such as copper is referred to as a NC (Normal Conducting) cavity, while an RF cavity manufactured from superconducting material (typically niobium) is referred to as a SC (Superconducting) cavity. SC cavities do not suffer from inefficiencies due to electrical resistance, but they must be cooled to temperatures 2-3°C above absolute zero, which requires a power-consuming cryogenic system.
Form particles into a beam	High-strength permanent magnets and electromagnets are used to efficiently focus and steer charged particles via the magnetic component of the Lorentz force.

Table 2: General Characteristics of Accelerators.

Characteristic	Description
Particle type	1) Electron. 2) Positive hydrogen ion (H^+): hydrogen atom stripped of its electron. Other ions may also be considered, such as positive deuterium ions. 3) Negative hydrogen ion (H^-): hydrogen atom with one extra electron. 4) Ions for implantation.
Accelerator type	LINAC (LINEar Accelerator): • A LINAC uses a series of radiofrequency (RF) cavities to impart energy to particles as they travel through the accelerator. The length and number of RF cavities determine the total energy the particles can attain. Despite the name, a LINAC can consist of a single straight-line segment, or multiple straight-line segments arranged in a polygonal shape. • LINACs can accelerate particles to very high energies over relatively short distances. • LINACs are commonly used in science and medicine, including cancer treatment (radiation therapy), nuclear physics research, and industrial applications such as sterilization and materials processing. • LINACs can be used as the first stage in an accelerator complex: the particles are accelerated in the LINAC, then injected into the synchrotron ring. • Examples: ➤ Canadian Light Source, University of Saskatchewan (LINAC upgrade) [3]. ➤ Spallation Neutron Source, Oak Ridge National Laboratory [4]. Cyclotron: • A cyclotron uses a fixed, uniform magnetic field to steer the particles in a circle. Particles injected into the middle of the device are periodically sped up with an electric field as they go around the ring. The particles spiral outward until they reach the outer edge of the device. • Cyclotrons produce beams of a single energy, which is limited by the size and strength of the magnets. Cyclotrons are thus more limited in particle energy than LINACs or synchrotrons. • Particles can be injected continuously into the device, yielding high beam currents. • Example: Paul Scherrer Institute proton accelerator [5].
Accelerator type (cont'd)	Synchrotron: • Synchrotrons use a series of electromagnets arranged in a ring. As the particles speed up, the magnetic fields are increased to prevent spiralling, forcing the particles to follow a constant-diameter path. • Since the magnetic fields must be ramped up as the particles gain speed, particles can only be introduced and accelerated in bunches. The current is thus limited by the size of a particle injection.

Characteristic	Description
	- Synchrotrons can achieve higher energies than cyclotrons, but at the expense of beam current. - Example: European Synchrotron Radiation Facility (ESRF) [6]. FFAG (Fixed-Field Alternating-Gradient) accelerator: - FFAGs combine the synchrotron's ring of magnets and the cyclotron's fixed magnetic field. Although the magnetic field is fixed in time, it increases with distance from the center of the ring to prevent faster-moving particles from spiraling outward. - Provided the field increases strongly enough, a FFAG can achieve higher energies than a cyclotron. - The fixed fields allow continuous injection of low energy particles while higher energy particles are still being accelerated, yielding higher currents than a synchrotron. - FFAGs were first proposed in the 1950s. However, synchrotrons and cyclotrons prevailed due to limitations in magnet technology. Example: Kyoto University Innovation Research Laboratory Accelerators [7].
Method of acceleration	- Single-stage. - Multi-stage (repetitive): - Multiple accelerating units arranged in series. - Single accelerating unit through which the particles pass multiple times.
Beam energy	The average energy, E , of an accelerated particle. E includes the rest energy of the particle as well as its kinetic energy.
Beam current	The total amount of electrical charge reaching the target per unit time. The higher the current, the more intense the beam. Dividing the current by the charge on the accelerated particle yields the number of particles per unit time impinging on the target.
Beam size	The cross-sectional area of the particle beam.
Beam Type	- Continuous Wave (CW): Constant beam current. - Pulsed: Current is produced in bursts. Though the intensity of a burst can be very high, the time-averaged current depends on both the burst frequency and the burst intensity.
Reliability	Accelerator reliability refers to the frequency and duration of beam interruptions, referred to as <i>trips</i>. Thus, reliability is commonly reported as the cumulative number of trips per day longer than a particular time interval. The reliability required depends on the application: Accelerators for research are highly specialized and often one-of-a-kind. By their nature, their performance characteristics push technological envelopes, such that they experience frequent failures and shutdowns, sometimes lasting years, for example in the case of the Large Hadron Collider (CERN) [8]. Reliability is important but not critical since failure of the accelerator typically only results in the loss of the experiment itself. A

Characteristic	Description
	useful analogy would be an engine in a high-performance race car, which is designed to perform at a very high level for a short period of time, after which it is refurbished or discarded. - Accelerators used in industry and medicine are off-the-shelf items which are highly reliable, as one would expect, for example, from production vehicles which run hundreds of thousands of kilometers with only occasional and well-understood maintenance requirements. - Accelerators for power generation and waste nuclear fuel transmutation represent the tip of the spear: they require the performance of a production sportscar (not quite a high-performance race car) with the reliability of an everyday commuter vehicle. The required combination of performance and reliability is not currently possible. Of particular importance is the number of trips per day longer than a few seconds. This stringent requirement arises because a lengthy trip can heavily load structures, spallation targets, and the sub-critical core. Other reliability metrics are commonly reported for accelerators, which, for ADS, are secondary in importance to the frequency and duration of trips. These metrics include: - Percentage on time: $\frac{6000 \text{ hours}}{8760 \text{ hours per year}} \times 100 = 68.5\% \text{ total availability per year}$ - Percentage on time with respect to planned operation: $\frac{5800 \text{ hours}}{6000 \text{ hours planned per year}} \times 100 = 96.7\% \text{ availability}$
Power loss	Accelerators for demanding applications such as neutron generation, X-ray generation, power generation, and nuclear fuel transmutation require high beam energies, which can currently only be achieved by repetitive cumulative acceleration occurring over long flight paths. Energy is lost as the particles move through the accelerator. A low power loss per unit acceleration distance is important for two reasons: - It helps ensure that a suitable beam current reaches the target. - It allows hands-on maintenance work to be performed safely during operation.
Beam stability	Beam stability refers to the fluctuations with time of the beam current.

3. Accelerator-Based Systems

3.1 Introduction

Accelerator-based systems for research include X-ray machines used in medical/biological, materials, physics, and chemistry research, light sources which produce light of varying wavelengths, and spallation neutron sources which produce neutrons. Since light (including photons, X-rays, and gamma rays) and neutrons interact very differently with matter, they yield complementary information about materials. Thus, depending on the material and/or phenomenon under investigation, it may be advantageous to use one or the other, or both. The

information obtained is then used, for example, to develop improved materials, pharmaceuticals, water purification membranes, cell phone batteries, and strategies to prevent corrosion of materials.

The International Atomic Energy Agency maintains an interactive map of all synchrotron and neutron spallation facilities worldwide ([IAEA Interactive Map of Synchrotron and Neutron Spallation Facilities](#) [9]).

3.2 Synchrotron Radiation Facilities

At the heart of a synchrotron is an accelerator which accelerates electrons or positrons to nearly the speed of light ($c \sim 3.0 \times 10^8$ m/s). The particles are accelerated around a ring (usually a polygon with rounded corners) using a combination of radio-frequency (RF) waves and powerful electromagnets. When the particles change direction (*“go around the bend”*), they emit energy in the form of bright and highly focused light. The light is directed down a beamline, at the end of which is an experimental endstation. Synchrotron facilities typically have multiple beamlines, each optimized for a specific type of experiment.

Synchrotron facilities are available in many countries, typically employing hundreds of full-time staff to maintain the equipment, perform experiments, and manage the facility. The facilities differ in the range of light energies that can be produced, the intensity (brightness) of the beams, the number and type of experimental endstations, and the ancillary equipment available for subjecting specimens to controlled experimental conditions, such as temperature, force, and atmosphere. Many facilities have programs for welcoming external users from industry, academia, and government, with support provided by facility staff who help plan and execute the experiments, analyze the data, and prepare publications. Most facilities welcome visitors from all over the world, based on a peer-review process which ranks user proposals.

The International Atomic Energy Agency maintains a comprehensive list of synchrotron facilities worldwide, which includes links to facility websites ([IAEA Up-to-date List of Synchrotron Facilities](#) [10]).

The [Canadian Light Source \(CLS\)](#) [3] is a national facility located in Saskatoon, Saskatchewan which supports a wide variety of national and international research efforts. The CLS synchrotron is one of the brightest in the world, with 22 synchrotron beamlines and 1 electron beamline.

The countries which house light sources are listed in Table 3.

Table 3: Number of Light Sources per Country/Region.

Country	Number of Light Sources
Europe Sweden (5), Germany (5), France (2), Italy (2), Spain (1), Poland (1), UK (1), Denmark (1), Switzerland (1)	19
Japan	12
USA	8
Russia	5
China	5
Brazil	2
India	2
Armenia	1
Australia	1
Canada (Canadian Light Source)	1
Iran	1
Jordan	1
Singapore	1
South Korea	1
Taiwan	1
Thailand	1
Turkey	1

3.3 Accelerator-Based Neutron Sources and Neutron Scattering Facilities

At the heart of an accelerator-based neutron source is an accelerator which accelerates H^+ or H^- ions to nearly the speed of light. The high-energy particles are directed onto a heavy-metal target (mercury, tungsten, lead, lead-bismuth eutectic), causing neutrons to be spalled (“chipped”) off the nuclei of the target atoms. The neutrons, which have a range of energies, are directed down beamlines and used for experiments at endstations. Each beamline / endstation is optimized for a specific type of experiment. An electron-based spallation neutron source is also under development [11].

Similarly, to light sources, accelerator-based neutron facilities are available in many countries, typically employing hundreds of full-time staff to maintain the equipment, perform experiments, and manage the facility. The facilities differ in the range of neutron energies that can be produced, the intensity of the beams, the number and types of experimental endstations, and the ancillary equipment available for subjecting specimens to controlled experimental conditions, such as temperature, force, and atmosphere. Many facilities have programs which welcome external users from industry, academia, and government, with support provided by facility beamline scientists who help plan / execute the experiments,

analyze the data, and prepare publications. Most facilities welcome visitors from all over the world, based on a peer-review process which ranks user proposals.

The International Atomic Energy Agency maintains a comprehensive list of spallation neutron scattering facilities worldwide, which includes links to facility websites ([Spallation Sources IAEA](#) [12]).

The importance of accelerator-based neutron sources and neutron scattering facilities is underlined by the many recent large-scale national and international efforts to build them (Table 4). With the shutdown in 2018 of the National Research Universal (NRU) reactor at the Chalk River Laboratories, Canada lost its only high-intensity neutron source. Besides providing neutrons for 6 beamlines operated by the Canadian Neutron Beam Centre (CNBC), the NRU reactor included test loops for irradiating nuclear fuel and was also one of the world's largest producers of medical isotopes, serving both Canada and the international community. Currently, Canada's only major neutron source is the [McMaster Nuclear Reactor \(MNR\)](#) [13] at McMaster University, in Hamilton, Ontario. The MNR is also used for producing small amounts of selected medical isotopes. Currently, the MNR has one operating neutron beamline, with four more under construction. Many of the neutron scattering instruments developed for NRU have been transferred to MNR.

Table 4: Spallation Neutron Sources Around the World.

Facility Name	Accelerator Characteristics	Availability (against plan)	Status	Number of Beamlines	User Program
LANSCE (USA) Los Alamos Neutron Science Center Los Alamos National Laboratory	0.8 GeV LINAC & Storage Ring 80 nA, 0.07 mA, 56 MW Pulsed 20 Hz	80 – 85%	Operational	6	No
SNS (USA) The Spallation Neutron Source Oak Ridge National Laboratory	1 GeV SC LINAC & 2 storage rings 1.7 mA, 1.7 MW Pulsed 60 Hz	89 – 93 %	Operational Continuous upgrade program	19	Yes
ESS (EU) The European Spallation Source Lund, Sweden	2 GeV LINAC & 2 storage rings 3.7 mA, 5 MW Pulsed 50 Hz	**	Under Construction	**	Yes

Facility Name	Accelerator Characteristics	Availability (against plan)	Status	Number of Beamlines	User Program
CSNS The China Spallation Neutron Source	1.6 GeV LINAC & Synchrotron 62.5 μ A, 0.1 MW Pulsed, 25 Hz	92 – 97%	First experiments in 2018	3 (18 planned)	Yes
JSNS The Japan Spallation Neutron Source	0.4 MeV LINAC & 3 GeV Synchrotron 333 μ A, 1 MW Pulsed, 25 Hz	**	Operational Continuous upgrade program		Yes
KENS KEK Japan	0.04 GeV LINAC & Synchrotron	11.2%	Operational	16	
PSI SINQ Swiss Spallation Neutron Source	0.59 GeV Cyclotron 2.4 mA, 1.4 MW Continuous	$88 \pm 6 \%$	Operational	15	Yes
ISIS Neutron and Muon Source (U.K.)	0.8 GeV LINAC 0.225 mA, 0.18 MW Pulsed	$86 \pm 7 \%$	Operational	17	Yes
MYRRHA** Multi-purpose Hybrid Research Reactor for High-tech Applications (Belgium)	0.6 GeV SC LINAC 4 mA, 2.4 MW Continuous Wave	**	Under Construction	**	Yes
IPNS Argonne Intense Pulsed Neutron Source	0.5 GeV LINAC & Synchrotron	95%	Operational	15	Yes

**Note: The MYRRHA facility under development at SCK-CEN in Belgium is unique among accelerator-based neutron sources in that it is a true ADS, with a sub-critical reactor surrounding the neutron source.

4. Accelerator-Driven Sub-Critical Systems (ADS)

4.1 Introduction

Accelerator Driven sub-critical Systems (ADS) are being developed actively within the international community for multiple applications to complement the use of conventional and

advanced nuclear fission reactors. The strategic use of ADS can help ensure the long-term sustainability, safety, and security of nuclear energy, while also minimizing the long-term liabilities of radioactive waste.

It is also anticipated that ADS would complement other low-carbon or zero-carbon non-nuclear sources of energy such as hydro-electric dams, variable renewable energy resources (wind, photovoltaic solar), and biomass.

To fully appreciate the scope and complexity of ADS for radioactive waste transmutation / destruction, fissile nuclear fuel breeding, and power generation, it is helpful to develop a working understanding of the underlying physical phenomena. A brief introduction to topics relevant to radioactive waste transmutation/incineration and nuclear power generation is provided in Appendix A.

In the following subsections, some background on radioactive waste is provided, followed by a discussion of fissile material breeding and short descriptions of thermal-spectrum and fast-spectrum reactors. The section ends with a discussion of how ADS can be used for breeding new fissile fuel, for transmuting radioactive waste, and for generating nuclear power.

4.2 Radioactive Waste

4.2.1 Some Facts

Radioactive waste is often perceived as the most problematic type of industrial waste. However:

1. The nuclear power industry is the only industry that takes full responsibility for the waste (both radioactive, and non-radioactive) it generates [14].
2. The potential dangers of nuclear waste are comparable to those of other types of industrial waste [14].
3. Of all the physical and chemical phenomena, radioactivity is the easiest to detect and measure: every radioactive nuclide generates a unique signature via the type and energy of the radiation it emits [14].
4. Nuclear power has a high energy density, resulting in a small volume of waste per unit of electricity generated.
5. The toxicity of radioactive waste decreases naturally over time. In contrast, many other types of industrial waste persist indefinitely [14].
6. A nuclear reactor produces radioactive waste but does not produce other forms of waste such as greenhouse gases.
7. All existing radioactive waste from conventional thermal power reactors is solid, making it straightforward to handle and confine.
8. Few actors are involved in civil nuclear power generation. Consequently, waste management can be organized and overseen by government via its agencies [14].
9. The Canadian [Nuclear Waste Management Organization \(NWMO\)](#) [15] has determined that radioactive nuclear waste can be safely stored in a deep geological repository for extended periods.

