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RP3 Fission Technology Brief

Group 1

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Introduction to Nuclear Fission

Nuclear fission is a cornerstone of modern energy production and scientific innovation, providing a reliable way to meet global energy needs while cutting greenhouse gas emissions. In Canada, with its abundant uranium resources and vast natural landscapes, nuclear fission contributes in the transition to sustainable energy while ensuring the protection of Indigenous lands. By understanding how nuclear generators work, and their environmental impacts, we can better comprehend how nuclear fission can help provide a clean future. This includes addressing challenges such as radioactive waste management and ecological considerations, to ensure the long-term viability of this energy source.

Nuclear Reactor Mechanisms

Nuclear fission generates energy by splitting heavy atomic nuclei, like uranium-235, into smaller fragments. In reactors, like the Canadian Bruce Nuclear Generating Stations, uranium is processed into ceramic pellets, assembled into sealed metal tubes called control rods, and submerged in water which cools and moderates the chain reaction (Canadian Nuclear Safety 2024). The heat produced from fission turns water into steam, driving a turbine connected to a generator. Using electromagnetic induction, the generator converts mechanical energy into electricity which is further distributed through the power grid (Figure 1) (Office of Nuclear Energy 2023).

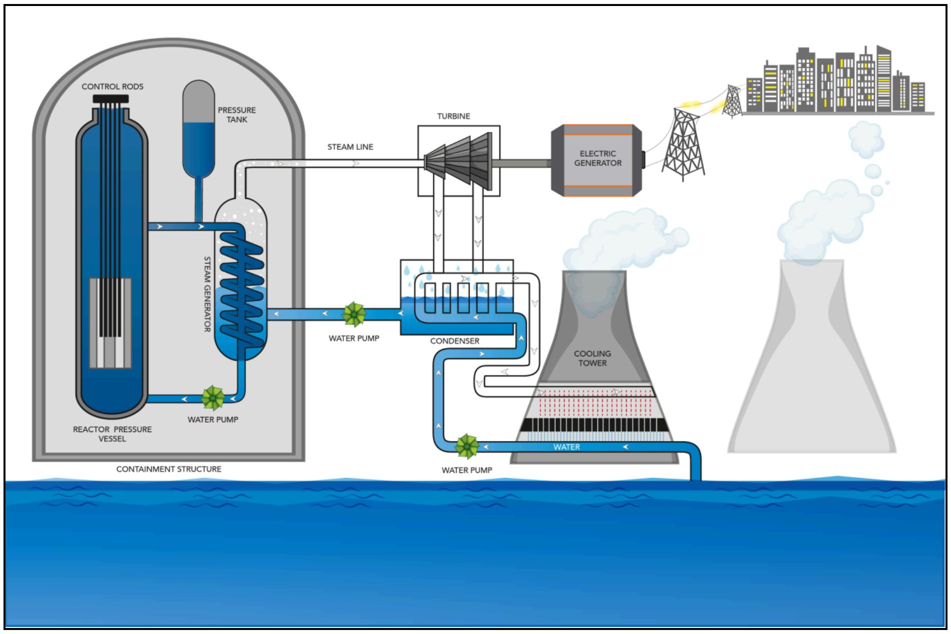

Figure 1: *Schematic of a nuclear power plant. The reactor pressure vessel houses fuel rods containing uranium-235, where fission generates heat. Control rods absorb excess neutrons to regulate the reaction. Heat converts water into high-pressure steam, driving a turbine connected to a generator producing electricity via electromagnetic induction. Steam is cooled in a condenser, with excess heat released through a cooling tower, while water is continuously recycled for efficiency (Office of Nuclear Energy 2023).*

The reaction begins with an incident neutron (*n*) colliding with a heavy nucleus, such as uranium-235, forming an unstable compound nucleus. As an example, the reaction U-238 + *n* → U-239 illustrates the formation of U-239. The unstable nucleus splits into two smaller fragments, releasing energy as heat and radiation, along with 2-3 neutrons (Figure 2). These released neutrons initiate further fission reactions, propagating the chain reaction (Schunck and Regnier 2022). The heat generated from this process produces steam, which then powers the turbine.

