A Controllability Study of TRUMOX Fuel for Load Following Operation in a CANDU-900 Reactor

A Controllability Study of TRUMOX Fuel for Load Following

Operation in a CANDU-900 Reactor

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Abstract

The CANDU-900 reactor design is an improvement on the current CANDU-6 reactor in the areas of economics, safety of operation and fuel cycle flexibility. As power grids start to rely more heavily on nuclear, it will be imperative for future nuclear generating station designs to be able to adjust their output to suit the fluctuating demands of the grid. Additionally, the need to reduce global nuclear waste has motivated research into mixed oxide fuel with the goal of maximizing spent fuel repository capacity and reducing decay heat via transmutation of transuranic actinides. The objective of this thesis is to provide insight into the load following capabilities of the CANDU-900 reactor design for a transuranic mixed oxide (TRUMOX) fueled core.

The three-dimensional fuel management code, RFSP-IST, was used to simulate a reactor operating history for week long load following operations in a generic CANDU-900 reactor. Daily refuelling operations as well as reactivity device movements supplementary to RFSP were performed using the RECORD RRS emulator program. Core snapshots were taken at periodic intervals using the SIMULATE module to observe and track various reactor parameters. Average liquid zone controller fills as well as core reactivity and channel power values were used to determine the controllability of the reactor for various load following depths.

The results of the load following simulations show that TRUMOX fuel has superior load following capabilities to that of conventional NU fuel for practical operational scenarios in a CANDU-900 reactor. Load following operations could be performed for TRUMOX fuel down to 85% full power in a safe and controllable manner using only the liquid zone controllers to account for the xenon transient reactivity as compared to NU which could only be done down to 90% full power. For load following simulations that both fuel types were capable of performing in a controllable manner, the TRUMOX fuelled core maintained on average a larger safety margin between the average liquid zone controller fills and the established safety limits.

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List of Abbreviations and Symbols

AECL	Atomic Energy of Canada Limited
CANDU	Canada deuterium-uranium
f_j	Channel ages
FP	Full power
IST	Industry standard toolset
MCA	Mechanical control absorber
MOX	Mixed oxide
N_z	Number of zone controllers
NU	Natural uranium
PWR	Pressurized water reactor
RECORD	RFSP External Control of Reactivity Devices
RFSP	Reactor Fuelling Simulation Program
RRS	Reactor regulating system
TRU	Transuranic
TRUMOX	Transuranic mixed oxide
WIMS	Winfrith Improved Multigroup Scheme
X, I	Concentrations of ^{135}Xe and ^{135}I
ZC	Zone controller

α_i	Bulk control manoeuvreing constant
γ_X, γ_I	Direct fission yield fraction of ^{135}Xe and ^{135}I
ΔZ_i	Fractional fill (0 to 1)
λ_X, λ_I	Beta-decay constants for ^{135}Xe and ^{135}I
ν	Fission yeild
ρ_{Xe}	Xenon reactivity
Σ_f	Macroscopic fission cross section
σ_a^x	Microscopic ^{135}Xe absorption cross-section
ϕ	Neutron flux
ω_{jk}	Fuel burnup

1 Introduction

The goal of this thesis is to provide some insight into the load following capabilities of the CANDU reactor design fuelled with transuranic mixed oxide fuel. Future power generation, both in Ontario and elsewhere, looks to be heavily reliant on nuclear reactor technology. As power grids start to rely more heavily on nuclear, it will be imperative for nuclear generating stations to be able to adjust their output to suit the fluctuating demands of the grid. Along with the need for more nuclear power will be the need to reduce global nuclear waste. By reprocessing used nuclear fuel and combining it with natural uranium in the form of TRUMOX fuel, many of these long lived actinides can be transmuted thus reducing decay heat and maximizing spent fuel repositories.

1.1 The CANDU Reactor

The CANada Deuterium Uranium (CANDU) reactor is a successful reactor design developed in Canada to utilize natural uranium (not enriched) as fuel to meet the Canadian requirements for the peaceful use of nuclear technology (Luxat, 2011). CANDU reactors currently operate in the Canadian provinces of Ontario, Quebec and New Brunswick as well as in Argentina, China, South Korea and Romania. The CANDU reactor design was developed from work performed at Chalk River Nuclear Laboratories during and immediately following WWII. Since Canada at the time did not wish to pursue uranium enrichment technology, it was decided to develop a reactor that could use natural uranium as fuel, of which Canada has abundant resources. A typical CANDU reactor assembly is shown in Figure 1.1 (CANTEACH, 2012).

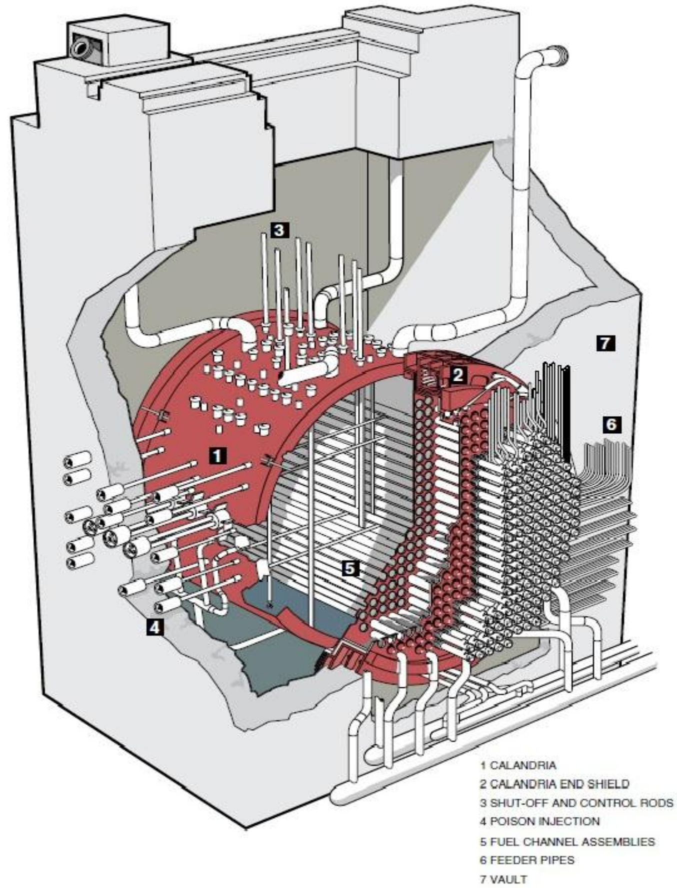

Figure 1.1 - CANDU-6 reactor assembly

Using natural uranium as fuel, which has less fissile content than enriched uranium, the CANDU reactor has two unique characteristics: heavy water as moderator and coolant, and on-line refuelling. Heavy water has a much lower neutron absorption cross section than light water, meaning fewer neutrons are captured in the moderator and coolant thus letting more neutrons interact with the fuel. On-line refuelling allows fresh fuel to be inserted into the core on a constant basis thus maintaining criticality in the reactor.

The CANDU reactor consists of a horizontally oriented cylindrical tank (the calandria) which contains the fuel channels as well as the reactivity control devices. The entire calandria is contained within a light water filled shield tank or concrete vault. Within the calandria is the heavy water moderator as well as the calandria tubes in which the in-core portion of the fuel channels are contained. The CANDU-900 reactor is based on the successful 900 MW CANDU reactors at Darlington and Bruce B. It is part of the ongoing CANDU development program, an improvement on the current CANDU-6 design in the areas of economics, fuel cycle flexibility and safety operation (Zhenhua, 2012). A basic comparison between a CANDU-6 and CANDU-900 reactor is shown below.

	CANDU-6	**CANDU-900**
Example	Gentilly-2 (Quebec, CA)	Darlington[1] (Ontario, CA)
Output (MW Electric)	675 MW	881 MW
No. of fuel channels	380	480
No. of bundles per channel	12	13
Calandria Vessel Diameter	7.6 m	8.5 m
Calandria Shielding	Water filled concrete vault	Water filled shield tank

Table 1.1 - CANDU quick comparison

The CANDU-900 reactor contains in core flux detectors to measure the neutron flux in 14 different zones (Bereznai, 2004a). Each of these zones (shown in Figure 1.2) contains a liquid zone controller controlled by the reactor regulating system (RRS) which uses light water to perform basic spatial and bulk reactivity control of the reactor. In addition to the liquid zone controllers, RRS also has control over 24 adjuster rods and 4 mechanical control absorber rods.

[1] While it is a 900 MW CANDU reactor, it is not technically a CANDU-900 as none have officially been built

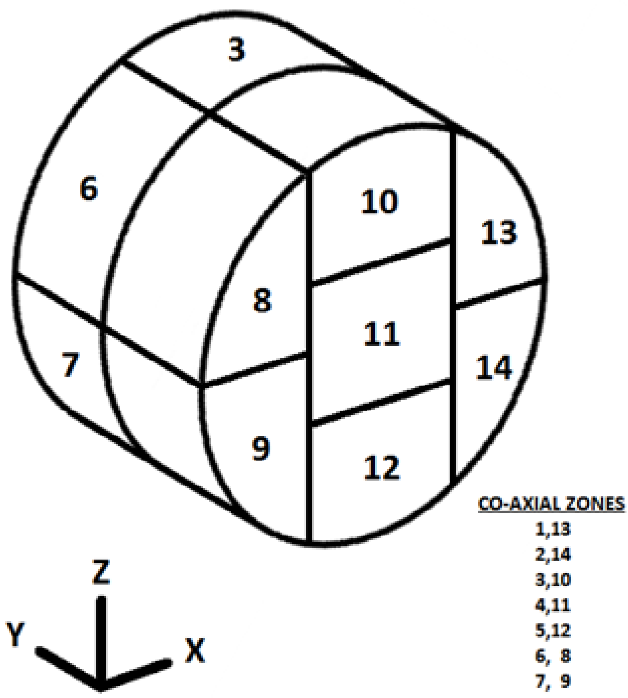

Figure 1.2 - Location of liquid zone controllers

The adjuster rods are made of stainless steel and are normally located in the core to shape the nuclear flux for optimum reactor power and fuel burnup; they can also be withdrawn from the core to add positive reactivity beyond the control range of the zone controllers. The mechanical control absorbers (MCAs) consist of cadmium tubes sandwiched between stainless steel and are used to add negative reactivity to the reactor core beyond the range of the zone controllers. Normally the MCAs are withdrawn from the core during normal operation as they are mainly used to perform quick reductions in reactor power (stepbacks or setbacks). The location of the reactivity devices in a CANDU-900 reactor are shown in Figure 1.3 (AECL, 1995).

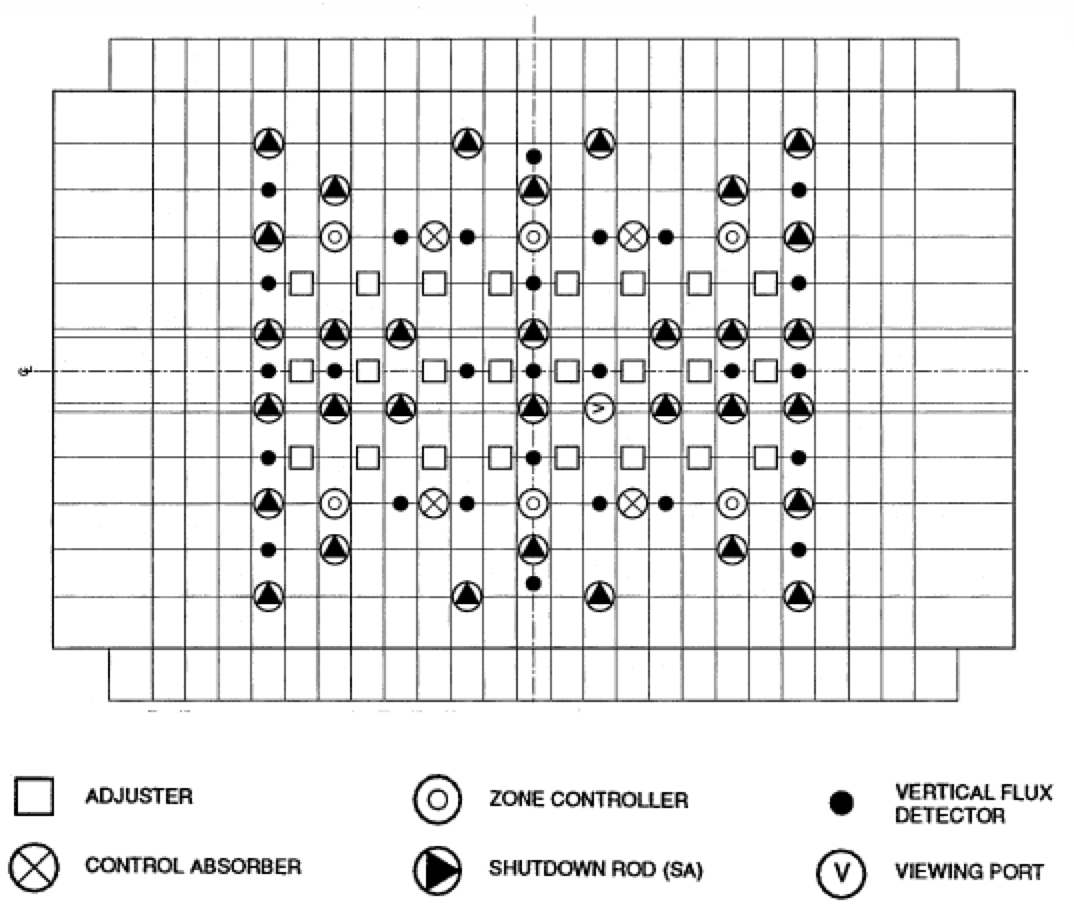

Figure 1.3 - Location of reactivity devices (top view)

1.2 Load Following

Load following refers to the ability of a power plant to respond to changing grid demands by adjusting its electrical output. As grid level energy storage is not currently a viable option, the ability for a power plant to adjust its power output to the demand of the grid makes the grid as a whole more efficient and wastes less energy.

Most nuclear reactors run at base load capacity, meaning they operate at maximum output whenever possible; the only time they tend to deviate from that is when it is necessary to shut down or reduce power due to maintenance or emergency situations. There are two main reasons most nuclear reactors run at base load capacity: It is the cheapest and most efficient mode of power generation and because constantly changing the power output of the plant can be a difficult and complex task.

The presence of long lived fission product poisons, mainly xenon-135 and to a minor extent samarium-149, can greatly affect the reactivity of the core during changes in reactor power. When a reactor runs at a constant power for a long period of time, its fission product poison concentration reaches equilibrium with the neutron population and doesn't have a noticeable effect. When reactor power is changed rapidly, the neutron population also changes quickly while the fission product poison concentration will take much longer to reach a new equilibrium. With an extremely high neutron absorption cross section and relatively long half-life (9.2 hours), ^{135}Xe can greatly affect the reactivity of the core. Accounting for the xenon reactivity transient is the largest factor to be overcome in load following with CANDU reactors, ^{135}Xe dynamics will be discussed further in chapter 2.

1.3 Transuranic Mixed Oxide Fuel (TRUMOX)

Mixed oxide fuel, commonly known as MOX, is a type of nuclear fuel that contains multiple fissile oxides. MOX fuel usually contains uranium oxide blended with reprocessed plutonium in the form of plutonium oxide. Reprocessing of spent nuclear fuel to extract the fissile materials can greatly reduce nuclear waste while providing more fuel in the form of MOX. Additionally, weapons grade plutonium from stockpiles or dismantled nuclear weapons can be combined with depleted uranium to form MOX fuel while reducing the risk of nuclear proliferation.

In addition to the fissile content of spent nuclear fuel, many of the transuranic (TRU) actinides produce decay heat for long durations, thus complicating long term nuclear waste management (Hyland, 2011). By combining these actinides with MOX fuel (TRUMOX), much of the actinides can be consumed as fuel or transmuted to shorter lived isotopes thus reducing decay heat and increasing the capacity of nuclear waste repositories.

While CANDU reactors were designed to utilize natural uranium as fuel, the design is quite adaptable and can therefore use MOX/TRUMOX fuel without any significant physical plant modification. The high neutron economy of CANDU allows for significant TRU actinide destruction while the online refuelling allows for individual bundles to be shuffled in and out of the core.

TRUMOX fuel, while behaving similar to the NU fuel, does present some unique challenges. Due to the different fuel composition, the reactivity worths of the zone controllers as well as the adjuster rods are quite a bit lower than for NU fuel. In addition, due to the higher fissile content of TRUMOX, rapid reactivity increases from refuelling can cause individual zone controllers to exceed their normal operational ranges (Morreale, 2011). A more in depth look at TRUMOX fuel will be presented in chapter 4.

1.4 Literature Review

Controllability

The concept of controllability was first introduced by Kalman in the 1960s (Kalman, 1961). Along with observability, controllability is an important concept in control theory which is the branch of engineering and mathematics that deals with the behavior of dynamic systems.

A formal definition of controllability would be "A system is said to be controllable if it is possible to find a control vector **u(t)** which, in specified finite time $\mathbf{t_f}$, will transfer the system between two arbitrarily specified finite states $\mathbf{x_0}$ and $\mathbf{x_f}$" (Elgerd, 1967). In general terms, controllability refers to the ability of a system to move from one stable state to another in a finite time interval by changing the inputs to the system (Sage, 1968). Using the concept of load following which is an integral part of this research, controllability refers to the ability of a reactor to move from one stable power level to another in a specified timeframe via only normal operation of the reactor regulating system.

Load Following

Studies concerning load following in the CANDU reactor design have been performed since the 1970s. Load following simulations by Chou (Chou, 1975) showed that the CANDU reactor design was indeed capable of short term load following. Computer modelling of the Pickering Unit A reactor showed the capability for short term load following (holding low power setpoints for about 10 minutes) down to 50% FP. The author concluded that the daily load following capabilities of CANDU should only be limited by the ability to account for the subsequent xenon transient for minimum power setpoints above 50% FP.

Venez et. al. (Vinez, 1986) and Lopez et. al. (Lopez, 1988) reported on CANDU load following studies performed in the mid-80s at the Embalse and Bruce B generating stations respectively. Results from the Embalse nuclear station in Argentina during 1984 and 1985 showed the CANDU design could perform weekly load following operations down to 50% FP without exceeding the control limits or design envelopes of the station. Furthermore, the author noted that the fuel defect rate during the study (0.07%) was lower than the average defect rate of similar plants operating at baseload capacity (0.10%). Results from Bruce B during 1986 and 1987 showed similar positive results with daily load following operations. Once again, there was no increase in fuel failure rates even with short lived power reductions to 20% FP.

Based on previous simulations and operational history, Jizhou et. al. (Jizhou, 1999) stated that the CANDU-6 reactor design is capable of load following operations involving rapid power reductions down to 60% with the capability to run continuously at 60% FP. The authors went on to comment that the only real constraint on the depth of the power reduction is the ability for the adjuster rods to compensate for the subsequent xenon reactivity transients.

MOX Fuels

In 1994, the United States Department of Energy (DOE) sponsored an AECL study for the dispositioning of weapons-grade plutonium using the CANDU reactor design, focusing on the utilization of mixed oxide (MOX) fuel. Bozcar et. al. (Boczar, 1995) reported that no significant modifications to the CANDU reactor design would be necessary to operate with a full MOX core. Simulations based on the Bruce A generating station using WIMS-AECL and RFSP showed the maximum bundle and channel powers as well as the power/burnup envelopes were below that of a NU fuelled core; the largest change being required would be the safe and secure storage of new MOX fuel.

A second study sponsored by the US DOE aimed increasing the plutonium disposition rate for MOX fuel in CANDU. Bozcar et. al. (Boczar, 1997) reported that a 50% increase in the rate of plutonium disposition (1t per year per reactor to 1.5t per year per reactor) could be achieved by increasing the plutonium content in each bundle. Similar to the previous 1994 study, the reactor would still operate within the license envelope of the NU fuelled core.

Another scenario involving MOX fuel is for the reduction of global stockpiles of used nuclear fuel. A major problem with spent fuel is the presence of transuranic (TRU) actinides which are responsible for much of the long term decay heat. Hyland and Gihm (Hyland, 2011) outline a scenario whereby the TRU actinides could be consumed as fuel or transmutated to shorter lived actinides in a CANDU reactor in the form of a transuranic mixed oxide fuel (TRUMOX). Lattice cell calculations in WIMS-AECL and full core modeling in RFSP showed that this scenario could transmutate 42% of the TRU actinides, corresponding in a decay heat reduction of about 40% at 1000 years.

Analysis of the TRUMOX fuel design in CANDU reactors is currently being done. Morreale et. al. (Morreale, 2011) found that TRUMOX could be controllable and safe during a wide variety of standard CANDU operational circumstances. The authors found that the TRUMOX core could be run without exceeding the bundle and channel power limits of the NU license, however some abnormal zone controller levels were observed.

Experience outside of CANDU

At this point in time, no CANDU reactor has been operated with a MOX fuelled core; however CANDU MOX fuel bundles have been irradiated at AECL in the past. Dimayuga et. al. (Dimayuga, 1995) reported on the MOX experiments performed in the NPD (Nuclear Power Demonstration) and NRU (National Research Universal) reactors. Post irradiation examination (PIE) showed excellent MOX fuel performance in the experiments with burnups up to 1190 MWh/kgHE and linear power ratings exceeding 50kW/m. The authors state that fission gas releases were comparable to similar experiments with NU fuel.

There are several other reactor designs that are approved for load following with a MOX fuelled core with similar results to a uranium fuelled core. In France, PWR nuclear generating stations have been operating with partial MOX cores since the late 1980s with extensive load following capabilities since the 1990s. Provost (Provost, 2006) reported on the operating experience of EDF (Electricite De France, France’s largest power generator) that load following is authorized and applied to all of their PWR reactors operating with MOX fuel. Furthermore, it was learned that MOX performs better than uranium in terms of PCI (pellet/cladding interaction).

1.5 Outline

In this chapter, a basic description of the major aspects pertaining to this thesis is presented. Chapter 2 will outline the effect of xenon-135 dynamics on reactor operation pertaining to load following. The methods, models, and safety criterion used during the simulations of the CANDU-900 reactor is presented in chapter 3. Chapter 4 will present the two fuels used during the simulations and their basic compositions and differences. The results of the load following and setback simulations will be presented in chapter 5. Chapter 6 will characterize the controllability of the reactor for different load following cycles as well as make suggestions for future research. In chapter 7, conclusions will be drawn from the results.

2 Xenon-135 Behaviour

A major factor that influences the reactivity of the reactor core is the presence of fission product poisons. These poisons have extremely large neutron absorption cross sections which can add large amounts of negative reactivity to the reactor core. The most prominent of these fission product poisons is xenon-135 which has a half-life of 9.15 hours and a thermal absorption cross section of 2.7 million barns (Singh, 2008). The next largest neutron absorbing fission product, samarium-149, has an absorption cross section about two magnitudes lower. In comparison, the thermal fission cross section for uranium-235 is on the order of 100-1000 barns.

While ^{135}Xe plays a large role in affecting the reactivity of the reactor core, after running at a constant power for a period of time (about 60 hours) it reaches an equilibrium concentration where its rate of production equals its rate of absorption and decay. During large changes in reactor power however, the change in neutron flux can upset the equilibrium balance leading to large changes in core reactivity. Management of these large changes in reactivity is paramount for reactor control and stability during load following operations and is the largest factor affecting the manoeuvreability limits of the reactor.

2.1 Xenon-135 Dynamics

Xenon-135 is produced from fission in one of two ways: directly from fission or as a decay product of iodine-135 as part of a beta decay chain. About 6.4% of ^{235}U fissions yield ^{135}Xe, 6.1% via a beta decay chain from ^{135}Sb (shown in Equation 2.1) and 0.3% directly from fission. In a CANDU operating at full power, about 90% of the ^{135}Xe absorbs a neutron and becomes the effectively stable ^{136}Xe (Ackerman, 2011) while about 10% decays to ^{135}Cs, a long lived fission product (Chadwick, 2011).

$$Fission \rightarrow \ ^{135}Sb^{1.6s} \rightarrow \ ^{135}Te^{29s} \rightarrow \ ^{135}I^{6.7h} \rightarrow \ ^{135}Xe^{9.15h} \rightarrow \ ^{135}Cs^{2My} \rightarrow \ ^{135}Ba \tag{2.1}$$

In the above beta decay chain, the half-lives of ^{135}Sb and ^{135}Te are quite short compared to those of ^{135}I and ^{135}Xe so for the simplicity of calculation we can treat ^{135}I as the direct fission product. The concentrations of ^{135}Xe and ^{135}I can be calculated using the simplified decay and production schemes represented by the coupled rate equations shown in Equations 2.2 and 2.3 (Duderstadt, 1976).

$$\frac{\partial I}{\partial t} = \underset{\substack{direct\ from\\ fission}}{\gamma_I \Sigma_f \phi(r,t)} - \underset{\substack{iodine\\ decay}}{\lambda_I I(r,t)} \tag{2.2}$$

$$\frac{\partial X}{\partial t} = \underset{\substack{direct\ from\\ fission}}{\gamma_X \Sigma_f \phi(r,t)} + \underset{\substack{iodine\\ decay}}{\lambda_I I(r,t)} - \underset{\substack{xenon\\ decay}}{\lambda_X X(r,t)} - \underset{\substack{xenon\\ absorption}}{\sigma_a^x \phi(r,t) X(r,t)} \tag{2.3}$$

Iodine-135 concentration is affected by two factors, the production from fission and the beta decay to ^{135}Xe. The xenon-135 concentration is a bit more complicated, involving two methods of production and two elimination methods. ^{135}Xe is created both directly from fission as well as decay from ^{135}I, while it is eliminated through beta decay to ^{135}Cs as well as absorption to ^{136}Xe. The reactivity associated with xenon concentration is given by Equation 2.4. (Luxat, 2010).

$$\rho_{Xe} = -\frac{\sigma_a^x X}{\nu \Sigma_f} \tag{2.4}$$

2.2 Xenon-135 at Stable Power

If a reactor has been operating at a constant power for a period of time, the methods of ^{135}Xe production and decay eventually reach equilibrium, thus stabilizing the ^{135}Xe concentration. This can be easily calculated from the related rate equations by setting the partial time derivatives to zero and solving for the concentrations, leading to Equations 2.5 and 2.6 below.

$$I(t) \underset{t\to\infty}{\longrightarrow} I_\infty = \frac{\gamma_I \Sigma_f \phi}{\lambda_I} \tag{2.5}$$

$$X(t) \underset{X\to\infty}{\longrightarrow} X_\infty = \frac{(\gamma_I + \gamma_x)\Sigma_f \phi}{\lambda_X + \sigma_a^x \phi} \tag{2.6}$$

From these equations it can be seen that the steady state iodine concentration is linear with flux while the xenon concentration is nonlinear. The xenon reactivity load can be calculated by substituting the steady state concentration into Equation 2.4. As ^{135}Xe is a neutron absorber, it contributes negative reactivity to the core; hence an increase in concentration means a decrease in core reactivity.

$$\rho_{Xe\infty} = -\frac{\phi\sigma_a^x(\gamma_I+\gamma_x)}{\nu(\lambda_X + \sigma_a^x\phi)} \tag{2.7}$$

Using a typical neutron flux value for a CANDU reactor (in this example, 9.11×10^{13} [n/cm^2/s]), we get a xenon reactivity load of -0.0252k or -25.2mk, which is about 1.5 times the reactivity worth of all the adjuster rods. On a clean startup to 100% FP, the xenon load will reach equilibrium after about 60 hours after which it will remain constant.

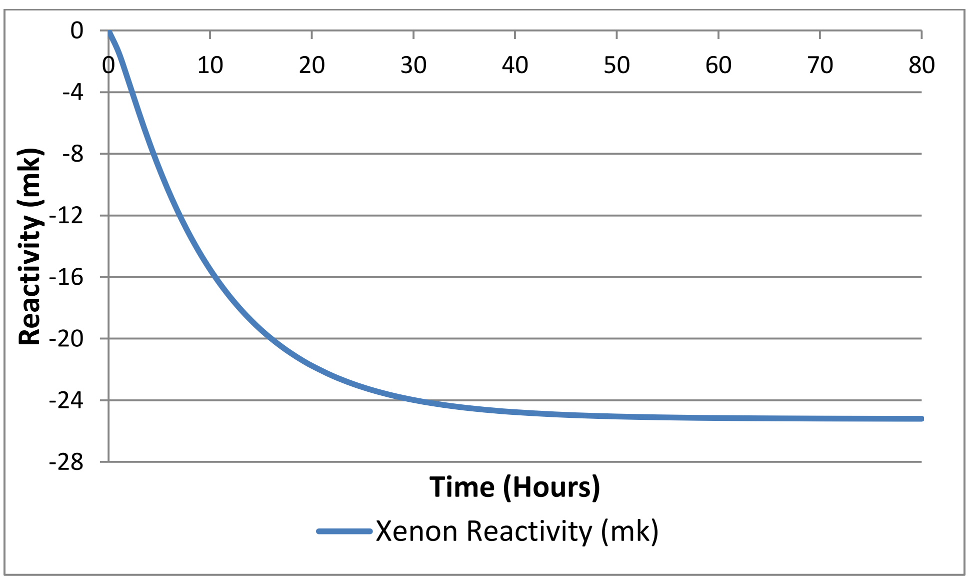

Figure 2.1 - ^{135}Xe reactivity from clean start-up to 100% FP

2.3 Xenon-135 Response to Power Changes

During daily load following operation of a reactor, the reactor power is never at a constant setpoint long enough for the ^{135}Xe concentration to reach equilibrium; therefore the reactivity of the core is constantly changing even when reactor power is not. The large changes in reactivity can be quite taxing on the reactor regulating system and dictate how quickly and by how much the reactor can reduce or increase power safely.

Xenon transient behaviour may be somewhat counter-intuitive as a reduction in neutron flux level leads to an increase in ^{135}Xe concentration before eventually settling to a lower equilibrium concentration. The inverse of this is true as well as increases in neutron flux leads to a decrease in ^{135}Xe concentration before settling to a higher equilibrium concentration. This is because at high flux levels experienced during normal reactor operation, removal of neutrons by absorption (which depends on neutron flux levels) is the most dominating factor in determining the change of ^{135}Xe concentration.

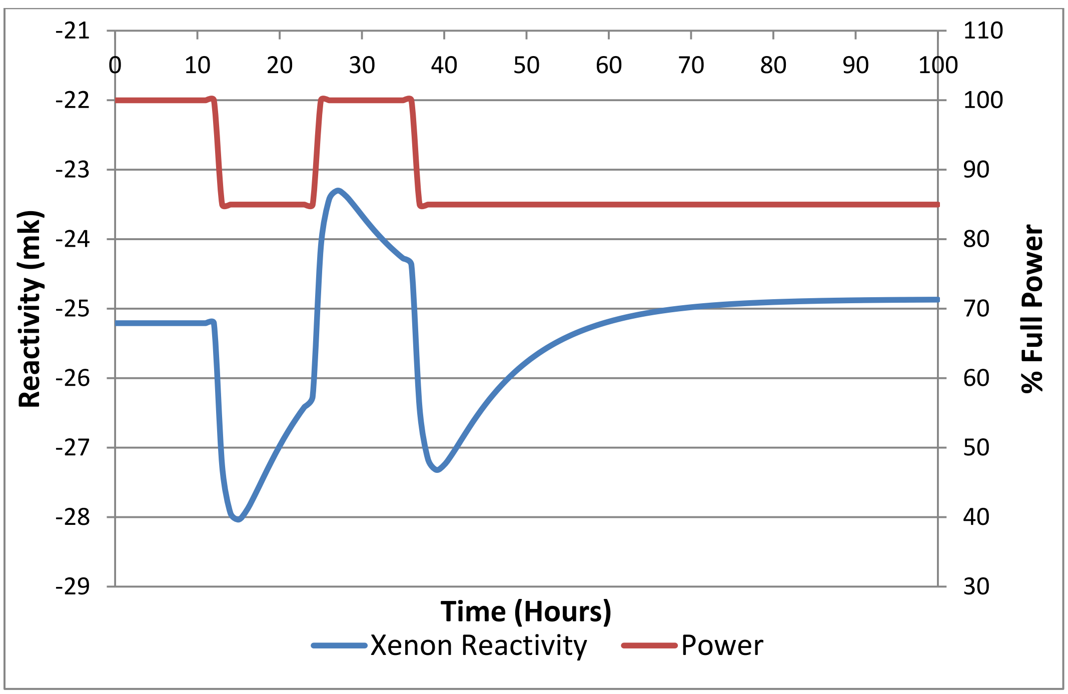

Figure 2.2 - ^{135}Xe reactivity during changes in power

In the above figure we can see the xenon transient behaviour for a series of power changes down to 85% FP after running at 100% FP for a long period of time. A reduction in reactor power will eventually lead to a reduction in xenon concentration if allowed to reach equilibrium, however for short periods of time (around 12 hours in this example) the xenon concentration increases and does not have enough time to level out before the power is changed once again.