4.2.2 Radioactive Waste Hazardous?

Free neutrons, α -particles, β -particles, γ -rays, and X-rays have sufficient energy to ionize atoms or molecules, including air molecules, water molecules and biological molecules, and are thus collectively referred to as *ionizing radiation*³. Ionizing radiation can cause damage in materials and in plant, animal, and human tissue: nuclides which emit ionizing radiation are referred to as *radiotoxic*. The radiotoxicity of a nuclide depends on 1) the rate at which it emits ionizing radiation (its *activity*), 2) the energy of the radiation, and 3) the quality factor, q , of the radiation, which expresses how damaging the ionizing radiation is to living tissue.

SUNF is radiotoxic due to the presence of relatively small quantities of certain nuclides, totalling ~1% by weight. Since the various nuclides have different half-lives and are present in different amounts, the relative contribution of a given nuclide to the decay heat and the radiotoxicity of the fuel varies with time. The various types of radionuclides in SUNF are described in Table 5.

Table 5: Radiotoxic Nuclides in Spent Nuclear Fuel.

Component	Description
Major actinides ⁴	Uranium and plutonium isotopes.
Minor actinides (MAs)	The minor actinides are actinides with atomic number greater than 92 (uranium), excluding plutonium, which are found in significant amounts in SUNF. They are generally considered to include the isotopes of neptunium ($^{237}_{93}\text{Np}$), americium ($^{241,243}_{95}\text{Am}$), and curium ($^{244-248}_{96}\text{Cm}$). The combined masses of the remaining actinides - actinium, thorium, protactinium, californium, berkelium, einsteinium, and fermium - are typically present in such small amounts in SUNF that they are considered trace contaminants which contribute negligibly to long-term storage issues.
Transuranic elements (TRUs)	The TRUs include all nuclides having atomic number greater than 92 (uranium). They are formed by the capture (or multiple capture) of neutrons by $^{235}_{92}\text{U}$ and $^{238}_{92}\text{U}$. Thus, the TRUs are a subset of the actinides, while the minor actinides are a subset of the TRUs.
Long-Lived Fission Products (LLFPs)	LLFPs include some isotopes of I, Cs, Sr, Tc, Te. LLFPs are radioactive nuclides with long half-lives which are produced in nuclear fuel as byproducts of fission reactions. They emit β - and γ - radiation and have mass numbers ranging from 70 to 170. The most important ones are the isotopes of iodine, caesium, strontium, technetium, and tellurium.
Long-Lived Activation Products (LLAPs)	LLAPs are radioactive nuclides with long half-lives which are formed when neutrons activate non-fuel materials in and around the reactor. Examples include $^{93}_{40}\text{Zr}$ and

³ The use of the term 'radiation' stems from the fact that the particles and photons radiate away from the emitting nuclide.

⁴ The actinides, or actinoids, are those elements in the periodic table from actinium ($Z = 89$) upwards.

Component	Description
	$^{95}_{41}\text{Nb}$, which are found in the irradiated Zircaloy pressure tubes of CANDU® reactors.
Lanthanides $57 < Z < 70$	The lanthanides are elements with atomic number between 57 and 70. In nature, lanthanides are nonradioactive, but they can form as radioactive isotopes during the fission of uranium and plutonium. Most of these isotopes have relatively short half-lives and thus decay into nonradioactive isotopes relatively quickly.

4.2.2.1 Reprocessing of Slightly Utilized Nuclear Fuel

A unique feature of SUNF is that it can be reprocessed to recover fissile and fertile materials for later use in existing and future advanced nuclear fuel cycles⁵. Currently, large-scale reprocessing only occurs in France and Russia. In the French process, purified plutonium is converted into an oxide then mixed with uranium oxide, yielding a mixed oxide (MOX) fuel which can be burned in a conventional reactor⁶.

In many countries, including Canada, the United States⁷, the United Kingdom⁸, Sweden, and Finland, reprocessing using existing processes is not considered necessary or economically viable, resulting in a once-through fuel cycle in which SUNF is placed in interim storage until final disposal in a deep geological repository. China has a pilot reprocessing plant, and continues to pursue a commercial reprocessing facility [18][19].

Significant resources are being dedicated worldwide to developing reprocessing methods. Some considerations regarding reprocessing are as follows:

1. Per unit of electricity produced, CANDU® reactor fuelling costs are the lowest of any commercial reactor[20], which limits the value of reprocessing.
2. The concentration of $^{235}_{92}\text{U}$ in CANDU® SUNF is approximately the same as that in depleted uranium from enrichment processes [20]. There is thus no value in reprocessing CANDU® SUNF to recover this nuclide as it is readily available from a non-radioactive source.
3. The concentration of $^{239}_{94}\text{Pu}$ in CANDU® SUNF is approximately one half that in light water reactor (LWR) SUNF [20], making reprocessing to retrieve this nuclide less economically attractive.
4. The once-through fuel cycle results in a single solid waste stream. In contrast, reprocessing results in separate solid, liquid, and gaseous waste streams [21].

⁵ The construction of reprocessing plants for LWR SUNF was originally justified as a way to obtain plutonium for nuclear weapons and, later, for liquid sodium-cooled plutonium-breeder reactors.

⁶ The proportion of plutonium in MOX fuel is limited by the fission characteristics of plutonium.

⁷ A commercial SUNF reprocessing plant operated at the West Valley site in New York State from 1966-1972 ([West Valley Reprocessing](#) [16]).

⁸ All SUNF reprocessing in the United Kingdom was stopped in 2022 ([U.K. Reprocessing Ends](#) [17]).

5. Per unit of energy produced, the once-through CANDU® fuel cycle results in 6-7 times more radioactive waste by volume than the once-through LWR cycle. However, this larger volume is mitigated by an approximately 10× lower decay heat production rate and a 20-30× lower dose rate per unit mass of CANDU® SUNF [22].
 6. Reprocessing mitigates the contributions from plutonium to the decay heat and radioactivity of SUNF and can significantly decrease the total volume of SUNF that must be placed in a long-term repository, thereby extending the capacity of the repository.
 7. Since the contribution from a long-lived nuclide to the activity of SUNF is proportional to its overall mass, transmutation or fissioning of part of the total inventory of all such nuclides could considerably shorten the required storage time.
- 1) The schedules and costs associated with setting up and operating reprocessing facilities have proven difficult to assess:
 - a. France reprocesses fuel on a commercial basis. Referring to France's policy of reprocessing SUNF, and without putting forward any recommendations, a report commissioned by the French prime minister in 2000 [23] concluded that "There is an evident disadvantage of the current approach". An additional analysis of the costs provided in this report is provided in [21].
 - b. The United States contracted with AREVA ~1999 to build a reprocessing plant and MOX fabrication facility based on the existing facilities in France [24]. The project was cancelled ~2015 due to cost and schedule overruns [25].
 - c. Japan started construction of a reprocessing plant in 1993. It is scheduled to begin operations in the first half of 2024 ([Japan SNF Reprocessing](#) [26]).
 - d. A recent report on the cost of reprocessing in China highlights the difficulties associated with estimating costs for reprocessing facilities [19].
 - 2) Numerous studies indicate that LWR SUNF, which contains more fissile uranium and plutonium than fresh CANDU® fuel, can be burned in a CANDU® reactor, and the DUPIC process has been developed to convert LWR SUNF into CANDU® fuel with minimal reprocessing [27][28]. CANDU® reactors can also be used to decrease the load of plutonium and minor actinides in SUNF, though reprocessing would be required [29].
 - 3) Many advanced reactor and ADS concepts for nuclear power generation and SUNF transmutation depend on the availability of economically viable, proliferation resistant, and environmentally safe reprocessing methods, leading to significant government-subsidized research into reprocessing methods to extract different radioactive nuclides, or groups thereof [30]. A recent exhaustive review of these processes [31], including their technology readiness levels [32], has been provided by the Expert Group on Fuel Recycling and Waste Technology [33]. Further information is available from the ASGARD project of the European Commission [34], which dealt with the reprocessing and dissolution of fuels for Generation IV reactors.

4.2.2.2 Disposal of Slightly Utilized Nuclear Fuel in a Deep Geological Repository

The international community in general has adopted the principle of the deep geological repository (DGR) as the safest solution for the disposal of spent nuclear fuel to 1) ensure the protection of humans and the natural environment over the long term, and 2) remove the burden of managing this radioactive waste from future generations. It is also generally accepted that reprocessing would not remove the need for a DGR, though it could ease the technical requirements of a DGR and increase the life of a DGR by decreasing the volume of fuel to be stored per unit of energy produced. The status of the DGR in a selection of countries is provided in the table in Appendix B.

4.3 Breeding Fissile Nuclear Fuel

The known worldwide reserves of $^{235}_{92}\text{U}$, the only naturally occurring fissile isotope, are considerable but not unlimited: it is estimated that there are 100-250 more years of easily accessible supply (estimates vary) with today's nuclear power park. As global energy demand rises and nuclear power generation increases, these reserves will come under stress. From the earliest days of nuclear power, breeding and recycling of fissile material in used fuel from conventional thermal-spectrum reactors were seen as eventually being necessary to ensure the long-term availability of fuel resources.

Current thermal-spectrum nuclear power reactors extract less than one percent of the energy content of mined uranium, the rest remaining in the SUNF and the depleted uranium from enrichment activities. Thus, the growing stockpiles of 1) slightly utilized nuclear fuel, 2) reprocessed plutonium and uranium, and 3) depleted uranium hold a large amount of energy, sufficient to meet mankind's energy needs for millennia. This situation has resulted in research into fuel cycles and reactors to exploit a higher fraction of the energy content of mined uranium.

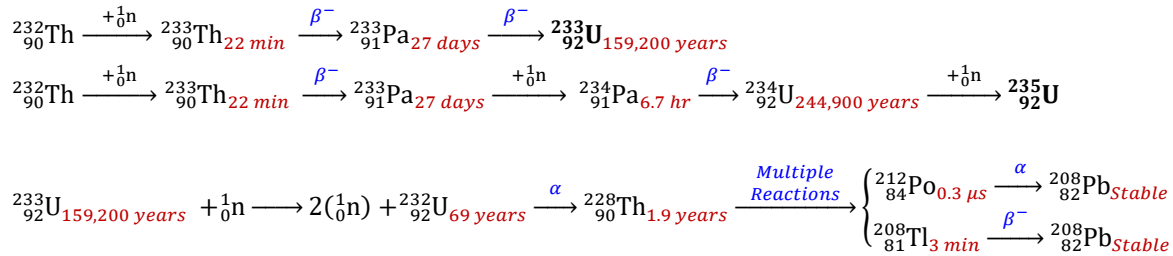
Breeding refers to the production of fissionable nuclides via the transmutation of fertile nuclides. For net production, the rate at which fissionable nuclides are produced must be greater than the rate at which they are consumed, corresponding to a value greater than 1 for the *breeding ratio*:

$$\text{Breeding Ratio} = \frac{\text{Rate of production of fissionable nuclides}}{\text{Rate of consumption of fissionable nuclides}} > 1.$$

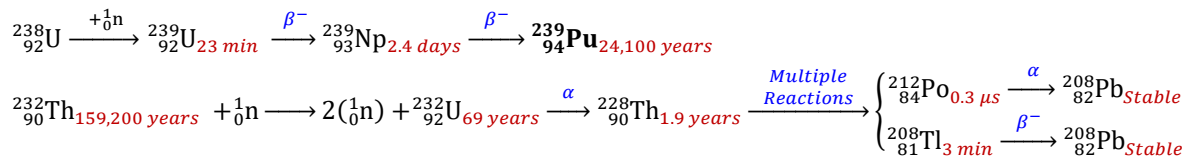
In such a scenario, the fissile nuclide inventory in nuclear fuel would remain stable, allowing the fuel to burn a significant fraction of its fertile inventory, which makes up the lion's share of nuclides of typical nuclear fuel.

Reaction paths for $^{232}_{90}\text{Th}$ breeding are shown below, the red time value associated with each nuclide corresponding to its half-life. Both reaction paths lead to a fissile nuclide, highlighted in bold. However, the first reaction path consumes only one neutron, while the second consumes 3 neutrons. The second reaction path has profound consequences for the thorium fuel cycle and for thorium breeding since it places more demands on neutron production and/or economy. A by-product of thorium breeding is $^{232}_{92}\text{U}$, which includes strong γ -emitters in its

decay chain, leading to high radioactivity. On one hand, this high radioactivity may be considered advantageous as it makes the fuel proliferation resistant. On the other hand, it makes the fuel more difficult to reprocess. However, $^{232}_{90}\text{Th}$ transmutes fairly efficiently into fissile $^{233}_{92}\text{U}$ via a single neutron capture and also has a non-negligible fission cross-section for thermal neutrons. The thorium fuel cycle underpins several ADS concepts for nuclear power generation (section 4.6). It is also possible to use a thorium-based fuel cycle in CANDU PT-HWR reactors [35][36][37][38].



The breeding reaction chain for $^{238}_{92}\text{U}$ is shown below. While $^{233}_{92}\text{U}$ can be effectively bred from $^{232}_{90}\text{Th}$ in a thermal-spectrum reactor, breeding $^{239}_{94}\text{Pu}$ from $^{238}_{92}\text{U}$ requires fast neutrons which are not available in large numbers in thermal-spectrum reactors. Nonetheless, CANDU® reactors do breed $^{239}_{94}\text{Pu}$, which accounts for approximately 40% of total power production [39]. A dual-zone CANDU® reactor has been proposed to increase the usage of $^{238}_{92}\text{U}$ [40][41]. The reactor would include a thermal neutron zone for fission and energy generation and a sub-critical epithermal zone which makes use of excess free neutrons generated in the thermal zone for breeding.



4.4 Thermal-Spectrum Reactors

Prompt neutrons emitted when $^{235}_{92}\text{U}$ undergoes fission are highly energetic. The fission cross-section of $^{235}_{92}\text{U}$ is low for these fast neutrons, making it difficult to sustain the fission chain reaction. In a thermal-spectrum reactor, this issue is dealt with in two ways:

1. The fuel is enriched, as discussed in Section A.4.3, to increase the density of fissile nuclides with which the neutrons can interact.
2. Fuel is surrounded by a *moderator*, which absorbs part of a neutron's energy during a collision, without, however, capturing the neutron and thus preventing it from contributing to the fission chain reaction. Since the fission cross-section of $^{235}_{92}\text{U}$ increases when the neutron energy decreases, each emitted neutron becomes more efficient at inducing fission. Suitable moderators include graphite, regular water, and

heavy water⁹. Thermal-spectrum reactors require only modest or, in the case of CANDU® reactors, no fuel enrichment.

The fertile nuclide $^{238}_{92}\text{U}$ also contributes indirectly to the chain reaction. While its fission cross-section for thermal neutrons is negligible, its capture cross-section for fast neutrons is appreciable. Thus, some of the fast prompt neutrons emitted in a thermal-spectrum reactor are captured by $^{238}_{92}\text{U}$, which then undergoes a two-stage β -decay to yield the nuclide $^{239}_{94}\text{Pu}$, which is fissile. Thus, all conventional thermal-spectrum reactors constantly breed new fissile fuel, with, however, a breeding ratio smaller than 1, such that the concentration of fissile material still decreases with time.

Most land-based power reactors in the world are thermal-spectrum reactors, corresponding to more than 19,000 years of operating experience globally.

4.5 Fast-Spectrum Reactors

In a fast-spectrum reactor, the neutrons are not slowed down using a moderator. Instead, criticality is achieved by compensating for the low probability¹⁰ that a fast neutron will cause fission when it encounters a $^{235}_{92}\text{U}$ nuclide, and by taking advantage of inherent characteristics of the interaction of fast neutrons with various nuclides:

1. The fuel composition is adjusted to increase the probability that a neutron will encounter a fissionable nuclide before it is captured by a non-fissionable nuclide and thus prevented from contributing to the fission chain reaction:
 - a. The fuel can be more highly enriched in $^{235}_{92}\text{U}$: though the fission cross-section is much lower for fast neutrons than for thermal neutrons, it remains appreciable for fast neutrons. Thus, on its own, $^{235}_{92}\text{U}$ can sustain the fission chain reaction in a fast-spectrum reactor, provided the fuel is sufficiently enriched.
 - b. A fuel comprising a mixture of $^{235}_{92}\text{U}$ and $^{239}_{94}\text{Pu}$ can be used.
2. A coolant is used which does not interfere with the fission chain reaction: a liquid metal or gas having a small neutron absorption cross-section.
3. On average, more neutrons are generated per fission with fast neutrons than with thermal neutrons.
4. The fission cross-section of $^{238}_{92}\text{U}$ is very low for thermal neutrons but it is appreciable for fast neutrons. Thus, in a fast-spectrum reactor, this isotope can contribute significantly to the fission chain reaction, the more so that it is the most abundant isotope of uranium and is thus automatically present in elevated concentrations in nuclear fuels that are not very highly enriched.