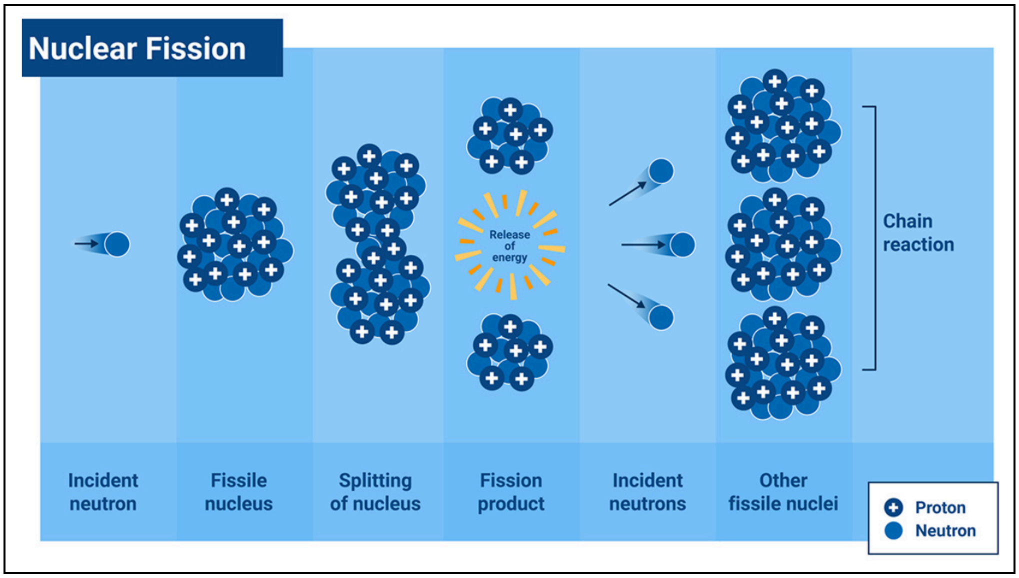

Figure 2: *The step-by-step process of fission and how it initiates a chain reaction. Key steps include the splitting of the nucleus, energy release, new neutron creation, and the formation of two smaller nuclei (Galindo 2022).*

Turbines are an integral part of converting thermal energy produced from fission, into mechanical energy, which is then transformed into electrical energy by a generator. This process relies on the principles of torque and rotational motion. Torque (τ), is the rotational equivalent of force, quantifying an object's tendency to rotate about an axis (pivot point). Equation 2 demonstrates how to calculate τ, where r is the moment arm (distance from the pivot point to where the force is applied), F is the applied force, and θ is the angle between F and r.

$$\tau = \vec{r} \times \vec{F} = rFsin(\theta) \tag{1}$$

Efficiency is critical to ensure energy systems remain cost-effective. To maximize torque, and thus efficiency, force must be applied at a 90-degree angle to the moment arm. Steam applies force to the blades at a distance r from the axis, at the optimal angle. Torque must also overcome resistive forces such as friction and electromagnetic resistance, for the rotor to spin effectively. In Equation 2, $\sum\tau$ is the sum of all the torques acting on the system, α is the angular acceleration, and I is the moment of inertia (a measure of the rotor's resistance to angular acceleration). This helps quantify the torque exerted by steam in a nuclear power plant

$$\sum \tau = I\alpha \tag{2}$$

For efficient operation, the rotor must spin steadily to maintain a constant magnetic field change and stable voltage output. In turbine systems, the torque generated by steam driving the turbine blades and the angular velocity of the rotor determines the mechanical power of the generator. The efficiency of power production increases with higher angular velocity and torque. In Equation 3, *P* represents the generated mechanical power, τ denotes the applied torque, and ω signifies the angular velocity.

$$P = \tau\omega \tag{3}$$

Electricity generation relies on electromagnetic generators based on Faraday's law of induction. This principle states that a changing magnetic field induces an electromotive force (EMF), generating an electric current through electromagnetic induction. Turbine rotation drives a rotor inside a stator wire coil within a stationary changing magnetic field that induces an electric current (Ebrahimi 2023). Faraday's law of induction is represented by Equation 4, and the efficiency of the generator relies heavily on this process. In Equation 4 the magnitude of the EMF (ε) is proportional to the rate of change of the magnetic flux *(Φ*) that cuts across the circuit over time (*t)*.