Another effect that can be seen is that reductions (or increases) in power from the same levels do not always lead to the same changes in reactivity as the depth of ^{135}Xe transients depend heavily on previous xenon concentrations. During the first reduction in power, the xenon concentration had reached equilibrium while during the second reduction in power the concentration in xenon had not yet leveled off. Even though the change in reactivity during the power reductions was about the same, the first reduction was from a greater xenon concentration, thus a greater reactivity spike during the first power reduction.

3 Simulation Methodology

3.1 RFSP-IST Reactor Model

All of the reactor core simulations presented in this study were performed with the Reactor Fuelling Simulation Program, Industry Standard Toolset (RFSP-IST v3.04) (Shen, 2006). RFSP-IST is a major computer code used in industry for design an analysis of CANDU reactors; it is capable of simulating a reactor operating history with core snapshots taken at user specified intervals with refuelling. This study examines load following operation of a generic 900 MW heavy water moderated CANDU type reactor (CANDU-900) (Snell, 1998).

3.1.1 RFSP Code

RFSP-IST is reactor physics code to perform fuel management simulations for CANDU reactors. It uses 3 dimensional, 2 energy group neutron diffusion theory to calculate full core neutron flux and power distributions. The program is capable of simulating operating histories including refuelling and incremental burnup steps (Schwanke, 2006). RFSP uses the neutron diffusion equation, which is an approximation of the neutron transport equation by assuming that neutrons diffuse from regions of high to low concentration. The diffusion equations solved by RFSP are as follows.

$$-\nabla \cdot D_1(r)\nabla\phi_1(r) + \big(\Sigma_{a1}(r) + \Sigma_{12}(r)\big)\phi_1(r) - \Sigma_{21}(r)\phi_2(r) - \frac{\nu}{k_{eff}}\Big(\Sigma_{f1}(r)\phi_1(r) + \Sigma_{f2}(r)\phi_2(r)\Big) = 0 \quad (3.1)$$

$$-\nabla \cdot D_2(r)\nabla\phi_2(r) + \big(\Sigma_{a2}(r) + \Sigma_{21}(r)\big)\phi_2(r) - \Sigma_{12}(r)\phi_1(r) = 0 \quad (3.2)$$

The finite-difference solution method used to solve the two group diffusion equation in RFSP is detailed in the RFSP Theory Manual (Shen, 2006).

RFSP is capable of tracking reactor operating history via periodic snapshots at a desired frequency (Rouben, 1999). During time intervals between snapshots, the code updates fuel burnup and irradiation, as well as taking into account any refuelling or reactivity device movement (both from user input as well as autonomous control). Each snapshot shows the instantaneous reactor configuration including position of all the reactivity devices as well as flux and power distributions of the core.

3.1.2 Simulation Procedure

The starting point for the simulations in this study was a generic CANDU-900 reactor core model in RFSP complete with fuel and cross section parameters for NU fuel. The TRUMOX fuel was designed using WIMS-AECL and the corresponding incremental cross sections were calculated for the reactivity devices using DRAGON (Morreale, 2011). From this point several simulation steps were required to produce a realistic model ready for load following simulation.

The first step required is to create a time average model, that is, a model that uses the averaged lattice cross sections over the entire dwell time of the fuel at each point (Rouben, 1999). This allows the effect of the actual refuelling scheme to be taken into account without having the day to day fluctuations encountered during actual refuelling. This model, implemented using the TIME-AVER module in RFSP, uses the given fuelling scheme and regional exit irradiations to calculate time average flux and power distributions in both the radial and axial directions. For the time average model, reactivity devices are set to their default positions, that being adjuster rods in core for NU and withdrawn for TRUMOX. The flux and power distributions calculated using this model and can be used as a benchmark to refine refuelling for target flux shapes (Shen, 2006).

While the time average model can provide target flux and power distributions, it does not represent the reactor on a day to day basis. Since there are no refuellings during the time average model, channel power ripples resulting from a refuelling scheme cannot be seen and thus the power and flux distribution is somewhat unrealistic. This problem can be solved by assigning channel ages throughout the core, thus creating an instantaneous reactor core model which better represents a realistic fuelling scheme.

The instantaneous core model, implemented using the INSTANTAN module in RFSP, creates a core with distributed burnup values for each bundle based on assigned channel ages. These channels are assigned an age value from 0 to 1, with 0 representing fresh fuel and 1 representing spent fuel (the assignment of channel ages is explained in detail in section 3.3.4). Once each channel has an assigned age, fuel burnups are calculated as follows:

$$\omega_{jk}(t) = \omega_{jk}^{BOC} + f_j(t) \cdot \left[\omega_{jk}^{BOC} - \omega_{jk}^{EOC}\right] \tag{3.3}$$

The fuel burnup for each bundle k in channel j is determined by using the channel ages f_j and the burnups for the beginning and ending of the fuelling cycle for each bundle from the time average calculation, designated ω^{BOC} and ω^{EOC} (Shen, 2006). This yields an instantaneous power distribution with a realistic refuelling scheme that can be compared to the time-average model to show expected channel power peaking factors (CPPF).

Having achieved a realistic reactor core model, day to day refuelling and load following operations can be carried out using the SIMULATE module in RFSP. This model simulates reactor operating history with instantaneous pictures or "snapshots" of the various reactor parameters by calculating the fuel bundle irradiations at set time intervals (Shen, 2006).

$$\omega_i(t + \Delta t) = \omega_i(t) + \frac{1}{2}\left[\hat{\phi}_{Fi}(t) + \hat{\phi}_{Fi}(t + \Delta t)\right] \cdot \Delta t \tag{3.4}$$

The time intervals Δt are specified in the SIMULATE module as well as the reactor power setpoints (which influence the flux values ϕ_{Fi}) and any channel refuellings that are to be carried out. In addition, reactor regulating system (RRS) operations such as zone controller levels and reactivity device movements are carried out in this module, some by RFSP and some via user input. The RRS control of the reactor as well as the sequential simulations of the SIMULATE module is discussed in detail in the following subsections.

3.2 Reactor Regulating System (RRS)

The reactor regulating system (RRS) in a CANDU reactor controls the reactivity of the core via manipulation of the zone controllers as well as the adjuster rods and mechanical control absorbers (MCAs). These devices are manipulated in such a way to fulfill two objectives: “bulk control” which is to maintain the reactor power at a specified level and “spatial control” which is to maintain a target power distribution within the core.

3.2.1 RFSP Reactor Control

RFSP does not solve the time-dependent diffusion equation during core follow simulation so it cannot mimic the RRS in the time domain, however it can maintain basic bulk and spatial control via manipulation of the zone controllers (Shen, 2006). Bulk control attempts to maintain a user-specified target value of k_{eff} by uniformly manipulating the zone controller fills during periodic flux iterations according to the following control algorithm:

$$\Delta Z_i = \alpha_i\left[k_{eff}(current) - k_{eff}(target)\right], i = 1..N_z \tag{3.5}$$

Spatial control attempts to maintain a desired flux shape by differentially manipulating the zone controller fills during periodic flux iterations. The algorithm for spatial control is much more complex than for bulk control as it also takes into account the flux levels and targets associated with each individual zone controller as well as stopping spatial control for zone controllers that are near their fill limits. The spatial control algorithm used closely mimics that of the CANDU RRS and is outlined in the RFSP Theory Manual (Shen, 2006).

Both bulk and spatial control are preformed between snapshots to maintain criticality of the core; however during power manoeuvres the movement of additional reactivity devices may be necessary to combat the subsequent xenon transients. While RFSP can take into account the insertion or withdrawal of adjuster rods and MCAs, it does not have the ability to move them autonomously as it does with the zone controllers therefore user input is required to manipulate them between each snapshot.

3.2.2 External RRS Emulator

Load following operation of a reactor can lead to large changes in core reactivity that may be beyond the control envelope of the zone controllers, therefore it may be necessary to utilize the adjuster rods and MCAs to supplement the reactivity control of the zone controllers. As explained in the previous section, RFSP does not have the ability to manipulate the adjuster rods or MCAs like it can for the zone controllers, however it can take into account their presence in the core if moved there via user input. For this reason, a program was developed to act as an external RRS emulator for RFSP, manipulating adjuster rods and MCAs in the RFSP input files to assist in reactivity control beyond the operating envelope of the zone controllers.

The RRS emulator, dubbed RECORD[2] (RFSP External Control of Reactivity Devices), uses the average zone controller fill and excess reactivity values from the previous reactor snapshot to manipulate the adjuster rod and MCA positions for subsequent simulations. The control logic is based off of CANDU-900 control logic (AECL, 1995) and was adapted for use with RFSP.

[2] The RECORD program was written by David A. Trudell while studying at McMaster University (2012)

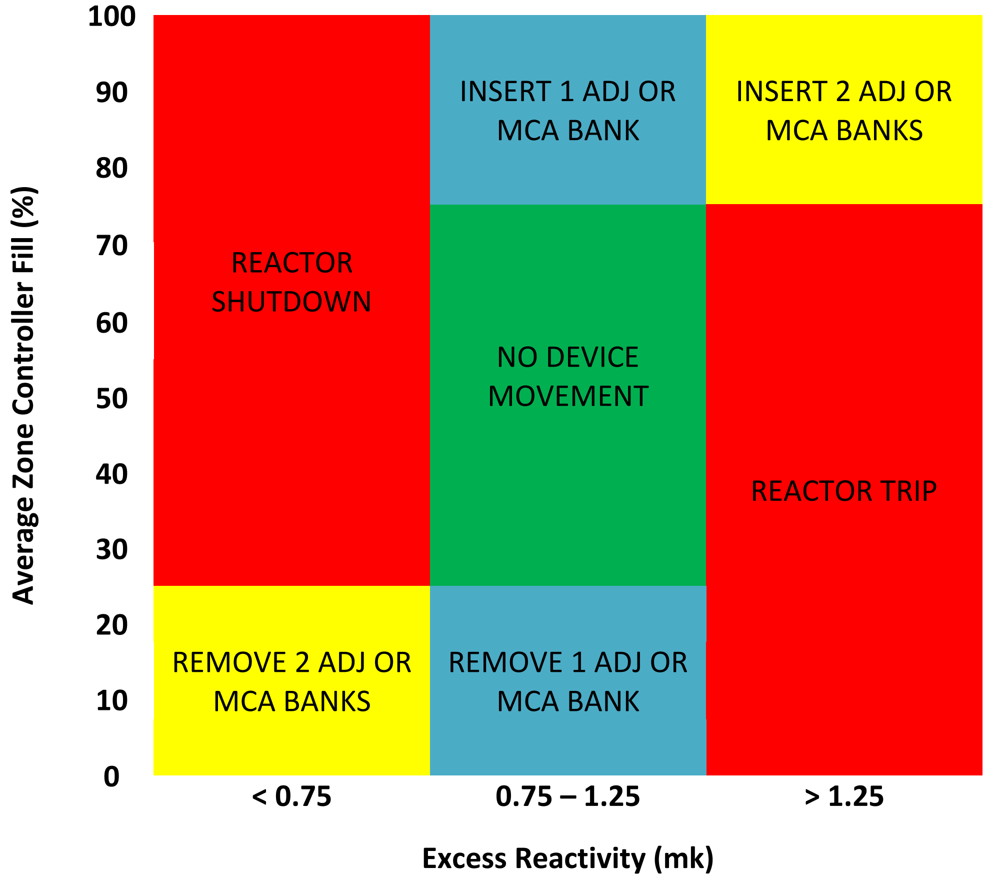

Figure 3.1 - RECORD control logic for NU fuelled core

RECORD takes user input on the type of simulation to be run (power setpoints, snapshot durations, refuelling order and frequency, etc.) and creates an input file for RFSP for the first snapshot. After execution in RFSP, the output file is analyzed for the average zone controller fill and excess reactivity values and manipulates the position of the reactivity devices based on the control logic. The next input file is then written, including adjuster rod and MCA movements, channel refuellings (if necessary) as well as the power and time durations for the next reactor snapshot. This process is repeated until the entire load following simulation is complete, usually requiring somewhere between 100 and 400 individual RFSP simulations run in succession.

For a week long load following simulation, RECORD is run via a short Linux script which also triggers the execution of RFSP, allowing them to run in succession one behind the other until all simulations are carried out. The entire load following simulation only requires initial user input specifying the snapshot frequency and power levels, channels to refuel and frequency, as well as what type of fuel is being used. The control logic differs slightly between TRUMOX and NU fuels, with adjuster rod and MCA banks acting in pairs for TRUMOX since their individual reactivity worths is about half compared to NU. Also, as the TRUMOX core runs without adjuster rods in the core, its limit on load following is mainly governed by the zone controllers as it has no other way of adding positive reactivity to the core, unlike the NU fuelled core which has the ability to remove adjuster rods. Both of these factors will be discussed in greater detail in the next chapter.

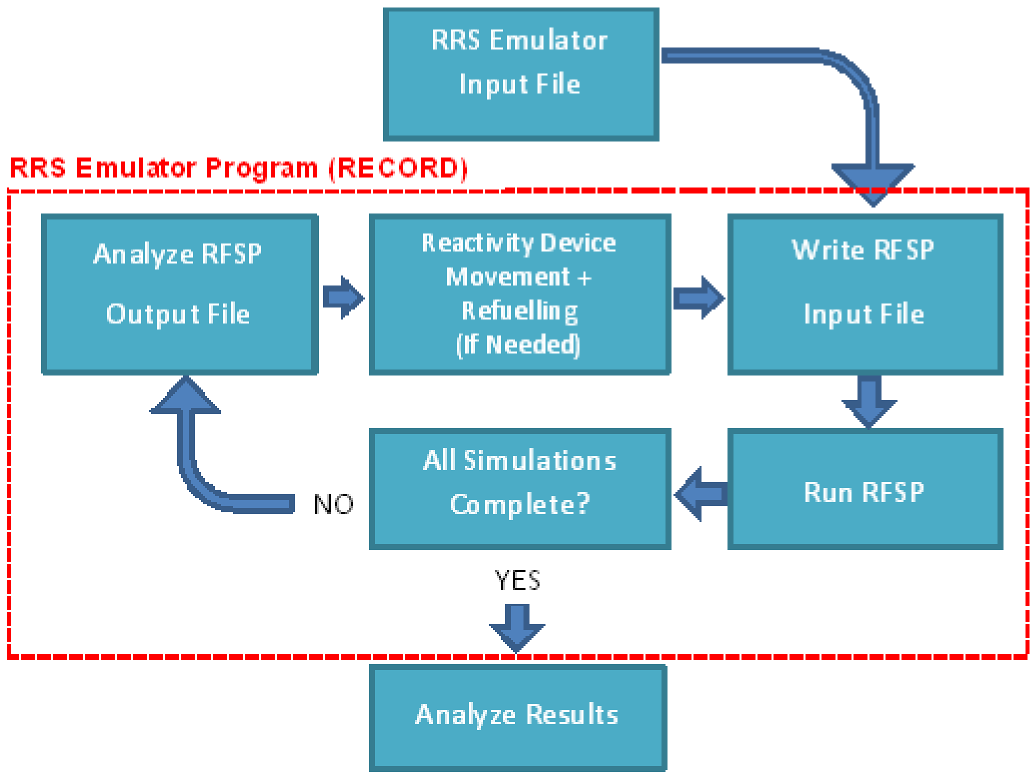

Figure 3.2 - Flowchart for simulation execution

All simulations were performed in the Linux environment using scripts to execute RFSP as well as the RECORD external RRS program. RECORD was written in Python for its simplicity as well as flexibility, the source code as well as sample input files are presented in appendix C. To ease in data analysis, other small programs were written to analyze the RFSP output files and extract the data presented in the results section.

3.3 Assumptions & Generalizations

While all attempts were made to make the data presented in this thesis as accurate as possible, there are some distinct differences between what can be simulated and actual operation of a CANDU reactor. The following sections point out what major differences there are and what, if any effect they have on the results.

3.3.1 Reactivity Device Control Logic

The control logic used in RECORD was based off of CANDU-900 control logic (AECL, 1995) but with a few key differences. Most prominent of all of these differences is the variable change from power error to excess reactivity. This change was made due to how RFSP simulates demand power in the SIMULATE module. When RFSP simulates a demanded power level, the neutron flux is automatically set to this level; there is never a power error. However the excess reactivity in the simulated core can fluctuate in a similar manner to the power error in a real reactor. For this reason, excess reactivity was chosen as the x-axis variable for the 2-D control logic of the RRS emulator.

Although similar, power error and excess reactivity do have distinct differences in their behaviour. Unlike power error, excess reactivity in the RFSP core tends to only change once the limits of the control devices are reached, thus indicating a larger control response is required. If however, excess reactivity strays from its normal range without the average zone controllers being at their limits, this usually indicates that the reactor is unstable and that there is most likely a high degree of variation between individual zone controllers.

The setpoints for movement of reactivity devices in the control logic are slightly modified from the CANDU-900 control logic; the range of no adjuster rod or MCA movement was moved from 15-80% to 25-75% average zone controller fill. This was done purely from simulator operating experience, using previous simulations to find more ideal control setpoints. As well, there were no previous setpoints established for excess reactivity so these setpoint values were also found from operating experience, optimized to find the best settings for reactor control.

3.3.2 Real Time vs. Incremental Control

In an operating CANDU reactor, all RRS responses happen in real time, as the power error and zone controller fills change in time, so can the reactivity devices be moved in an out at set rates. The simulated RRS with RECORD however can only respond to zone controller levels and excess reactivity values between simulations, meaning its response is only as quick as the time steps during simulation. This factor can heavily influence RRS performance and therefore was taken into account during control logic design.

A balance had to be found between external RRS response and simulation length. The shorter the time step used for each simulation, the quicker and more realistic the RRS response, however the length of time required to run the week long simulation increased. If time steps were set up such that a reactor snapshot was taken every 10 to 15 minutes, a week long simulation would take about as long to perform as the situation it was simulating. At the same time, if snapshots were taken every hour or so, a week long simulation could finish in about 36 hours, however external RRS response would be too slow to respond effectively, leading to reactor instability.

The solution that was implemented was to increase the snapshot frequency during the first few hours after a change in power and then decrease the snapshot frequency during the remaining few hours leading up to the next change in power. As will be seen from the reactivity device response in the results section, the core reactivity changes most rapidly immediately following a change in power or channel refuelling and then slows its rate of change as the xenon concentration start to approach their steady state levels at that power. A typical simulation pattern would be 10 minute snapshots during the first 2 hours after a change in power, 20 minute snapshots during hours 3 and 4, 30 minute snapshots for hours 5-7 and hour long snapshots for the last 5 hours. Snapshot frequency would also increase immediately after channel refuellings to better see their effect on local zone controller fills.

Another major difference between real time RRS control and the external RRS emulator for the simulations is the rate of reactivity device insertion. For a typical RRS in CANDU, the maximum rate of reactivity insertion of any one adjuster rod bank is ± 0.07 mk/s which means it will take around 30 seconds for the adjuster rod bank to completely be removed or inserted into the core. As well during real time RRS control, an adjuster rod may be left partially inserted or withdrawn from the core. Since the response of RECORD is limited to the snapshot frequency, which never breaches 10 minute intervals, adjuster rods and MCAs are moved in a binary fashion, either completely in or completely out of the core. If the reactivity devices were moved incrementally in or out at a specified rate, they might not be able to respond in time to the xenon transients experienced during load following operation. In addition, this simplifies the control logic of the RRS emulator; however this was not the motivation for binary operation of the adjuster rods and MCAs.

3.3.3 Power Ramps

A typical CANDU-900 reactor has a maximum manoeuvreing rate of 0.15% FP per second within the 80-100% FP range, this being the range most of the simulations will be occurring. This means that for a realistic reactor to cycle down to 80% FP from 100% FP it would take a minimum of 2.2 minutes, and the power decrease would be at a steady and constant rate during that time. During the simulations in RFSP, the power is decreased instantly to the next setpoint without any sort of power ramp to reduce the number of individual simulations required thus greatly shortening the time required for a week long simulation.

The consequences of an instantaneous power change over a realistic power ramp turn out to be quite negligible and have no noticeable effect on xenon transient response for the load following simulations. Several manoeuvreing rates much slower than the maximum rate were simulated and compared to the instantaneous power change; variations in the average zone controller levels were found to differ by less than 0.5% during any time in the subsequent 24 hours (see Figure 3.3).

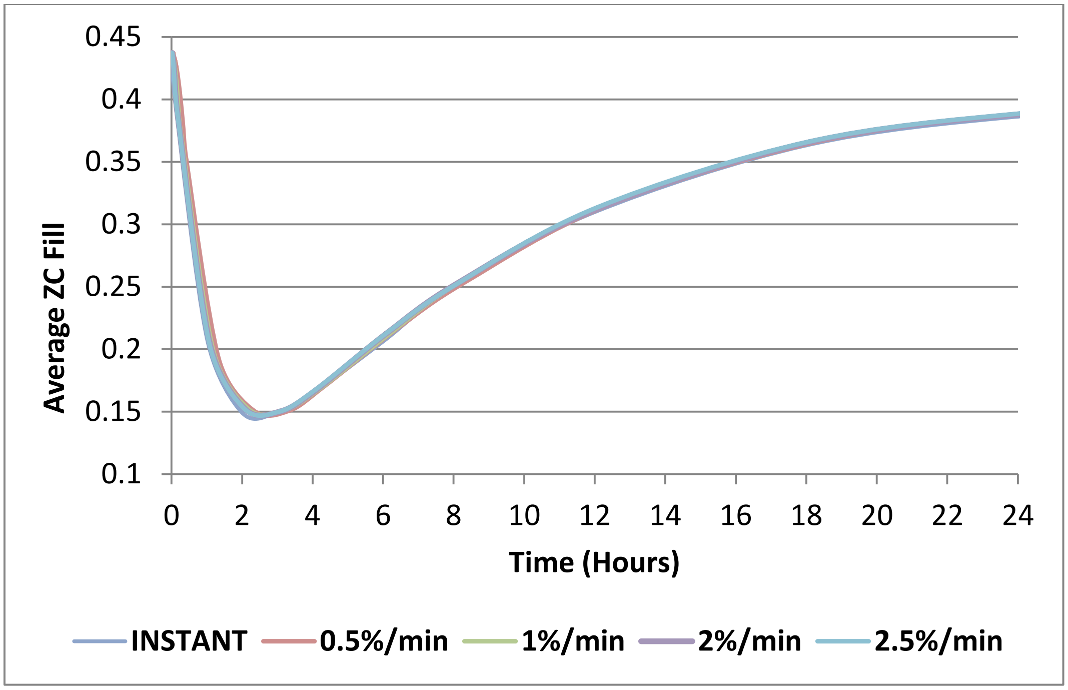

Figure 3.3 - Comparison of manoeuvreing rates for NU 100-90% FP

3.3.4 Refuelling

The refuelling pattern and frequency differed between the two different fuel types and between load following cycles. When and what channels to refuel was decided based on individual and average zone controller fills as well as the channel age as dictated by the INSTANTAN core. As refuelling was dictated by the state of the simulated core, the refuelling pattern used might not accurately reflect that of an operating CANDU reactor.

The INSTANTAN core for these simulations consists of random channel ages distributed throughout the core ranging in value from 0 to 1. Channel ages were assigned by creating a 7x7 grid with a channel age distribution created to best represent realistic operating conditions (Morreale, 2012). This 7x7 grid is known as a "patterned random channel age distribution" or PRCAD. The PRCAD grid was then patterned across the core to create a 480 channel age distribution. The starting channel age map can be found in appendix A and details on refuelling rates can be found in chapter 4.

3.3.5 Load Following Cycles

The load following cycles presented in this thesis were designed to represent realistic daily load following as closely as possible. All load following simulations are a week long in duration, with power levels changing every 12 hours. A period of 12 hours at full power is followed by a 12 hour period at a lower setpoint, cycling back to 100% for the next 12 hours and continuing the pattern until the entire week long simulation is complete. This was done to replicate a reactor operating at full capacity during the day and cycling down to a lower power setpoint at night.

The refuelling operations are performed during the "daytime" hours where the reactor is at 100% FP. This is done to best replicate realistic operating conditions, and since the reactors were designed to operate mostly at 100% FP, the stability of the reactor will probably be at a maximum during this time thus leaving more room for the zone controllers to handle the reactivity insertion caused by the fresh fuel.

Load following simulations were performed at decreasing low power setpoints from 95% FP down to 80% FP at 5% FP increments for both TRUMOX and NU fuelled cores. In addition to the regular load following simulations where power is fluctuated between 100% FP and a low power setpoint, stepped simulations were also performed where the low power setpoint gradually decreases to the final desired setpoint in increments of 5% FP. For example, for a load following cycle down to 85% FP, the first two low power setpoints would be 95% and 90%, with the remainder being at the target 85% FP. This was done to combat the initial spike in reactivity that occurs after a reactor has been operating at a constant power for long enough to let the xenon concentration reach equilibrium.

For simulations involving NU fuel, two separate simulations were performed where additional reactivity device movement may be necessary, that is one set of simulations with adjuster rod and MCA movement enabled, and one with it disabled. This was done to see what type of reactor control could be achieved with only the zone controllers combating the xenon transient since removing adjuster rods from the core for daily load following might not be appropriate.

Cycle	Fuel Type		
	TRUMOX	**NU (ZC control only)**	**NU (all reactivity devices)**
100-95% FP	Yes	Yes	Same as ZC only
100-90% FP	Yes	Yes	Same as ZC only
100-90% FP Stepped	Yes	Yes	Same as ZC only
100-85% FP	Yes	Yes	Yes
100-85% FP Stepped	Yes	Yes	Yes
100-80% FP	Yes	No	Yes
100-80% FP Stepped	Yes	No	Yes

Table 3.1 - Load following cycles performed

3.4 Refuelling Patterns

The refuelling patterns and frequency were developed through experimentation in RFSP for both the NU and TRUMOX fuelled cores. Although the main focus of this research isn't to analyze and develop refuelling patterns, the best effort was made to make a realistic load following simulation and that includes a refuelling pattern which satisfies basic requirements.

The first of those requirements is establishing how many channels to refuel per day to keep the average zone controller fill consistent throughout the simulations during the same power setpoints, such that the refueling compensates for the reactivity lost through fuel burnup. These rates were found through experimentation in the simulations, first making a guess as to how often to refuel and modify the rate depending on the results. The refuelling rates used for the simulations are discussed in chapter 4.

The second of those requirements was establishing a refuelling pattern as to not introduce a large variation in the individual zone controller fills as that would indicate a large variation in the flux of the reactor core. Channels were chosen based on what parts of the reactor had a flux depression (indicated by low individual zone controllers), the age of the channels and whether or not channels in close proximity had been refueled lately. As the same for the refuelling rate, the choice of channels to refuel was based upon experimentation in the simulations and patterns were refined based on previous results. Also taken into account was the refuelling region of the core, whether it was a 4 or 8 bundle shift region for NU or a 1 or 2 bundle shift region for TRUMOX, this factor both affecting the refuelling rate as well as channels chosen.

3.5 Controllability Criterion & Safety Limits

The goal of this research is to assess the controllability of a TRUMOX fuelled CANDU-900 reactor for load following operation. The controllability of a reactor depends on several factors, but it requires that the reactor can be safely controlled by the RRS as well as the operators. The main factor that will be looked at to judge controllability is the level of the liquid zone controllers. Another strong indicator of reactor controllability is the excess reactivity of the core; however the level of the liquid zone controllers will usually have reached the end of their limits before any large perturbations in the excess reactivity of the core become apparent. In addition to reactor control, the reactor must operate within the prescribed maximum channel and bundle power limits.

3.5.1 Liquid Zone Controller Levels

The level of the liquid zone controllers are the primary focus for determining the controllability of the reactor as it is within the zone controllers where most of the day to day reactivity control stems from. For this study, it has been chosen any load following cycle will be deemed uncontrollable if the average liquid zone controller level comes within 15% of its operational bounds; that is the average fill level exceeds 85% or drops below 15%. This has been chosen for several reasons.

A major reason for limiting the average zone controller level to within 15% and 85% is that individual zone controller fills can be slightly deviated from the average value. There is usually a slight variance between individual zone controller fills due to local channel ages and flux distribution, so if the average zone controller level is 15% full, it is very likely that several individual zone controller fills will be below 15% full, the same goes for the upper limit of 85% as well. It is very important that no individual liquid zone controllers become completely full or completely voided as that would severely hamper the ability of the RRS to control flux levels in that zone.

Not only is there a variation between individual zone controller fills, the reactivity worth of the liquid zone controllers isn't linear with fill level. As can be seen in the diagram below, the reactivity worth of the zone controllers tapers off as the fill level approaches 100%, so when the zone controllers reach 85% full, the percent of reactivity worth left is actually less than 15% of the total worth (Bereznai, 2004a).

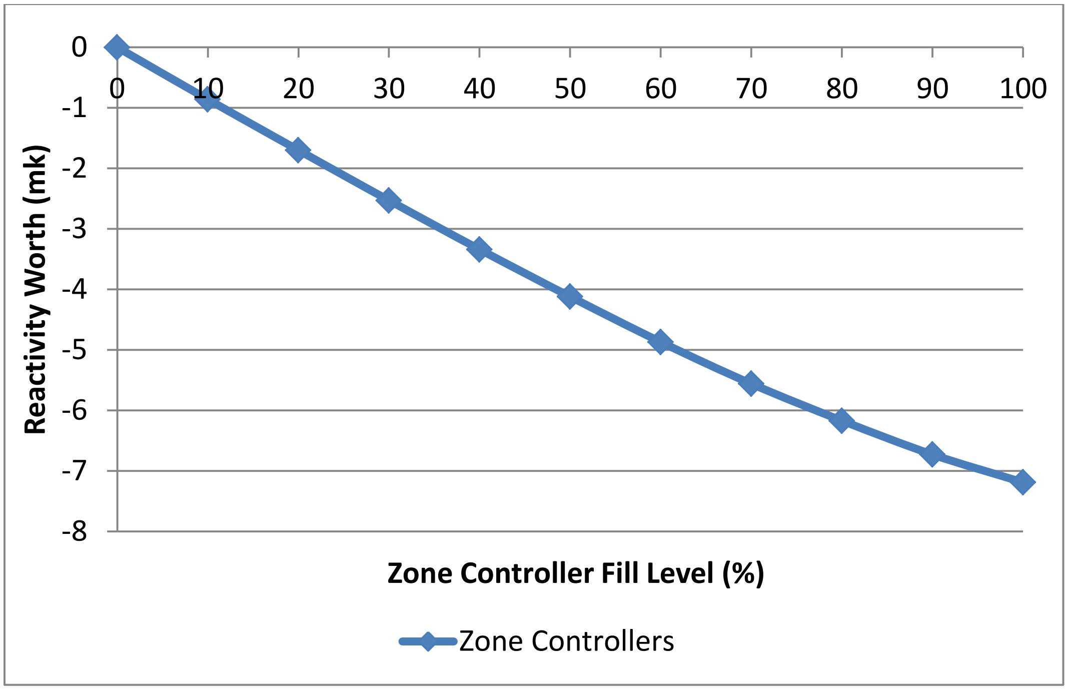

Figure 3.4 - Reactivity worth of liquid zone controllers (NU)

In addition to the variation and non-linearity of the zone controllers, it is necessary to incorporate a safety margin between the operating and physical limits of the liquid zone controllers for several reasons. Any unforeseen circumstances, such as a disabled zone controller or a poor choice of channel refuelling, can require the zone controllers to account for unplanned excess reactivity in the core or to control a larger zone than was initially designed. In these types of situations it is beneficial to have the ability to add or remove reactivity in the core without requiring the insertion or removal of adjuster rods or MCAs.

