Simulation of A CANDU Reactor Approach to Criticality after a Long Shutdown

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Abstract

This study addresses the approach to criticality of CANDU reactors during their start-up after a long shutdown. The simulation study is based on the point kinetics model, which represents the prompt neutron kinetics and 17 delayed neutron precursor groups. The parameters of the neutronic model used in this model, are chosen to be the same parameters of Bruce-A reactor fresh core to simulate its start-up. Other dynamics were also included in the model such as the Gadolinium extraction dynamics, and the Xenon dynamics. The factors, which affect the core approach to criticality, have been well simulated and analyzed separately.

1. Introduction

It is well known that starting up a nuclear reactor after it has been shut down for a long time is achieved by going through two stages, and these are:

1. The approach to criticality during which the value of reactivity is increased until the reactor becomes critical at a very low power level.
2. Increasing the power until the operating level (i.e., the reactor regulating system (RRS) range) is reached.

Normally the reactivity excess due to the fresh fuel in a CANDU reactor core is suppressed by using Gadolinium to maintain the moderator in the over-poisoned state. Removing the Gadolinium from the moderator gradually then carries out the approach to criticality at a low power level, while monitoring the count rate. Some intrinsic neutron sources such as photo-neutron source, which is inherent in the core structure itself, play important role at a very low power level.

The objective of this simulation study is twofold. The first aspect is to analyse the behaviour of the CANDU reactor during its approach to criticality at a very low power level, that is, when the reactor is start up for the first time or after a long shut down. The effects of the initial over-poisoned core reactivity, the time constant of Gadolinium removal, and the intensity of the external photo-neutron source will be taken into account in this study. The second aspect addresses the raise of the reactor power to the RRS control range. The effect of addition/removal of small amounts of reactivity due to the removal/insertion of an MCA rod is taken into account in this part of the transient. The RRS range of power is defined as the level of neutronic power, where the ion chambers signals are rational i.e. above the 10^{-7} power level.

2. Modelling

In order to model the CANDU reactor during its approach to criticality, several assumptions have to be made. The initial neutronic power of the reactor core is assumed to be zero. Fission product (mainly Xenon) and delayed neutron precursor concentrations are also assumed to be zero. The external photo-neutron source is considered deterministic with a constant intensity. Furthermore, the Gadolinium extraction is assumed to be an exponential function of time. Finally, the reactor is considered to be critical with –0.2 mk of extra poison in the moderator. The dynamics, which have been taken into consideration in this study, can be classified as follows:

2.1 Neutronic power dynamics:

The neutronic power dynamics used in this simulation study are based on the point kinetics model [2], which represents the prompt neutron kinetics and 17 delayed neutron precursor groups. The neutronic power dynamics (i.e., neutronic density dynamics) including the photo-neutron source SR are represented by the differential equations (1) and (2), where the prompt neutron life time $l^* = 0.8975 \times 10^{-3}\ \text{sec}$:

$$\frac{dn(t)}{dt} = \frac{\delta\rho\ (t) - \beta}{l^*}.n(t) + \sum_{i=1}^{17} \lambda_i.C_i(t) + SR \tag{1}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i.n(t)}{l^*} - \lambda_i C_i(t)\ ; \quad i = 1\ to\ 17 \tag{2}$$

The dynamics associated with the external photo-neutron source SR is described in section 2.2. Furthermore, the dynamics of the reactivity change δρ(t) caused by Xenon and Gadolinium extraction are described Sections 2.3 and 2.4. The parameters of the neutronic model (i.e., the delayed fraction and decay constants) used in this model, are chosen to be the same parameters of Bruce-A fresh core so as to simulate a realistic case [1]. The various neutronic parameters are shown in Table 1. It should be mentioned that the reactivity in the point kinetics model, represents the change in reactivity due to the Xenon effect and the Gadolinium extraction from the moderator.

2.2 External photo-neutron source dynamics:

Intrinsic neutron sources are sources of neutrons from materials that are in the reactor for other purposes such as fuel, burnable poison, moderator, or the core structure itself. Neutrons from such sources are very important because they ensure high neutron population enough to start the fission reaction during the start-up sequence. Examples of intrinsic neutron sources are listed as follows [2]:

1. Spontaneous fission of heavy nuclides in fuel, such as Uranium 238, which results in fission fragments and free neutrons.
2. Boron mixed with the fuel undergoes an alpha-neutron reaction and becomes nitrogen 14.

