

DYNAMIC XENON RESPONSE IN A CANDU-600 REACTOR: A SIMULATION STUDY OF POWER VARIATIONS

Andrei Stan and Geoşchun Ferat

Cernavodă Nuclear Power Plant
stanandrei50@gmail.com
feratgeo@gmail.com

Article Info	Abstract
<i>Received: 13.07.2025</i> <i>Accepted: 17.09.2025</i> Keywords: CANDU-600, reactor physics, fission products	This paper presents a comparative simulation study of xenon and fission product behavior in a CANDU-600 reactor core operating at nominal full power (100%) and an aging CANDU-600 core limited to 90% power due to end-of-life constraints. The analysis includes not only steady-state operating conditions but also transient phases such as shutdown and start-up, where xenon dynamics significantly impact reactivity management. Using theoretical reactor physics simulations, the study investigates xenon reactivity worth in both reactor conditions, with particular attention to the influence of fission product buildup and depletion. The simulations are supported by detailed evaluations of the reactivity compensation provided by the Liquid Zonal Controllers (LZCs), Adjuster Banks and Mechanical Control Absorbers (MCAs). The results highlight that while the 90% power core experiences reduced xenon production, it exhibits higher sensitivity to xenon-induced reactivity swings, particularly during power maneuvers and recovery from shutdown. The total reactivity worth of xenon, in conjunction with the control mechanisms, is quantified throughout the operational cycle. The findings reveal a tighter reactivity balance and reduced control flexibility in the aged core, emphasizing the increasing operational constraints as the reactor approaches end-of-life. These insights are critical for refining control strategies, ensuring safe operation, and optimizing performance across the full power range and operational scenarios of CANDU reactors.

1. Introduction

Nuclear reactors, particularly CANDU designs, face unique challenges in managing xenon-135 poisoning due to its substantial thermal neutron absorption cross-section (~2.8 million barns) and dynamic production-decay characteristics. While xenon's equilibrium behavior under full-power operation is well-documented, its transient dynamics during operational maneuvers and core aging remain critical areas for reactor safety and performance

optimization. This study addresses a pivotal gap in understanding how power limitations in aging CANDU-600 cores – constrained to 90% nominal output – alter xenon reactivity interactions compared to unrestricted operation.

The analysis focuses on three key aspects:

- Xenon production-depletion asymmetry during shutdown/restart sequences, where iodine decay temporarily dominates neutron absorption effects
- Control system compensation through Liquid Zone Controllers (LZCs), Adjuster Banks, and Mechanical Control Absorbers (MCAs), which collectively manage -30.7 to +30.7 mk reactivity ranges
- Aging core effects, including flattened flux profiles and reduced fission product clearance rates that exacerbate reactivity management challenges

These factors are investigated through first-principle reactor physics simulations that model both steady-state and transient conditions. Particular attention is given to the heightened sensitivity of power-limited cores to xenon spatial oscillations – a phenomenon where localized flux depressions create propagating reactivity waves. The results quantify how reduced thermal margins in aged cores constrain traditional control strategies, necessitating advanced operational protocols for safe lifecycle extension. By contrasting fresh and end-of-life core behaviors, this work provides essential insights for optimizing CANDU reactor control architectures under increasingly prevalent power-derating scenarios.

2. Method and samples

2. 1. Reactivity mechanisms

In CANDU reactors, power regulation is fundamentally governed by the principle of reactivity control, a mechanism shared across nuclear reactor designs [1]. Reactivity modulation is achieved through the insertion or withdrawal of specialized reactivity devices into the reactor core. These devices alter neutron absorption rates within the core, thereby enabling precise adjustments to the reactor's neutron economy. By strategically positioning these devices, operators can increase or decrease reactor power, maintain steady-state operation, or initiate a complete shutdown. The reactivity control infrastructure in CANDU systems operates under the authority of two distinct safety and operational frameworks: the Reactor Regulating System (RRS), which manages routine power adjustments, and two independent, redundant Shutdown Systems (SDS1 and SDS2) [2]. The latter are engineered to ensure fail-safe reactor deactivation under predefined safety-critical conditions, adhering to stringent nuclear safety standards.