Lastly, there may be slight variations between the results of simulation in a program such as RFSP and actual reactor operational results. It is impossible to model something as complex as a CANDU reactor core with complete precision and accuracy, so it is beneficial to have a safety margin to account for any possible differences between the RFSP simulation and real world operational results.

3.5.2 Excess Reactivity

For both the NU and TRUMOX simulations, the bulk control target of the liquid zone controllers has been set at 1.001 k, meaning the excess reactivity of the core is set at 1 mk. Any variation from this target exceeding 0.1 mk usually indicates reactor instability from lack of sufficient reactivity such as all liquid zone controllers being voided or full, or very large variations between individual zone controllers indicating loss of spatial control.

In both cases, reactor instability will be evident in the zone controller fills before becoming present in the form of excess reactivity perturbations. From simulation experience, excess reactivity spikes as a result of large individual zone controller variations usually occurs after the average zone controller fill of the reactor has breached the 15% safety margin of both the maximum and minimum fill levels.

3.5.3 Maximum Channel & Bundle Powers

The maximum channel and bundle powers for an NU fuelled CANDU-900 reactor are 7.3 MW and 935 kW respectively (Morreale, 2012). Since there are no prescribed maxima for TRUMOX fuel, these channel and bundle power limits will be used for both the NU and TRUMOX fuelled cores. Although not indicative of reactor instability, conformance to safety standards is still important in determining safe operation of a reactor. It is worth noting that if only a few channels that were recently refueled breach these safety limits, it is most likely due to a poorly chosen refuelling pattern rather than inability for the fuel to conform to the safety limits. While every effort was made to choose a suitable pattern of refuelling, it is not the primary focus of this study.

3.5.4 Use of Adjuster Rods and MCAs

As will be touched on in the following chapter, the TRUMOX fuelled CANDU-900 reactor operates with adjuster rods withdrawn from the core, while the adjuster rods are present in core for NU fuel. Just like most CANDU reactors operating today, the presence of adjuster rods in the core provide flux flattening to shape the flux distribution of the core as well as to allow for large insertions of reactivity beyond the ability of the zone controllers. Large reactivity changes due to xenon transients, such as those encountered during turbine trips or setbacks, can be compensated for by withdrawing these adjuster rods from the core.

Since these adjuster rods play an important role in shaping the neutron flux of the NU core, it may not be appropriate to use them for day to day load following operation. Taking this into account, simulations have been performed both with and without the ability to withdraw the adjuster rods from the NU fuelled core.

4 Fuel Comparison

4.1 Natural Uranium (NU)

CANDU reactors have been using natural uranium fuel since the first reactor, NPD (Nuclear Power Demonstration, a CANDU prototype), came online in 1962. Since then and for the last 40 years, CANDU reactors have been producing safe and reliable power using natural uranium that has been mined and processed right here in Canada. Natural uranium, like the name suggests, occurs naturally in the earth and unlike the fuel for other reactor designs, requires no enrichment to be used in CANDU reactors.

4.1.1 Composition

Natural uranium fuel is composed of uranium dioxide (UO_2) that has been processed from uranium ore. The NU fuel has not been enriched, the only fissile content being uranium-235 which is naturally occurring. Most of the uranium is composed of uranium-238, a non-fissile isotope, making up 99.28% of the uranium by weight. The ^{235}U is only 0.771% of the total uranium content, with trace amounts of ^{234}U (0.0054%) which is also non-fissile. The NU composition is also listed in Table 4.1.

Uranium Oxide (UO_2) Composition		**Uranium Composition**	
Element	**% (wt.)**	**Isotope**	**% (wt.)**
Uranium	88.15	Uranium-234	0.0054
Oxygen	11.85	Uranium-235	0.7110
		Uranium-238	99.2836

Table 4.1 - NU isotopic composition

4.1.2 Reactivity Worths of Control Devices

The reactivity worth of control devices (liquid zone controllers, adjuster rods, and mechanical control absorbers) is measured using k, which is a ratio of the number of neutrons in two successive fission neutron generations

(Duderstadt, 1976). The 14 liquid zone controllers have a total worth of about -5.7 mk, the 24 adjuster rods, divided into 8 banks, have a reactivity worth of around -15.5 mk and the 4 mechanical control absorbers (MCAs), divided into 2 banks, have a reactivity worth of about -7.7 mk. These values are the result of simulations performed in RFSP and match well with literary values for an NU fuelled CANDU-900 core (Chapter 2: Reactor and Moderator, 2004a). The reactivity worth values are listed below in Table 4.2.

Zone Controller		**Adjuster Rod**	
Zone Controller % Fill	**Reactivity Worth (mk)**	**No. of Banks In**	**Reactivity Worth (mk)**
		1	-2.137
		2	-4.133
10	-0.69	3	-5.733
20	-1.342	4	-7.72
30	-1.987	5	-9.635
40	-2.638	6	-11.601
50	-3.275	7	-13.451
60	-3.882	8	-15.517
70	-4.431	**Mechanical Control Absorber**	
80	-4.917	**No. of Banks In**	**Reactivity Worth (mk)**
90	-5.326	1	-3.467
100	-5.673	2	-7.681

Table 4.2 - Reactivity worths of reactivity control devices (NU)

4.1.3 Parameters

To obtain the most accurate simulation results, the aspects and parameters of the CANDU-900 reactor model were selected to best reflect realistic operating conditions. The 480 channel reactor core is set up identical to the CANDU-900 core with the same bundle shift regions. There are 100 channels that experience an 8-bundle shift and the remaining 380 channels undergo a 4-bundle shift refuelling scheme. The core map showing the bundle shift regions is shown below.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
A								8	8	8	8	8	8	8	8	8	8								A
B						8	8	8	8	8	4	4	4	4	8	8	8	8	8						B
C					8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	8					C
D				8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8				D
E			8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8			E
F		8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8		F
G		8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8		G
H		8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8		H
J	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	J
K	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	K
L	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	L
M	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	M
N	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	N
O	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	O
P	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	P
Q	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	Q
R		8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8		R
S		8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8		S
T		8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8		T
U			8	8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8	8			U
V				8	8	4	4	4	4	4	4	4	4	4	4	4	4	4	4	8	8				V
W					8	8	8	4	4	4	4	4	4	4	4	4	4	8	8	8					W
X						8	8	8	8	8	4	4	4	4	8	8	8	8	8						X
Y								8	8	8	8	8	8	8	8	8	8								Y
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

Figure 4.1 - Bundle shift refuelling map for NU fuelled core

On average, 6 channels per day were refueled while operating at 100% FP which equals about 29 bundles per day. During weekly load following operations, refuelling rates tended to decrease as the average output power or the reactor decreased. Refuelling rates for the various load following simulations are given in Table 4.3. These refuelling rates were found through experimentation with the reactor model.

Simulation	Average Channels/Day	Average Bundles/Day
100% FP	6.00	29.00
100-95%	6.00	29.00
100-90% stepped	5.00	24.17
100-90%	5.00	24.17
100-85% stepped	4.00	19.33
100-85%	4.00	19.33
100-80% stepped	4.00	19.33
100-80%	4.00	19.33

Table 4.3 - Refuelling rates (NU)

During normal reactor operation, 6 of the 8 adjuster rod banks are present in the core to create a flatter flux profile and to provide the ability to add positive reactivity to the core to assist with mitigating the xenon transient reactivity. The average zone controller level for 100% FP operation is set at 44% full. These parameters were chosen to best reflect realistic operating conditions of the reactor.

4.2 TRUMOX

The transuranic mixed oxide (TRUMOX) fuel used for this controllability study is a blend of natural uranium fuel mixed with transuranic actinides. The actinides are a group of fifteen metallic elements with the atomic numbers 89 through 103, actinium to lawrencium. Transuranic elements are all of the elements that come after uranium in the periodic table, that is have an atomic number greater than 92. The term transuranic actinide refers to all elements that are transuranic as well as belong to the actinide series. The transuranic actinides that can be found in TRUMOX fuel are highlighted in red in Figure 4.2.

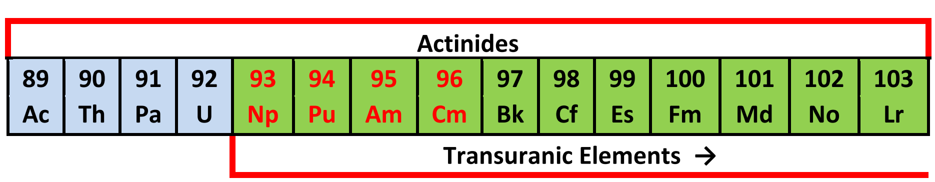

Figure 4.2 - Transuranic actinides

The reprocessing of spent fuel provides the benefits of overall reduction in waste as well as more efficient usage of the energy in nuclear fuel. For the TRUMOX fuel in this thesis, the transuranic actinides were extracted from spent LWR fuel that has been cooled for 30 years. Rather than using recently spent LWR fuel to reprocess, fuel that had been cooled for 30 years was a better representation of the large stockpiles of spent fuel from over 50 years of nuclear power plant operation. The CANDU reactor design is an excellent choice for actinide burning due to the high neutron economy, simple fuel design and the availability of online refueling (Morreale, 2011). Similar to the bundles used for NU in a CANDU-900, the bundles are a 43 pin design; however, in the TRUMOX bundle the central pin consists of the burnable poison dysprosium to reduce coolant void reactivity effects.

The fuel was designed for high burnups with a target of 45MWd/kgHE, which is about 4 times that of standard NU fuel. WIMS-AECL, a 2-D multi group transport code, was used to model the lattice cell and calculate the 2 neutron group properties of the fuel. The incremental cross sections for all of the reactivity devices were calculated using the 3-D neutron transport code DRAGON (Morreale, 2012). RFSP as well as WIMS-AECL and DRAGON are all standard industry reactor physics cods and are therefore part of the Industry Standard Toolset (IST) for reactor analysis in Canada.

4.2.1 Composition

TRUMOX fuel is composed of 96.9% uranium oxide (natural uranium fuel) and the remaining 3.1% is a mix of transuranic actinides (TRU) as shown in Table 4.4 (Forsberg, 2004). The only fissile isotope in NU fuel is ^{235}U, making up 0.711% of the fuel by weight. The two major fissile actinides in the TRU mix are ^{239}Pu and ^{241}Pu, making up 59.283% of the TRU mix by weight. This gives the TRUMOX fuel an overall fissile content of 2.527%, roughly 3.5 times the fissile content of conventional NU fuel. The remainder of the TRU mix comprises of non-fissile isotopes of plutonium as well as americium, neptunium, and curium. The central pin of the 43 pin TRUMOX fuel bundle is composed of a burnable poison, dysprosium (in the form of dysprosium zirconium oxide), to reduce coolant void reactivity effects.

TRUMOX Composition		**Actinides**	
Actinide Oxide (AOX)	3.1 % (wt.)	**Isotope**	**% (wt.)**
Uranium Oxide (UO_2)	96.9 % (wt.)	Neptunium-237	4.698
Uranium Oxide (UO_2) Composition		Plutonium-238	1.301
Uranium	88.15 % (wt.)	Plutonium-239	56.243
Oxygen	11.85 % (wt.)	Plutonium-240	20.099
Actinide Oxide (AOX) Composition		Plutonium-241	3.040
Actinides	88.207 % (wt.)	Plutonium-242	3.800
Oxygen	11.793 % (wt.)	Americium-241	9.907
Uranium Composition		Americium-243	0.763
Isotope	**% (wt.)**	Curium-243	0.001
Uranium-234	0.0054	Curium-244	0.072
Uranium-235	0.7110	Curium-245	0.012
Uranium-238	99.2836	Curium-246	0.001

Table 4.4 - TRUMOX isotopic composition

4.2.2 Reactivity Worths of Control Devices

The reactivity worth of control devices is significantly less for the TRUMOX fuelled core. The 14 liquid zone controllers have a total worth of about -3.7 mk, the 24 adjuster rods have a reactivity worth of around -4.8 mk and the 4 MCAs have a reactivity worth of about -4.9 mk. Compared to NU, the liquid zone controllers and MCAs are worth about 2/3rds of their worth for NU while the adjuster rods are only worth 1/3rd of their value for the NU fueled core. These values are the result of simulations performed in RFSP and are consistent with other TRUMOX simulation values in a CANDU-900 reactor (Morreale, 2011). The reactivity worth values are listed in Table 4.5 below.

Zone Controller		**Adjuster Rod**	
Zone Controller % Fill	**Reactivity Worth (mk)**	**No. of Banks In**	**Reactivity Worth (mk)**
		1	-0.519
		2	-1.022
10	-0.458	3	-1.596
20	-0.883	4	-2.198
30	-1.294	5	-2.763
40	-1.702	6	-3.375
50	-2.106	7	-4.033
60	-2.504	8	-4.762
70	-2.872	**Mechanical Control Absorber**	
80	-3.197	**No. of Banks In**	**Reactivity Worth (mk)**
90	-3.468	1	-2.319
100	-3.696	2	-4.942

Table 4.5 - Reactivity worths of reactivity control devices (TRUMOX)

4.2.3 Parameters

The aspects and parameters of the CANDU-900 reactor model for TRUMOX fuel were selected to best reflect probable operating conditions. The 480 channel reactor core is similar to the NU fuelled core with different bundle shift regions and values. There are 136 channels that experience a two-bundle shift and the remaining 344 channels undergo a one-bundle shift refuelling scheme. This refuelling scheme is different than that used for the NU fuelled core due the higher fissile content of the TRUMOX fuel, hence a higher reactivity insertion per bundle. The core map showing the bundle shift regions is shown in Figure 4.3.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
A								2	2	2	2	2	2	2	2	2	2								A
B						2	2	2	2	2	2	2	2	2	2	2	2	2	2						B
C					2	2	2	1	1	1	1	1	1	1	1	1	1	2	2	2					C
D				2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2				D
E			2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2			E
F		2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2		F
G		2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2		G
H		2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2		H
J	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	J
K	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	K
L	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	L
M	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	M
N	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	N
O	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	O
P	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	P
Q	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	Q
R		2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2		R
S		2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2		S
T		2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2		T
U			2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2			U
V				2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2				V
W					2	2	2	1	1	1	1	1	1	1	1	1	1	2	2	2					W
X						2	2	2	2	2	2	2	2	2	2	2	2	2	2						X
Y								2	2	2	2	2	2	2	2	2	2								Y
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

Figure 4.3 - Bundle shift refuelling map for TRUMOX fuelled core

On average, 4.29 channels per day were refueled while operating at 100% FP which equals about 5.51 bundles per day. As with the NU fuelled core, weekly load following operations resulted in decreased refuelling rates due to the lower average output power of the reactor. Refuelling rates for the various load following simulations are given in Table 4.6. These refuelling rates were found through experimentation with the reactor model.

Simulation	Average Channels/Day	Average Bundles/Day
100% FP	4.29	5.51
100-95%	4.00	5.13
100-90% stepped	4.00	5.13
100-90%	4.00	5.13
100-85% stepped	3.57	4.58
100-85%	3.43	4.40
100-80% stepped	3.29*	4.22*
100-80%	3.29*	4.22*

Table 4.6 - Refuelling rates (TRUMOX)

Unlike the NU fuelled reactor, during normal operation all of the adjuster rod banks are withdrawn from the core. TRUMOX fuel does not require flux flattening due to the neutron absorbing properties of the transuranic actinides present in the fuel as well as the burnable poison dysprosium in the central pin of the bundle. Furthermore, less neutron absorbing materials in the core will lead to higher fuel burnups thus increasing rates of transuranic actinide transmutation. The average zone controller level for 100% FP operation is set at 45% full which is similar to the level experienced in the NU fuelled core. These parameters were chosen to best reflect projected operating conditions of the reactor.

* Extrapolated Values

5 Results

The results in this chapter are presented by simulation type, either load following, setback or turbine trip. Each section is then further broken down by fuel type, first for TRUMOX then for NU to compare. Since natural uranium is currently the fuel being used in CANDU reactors, it is most beneficial to see how TRUMOX performs compared to NU.

5.1 Initial Reactor Core

All of the results for each simulation started with the same initial NU or TRUMOX core. The initial cores all start at 100% FP and have been simulated at that power level for a period of time to portray a reactor that has been operating at base load capacity long enough for xenon concentrations to reach a stable level. The parameters for both the initial reactor cores are listed in the chart below and 3-D core power distributions can be found in appendix B.

Fuel	Average ZC Fill	Channel Power (kw)				
		F 12	F 13	O 7	M 12	MAX
TRUMOX	.4507	5397	5423	6442	6077	6870 (O 17)
NU	.4379	6147	6157	6231	6155	6374 (K 10)

Table 5.1 - Initial core zone controller fills and select channel powers

5.2 Load Following

For each week long load following simulation, a graph of the average zone controller fill level along with the reactor power level is presented. In addition, several select channel powers as well as the maximum channel and bundle powers are tracked for the entire simulation. The particular four channels selected for tracking are radially positioned at the center, midpoint, and edge of the core. For each simulation, one of these channels is refueled and an adjacent channel power is also tracked to see the local effects of refuelling. It should be noted that the location of the maximum channel power may change throughout the course of the simulation.

For simulations involving a natural uranium (NU) fuelled core, two different scenarios were simulated: zone controller movement only with adjuster rods and MCAs in their day to day operating locations (denoted NU), and zone controller movement plus adjuster rod and MCA movement (denoted NU with reactivity device control). This was done to make a better comparison between the TRUMOX and NU fuelled cores for load following since TRUMOX really only has the zone controllers available to combat the xenon transients. For these simulations, the adjuster rods and MCA movements are only enabled for NU once the ability of the zone controllers to control the reactor core has been exceeded.

5.2.1 100-95% FP

Both the TRUMOX and NU cores perform well for load following to 95% FP. In both cases do the zone controller fill levels stay within the 15-85% imposed safety limit throughout the simulation in addition to all channel powers remaining below the 7.3 MW limit and all bundle powers remaining below the 935 kW limit. The TRUMOX fuelled core requires less variation in the zone controller fills versus NU, but both appear to be quite stable.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint of 95% FP. The maximum and minimimum average zone controller fractional fills were .5816 and .3591 resulting in a maximum deviation of .1309 in either direction from the starting fill value of .4507. Maximum and minimum values stay fairly consistent throughout the week long simulation with a slight dip in average zone controller fill during the first power reduction from 100% FP.

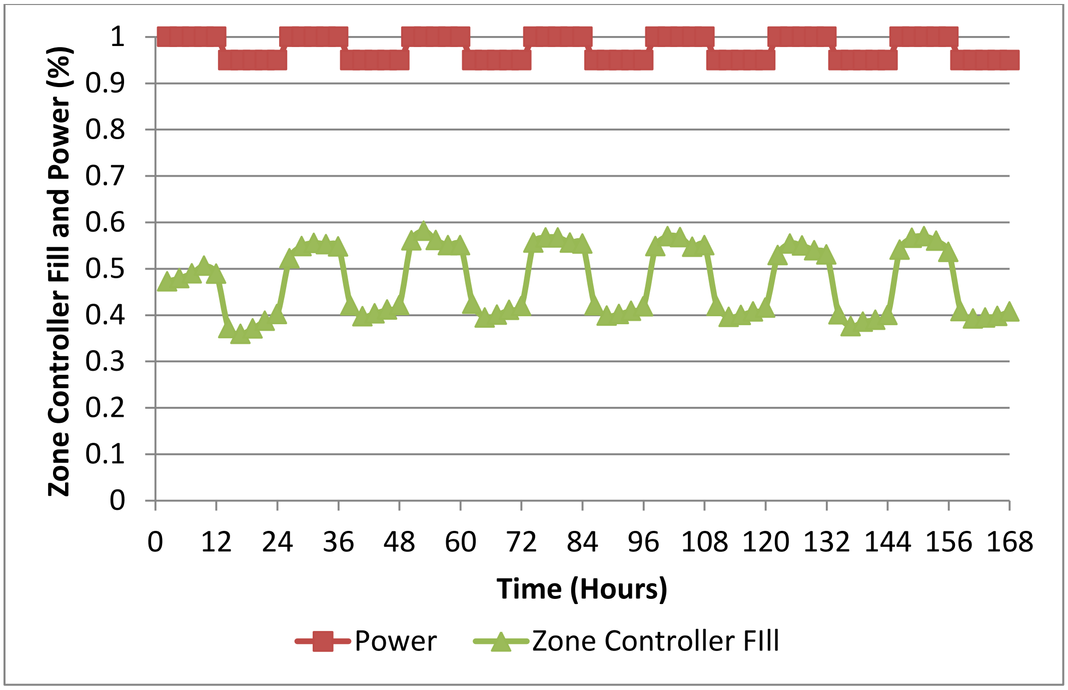

Figure 5.1 - 100-95% FP load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted below. The refuelling of channels O 7 and F12 are evident by the large increases in individual channel powers around hours 74 and 125 respectively. Maximum channel and bundle powers peaked at 7221.55 kW and 885.21 kW respectively, both being below their respective power limits of 7.3 MW and 935 kW.

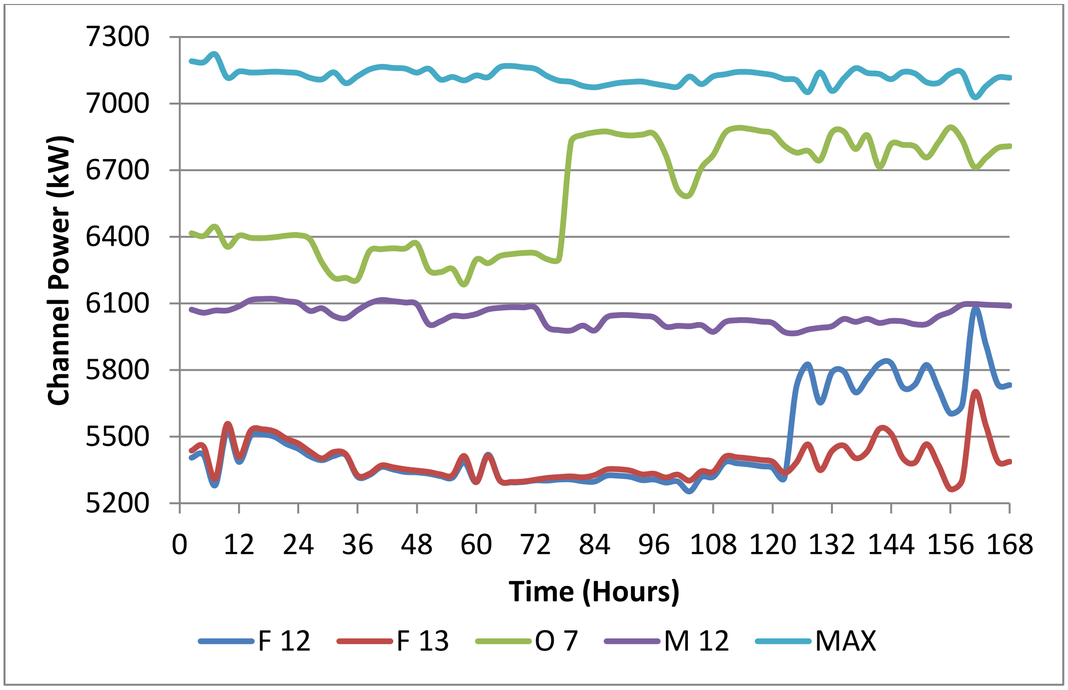

Figure 5.2 - 100-95% FP load following channel powers (TRUMOX)

NU

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with a lower setpoint of 95% FP. The maximum and minimimum average zone controller fractional fills were .5989 and .3255 resulting in a maximum deviation of .1610 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation with a dip in average zone controller fill during the first power reduction.

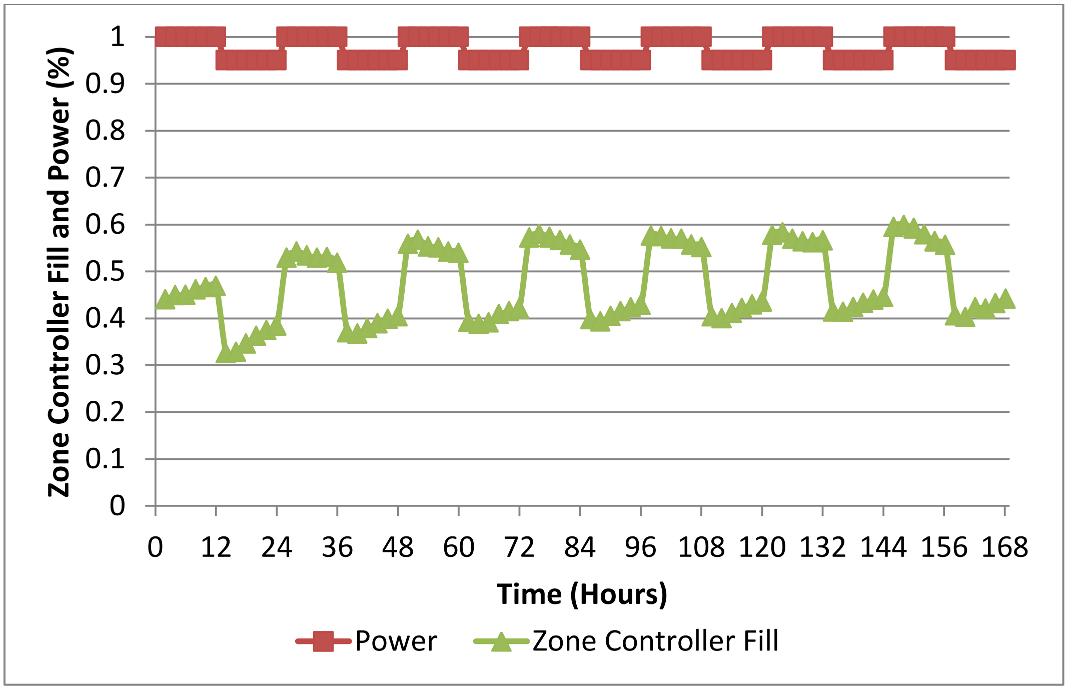

Figure 5.3 - 100-95% FP load following ZC fills (NU)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F12 is evident in the large increases in individual channel power around hour 106. Maximum channel power peaked at 6954.59 kW while the maximum bundle power peaked at 858.78 kW, both being below their respective power limits.

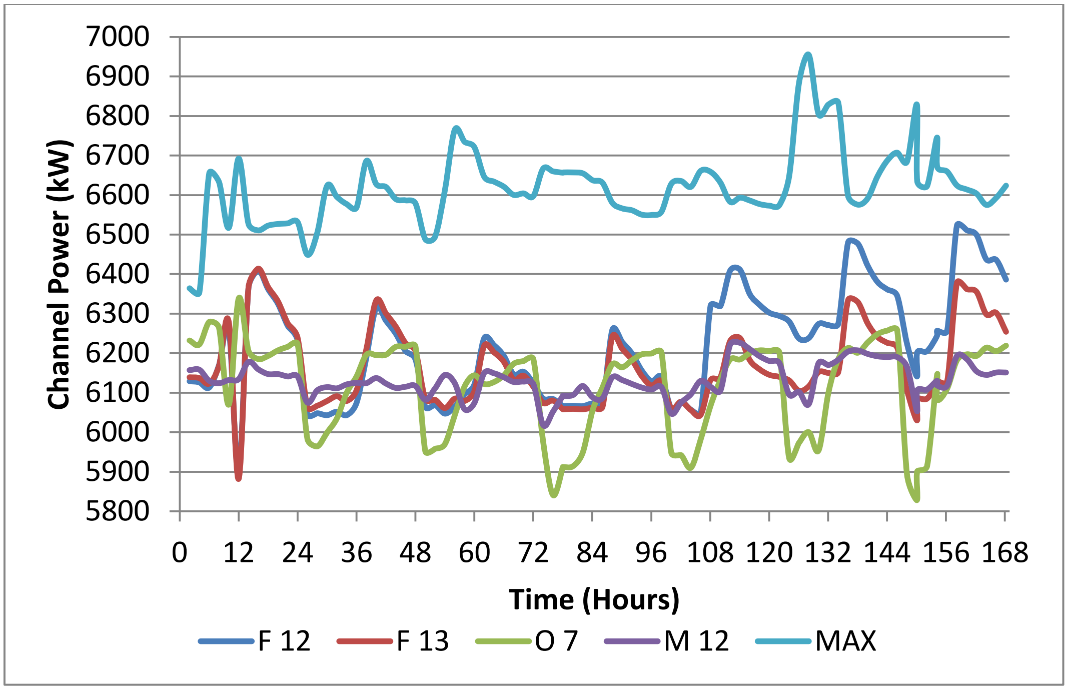

Figure 5.4 - 100-95% FP load following channel powers (NU)

5.2.2 100-90% FP

Both the TRUMOX and NU cores are capable of load following to 90% FP, although the NU fuelled core comes quite close to the imposed safety limits. In both cases do the zone controller fill levels stay within the 15-85% imposed safety limit throughout the simulation, however zone controller fills for NU come within 4% of the safety limit while those for TRUMOX do not come within 9%. All of the channel and bundle powers remain below their maximum power limits for both fuels and similarly to the previous simulation, the TRUMOX fuelled core requires less variation in the zone controller fills versus NU.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint of 90% FP. The maximum and minimimum average zone controller fractional fills were .7045 and .2401 resulting in a maximum deviation of .2538 in either direction from the starting fill value of .4507. Maximum and minimum values stay fairly consistent throughout the week long simulation with a dip in average zone controller fill during the first power reduction.