3. Deuterium present in the reactor coolant undergoes a Gamma rays-neutron reaction and becomes hydrogen 1. This type of source is considered in this study because it is more inherent in CANDU reactors.

Group, í	**Fraction, β_i**	**Decay Constant, λ_i (s^{-1})**
Direct Delayed Neutrons:		
1	0.201972e-3	0.133177e-1
2	0.113143e-2	0.320774e-1
3	0.969553e-3	0.121166e+0
4	0.209515e-2	0.316059e+0
5	0.110582e-2	0.960256e+0
6	0.521558e-3	0.295226e+1
Photo-neutrons:		
7	0.124537e-6	0.625969e-6
8	0.260397e-6	0.363255e-5
9	0.826475e-6	0.437566e-4
10	0.596646e-5	0.117003e-3
11	0.527583e-5	0.427889e-3
12	0.857048e-5	0.149993e-2
13	0.178429e-4	0.481036e-2
14	0.507210e-5	0.124429e-1
15	0.253492e-4	0.305344e-1
16	0.219639e-4	0.111446e+0
17	0.219639e-4	0.301357e+0
Total	0.613872e-2	---

Table 1 Bruce-A fresh core neutronic parameters

The dynamics of the source is considered deterministic with a constant intensity along the simulation time. The intensity of the source is varied during the simulation according to Table 2.

Photo-neutron Source Intensity, n/cm3/sec	10^{-14}	10^{-13}	10^{-12}	10^{-11}	10^{-10}

Table 2 Photo-neutron source intensity simulated values

2.3 Xenon dynamics:

In order to make the model more realistic, and to study the effect of Xenon-135 during the approach to criticality at a low power level, its dynamics were included in the point kinetics model. Of course the Xenon effect is translated as a reactivity feedback in the point kinetics model, and equations (3) and (4) represent the Xenon dynamics:

$$\frac{dI}{dt} = \lambda_I (I_0 P - I) \tag{3}$$

$$\frac{dX}{dt} = \lambda_I (\frac{\gamma_X}{\gamma_I} I_0 P + I) - (\lambda_X + \sigma_X \phi_0 P) X \tag{4}$$

where $I_0 = (\frac{\gamma_I}{\gamma_I + \gamma_X} \frac{\lambda_X + \sigma_X \phi_0}{\lambda_I}) X_0$ is the Iodine reactivity at 100% full power (mk).

$X_0 = 28\ mk$: Xenon-135 reactivity at 100% full power.
I : Iodine-135 reactivity (mk).
X : Xenon-135 reactivity (mk).
$\gamma_I = 6.14e-2$: Total yield of Iodine-135 per fission.
$\gamma_X = 5.801e-3$: Total yield of Xenon-135 per fission.
$\lambda_I = 2.925e-5\ hr^{-1}$: Decay constant of Iodine-135.
$\lambda_X = 2.1158e-5\ hr^{-1}$: Decay constant of Xenon-135.
$\phi_0 = 2.495e14\ n/cm^2/s$: Thermal flux at 100% full power.
$\sigma_X = 1.278e-18 cm^2$: Thermal microscopic Xenon-135 cross section.
$P = 1.0$: Reactor power in fraction of full power.

2.4 Gadolinium removal dynamics:

The approach to criticality is achieved by the gradual removal of Gadolinium from the moderator. The Gadolinium removal is represented by an additive reactivity in the point kinetics model. In order to simulate the dynamic behaviour of the chemical process, the dynamics of the Gadolinium removal were represented by an exponential function of time with initial over-poisoned core reactivity ρ_{Gd} and a time constant τ. The parameters of the Gadolinium model are varied during the simulation according to Table 3. The dynamics of the Gadolinium removal is given by equation (5):

$$\frac{dG}{dt} = -\frac{G}{\tau_{Gd}} \tag{5}$$

where G is the Gadolinium reactivity (mk). In real nuclear power plants the Gadolinium removal is stopped for some time to monitor and examine the state of the reactor in terms of its criticality. If the reactor is still sub-critical, then the poison extraction is resumed. Once the criticality at a low power level is reached, the poison extraction from the moderator is stopped.