A CANDU-6 reactor uses, through RRS, the following reactivity devices:

- 14 liquid zones controllers (LZC) filled with light water
- 21 adjuster rods, grouped in 7 banks
- 4 mechanical control absorbers, grouped in 2 banks
- moderator poison addition system.

Under the direct and only control of the shutdown systems, there are:

- 28 cadmium shutoff rods, grouped in 2 banks
- 6 tanks of high pressure Gd/B poison.

In the table below are mentioned all the available reactivity devices in a CANDU-600 reactor, along with the correspondent reactivity worth [1]:

Table 1 - CANDU-600 reactivity devices worth

Device	Function	Total reactivity worth [mk]	Maximum reactivity rate [mk/s]
14 Liquid Zone Controllers (LZC)	control	7.1	± 0.14
21 Mechanical Adjusters (ADJ)	control	15.3	± 0.09
4 Mechanical Control Absorbers (MCA)	control	10.8	± 0.075 driving -3.5 dropping
Moderator poison (Boron)	control	(depends on poison addition amount)	-0.0125 extracting
<i>Gross total reactivity of control devices:</i>		± 30.4 mk	
28 Shutoff rods (SDS1)	safety	80	-50
Poison injection (SDS2)	safety	>300	-50

Furthermore, the overall core reactivity affected by internal causes is named as feedback effects and includes the inherent reactivity changes due to the variation of local core parameters. Sources of reactivity variations in reactor core consist of power variation (shutdown to full power), fresh fuel burnup (small burnup), flux oscillation, plutonium and samarium buildup. For the CANDU-600 reactor, the most important local core parameters are the following: fuel burnup, fuel temperature and neutron flux.

2. 2. Temperature coefficients

Operational data from nuclear reactors demonstrate that reactivity—a measure of neutron population equilibrium—is governed by inherent physical phenomena that induce perturbations in the neutron balance. These reactivity mechanisms, arising from thermodynamic and neutronic interactions, necessitate continuous monitoring and control to maintain operational stability. The primary reactivity changes which can appear in the reactor could be caused by moderator temperature, coolant temperature and pressure, and the fuel temperature [3], [4]. The density variation and apparition of void in the coolant is characterized by the void reactivity coefficient.

The overall reactivity coefficient of temperature varies for the type of nuclear power plant, even if they share similar principles underlying nuclear power production and control. As an example, the temperature coefficient for a PWR reactor is $-5.5 \cdot 10^{-6} [^{\circ}\text{C}^{-1}]$ and for a CANDU 600 (PHWR) is $-3.0 \cdot 10^{-6} [^{\circ}\text{C}^{-1}]$ [2]. The table below illustrates the values of the overall core reactivity temperature coefficient and calculations of the reactivity worth for a certain temperature of the coolant [3], [4]:

Table 2 - Values of temperature coefficients across different types of reactors

Reactor name (Type)	Moderator	Coolant	Temperature coefficient [$^{\circ}\text{C}^{-1}$]	Coolant temperature [$^{\circ}\text{C}$]	Results
CANDU 600 (PHWR)	Heavy water	Heavy water	$-3.0 \cdot 10^{-6}$	230	-0.1265
Shippingport (PWR)	Water	Water	$-5.5 \cdot 10^{-4}$	230	-0.00069
Water Boiler (BWR)	Water	Water	$-3.0 \cdot 10^{-4}$	230	-0.069
Brookhaven (thermal reactor)	Graphite	Water	$-4.0 \cdot 10^{-5}$	230	-0.0092
Argonne CP-5 (thermal power)	Heavy Water	Water	$-4.0 \cdot 10^{-4}$	230	-0.092

When the temperature coefficient is negative, it indicates a decrease of the reactivity with the increase of temperature. Otherwise, the reactivity would increase with the increasement of temperature and will lead to core instability. Negative temperature reactivity is desirable since

it tends to counteract the effects of transient temperature changes. As can be seen, in the table above, the reactivity induced by the temperature is negative for the main types of reactors. Values considered are given at ordinary temperature which means that the reactivity variation is obtained by the multiplication of the coefficient by the difference between operating and ordinary temperatures.