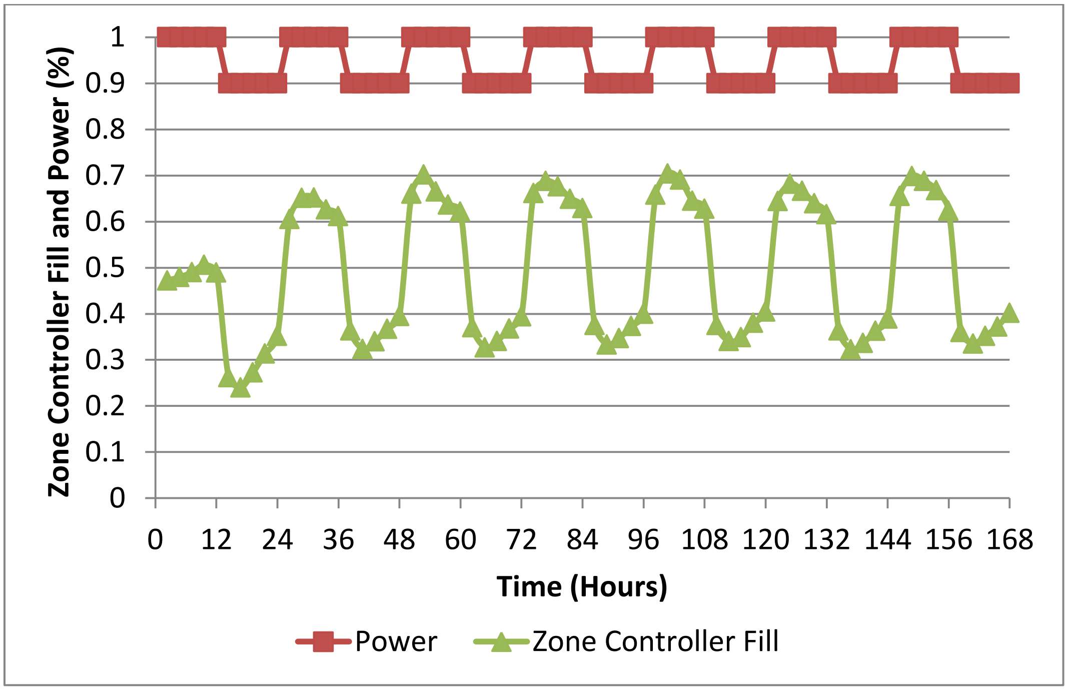

Figure 5.5 - 100-90% FP load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channels O 7 and F12 are evident in the large increases in individual channel powers around hours 74 and 125 respectively. Maximum channel power peaked at 7227.50 kW and the maximum bundle power peaked at 885.21 kW, both below their power limits.

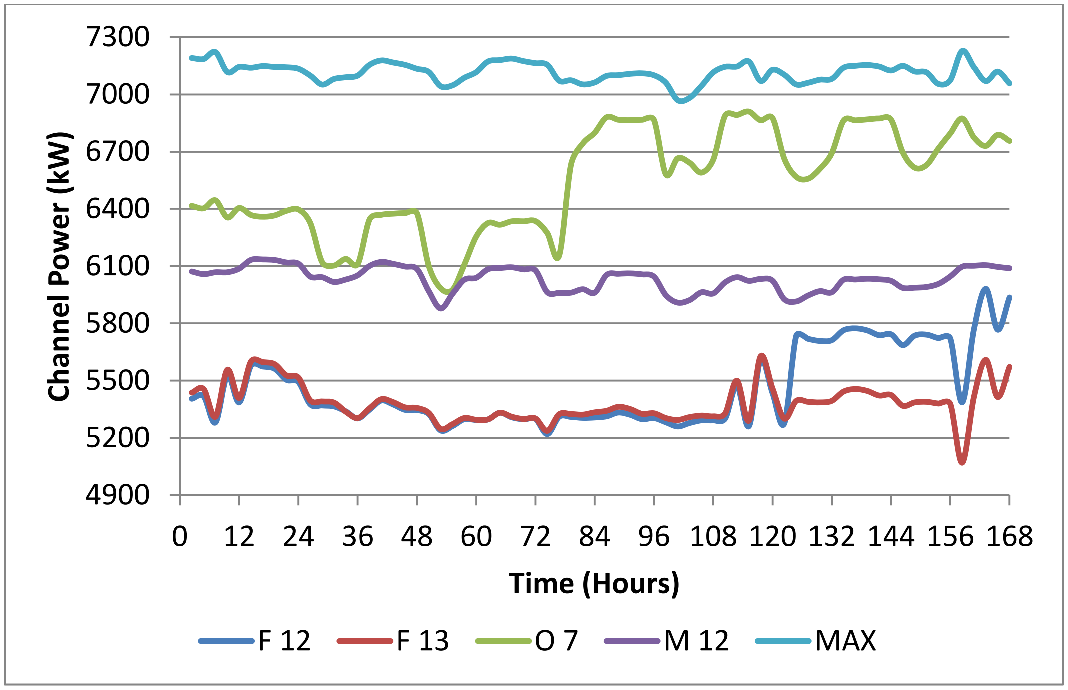

Figure 5.6 - 100-90% FP load following channel powers (TRUMOX)

NU

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with a lower setpoint of 90% FP. The maximum and minimimum average zone controller fractional fills were .6990 and .1854 resulting in a maximum deviation of .2611 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation with a large dip in average zone controller fill during the first power reduction. The initial dip to 18.54% full comes within 4% of the lower fill safety margin of 15%, this indicates that this is probably the lowest low power setpoint for which the zone controllers could handle safely for NU fuel.

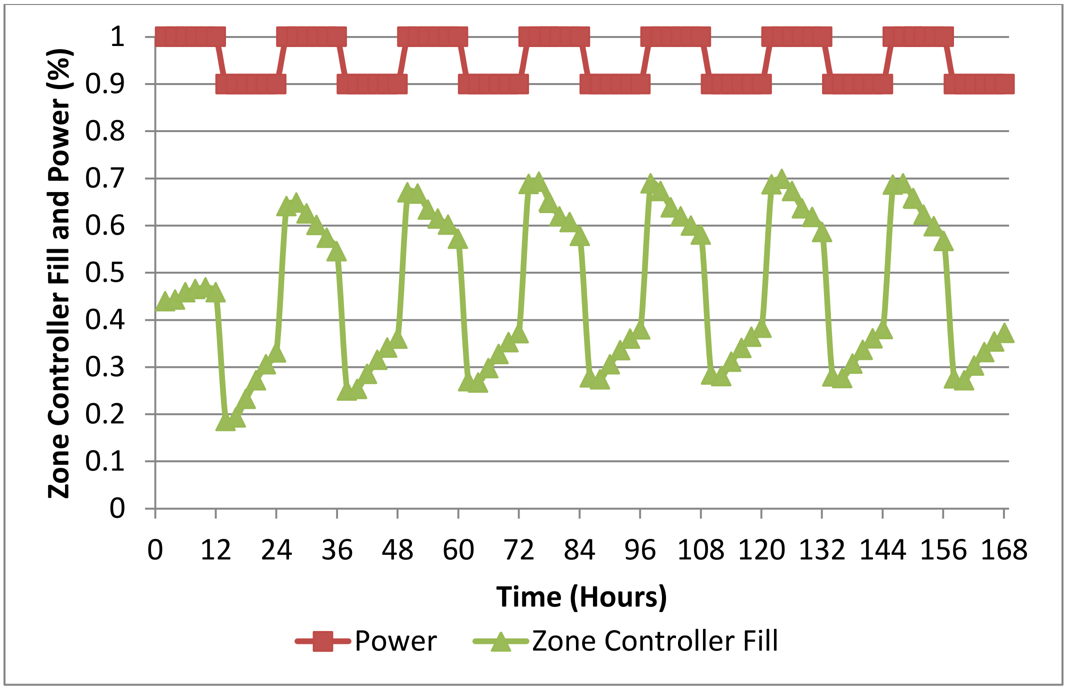

Figure 5.7 - 100-90% FP load following ZC fills (NU)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F12 is evident in the large increases in individual channel power around hour 106. Maximum channel and bundle powers remain below their power limits with maximum channel power peaking at 6921.96 kW and the maximum bundle power peaking at 853.86 kW.

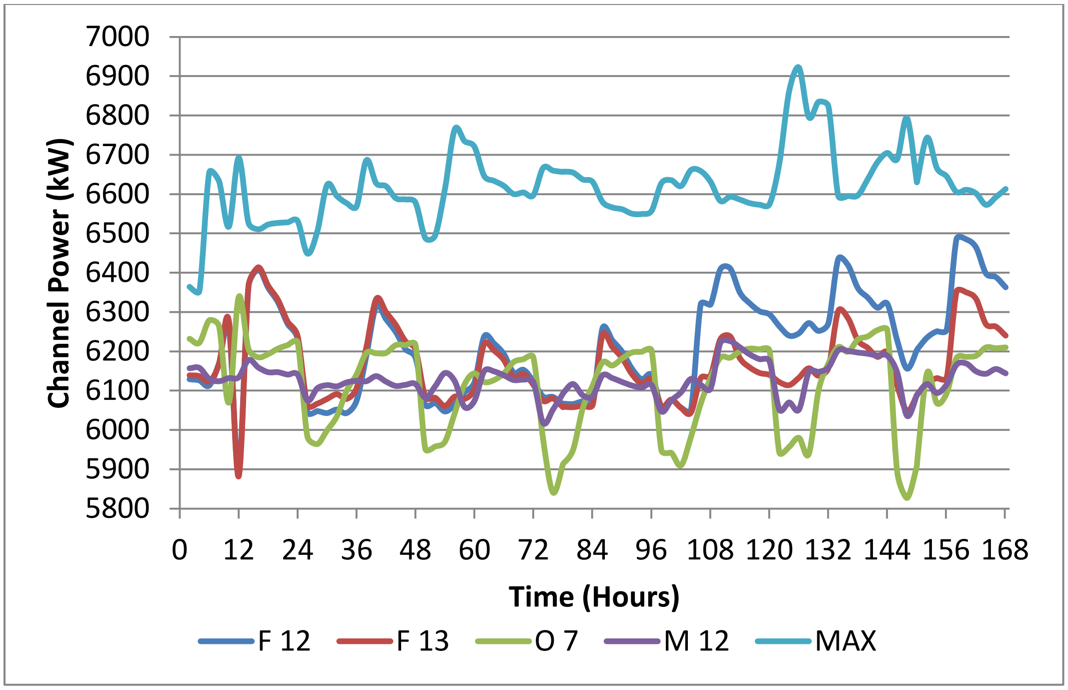

Figure 5.8 - 100-90% FP load following channel powers (NU)

5.2.3 100-90% FP Stepped

This trial is similar to the previous one except that the low power setpoints is stepped down 5% each time until the final target of 90% FP is reached. By doing this, the initial xenon reactivity spike is reduced thus allowing for a greater safety margin between the average zone controller level and the established safety limit. As in the previous trial, both the TRUMOX and NU cores are capable of load following to 90% FP in a stepped down fashion, however variation in the zone controller fills is reduced for both fuel types leading to greater ranges of controllability. Reducing power in a stepped down fashion appears to have negligible effects on the maximum channel and bundle powers as they remain virtually the same between the two trials.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint stepped down to 90% FP. The maximum and minimimum average zone controller fractional fills were .6990 and .2798 resulting in a maximum deviation of .2483 in either direction from the starting fill value of .4507. Maximum and minimum values stay fairly consistent throughout the week long simulation once the lower setpoint of 90% FP had been reached. The stepped power reduction results in a larger margin between the safety limit and the minimum average zone controller fill level (13% for the stepped power reduction vs. 9% for the non-stepped reduction).

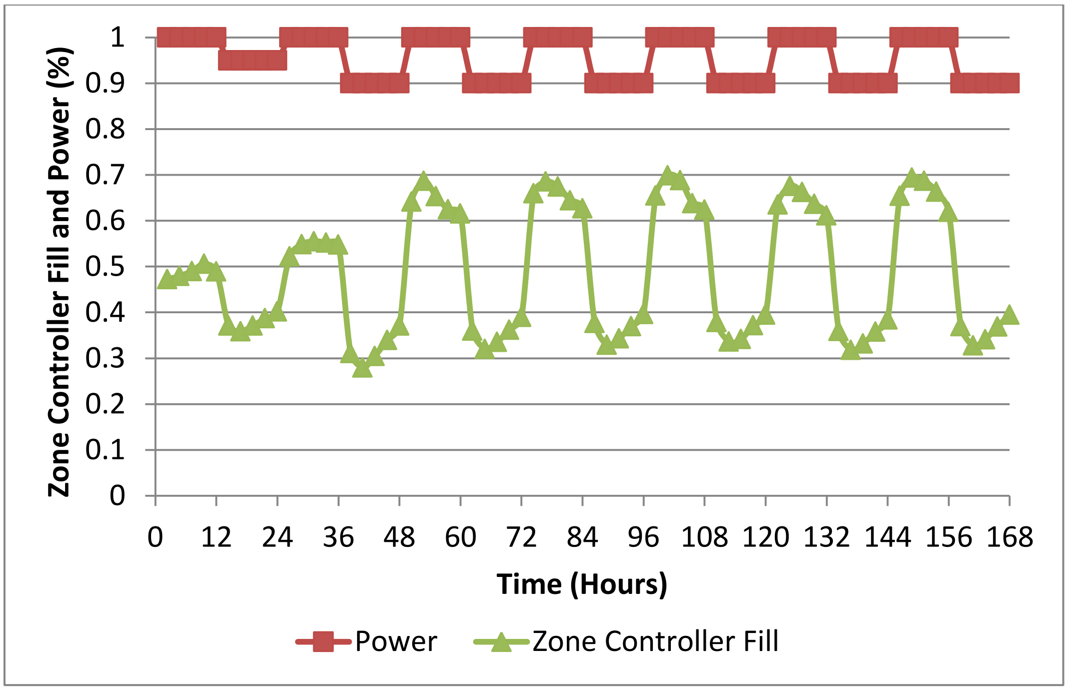

Figure 5.9 - 100-90% FP stepped load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channels O 7 and F12 are evident in the large increases in individual channel powers around hours 74 and 125 respectively. Maximum channel power peaked at 7221.55 kW and the maximum bundle power peaked at 885.21 kW, both below their respective power limits.

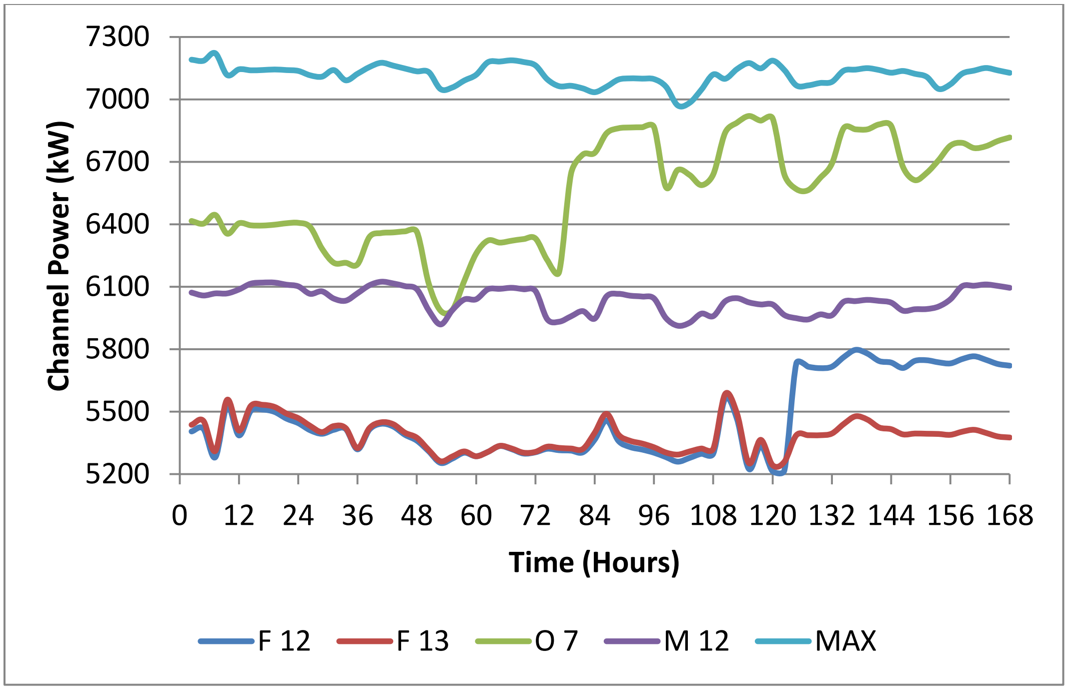

Figure 5.10 - 100-90% FP stepped load following channel powers (TRUMOX)

NU

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with a lower setpoint stepped down to 90% FP. The maximum and minimimum average zone controller fractional fills were .6902 and .2092 resulting in a maximum deviation of .2523 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation once the lower power setpoint of 90% has been reached with a dip in average zone controller fill during the first power reduction to 90% FP. Similar to the TRUMOX simulation, the stepped power reduction results in a larger margin between the safety limit and the minimum average zone controller fill level (6% for the stepped power reduction vs. 3.5% for the non-stepped reduction).

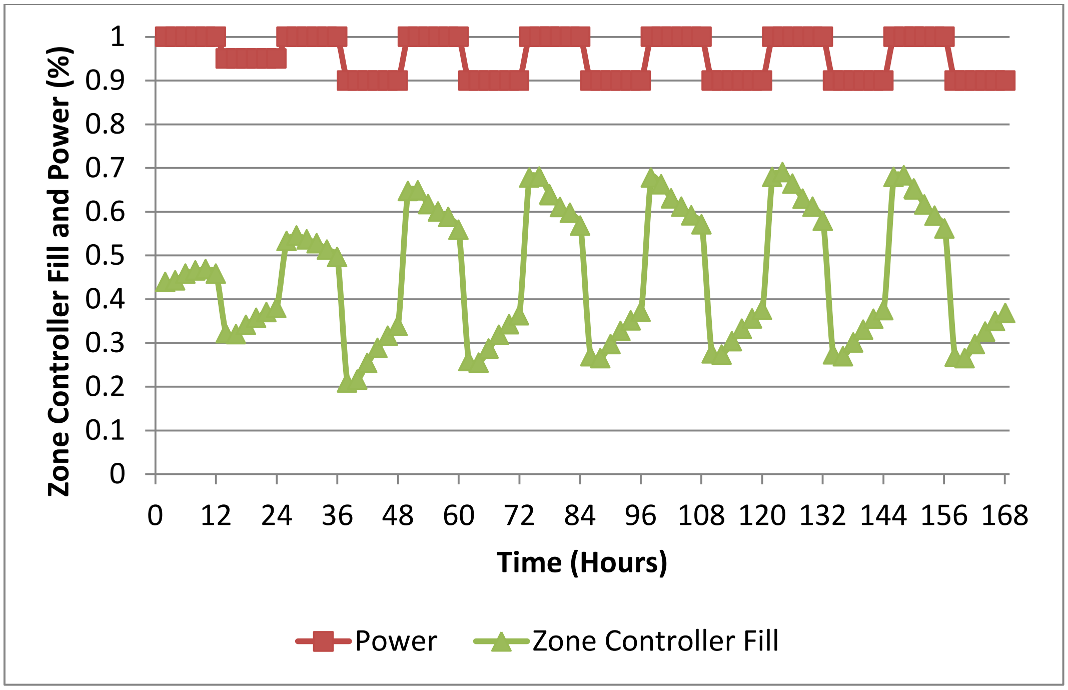

Figure 5.11 - 100-90% FP stepped load following ZC fills (NU)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F12 is evident in the large increases in individual channel power around hour 106. Maximum channel and bundle powers peaked at 6895.67 kW and 849.78 kW respectively, both below their maximum power limits.

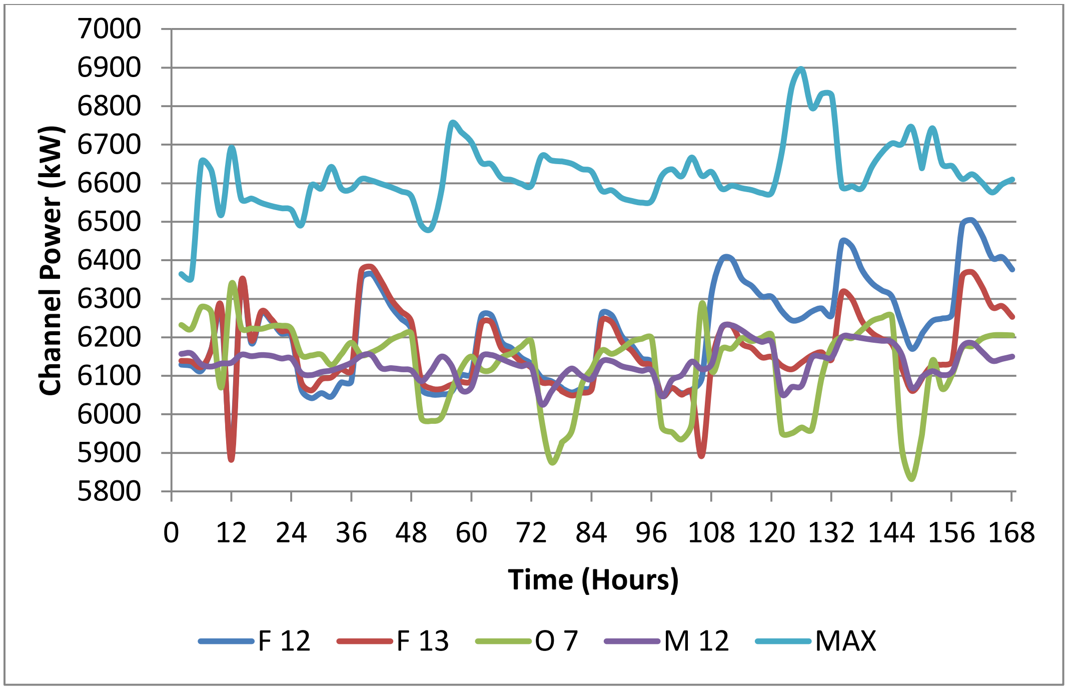

Figure 5.12 - 100-90% FP stepped load following channel powers (NU)

5.2.4 100-85% FP

Both the TRUMOX and NU fuelled cores appear to be capable of load following to 85% FP, although the NU core requires adjuster rod movement since the xenon transient is too big to be handled by the zone controllers alone. For TRUMOX, the first initial dip and average zone controller level just breaches the 15% fill limit, however all channel powers remain below the channel limits. The NU core with reactivity device movement enabled stays within the 15-85% imposed safety limit throughout the simulation, however a channel power above 7.3 MW was recorded during one core snapshot in the region of a withdrawn adjuster rod.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint of 85% FP. The maximum and minimimum average zone controller fractional fills were .8094 and .1447 resulting in a maximum deviation of .3587 in either direction from the starting fill value of .4507. Maximum and minimum values stay fairly consistent throughout the week long simulation with a dip in average zone controller fill during the first power reduction. Aside from the first reduction in reactor power, all zone controller fills stay within the 15% buffer zone throughout the simulation; a stepped power scheme reduces the initial reactivity spike and should alleviate this problem. Based on the outlined safety criterion, this load following simulation does not perform in a safe and controllable manner; however a slight increase in the initial average zone controller level (such as .4700 vs. the current value of .4507) would most likely relieve this problem without causing the maximum zome controller fill to breach its safety limit.

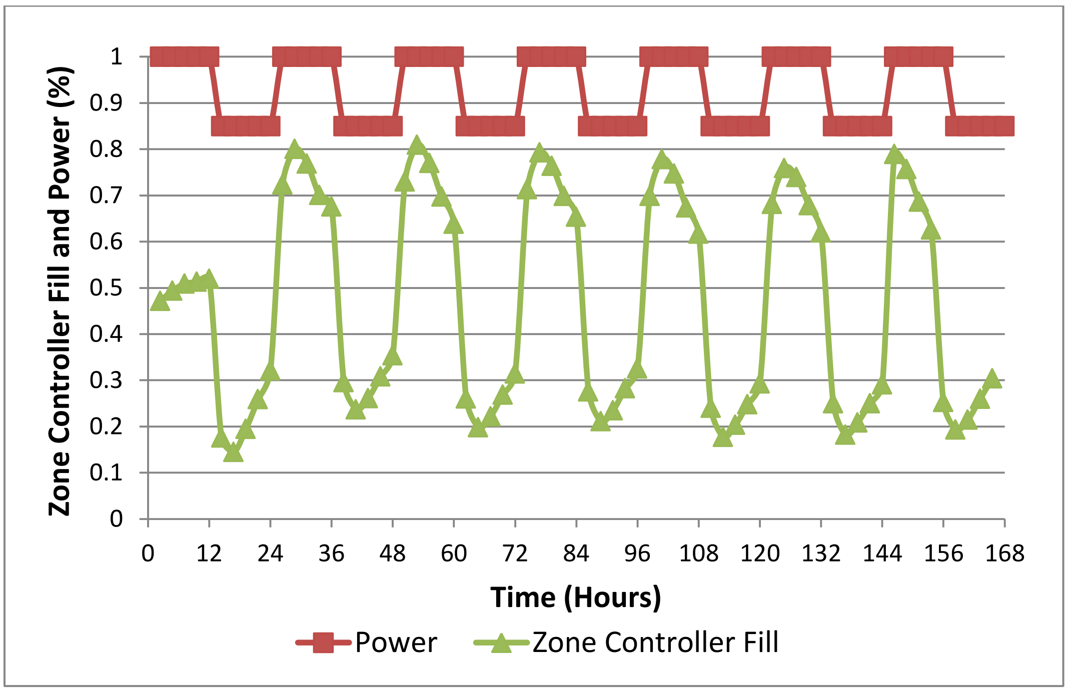

Figure 5.13 - 100-85% FP load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channels F 12 and O 7 are evident in the large increases in individual channel powers around hours 4 and 80 respectively. Maximum channel power peaked at 7028.61 kW and the maximum bundle power peaked at 860.91 kW, both below their respective limits.

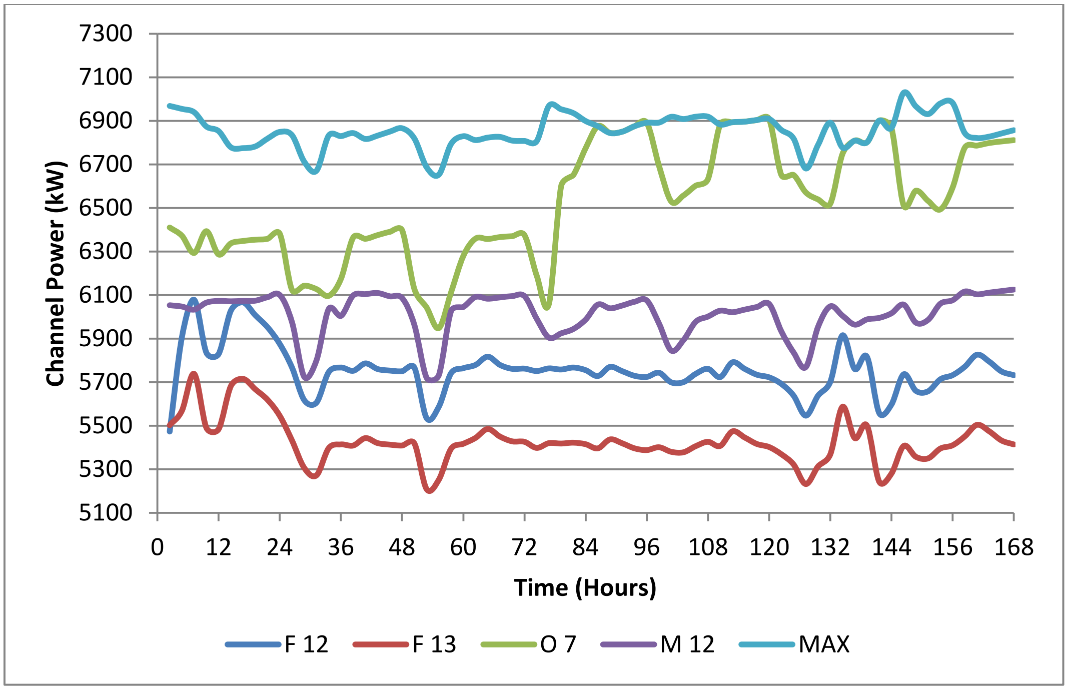

Figure 5.14 - 100-85% FP load following channel powers (TRUMOX)

NU

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with a lower setpoint of 85% FP. During the first power decrease to 85% FP, the average zone controller fill drops to well below the 15% full safety limit. As well as the average zone controller fill being extremely low, a large variation between the individual zone controller fills also occurs with several of them becoming completely voided. Not only do the zone controllers lose the ability to maintain bulk control of the reactor, the spatial control capabilities are also lost and would normally result in a setback or reactor shutdown. The maximum and minimimum average zone controller fractional fills were 1.000 and .0652 during the duration of the week long simulation, however under normal operating circumstances the reactor would have required either the movement of the adjuster rods and MCAs to assist in reactivity control or experience a shutdown via poison out or one of the emergency shut down systems.

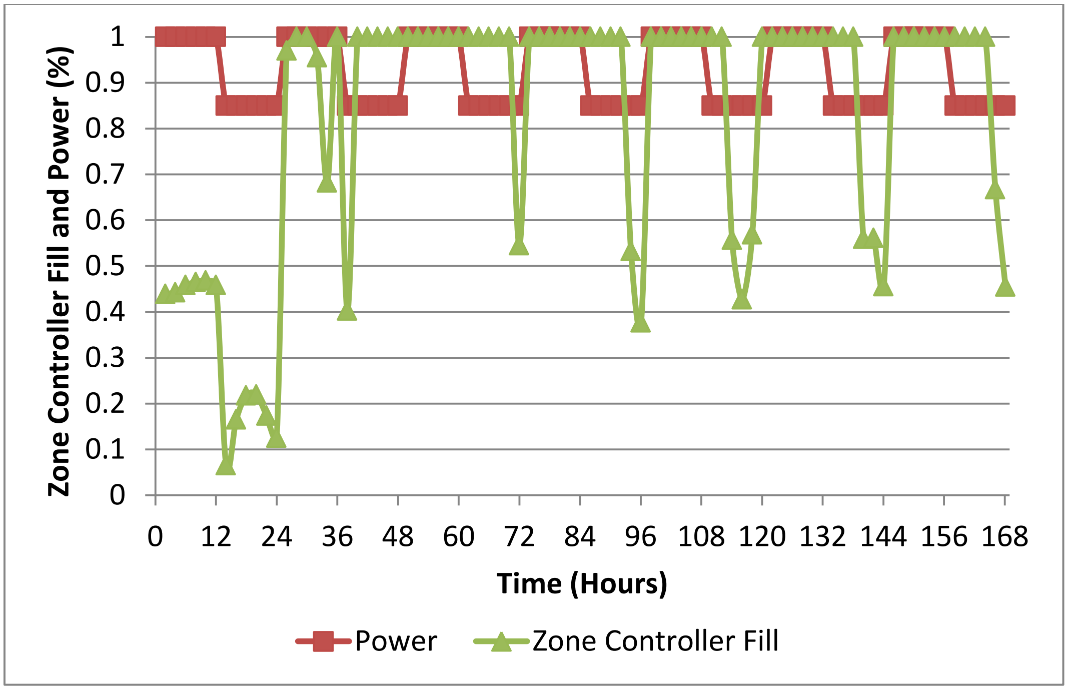

Figure 5.15 - 100-85% FP load following ZC fills (NU)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The channel powers start to deviate wildly from their initial values at around hour 12 which coincides with the first reduction in power to 85% FP. This is evident of a loss of ability to control the reactivity of the core as several channels and bundle powers greatly exceeded their maximum power limits soon after the initial power decrease.