Initial Core Reactivity ρGd, mk	-300.00	-350.00	-400.00
Time Constant τ, hours	4.00	6.00	------

Table 3 Gadolinium model parameters simulated values

The dynamics of the Gadolinium removal for initial core reactivity $\rho_{Gd} = 300.00\ mk$ are shown in Figure 1.

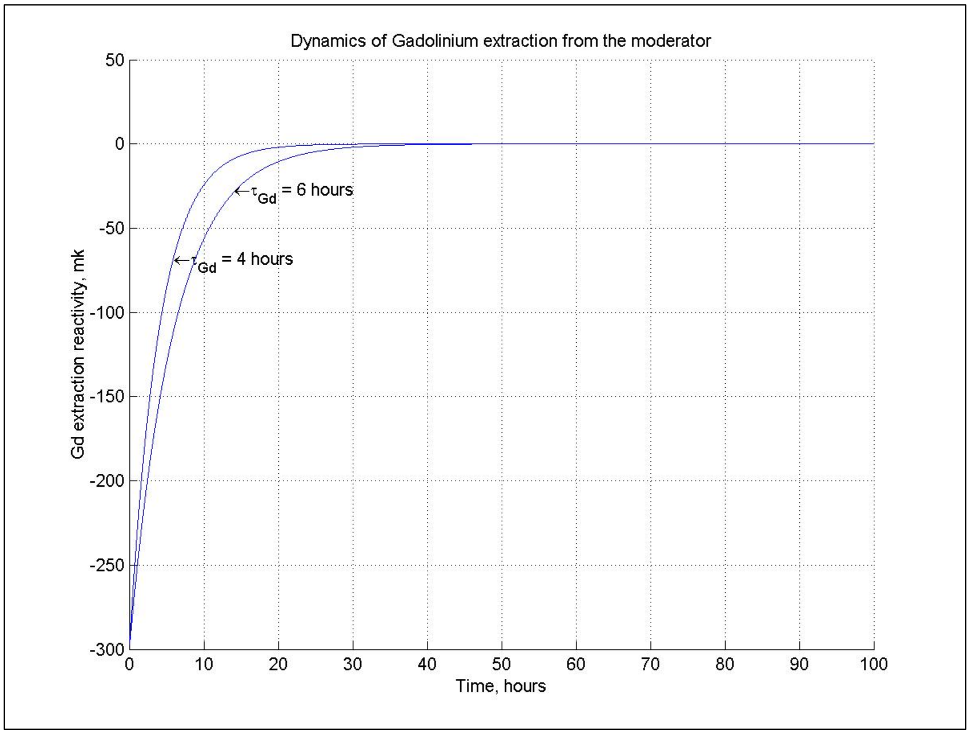

Figure 1 Gadolinium extraction dynamics

3. Simulation results

A model was developed to study the behaviour of starting the CANDU reactor for the first time or after a long shutdown. The simulation study was done by varying the levels of the factors, which affect the dynamic behaviour of the reactor when approaching criticality at a very low power level. The affecting factors include the Gadolinium extraction time constant, the initial over-poisoned core reactivity, and the intensity of the photo-neutron source.

The MATLAB simulation package was used to write the model and to simulate the behaviour of the CANDU reactor at the different situations, where the affecting factors are varied. The simulation problem was found to be very stiff problem to solve by ordinary ODE solvers, and highly sensitive to errors since the level of the power is very low. Therefore a stiff ODE solver with very small error tolerances was used to tackle the stiffness of the problem and to produce accurate results.

3.1 Case study 1: Low power approach to criticality

The simulation results of the different factors, which affect the behaviour of the CANDU reactor during its start-up after a long shutdown, can be summarized as follows:

3.1.1 Effect of photo-neutron source intensity

In order to study the effect of the photo-neutron source on the behaviour of the CANDU reactor at a very low power level, the source intensity was varied at initial over-poisoned core reactivity of –300 mk and Gadolinium extraction time constant of 4 hours. The Gadolinium in this case was extracted completely from the moderator. Consequently the neutron flux increased steadily till it reached a steady state, where the reactor was slightly above criticality due to the effect of the source. The reactor showed the same transient behaviour when the intensity of the source was increased, however the neutron flux level was higher due to the higher source intensity, as illustrated in Figure 2.