2. 3. Reactor power level and aging:

The CANDU-600 Heat Transport System (HTS) contains 380 reactor channels, which are distributed in four groups of 95 pressure tubes [2]. Each group of channels is connected to a corresponding inlet and outlet headers via individual feeder pipes. The core is cooled by two distinct circuits, each one including two main coolant pumps and two steam generators. Each circuit is designed as a figure of 8 loop with two reactor passes containing 95 channels per pass.

The aging mechanism in CANDU-6 involves a range of physical and chemical processes that affect the long-term performance and safety of components and systems [5] [6]. The main aging mechanism is determined by Flow-Accelerated Corrosion (FAC) and creep of pressure tubes [7]. The combined effect by these two mechanisms affects directly the power level of the reactor [3] [4]. Before emerging into power dependency by age of the reactor, let's describe the aging mechanism:

- Flow-Accelerated Corrosion (FAC): means a degradation mechanism that affects carbon steel components in water and steam systems. Key factors that influence FAC are flow velocity (in this case, the high velocity of the coolant affects the integrity of the outlet feeders, velocity in the fuel channels is around 20-28 kg/s), temperature (FAC is most aggressive at the temperature above 200°C – the temperature of the inlet header at 0%FullPower is 260°C, up to 290 °C at 100%FP) and geometry.
- Creep of pressure tubes: mainly in the Zr-2.5 Nb pressure tubes that house the fuel bundles and carry pressurized heavy water (D₂O) coolant, at around 310°C and 10 MPa. There are three types of creep in a CANDU reactor pressure tube: axial creep, radial/transverse creep and sagging (vertical creep). Furthermore, the pressure tubes are directly affected by temperature, neutron flux, stress level and material microstructures. Over time, because of creep increase, the drop pressure between headers is decreasing and the flow through channels is redistributed

Considering the combined effect by the two aging factors, the reactor power is affected by the response of ROP detectors. The Regional Overpower Protection (ROP) system protects

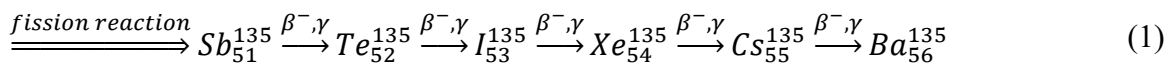
the reactor against excessively high power in the fuel, which could originate from a local power peaking within core due, for example, to an off-nominal reactivity device configuration, or a general increase in the core power level during a slow-loss-of-regulation (SLOR) event [8]. In the CANDU-600 design, there are two ROP systems in the core, each containing three independent safety channels. Each system includes several fast-response, self-powered flux detectors which are distributed throughout the core within vertical and horizontal assemblies [2].

To protect the reactor from an overpower event, the ROP trip setpoint (TSP) for these detectors is calculated using the thermohydraulic parameters, named boundary conditions, of the PHT [9], [10]. Inlet header temperature, pressure drop header to header and pressure of outlet header, including creep of pressure tube, affects the ROP trip setpoint. Over time, because of flow assisted corrosion (FAC) the inlet header temperature starts to increase, the pressure drop (dpHH) decreases, there will be a reduction of the value of critical channel power (CCP,) which represents the power level at which an onset of intermittent dry-out (OID) starts to develop. The decrease in the CCP value will eventually require a reduction in the ROP TSP value to maintain the appropriateness of the safety margin provided by the ROP system [11]. A progressive reduction in the ROP TSP value will eventually result in a need for a reduction in the maximum operating power level.

Therefore, the CANDU 6 reactors can't operate in the whole time at full power and a power reduction is necessary to maintain a safe margin operation. This event affects directly the xenon load in the reactor, because it depends on the power level.