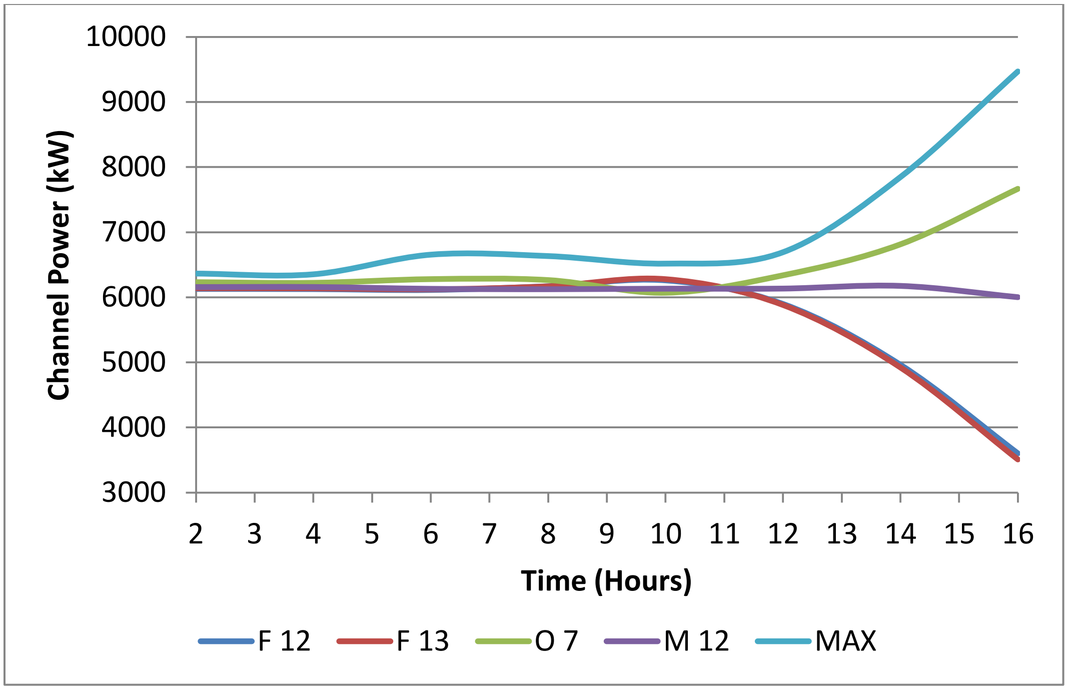

Figure 5.16 - 100-85% FP load following channel powers (NU)

NU with Reactivity Device Control

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with adjuster rod and MCA movement for a low power setpoint of 85% FP. The maximum and minimum average zone controller fractional fills were .7927 and .1837 resulting in a maximum deviation of .3548 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation with a sliglhtly less prononced dip in average zone controller fill during the first power reduction to 85% FP.

Large and short lived spikes in average zone controller fills are due to the insertion and withdrawl of adjuster rods during the simulation which is controlled by the RECORD program. The program only has the ability to fully insert or fully withdraw banks of adjuster rods or MCAs and does so without regard for maximum rates of reactivity insertion. Real time control of ajudster rods and MCAs isn't possible in RFSP so movment is limited by the time between core snapshots, therefore previous zone controller fill levels must be used as a guide to insert of withdraw adjuster rods.

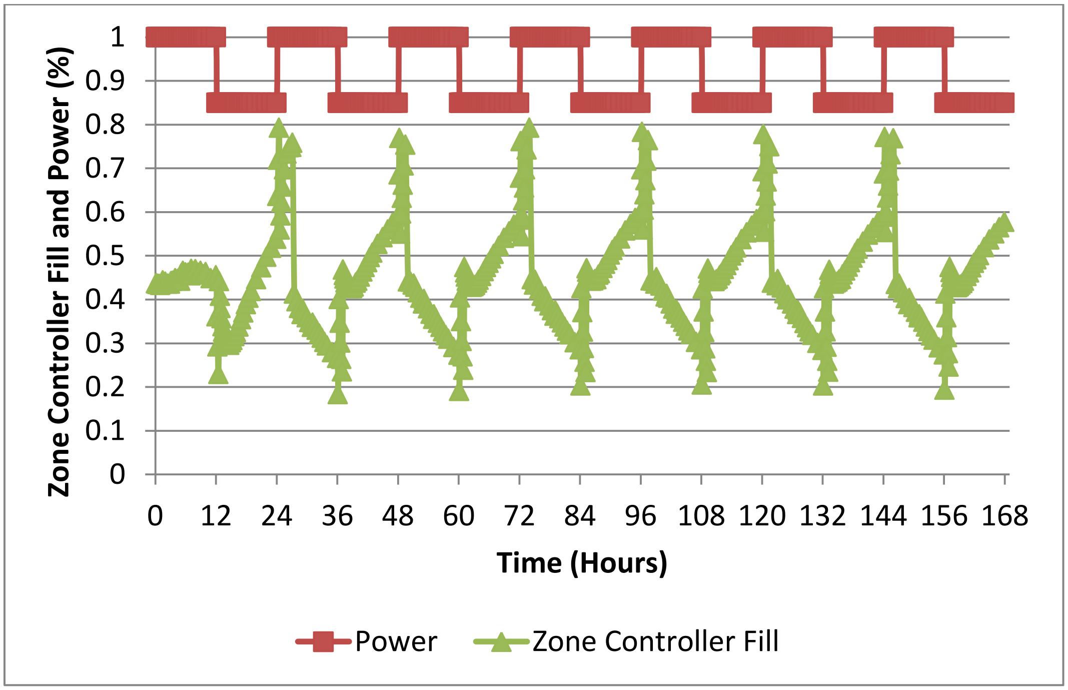

Figure 5.17 - 100-85% FP load following ZC fills (NU with adjuster rod control)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F 12 is evident in the large increases in individual channel power around hours 126 respectively. Aside from one instance which breaches the channel power limit, the maximum channel power is 6965.51 kW which is below the 7.3 MW limit; all bundle powers remained under the 935 kW limit with a peak bundle power of 895.96 kW.

Maximum channel power during the simulation peaks at 7358.87 kW during one core snapshot which is above the 7.3 MW limit, this is due to the simplified control logic used for the RECORD program. Control logic for the movement of adjuster rods in the program depends only on average zone controller fill levels and excess reactivity in the core, therefore it does not take into account local flux levels or individual zone controller fills; adjuster rod banks that are withdrawn or inserted are done so in a predetermined order. During this simulation, an adjuster rod bank was withdrawn in the immediate vicinity or a recently refueled channel (V 10) which caused the channel power to spike up by over 400 kW. Upon reinsertion of the adjuster rod bank, the channel power returned to under 7 MW and remained there for the duration of the simulation.

Modification to the reactivity device control program could be done to alleviate this problem; however it is not the primary focus of this study as well as experimental evidence from operations shows that the CANDU design is capable of deep load following operation for NU fuel (Vinez, 1986).

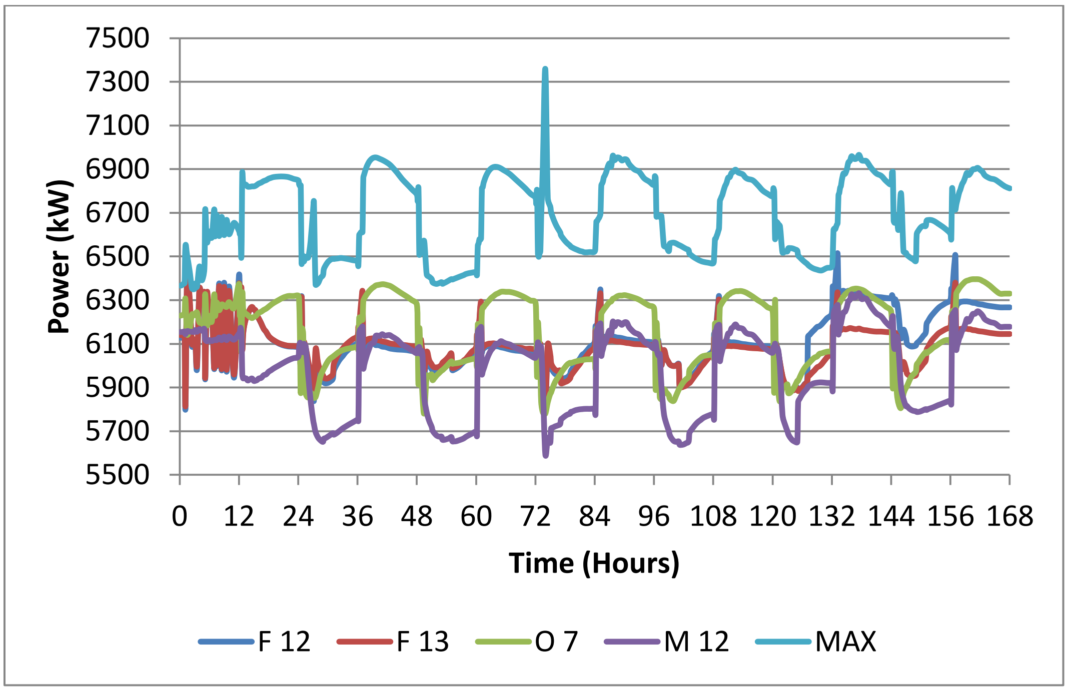

Figure 5.18 - 100-85% FP load following channel powers (NU with adjuster rod control)

5.2.5 100-85% FP Stepped

As with the previous simulation, both the TRUMOX and NU fuelled cores appear to be capable of load following to 85% FP, although the NU core requires adjuster rod movement since the xenon transient is too big to be handled by the zone controllers alone. The stepped power reduction greatly helps to reduce the initial spike in xenon reactivity and as a result, the TRUMOX core stays within the 15-85% average zone controller fill safety zone for the duration of the load following simulation. Results are very similar for the NU core, requiring reactivity device movement to remain stable, however the stepped power reduction doesn't seem to offer the same benefits for the NU core as it did for TRUMOX. This is most likely due to the fact that the limiting factor for NU performance isn't the large initial reactivity spike, but the time intervals between reactivity device movements. Maximum channel powers remain virtually the same as with the previous simulation without the stepped power reduction.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint stepped down to 85% FP. The maximum and minimimum average zone controller fractional fills were .7905 and .1848 resulting in a maximum deviation of .3398 in either direction from the starting fill value of .4507. Maximum and minimum values stay fairly consistent throughout the week long simulation once the lower setpoint of 85% FP had been reached. Compared to the non-stepped power reduction, the minimum average zone controller fill increased by 4% bringing it back to within the safety limits.

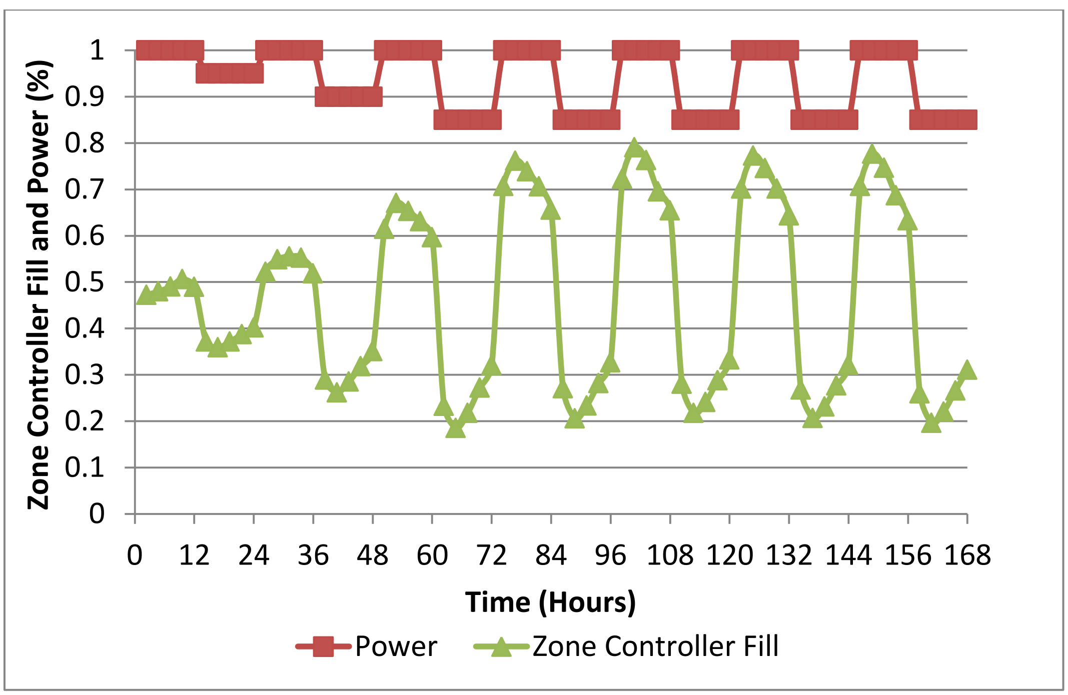

Figure 5.19 - 100-85% FP stepped load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channels O 7 and F12 are evident in the large increases in individual channel powers around hours 96 and 144 respectively. Maximum channel power peaked at 7221.55 kW which is just below the 7.3 MW limit while the maximum bundle power peaked at 885.21 kW.

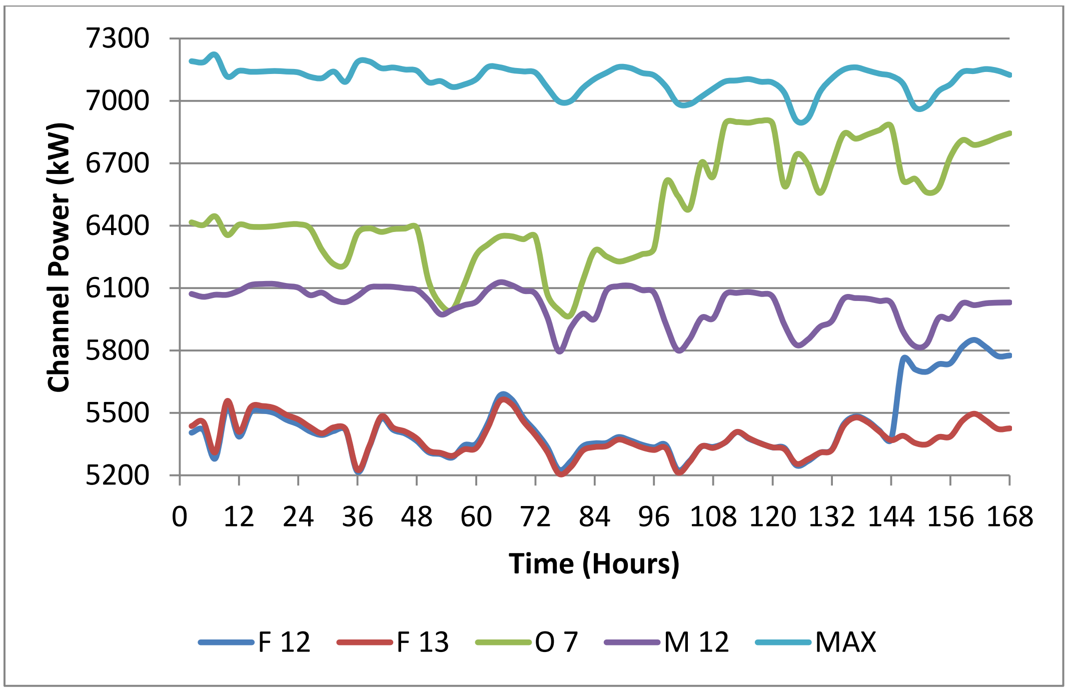

Figure 5.20 - 100-85% FP stepped load following channel powers (TRUMOX)

NU

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with a lower setpoint stepped down to 85% FP. The reactor reponds in a safe and controllable way until the power reaches the target 85% FP. During the first decrease to 85% FP, the average zone controller dips to .1104 which is below the safety limit of 15%, this is similar to the non-stepped power reduction however it does recover during the 12 hours at low power and spatial control is maintained during that time. While the stepped decrease in power allowed the reactor to reach 85% FP without encountering a poison out situation, the subsequent increase to 100% FP results in an emergency shutdown situation. There is insuffient negative reactivity in the zone controllers to handle the 85-100% full power transition and the excess reactivity spikes to well over 2 mk despite all the zone controllers being completely flooded. The maximum and minimimum average zone controller fractional fills were 1.000 and .1104 during the duration of the week long simulation, however under normal operating circumstances the reactor would have required either the movement of the adjuster rods and MCAs to assist in reactivity control or experience a shutdown via one of the emergency shut down systems.

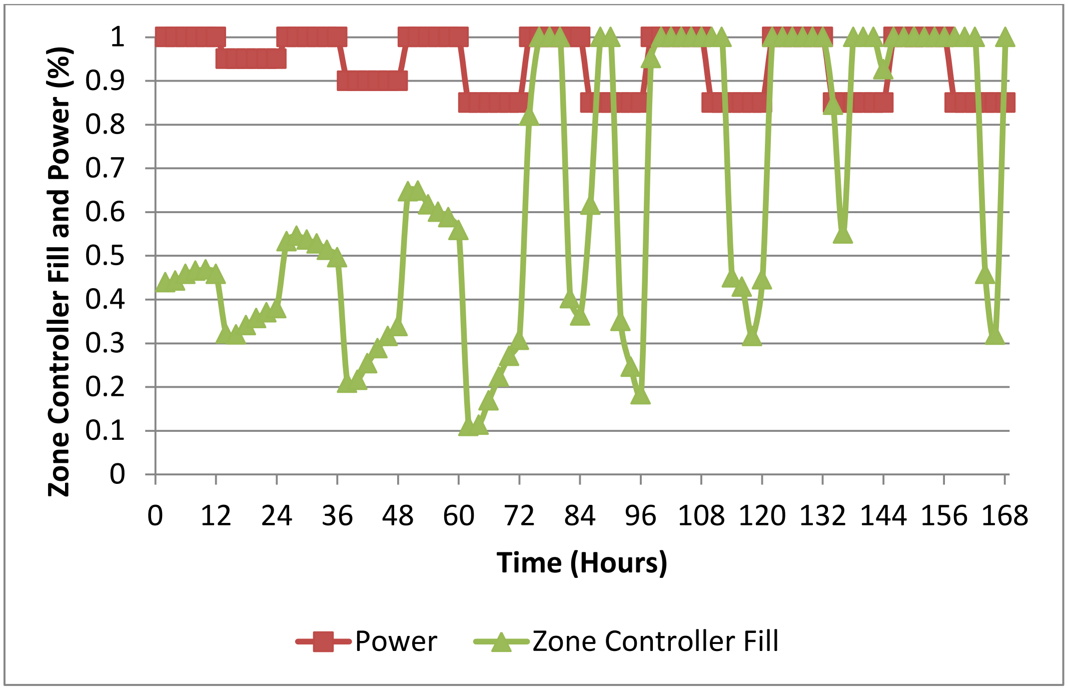

Figure 5.21 - 100-85% FP stepped load following ZC fills (NU)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The channel powers stay fairly consistent until around hour 74 where they begin to deviate wildly, this coincides with the first 85 to 100% FP increase. The maximum channel power, as well as several other channels, greatly exceeded the channel power limit of 7.3 MW after this time which is further proof of a very unstable reactor core. Along with several channel powers, the maximum bundle power also beached its 935 kW limit.

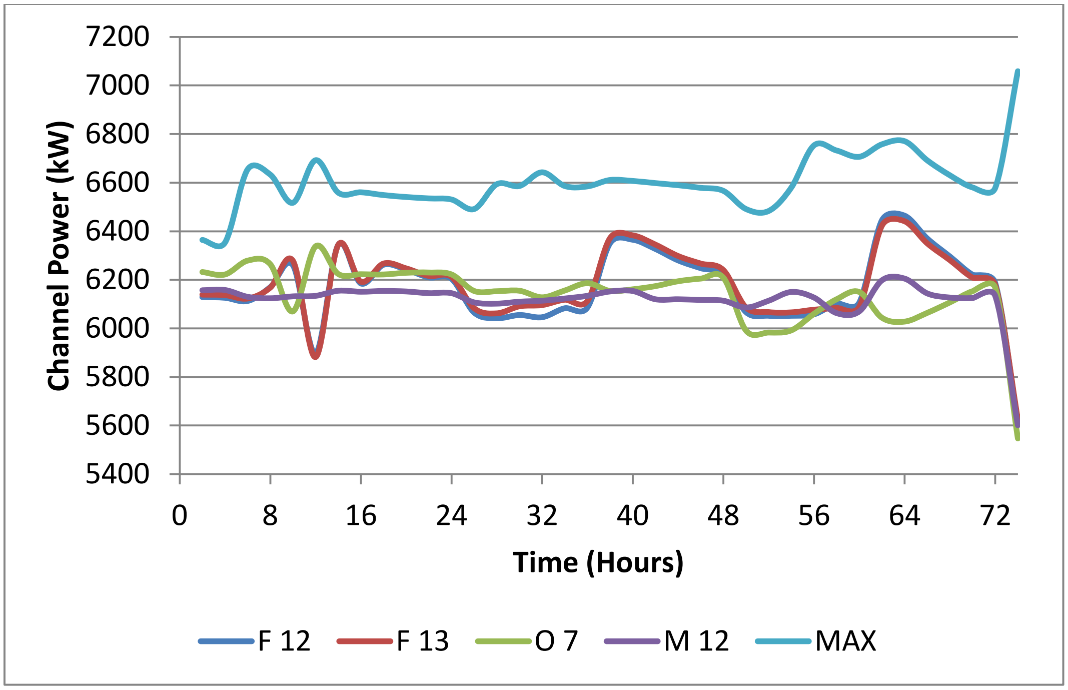

Figure 5.22 - 100-85% FP stepped load following channel powers (NU)

NU with Reactivity Device Control

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with adjuster rod and MCA movement for a low power setpoint stepped down to 85% FP. The maximum and minimimum average zone controller fractional fills were .8324 and .1734 resulting in a maximum deviation of .3945 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation once the final low power setpoint of 85% FP is reached. Large and short lived spikes in average zone controller fills are due to the full insertion and full withdrawl of adjuster rods during the simulation which is controlled by the RECORD program.

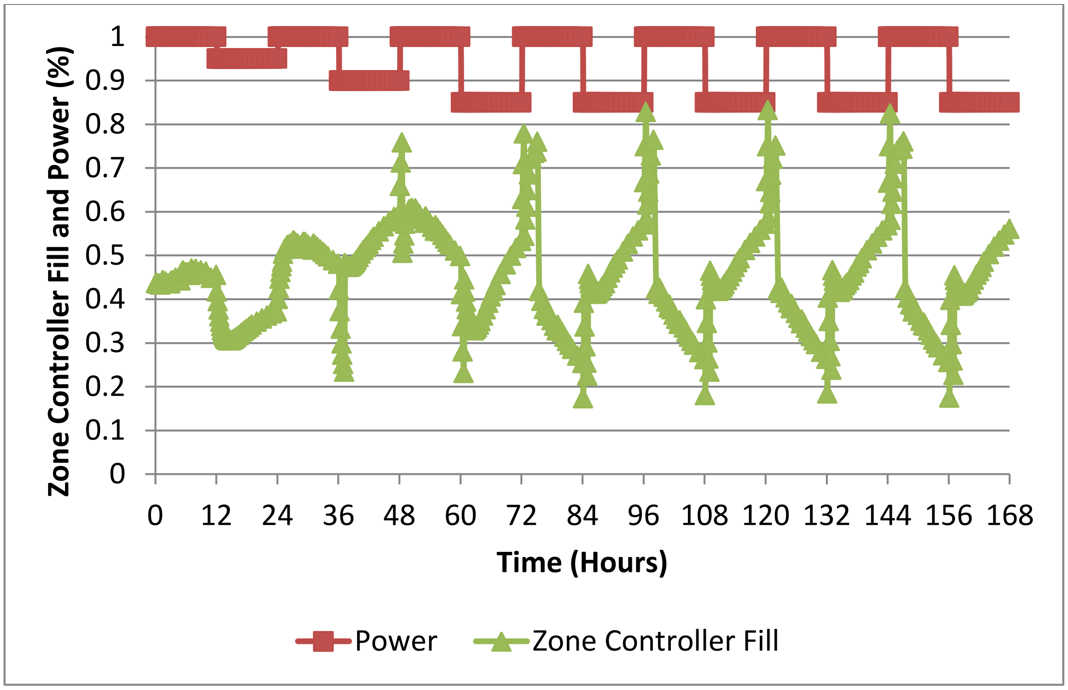

Figure 5.23 - 100-85% FP stepped load following ZC fills (NU with adjuster rod control)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F 12 is evident in the large increases in individual channel power around hour 126. As with the non-stepped simulation, maximum channel power peaks above the 7.3 MW limit for a brief moment due to locally withdrawn adjuster rods during a refuelling operation. Just as before, besides the one instance which breaches the limit, maximum channel power peaks below the 7.3 MW limit (7036.94 kW). All bundle powers remained under the 935 kW limit with a peak bundle power of 931.56 kW during one of the channel overpower instances.

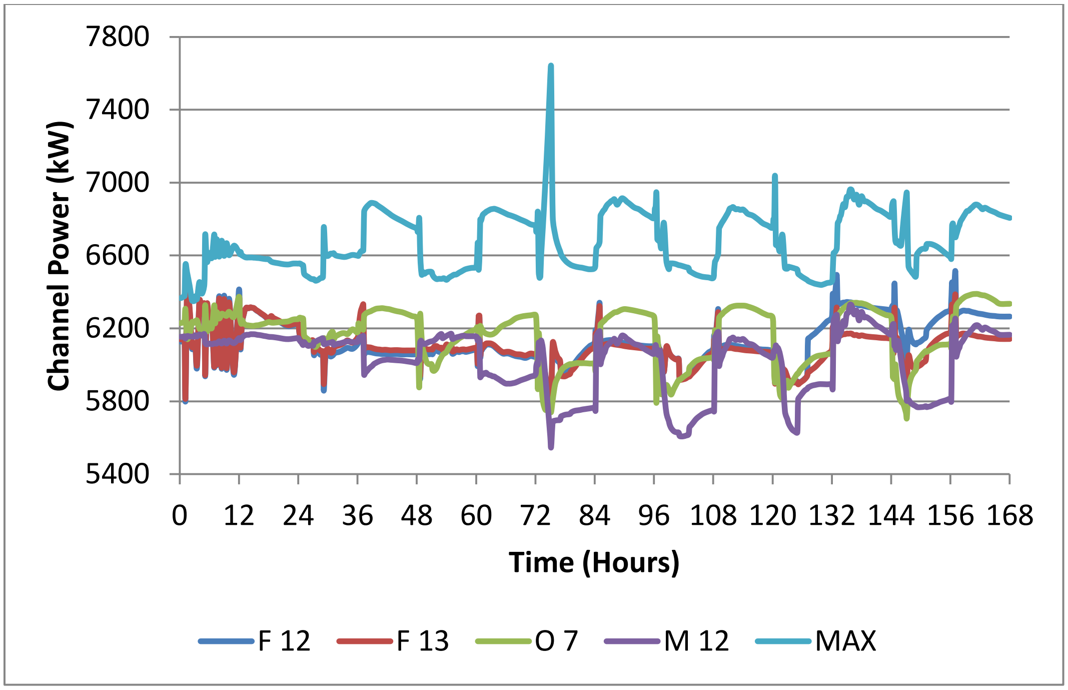

Figure 5.24 - 100-85% FP stepped load following channel powers (NU with adjuster rod control)

5.2.6 100-80% FP

For low power setpoints of 80% FP or below, it appears that the TRUMOX fuelled core is incapable of load following as the zone controllers are unable to compensate for the reactivity changes due to the xenon transients. The NU fuelled core with adjuster rod movement is capable however since it has the ability to insert or remove reactivity from the core via adjuster rods or MCAs. The TRUMOX core also has the capability to add reactivity via rod insertion, however since the core operates with all adjuster rods and MCAs withdrawn from the core, it becomes unstable during the first power change to 80% FP since it has no means of reducing reactivity in core beyond voiding the zone controllers. Since previous simulations showed that the zone controllers alone were insufficient for load following to 85% FP for a NU fuelled core, further simulations with reduced low power setpoints are also assumed to be unstable and therefore are not simulated.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint of 80% FP. During the first decrease to 80% FP, the average zone controller fill drops well below the 15% safety margin to .0311, however it appears that spatial and bulk control are maintaned and the average fill eventually climbs back above 15% during the 12 hours at 80% FP. The subsequent increase back to 100% FP results in the zone controllers being overwhelmed and the excess reactivity in the core quickly increases. The maximum and minimimum average zone controller fractional fills over the week long simulation were 1.000 and .0311, however under normal operating circumstances the reactor would have most likely experienced an emergency shutdown or setback due to the extremely low average zone controller levels.

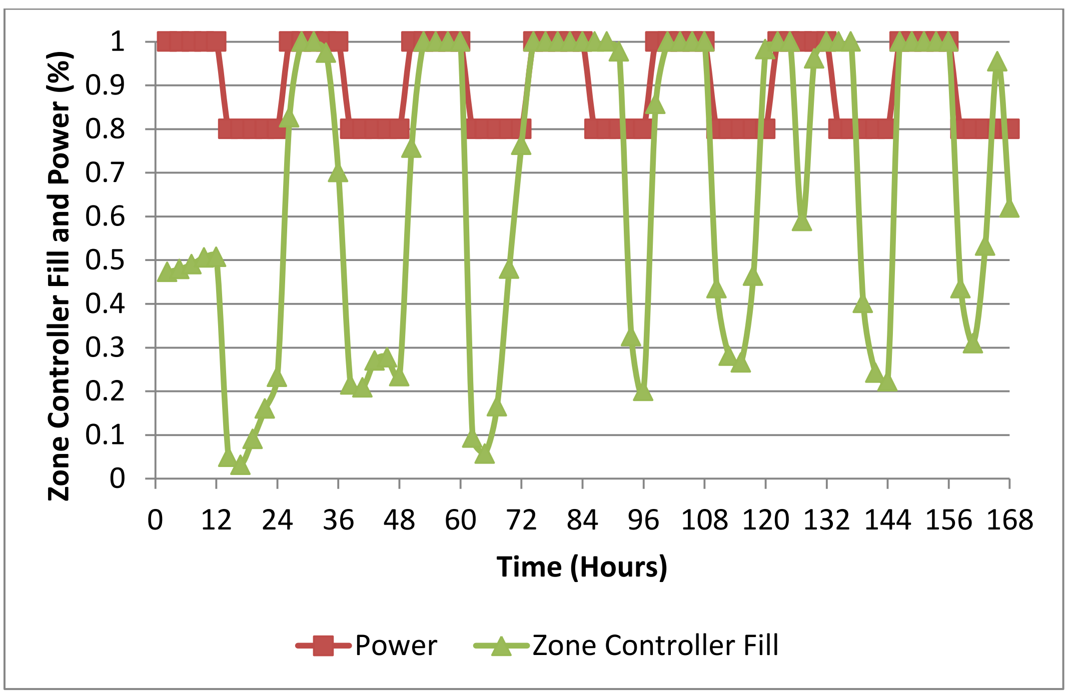

Figure 5.25 - 100-80% FP load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The channel powers deviate wildly from their initial values, greatly surpassing the channel power limit of 7.3 MW during the first reduction of power to 80% FP as well as the subsequent return to 100% FP; this is evident of a very unstable core. As is to be expected, bundle powers also greatly exceed their power limits.