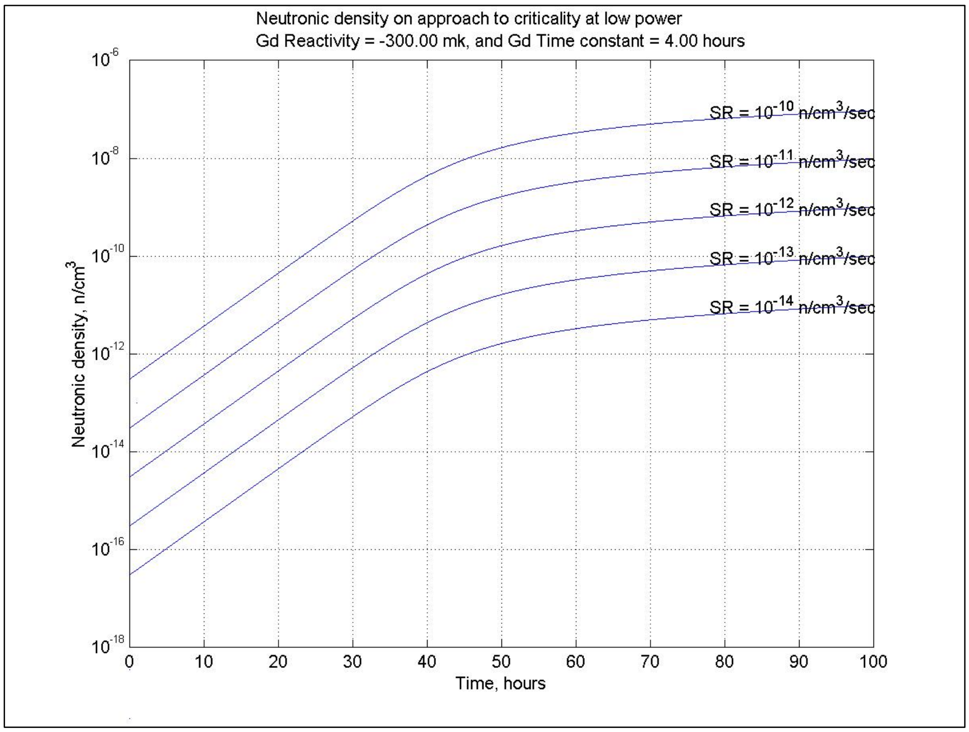

Figure 2 Neutronic density dynamics during the approach to criticality

3.1.2 Effect of initial over-poisoned core reactivity

The dynamic behaviour of the CANDU reactor did not show a significant change, when it was simulated at different initial over-poisoned core reactivity levels, and keeping the other parameters constant. In fact the prompt jump component of the reactor dynamics is only affected when the initial core reactivity is changed, which slightly raised the neutron flux level in the core. The prompt jump component of the reactor dynamics is characterized by its steady state level and time constant, which are given by equations (6) and (7):

$$n_{SS} = -\frac{l^* SR}{\rho_{Gd}} \tag{6}$$

$$\tau_{PJ} = \frac{l^*}{\rho_{Gd}} \tag{7}$$

In order to demonstrate the slight effect of the initial over-poisoned core reactivity on the prompt jump component of the reactor dynamics, the prompt component of the neutron density is tabulated at different source intensity levels and initial core reactivity levels, as shown in Table 4.