⁹ Heavy water is water in which hydrogen is replaced with deuterium. A hydrogen nucleus has only one proton, while a deuterium nucleus has one proton and one neutron. The chemical formula for water is H_2O . Heavy water is usually written D_2O , even though there is no element “D” in the periodic table.

¹⁰ About 585 times lower than for a thermal neutron.

5. As discussed in section 4.3, $^{238}_{92}\text{U}$ can capture a fast neutron then β -decay to $^{239}_{94}\text{Pu}$, which has a large fission cross-section for fast neutrons. This reaction pathway results in a constant re-supply of fissionable nuclides. If the breeding ratio of the reactor is greater than 1, the reactor is said to be operating as a breeder. Conversely, if the breeding ratio is less than 1, the reactor is said to be operating as a burner.

Fast-spectrum reactors have been an integral part of the international strategy for the long-term sustainability of nuclear power generation, with periodic IAEA and NEA status updates [42][43][44]. A recent overview of fast-spectrum reactors past and present was also provided by the World Nuclear Association ([Fast Neutron Reactors - World Nuclear Association](#) [45]). A summary highlighting important developments and experience is as follows:

1. Over the last several decades, about 20 land-based fast-spectrum reactors have been built and operated which have provided hundreds of years of fast-spectrum reactor operating experience globally.
2. Several sodium-cooled reactors have operated successfully. At the same time, however, many have experienced major difficulties, including sodium fires.
3. It has been demonstrated conclusively that a breeding ratio greater than 1 can be achieved, and that recycled fuel can be burned in a fast-spectrum reactor [46].
4. Fast-spectrum reactors are currently considered economically uncompetitive with thermal-spectrum reactors. Nonetheless, extensive research into fast-spectrum reactors continues worldwide, and many ADS concepts for nuclear power generation and SUNF transmutation incorporate a fast-spectrum sub-critical core.
5. For each neutron absorbed, the probability of fission for all actinide isotopes is significant for fast neutrons, including for those nuclides for which this probability is negligible for thermal neutrons [47]. This property of fast neutrons has the following consequences:
 - a. SUNF from fast-spectrum reactors should be less radiotoxic than SUNF from thermal-spectrum reactors.
 - b. A fast-spectrum reactor could potentially be used to burn reprocessed SUNF from thermal-spectrum reactors, thereby lessening the burden on a deep geological repository.
 - c. Fast-spectrum reactors were seen from the outset as a way to deal with radioactive waste accumulated over decades of operation of thermal-spectrum reactors, and as a way to extract a much larger portion of the energy in nuclear fuel.
 - d. Several proposed ADS for nuclear power generation and radioactive waste management include a sub-critical core operating in the fast-spectrum regime.
6. The neutron loss to fission products is larger in a fast-spectrum reactor than in a well moderated thermal-spectrum reactor [47].
7. Fast-spectrum reactors have generally proven to be more expensive to construct and more difficult to operate than thermal-spectrum reactors, largely due to the need for liquid metal or gas cooling to avoid moderating the prompt fission neutrons [42]. At the

time of writing, there are only two fast power reactors operating in Russia and one pilot scale fast-spectrum reactor operating in India.

4.6 ADS for Radioactive Waste Transmutation/Destruction and Fission-Based Nuclear Power Generation

Nuclear power has the potential to sustainably meet future generations' energy needs over the long term, provided sufficient fissile material is available and/or it becomes possible to make more efficient use of fissile, fissionable, and fertile nuclides¹¹. Public concerns regarding the perceived long-term hazard associated with radioactive waste must also be addressed.

ADS potentially offer a way to generate fissile material for the long-term viability of nuclear power generation, and also a pathway to mitigate radioactive waste. In an ADS power generator or transmuter/incinerator, a heavy-metal target, such as mercury, lead, or tungsten, is bombarded with accelerated protons to generate neutrons by spallation, as in the neutron spallation sources for research discussed in Section 3.3. The spallation neutrons, which can be moderated if desired, drive fission in a sub-critical fuel assembly, most often comprising a blanket surrounding the neutron source. All the neutrons needed to start the fission chain reaction and maintain it in the early stages are provided by the spallation source, which typically provides 20-30 neutrons per proton incident on the spallation target. However, once the fuel assembly has been activated, a smaller fraction of the required neutrons come from the accelerator, the rest being generated by fission events in the fuel assembly. Thus, an ADS for power generation operates like a conventional reactor, except that it is always sub-critical.

Spallation neutron sources with high-energy and high-current proton accelerators, as described in section 3.3, have been proposed as a source of neutrons to perform one or more of the following functions:

1. Drive a sub-critical fuel assembly to generate electricity.
2. Breed fissile material from the fertile nuclides $^{238}_{92}\text{U}$ and $^{232}_{90}\text{Th}$ to ensure the long-term availability of fissile material to fuel nuclear reactors. In the early 1960s, prior to the discovery of substantial uranium resources, world shortages of fissile material were considered to be a major impediment to the deployment of nuclear power and thus led many countries, including Canada, to propose research programs to develop an ADS breeder [48][49].
3. Mitigate radioactive waste such as long-lived fission products and activation products found in SUNF by transmuting long-lived radioactive species either through neutron capture, which converts a long-lived radioactive nuclide into a short-lived one, or fission, which replaces a long-lived radioactive nuclide with two shorter-lived ones (section 4.6).
4. Mitigate the problem of radioactive minor actinides (various isotopes of Np, Am, and Cm) found in SUNF by transmuting them from non-fissile to fissile isotopes, which undergo fission, or to cause direct fast fission of such isotopes in a fast-spectrum sub-critical reactor, which is driven by an accelerator-based neutron source. At neutron

¹¹ Conventional thermal power reactors extract only ~1% of the total energy content of the fuel.

energies above 1 MeV, most minor actinides will undergo fission, with a fission cross section between 1 barn and 2 barns.

ADS to perform these functions have been proposed since the early 1950s, and several roadmaps by various nations have been developed. A selection of these projects and roadmaps is provided in Table 6. For each entry, the current status of the project is included, along with a brief description of the scope of the proposal or project and references with additional details.

Table 6: ADS proposals past and present for fission power generation, breeding, and spent nuclear fuel transmutation. Institutional acronyms are included at the end of the table.

Year(s)	Institution	Current Status	Description
1950s to 1970s [48][49][50]	AECL	Not pursued	Intense Neutron Generator (ING) Breed $^{233}_{92}\text{U}$ or $^{239}_{94}\text{Pu}$ to generate a stock of fissile material. Electro-Breeder Concept using ING to drive a sub-critical fission reactor with ($^{239}_{94}\text{Pu}$, $^{238}_{92}\text{U}$) or ($^{233}_{92}\text{U}$, $^{232}_{90}\text{Th}$) fuels.
1949-1954 [51]	LLNL	Program was terminated when extensive deposits of mineable uranium were found in the U.S.	Materials Testing Accelerator (MTA) Deuteron accelerator and target assembly for breeding $^{233}_{92}\text{U}$ and $^{239}_{94}\text{Pu}$. A conceptual design of a production plant was developed and the necessary capital investment was estimated.
1979 [52]	BNL	Not pursued	Linear Accelerator Fuel Enricher Generator (LAFER) combined with Accelerator Fuel Producer and Fission Product Exterminator (APEX) Regenerate / burn LWR SUNF one or more times by breeding $^{239}_{94}\text{Pu}$, without reprocessing, followed by transmutation of fission products.
1980 [53]	ORNL	Feasibility study	Feasibility study for actinide partitioning and transmutation using light water reactors, fast-spectrum reactors, and ADS. The study included cost analyses.
1981 [54]	JAERI	Not pursued	Thorium Molten-Salt Nuclear Energy Synergetics (THORIMSNES) Molten salt based ADS to breed $^{233}_{92}\text{U}$ and generate electricity.
1992 [55][56][57]	LANL	Not pursued.	Accelerator Transmutation of Nuclear Waste (ATW) Waste transmutation with optional electricity generation. Both thermal and fast transmuters were investigated. Plutonium and the actinides were to be separated from SUNF using an existing LANL process, mixed into a molten salt, then transmuted. It was claimed that ATW would eliminate the need for nuclear waste storage in a DGR.

Canadian White Paper on Accelerator Driven Systems (ADS) – Past Experience, Present Status and the Future Benefits for Canada

153-129100-REPT-005718 Rev. 0

Page 30 of 67

Year(s)	Institution	Current Status	Description
1993 [58]	CERN	Not pursued.	Energy Amplifier (EA): thorium based Generate electricity in a self-sustaining way by breeding then burning $^{233}_{92}\text{U}$ in a sub-critical assembly using thermal neutrons. Thorium was selected as the fuel because it is abundant and does not result in the formation of plutonium or minor actinides. The proposed device would operate at a neutron flux similar to that in a conventional thermal power reactor. This detailed publication included a cost estimate.
1995 [59]	CERN	Not pursued	Fast Energy Amplifier (FEA): plutonium-based This proposal was an extension of the earlier thorium-based Energy Amplifier to allow the burning of actinides and plutonium using a fast neutron spectrum.
1999 [60]	LANL	USDOE report to congress	Roadmap for developing Accelerator Transmutation of Waste Report requested by congress to evaluate ATW as to potential and costs. It was determined that no current P&T system offered sufficient promise to abandon the once-through cycle.
2001 [61]	European Technical Working Group	Roadmap	European roadmap for developing ADS for nuclear waste incineration This document provides detailed specifications for the accelerator and sub-critical assembly to be developed. It also provides a summary of activities in Japan and the United States, and also a comprehensive list of European projects past and present.
1998 – [62][63]	SCK-CEN MYRRHA (follow-on from ADONIS)	Under construction.	Multi-purpose Hybrid Research Reactor for High-tech Applications (MYRRHA) ADS for generating electricity and breeding fissile materials. Accelerator delivering a 600 MeV/ 2.5 mA proton beam to a liquid lead-bismuth (Pb-Bi) spallation target coupled to a Pb-Bi cooled sub-critical fast-spectrum nuclear core. Project timeline has evolved significantly since its first inception. The risks involved in this complex development are well recognized. The project is thus structured such that, should the coupling of the two complex systems prove impossible, the accelerator will be operated independently for other uses, and the reactor will be operated as a standalone critical fast-neutron reactor for research.
2003 [64][65]	BARC	Under construction	India ADS for power generation, breeding, and SNF transmutation Superconducting radio-frequency accelerator delivering a 1 GeV / 30 mA proton beam. Several scenarios are under

Canadian White Paper on Accelerator Driven Systems (ADS) – Past Experience, Present Status and the Future Benefits for Canada

153-129100-REPT-005718 Rev. 0

Page 31 of 67

Year(s)	Institution	Current Status	Description
			investigation, all focused on allowing India to benefit from its large thorium reserves for nuclear power generation. Scenario 1: Power producing breeder ADS Scenario 2: Heavy water moderated thorium-burning ADS Scenario 3: Fast-spectrum thorium burning ADS Scenario 3: ADS production of $^{233}_{92}\text{U}$ for critical reactors Scenario 4: Thorium use in molten salt reactors
2006	NSCKIPT and ANL	Under active development	Ukraine Electron Accelerator Neutron Source Accelerator delivering a 150 MeV / 0.7 mA electron beam to a solid uranium or tungsten target coupled to a thermal-spectrum sub-critical assembly (water-moderated and cooled, 20% enriched uranium fuel). Since electrons are much easier to accelerate than protons, electron accelerators have a significant cost advantage. However, electrons yield fewer spallation neutrons per impact.
2010 [66][67]	Muons Inc. ORNL PNNL, BNL Texas A&M ...	Under active development	MU*STAR Superconducting radio-frequency proton accelerator delivering a 1 GeV / 2.5 mA proton beam to a liquid lead spallation target coupled to a sub-critical thermal-spectrum molten salt-fuelled core. Only passive air cooling is required. Molten salt fuel is continually reprocessed, requiring hot cells for remote fuel handling and pyrochemical operations.
2011 [68][69][70]	CAS, INEST	Under construction	Future Advanced Nuclear Fission Energy-ADS Transmutation System, which includes: 1) China initiative Accelerator Driven System (CiADS) 2) China Lead-Based Reactor (CLEAR) Superconducting radio-frequency proton accelerator delivering a 0.5 GeV / 5 mA proton beam to a liquid lead-bismuth eutectic spallation target coupled to a pool-type fast-spectrum reactor fuelled with 19.75% enriched UO_2. The reactor can be operated in both critical and sub-critical modes. The construction of the accelerator is expected to be completed in 2027. This development program can be expected to benefit from experience gained constructing and operating the China Experimental Fast Reactor (CEFR).
2019 [71]	NEA		Review of operating and forthcoming experimental facilities for advanced fuel cycles This document covers existing and upcoming facilities associated with separation processes related to current and future fuel cycles.

Year(s)	Institution	Current Status	Description
	AECL = Atomic Energy of Canada Limited ANL = Argonne National Laboratory BARC = Bhabha Atomic Research Centre (India) BNL = Brookhaven National Laboratory CAS = Chinese Academy of Sciences CERN = European Council for Nuclear Research INEST = Institute of Nuclear Energy Safety Technology (China) JAERI = Japan Atomic Energy Research Institute LANL = Los Alamos National Laboratory LLNL = Lawrence Livermore Laboratory NSCKIPT = National Science Center Kharkov Institute of Physics and Technology (Ukraine) ORNL = Oak Ridge National Laboratory PNNL = Pacific Northwest National Laboratory SCK CEN = Belgian Nuclear Research Centre USDOE = United States Department of Energy		

Some advantages, disadvantages, and challenges associated with ADS for fission power generation and radioactive waste transmutation are discussed below.

Advantages:

1. It is often stated that an ADS for power generation is inherently safer than a conventional nuclear power reactor, since the ADS can be shut down by simply turning off the accelerator, thereby cutting off the supply of spallation neutrons needed to maintain criticality. The strong safety record of nuclear power generation in Canada and the ease with which conventional power reactors are shut down are such that this advantage could be considered negligible.
2. Since the fuel assembly is relieved of the responsibility of generating the free neutrons needed to maintain criticality, there is the possibility of burning a wider variety of nuclides, including minor actinides and transuranics contained in SUNF from thermal-spectrum reactors. ADS are also expected to be relatively insensitive to fuel variations. However, it is necessary to closely control the reactivity of the sub-critical assembly to ensure stable and economical performance.
3. The neutron energy spectrum can be tailored, making it possible to design systems with either a thermal spectrum, a fast spectrum, or a combined spectrum.
4. Another advantage of ADS relative to either a thermal-spectrum or fast-spectrum reactor is that they do not require a minimum core size, or inventory or density of fissile fuel, to operate, to generate high neutron fluxes, and to generate power. Most fast-spectrum reactors require a minimum fissile content of 12 to 15 wt.% to stay critical and must be refuelled periodically to stay critical and to be economical to operate. However, ADS with a sub-critical fast-spectrum reactor can operate with a much lower fissile content.

5. It is generally agreed that a partitioning/transmutation strategy would not remove the need for a deep geological repository. However, it could decrease the required storage volume of the DGR and/or ease the technical requirements. In principle, an ADS could be used to destroy all minor actinides, and possibly transmute a number of LLFPs and LLAPs. In this scenario, it would only be necessary to place in a DGR those radioactive fission products that have a low neutron capture cross section and that are not easily transmuted to stable or short-lived isotopes. Examples of such “*hard-to-transmute*” radioisotopes include $^{90}_{38}\text{Sr}$ and $^{137}_{55}\text{Cs}$.