$$\varepsilon = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{4}$$

The induced EMF created from this law produces an electric field within the conductor, exerting a force on the free electrons and causing them to move. This movement of the charged particles generates the electric current and is represented by Coulomb's law, which describes this interaction between charges. In Equation 5, force (F) is between the two charges (q_1 and q_2) and is proportional to the product of their charges while being inversely proportional to the square of the distance (r) between them. k_e represents Coulomb's constant.

$$F = \frac{k_e q_1 q_2}{r^2} \tag{5}$$

This explains the charge behaviour in the generator and ensures a current flow. The true current flow, however, is not just determined by this equation, the flow depends on the circuit's resistance. Low resistance allows for a higher current and efficient power output, while high resistance reduces the current and lowers the efficiency. These principles can be seen in Equation 6 where the Ohm's law equation and the rearranged form demonstrate how the current (I) decreases as resistance (R) increases since the voltage (V) measured across the conductor is divided by the resistance.

$$\begin{gathered} V = IR \\ I = \frac{V}{R} \end{gathered} \tag{6}$$

These principles guide the design of efficient circuits and ensure the effective power transmission of electrical energy from generators to the grid.

Environmental and Ecological Impacts of Nuclear Energy

The construction of nuclear power plants provides benefits for energy production, while equally, raising environmental concerns. Suitable site selection and planning are crucial to minimize risks and ensure sustainability. Several factors influence site selection, including the distance from populated areas, proximity of geological features, uranium sources, and radioactive waste disposal options. The overall site must be geologically stable to prevent damage from tectonic activity while maintaining a safe distance from populated areas. Although there is no universal standard, a 16 km radius is generally recommended for safety (Government of Canada 2014). Constructing the plant near uranium mines reduces transportation challenges, however, radiation safety concerns must be considered (“Emergency Planning Zones” 2024).

An example of a proposed waste disposal site is Chalk River, Ontario, which aligns with the discussed criteria. It is distant from both populated areas and wildlife environments while respecting indigenous lands. In Canada, many scientific and industrial developments have historically taken over indigenous territories. Ethical site selection must prioritize respecting traditional lands amidst technical and environmental considerations. Additionally, the found borehole data indicates that Chalk River’s granite formation has low permeability and porosity, limiting groundwater movement and the spread of contaminants (Figure 3). The groundwater contains major ions, trace metals, and dissolved organic carbon, which interact with the rock to trap radioactive elements and prevent their migration. The restricted flow and stable chemistry make the site geologically suitable for long-term nuclear waste containment (Beaton et al. 2016).

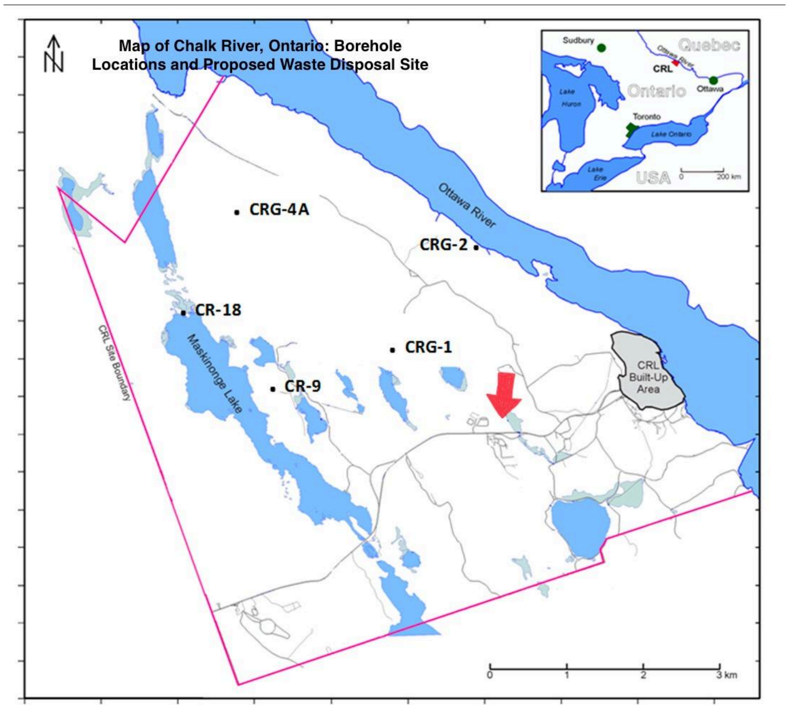

Figure 3: *Map of the Chalk River site in Eastern Ontario, Canada, with indicated boreholes and proposed site (red arrow). The site is bounded by the Mattawa Fault (Ottawa River), and Maskinonge Lake Fault, with dykes forming additional geological boundaries (Beaton et al. 2016).*