2. 4. Xenon production and loss:

The production and loss of Xe-135 in a CANDU reactor is shown in the following equation [12]:



Considering the facts that Xe^{135} originates from:

- direct fission product
- decay of I^{135}

Therefore, the equation of Xe^{135} production would be represented in the following equation:

$$\frac{d}{dt} N_{Xe}(prod.) = \gamma_{Xe} \Sigma_{fission} \Phi + \lambda_I N_I \quad (2)$$

where Φ – represents the nominal neutron flux in a CANDU-600 reactor, γ_{Xe} – represents the fission Xe yield, $\Sigma_{fission}$ – macroscopic cross section of the fission, and $\lambda_I N_I$ – represents the fraction of I^{135} that decays into Xe^{135} .

Analyzing the equation, it can be observed that the Xe rate of production directly depends on production and decay of iodine. Even though the production of I^{135} is greatly higher, in terms of reactivity, I^{135} does not act as a poison in the core, because its cross section of neutron absorption is insignificant compared to the one of Xe^{135} ($\sigma_{absorbition}^I \ll \sigma_{absorbition}^{Xe}$). Thus, the main neutron-absorber poison in a PHW reactor, while at operating at a steady state, remains Xe^{135} [12].

The Xe^{135} is removed through by 2 individual mechanisms:

- neutron absorption, thus direct burn-up
- radioactive decay.

Hence, the rate of loss of Xe^{135} would be represented in the following equation:

$$\frac{d}{dt} N_{Xe}(loss) = \lambda_{Xe} N_{Xe} + \sigma_{absorbition}^{Xe} N_{Xe} \phi \quad (3)$$

where $\lambda_{Xe} N_{Xe}$ – represents the decay rate of Xe^{135} nuclei and $\sigma_{absorbition}^{Xe}$ – represents the microscopic cross section of the neutronic absorption by Xe^{135} (basically $\sigma_{absorbition}^{Xe} N_{Xe} \phi$ gives an accurate approximation of the Xe poison burn-up rate, depending of the neutron flux in the core).

Considering both the production and loss phenomena of the poison, the final equation of Xe^{135} would be [3] [4]:

$$\frac{d}{dt} N_{Xe} = \underbrace{(\gamma_{Xe} \Sigma_{fission} \Phi)}_{5\%} + \underbrace{\lambda_I N_I}_{95\%} - \underbrace{(\lambda_{Xe} N_{Xe})}_{10\%} - \underbrace{(\sigma_{absorbition}^{Xe} N_{Xe} \phi)}_{90\%} \quad (4)$$

In terms of reactivity, the reactivity worth induced by Xe - ρ_{Xe} , in a steady state reactor flux - ϕ_{ss} , with any Xe flux - ϕ_{Xe} and a number of ν – neutrons produced per fission, would be:

$$\rho_{Xe} = -\frac{\Sigma_{absorption}^{Xe}}{\nu\Sigma_{fission}} = \frac{1}{\nu\Sigma_{fission}} \frac{\phi_{ss}\Sigma_{fission}(\Upsilon_I + \Upsilon_{Xe})}{\phi_{ss} + \phi_{Xe}} = -\frac{\Upsilon_I + \Upsilon_{Xe}}{\nu} \frac{\phi_{ss}}{\phi_{ss} + \phi_{Xe}} \quad (5)$$

In case of a high neutron flux in a steady-state core, where the neutron flux is much higher compared to the neutron flux ($\phi_{ss} \gg \phi_{Xe}$), the resulting reactivity induced by Xe^{135} , would be:

$$\rho_{Xe} \cong \frac{\Upsilon_I + \Upsilon_{Xe}}{\nu} \quad (6)$$

3. Results and discussions

The operational derating of CANDU-6 reactors to approximately 90% full power (FP) at end-of-life arises from synergistic aging mechanisms that compromise reactivity margins and thermal-hydraulic safety limits. Cumulative fuel burnup reduces lattice reactivity due to uranium-235 depletion and fission product accumulation, particularly neutron absorbers like Xe-135. Concurrently, pressure tube radial creep—reaching 5.1% diametral expansion by end-of-life—alters channel geometry, increasing coolant bypass flow and reducing critical heat flux (CHF) margins by ~20%. Flow-accelerated corrosion (FAC) in carbon steel feeder pipes exacerbates these effects, with wall thinning rates up to 0.3 mm/year inducing asymmetric coolant distribution and pressure drops that challenge core flow stability. These aging phenomena collectively necessitate power reduction to maintain shutdown system effectiveness, as regional overpower protection (ROP) trip setpoints become constrained by increased uncertainty margins (~2–3% FP) in detector response to localized flux perturbations.