Initial core reactivity ρ_{Gd} (mk)	-300.00	-350.00	-400.00
Source intensity **SR** (n/cm^3/sec)	Neutron density n_{SS} (n/cm^3)		
10^{-14}	2.9916×10^{-17}	2.5643×10^{-17}	2.2437×10^{-17}
10^{-13}	2.9916×10^{-16}	2.5643×10^{-16}	2.2437×10^{-16}
10^{-12}	2.9916×10^{-15}	2.5643×10^{-15}	2.2437×10^{-15}
10^{-11}	2.9916×10^{-14}	2.5643×10^{-14}	2.2437×10^{-14}

Table 4 Effect of initial over-poisoned core reactivity on reactor dynamics

3.1.3 Effect of Gadolinium extraction time constant

Gadolinium extraction process has a significant effect on the dynamic response of the CANDU reactor when it is started after a long shutdown. The time constant of the Gadolinium extraction process was varied at a constant photo-neutron intensity of 10^{-11} n/cm^3/sec and an initial core reactivity of –300.00 mk, in order to simulate the behaviour of the reactor during its start-up.
As illustrated in Figure 3 (top plot), when the time constant of the Gadolinium extraction is 4 hours, the neutron density reaches its steady state earlier than the case of the time constant of 6 hours. Another important parameter, which helps reveal the effect of the gadolinium extraction on the transient behaviour of the reactor power, is the stable time constant of the reactor. The time constant of the reactor can be expressed as a function of the log rate of reactor power by equation (8):

$$\tau_{\mathrm{Re}actor} = \left(\frac{1}{P} \frac{dP}{dt} \right)^{-1} \tag{8}$$

It is clear in Figure 3 (bottom plot) that the smaller the time constant of the Gadolinium extraction process, the smaller the time constant of the reactor, and the faster the transient response of the neutron density.

3.2 Case study 2: Power raise to the RRS control range

Once criticality is reached at a low power level with some extra gadolinium poison remaining in the moderator, further extraction of negative reactivity or addition of positive reactivity is needed in order to raise power further. During final approach to criticality the doubling time is used as a measure of the rate at which the reactor power changes. Doubling time with exponential growth is defined as the amount of time it takes reactor power to double, and given by equation (9):

$$t_{double} = \frac{\ln(2) = 0.69315}{\frac{1}{n(t)}\frac{dn(t)}{dt}} \tag{9}$$

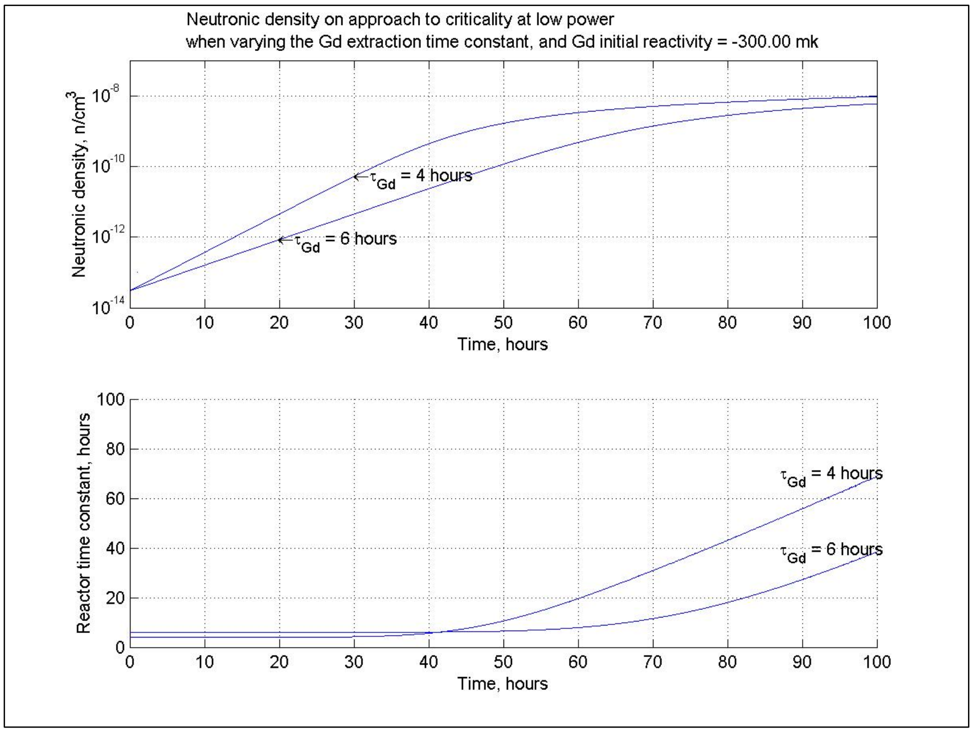

Figure 3 Effect of Gadolinium extraction time constant on the reactor dynamics

Examples of doubling times corresponding to various rates of power increases are given by Table 5. In the simulation, the withdrawal of an initially inserted MCA rod was used to provide positive reactivity in order to be able to raise neutronic power to the RRS range. Positive reactivity insertion was simulated by MCA rod withdrawal at the maximum driving speed, with photo-neutron intensity of 10^{-11} n/cm^3/s. Hence, the reactivity rate of change at this phase of the transient was characterized by equation (10):

