Canadian Nuclear Safety Commission   Commission canadienne de sûreté nucléaire

Technical Note

Positive coolant void reactivity feedback phenomenon in currently operating CANDU reactors

Last updated on July 14, 2009

Canada

E-DOCS #3399585

1. A FEW FACTS ABOUT THE CANDU DESIGN

The nuclear fission chain reaction – basic concepts

- The nuclear fission process involves the splitting of an atomic nucleus (such as the uranium) using tiny particles called neutrons. The uranium nucleus splits into two fragments, which fly apart. When this happens, gamma rays are also emitted, along with two or three fast neutrons. These neutrons will continue to break other nuclei, and induce more nuclear fissions, in a cascading manner. This process is called a *nuclear fission chain reaction.*

- In order for the process to be self-sustaining, at least one neutron from each fission event must cause another nuclear fission. In scientific terms, such a fission chain reaction is designated as *critical.* If the number of fission events arising from each event is less than one, the fission chain reaction is *subcritical*; it is *supercritical* if it is more than one.

- When the chain reaction is critical, the overall neutron population within the reactor, as well as the energy being produced, will remain constant. In industry terms, at this equilibrium level, *the reactor is said to be critical*, and the neutron population and power level are in a *steady state condition*.

- Any deviation from the steady state of the overall neutron population within a reactor is represented by a quantity called *reactivity,* which we denote by ρ. For a steady state (or critical) reactor, $\rho=0$. When the reactor deviates from criticality, the reactivity becomes either positive ($\rho>0$) or negative ($\rho<0$). Therefore, $\rho<0$ implies a decreasing rate of the fission reactions (a subcritical state), while $\rho>0$ implies an increase (a supercritical state).

Heat production in CANDU reactors:

- CANDU (CANada Deuterium Uranium) reactors produce energy through a controlled nuclear fission chain reaction, using natural uranium as fuel.

- Most of the recoil energy of the fission fragments is deposited as heat within the fuel.

- The fast neutrons emitted during the fission reactions must be slowed down (*moderated*), in order to increase the chances of them causing further fissions in the uranium. This moderation is achieved using heavy water. Heavy water consists of 2 atoms of deuterium and 1 atom of oxygen.

Cooling the fuel in CANDU reactors:

- CANDU reactors use nuclear fuel in the form of natural uranium dioxide pellets, stacked in an array (*bundle*) of thin-walled tubes of zirconium alloy, each about 12 mm in diameter and about 0.5 m in length, and called *fuel bundles*.

- The fuel bundles are inserted in horizontal fuel channels, each typically housing 12 fuel bundles. The *reactor core* is composed of 380 fuel channels (for CANDU-6 and Pickering reactors) or 480 fuel channels (for Bruce and Darlington reactors).

- The heat generated within the fuel is removed by heavy water – acting as a coolant – which is circulated at high pressure through the fuel channels. The high pressure is necessary to maintain the coolant in a liquid state, and prevents significant boiling.

- Through a *heat transfer process*, the heat from the coolant is used for the production of steam – which is, in turn, used to generate electricity in the nuclear power plant's turbines.

- CANDU reactors are equipped with an *emergency core cooling system* (ECCS) to provide back-up cooling in the unlikely event of a large loss of coolant. This is a safety feature in all water-cooled reactors.

Controlling the generation of power:

- The generation of power through the fission process in the reactor core is controlled by the automated continuous action of the Reactor Regulating System.

- Major deviations from normal operating conditions are quickly detected and arrested by two independent, automated, fast-acting shutdown systems.

Containment:

- A massive concrete structure provides *containment* for the entire reactor coolant system. The containment is a structural envelope, surrounding the nuclear components of the plant and the systems that limit the pressure within the envelope in the event of accidents involving a loss of coolant.

- A large portion of the nuclear safety design and analysis effort is directed toward ensuring that radioactive materials are retained within the containment, and to limit any releases to CNSC-prescribed values for all possible accident scenarios, including large loss of coolant accidents.