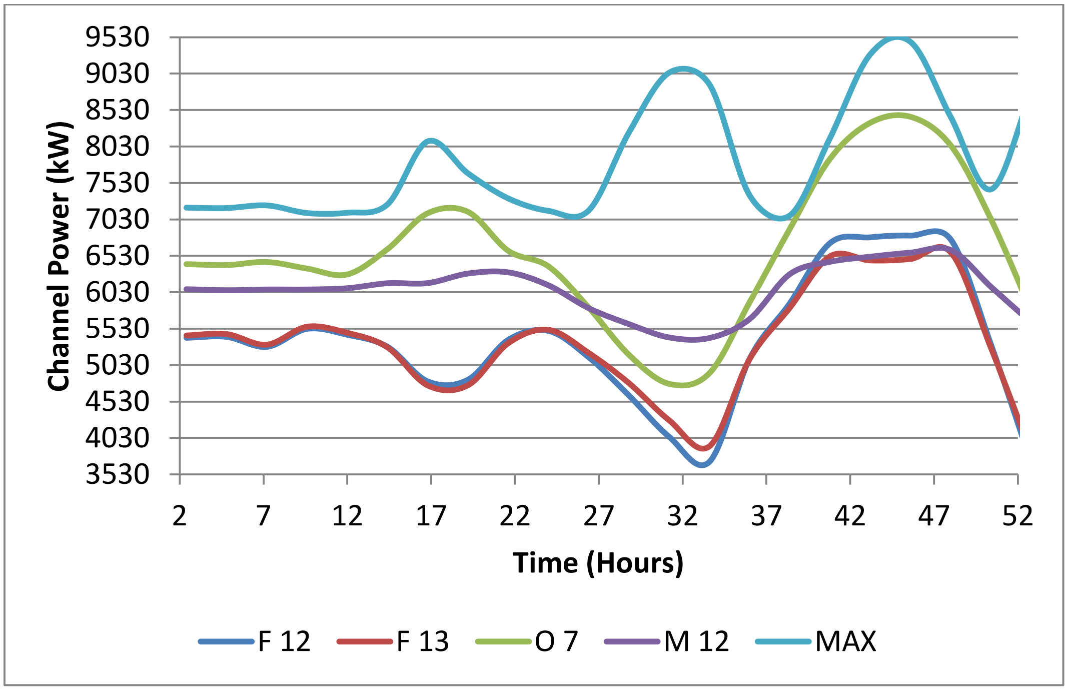

Figure 5.26 - 100-80% FP load following channel powers (TRUMOX)

NU with Reactivity Device Control

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with adjuster rod and MCA movement for a low power setpoint of 85% FP. The maximum and minimimum average zone controller fractional fills were .8537 and .1611 resulting in a maximum deviation of .4158 in either direction from the starting fill value of .4379. The average zone controller fill breaches the 85% fill iposed safety limit for one instance, otherwise maximum and minimum values stay fairly consistent throughout the week long simulation and stay within the 15-85% fill limit Large and short lived spikes in average zone controller fills are due to the full insertion and full withdrawl of adjuster rods during the simulation which is controlled by the RECORD program. Similar to previous simulations for NU with reactivity device movement enabled, adjuster rod response is limited by the snapshot frequency and therefore can lead to breaches of safety magins.

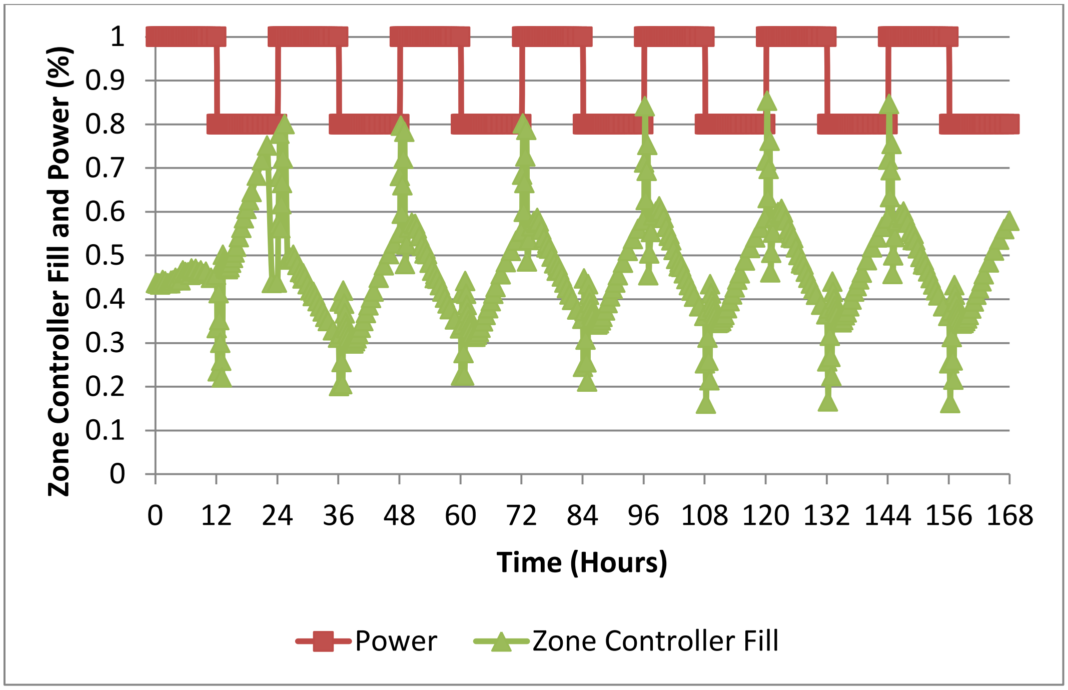

Figure 5.27 - 100-80% FP load following ZC fills (NU with adjuster rod control)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F 12 is evident in the large increases in individual channel power around hour 126. Maximum channel power peaks at 7523.02 kW which is above the 7.3 MW limit, this is due to the simplified control logic used for the RECORD program which resulted in withdrawn adjuster rods in the vicinity of recently refueled channels. Upon re-insertion of the withdrawn adjuster rod bank, maximum channel power reaches a maximum of 7011.89 kW which is below the 7.3 MW limit. During the instances of channel overpower, some bundle powers in those channels also exceeded their 935 kW limit, otherwise they remained under the limit.

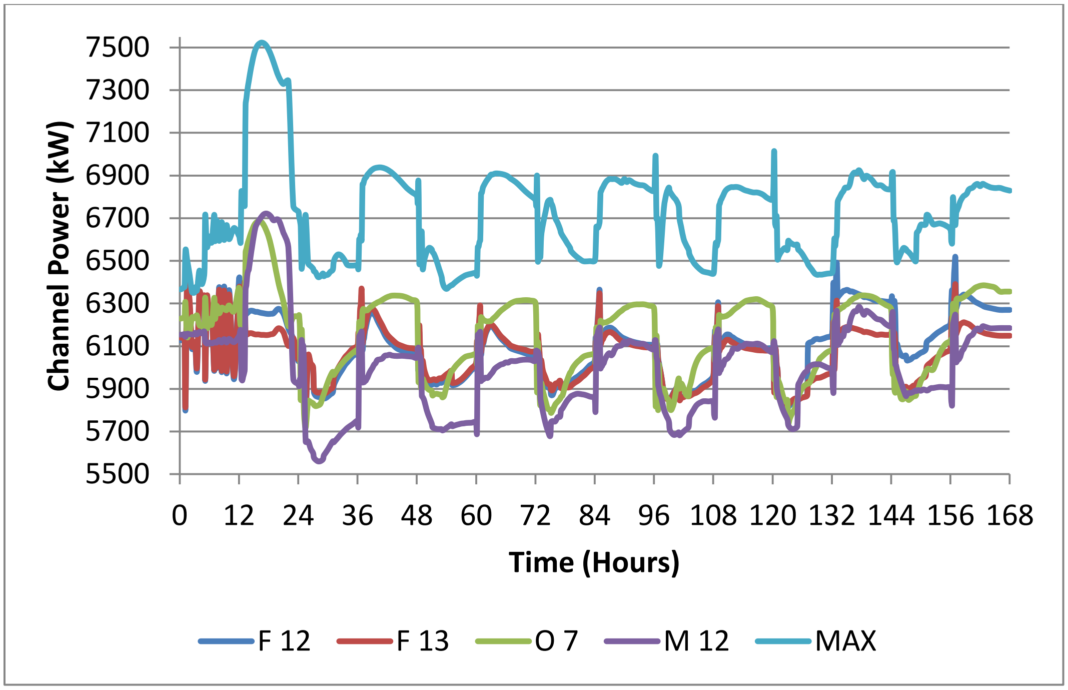

Figure 5.28 - 100-80% FP load following channel powers (NU with adjuster rod control)

5.2.7 100-80% FP Stepped

As with the previous non-stepped simulation, the TRUMOX core appears to be incapable of load following to 80% FP as the zone controllers are unable to compensate for the reactivity changes due to the xenon transients. Also as before, the NU fuelled core with adjuster rod movement is capable although the stepped reduction in power appears to provide no improvement over the non-stepped simulation. As with the load following simulations to 85% FP, the limiting factor for NU performance with reactivity device movement capability appears to be response time rather than initial reactivity spikes.

TRUMOX

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for TRUMOX with a lower setpoint of 80% FP. The core is able to operate in a safe and controllable manner until the first decrease to 80% FP when the average zone controller fill drops below the 15% safety margin to .0816. It appears that spatial and bulk control are maintaned during this time and the average fill eventually climbs back above 15% during the 12 hours at 80% FP. The subsequent increase back to 100% FP results in the zone controllers being overwhelmed and the excess reactivity in the core quickly increases. The maximum and minimimum average zone controller fractional fills over the week long simulation were 1.000 and .0311, however under normal operating circumstances the reactor would have most likely experienced an emergency shutdown or setback during the first decrease to 80% FP due to the extremely low average zone controller levels.

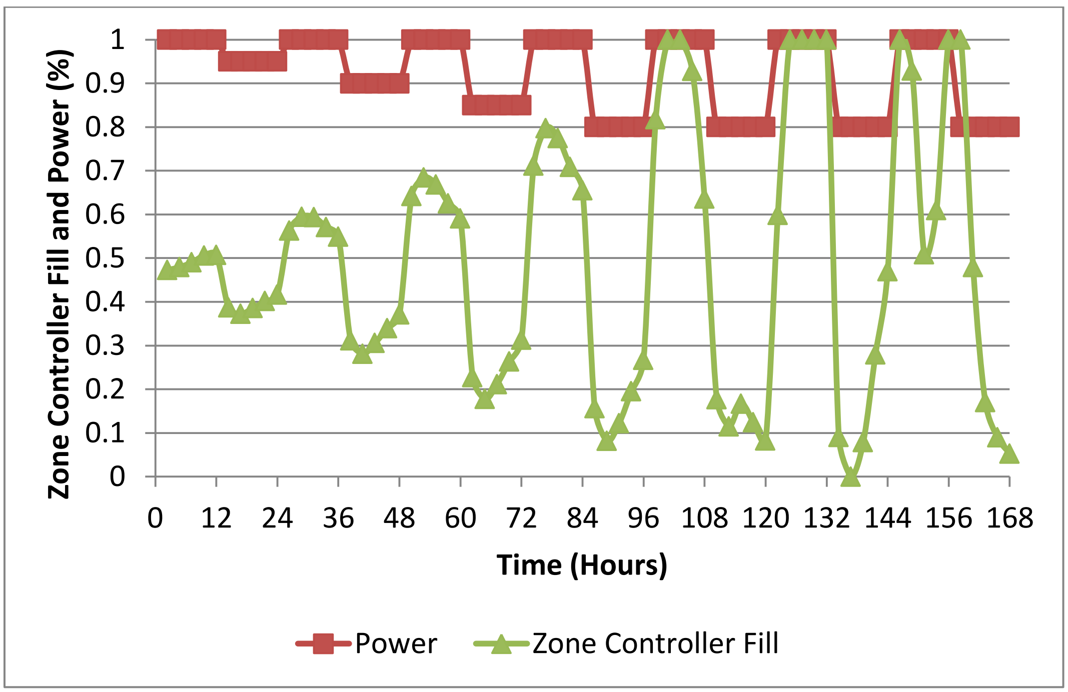

Figure 5.29 - 100-80% FP stepped load following ZC fills (TRUMOX)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The channel powers stay fairly consistent until around hour 92 where they begin to deviate wildly, this coincides with the first low power setpoint of 80% FP. The maximum channel power, as well as the power of several other channels, greatly exceeded the channel power limit of 7.3 MW during this time which is evident of a very unstable reactor core. As is to be expected, bundle powers also greatly exceed their power limits.

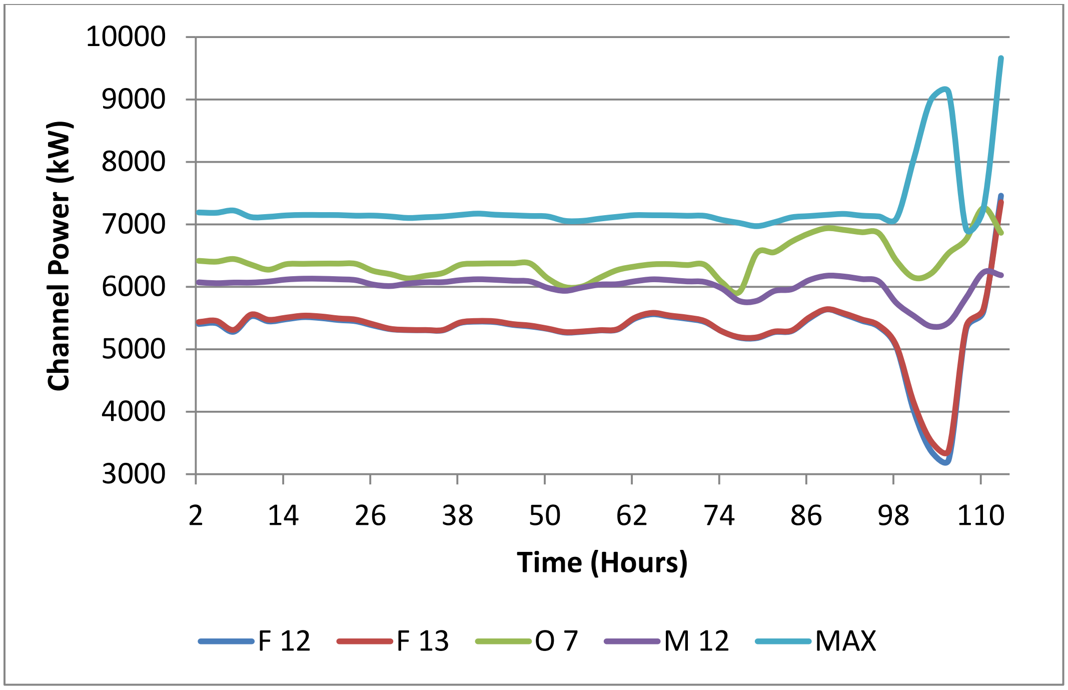

Figure 5.30 - 100-80% FP stepped load following channel powers (TRUMOX)

NU with Reactivity Device Control

Zone controller fills are plotted in the diagram below along with power level for week long load following operations for NU with adjuster rod and MCA movement for a low power setpoint stepped down to 80% FP. The maximum and minimimum average zone controller fractional fills were .8236 and .1470 resulting in a maximum deviation of .3857 in either direction from the starting fill value of .4379. Maximum and minimum values stay fairly consistent throughout the week long simulation once the final low power setpoint of 80% FP is reached. Large and short lived spikes in average zone controller fills are due to the full insertion and full withdrawl of adjuster rods during the simulation which is controlled by the RECORD program.

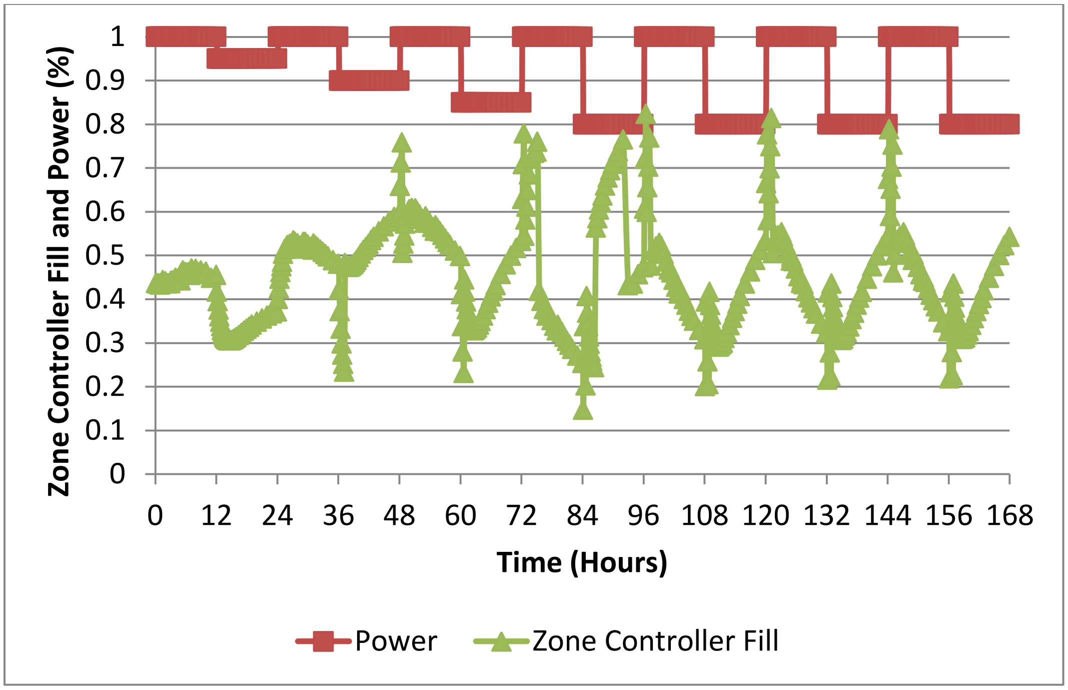

Figure 5.31 - 100-80% FP stepped load following ZC fills (NU with adjuster rod control)

Channel power for the four selected channels plus the maximum channel power are plotted in the diagram below. The refuelling of channel F 12 is evident in the large increases in individual channel power around hour 126. As before, maximum channel power peaks above the 7.3 MW limit (7635.84 kW) due to the simplified control logic used for the RECORD program and will be explained later in greater detail. Aside from the channel power breaches due to locally withdrawn adjuster rods, two instance which breaches the limit, maximum channel power peaks at 6890.25 kW which is below the 7.3 MW limit. During the instances of channel overpower, some bundle powers in those channels also exceeded their 935 kW limit, otherwise they remained under the limit.

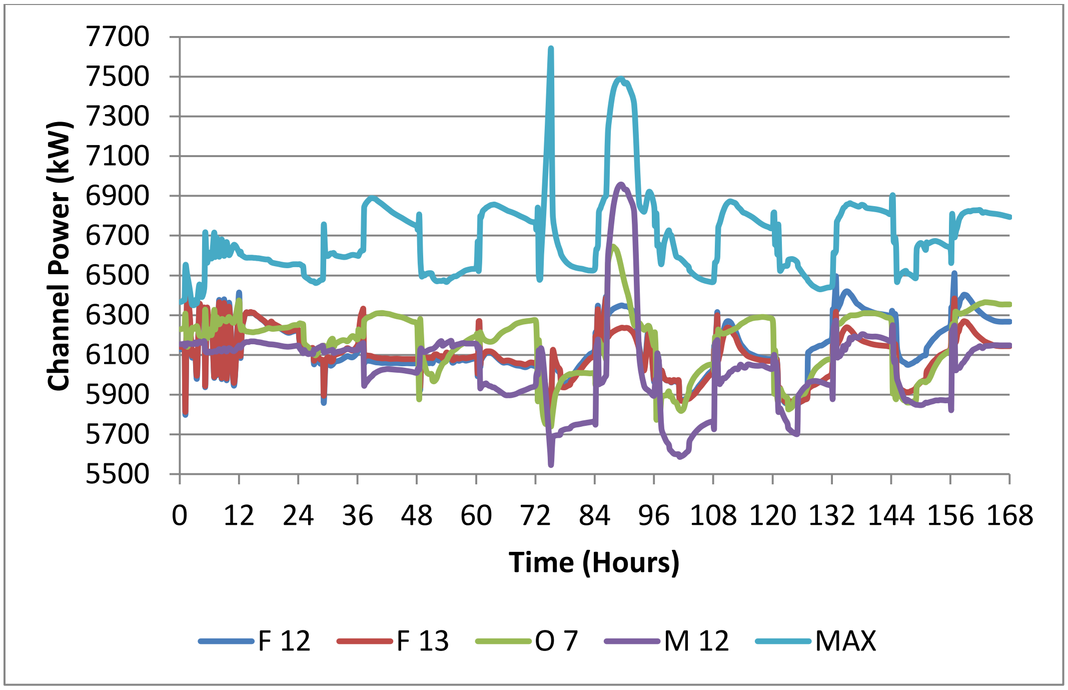

Figure 5.32 - 100-80% FP stepped load following channel powers (NU with adjuster rod control)

5.3 Setback and Turbine Trip

Simulations involving typical reactor setback and turbine trips were included to obtain a greater understanding of how the reactor fuelled with TRUMOX performs under large, unplanned quick reductions in reactor power. As for the load following routine, simulations were performed for TRUMOX as well as NU, and results are divided by scenario then by fuel type.

Setback simulations were performed down to 60 and 40% FP with reductions in reactor power set at 0.1, 0.2 and 0.8% FP per second. These values were chosen to represent a large number of different setback conditions, although all possible conditions are not represented by these scenarios (Bereznai, 2004a). Simulations for both TRUMOX and NU have full reactivity device movement capability for each simulation via the RECORD program. Unlike some of the load following simulations for which adjuster rod movement is considered unrealistic, all setback routines are expected to use reactivity device movement.

Turbine trip simulations were also performed down to 60 and 40% FP but without set rates of power reduction. Upon execution of the turbine trip, all MCAs are instantly inserted into the core to reduce reactor power as quickly as possible; this is reflected in the turbine trip simulations. As mentioned previously, due to the fact that RFSP's method of simulation instantly sets the flux level in the reactor to reflect the demanded power, insertion of the MCAs isn't necessary to reduce reactor power in the simulations. The initial dip in zone controller fill is due to the insertion of the MCAs and their subsequent withdrawal at rates reflective of realistic operating conditions (Bereznai, 2004b). As the RECORD program was designed to deal with controlling reactivity for load following operations, MCA movements for this type of simulation were controlled manually.

5.3.1 100-60% FP Setback

Power setbacks to 60% FP were performed for both the TRUMOX and NU fuelled cores. Three different rates of power reduction were simulated; 0.1, 0.2 and 0.8% FP per second, reaching the 60% FP setpoint in 6m40s, 3m20s and 50s respectively. As reducing power to 60% FP over a short period of time creates a large xenon transient, it is necessary to have the ability to remove core reactivity beyond the range of the zone controllers to prevent a poison out. As was expected the TRUMOX core, not having adjuster rods present in the core during normal operation, was unable to remove enough negative reactivity from the core and thus it resulted in a poison out. The NU core, running with adjuster rods inserted, was able to remove enough negative reactivity from the core and thus is capable of running indefinitely at 60% FP provided refuelling operation continues.

TRUMOX

The TRUMOX core was unable to remove enough negative reactivity from the core to account for the xenon transient, thus resulting in an eventual poison out. Despite the three different rates of power reduction, the average zone controller fills all reached zero at about the same time resulting in onset of poison out in the range of 45.5 ± 1.1 minutes.

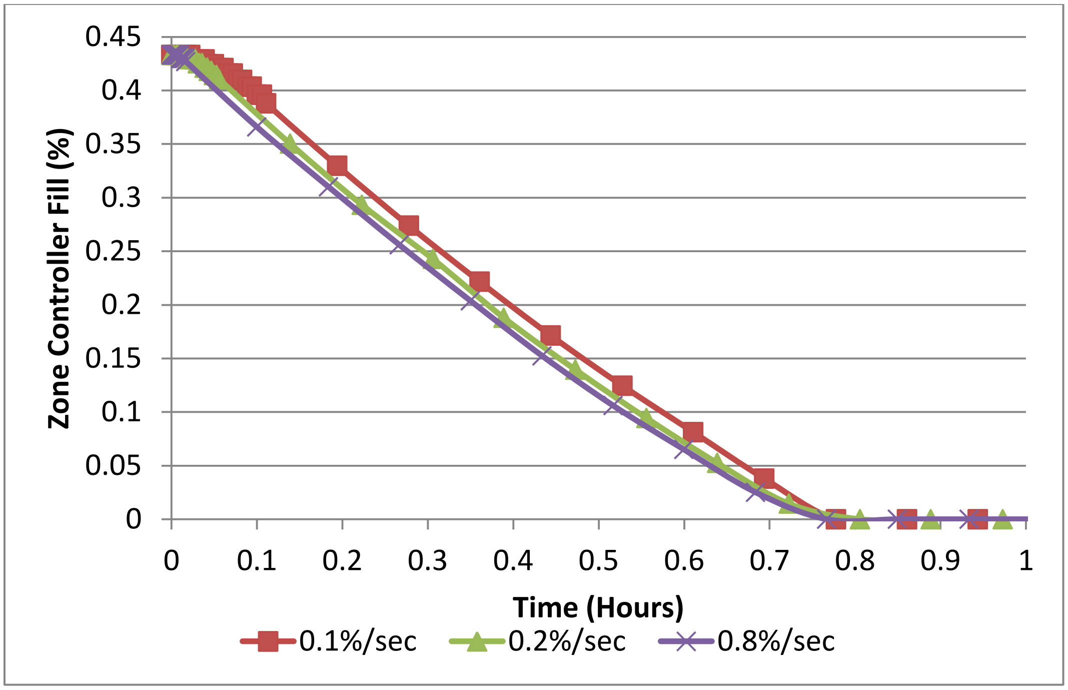

Figure 5.33 - 100-60% FP setback average ZC fills (TRUMOX)

Power Reduction Rate	0.1% FP/s	0.2% FP/s	0.8% FP/s
Time until onset of poison out	46.6 min	45.2 min	44.4 min

Table 5.2 - Time until onset of poison out at 60% FP (TRUMOX)

NU

The NU core was able to remove enough negative reactivity from via withdrawal of adjuster rods, thus overriding the xenon transient. The three different rates of power didn't seem to affect the final result and assuming refuelling operations continued, the NU core would be able to operate at 60% FP indefinitely.

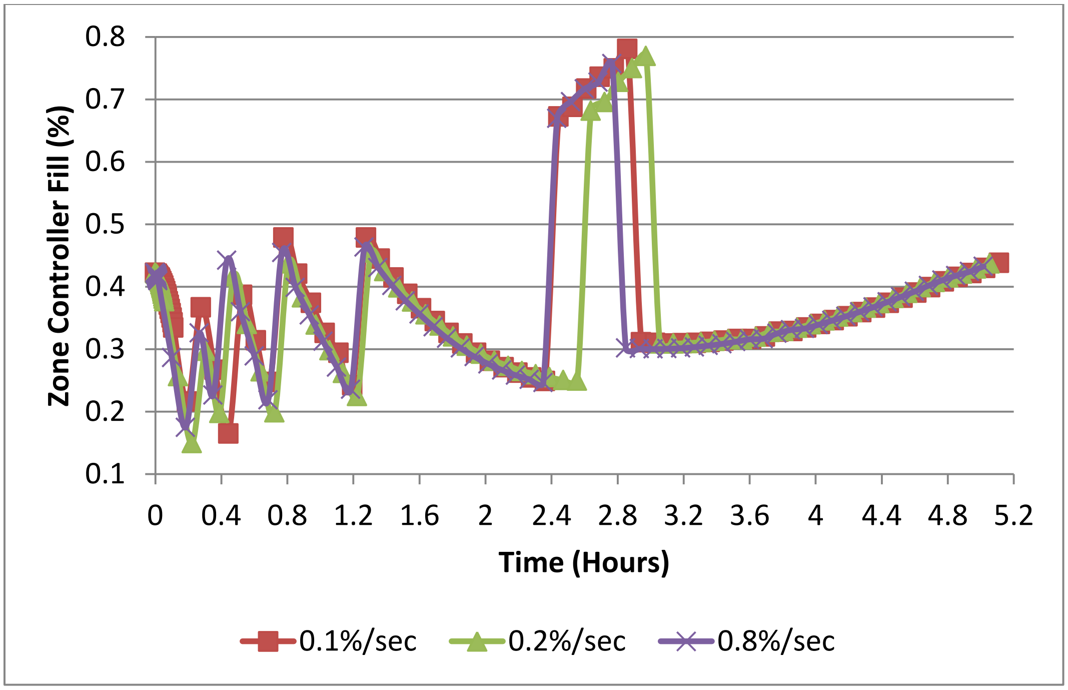

Figure 5.34 - 100-60% FP setback average ZC fills (NU)

5.3.2 100-40% FP Setback

Power setbacks to 40% FP were performed for both the TRUMOX and NU fuelled cores. Three different rates of power reduction were simulated; 0.1, 0.2 and 0.8% FP per second, reaching the 40% FP setpoint in 10m, 5m and 1m15s respectively. As reducing power to 40% FP over a short period of time creates a large xenon transient, it is necessary to have the ability to remove core reactivity beyond the range of the zone controllers to prevent a poison out. Both the TRUMOX and NU core were unable to account for the large xenon transient and both situations resulted in an eventual onset of poison out, albeit at different rates.

TRUMOX

The TRUMOX core, like the 100-60% FP setback, was unable to remove enough negative reactivity from the core to account for the xenon transient, thus resulting in eventual poison out. The three different rates of power resulted in a greater variation in time until onset of poison out compared to the previous 100-60% FP setback. The average zone controller fills all reached zero in the range of 29.5 ± 2 minutes.

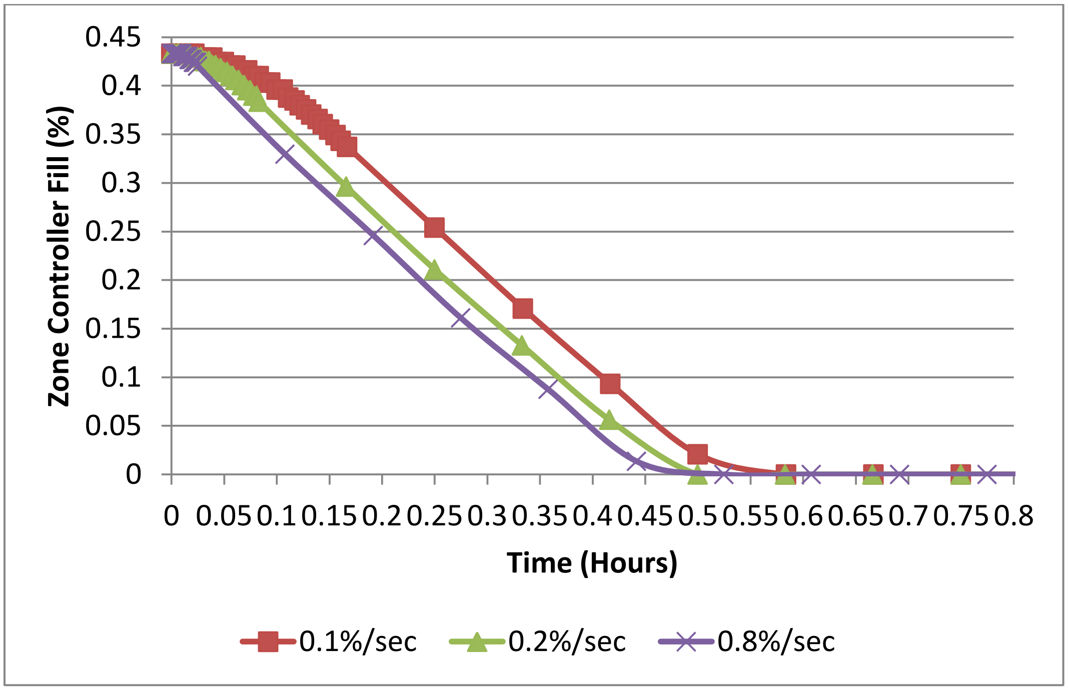

Figure 5.35 - 100-40% FP setback average ZC fills (TRUMOX)

Power Reduction Rate	0.1% FP/s	0.2% FP/s	0.8% FP/s
Time until onset of poison out	31.4 min	28.8 min	27.5 min

Table 5.3 - Time until onset of poison out at 40% FP (TRUMOX)

NU

The NU core, unlike the 100-60% FP setback, was unable to remove enough negative reactivity from the core to account for the xenon transient despite withdrawing all adjuster rod banks, thus resulting in an eventual onset of poison out. Despite the three different rates of power reduction, the average zone controller fills all reached zero at about the same time resulting in onset of poison out in the range of 105.1 ± 2.2 minutes.