$$\left.\frac{d\rho}{dt}\right|_{\max} = \frac{\text{Positive Reactivity worth inserted by MCA movement}}{\text{Minimum travel time}}$$

$$= \frac{0.5}{70} = 7.14x10^{-3}\ \frac{mk}{\sec} \tag{10}$$

	Power log rate, %pp/s	Doubling time, s
Prompt Critical with β=6 mk, Ln(2)/(0.006/l*)	668%	0.104
Upon SDS2 Trip	15%	4.62
Upon SDS1 Trip	10%	6.93
Upon Stepback	7%	9.90
Upon RRS Fast Manoeuvre	4%	17.33

Table 5 Doubling time as a function of power rate for different CANDU reactor operating conditions

As illustrated in Figure 4, the neutronic density starts to increase when the MCA rod was moved out for a certain time period. It can be also noticed that the longer the time of the MCA rod withdrawal which amounts to larger values of positive reactivity insertion, results in higher the rate of power change, and takes a shorter time for reactor power to reach the RRS control range. The steady state core reactivity after withdrawal of the MCA rod for a specified time is tagged on each corresponding curve.

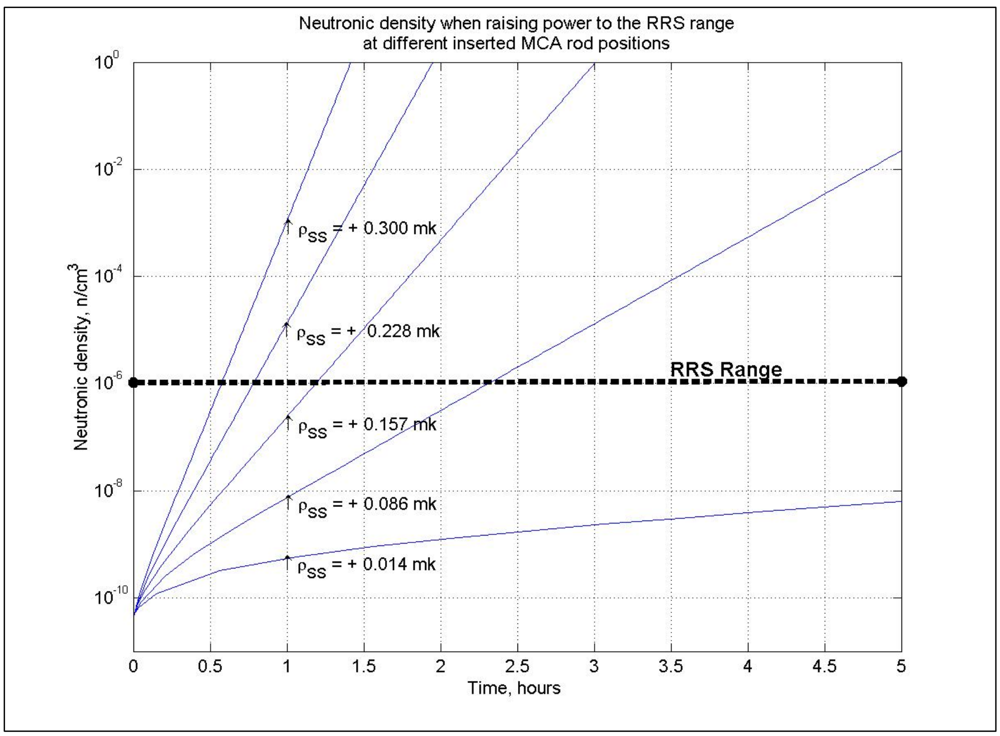

Figure 4 CANDU reactor dynamics during power raise to the RRS range

The minimum doubling times corresponding to the maximum lag rate observed during the transient, for the various different MCA rod withdrawal times, are shown in Table 6.