Disadvantages/Challenges:

1. ADS require the coupling of two highly complex systems: a next-generation accelerator and a sub-critical fuel assembly, both of which require considerable technological development.
2. Current accelerator technology cannot provide the required performance. In particular, the reliability of the accelerator and the longevity and performance of the spallation target require very significant improvements.
3. Most ADS proposals for power generation call for a fast neutron spectrum to minimize the radiotoxicity of SUNF. As in critical fast-spectrum reactors, it would be necessary to rely on liquid metal or gaseous cooling, which have proven challenging to manage safely. However, in principle, an ADS system could also operate successfully with a sub-critical thermal-spectrum reactor. In such a scenario, most of the destruction of minor actinides would occur indirectly, first through transmutation from fissionable to fissile isotopes by neutron capture, and then subsequent fission.
4. As in a conventional reactor, decay heat remains a concern after the system is shutdown, such that active cooling of the fuel assembly must be maintained even after the accelerator is shut off.

The main accelerator requirements for ADS for nuclear fission, and the reason behind each requirement, are given in Table 7. Currently, accelerators do not have the required performance characteristics and reliability for nuclear fuel transmutation and fission power generation.

Table 7: Accelerator Requirements for Fission Power Generation and Radioactive Waste Transmutation.

Characteristic	Required	Reason for Requirement
Beam power	10 – 30 MW [61]	Minimum power to ensure the efficient and economical operation of the ADS.
Beam energy	0.5 – 2 GeV Currently available	This parameter determines the number of neutrons generated per proton, which saturates at ~2 GeV. Higher proton energies lead to more damage to the target [2][61].
Beam structure	Continuous-wave or high-frequency pulsed beam.	Most proposals require a continuous-wave accelerator to avoid heating/cooling transients which can be very hard on structural materials. However, it is now believed that a pulsed beam could be acceptable, provided the period is much smaller than the time constants for these deleterious processes [61].
Beam loss rate (accelerator)	< 1 W/m	A low beam loss rate is necessary to allow hands-on maintenance while the accelerator is running [61]. The current state of the art is not relevant as there are no accelerators in operation that meet the main requirements of power and reliability.
Flexibility	Ability to vary beam intensity by a factor of two.	This requirement is to provide operational flexibility [61]. The current state of the art is not directly relevant, as spallation neutron sources are generally not designed for this level of flexibility.
Reliability	Per year, fewer than 2 – 3 unplanned operational interruptions longer than 1 second. Full-time operation.	A 10-100-fold improvement is required [72][73][74]. Currently, the best high-performance spallation sources: 1) experience on the order of hundreds of trips per day longer than a few seconds, and 2) operate for a maximum of ~6000 hours per year.
Beam efficiency	≥ 25%	Currently 3 – 19% [72]. $\text{Beam efficiency} = \frac{\text{Beam power}}{\text{Total energy drawn from grid}}$
Affordability	Including all associated infrastructure, the cost of the accelerator should not exceed ~30% of the total system cost [2][61].	This requirement will be strongly influenced by the added value provided by the accelerator (cost savings, perceived risk reduction of an ADS versus a conventional nuclear reactor, etc.). A multi-use accelerator incorporating multiple target stations could be costed differently.

5. Accelerator Systems to Support Fusion Energy Development

Because of the potential of nuclear fusion to provide clean abundant power, research into fusion-based power generation has exploded in the past ~30 years, both at government laboratories and at private companies, which often benefit from government subsidies. An exhaustive account of the state of fusion energy as of 2022 is provided in a recent CNL report

[75]. A brief introduction to fusion power generation is provided in Appendix C, which also includes a partial list of government facilities and private companies currently active in fusion research.

5.1 Use of Accelerators in Fusion Reactor Technology

Accelerators can contribute to fusion power generation directly and indirectly in a variety of ways:

1. Spallation neutron sources can be used to breed tritium from lithium-based targets [76]. Recognizing that one of the most significant challenges confronting tritium breeding from lithium is the development of an efficient extraction process, CNL recently entered into a collaboration agreement with [First Light Fusion](#) [77] to develop tritium extraction, processing, and storage [78].
2. High energy particles generated by accelerators can be injected into the plasma of a magnetic confinement fusion reactor to heat it. The injected particles transfer energy to the plasma by colliding with them. Since the plasma is ionic and its volume is large, the particles must be neutral and must be 3-4 times faster than in typical existing injectors to enable them to penetrate far enough into the plasma¹². The charged particles from accelerators must thus be made electrically neutral prior to injection. Since it is difficult to neutralize positive ions travelling at such high speeds, injectors using negative ions are under development¹³.
3. Ion beams from accelerators can be used as an alternative to lasers to drive inertial confinement fusion (Heavy Ion Inertial Fusion, HIF). In this approach, the ions must be accelerated and bunched into a pulse lasting on the order of 1 nanosecond, and multiple ion beams are required to ensure a uniform compression of the fuel pellet [79].

Estimates of the accelerator characteristics required for fusion power generation are summarized in the table below [2]. These characteristics may vary significantly depending on the function fulfilled by the accelerator.

¹² The problem is compounded in the case of magnetic confinement.

¹³ Negative ions are easier to neutralize but more challenging to create and handle than positive ions, because the additional electron that makes the ion negative is only loosely bound and thus readily lost.

Table 8: Accelerator Characteristics for Fusion Energy Generation.

Characteristic	Magnetic Confinement (heating)	Inertial Confinement
Particle type	Neutral ions	Heavy ions (e.g., Bi ⁺)
Beam type	Continuous Wave (Pulsed with high frequency may be acceptable?)	Pulsed, Frequency > 100 Hz Highly focused
Instantaneous power level	~10 MW	10 ³ – 10 ⁶ MW
Beam energy	~ 1 MeV Particles must be neutralized prior to injection into the plasma	10 GeV Bi ⁺
Beam current	Tens of Amperes	~400 mA

5.2 Accelerator-Based Irradiation Facilities for Testing Materials for Future Fission and Fusion Reactors.

In the many fission and fusion reactor concepts under development, materials will be subjected to extreme conditions, under which their performance must be well understood. Facilities are thus required to fully qualify candidate materials.

The critical reactions in a fusion reactor have an incident neutron energy threshold between 0.9 MeV and 2.9 MeV, somewhat outside the energy range of neutrons produced in a conventional fission reactor (up to ~2 MeV). Furthermore, ion implantation facilities like the [Queen's University Reactor Materials Testing Laboratory \(RMTL\)](#) [80] offer insufficient irradiation volume¹⁴ to carry out standardized mechanical property tests, and the low elastic scattering cross section for light ions makes it impractical to achieve damage levels representative of those in a working reactor. Spallation neutron sources produce a wide spectrum of energies, up to hundreds of MeV, leading to potentially different types of defects [81].

The [Irradiation Fusion Materials Irradiation Facility \(IFMIF\)](#) [82] is an accelerator-based neutron source that produces a large neutron flux with a spectrum similar to that expected at the first wall of a fusion reactor. The basis of the neutron production is the deuterium-lithium nuclear reaction. The IFMIF project was started in 1994 as an international scientific research program, carried out by Japan, the European Union, the United States, and Russia, and managed by the International Energy Agency. Since 2007, it has been pursued by the Japanese Government and EURATOM under the Broader Approach Agreement in the field of fusion energy research,

¹⁴ The irradiation volume of maximum values of a few hundreds µm thick layer

through the IFMIF/EVEDA project, which conducts engineering validation and engineering design activities for IFMIF.

Though not providing an ideal neutron energy spectrum, fission research reactors such as the [High Flux Isotope Reactor](#) [83] at Oak Ridge National Laboratory can provide a partial simulation of irradiation expected in a deuterium-tritium fusion reactor. The microstructure and mechanical properties of irradiated materials are then characterized in hot cell facilities such as those at Canadian Nuclear Laboratories.

6. An Alternative / Complementary Technology for ADS: The CANDU PT-HWR

The CANDU® pressure tube heavy water reactor (PT-HWR) has served Canada well for many decades. Thanks to its online refuelling capability, the high neutron economy due to the heavy water moderator and coolant, and a relatively simple fuel bundle design, it can credibly lay claim to being one of the most versatile commercial power reactors in the world.

As Canada looks to increase nuclear power generation capacity in the years ahead [84], the following ideas should be taken into consideration when assessing the future need for alternative reactor technologies and ADS for achieving long-term goals of nuclear energy sustainability, security, and safety, while minimizing the liabilities of radioactive waste:

1. CANDU® reactors can be used to burn plutonium and minor actinides to decrease the burden on the deep geological repository [20][29][85].
2. Thanks to many investigations of thorium fuel cycles in CANDU® reactors, there is significant experience and expertise to support thorium fuel cycles both in CANDU® and in other reactor technologies [37][38].
3. Modified CANDU® reactor concepts have been proposed to increase the energy extracted from nuclear fuel, with no need for reprocessing [40][41].

Thus, while various design concepts for ADS have been proposed and investigated over the last 70 years (since the early 1950s) for the purpose of consuming/destroying minor actinides, for breeding new fissile fuel, for generating power, and for producing certain medical and industrial isotopes of commercial value, it is worth considering that CANDU® PT-HWRs can be adapted for many of the same applications. Thus, it may not be necessary to construct a large future fleet of ADS systems. Instead, it may be sufficient and more cost-effective to implement a mixed-fleet or tandem fleet of PT-HWRs, augmented by a smaller number of national ADS facilities.

7. Summary and Conclusions

Significant human and financial resources are being invested by many nations to develop and deploy accelerator-based neutron sources and accelerator-driven sub-critical systems (ADS) for various applications.

Accelerator-Based Systems for X-Ray and Neutron Irradiation

Accelerator-based systems for generating X-rays and neutron beams have been deployed successfully in Canada, the United States, the United Kingdom, Europe, China, Japan, and other

nations. These light sources and spallation neutron sources are relatively mature technologies which can be deployed with little risk and with well-quantified costs and operational requirements. In addition to providing the necessary particle beams, the high-performance accelerators which underpin these facilities are used as test beds to develop new accelerator technologies.

With the shutdown of the NRU multi-purpose research reactor in 2018, Canada, which considers itself to be a “*Tier 1 Nuclear Nation*”, currently has no world-class facility for neutron irradiation of materials and fuels for fission and fusion reactors. Currently, in Canada, there are only the modest capabilities offered by the McMaster Nuclear Reactor (MNR) and the Queen’s University Reactor Materials Testing Laboratory (RMTL).

An accelerator-based spallation neutron source facility could be developed in Canada that would serve multiple needs for neutron irradiation testing of materials and for neutron beam experiments for research. This type of investment, while potentially substantial, is considered to be a relatively low-risk approach with a high probability of achieving success and delivering added value in the short-term (less than 20 years). The capabilities offered by such a facility could complement the irradiated materials characterization methods offered by the Advanced Nuclear Materials Research Centre (ANMRC) which is currently under construction by CNL at the Chalk River Laboratories. A Canadian national spallation neutron source could also complement the Canadian Light Source, which is currently undergoing significant upgrades to ensure that it continues to offer world-class performance.

Progress in Accelerator Driven Sub-Critical Systems

It is anticipated that the use of ADS for radioactive waste transmutation/destruction, fissile fuel breeding, and nuclear power generation will require 20 or more years of focused effort and investment to bring these applications to practical fruition and commercialization. However, the efforts currently underway with key ADS projects, such as the MYRRHA European ADS facility in Belgium [61], [62], and the CiADS facility in China [68], [69], [70], are very encouraging.

Additional efforts will be required to achieve the required improvements in the power levels, efficiency, reliability, and maintainability of both high-energy proton accelerators and spallation neutron targets. While both thermal-spectrum and fast-spectrum sub-critical reactors are relatively well characterized and understood, additional efforts in science, engineering, and technology will be required to integrate these systems with an accelerator-based spallation neutron source, and to develop high system performance and reliability.

Associated Technologies Needed for ADS Applications – Reprocessing and Recycling Irradiated Nuclear Fuels

With regards to using an ADS system for radioactive waste transmutation and fissile fuel breeding, it will also be necessary to develop and scale up safe and economically viable reprocessing methods. The availability of such processes comprises one of the main assumptions underpinning several ADS proposals. Ambitious research programs have been

launched worldwide to meet these challenges. However, it is noted that reprocessing and recycling technologies are desirable and likely needed to ensure long-term nuclear energy sustainability, regardless of the development and implementation of ADS technology.

Potential Option for Spallation Neutron Source Development in Canada in the Short-Term

From the Canadian perspective, a potential option for initial ADS development in the short-term (within the next 20 years) would be an accelerator-based, multi-target spallation neutron source facility. This facility would comprise a single high-performance particle accelerator (such as a 500-MeV to 1,000-MeV proton accelerator), coupled to multiple spallation target stations. Each target station would be tailored to a specific application.

This staged, evolutionary development approach, which is expected to be more cost-effective and lower risk than a single-use / single-purpose facility, has been implemented at both the ISIS spallation neutron source in the United Kingdom [86] and also at the ORNL Spallation Neutron Source [4]. A staged, multi-year, modular approach to facility construction, testing and commissioning is considered to be more effective in managing costs and technical risks. The main requirement would be planning to identify the appropriate accelerator performance specifications and to ensure an optimal layout of the target stations and support buildings. In this respect, the considerable experience available at the TRIUMF facility in British Columbia would be a significant asset.

An accelerator-based spallation neutron source coupled to a sub-critical reactor would augment and complement a multi-purpose research reactor. Such a facility could also be a testbed for the later development of a stand-alone commercial ADS facility for radioactive waste transmutation and fissile fuel breeding.

Considerations for Future Use of ADS in Canada – Challenges and Alternatives

In evaluating ADS for the potential applications of radioactive waste transmutation, fissile fuel breeding, and nuclear power generation for Canada, the following considerations must be kept in mind:

4. The Canadian nuclear industry has had a strong safety record over the last 50 years or more, such that the often-stated advantage that an ADS is inherently safer than a critical reactor can be credibly challenged. Thus, it is anticipated that any real or perceived safety concerns would not be a driving or deciding factor for the construction and operation of ADS in Canada.
1. Canada has limited experience in the commercial reprocessing and recycling of irradiated nuclear power reactor fuel due to:
 - a. the relatively low concentration of fissile uranium and plutonium nuclides in CANDU® SUNF compared with LWR SUNF,
 - b. the short-term costs and risks of reprocessing, have generally been shown to be higher than initially estimated,
 - c. the production of multiple partially-understood solid, gaseous, and liquid waste streams rather than a single well-understood solid waste stream.

2. However, the long-term sustainability, safety, and security of nuclear energy, while minimizing the long-term liability of radioactive waste, will likely require the implementation of nuclear fuel reprocessing and recycling, regardless of whether or not ADS facilities are constructed and operated in Canada.
3. The CANDU® pressure tube heavy water reactors (PT-HWRs), currently in operational in Canada, comprise a highly flexible and capable technology, which could be adapted to carry out a number of the applications for which ADS are considered most suited. The CANDU® reactor technology offers a multitude of possible fuel cycles: it is possible to burn plutonium and minor actinides (with reprocessing) and also, potentially, to develop a thorium-based fuel cycle. It may be advantageous to develop further advanced CANDU® reactors and fuel cycles, possibly through collaborations with other countries which also operate CANDU® reactors. In the longer-term (beyond 20 years), it may be advantageous to use a mixed fleet of ADS facilities and CANDU® reactors to carry out the key applications of radioactive waste transmutation/destruction, fissile fuel breeding, and nuclear power generation.
4. Thanks to careful community engagement, the Canadian Nuclear Waste Management Organization (NWMO) has made very good progress toward siting and developing a deep geological repository (DGR), which is considered a viable solution internationally. If slightly utilized nuclear fuel (SUNF) placed in the DGR is easily retrievable until the DGR is finally sealed, there would be an opportunity for Canada to take advantage of new developments in ADS and supporting reprocessing and recycling technologies.