Uranium mining in Canada primarily occurs in Saskatchewan through underground methods (Brown and Chambers 2017). The ore is extracted, crushed, and chemically leached to separate uranium from the surrounding rock. After further refining, it is compressed into uranium dioxide pellets and assembled into fuel rods for nuclear reactors. Mining methods aim to balance resource efficiency with environmental guidelines.

A primary environmental concern of nuclear power is waste disposal. Canada enforces stringent guidelines for containment and sustainability. Short-term storage, like interim and in-situ methods, allows radioactive decay before transfer to long-term facilities (“Storage and Disposal of Radioactive Waste” 2014). Near-surface disposal stores waste in vaults with impermeable covers but may impact local geology and release radon (Figure 4) ("Storage and Disposal of Radioactive Waste" 2014). Deep geological disposal, currently under study in Canada, encases waste in insulated canisters within buffer materials underground (Figure 5).

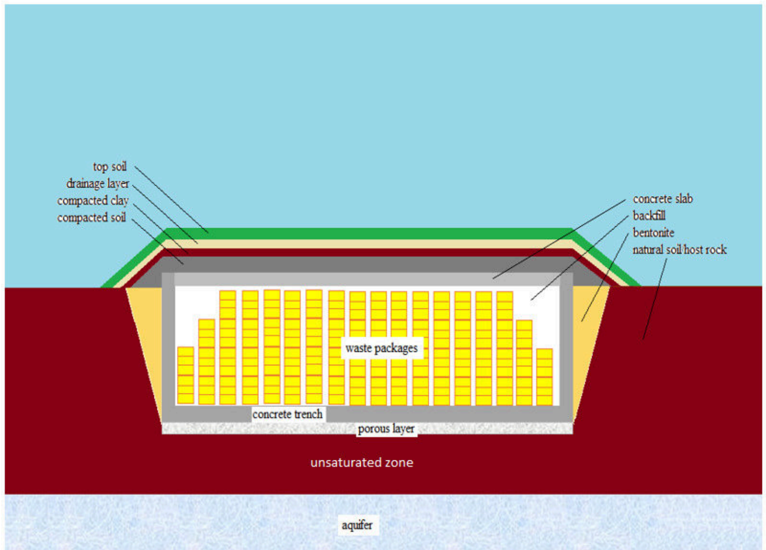

Figure 4: *Schematic of a near-surface nuclear waste disposal facility. Waste is stored in concrete trenches above the aquifer, with multiple barriers preventing water infiltration and ensuring stability (Setiawan and Ekaningrum. 2019).*

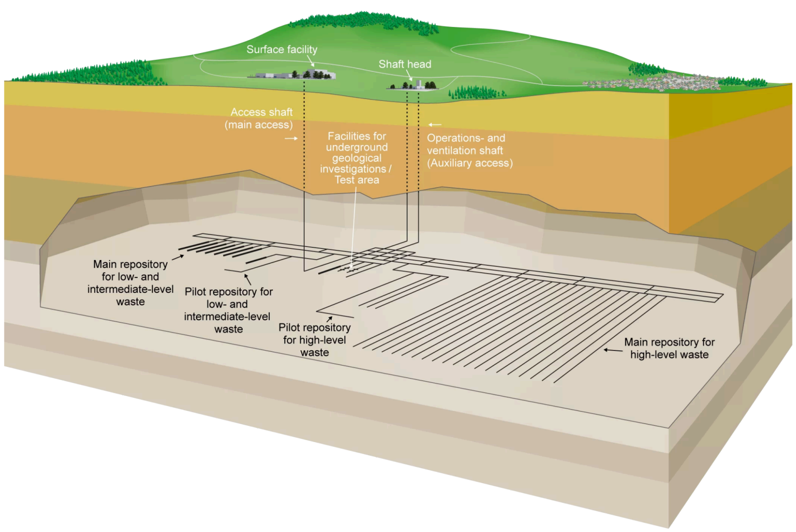

Figure 5*: Cross-section of a deep geological nuclear waste repository, showing surface access, ventilation shafts, and underground storage for low, intermediate, and high-level waste. Pilot and main repositories are designed for containment and long-term stability (Müller et al. 2024).*