2. WHAT IS MEANT BY "POSITIVE COOLANT VOID REACTIVITY FEEDBACK" IN CANDU REACTORS?

- For all reactor designs, including the CANDU design, any change in coolant density will result into a change in the rate of fission reactions. This is known as the *coolant void reactivity effect*. In CANDU reactors, the effect is positive ($\rho>0$) which means that a decrease in coolant density will result in an increase of reactivity, which leads to an increased heating of the fuel, which further contributes to the decrease in the coolant density. This represents a specific feature of the CANDU reactor, which is referred to as the ***positive coolant void reactivity feedback***.

- The main design feature of the CANDU reactor that introduces this effect is a particular physical separation of the coolant from the moderator combined with the use of natural uranium fuel.

- *Coolant void reactivity feedback* is just one of the many feedback mechanisms which exist in nuclear reactors. Other such mechanisms include fuel temperature feedback (also known as Doppler feedback), moderator temperature feedback, etc. When added up, these phenomena constitute the *power reactivity feedback*, represented by the *power coefficient of reactivity* (PCR). It is entirely possible to have a positive coolant void reactivity feedback and a negative PCR, since the latter is a sum of all reactivity feedbacks, both positive and negative.

3. IS THE POSITIVE COOLANT VOID REACTIVITY FEEDBACK IN CANDU REACTORS A NEWLY-DISCOVERED PHENOMENON?

- ***Not a new phenomenon*** - The existence of the positive coolant void reactivity feedback effect in CANDU reactors has been known to both the designers and the Commission staff since the design of first CANDU commercial reactors.

- ***The phenomenon is well understood* -** Over the years, this phenomenon has been the object of close scrutiny by AECB/CNSC staff and the nuclear industry, and has been the object of numerous research and development (R&D) activities. By now, this phenomenon is well understood

- ***Ongoing R&D activities*** - The positive coolant void reactivity issue continues to be the subject of several industry-sponsored R&D projects, the results of which have been closely monitored by CNSC staff. The CNSC staff has also undertaken a number of separate research projects on this issue.

4. WHY CANDU REACTORS ARE SAFE, EVEN WITH THE PRESENCE OF POSITIVE COOLANT VOID REACTIVITY FEEDBACKS

4.1 Both *design* and *operational provisions* are in place to mitigate the adverse effects of the positive coolant void reactivity feedback in CANDU reactors. These provisions include:

- *Shutdown systems*

  - Current CANDU designs include specific safeguards to address this intrinsic feature of the CANDU design, by employing multiple protective measures to provide *defense-in-depth*.

  - The primary protective provision is the presence of two independent, equally effective, fast-acting automated shutdown systems, which incorporate the important principles of redundancy, diversity and independence in their design. The first shutdown system consists of spring-assisted, gravity-driven neutron absorbing shut-off rods, which drop in the core. The second shutdown system is based on the injection of neutron-absorbing liquid into the moderator. Either one of these two shutdown systems is fully capable of safely shutting down the reactor, even in the unlikely event of a large loss of coolant accident (LLOCA).

- *Operational constraints following new R&D findings*

  - In the mid-1990s, R&D activies focusing on the Bruce and Darlington reactors resulted in the prediction of a larger than anticipated increase in the rate of the fission reaction. Given the Bruce reactors' greater sensitivity to core voiding, this finding led to *power derating* at the Bruce site.

  - Later in the 1990s, further R&D led to recognition that the computer codes previously used in reactor physics analysis of LLOCA had significantly underestimated the magnitude of the coolant void reactivity. As a result of this discovery, a series of measures was implemented. These included more restrictive performance limits for shutdown systems (which are verified through periodic testing), and a number of operational constraints, such as bundle and channel power limits, and limits on coolant and moderator purity. The previous reactor physics codes were replaced with a more modern set of codes, which have a more substantial validation basis.

- *Additional safety features of the CANDU design*

  - Additional CANDU design features provide further assurance that, in the unlikely event of a LLOCA (a scenario in which the positive void reactivity feedback would have its most significant impact), any potential radioactive releases will be within CNSC-prescribed limits.

- *Inherent safety feature* - The time during which a neutron born in a fission event survives, before it disappears while causing another fission event, is called *neutron lifetime*, and it influences the dynamic behavior of a reactor The neutron lifetime in CANDU reactors is ten times longer than in light water reactors. The longer the neutron lifetime, the slower the reactor's response to a reactivity insertion. In the event of a CANDU reactor coolant voiding, the positive void reactivity feedback will increase the fission rate in the fuel, leading to a *reactor power increase*. However, the speed of this power increase will be much slower than it would be in a light water reactor, providing sufficient time for a shutdown system to be activated, so that the consequences of the accident are maintained within CNSC-prescribed limits.