8. Acronyms

ADS	Accelerator-Driven System(s)
AECL	Atomic Energy of Canada Limited
ANL	Argonne National Laboratory
ATW	Accelerator Transmutation of Waste
BARC	Bhabha Atomic Research Centre (India)
BNL	Brookhaven National Laboratory
CANDU®	Canada Deuterium Uranium
CAS	Chinese Academy of Sciences
CEFR	China Experimental Fast Reactor
CERN	European Council for Nuclear Research
CLS	Canadian Light Source
DGR	Deep Geological Repository
FP	Fission Product

HIF	Heavy Ion Inertial Fusion
HLW	High Level Waste
INEST	Institute of Nuclear Energy Safety Technology (China)
ITER	International Thermonuclear Experimental Reactor
JAERI	Japan Atomic Energy Research Institute
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore Laboratory
LLFP	Long-Lived Fission Product
LWR	Light Water Reactor
MA	Minor Actinide
MNR	McMaster Nuclear Reactor
NWMO	The Nuclear Waste Management Organization (Canada)
MYRRHA	Multi-Purpose Hybrid Research Reactor for High-Tech Applications
NSCKIPT	National Science Center Kharkov Institute of Physics and Technology (Ukraine)
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
RMTL	Reactor Materials Testing Laboratory (Queen's University)
SCK CEN	Belgian Nuclear Research Centre
SNF	Spent Nuclear Fuel
SNS	The Spallation Neutron Source, Oak Ridge National Laboratory
SUNF	Slightly Utilized Nuclear Fuel
TRU	Transuranic element
USDOE	United States Department of Energy

9. Acknowledgements

The author recognizes the help and assistance provided by the following staff: Blair P. Bromley (Project Lead / Principal Investigator), Zahra Yamani, Helmut Fritzsche, Alexandre Trottier, Ashlea V. Colton, Niki Lachance, Tina Wilson, and Ali Siddiqui (Head of Directorate).

This high-level review and assessment was funded under Project LDST-55020.0.A221: Development of Canadian White Paper on Accelerator Driven Systems (ADS) (2023-2024).

10. References

- [1] Canadian Small Modular Reactor Roadmap Steering Committee "A call to action: A Canadian roadmap for small modular reactors," 2018, https://smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf?x93402.
- [2] U.S. Department of Energy, "Accelerators for America's future," 2010, https://science.osti.gov/-/media/hep/pdf/files/pdfs/Accel_for_Americas_Future_final_report.pdf.
- [3] "Canadian Light Source (CLS) - LINAC Upgrade," (webpage) <https://www.lightsource.ca/public/news/2022-23-q3-oct-dec/canadian-light-source-begins-major-upgrade.php>.
- [4] "Spallation Neutron Source," (webpage) <https://neutrons.ornl.gov/sns>.
- [5] "Paul Scherrer Institute (PSI) Proton Accelerator", (webpage) <https://www.psi.ch/en/media/the-psi-proton-accelerator>.
- [6] "European Synchrotron Radiation Facility (ESRF)," (webpage) <https://www.esrf.fr/cms/live/live/en/sites/www/home.html>.
- [7] "Kyoto University Innovation Research Laboratory Accelerator," (webpage) <https://www.rri.kyoto-u.ac.jp/en/facilities/irl>.
- [8] "Large Hadron Collider (CERN)," (webpage) <https://home.cern/science/accelerators/large-hadron-collider>.
- [9] "IAEA Interactive Map Of Synchrotron and Neutron Spallation Facilities," (webpage) <https://nucleus.iaea.org/sites/accelerators/Pages/default.aspx>.
- [10] "IAEA Up-to-date List of Synchrotron Facilities," (webpage) <https://nucleus.iaea.org/sites/accelerators/lists/synchrotron/allitems.aspx>.
- [11] V. Azhazha, A. Dovbnya et al., "Project of a neutron source based on the sub-critical assembly driven by electron linear accelerator," in Proceedings of the XXIV Linear Accelerator Conference (LINAC08), Victoria, BC, Canada, 29 September - 3 October 2008, 2008, <https://accelconf.web.cern.ch/LINAC08/papers/tup068.pdf>.
- [12] "Spallation Neutron Sources (IAEA)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [13] "McMaster Nuclear Reactor (MNR)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [14] J.-P. Bouttes, Fondation pour l'innovation politique (fondapol.org), "Nuclear waste: A comprehensive approach 1 (Waste and nuclear waste: decay periods and potential hazards)," 2022, <https://www.fondapol.org/en/study/nuclear-waste-a-comprehensive-approach-1/>.
- [15] "Nuclear Waste Management Organization (NWMO, Canada)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.

- [16] "West Valley: Fuel reprocessing history (New York State government)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [17] "U.K. spent nuclear fuel reprocessing ends (World Nuclear News)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [18] World Nuclear Association, "China's Nuclear Fuel Cycle," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [19] M. Bunn, H. Zhang et al., "The cost of reprocessing in China," Cambridge, Mass.: Project on Managing the Atom, Report, Belfer Center for Science and International Affairs, Harvard Kennedy School, 2016, <https://www.belfercenter.org/sites/default/files/legacy/files/The%20Cost%20of%20Reprocessing.pdf>.
- [20] P. G. Boczar, J. T. Rogers et al., "Considerations in recycling used natural uranium fuel from CANDU reactors in Canada," in Proceedings of the 31st Annual Conference of the Canadian Nuclear Society (CNS2010), Montréal, Québec, Canada, 24-27 May 2010, 2010, https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/101/49101472.pdf.
- [21] F. von Hippel, "Managing spent fuel in the United States: The illogic of reprocessing," International Panel on Fissile Materials report, No. 3, 2007, <https://fissilematerials.org/library/rr03.pdf>.
- [22] H. A. Feiveson, Z. Mian et al., "Managing spent fuel from nuclear power reactors: Experience and lessons from around the world," International Panel on Fissile Materials report, No. 10, 2011, <https://fissilematerials.org/library/rr10.pdf>.
- [23] J.-M. Charpin, B. Dessus et al., Commissariat Général du Plan (France), "Report to the Prime Minister: Economic forecast study of the nuclear power option," 2000, <https://fissilematerials.org/library/cha00.pdf>.
- [24] U.S. Department of Energy, National Nuclear Security Administration, "Report to Congress: Disposition of surplus defense plutonium at Savannah River site," 2002, <https://www.nci.org/pdf/doe-pu-2152002.pdf>.
- [25] U.S. Department of Energy, Office of the Inspector General, "Cost and schedule of the mixed oxide fuel fabrication facility at the Savannah River site," Audit Report DOE/IG-0911, 2014, <https://www.energy.gov/sites/default/files/2014/05/f16/DOE-IG-0911.pdf>.
- [26] (2023). "Reprocessing of spent nuclear fuel in Japan (International Panel on Fissile Materials)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [27] J. D. Sullivan, P. G. Boczar et al., "Benefits of the DUPIC fuel cycle strategy," in Proceedings of the International Conference on Future Nuclear Systems (Global'99), Las

- Vegas, Nevada, USA, 29 August - 3 September 1999, 1999,
http://inis.iaea.org/search/search.aspx?orig_q=RN:53059409.
- [28] J. Whitlock, "The evolution of CANDU® fuel cycles and their potential contribution to world peace," in *Proceedings of the First International Youth Nuclear Congress (IYNC 2000)*, Bratislava, Slovakia, 9-14 April 2000, 2001,
https://inis.iaea.org/collection/NCLCollectionStore_Public/33/011/33011302.pdf.
- [29] P. G. Boczar, M. J. N. Gagnon et al., "Advanced CANDU systems for plutonium destruction," in *Advanced Nuclear Systems Consuming Excess Plutonium*, E. R. Merz and C. E. Walter, Eds., Dordrecht, Springer Netherlands, pp. 163-179, 1997,
https://doi.org/10.1007/978-94-007-0860-0_14.
- [30] D. Kramer, "US takes another look at recycling nuclear fuel," *Physics Today*, vol. 77, no. 2, pp. 22-25, 2024, <https://doi.org/10.1063/pt.mrdv.volt>.
- [31] P. Baron, S. M. Cornet et al., "A review of separation processes proposed for advanced fuel cycles based on technology readiness level assessments," *Progress in Nuclear Energy*, vol. 117, pp. 103091, 2019, <https://doi.org/10.1016/j.pnucene.2019.103091>.
- [32] "Government of Canada Technology Readiness Level (TRL) Assessment Tool," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [33] "WPFC Expert Group on Fuel Recycling and Waste Technology (EGFRW)," (webpage) https://www.oecd-neo.org/icms/pl_22421/wpfc-expert-group-on-fuel-recycling-and-waste-technology-egfrw.
- [34] "Advanced Fuels for Generation IV Reactors: Reprocessing and Dissolution (ASGARD)," (webpage) <https://cordis.europa.eu/project/id/295825>.
- [35] A. R. Bancroft and J. D. Gamble, Atomic Energy of Canada Limited, "Thorium fuel cycles in CANDU reactors: A review," Atomic Energy of Canada Limited report, AECL-8326, 1984.
- [36] M. S. Milgram, Atomic Energy of Canada Limited, "Once-through thorium cycles in CANDU reactors," Atomic Energy of Canada Limited report, AECL-7516, 1982.
- [37] M. Floyd, B. Bromley et al., "A Canadian Perspective on progress in thorium fuel science and technology," *CNL Nuclear Review*, vol. 6, no. 1, pp. 1-17, 2016,
<https://doi.org/10.12943/CNR.2016.00016>.
- [38] A. D. Mendoza España and B. P. Bromley, "A Canadian perspective of the economic issues associated with deploying thorium-based fuel cycles and breeding in heavy-water reactors," *CNL Nuclear Review*, vol. 8, no. 2, pp. 109-130, 2019,
<https://doi.org/10.12943/CNR.2017.00021>.
- [39] J. Boulton, "Management of radioactive fuel wastes: The Canadian disposal program," Atomic Energy of Canada Limited report, AECL-6314, 1978.
- [40] A. R. Dastur and A. C. Mao, "CANDU advanced plutonium burner: The Canadian response to the ALWR," *Canadian Nuclear Society (CNS) Bulletin (Technical Supplement)*, vol. 10, no. 3, 1989, <https://canteach.candu.org/Content%20Library/19890101.pdf>.

- [41] F. Allen and H. Bonin, "Extending the CANDU nuclear reactor concept: The multi-spectrum nuclear reactor " in Proceedings of the International Youth Nuclear Congress 2008 (IYNC 2008), Interlaken, Switzerland, 20-26 September 2008, 2008, <https://inis.iaea.org/collection/NCLCollectionStore/Public/40/048/40048159.pdf>.
- [42] T. B. Cochran, H. A. Feiveson et al., "Fast breeder reactor programs: History and status," International Panel on Fissile Materials report, No. 8, 2010.
- [43] International Atomic Energy Agency, "Status of fast reactor research and technology development," IAEA-TECDOC-1691, 2012, 2012, https://www-pub.iaea.org/MTCD/Publications/PDF/te_1691_web.pdf.
- [44] NEA, "Accelerator-driven systems (ADS) and fast reactors (FR) in advanced nuclear fuel cycles: A comparative study," 2002, https://www.oecd-neo.org/jcms/pl_33830/accelerator-driven-systems-ads-and-fast-reactors-fr-in-advanced-nuclear-fuel-cycles?details=true.
- [45] "Fast Neutron Reactors (World Nuclear Association)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [46] C. Westfall, "Vision and reality: The EBR-II story," *Nuclear News*, vol. 47, no. 2, pp. 25-32, 2004.
- [47] D. C. Wade and R. N. Hill, "The design rationale of the IFR," *Progress in Nuclear Energy*, vol. 31, no. 1, pp. 13-42, 1997, [https://doi.org/10.1016/0149-1970\(96\)00002-9](https://doi.org/10.1016/0149-1970(96)00002-9).
- [48] W. B. Lewis, "The significance of the yield of neutrons from heavy nuclei excited to high energies," Atomic Energy of Canada Limited report, AECL-968, 1952.
- [49] P. Grand, K. Batchelor et al., "The accelerator-breeder, an application of high-energy accelerators to solving our energy problems," *IEEE Transactions on Nuclear Science*, vol. 24, no. 3, pp. 1043-1045, 1977, <https://doi.org/10.1109/TNS.1977.4328845>.
- [50] S. O. Schriber, "Canadian accelerator breeder system development," Atomic Energy of Canada Limited report, AECL-7840, 1982.
- [51] C. M. Van Atta, "A brief history of the MTA project," Lawrence Livermore Laboratory report, UCRL-79151, 1977, http://inis.iaea.org/search/search.aspx?orig_q=RN:08322162.
- [52] M. Steinberg, J. R. Powell et al., "The linear accelerator fuel enricher regenerator (LAFFER) and fission product transmutor (APEX)," *Atomkernenergie Kerntechnik*, vol. 36, no. 1, pp. 42-46, 1980, [https://scholar.google.com/scholar_lookup?title=The%20Linear%20Accelerator%20Fuel%20Enricher%20Regenerator%20\(LAFER\)%20and%20Fission%20Product%20Transmutor%20\(APEX\)&author=M.%20Steinberg&publication_year=1979](https://scholar.google.com/scholar_lookup?title=The%20Linear%20Accelerator%20Fuel%20Enricher%20Regenerator%20(LAFER)%20and%20Fission%20Product%20Transmutor%20(APEX)&author=M.%20Steinberg&publication_year=1979).
- [53] A. Croff, J. Blomeke et al., "Actinide partitioning-transmutation program final report. I. Overall assessment," Oak Ridge National Laboratory report, ORNL-5566, 1980, <https://doi.org/10.2172/5417858>.

- [54] K. Furukawa, A. Lecocq et al., "Thorium molten-salt nuclear energy synergetics," *Journal of Nuclear Science and Technology*, vol. 27, no. 12, pp. 1157-1178, 1990, <https://doi.org/10.1080/18811248.1990.9731310>.
- [55] C. D. Bowman, "Accelerator-driven systems for nuclear waste transmutation," *Annual Review of Nuclear and Particle Science*, vol. 48, no. 1, pp. 505-556, 1998, <https://doi.org/10.1146/annurev.nucl.48.1.505>.
- [56] C. D. Bowman, E. D. Arthur et al., "Nuclear energy generation and waste transmutation using an accelerator-driven intense thermal neutron source," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 320, no. 1, pp. 336-367, 1992, [https://doi.org/10.1016/0168-9002\(92\)90795-6](https://doi.org/10.1016/0168-9002(92)90795-6).
- [57] F. Venneri, M. A. Williamson et al., "The Los Alamos accelerator driven transmutation of nuclear waste (ATW) concept development of the ATW target/blanket system," in *Accelerator driven systems: Energy generation and transmutation of nuclear waste, status report*, International Atomic Energy Agency report, IAEA-TECDOC-985, pp. 154-178, 1997, https://www-pub.iaea.org/MTCD/Publications/PDF/te_985_prn.pdf.
- [58] F. Carminati, R. Klapisch et al., "An energy amplifier for cleaner and inexhaustible nuclear energy production driven by a particle beam accelerator," CERN report, CERN-AT-93-47 (ET), 1993, <https://cds.cern.ch/record/256520/files/at-93-047>.
- [59] C. Rubbia, J. Rubio et al., "Conceptual design of a fast neutron operated high power energy amplifier," CERN report, CERN-AT-95-44 (ET), 1995, <https://cds.cern.ch/record/289551/files/cer-0210391>.
- [60] U.S. Department of Energy, "A roadmap for developing accelerator transmutation of waste (ATW) technology," DOE/RW-0519, 1999, https://sciencepolicy.colorado.edu/about_us/archives/projects/gccs/2002/jvc/pdf-docs/doe_rw-0519.pdf.
- [61] C. Rubbia, H. A. Abderrahim et al., "A European roadmap for developing accelerator driven systems (ADS) for nuclear waste incineration," 2001, <https://www.oecd-neo.org/pt/docs/ADS%20ROADMAP.pdf>.
- [62] H. A. Abderrahim and M. Giot, "The accelerator driven systems, a 21st century option for closing nuclear fuel cycles and transmuting minor actinides," *Sustainability*, vol. 13, no. 22, 2021, <https://doi.org/10.3390/su132212643>.
- [63] A. C. Mueller, "Transmutation of Nuclear Waste and the future MYRRHA Demonstrator," *Journal of Physics: Conference Series*, vol. 420, no. 1, pp. 012059, 2013, <https://doi.org/10.1088/1742-6596/420/1/012059>.
- [64] S. B. Degweker, P. V. Bhagwat et al., "Physics and technology for development of accelerator driven systems in India," *Progress in Nuclear Energy*, vol. 101, pp. 53-81, 2017, <https://doi.org/10.1016/j.pnucene.2017.04.001>.