Similar to near-surface disposal, deep geological disposal is designed for highly radioactive waste (Müller et al. 2024). Site selection prioritizes geological stability and Indigenous reserves to ensure safety and respect for traditional lands to ensure long-term stability. The site's mild elevation variation and lack of nearby tectonic plates further support its stability (Figure 6).

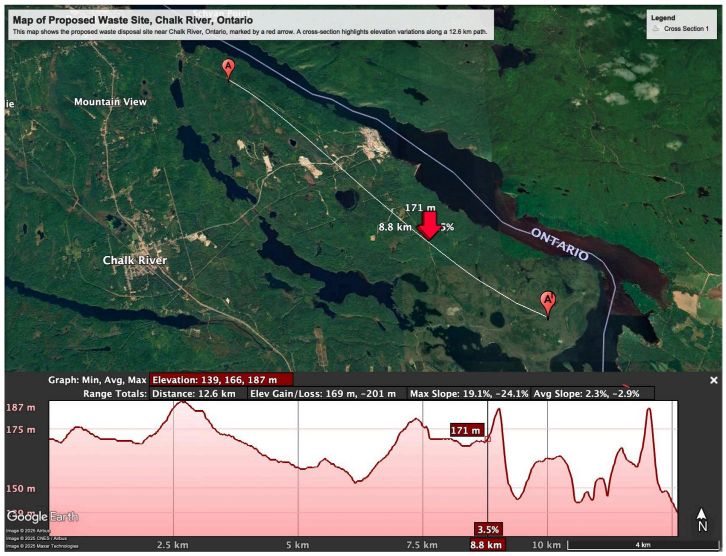

Figure 6: *The example proposed location of near-surface nuclear waste disposal in Chalk River, Ontario, is marked with a red arrow, highlighting elevation variations across the site ("Satellite view of Chalk River, Ontario" Google Earth Accessed January 29, 2025).*

The geological stability and isolation of Chalk River make it a strong example of a good waste disposal site, aligning with both technical feasibility and ethical considerations in Canada's energy planning.

Evaluating Nuclear Fission as an Energy Source

In conclusion, nuclear fission provides a reliable and steady source of energy, meeting growing demands while reducing emissions. As of 2024, Canada's electricity grid is among the cleanest globally, with 82.5% of generation coming from non-emitting sources (Natural Resources of Canada 2009). Nuclear energy supplies approximately 15% of Canada's electricity and 56% of Ontario's (Canada Energy Regulator 2023). Canada operates four nuclear plants, three in Ontario, and one in New Brunswick, with 19 reactors producing 14,629 megawatts (Canadian Nuclear Safety 2024). The Bruce A and B Nuclear Generating Stations alone have eight units with a capacity of 6,232 MW, enough to power approximately 10 million households, considering that the average Canadian household consumes about 750 kWh per month (Ontario Energy Board 2023). Given that Toronto's peak electricity demand is approximately 4,700 megawatts, the Bruce stations' capacity could supply the entire city (Government of Ontario 2024). As of 2022, nuclear energy remains a dominant clean energy source, though hydroelectricity leads at 61.6% of Canada's energy supply. However, in Ontario, nuclear energy surpasses all other sources (Natural Resources of Canada 2024). Its efficiency, often exceeding 90%, makes it Canada's most efficient green energy source compared to wind (20-40%), solar (15-20%), bioenergy (20-25%), and hydro/geothermal (90%) ("Renewable Energy and Electricity" 2024). While hydroelectricity remains Canada's main source of energy and wind and solar energy continue to grow, nuclear energy should remain a key part of Canada's future. Its high output, exceptional efficiency, and low operating costs make it vital for a reliable and sustainable future.

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