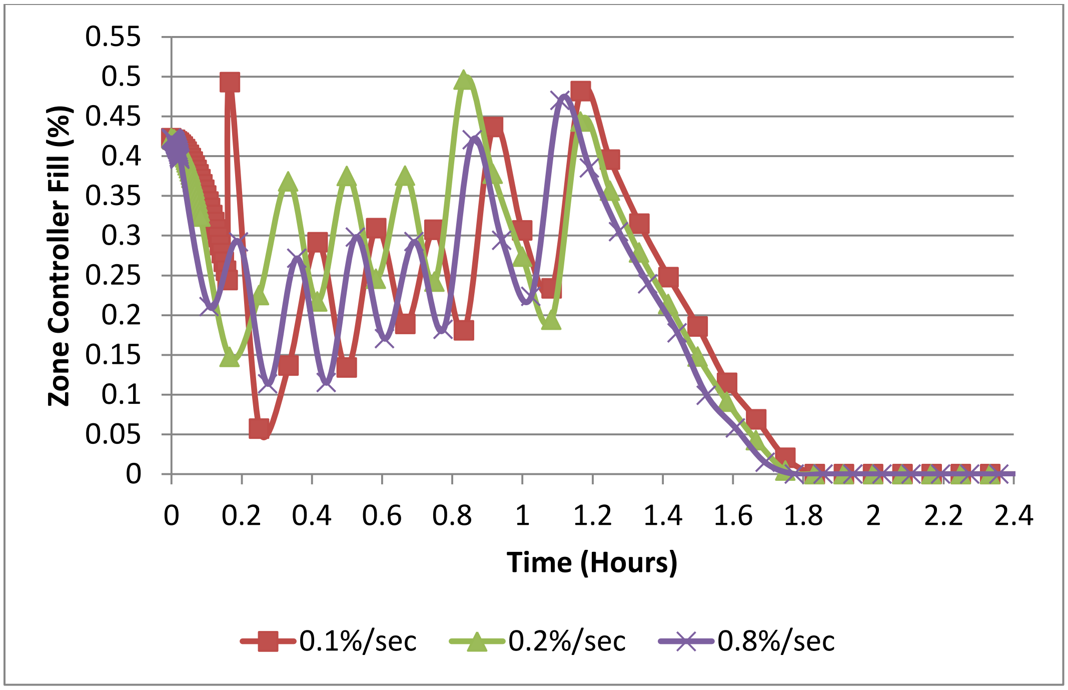

Figure 5.36 - 100-40% FP setback average ZC fills (NU)

Power Reduction Rate	0.1% FP/s	0.2% FP/s	0.8% FP/s
Time until onset of poison out	107.3 min	105.4 min	102.9 min

Table 5.4 - Time until onset of poison out at 40% FP (NU)

5.3.3 100-60% FP Turbine Trip

Turbine trips to 60% FP were performed for both the TRUMOX and NU fuelled cores. Power was instantly set to 60% FP in RFSP and MCAs were inserted into the core. Mechanical control absorbers were withdrawn from the core at a rate reflective of realistic operating conditions. Echoing the results from the 100-60% setback simulation, the TRUMOX core, not having adjuster rods present in the core during normal operation, was unable to remove enough negative reactivity from the core and thus it resulted in an eventual onset of poison out. The NU core, running with adjuster rods inserted, was able to remove enough negative reactivity from the core and thus is capable of running indefinitely at 60% FP provided refuelling operation continues.

TRUMOX

The TRUMOX core was unable to remove enough negative reactivity from the core to account for the xenon transient, thus resulting in an eventual poison out. The initial dip in average zone controller level was due to the rapid insertion of the MCAs, the zone controllers returned to normal operating levels once the MCAs were withdrawn from the core. The average zone controller level steadily declined once the MCAs were fully withdrawn from the core, leading to onset of poison out in 43.7 minutes.

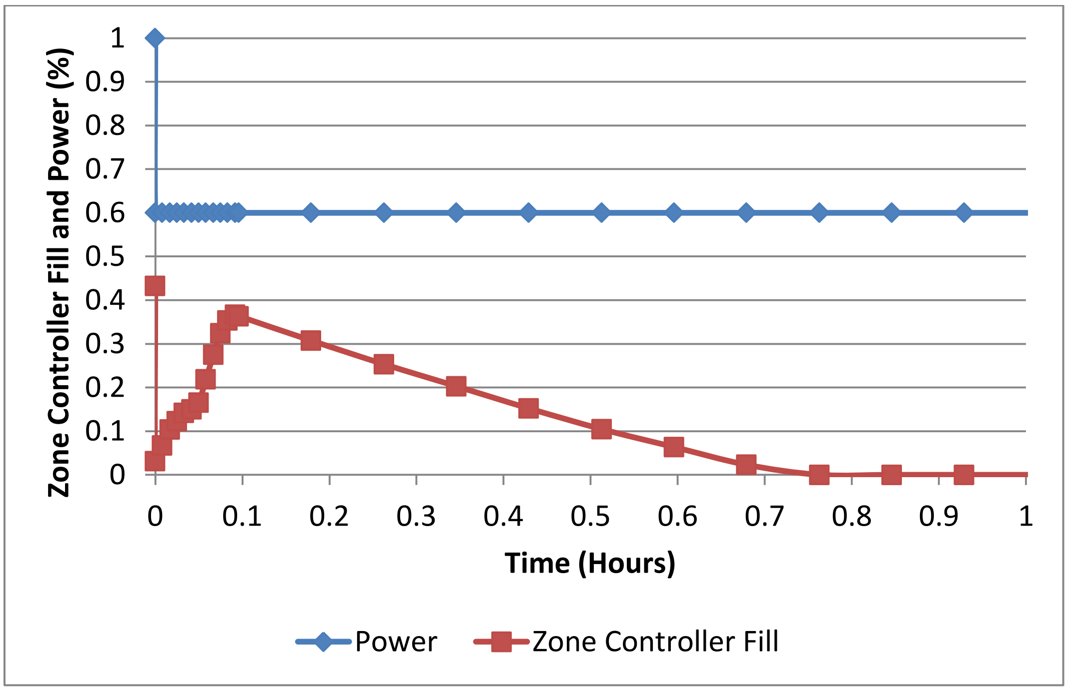

Figure 5.37 - 100-60% FP turbine trip average ZC fills (TRUMOX)

NU

The NU core was able to remove enough negative reactivity from the core via adjuster rod withdrawal to account for the xenon transient, thus avoiding a poison out. The initial dip in average zone controller level was due to the rapid insertion of the MCAs, the zone controllers returned to normal operating levels once the MCAs were withdrawn from the core. Similar to the 100-60% FP setback simulation, the NU core would be able to operate at 60% FP indefinitely assuming refuelling operations continued.

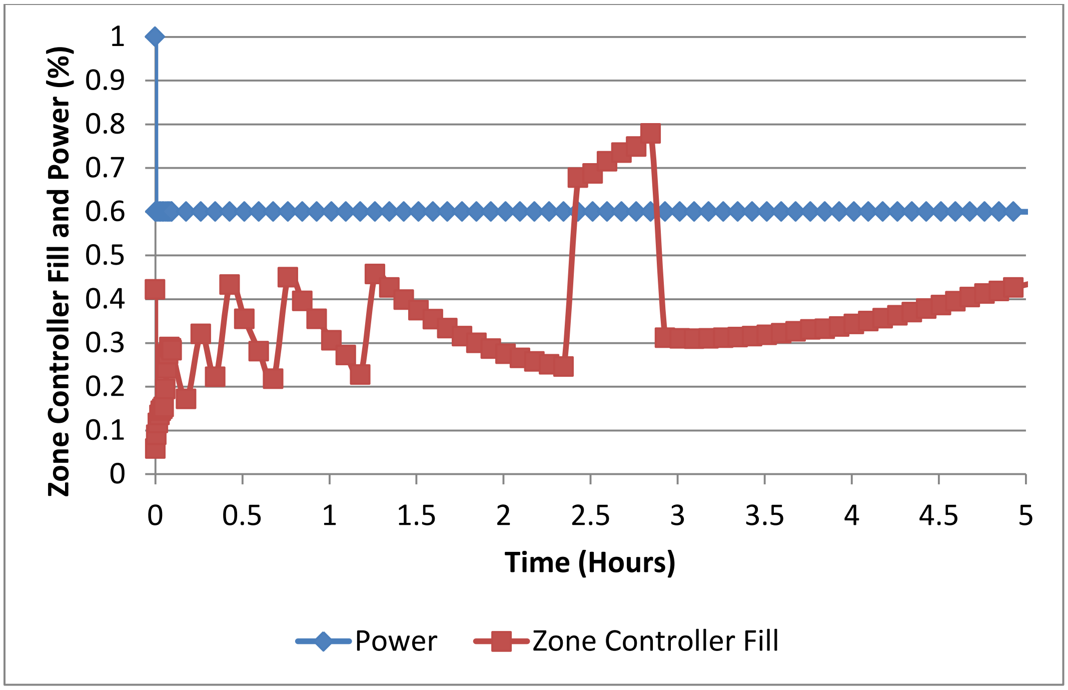

Figure 5.38 - 100-60% FP turbine trip average ZC fills (NU)

5.3.4 100-40% FP Turbine Trip

Turbine trips to 40% FP were performed for both the TRUMOX and NU fuelled cores. Power was instantly set to 40% FP in RFSP and MCAs were inserted into the core. Mechanical control absorbers were withdrawn from the core at a rate reflective of realistic operating conditions. Echoing the results from the 100-40% Setback simulation, both the TRUMOX and NU fuelled cores were unable to remove enough negative reactivity from the core and thus resulting in an eventual onset of poison out, albeit at different rates.

TRUMOX

The TRUMOX core, similar the 100-60% FP turbine trip, was unable to remove enough negative reactivity from the core to account for the xenon transient, thus resulting in an eventual poison out. The initial dip in average zone controller level was due to the rapid insertion of the MCAs, the zone controllers returned to normal operating levels once the MCAs were withdrawn from the core. The average zone controller level steadily declined once the MCAs were fully withdrawn from the core, leading to onset of poison out in 26.6 minutes.

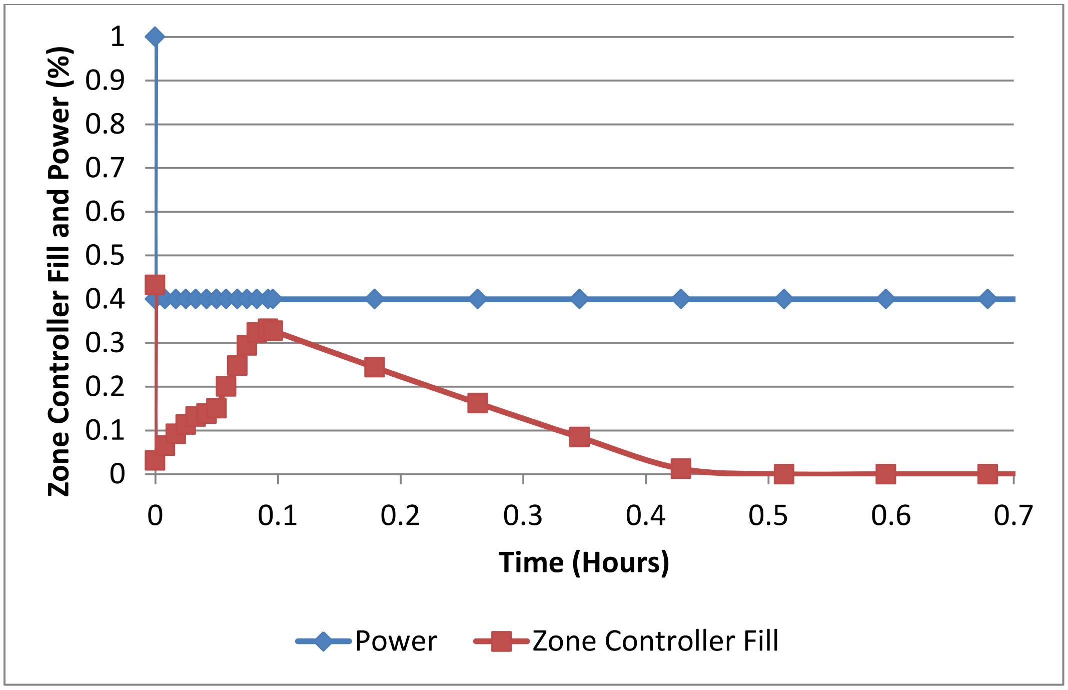

Figure 5.39 - 100-40% FP turbine trip average ZC fills (TRUMOX)

NU

The NU core, unlike the 100-60% FP turbine trip, was unable to remove enough negative reactivity from the core to account for the xenon transient despite withdrawing all adjuster rod banks, thus resulting in an eventual onset of poison out. The initial dip in average zone controller level was due to the rapid insertion of the MCAs, the zone controllers returned to normal operating levels once the MCAs were withdrawn from the core. The average zone controller level steadily declined once the MCAs and adjuster rods were fully withdrawn from the core, leading to onset of poison out in 101.9 minutes.

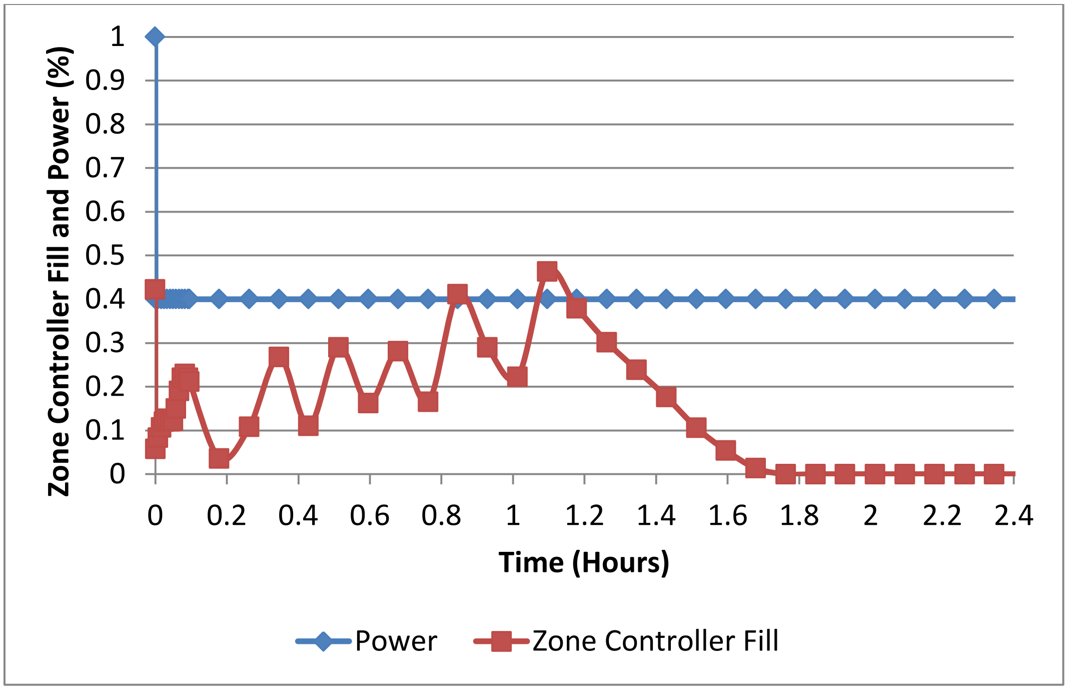

Figure 5.40 - 100-40% FP turbine trip average ZC fills (NU)

6 Discussion

This chapter opens by discussing the results that were presented in chapter 5, stating the depth of the load following operations that each fuel is capable of as well as comparing the performance of TRUMOX and NU for cycles which both fuels can perform safely. The difficulties encountered during the simulations are then explained as well as a discussion of how certain aspects and variables of the simulations may affect the results. Lastly, suggestions of further research on the subject are presented.

6.1 Interpretation of Results

6.1.1 Safe Cycle Limits

The determination of what load following operations can be performed safely and controllably are based on the criterion outlined in chapter 3. The average zone controller fills are what is primarily used to determine controllability but maximum channel powers are also tracked to ensure they stay within the established safety limits.

TRUMOX

Based on the results of the load following simulations, the TRUMOX fuelled CANDU-900 can perform load following operations down to 85% FP in a controllable manner without violating the established safety limit criterion. Load following operations to 80% FP showed that the zone controllers were unable to account for the xenon transient reactivity change resulting in an unstable reactor core.

There were two separate 100-85% FP load following simulations, one with a stepped power decrease and one without. During the stepped power decrease, zone controller fills never left the 15-85% fill range while the maximum channel power never exceeded the 7.3 MW limit. Similar results were shown for the non-stepped power decrease save for one core snapshot during the initial reduction in power to 85% FP where the average zone controller fill dipped below the 15% fill limit to 14.47% full. This one instance could most likely been avoided by having a slightly higher starting average zone controller fill such as 50% full as opposed to the 45% fill level used which was based on base-load operation of NU fuel.

NU

Based on the results of the load following simulations, the NU fuelled CANDU-900 using only zone controllers to account for xenon transients can perform load following operations down to 90% FP in a controllable manner without violating the established safety limit criterion. Load following operations to 85% FP showed that the zone controllers were unable to account for the xenon transient reactivity change resulting in an unstable reactor core.

There were two separate 100-90% FP load following simulations, one with a stepped power decrease and one without. During both simulations, zone controller fills never left the 15-85% fill range while the maximum channel power never exceeded the 7.3 MW limit. The only major difference between the stepped and non-stepped simulations was the reduced initial reactivity spike during the first power reduction for the stepped simulation.

Load following simulations with adjuster rod and MCA movement enabled showed that load following operation down to 80% were possible, however due to limitations of the RRS emulator program RECORD as well as the limitations of core snapshot frequency, there were several instances where the established safety criterion were breached. The capability of the CANDU design for load following with full RRS control is outside of the scope of this research and has been shown as possible during trials performed on CANDU reactors at Bruce (Lopez, 1988) and Embalse (Vinez, 1986).

6.1.2 Direct Comparison of TRUMOX to NU

Although TRUMOX can perform deeper load following cycles than NU in CANDU, that’s not the only area in which it out performs NU; for load following operation at which both fuels are stable and controllable, the TRUMOX fuelled core maintains a larger margin than NU between the average zone controller fill level and the established safety limit.

100-95% Full Power

Both TRUMOX and NU are capable of performing load following with a low power setpoint of 95% FP. The liquid zone controller response is similar for the two fuels and at no point do any of the average zone controller fills exceed 60% or dip below 30% full. The TRUMOX core does perform slightly better however with the range of average zone controller movement being 23% smaller than that of NU (22.25% vs. 27.34%) as well as a 12% larger on average safety margin between the maximum and minimum average zone controller fills and their respective safety limits.

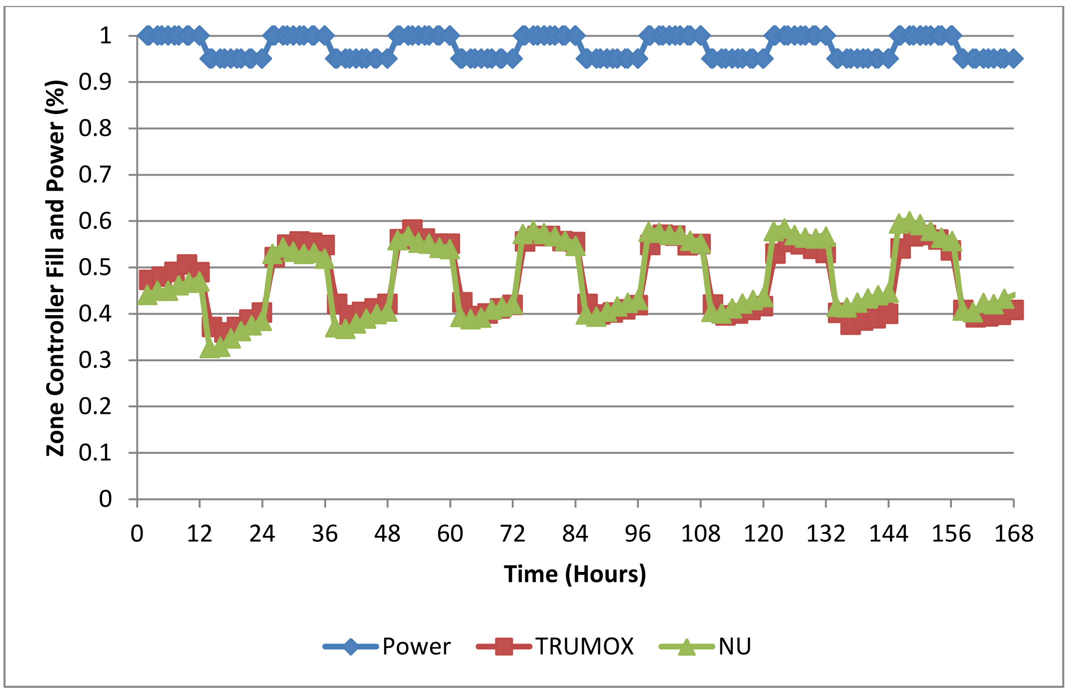

Figure 6.1 - 100-95% FP load following average zone controller fills

100-90% Full Power

Similar to the 100-95% FP load following simulation, both TRUMOX and NU are capable of performing load following with a low power setpoint of 90% FP. The liquid zone controller response is noticeably different for the two fuels but at no point do any of the average zone controller fills exceed 75% or dip below 15% full. The TRUMOX core does perform significantly better however with the range of average zone controller movement being 10% smaller than that of NU (46.44% vs. 51.45%) as well as a 26% larger on average safety margin between the maximum and minimum average zone controller fills and their respective safety limits. The NU fuelled core comes extremely close to the 15% fill safety limit (18.54% at one instance) however this is due to the initial large spike in reactivity during the first transition from 100% FP and can be avoided using a stepped power reduction scheme.

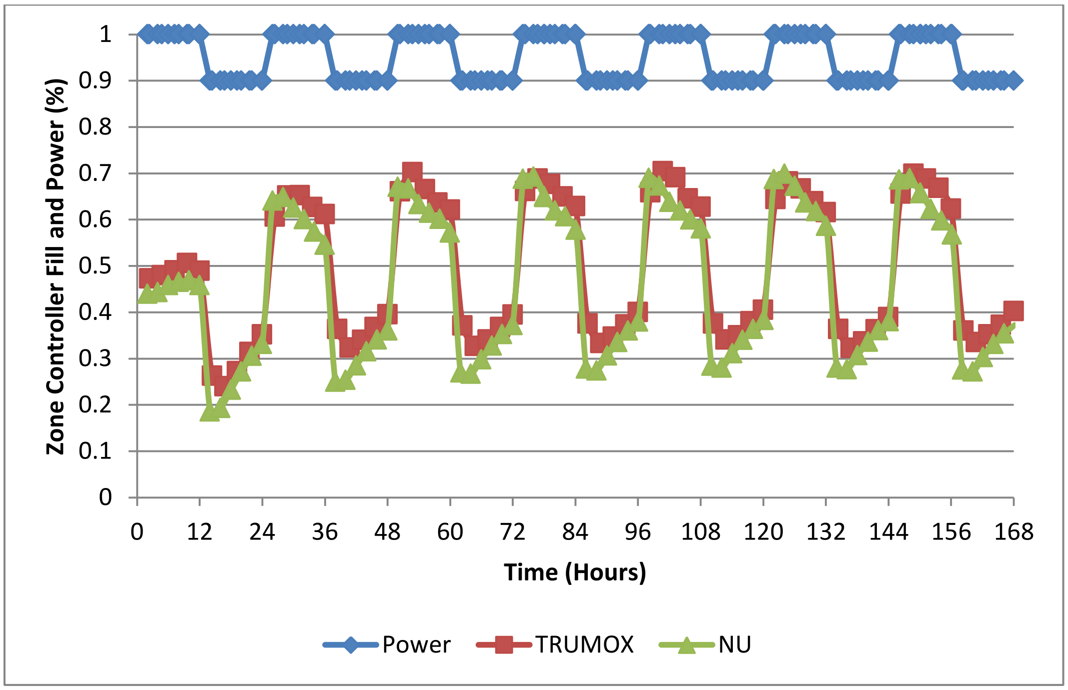

Figure 6.2 - 100-90% FP load following average zone controller fills

Setbacks and Turbine Trips

Despite the better performance of TRUMOX during daily load following operation, there are aspects of NU that it cannot match, mainly the ability to run at low power for extended periods of time. Unlike for daily load following, the use of adjuster rods and MCAs are appropriate and necessary for certain power manoeuvres such as those experienced during setbacks and turbine trips. As TRUMOX runs without any adjuster rods in core, it does not have the ability to remove negative reactivity on the same scale as NU; therefore for power reductions to 60% or lower, the TRUMOX core will eventually poison out.

During setbacks or turbine trips which result in the reactor running for prolonged periods at 60% FP, the NU core is able to remove adjuster rods to account for the large xenon transient and can therefore sustain that power level indefinitely given refuelling operations continue. The TRUMOX fuelled core however cannot sustain this power level as the xenon transient is too large to be accounted for within the zone controllers and onset of poison out occurs around 45 minutes after the reduction in power.

For setbacks or turbine trips to a lower setpoint of 40% FP, both the NU and the TRUMOX core are unable to account for the reactivity change and eventually poison out, however the time until the onset of poison out is much longer for NU. For the TRUMOX fuelled core, onset of poison out occurs around 28 minutes after the reduction in power. The NU fuelled core, having the ability to withdraw adjuster rods from the core, takes around 104 minutes until the onset of poison out which is 271% longer than the time for TRUMOX.

It should be noted however that the inability of TRUMOX to match the performance of NU for setbacks and turbine trip situations is not unique to load following operation and is an issue for base load operation as well. The TRUMOX fuel is designed to be run without adjuster in core and therefore different operational procedures must be employed compared to the NU fuel. An inability to sustain low power operation during setbacks and turbine trips isn't so much a safety issue as it is an issue of operational efficiency. If a reactor must be shut down each time a turbine trip or similar situation occurs, the resultant downtime while the xenon decays reduces the reactors capacity factor while reactor safety is maintained. The reduced ability of TRUMOX to avoid reactor shutdown is one of the many factors that must be taken into account when determining if TRUMOX fuel is a viable alternative to NU.

6.1.3 Explanation of Results

TRUMOX has shown that it is capable of performing load following operations to lower power setpoints than NU when just the zone controllers are being used to mitigate the xenon transients. However, it has also been shown that the reactivity worth of the liquid zone controllers for TRUMOX is less than that of the natural uranium fuel.

The reason that the TRUMOX liquid zone controllers can handle load following to lower power setpoints is that the ^{135}Xe transients experienced with TRUMOX fuel is less than that of NU fuel. Xenon-135 concentration (and as a result, xenon reactivity) is highly dependent on the neutron flux experienced in the reactor core (see Equations 2.2-2.4). A smaller neutron flux results in smaller xenon concentrations and smaller changes in xenon reactivity during changes in reactor power. Typical neutron fluxes experienced during 100% full power operation are listed in Table 6.1 below.

Fuel	Group 1 Flux (Fast)	Group 2 Flux (Thermal)	Total
Natural Uranium (NU)	1.28601 x10^{14} (n/cm^{2}s)	2.41274 x10^{14} (n/cm^{2}s)	3.69875 x10^{14} (n/cm^{2}s)
TRUMOX	1.05651 x10^{14} (n/cm^{2}s)	1.40556 x10^{14} (n/cm^{2}s)	2.46207 x10^{14} (n/cm^{2}s)
Ratio TRUMOX/NU	0.82154	0.58256	0.66565

Table 6.1 - Typical neutron fluxes

As can be seen from the table above, the ratio of total flux between TRUMOX and NU is about the same as the ratio between reactivity worths of the liquid zone controllers for both fuels. It should be mentioned however that although xenon concentration is heavily influenced by the neutron flux, it is not a completely linear relationship. Also worth mentioning is that even though neutron flux is the largest factor effecting the xenon concentration in the reactor core, fission yields of the fissile isotopes also play a role in the xenon concentration. TRUMOX, having a different blend of fissile materials in the fuel, will lead to slightly different fission yield ratios than those experienced using natural uranium.

6.2 Difficulties Encountered During Simulation

Several difficulties arose during the design and execution of the simulations that had to be overcome to produce the results that are presented in this research. All practical efforts were made to ensure that the simulations were executed in such a way to be as realistic as possible, however there are certain aspects that still have room for improvement due to lack of experience.

6.2.1 Refuelling

Due to the reactor being simulated for load following over a week long period, refuelling was an important aspect that had to be addressed to obtain accurate simulations. Although finding the optimal frequency of refuelling was rather straightforward, finding a satisfactory refuelling pattern was quite a bit more difficult.

Finding a useable refuelling pattern for the TRUMOX core was significantly more difficult than for the NU core. Each bundle of TRUMOX contains much more fissile material than NU bundles and it was found that each time a channel was refueled there was a large increase in local neutron flux which leads to high local channel powers. Many modifications were made to the refuelling pattern for the TRUMOX fuel to try and minimize the ripple and maximum channel powers although there is still room for improvement. Despite the TRUMOX maximum channel power never exceeding 7.3 MW during any of the stable load following operations, it usually fluctuated within the 7-7.2 MW range which very near the limit and much higher than the average experienced for the NU core.

The NU core presented a different problem in the realm of refuelling due to the periodic insertion and withdrawal of adjuster rod banks. The effect of absent adjuster rods near a recently refueled channel was not taken into account during either the refuelling pattern selection or during the control logic design of the RECORD program, thus leading to several maximum channel power spikes during the simulations involving reactivity device control. In the future a modification could be made to the RRS emulator to take into account the location of recently refueled channels or areas of high local flux when choosing an adjuster rod bank to insert or withdraw.

6.2.2 RRS Emulator Response

Although the control logic for the RRS emulator was based on CANDU-900 control logic, certain aspects in its method of operation had to be modified to work with RFSP. The largest of these modifications was to translate the rate of reactivity insertion in real time control to instantaneous reactivity insertion for periodic core snapshots experienced using RFSP.

During the week long load following simulations the shortest time interval between simulations was 10 minutes, usually immediately following any changes in reactor power. These short time steps were performed to allow the

RRS emulator enough time to respond to the changes in core reactivity before they caused instability or loss of control, while at the same time not being so short that they caused the simulation to take an unreasonable amount of time to execute. Since the RRS emulator could only respond every 10 minutes rather than several times per second, the controller logic was modified to give the average zone controller level less room to manoeuvre before reactivity devices were inserted or withdrawn (25-75% from the original 15-80%) (AECL, 1995). In addition, adjuster rod and MCA logic was modified to move in a binary fashion, that is either completely in or completely out of the core rather than at a certain rate of insertion/withdrawal.

The above mentioned modifications were necessary to allow the NU core to perform load following down to 80% FP or lower and are reflective of the realistic operational capabilities of a CANDU-900 reactor, however the actual RRS response in a CANDU-900 is quite different. The difference is quite evident when comparing the average zone controller fills between the 100-90% and 100-80% load following simulations for NU. During the 100-90% simulation, only the zone controllers were required to control the reactivity of the core and since RFSP has real time control of the zone controllers, the average zone controller fill over the week long simulation moves in a smooth, continuous pattern. For the 100-80% case, adjuster rod movement is necessary, and since the adjuster rods can only be moved completely in or completely out every 10 minutes at best, the average zone controller fill over the week long simulation is quite choppy with large changes in fill level over short time intervals. In a realistic CANDU-900 reactor, adjuster rod movement would be performed in real time and at set insertion or withdrawal rates and therefore the average zone controller fill would move similar to that shown in the 100-90% FP case.