- [65] S. B. Degweker, P. Singh et al., "Accelerator-driven systems for thorium utilization in India," in *Thorium Energy for the World: Proceedings of the ThEC13 Conference*, Geneva, Switzerland, Springer International Publishing, 2016.
- [66] C. D. Bowman, R. B. Vogelaar et al., "GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators," in *Handbook of Nuclear Engineering*, D. G. Cacuci, Ed., Boston, MA, Springer US, pp. 2841-2894, 2010, https://doi.org/10.1007/978-0-387-98149-9_24.
- [67] P. Taylor, B. Spencer et al., "Mu*Star ADSR fuel conversion facility evaluation and cost analysis," ORNL/TM-2018/989, 2019, <https://info.ornl.gov/sites/publications/Files/Pub117081.pdf>.
- [68] Z. J. Wang, F. F. Wang et al., "The status of the CiADS superconducting LINAC," in *Proceedings of the 10th International Particle Accelerator Conference (IPAC2019)*, Melbourne, VIC, Australia, 19-24 May 2019, 2019, <https://doi.org/10.18429/JACoW-IPAC2019-MOPTS059>.
- [69] Y. He, H. Jia et al., "Accelerator driven system – a solution to multiple problems of society," in *Proceedings of the 14th International Particle Accelerator Conference (IPAC2023)*, Venice, Italy, 7-12 May 2023, 2023, <https://doi.org/10.18429/JACoW-IPAC2023-FRYG2>.
- [70] Y. Wu, "Design and R&D Progress of China Lead-Based Reactor for ADS Research Facility," *Engineering*, vol. 2, no. 1, pp. 124-131, 2016, <https://doi.org/10.1016/J.ENG.2016.01.023>.
- [71] NEA, "Review of operating and forthcoming experimental facilities opened to international R&D co-operation in the field of advanced fuel cycles," 2018, https://www.oecd-neo.org/icms/pl_19894/review-of-operating-and-forthcoming-experimental-facilities-opened-to-international-r-d-co-operation-in-the-field-of-advanced-fuel-cycles.
- [72] L. Hardy, "Accelerator reliability-availability," in *Proceedings of the 8th European Particle Accelerator Conference (EPAC 2002)*, Paris, France, 3-7 June 2002, 2002, <https://accelconf.web.cern.ch/e02/PAPERS/WEXLA001.pdf>.
- [73] J. W. G. Thomason, S. A. Fisher et al., "Availability and reliability statistics at ISIS and at other high-power proton accelerators," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1053, pp. 168338, 2023, <https://doi.org/10.1016/j.nima.2023.168338>.
- [74] J. W. G. Thomason, "The ISIS spallation neutron and muon source—the first thirty-three years," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 917, pp. 61-67, 2019, <https://doi.org/10.1016/j.nima.2018.11.129>.
- [75] B. P. Bromley, "Fusion energy: Current state of affairs in Canada and on the world stage in 2021," CNL Report, 153-129000-REPT-003, Revision 0, 2022 February, 55613165.

- [76] P. W. Lisowski, "The accelerator production of tritium project," in Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B.C., Canada, 12-16 May 1997, 1998, <https://accelconf.web.cern.ch/pac97/papers/pdf/9B003.pdf>.
- [77] "First Light Fusion - Projectile Based Inertial Confinement Fusion," (webpage) <https://firstlightfusion.com/>.
- [78] "CNL and First Light Fusion partner to explore tritium extraction technologies (28 November 2022)," (webpage) <https://www.cnl.ca/cnl-and-first-light-fusion-partner-to-explore-tritium-extraction-technologies/>.
- [79] I. Hofmann, "Review of accelerator driven heavy ion nuclear fusion," *Matter and Radiation at Extremes*, vol. 3, no. 1, pp. 1-11, 2018, <https://doi.org/10.1016/j.mre.2017.12.001>.
- [80] "Queen's University Reactor Materials Testing Laboratory (RMTL)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [81] J. Knaster and Y. Okumura, "Accelerators for fusion materials testing," in *Reviews of Accelerator Science and Technology*, WORLD SCIENTIFIC, pp. 115-142, 2016, https://doi.org/doi:10.1142/9789813108905_0007.
- [82] "International Fusion Materials Irradiation Facility (IFMIF)," (webpage) <https://www.ifmif.org/>.
- [83] "High Flux Isotope Reactor (HFIR) -Oak Ridge National Laboratory," (webpage) <https://neutrons.ornl.gov/hfir>.
- [84] Canada Energy Regulator, "Canada's Energy Future 2023: Energy Supply and Demand Projections to 2050," 2023, <https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2023/canada-energy-futures-2023.pdf>.
- [85] P. G. Boczar, P. J. Fehrenbach et al., "CANDU advanced fuel cycles: Key to energy sustainability," in Proceedings of the 10th Pacific Basin Nuclear Conference (AECL-11629), Kobe, Japan, 20-25 October 1996.
- [86] "ISIS Neutron and Muon Source," (webpage) <https://www.isis.stfc.ac.uk/Pages/home.aspx>.
- [87] "The big deal in going small: Canada's nuclear energy future," (webpage) <https://www.conferenceboard.ca/insights/the-big-deal-in-going-small-canada-s-nuclear-energy-future/>.
- [88] "US Office of Environmental Management: Waste Isolation Pilot Plant (WIPP)," (webpage) <https://www.energy.gov/em/waste-isolation-pilot-plant-wipp>.
- [89] "Nuclear Waste Management Organization of Japan (NUMO)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.

- [90] "French National Radioactive Waste Management Agency (ANDRA)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [91] ANDRA (Agence nationale pour la gestion des déchets radioactifs), "The Cigeo Project: France's industrial centre for geological disposal of radioactive waste," 2020, https://international.andra.fr/sites/international/files/2021-11/Andra-Plaqueette_Cigeo-MAJ-19_08-ALR_C02_V2_EN.pdf.
- [92] "Industrial Centre for Geological Disposal (Cigeo, France)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [93] "Swedish Radiation Safety Authority (SSM)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [94] "Swedish Land and Environment Courts," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [95] "Swedish Nuclear Fuel and Waste Management Company (SKB)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [96] "Finnish Radiation and Nuclear Safety Authority (STUK)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [97] "Posiva Oy Solutions (Finnish company handling nuclear waste in Finland)," (webpage) <https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool>.
- [98] "Isowater Corporation (Canadian producer of heavy water)," (webpage) <https://www.isowater.com/>.
- [99] "Joint European Torus (JET)," (webpage) <https://euro-fusion.org/devices/jet/>.
- [100] "Experimental Thermonuclear Experimental Reactor (ITER)," (webpage) <https://www.iter.org/>.
- [101] J. Hu, W. Xi et al., "All superconducting tokamak: EAST," *AAPPS Bulletin*, vol. 33, no. 1, pp. 8, 2023, <https://doi.org/10.1007/s43673-023-00080-9>.
- [102] "Japan Torus JT-60SA," (webpage) <https://www.jt60sa.org/wp/>.
- [103] "Wendelstein 7-X Stellarator," (webpage) <https://www.ipp.mpg.de/w7x>.
- [104] "National Ignition Facility (NIF) - Lawrence Livermore National Laboratory," (webpage) <https://lasers.llnl.gov/about/what-is-nif>.
- [105] I. Hofmann, "HIDIF – an approach to high repetition rate inertial fusion with heavy ions," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators*,

Spectrometers, Detectors and Associated Equipment, vol. 415, no. 1, pp. 11-19, 1998,
[https://doi.org/10.1016/S0168-9002\(98\)00512-9](https://doi.org/10.1016/S0168-9002(98)00512-9).

- [106] "General Fusion - Magnetized Target Fusion," (webpage) <https://generalfusion.com/>.
- [107] "Tokamak Energy," (webpage) <https://tokamakenergy.com/>.
- [108] "SHINE Technologies," (webpage) <https://www.shinefusion.com/>.
- [109] "TAE Technologies," (webpage) <https://tae.com/>.

Appendix A Where Nuclear Energy Comes From

A.1 Nuclear Basics

1. An atom consists of protons and neutrons, which make up the nucleus, and electrons that orbit the nucleus in clouds, or shells.
2. Neutrons are electrically neutral, protons carry an elementary positive charge (+ e), and electrons carry an elementary negative charge (- e). Thus, the electrical charge of a proton is equal in magnitude but opposite in sign to that of an electron.
3. The nucleus is characterized by two numbers:
 - a. The number of protons in the nucleus, Z , referred to as the *atomic number*. Z is the charge on the nucleus, expressed as a multiple of the elementary charge e , and also determines the chemical element (position in the Periodic Table).
 - b. The number of neutrons in the nucleus, N , referred to as the *neutron number*.
4. Since protons and neutrons occur in the nucleus, they are collectively referred to as *nucleons*. The number of nucleons, also referred to as the mass number, A , is the sum of Z and N :

$$\underbrace{A}_{\text{Number of nucleons}} = \underbrace{Z}_{\text{Atomic number}} + \underbrace{N}_{\text{Neutron number}}$$

5. Protons and neutrons have almost the same mass, while electrons are about 2000 times lighter. The number of nucleons, A , thus determines the weight of an atom.
6. An atom is electrically neutral: the positive charge carried by the protons in the nucleus is balanced by the negative charge carried by an equal number of orbital electrons.
7. A positive ion is an atom which has lost one or more orbital electrons while a negative ion is an atom which has gained one or more orbital electrons.
8. An atom with atomic number Z , mass A , and represented in the periodic table of the elements by the symbol X , is written:
 - a. ${}^A_ZX$
9. This notation can be extended as follows:
 - a. For an ion, the net charge may be included by specifying its sign as well as its magnitude as a multiple of the elementary charge. For example, an ion with a 3+ charge is written:
 - i. ${}^A_ZX^{3+}$
 - b. A neutron, with a mass of 1 and an electrical charge of zero, is written ${}_0^1n$.
 - c. A proton, with a mass of 1 and a positive elementary charge, is written ${}_1^1p$, or simply p . A proton can also be written H^+ since the nucleus of the most common isotope of hydrogen consists of one proton and no neutrons.
 - d. An orbital electron is typically written e^- , but can also be written ${}_{-1}^0e$ as it is negatively charged, and its mass is very small compared with that of a nucleon.
 - e. A beta-minus particle is a high-energy electron ejected from a nucleus. It is written β^- or ${}_{-1}^0\beta$ as it carries an elementary negative charge and has a very small mass.

- f. A beta-plus particle is a high-energy positron ejected from a nucleus. It is written β^+ or ${}^0_1\beta$ as it carries an elementary positive charge and has a very small mass.
 - g. An alpha particle is a helium nucleus. It is written α , ${}^4_2\alpha$, ${}^4_2\text{He}$, or ${}^4_2\text{He}^{2+}$.
10. *Nuclide* is a general term referring to any atom, ion, or nucleus.
 11. *Isotopes* are nuclides with the same atomic number but different numbers of neutrons, and therefore also different numbers of nucleons. Thus, ${}^{235}_{92}\text{U}$ and ${}^{238}_{92}\text{U}$ are different isotopes of the element uranium:
 - a. Same atomic number: 92.
 - b. Different numbers of nucleons: 235 vs 238.
 - c. Different numbers of neutrons: 143 vs 146 i.e., $(235 - 92)$ vs $(238 - 92)$.
 - d. Most nuclides are stable, which is why they are found in nature.
 - e. A nuclide can be unstable for two reasons:
 - f. The nucleus is too big, i.e., it contains too many nucleons. The largest stable nuclide which occurs in nature is ${}^{238}_{92}\text{U}$.
 - g. There is an imbalance between the number of neutrons and the number of protons in the nucleus.
 12. An unstable nuclide eventually decays (disintegrates) by emitting an alpha particle or a beta particle, often accompanied by the emission of a high-energy γ -ray. The new nuclide formed, referred as a daughter, may also decay until a stable nuclide of atomic number 82 or less is formed. Unstable nuclides are *radioactive*.
 13. All nuclides of atomic number greater than 82 (lead, Pb) are unstable.
 14. There are several naturally occurring radioactive nuclides with atomic number less than 82, and many artificial radioactive nuclides have been discovered.
 15. A neutron which is not confined to an atomic nucleus is referred to as a *free neutron*.
 16. A nuclide can capture a free neutron, meaning that it forms a compound nucleus by incorporating the neutron into its nucleus, thereby increasing its inventory of nucleons by 1.
 17. An unstable nuclide can split into two new nuclides, referred to as *fission fragments*. One to three neutrons are usually emitted at the same time. Fission can occur spontaneously but is most often preceded by neutron capture: a nuclide captures a free neutron, becomes unstable, then splits.

A.2 Matter and Energy

Matter has a very high energy density. Unlocking this energy requires nuclear reactors, either fission-type or fusion-type, which are essentially devices for creating the conditions necessary to extract energy from nuclei safely and controllably.

The complementary nature of matter and energy is embodied in Einstein's formula, $E = mc^2$ where E is energy, m is mass, and c is the speed of light in a vacuum. An example of the application of this relation is as follows:

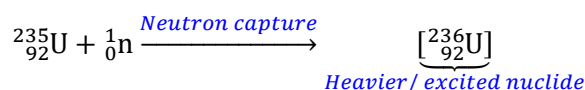
$$\text{The energy of 1 g of matter} = 0.001 \text{ kg} \times (3 \times 10^8)^2 \left(\frac{\text{m}}{\text{s}}\right)^2 = 9 \times 10^{13} \text{ J}$$

This quantity of energy is sufficient to turn 34.7 metric tonnes of water at room temperature into steam at 100 C. Another way to put the energy density of matter into perspective is to realize that the total quantity of electrical energy consumed in Canada in a year is equivalent to the energy in about $\frac{1}{100}$ th of the water in an Olympic-size swimming pool.

A.3 Energy From Nuclear Fission

A.3.1 Neutron Capture

Neutron capture refers to the process by which a nuclide merges with a free neutron: the nuclide incorporates the free neutron into its nucleus to form a *compound nucleus*, thereby increasing the number of nucleons by 1 and making the nuclide heavier:

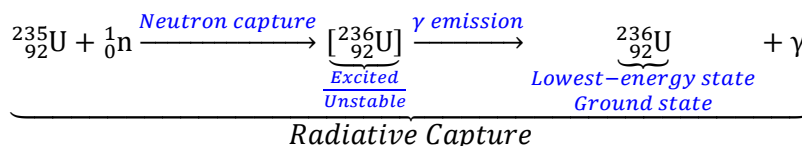


In the above reaction, the uranium nuclide ${}^{235}_{92}\text{U}$ captures a free neutron to form ${}^{236}_{92}\text{U}$ in an excited, or high-energy, state, indicated by the square brackets. Over time, the excited nuclide will remedy its high-energy state in one of three ways:

1. **γ -emission:** It will shed energy by emitting high-energy electromagnetic radiation, or γ -rays. Neutron capture followed by γ -emission is referred to as *radiative capture* (section A.3.2).
2. **Decay:** It will convert into a more stable nuclide by emitting α -particles or β -particles (section A.3.3).
3. **Fission:** It will split into a collection of new nuclides and free neutrons, releasing energy in the process (section A.3.4).

A.3.2 Radiative Capture

Much as a ball rolls down a hill to reduce its gravitational potential energy and thus reach a more stable state, an excited nuclide may lower its energy and thereby become more stable by emitting one or more γ -rays, which are high-energy light photons (packets of light)¹⁵.



In the above reaction, the uranium nuclide ${}^{235}_{92}\text{U}$ captures a free neutron to form an excited ${}^{236}_{92}\text{U}$ nuclide. The excited nuclide then emits an energetic γ -ray, thereby shedding energy to bring the nuclide to its lowest-energy, or ground, state. The ground state may be reached by

¹⁵ The terms γ -ray and γ -photon are used interchangeably in the literature. The term γ -particle is also ubiquitous, which can cause confusion as it implies that a γ -ray has mass, which it does not.

the emission of a single high-energy γ -ray, or by the emission, over time, of multiple lower-energy γ -rays. The energy of the nuclide decreases with each emission.