Xe-135 transients further underscore the operational rationale for end-life derating. Following a 100% FP shutdown, Xe-135 concentration peaks at ~100 mk above equilibrium within 10 hours due to sustained iodine-135 decay (6.57-hour half-life) and neutron flux cessation. In contrast, a reactor operating at 90% FP prior to shutdown exhibits a 10% lower equilibrium Xe-135 load and a reduced post-trip reactivity deficit, shortening the xenon override window by ~3 hours. This mitigation stems from proportional reductions in pre-shutdown iodine inventory and neutron absorption rates at derated flux levels. ROP systems, calibrated to account for aged-core spatial power peaking, benefit from derating by maintaining detector response within licensed trip probabilities despite aging-induced uncertainties in flux mapping. Graphical comparisons would illustrate these dynamics through diverging Xe-135 trajectories, with 90% FP cases showing flattened buildup rates and earlier convergence to decay-dominated regimes.

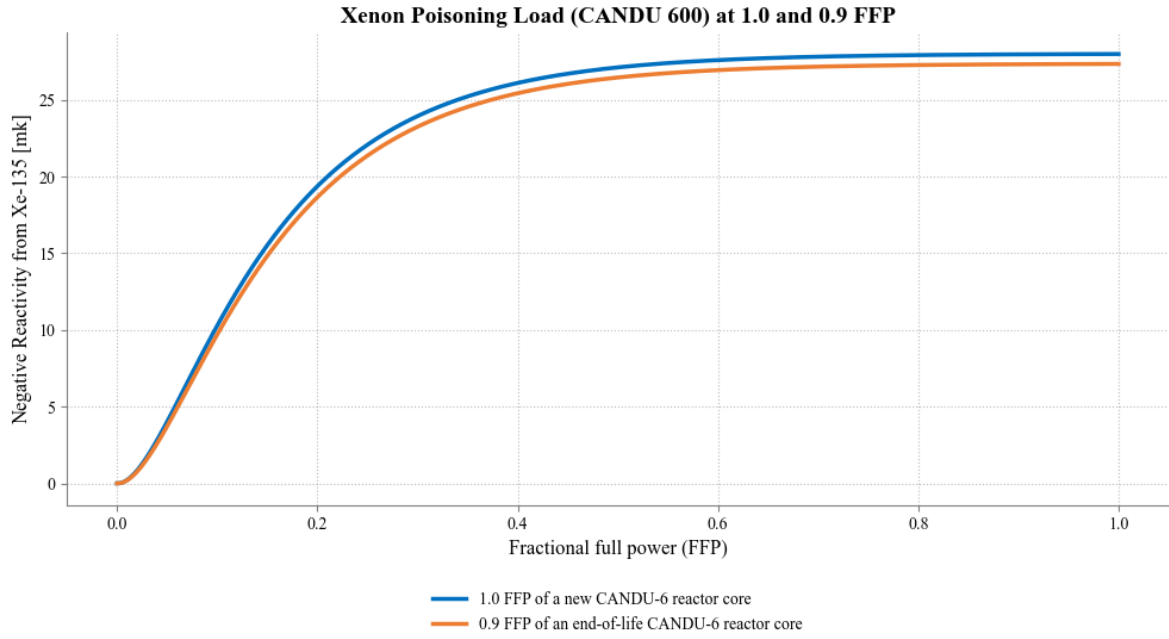


Figure 1. Representation of Xe loss and production in both new and end-of-life CANDU-600 reactor cores