MCA withdrawal time, s	Steady state reactivity, mk	Max Power log rate, %pp/s	Min. Doubling time, s
30	0.014	0.56295	123.13
40	0.086	0.67117	103.34
50	0.157	0.77926	88.95
60	0.228	0.89318	77.60
70	0.300	1.01082	68.57

Table 6 Effect of MCA rod withdrawal time on CANDU reactor dynamics

3.3 Nuclear power plants practices

Having studied the dynamic behaviour of the CANDU reactor during the approach to criticality at a low power level taking into account all the affecting factors, it would be informative to simulate how the approach to criticality is achieved in real nuclear power plants. It is assumed that the Gadolinium is extracted at time constant of 4 hours in the first 24 hours, then the time constant is increased to 6 hours (i.e., slower extraction rate) till the reactor is -0.2 mk below criticality, where the extraction is stopped. The reactor is considered critical at -0.2 mk as practiced in Bruce A NGS.

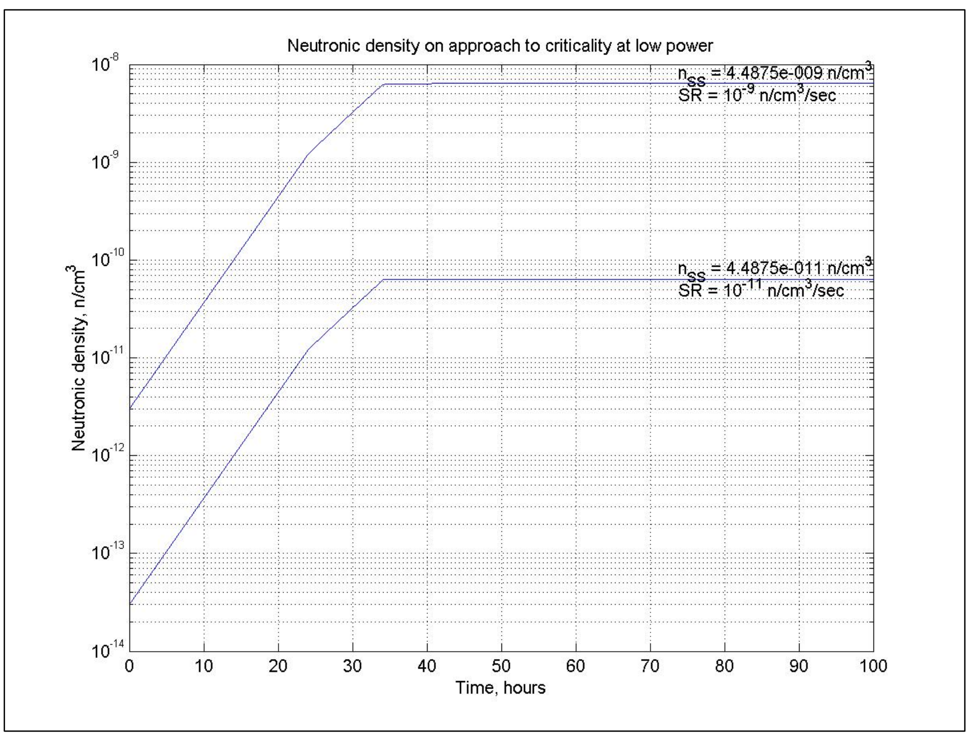

Figure 5 CANDU reactor dynamics during typical practice of approach to criticality

The simulation was done for two different levels of photo-neutron source intensity. As illustrated in Figure 5, the neutron density started to increase till the point where the increase is slowed down by the slower Gadolinium extraction rate. When the reactor reactivity is 0.2 mk below criticality the power reached its steady state immediately after stopping the Gadolinium extraction. It takes approximately 34 hours to complete the whole process. Apparently the neutron density response will be higher for higher photo-neutron source intensity.