The combined process of capture followed by the emission of one or more γ -rays is referred to as *radiative capture*, which is often simplified to *capture*. This simplification can result in confusion since capture proper is only the first step in radiative capture or neutron-induced fission (section A.3.4).

A.3.3 Decay¹⁶, Half-Life, and Activity

Rather than emitting a γ -ray, an unstable or excited nuclide can become more stable by undergoing *decay*, in which it emits an energetic particle from its nucleus. Often, the nuclide is still in an excited state after it has undergone a single decay, such that it can undergo another decay or emit one or more γ -rays to further decrease its energy.

The probability that a nuclide will decay in a given time interval is directly proportional to the length of the time interval, with the constant of proportionality depending only on the nature of the nuclide. The main consequence of this behaviour is that, in a material or component made up of many different nuclides, the number of nuclides of a particular type decreases exponentially with time. The rate of this exponential decay is usually expressed using the concept of *half-life*, which is the time for the population of a particular nuclide in a sample to decrease by a factor of 2. Thus, the population of the nuclide will decrease by a factor of two after one half-life, by a factor of 4 after two half-lives, and by a factor of 2^n after n half lives. Half lives can be very short or very long and can vary enormously from one isotope to another: $^{232}_{92}\text{U}$ has a half-life of ~69 years while $^{238}_{92}\text{U}$ has a half-life of ~5 billion years.

Unstable nuclides are said to be radioactive. The radioactivity, or simply the activity, of a nuclide refers to the number of decays the nuclide undergoes per unit time. Activity thus varies inversely with half-life: the longer the half-life, the lower the activity. With a half-life of 4.5 billion years, only one nuclide out of 45 million decays, on average, per century.

Decay reactions ensure that the radioactivity of a sample diminishes naturally over time.

α -decay and β -decay processes are described in Table 9:. Both processes result in *transmutation*: the atomic number of the nuclide changes, turning it into a different element. The resulting nuclide is referred to as the *daughter*. As discussed in sections 4.3 and 4.6, transmutation can be used to breed nuclear fuel and to treat radioactive waste.

¹⁶ Also referred to as *disintegration*.

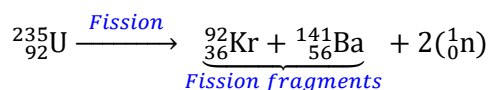
Table 9: Decay reactions.

Decay Type	Description
α-decay	An α-particle, ${}^4_2\text{He}$ or ${}^4_2\text{He}^{2+}$, is a helium nucleus – a helium atom which has been stripped of its orbital electrons and which thus carries a positive charge. In the α-decay reaction below, uranium transmutes into thorium, a different element. Thorium has two fewer protons in its nucleus than uranium and is thus two positions down from uranium in the periodic table of the elements. $\begin{array}{ccc} \text{}^{238}_{92}\text{U} & \longrightarrow & \text{}^{234}_{90}\text{Th} + \text{}^4_2\text{He} \\ \text{Uranium-238} & & \text{Thorium-234} \quad \alpha\text{-particle} \\ Z=92 & & Z=90 \quad \text{Carries a charge of +2} \end{array}$
β^--decay	A β^--particle is an electron ejected from a nucleus: it is identical to a normal orbital electron, except that it has a higher energy. In the β^--decay reaction below, barium transmutes into lanthanum, a different element. $\text{}^{141}_{56}\text{Ba} \longrightarrow \text{}^{141}_{57}\text{La} + {}^0_{-1}\beta^-.$ It is helpful to picture a neutron as a combination of a proton and an electron. β^--decay then corresponds to a neutron splitting into a proton and an electron, the electron being ejected from the nucleus as a β^--particle. The resulting nuclide contains one less neutron and one more proton. Thus, compared with the original nuclide, the daughter is up one place in the periodic table of the elements, but it has the same number of nucleons.
β^+-decay	A β^+-particle is a positron ejected from a nucleus. A positron has the same mass as an electron but carries an elementary positive charge instead of an elementary negative charge. In the β^+-decay reaction below, carbon transmutes into boron, a different element. $\text{}^{11}_6\text{C} \longrightarrow \text{}^{11}_5\text{B} + {}^0_1\beta^+.$ It is helpful to picture a proton as a combination of a neutron and a positron. β^+-decay then corresponds to a proton splitting into a neutron and a positron, the positron then being ejected from the nucleus. The resulting nuclide contains one less proton and one more neutron. Thus, compared with the original nuclide, the daughter is down one place in the periodic table of the elements, but it has the same number of nucleons.
By changing the proton to neutron ratio in the nucleus without changing the overall number of nucleons, β^--decay and β^+-decay allow the nucleus to restore the balance between these two nuclear constituents: • β^--decay helps the nucleus deal with an excess of neutrons. • β^+-decay helps the nucleus deal with an excess of protons. Since an excess of neutrons is far more common than an excess of protons, the generic term β-decay (no sign) generally refers to β^--decay. β^--particles can be slowed when they pass near a nucleus, in which case they emit energy in the form of an X-ray, which is identical to a γ-ray (or any other type of electromagnetic radiation, including light) but of lower energy. This X-ray is called “braking radiation” or “Bremsstrahlung”.	

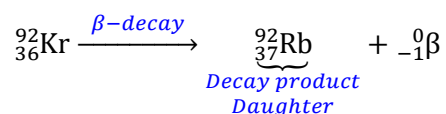
A.3.4 Fission and Fission Products

Fission is the splitting up of a nuclide into a collection of smaller nuclides and subatomic particles. Some of the binding energy of the original nuclide is released during fission.

Fission can occur spontaneously, without any external cause. An example of a spontaneous fission reaction is:



In this reaction, a uranium ${}_{92}^{235}\text{U}$ nuclide splits into two smaller nuclides, ${}_{36}^{92}\text{Kr}$ and ${}_{56}^{141}\text{Ba}$, and two neutrons, $2({}_{0}^{1}\text{n})$. Fission fragments can undergo subsequent decay, yielding daughter nuclides:



Thus, fission is a multi-step process which yields a wide variety of nuclides. The nuclides formed in nuclear fuel, including the fission fragments formed directly from fission and all daughters formed subsequently by decay of the fission fragments, are referred to collectively as *fission products*.

Certain heavy nuclei can be induced to undergo fission after capturing a neutron, resulting in *neutron-induced fission*. The rate of spontaneous fission is very low for all naturally occurring radioactive nuclides but can be appreciable for nuclides created artificially in a nuclear reactor. Since fission is most often preceded by neutron capture, the term *fission* is often used interchangeably with *neutron-induced fission*.

A.3.5 Activation Products

In addition to the radioactive nuclides generated both directly and indirectly by nuclear reactions in nuclear fuel, activation products are also formed when neutrons interact with non-fuel materials in and around a nuclear reactor. These materials include, for example, concrete in containment structures, materials used to contain the fuel and fission products, materials in control rods, and coolant piping.

These materials are activated – become radioactive – when they capture a neutron. They are distinguished from fission products as they do not occur in the fuel.

A.3.6 Neutron Cross Sections

A uranium nuclide may or may not interact with a free neutron. Furthermore, the nuclide can interact with the neutron in different ways. The likelihood of a given interaction, which depends mainly on the energy of the free neutron and the nature of the nuclide, is embodied in the associated interaction *cross-section*. The main interactions of interest are fission, radiative capture, and scattering. Fission and radiative capture together make up absorption.

Confusion can arise when dealing with interaction cross-sections because the *radiative capture* cross-section is often referred to simply as the *capture* cross-section, and neutron capture is the first step in both neutron-induced fission and radiative capture. It is thus important to recognize that fission means neutron capture WITH subsequent fission, while capture (short for radiative capture) means neutron capture WITHOUT subsequent fission. The two interactions, and therefore their corresponding cross-sections, are distinct – there is no overlap.

The main neutron cross-sections of interest in this report are described in Table 10.

Table 10: Neutron cross sections.

Interaction	Cross Section Symbol	Meaning
Fission	σ_f	The likelihood that a nuclide will capture a neutron then undergo fission.
Radiative Capture, or simply Capture	σ_c	The likelihood that a nuclide will capture a neutron without subsequently undergoing fission. Following capture, radiation is emitted in the form of a γ -ray.
Note: “Capturing a neutron” means that a nuclide merges with a free neutron, incorporating it into its nucleus and thereby increasing the number of nucleons by 1. While fission and radiative capture (usually simplified to <i>capture</i>) both include neutron capture as a first step, they are distinct processes with not overlap: Fission = neutron capture WITH subsequent fission Capture = neutron capture WITHOUT subsequent fission		
Absorption	$\sigma_a = \sigma_f + \sigma_c$	The likelihood of either capture or fission. In a fission reactor, the ratio $\frac{\sigma_f}{\sigma_a}$ is important as it is the proportion of absorbed neutrons that cause fission. If it is too low, a fission chain reaction cannot be established (see below).
Elastic Scattering	σ_{es}	The likelihood of an elastic neutron-nucleus scattering event. In elastic scattering, the kinetic energy and the linear momentum of the neutron-nucleus system are conserved. The neutron transfers some of its kinetic energy to the nucleus without, however, exciting the nucleus.
Inelastic Scattering	σ_{is}	The likelihood of an inelastic neutron-nucleus scattering event. In inelastic scattering, the kinetic energy of the neutron-nucleus system is not conserved, leaving the nucleus in an excited state.
Overall scattering	$\sigma_s = \sigma_{es} + \sigma_{is}$	The likelihood that a neutron will be scattered either elastically or inelastically.

A.3.7 Fissionable, Fissile, and Fertile Nuclides

Neutrons are classified according to their energy level as shown in Table 11.

Table 11: Neutron Energies (1 eV = 1.6×10^{-19} Joule)¹⁷

Neutron Energy	Type of Neutron	
0 – 0.025 eV	Very low energy	Cold
~0.025 eV – 1 eV	Low-energy	Thermal
1 eV – a few eV	Medium-energy	Epithermal
> a few eV	High-energy	Fast

With regards to different nuclides, and how they can be harnessed to extract nuclear energy, there are three types: fissionable, fissile, and fertile.

1. A fissionable nuclide can undergo fission after capturing a neutron of *any* energy – high, medium, or low. In other words, the fission cross-section of a fissionable nuclide is non-negligible for at least some range of neutron energies. For example, if the uranium isotope $^{238}_{92}\text{U}$ is hit with very high-energy neutrons (> 10 MeV), the probability of fission is low but non-zero (fission cross section ~ 1 barn).
2. A fissile nuclide is a special type of fissionable nuclide which has a very high probability of capturing a thermal neutron and subsequently undergoing fission. In other words, a fissile nuclide has a large fission cross-section for thermal neutrons. For example, the uranium isotope $^{235}_{92}\text{U}$ has a fission cross section of ~ 500 barns for thermal neutrons.
3. A fertile nuclide is not fissile but it can transmute into a fissile nuclide when it captures a neutron. For example, $^{238}_{92}\text{U}$ is fertile: it transmutes by neutron capture into $^{239}_{92}\text{U}$, which β -decays to $^{239}_{93}\text{Np}$, which then in turn β -decays to $^{239}_{94}\text{Pu}$, a highly fissile nuclide with a thermal neutron fission cross section of ~ 700 barns, even larger than that of $^{235}_{92}\text{U}$.

As discussed in later sections, all current nuclear reactors depend primarily on the fissile nuclide $^{235}_{92}\text{U}$, which is available in generous but nonetheless limited amounts on earth. The existence of fertile nuclides, however, opens the possibility of creating, or *breeding*, more new fuel than is consumed – as if a car could produce gasoline more quickly than it consumes it (section 4.3).

A.4 Conventional Nuclear Fission Energy Production**A.4.1 The Fission Chain Reaction**

In a conventional nuclear power reactor, a nuclide captures a free neutron to become an unstable compound nucleus, then fissions into a collection of fission fragments and neutrons. As a result of this process, some of the internal kinetic and potential energy of the free neutron and the original nuclide appear as the kinetic energy of the fission fragments and emitted neutrons. A significant portion of this kinetic energy is deposited in the fuel, causing the fuel

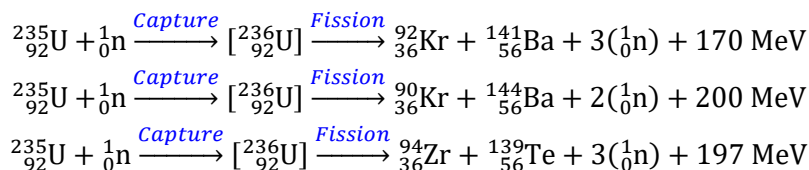
¹⁷ Definitions of the various neutron energy categories vary widely.

temperature to increase. The additional heat energy is transferred to the reactor coolant and is then used to turn water into steam which in turn drives turbines to generate electricity.

The rate of energy generation depends on the number of fissions that occur per unit time, referred to as the *fission rate*, which must be controlled to avoid overheating the reactor. Two questions thus arise:

1. Where do the free neutrons required for fission come from?
2. How can the rate of fission be controlled?

In a conventional nuclear reactor, the neutrons come from the nuclear fuel itself¹⁸: each fission produces free neutrons, resulting in a constant supply. Three possible fission reactions for $^{235}_{92}\text{U}$ are shown below, resulting in different fission products, different numbers of emitted neutrons, and different amounts of kinetic energy:



The energy associated with each fission reaction ($\sim 200 \text{ MeV}$, $1 \text{ eV} \sim 1.6 \times 10^{-19} \text{ Joule}$) appears as the kinetic energy of the two new nuclides and the free neutrons. For reference, the combustion of a carbon atom releases about 4 eV – about 50 million times less. Since the fission reactions produce more neutrons than they consume, a self-sustaining chain reaction can be established in which the neutrons generated by one fission go on to induce further fissions. Sustaining the chain reaction requires that the emitted neutrons be able to reach other fissile nuclides and cause fission before 1) they are captured by non-fissile nuclides, 2) they are captured by fissile nuclides which subsequently emit a γ -ray rather than undergo fission, or 3) leak out of the reactor altogether. In practice, it is non-trivial to establish the necessary conditions, which is why nuclear reactors do not generally occur in nature, even where $^{235}_{92}\text{U}$ is abundant.

If the fission rate is allowed to increase unchecked, the energy released can damage the reactor due to overheating. Control of the chain reaction is achieved by carefully arranging the nuclear fuel and by using control rods. The control rods contain material with a high capture cross-section: the material captures neutrons without subsequently undergoing fission, thereby making the neutrons unavailable to contribute to the chain reaction and allowing tight control of the fission rate.

Conventional nuclear power reactors operate in the thermal neutron regime and thus require fissile fuel which can absorb a thermal neutron and subsequently undergo fission with a high probability. $^{235}_{92}\text{U}$ is the only naturally occurring fissile nuclide: other fissionable nuclides occur

¹⁸ In a CANDU® reactor, the quantity of $^{235}_{92}\text{U}$ is large enough that sufficient free neutrons are generated by spontaneous emission to start the fission chain reaction – a CANDU® can generate its own ‘first neutrons’.

in nature, but, on their own, they cannot keep a reactor running because the efficiency with which they can capture a thermal neutron then undergo fission is too low.

Over time, due to a variety of fissions and decays, the composition of the fuel changes:

1. The concentration of $^{235}_{92}\text{U}$ decreases.
2. A variety of fission products with a wide range of half-lives form.
 - a. Some fission products have a large capture cross-section, such that they interfere with the fission chain reaction. These fission products are referred to as poisons.
 - b. Some fissile nuclides, such as $^{239}_{94}\text{Pu}$ and $^{241}_{94}\text{Pu}$, are generated by transmutation of the non-fissile $^{238}_{92}\text{U}$ which makes up the bulk of nuclear fuel. These nuclides contribute to the fission chain reaction and thus partially make up for the loss of $^{235}_{92}\text{U}$ due to fission. As a result, the fuel remains viable for a longer period in the reactor. The efficiency with which new fissile nuclides are generated by transmutation is too low for the fissile nuclide inventory to sustain itself indefinitely.