- *Engineered safety features* - The cornerstone of CANDU design, operation and licensing, is the *defence-in-depth principle*, which requires employing multiple physical barriers and protective functions to prevent potential radioactive releases.

  - Physical barriers include the fuel matrix, the fuel rod cladding, the fuel channel pressure tube and the pressure boundary of the reactor coolant system. The containment system described earlier constitutes a fourth barrier against the release of radioactive materials.
  - Similar to all water-cooled reactors, CANDU uses an emergency core cooling system, to provide backup cooling in an unlikely LLOCA event.

4.2 Demonstrations, through safety analysis, of the effectiveness of the design and operational provisions put in place:

- *Safety analysis* is performed to demonstrate the adequacy of design and operational practice during normal operation, as well as following accident conditions. The analyses, included in the nuclear generating station's Safety Report, cover a range of postulated accident scenarios (known as "design basis accidents"). The current safety analysis methodology incorporates numerous conservative assumptions with regard to the state of reactor, both before and after the accident initiation.
- The positive coolant void reactivity feedback phenomenon does not pose a problem during normal operations. The reactor control system is designed to control small variations in power, resulting from local coolant density changes.
- The postulated accident scenarios usually result in a degradation of the reactor's cooling capability (i.e., a mismatch between heat generation and

heat removal.) The mismatch causes coolant density transients, which – as explained above – has a consequence on the heat generated by the fission process. Consequently, accidents which involve a decrease in coolant density, such as *loss of coolant accidents* (LOCA) or *loss of forced coolant circulation*, result in a simultaneous increase in power and degradation in cooling.

- Positive void reactivity feedback has the most severe impact in the largest pipe break scenarios, which postulate a sharp decrease in coolant density, resulting in a power pulse and a rapid initiation of reactor shutdown by one of the two shutdown systems. It must be noted that **the possibility of accidents resulting in a rapid pulse is extremely low.**

4.3 Regulatory oversight ensures that CANDU reactors are operated safely:

- The CNSC regulates the use of nuclear energy and substances in Canada. Through its licensing, certification and compliance processes, the CNSC ensures that nuclear activities are carried out safely, in order to protect the health and safety of Canadians and their environment.

- Similar to any other regulatory jurisdiction, and consistent with international best practices, the construction and operation of a nuclear reactor in Canada is considered safe as long as it meets the Canadian regulatory requirements stated in the *Nuclear Safety and Control Act* and its *Regulations*, as well as the CNSC's expectations (outlined in various regulatory documents), and conforms to the design requirements and operating limits and conditions described in its Safety Analysis Report and accepted by the Commission.

4.4 CANDU reactors continue to be safe:

- All CANDU reactors in operation have been subject to close regulatory oversight and an effective licensing process. The licensing period covers 5 years, and license renewal requires close technical scrutiny and regulatory oversight.

- This intrinsic feature (<u>*positive reactivity feedback*</u>) of CANDU designs, as well as the adequacy of design and operating safeguards put in place to address it, have been, and continue to be, the subject of close scrutiny and constant questioning. Both the operators and the CNSC have been, and continue to be, proactive in identifying and implementing any necessary measures to assure a high level of confidence in the adequacy of safeguards provisions in place.

- CANDU reactors have been operating safely for over 35 years.

- Regarding the positive reactivity feedback effect in CANDU reactors, no major finding to date challenges the judgement that, with the existing safeguards in place and additional compensatory measures implemented following new R&D, the CANDU operating reactors continue to meet the licensing legal requirements.

Note:

More detailed technical information about the positive coolant void reactivity feedback phenomenon in currently operating CANDU reactors is available at the CANTEACH project Web address canteach.candu.org.

CANTEACH is a knowledge repository of high-quality technical documentation relating to the CANDU nuclear energy system. The CNSC has provided numerous documents to this repository – the information is public, and intended for use in various aspects of education, training, design and operation.

Any questions regarding this technical note should be addressed at the CNSC Public Affairs and Media Relations Division – 613-996-6860 or 613-995-2903