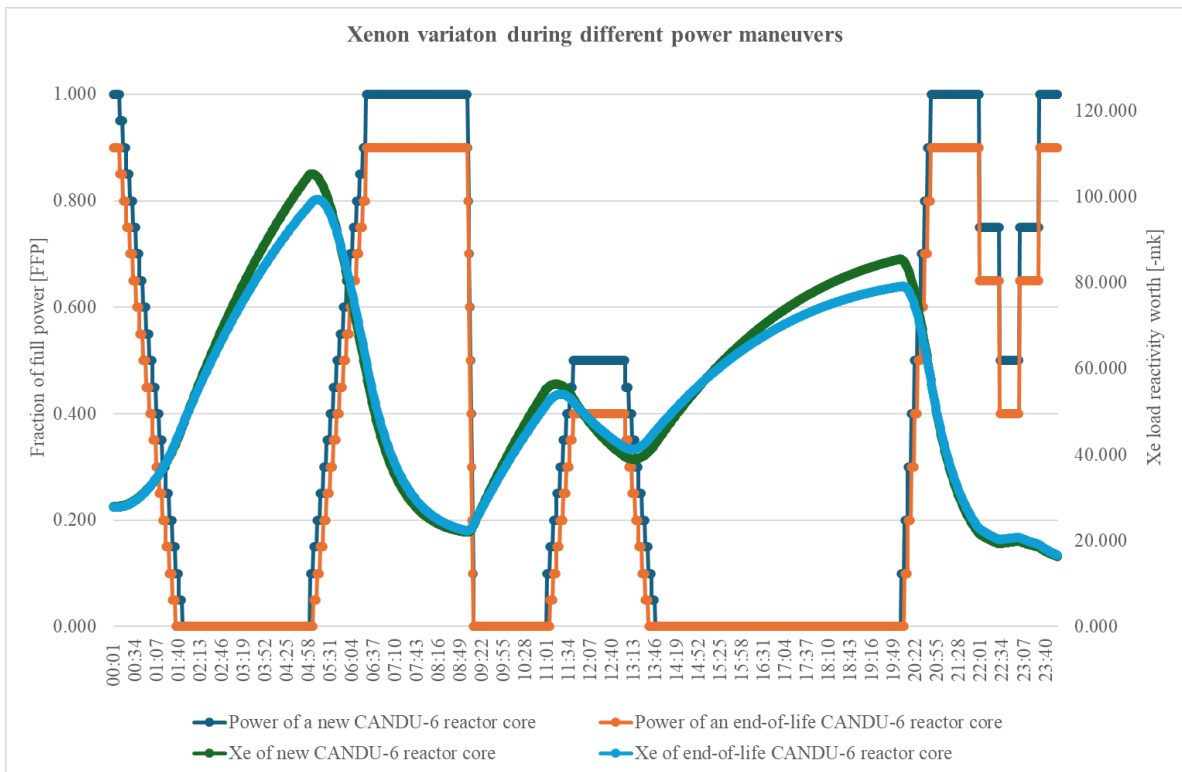


Figure 2. The Xenon load variation during power maneuvers

4. Conclusions

Due to degradation of thermohydraulic conditions and the reduction of the operating margin, the reactivity of the core is directly affected. Consequently, lowering the trip thresholds

of the ROP detectors leads to a decrease in reactor power, thus changing the xenon load. The change in xenon load in a CANDU-600 reactor alters the expected effects that may occur at the moment an adjuster bank is withdrawn, as the neutron flux changes, thus causing a different spatial distribution. As shown in the xenon simulations at different power levels, the variations in reactivity worth of the xenon load varies. Over time, this phenomenon must be monitored more carefully and new considerations should be taken into account when planning power reductions as the reactor ages.

The findings demonstrate that aged CANDU-6 cores exhibit heightened xenon sensitivity despite reduced equilibrium Xe-135 production, a paradox stemming from diminished reactivity margins and cumulative neutron poison accumulation. This phenomenon, compounded by aging mechanisms like fuel burnup and pressure tube creep, tightens the reactivity balance, amplifying xenon-induced swings during power maneuvers and shutdown recovery. Operational flexibility erodes progressively, necessitating adaptive control strategies to manage constrained override capabilities while ensuring adherence to regional overpower protection limits. These insights underscore the imperative for xenon-aware operational protocols in late-life reactors to mitigate asymmetric flux perturbations and maintain safety-critical reactivity reserves.

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