3.4 Typical raise of reactor power to the RRS control Range

Once criticality is reached at low power level, an MCA rod, which is initially partially inserted in the core, is pulled out while raising power and reinserted again in order to stabilize the power in the RRS control range. This case was simulated at photo-neutron intensity of 10^{-11} n/cm^3/s and after the neutronic density had reached its steady state value. The MCA rod was pulled out of the core at the maximum driving speed for 40 seconds; this caused the neutronic density to rise at a constant rate. When the neutronic density reached the RRS range (i.e., 10^{-6}) at time $t = 3.0$ hours, the MCA rod was reinserted for 11.6 seconds. This in turn resulted in stopping the rise in neutronic density, at the appropriate RRS control range as illustrated in Figure 6.

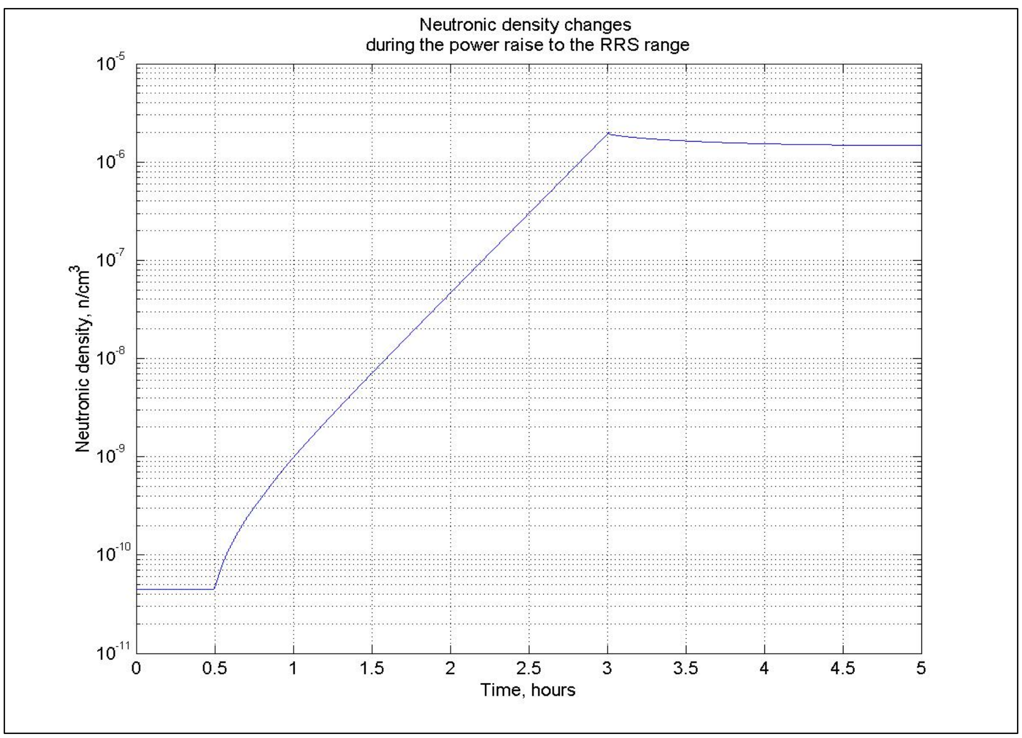

Figure 6 CANDU reactor dynamics during typical practice of power raise to the RRS range

4. Conclusions:

Several interesting conclusions, which were revealed by this study, can be summarized as follows:

1. Intrinsic neutron sources such as the photo-neutron source play an important role during the approach to criticality at low power level. The simulation results showed that the higher the source intensity the higher the transient response of the neutron density.
2. The initial over-poisoned core reactivity affects the prompt jump component of the reactor dynamics during its start-up after a long shutdown. This implies that the initial reactivity does not have a significant effect on the whole dynamic behaviour of the reactor since the delayed neutron dynamics are more dominant.
3. The time constant of the Gadolinium extraction process is the most dominant factor in the dynamics of the CANDU reactor during the approach to criticality at low power level. In fact the faster the extraction rate (i.e., the time constant of the extraction process) the faster the transient response of the reactor dynamics.
4. Simulation results have also shown that Xenon has no effects whatsoever on the dynamics of the CANDU reactor at very low power levels.
5. When the reactor power is raised to the RRS range, it is noticed that more positive reactivity addition results in the higher rate of power change and the shorter the time at which the reactor power reaches the RRS range.

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6. References

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