Eventually, the fuel composition becomes such that it can no longer sustain the chain reaction, at which point the spent fuel must be replaced with new fresh fuel. Uniquely, CANDU® reactors allow spent fuel to be removed and replaced without shutting down the reactor.

A.4.2 Criticality and Reactivity

In a nuclear reactor, the fuel assembly comprises the nuclear fuel itself, the control rods, and the structural components which contain / support the fuel and allow coolant to flow around it. We distinguish between a *sub-critical*, a *critical*, and a *super-critical* fuel assembly:

1. In a critical fuel assembly, one neutron from each fission reaction, on average, goes on to cause a further fission, such that the fission rate, the power level and the neutron population are constant. A fuel assembly can be critical at any power level.
2. In a super-critical fuel assembly, more than one neutron from each fission reaction, on average, cause further fissions, such that the fission rate, power level and neutron population increase with time.
3. In a sub-critical fuel assembly, fewer than one neutron from each fission reaction, on average, go on to cause further fissions, such that the fission rate, power level and neutron population decrease with time.

A nuclear reactor can be considered as a system for maintaining a fuel assembly in a critical state.

Two terms are generally used to express how far a fuel assembly is from criticality:

1. The neutron multiplication factor, k , is defined as the ratio of the number of neutrons produced in one generation of fission reactions to the number of neutrons absorbed or lost in the same generation: it is less than one for a sub-critical assembly, greater than one for a super-critical assembly, and equal to one for a critical assembly.

2. The degree of sub-criticality or super-criticality is determined by how far k is from 1. The reactivity, ρ , of a fuel assembly, given by $\rho = \frac{k-1}{k}$, is thus a measure of a reactor's relative departure from criticality. It is positive when a reactor is super-critical, zero at criticality, and negative when the reactor is sub-critical.

A.4.3 Fuel Enrichment and Depleted Uranium

As discussed below, different approaches are used to maintain a balance between the rate at which free neutrons are generated and the chance that these neutrons will encounter fissile nuclides and cause fission before they are captured.

Both factors are improved by increasing the concentration of $^{235}_{92}\text{U}$ in the fuel. Fuel made directly from ores contains only ~0.7% by weight of fissile $^{235}_{92}\text{U}$, the rest comprising mainly $^{238}_{92}\text{U}$, which is fertile but not fissile. All thermal-spectrum reactors in the world except CANDU®-type reactors require a higher concentration of $^{235}_{92}\text{U}$ to achieve criticality. The process by which this concentration is increased in nuclear fuel is called *enrichment*. Typical reactors require fuels enriched in $^{235}_{92}\text{U}$ to a level of 2-5% by weight. Fast-spectrum reactors, discussed below, require much higher enrichment levels, ~25-75%, and nuclear weapons require still higher enrichment levels, ~90%. Uranium enrichment results in two product streams: the stream in which the concentration of $^{235}_{92}\text{U}$ is enriched, and the stream in which the concentration is decreased. This second stream, comprising mostly $^{238}_{92}\text{U}$ with 0.2% - 0.3% $^{235}_{92}\text{U}$ by weight, is referred to as *depleted uranium*, or *DU*.

Since the fabrication of nuclear weapons requires highly enriched uranium, there are many international efforts to prevent or discourage countries from developing enrichment capabilities. Canada has no uranium enrichment plants, though the expertise exists to develop and operate them safely and with due regard to nuclear proliferation issues. Furthermore, there is no Canadian policy preventing the development and deployment of enrichment facilities. Important questions to address as Canada pursues the development and deployment of small modular reactors (SMRs) include the following [87]:

1. All current SMR designs require enriched fuel, which is not produced in Canada, despite a significant uranium mining industry and extensive fuel fabrication facilities. Where will the enrichment for these reactors be done, and is it acceptable for Canada to depend on foreign suppliers?
2. Canada exports uranium, which is then enriched abroad. Is it acceptable for Canada to export the economic value associated with providing enrichment services to domestic and foreign customers?

A.4.4 Prompt and Delayed Neutrons

Most neutrons emitted during fission are *prompt neutrons*: they are emitted within $\sim 10^{-14}$ s of the initial neutron capture. A fission fragment may then decay, leaving a nuclide in a highly excited state, which emits *delayed* neutrons milliseconds to minutes after the initial fission reaction. Delayed neutrons represent a small fraction, on the order of 1%, of the total number

of neutrons generated in a reactor, but they are crucial for maintaining control of the fission rate. If the prompt neutrons were sufficient on their own to make the fuel assembly critical, the characteristic response time of the reactor would be too short: reactor power would increase exponentially before the control system could react. However, if delayed neutrons are needed to achieve and maintain criticality, the reactor response time is slow enough to allow effective control. The delayed neutron fraction, meaning the fraction of the total neutron population that corresponds to delayed neutrons, must be maintained within a well-defined range for safe reactor operation.

The delayed neutron fraction depends on the fuel composition as different nuclides have different delayed neutron fractions. For example, $^{235}_{92}\text{U}$ has a relatively high delayed neutron fraction, while $^{239}_{94}\text{Pu}$ has a much lower one, placing an upper limit on the plutonium content of fuel: the response time of a thermal-spectrum reactor fuelled exclusively with $^{239}_{94}\text{Pu}$ would be too low for effective control. Currently, reactors fuelled using a mixture of $^{235}_{92}\text{U}$ and $^{239}_{94}\text{Pu}$ can only handle fuel with a uranium-to-plutonium ratio on the order of 0.03 – 0.07 by weight.

A.4.5 Decay Heat

The α , β , and γ radiation emitted during decay reactions heats up material it encounters as it radiates away from the originating nuclide. Since partially or fully spent fuel contains both short-lived and long-lived fission products, significant decay heat is generated immediately following the shutdown of a reactor, and for extended periods thereafter. Active cooling is thus required to manage the decay heat in a newly shut down reactor to prevent overheating. Similarly, spent nuclear fuel (SNF) continues to generate decay heat such that it must be kept for periods on the order of years in a pool of water before it can be reprocessed or placed in dry storage.

Appendix B Deep Geological Repositories Around the World**Table 12: Status of some deep geological repositories.**

Country	Responsible Agency	Status of the Deep Geological Repository
Canada	The Nuclear Waste Management Organization (NWMO) [15]	1) Two potential sites for have been identified and discussions are ongoing with the local communities. 2) The NWMO is conducting and commissioning research to develop the various components of the DGR. 3) The NWMO continuously monitors relevant technologies for potential application in the DGR. In this regard, a phased management approach has been adopted to allow the DGR to take advantage of new developments as they arise.
USA	Waste Isolation Pilot Plant (WIPP) [88]	1) The Waste Isolation Pilot Plant (WIPP) has been operating since 1999 but currently only accepts waste generated by atomic energy defence activities. 2) An application to construct the Yucca Mountain repository was submitted by the USDOE in 2008. The approval process is not yet complete, having encountered several delays.
Japan	The Waste Management Organization of Japan (NUMO) [89]	1) Site selection is expected to be completed in the mid-late 2020s. 2) Operations are expected to start in the late 2030s – early 2040s.
France	French National Radioactive Waste Management Agency (ANDRA) [90] The Industrial Centre for Geological Disposal (Cigeo) [91][92]	1) Site selection has been completed. 2) An application for a license to build the DGR has been submitted. 3) It is planned to start building a pilot industrial phase in in the mid 2020s.
Sweden	The Swedish Radiation Safety Authority (SSM) [93] The Swedish Land and Environment Courts [94] The Swedish Nuclear Fuel and Waste Management Company (SKB) [95]	1) Sites have been selected for the DGR and for an encapsulation facility. 2) Plans for building the DGR and the encapsulation facility were approved in January 2024. 3) Construction will start once the Land and Environment Court sets conditions for the facilities and the Swedish Radiation Safety Authority sets the permit conditions for the facilities. 4) The planned capacity of the DGR is 6,000 canisters of spent fuel.
Finland	Finnish Radiation and Nuclear Safety Authority (STUK) [96] Posiva Oy Solutions [97]	1) The DGR and encapsulation facility are mostly constructed, and are expected to start operating in the mid 2020s.

Appendix C Fusion Power Generation**C.1 Definition and Advantages of Fusion**

In contrast to nuclear fission, where an atom of a heavy element splits into a collection of lighter atoms and subatomic particles, in nuclear fusion two light-weight atoms combine to form a collection of heavier atoms and subatomic particles. Since the binding energy per nucleon increases rapidly with atomic mass, A , reaching a maximum in the range $50 \leq A \leq 80$, the fusion of two light atoms with a combined mass in this range results in a release of binding energy.

In the Sun, fusion occurs thanks to temperatures on the order 15 million °C combined with the large gravitational forces that confine hydrogen atoms at high densities and pressures for a sufficient time. Despite the low probability of fusion of hydrogen atoms to produce helium, the Sun is large enough to make it a self-sustaining fusion reactor.

Since it is difficult, if not impossible, to replicate the conditions at the centre of a star which give rise to hydrogen fusion, efforts to achieve fusion power generation on Earth must rely on much easier fusion reactions, such as the D-T reaction, in which one deuterium (D) atom and one tritium (T) atom fuse to produce helium and one neutron. Even with this easier reaction, fusion power generation has not been achieved on Earth at a scale suitable for commercial use despite decades of effort starting in the 1950s¹⁹.

The potential benefits of fusion energy production are compelling:

1. Fusion has the highest energy payback ratio of all clean energy sources, including solar, wind, and fission.
2. The byproduct of fusion is helium, a safe and inert gas: no air pollutants, carbon dioxide or other greenhouse gases are produced.
3. Though neutron activation in fusion reactors will produce radioactive nuclides, none are expected to be long-lived: they will decay to insignificant levels within decades.
4. The heat generation rate from the decay of radioactive tritium is insufficient to cause a meltdown. However, protection protocols such as those applied to existing tritium-handling facilities like the Darlington Tritium Removal Facility will apply to fusion power plants.
5. The difficulty of achieving and maintaining the conditions necessary for fusion is such that any disturbance in the reactor will cause the fusion reaction to stop with no decay heat generation.

In addition to creating the conditions necessary for fusion, it is also necessary to source the fuel:

1. Deuterium is non-radioactive and can be distilled from all forms of water. It thus comprises an available, harmless, and virtually inexhaustible resource. Current

¹⁹ Compact D-T fusion-based neutron generators are available commercially. They are low-flux devices suitable for applications such as neutron radiography.

processes for extracting deuterium from water are energy-intensive. However, heavy water production is pursued at the national level (India) as well as commercially (Canada, [Isowater Corporation](#) [98]) and there is active research in developing more efficient extraction processes.

2. Unlike deuterium, tritium occurs only in trace quantities in nature because it is radioactive, undergoing β -decay with a half-life of only 12.33 years. Thus, tritium must be continuously bred to ensure the long-term supply of fuel for D-T fusion reactors. Fusion reactor concepts thus often include a breeding lithium blanket surrounding the reaction chamber. The lithium in the blanket captures a neutron then undergoes α -decay to yield tritium, which is extracted and purified via thermal desorption or chemical processes.

C.2 Fusion Reactor Concepts

Many different fusion power reactor concepts are under active development, as described in detail in [75]. In all concepts, a plasma - an ionized gas in which the atoms are separated from some of their electrons - is heated to a high enough temperature and confined for a long enough time for fusion to occur. A variety of approaches are under investigation:

1. In magnetic confinement fusion (MFC) reactors, which include tokamaks, stellarators, and reversed field pinches, magnetic fields are used to contain and compress a large volume of plasma contained in a vacuum chamber, while a separate energy source is used to heat the plasma. Magnetic confinement devices increase the probability of a fusion reaction by using a low pressure combined with a long confinement time [70]. Accordingly, the costs of these steady-state or long-pulse-duration devices tend to be dominated by the costs of the plasma confinement system.
2. In inertial confinement fusion (ICF), including laser ICF, particle ICF, and projectile ICF, a small fuel pellet is compressed and heated to trigger a fusion reaction. The reaction occurs over a very short timescale, typically on the order of nanoseconds to microseconds, such that precise timing and control of the compression and heating processes are required to achieve and sustain fusion. Inertial confinement devices increase the probability of a fusion reaction by using a high pressure combined with a short confinement time [2]. The fuel pellet is small and dense, easing the demands on the confinement system. The cost of an inertial confinement device thus tends to be dominated by the cost of the high-power driver system.
3. In magneto-inertial confinement fusion (MICF) and magnetized target fusion (MTF), a magnetic field is initially used to confine and pre-heat the plasma, which is then further compressed rapidly by an external force, such as the implosion of a cylindrical liner driven by an intense electrical current or laser pulses.

Table 13: Past and current fusion power generation efforts.

Current Status	Description
Project started in 1983. Concluded operations 18 December 2023. Currently undergoing decommissioning and repurposing.	Joint European Torus (JET) [99] Magnetic confinement tokamak with a large-volume plasma vacuum chamber and an auxiliary heating system comprising a neutral beam injector and an ion cyclotron resonance heating system.
Under construction. Project started in 2005. Civil works to be completed in 2023. Initial budget was 5 billion Euros, but costs have spiralled. An updated baseline schedule and costing to be proposed in 2024.	Experimental Thermonuclear Experimental Reactor (ITER) [100] Magnetic confinement tokamak with a large-volume plasma vacuum chamber and an auxiliary heating system comprising a neutral beam injector and an ion cyclotron resonance heating system. The two main objectives of ITER are to: 1) Demonstrate that a burning plasma, in which the heat from the fusion reactions is enough to maintain the temperature of the plasma, thereby reducing or eliminating the need for external heating. 2) Test tritium breeding concepts.
Project started in 1998. Operation started in 2006.	Experimental Advanced Superconducting Tokamak (EAST) [101] Magnetic confinement tokamak with a large-volume plasma vacuum chamber and an auxiliary heating system comprising a neutral beam injector, an ion cyclotron range of frequency heating system, an electron cyclotron range of frequency heating systems, an electron cyclotron resonance heating system, and a low hybrid current drive system.
Project started in 2007. First plasma achieved in October 2023. Commissioning is ongoing.	Japan Torus JT-60SA [102] Magnetic confinement tokamak with a large-volume plasma vacuum chamber and an auxiliary heating system comprising a neutral beam injector and an electron cyclotron range of frequencies heating system.
Project started in 1980. Upgraded in 2022, currently operating.	Wendelstein 7-X Stellarator [103] Stellarator equipped with superconducting magnets designed for continuous operation and equipped with an auxiliary plasma heating system comprising a microwave heating systems and a neutral beam injection system.
December 5, 2022: First controlled fusion experiment to have produced more energy from fusion than the laser energy used to drive the reaction (DOE newslink).	National Ignition Facility (NIF) [104] High-energy laser facility at Lawrence Livermore National Laboratory.
1993 - ?? Ended	Heavy Ion Driven Ignition Facility (HIDIF) [79][105] Research program to demonstrate the accelerator needs for particle-driven inertial confinement fusion.
Founded in 2002.	General Fusion - Magnetized Target Fusion [106]

Canadian White Paper on Accelerator Driven Systems (ADS) – Past Experience, Present Status and the Future
Benefits for Canada

153-129100-REPT-005718 Rev. 0

Page 67 of 67

Current Status	Description
Plasma injector commissioned in 2018. Aim for demonstrator in 2025.	Canadian private company (B.C.) developing a commercial fusion reactor based on magnetized target fusion. The main components of the system are: 1) Plasma injector 2) Piston/liquid metal compression system
Founded 2009.	Tokamak Energy [107] U.S. company developing a compact spherical tokamak incorporating high-temperature superconductors.
Founded 2011.	First Light Fusion - Projectile Based Inertial Fusion[77] U.K. company developing projectile based fusion inertial confinement fusion. In projectile based fusion, a projectile is fired at high velocity into a fuel pellet. The impact creates shockwaves that are made to converge within the fuel, rapidly compressing it and raising its temperature and density. The
Founded 2010.	SHINE Technologies [108] U.S. company with a long-term goal of developing large-scale commercial fusion power generation. This company is perhaps
Founded 1998.	TAE Technologies U.S. company developing hydrogen-boron based fusion power generation. It is proposed to have the proposed system uses