6.3 Influential Factors

The load following simulations were designed to be representative of true CANDU-900 operating conditions and characteristics while being aware that the parameters used may not be as optimal for load following operation as they are for base-load operation. Several factors have been identified that may increase the controllability and range of load following operation in CANDU, however these ideas have not been applied since it is not exactly known the full implications they would have on CANDU operation.

6.3.1 Zone Controller Initial Levels

The starting average zone controller fills were set to best represent a realistic operating CANDU-900 reactor with starting fills being around the 44% mark (.4507 for TRUMOX and .4379 for NU). These values were based on a CANDU-900 running at base load capacity; however they may not be the optimal starting fill levels for load following operation.

The range of controllability for a TRUMOX fuelled core might be able to increase if starting zone controller fills were set at a higher level (70% for example). Since TRUMOX runs with no adjuster rods in the core, the zone controllers are the only method available to remove negative reactivity while the adjuster rods and MCAs exist to add negative reactivity to the core. By running at a higher average zone controller level, larger power decreases could be accommodated with the added ability to remove negative reactivity from the core due to the higher zone controller levels, while the lost ability to add negative reactivity via the zone controllers could be compensated for with adjuster rod insertion. While running a TRUMOX core with higher zone controller levels may decrease efficiency and rely more heavily upon adjuster rods for flux moderation, it would most likely increase the range of controllable load following operation.

6.3.2 TRUMOX Fuel with Adjuster Rods in Core

The TRUMOX fuel bundles are designed to be run in a CANDU-900 reactor without any adjuster rods present in the core. Unlike the natural uranium fuel, the higher concentration of neutron absorbing transuranic actinides in the fuel as well as the presence of a central pin of the burnable poison dysprosium negate the need for flux shaping with adjuster rods. Running the TRUMOX core sans adjuster rods gives the benefit of higher burnups and rates of actinide transmutation. On the other hand, lack of adjuster rods in core reduces the ability to remove negative reactivity from the core, thus limiting the low power setpoint for load following operation.

Running TRUMOX with adjuster rods in core would almost definitely increase the range of manoeuvreability of the reactor, allowing it to safely perform load following operations to lower low-power setpoints. The presence of adjuster rods would affect the flux profile of the core however and would almost definitely limit burnup and actinide transmutation. Finding a balance between these two factors would be beneficial and could be the topic of future research, but for this research the TRUMOX core is being operated as originally intended.

6.3.3 Refuelling Cycle

During simulations it was apparent that the largest factor affecting reactor controllability was the average zone controller fill approaching zero rather than full. If the average zone controller fill could be increased immediately before a transition to lower power, the zone controllers would have more room to account for the xenon transient. One possibility is to perform all refuelling operations near the end of the period of operation at 100%, boosting the fill level before the drop after the power transition. The effectiveness of this may not be that pronounced however, not to mention the real would implications such as being physically able to refuel all the needed channels in such a short period of time. Although probably not very feasible, it's a possibility that may be worth exploring.

6.3.4 TRUMOX Composition

The main reason that TRUMOX is able to perform load following to lower power setpoints than NU using only the liquid zone controllers is due to the composition of the fuel itself. The increased fissile content in the TRUMOX fuel, as well as the absence of adjuster rods in core during normal operation, leads to lower levels of neutron flux in the core and as a result lower concentrations of ^{135}Xe. By adjusting the fissile content of the TRUMOX fuel, as well as adjusting the amount of transuranic actinides that act to absorb neutrons, it may be possible to achieve controllable load following to lower power setpoints. The increased presence of fissile actinides in the fuel may also result in several other problems, such as difficulty during channel refuellings from large ripples in channel power.

6.4 Further Research

The research presented in this thesis answers some questions pertaining to load following operation of TRUMOX fuel in CANDU but is by no means definitive. There are a few important questions that remain regarding load following for TRUMOX fuel, mainly dealing with the effect of load following on fuel burnup and actinide transmutation. A driving factor in the development of TRUMOX was its usefulness the reduction of long lived transuranic actinides from spent PWR fuel. Rates of actinide transmutation and fuel burnup values have been simulated for base load operation (Morreale, 2012); however the effect of load following on these values is currently unknown. The reduced flux values occurred during periods of reduced power may make TRUMOX less efficient at performing one of its primary goals. Another factor most likely affecting burnup and actinide transmutation in a negative way is using adjuster rods in core for TRUMOX with the added benefit of lower load following capability as well as improving reactor response to setback and turbine trip situations. The balance between the benefits of load following and the reduced rates of actinide transmutation is an important question for TRUMOX and would benefit from detailed analysis and future study.

7 Conclusion

This thesis has presented simulations of load following operations of a CANDU-900 reactor performed for both TRUMOX and NU fuel. Using RFSP to perform the simulations, periodic core snapshots were taken for week long load following cycles with power varying between 100% and a lower power setpoint every 12 hours. Daily refuelling operations as well as reactivity device movements supplementary to RFSP were performed using the RECORD RRS emulator program.

It was found that load following operations could be performed for TRUMOX fuel from 100% to 85% full power in a safe and controllable manner using only the liquid zone controllers to account for the xenon transient reactivity change as there are no adjuster rods in core for normal operation. Reducing power in a stepped fashion resulted in a larger safety margin between the average zone controller fill and the established safety limit by reducing the large reactivity spike from the first reduction in power from base load operation.

Simulations involving NU fuel showed that safe and controllable load following operations down to 85% full power could not be achieved using only the liquid zone controllers to account for the xenon transient reactivity change. Load following operation down to 90% full power using only the liquid zone controllers could be performed in a safe and controllable manner; however any further reduction in the low power setpoint required additional reactivity insertion and withdrawal via adjuster rods and MCAs.

For load following simulations that both fuel types were capable of performing in a safe and controllable manner, the TRUMOX fuelled core maintained a larger safety margin between the liquid zone controller fills and the established safety limit. During load following down to 95% FP, the variation of the average zone controller fill for NU was 23% larger than for TRUMOX while fill levels came on average 12% closer to the established safety limits. For load following down to 90% FP, the variation of the average zone controller fill for NU was 11% larger than for TRUMOX while fill levels came on average 26% closer to the established safety limits.

The results of the load following simulations show that TRUMOX fuel has superior load following capabilities to that of NU for practical operational scenarios in a CANDU-900 reactor (no adjuster rod movement for day to day operation). Results also show that unlike NU, TRUMOX is not capable of overriding the large xenon transient incurred from large power reductions to 60% FP during setbacks or turbine trips, although this is a factor for both normal base-load operation as well as load following operation.

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Appendix A - INSTANTAN Channel Age Map

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A								.44	.54	.96	.02	.48	.04	.14	.44	.82	.12							
B						.58	.28	.82	.16	.42	.64	.86	.30	.76	.54	.16	.70	.36	.84					
C					.38	.20	.94	.12	.70	.08	.18	.32	.56	.22	.96	.42	.08	.90	.38	.20				
D				.52	.92	.74	.40	.62	.36	.90	.52	.78	.10	.68	.02	.64	.18	.52	.92	.74	.40			
E			.32	.78	.50	.98	.24	.66	.84	.38	.92	.50	.80	.26	.48	.86	.32	.78	.50	.98	.24	.66		
F		.30	.56	.10	.80	.60	.34	.72	.58	.20	.74	.98	.60	.46	.04	.30	.56	.10	.80	.60	.34	.72	.58	
G		.76	.22	.68	.26	.46	.88	.06	.28	.94	.40	.24	.34	.88	.14	.76	.22	.68	.26	.46	.88	.06	.28	
H		.54	.96	.02	.48	.04	.14	.44	.82	.12	.62	.66	.72	.06	.44	.54	.96	.02	.48	.04	.14	.44	.82	
J	.82	.16	.42	.64	.86	.30	.76	.54	.16	.70	.36	.84	.58	.28	.82	.16	.42	.64	.86	.30	.76	.54	.16	.70
K	.12	.70	.08	.18	.32	.56	.22	.96	.42	.08	.90	.38	.20	.94	.12	.70	.08	.18	.32	.56	.22	.88	.42	.08
L	.62	.36	.90	.52	.78	.10	.68	.02	.64	.18	.52	.92	.74	.40	.62	.36	.90	.52	.78	.10	.68	.02	.64	.18
M	.66	.84	.38	.92	.50	.80	.26	.48	.86	.32	.78	.50	.98	.24	.66	.84	.38	.92	.50	.80	.26	.48	.86	.32
N	.72	.58	.20	.74	.98	.60	.46	.04	.30	.56	.10	.80	.60	.34	.72	.58	.20	.74	.98	.60	.46	.04	.30	.56
O	.06	.28	.94	.40	.24	.34	.88	.14	.76	.22	.68	.26	.46	.88	.06	.28	.94	.40	.24	.34	.88	.14	.76	.22
P	.44	.82	.12	.62	.66	.72	.06	.44	.54	.96	.02	.48	.04	.14	.44	.82	.12	.62	.66	.72	.06	.44	.54	.96
Q	.54	.16	.70	.36	.84	.58	.28	.82	.16	.42	.64	.86	.30	.76	.54	.16	.70	.36	.84	.58	.28	.82	.16	.42
R		.42	.08	.90	.38	.20	.94	.12	.70	.08	.18	.32	.56	.22	.96	.42	.08	.90	.38	.20	.94	.12	.70	
S		.64	.18	.52	.92	.74	.40	.62	.36	.90	.52	.78	.10	.68	.02	.64	.18	.52	.92	.74	.40	.62	.36	
T		.86	.32	.78	.50	.98	.24	.66	.84	.38	.92	.50	.80	.26	.48	.86	.32	.78	.50	.98	.24	.66	.84	
U			.56	.10	.80	.60	.34	.72	.58	.20	.74	.98	.60	.46	.04	.30	.56	.10	.80	.60	.34	.72		
V				.68	.26	.46	.88	.06	.28	.94	.40	.24	.34	.88	.14	.76	.22	.68	.26	.46	.88			
W					.48	.04	.14	.44	.82	.12	.62	.66	.72	.06	.44	.54	.96	.02	.48	.04				
X						.30	.76	.54	.16	.70	.36	.84	.58	.28	.82	.16	.42	.64	.86					
Y								.96	.42	.08	.90	.38	.20	.94	.12	.70	.08							

Figure A.1 - INSTANTAN channel age map

Appendix B - Initial Core 3-D Power Distributions

TRUMOX

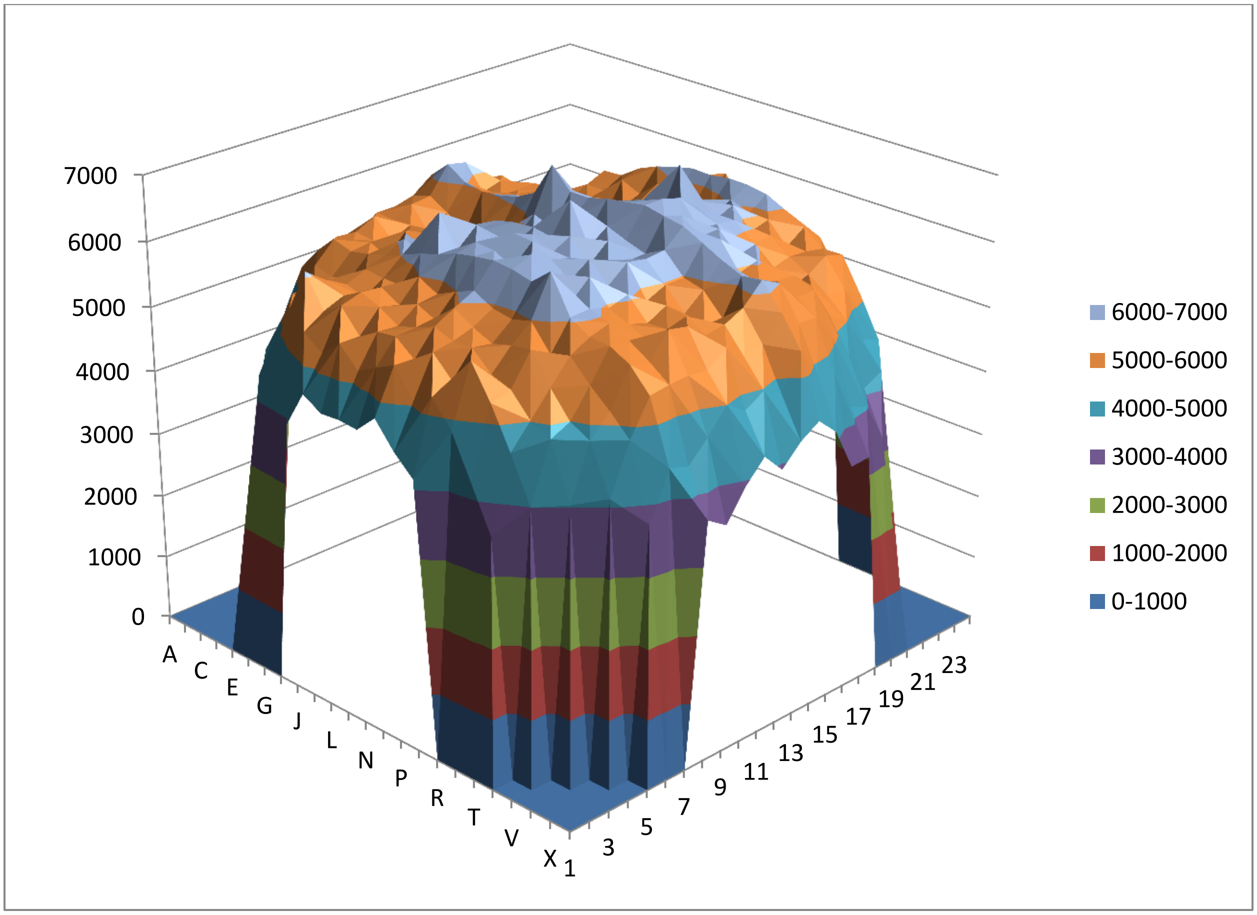

Figure B.1 - TRUMOX initial core 3-D power distribution (kW)

NU

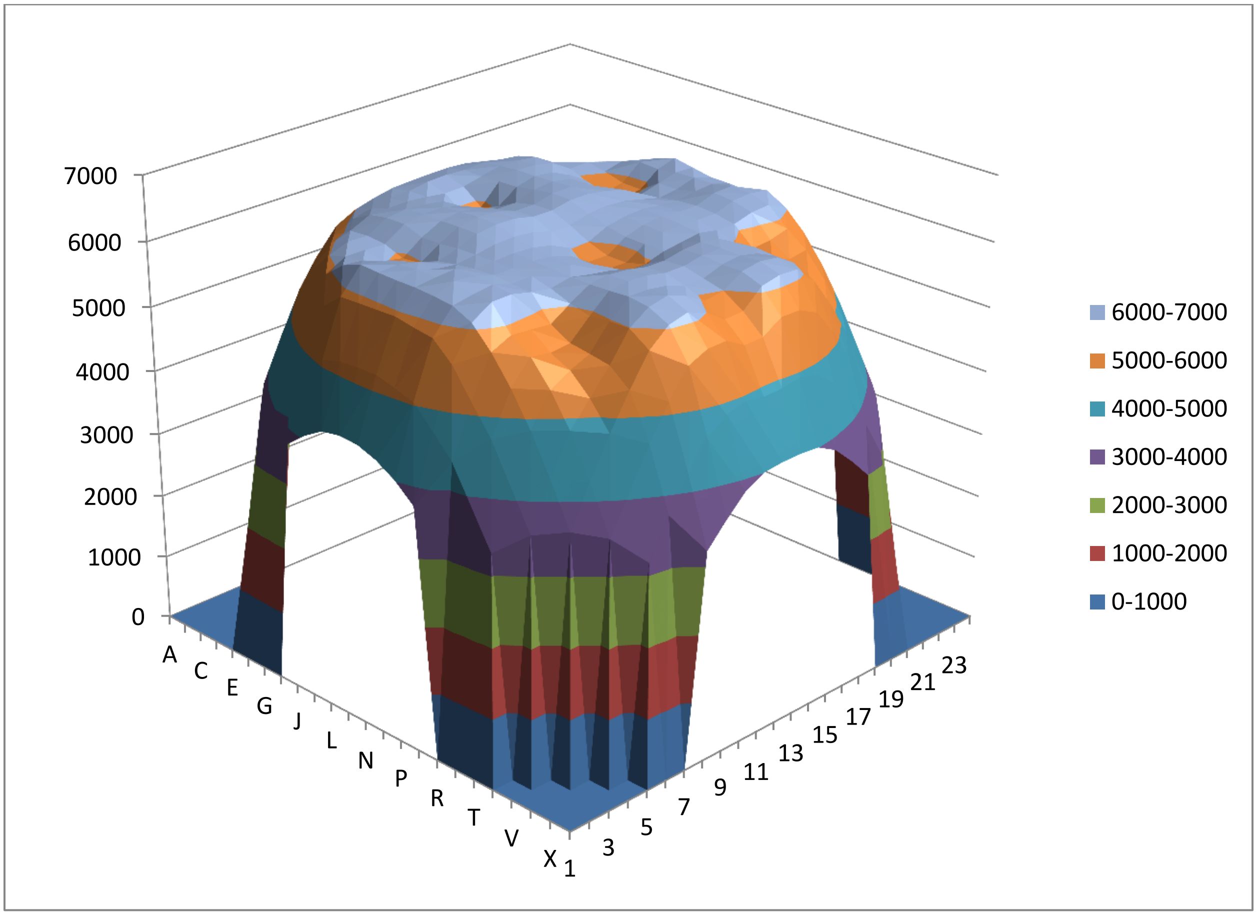

Figure B.2 - NU initial core 3-D power distribution (kW)

Appendix C - RECORD Program Code

RECORD Program (record.py)

```
#RFSP EXTERNAL CONTROL OF REACTIVITY DEVICES (RECORD) RRS EMULATOR
#RECORD.PY
#WRITTEN IN PYTHON BY: DAVID A. TRUDELL
#LAST MODIFIED APRIL 5, 2012
#-----------------------------------------------------------------
#THIS SECTION READS PARAMETERS FROM param.txt
thisisuseless=1
timeclock=' '
param=open('param.txt','r')
filename=str(param.readline())
filename = filename.replace("\n", "")
usedaf=str(param.readline())
itera=str(param.readline())
itera=itera[0:3]
itera=itera.replace("\n","")
iteration=int(itera)
mode=(param.readline())
mode=mode[0:2]
mode=int(mode)
adjpos=str(param.readline())
adjpos=adjpos[0:2]
adjpos=int(adjpos)
rnc=str(param.readline())  #refuel nth channel in refuel.txt
rnc=rnc[0:4]
rnc=int(str(rnc))
param.close
#THIS SECTION READS PARAMETERS FROM sims.txt
sims=open('sims.txt','r')
simcount=0
while simcount<=iteration:
	waste=str(sims.readline())
	simcount=simcount+1
simlineread=str(sims.readline())
simlineread=simlineread.replace('\n','')
sims.close
parsed=simlineread.split('\t')
if simlineread.find('OF')>0:
	thisisuseless=0
else:
	time=str(parsed[1])
	powr=str(parsed[2])
	refuelnow=str(parsed[3])
	refdate=str(parsed[4])
#READ .OUTPUT FILE
if thisisuseless==1:
	if iteration>0:
		olditeration=int(iteration)-1
		f=open(str(filename)+str(olditeration)+'.output','r')
		reactivity=' '
		zone=' '
		zap='no stop'
		exiter=0
		while exiter!=-1:
			zap=str(f.readline())
			if zap.find('NOTE: COMMENT CARDS')>0:
				exiter=-1
```

```
			zap='no stop'
			while zap!='':
				temp=str(f.readline())
				if temp.find('REACTIVITY')>0:
					reactivity=temp[37:42]
				if temp.find('AVERAGE ZONE')>0:
					zone=temp[32:38]
				if temp.find('EXISTING ENERGY WHICH IS')>0:
					timeclock=temp[58:69]
				zap=temp
			f.close
		#LOGIC TO DETERMINE HOW TO MOVE ADJUSTERS AND MCAS
		if int(iteration)!=0:
			zone=float(zone)
			reactivity=float(reactivity)
			if mode==0:#NATU
				mfactor=1
			if mode!=0:#TRUMOX
				mfactor=2
			if zone>0.75:#ZONE TRIGGER OVER 75% FULL
				adjpos=adjpos-1*mfactor
				if reactivity>1.25:#ADDITIONAL TRIGGER FOR EXCESS REACTIVITY OVER
1.25mk
					adjpos=adjpos-1*mfactor
			if zone<0.25:#ZONE TRIGGER LESS THAN 25% FULL
				if adjpos!=8:
					adjpos=adjpos+1*mfactor
					if reactivity<0.75:#ADDITIONAL TRIGGER FOR EXCESS
REACTIVITY LESS THAN 0.75mk
						adjpos=adjpos+1*mfactor
		#THIS SECTION WRITES NEW INPUT FILE
		f=open(str(filename)+str(iteration)+'.input','w')
		if mode==1:
			readcard='RIGFILE/readcard-trumox.txt'
			spabul='RIGFILE/spatial-bulk-trumox.txt'
		if mode==0:
			readcard='RIGFILE/readcard-nat.txt'
			spabul='RIGFILE/spatial-bulk-nat.txt'
		if mode==2:
			readcard='RIGFILE/readcard-trumoxnoadj.txt'
			spabul='RIGFILE/spatial-bulk-trumoxnoadj.txt'
			if int(iteration)==0:
				adjpos=8
		if refuelnow=='Y':
			reffile=open('ref.txt','r')
			cz=0
			while cz<rnc:
				temps=str(reffile.readline())
				cz=cz+1
			c2ref=str(temps)
			reffile.close
			rnc=rnc+1
		freadcard=open(readcard,'r')
		fspabul=open(spabul,'r')
		treadcard=freadcard.read()
		tspabul=fspabul.read()
		freadcard.close()
		fspabul.close()
		f.write('*USE DAF  '+usedaf)
		f.write('*START    D. TRUDELL')
		f.write('\n*MODEL    CANDU 9 RFSP\n')
		f.write('$********SIM '+str(iteration)+'*********\n')
		f.write(treadcard)
```

```
        f.write('\nWIMSHI   ITER 5        \\\n')
        f.write('         NGRO 2        \\\n')
        f.write('         MODT 63.0     \\\n')
        f.write('         MODP 99.918   \\\n')
        f.write('         MODB 0.0      \\\n')
        f.write('         MODG 0.0      \\\n')
        f.write('         COOLP 98.764  \\\n')
        f.write('         POWR '+powr+'      \\\n')
        f.write('         STEP '+time+'     \\\n')
        f.write('         BURNT NORM   \\\n')
        f.write('         EDIT 0\n')
        #INSERTING LOGIC
        if adjpos>8:
              adjpos=8
        if mode==0:
              if adjpos<0:
                    adjpos=0
              if adjpos==0:
                    f.write('C        ADJ04     +1000     ADJ08     +1000     ADJ17
+1000\n')
                    f.write('C        ADJ21     +1000\n')
                    f.write('C        ADJ01     +1000     ADJ06     +1000     ADJ19
+1000\n')
                    f.write('C        ADJ24     +1000\n')
              if adjpos==1:
                    f.write('C        ADJ04     +1000     ADJ08     +1000     ADJ17
+1000\n')
                    f.write('C        ADJ21     +1000\n')
        if mode!=0:
              if adjpos<-2:
                    adjpos=-2
              if adjpos==-2:
                    f.write('C        ADJ04     +1000     ADJ08     +1000     ADJ17
+1000\n')
                    f.write('C        ADJ21     +1000\n')
                    f.write('C        ADJ01     +1000     ADJ06     +1000     ADJ19
+1000\n')
                    f.write('C        ADJ24     +1000\n')
              if adjpos==0:
                    f.write('C        ADJ04     +1000     ADJ08     +1000     ADJ17
+1000\n')
                    f.write('C        ADJ21     +1000\n')
        if adjpos==3:
              f.write('C        ADJ11     -1000     ADJ14     -1000\n')
        if adjpos==4:
              f.write('C        ADJ11     -1000     ADJ14     -1000\n')
              f.write('C        ADJ07     -1000     ADJ10     -1000     ADJ20     -
1000\n')
        if adjpos==5:
              f.write('C        ADJ05     -1000     ADJ15     -1000     ADJ18     -
1000\n')
              f.write('C        ADJ11     -1000     ADJ14     -1000\n')
              f.write('C        ADJ07     -1000     ADJ10     -1000     ADJ20     -
1000\n')
        if adjpos==6:
              f.write('C        ADJ03     -1000     ADJ22     -1000\n')
              f.write('C        ADJ05     -1000     ADJ15     -1000     ADJ18     -
1000\n')
              f.write('C        ADJ11     -1000     ADJ14     -1000\n')
              f.write('C        ADJ07     -1000     ADJ10     -1000     ADJ20     -
1000\n')
        if adjpos==7:
              f.write('C        ADJ03     -1000     ADJ22     -1000\n')
```

```
            f.write('C          ADJ12     -1000     ADJ13     -1000\n')
            f.write('C          ADJ05     -1000     ADJ15     -1000     ADJ18     -
1000\n')
            f.write('C          ADJ11     -1000     ADJ14     -1000\n')
            f.write('C          ADJ07     -1000     ADJ10     -1000     ADJ20     -
1000\n')
      if adjpos==8:
            f.write('C          ADJ**     -1000\n')
      if refuelnow=='Y':
            if mode==0:
                  f.write('$-------------------------------------------\n')
                  f.write('$--------------REFUELLING NOW--------------\n')
                  f.write('$-------------------------------------------\n')
                  f.write('U         37-ELM_NAT\n')
                  f.write('S       '+refdate+'  20 21\n')
                  f.write('R           '+c2ref[0:4]+'    0.001\n')
                  f.write('$-------------------------------------------\n')
            else:
                  f.write('$-------------------------------------------\n')
                  f.write('$--------------REFUELLING NOW--------------\n')
                  f.write('$-------------------------------------------\n')
                  f.write('U         TRUMOX\n')
                  f.write('S       '+refdate+'   5  1\n')
                  f.write('R           '+c2ref[0:4]+'    0.001\n')
                  f.write('$-------------------------------------------\n')
      #
      f.write(tspabul)
      if timeclock!=' ':
            if timeclock.find('99999')>0:
                  f.write('$*DELETE   SIMULDATA TAEQ
999999'+str(timeclock))
                  f.write('$*DELETE   PHYS PARMSFAST FLUX
999999'+str(timeclock))
            else:
                  f.write('*DELETE   SIMULDATA TAEQ          999999'+str(timeclock))
                  f.write('*DELETE   PHYS PARMSFAST FLUX     999999'+str(timeclock))
      f.write('*MAKE DAF '+'CANDU-'+str(filename)+str(iteration))
      f.write('\n*CLOSE')
      f.close
      #REWRITING PARAM.TXT
      f=open('param.txt','w')
      f.write(filename+'\n')
      f.write('CANDU-'+str(filename)+str(iteration)+'\n')
      iteration=str(int(iteration)+1)
      f.write(iteration+'\t\t\t\tCounter for current simulatioin\n')
      f.write(str(mode)+'\t\t\t\tMode: 0-Natu, 1-TRU, 2-TNA\n')
      f.write(str(adjpos)+'\t\t\t\tReactivity Device Position\n')
      f.write(str(rnc)+'\t\t\t\tRefuel Nth channel in refuel.txt\n')
      f.close
if thisisuseless==0:
      print "SIMULATION COMPLETE"
# END OF FILE
```

Execution Scripts and Sample RECORD Input Files

RUN_RRS (linux script to begin execution)

```
python makerunner.py
chmod 755 runner
./runner
```

makerunner.py (writes script to run all simulations)

```
ff=open('sims.txt','r')
exit=0
while exit!=1:
	test=str(ff.readline())
	test=test.replace('\n','')
	if test.find('EOF')>0:
		exit=1
stopper=ff.readline()
stopper=stopper.replace('\n','')
stopper=stopper.split('\t')
stopper=str(stopper[1])
stopper=int(stopper)
f=open('runner','w')
#filename=raw_input("ENTER NAME OF FILE: ")
rrs=str('record.py')
sp=str('setparam.py')
f.write('python '+str(sp)+'\n')
f.write('python '+str(rrs)+'\n')
f.write('run_rfsp PM0\n')
i=1
while i!=stopper:
	f.write('python '+str(rrs)+'\n')
	f.write('run_rfsp PM'+str(i)+'\n')
	f.write('if test -f CANDU-PM'+str(i)+';\n')
	f.write('then\n')
	f.write('    rm CANDU-PM'+str(i-1)+'\n')
	f.write('else\n')
	f.write('    echo "file does not exist"\n')
	f.write('fi\n')
	i=i+1
f.close
```

setparam.py (writes RECORD input file based on user input files)

```
f=open('param.txt','w')
#mode=raw_input("Enter 0 for NatU, 1 for TRUMOX30, 2 for TRUMOX30 no ADJ: ")
#filename=raw_input("Enter name for files: ")
#daf=raw_input("Enter name of DAF to use: ")
f.write('PM\n')#Name of Files, usually PM
f.write('CANDU-NATU\n')#name of DAF
f.write('0\t\t\t\tCounter for current simulatioin\n')#Counter for what simulation its
on
f.write('0\t\t\t\tMode: 0-Natu, 1-TRU, 2-TNA\n')#Denotes, NATU, TRUMOX30, or
TRUMOX30NOADJ
f.write(str(2)+'\t\t\t\tReactivity Device Position\n')#Reactivity Device Position
f.write(str(1)+'\t\t\t\tRefuel Nth channel in ref.txt\n')#start at first channel in
refuel.txt
f.close
```

sims.txt (sample user input file outlining simulations to be run)

```
0       TIME   POWER  REF    DATE
1       60 M   1      N      20120101
2       10 M   1      N      20120101
3       10 M   1      N      20120101
4       10 M   1      N      20120101
5       10 M   1      N      20120101
6       10 M   1      N      20120101
7       10 M   1      Y      20120101
8       20 M   1      N      20120101
9       30 M   1      N      20120101
…
…
…
411     60 M   0.8    N      20120107
412     60 M   0.8    N      20120107
413     60 M   0.8    N      20120107
414     EOF
TOTAL   413
```

ref.txt (sample user input file outlining refuelling order)

```
E  6
R 21
P 10
K 22
R  4
C 15
R 15
L  3
R 18
Y  8
E 20
C  7
V 10
```

readcard-trumox.txt (parameters to be written into RFSP input file)

```
$--------1---------2---------3---------4---------5---------6---------7---------8
*READ CARD
BLOCK     LOCAL PARMDENSITY
FORMAT    (8F10.4)
SET                1      6240 0.8074
$--------1---------2---------3---------4---------5---------6---------7---------8
*READ CARD
BLOCK     LOCAL PARMCOOL TEMP
FORMAT    (8F10.4)
SET                1      6240 288.135
$--------1---------2---------3---------4---------5---------6---------7---------8
*READ CARD
BLOCK     LOCAL PARMFUEL TEMP
FORMAT    (8F10.4)
SET                1      6240 687.01
$  Execution of SIMULATE module
$--------1---------2---------3---------4---------5---------6---------7---------8
*SIMULATE C9TRU30    9999999990.0                   1                   20
$*SIMULATE CANDU 6    9999999990.0                   1                   20
$  C -> current positions of devices
$  E -> Iteration Data
$--------1---------2---------3---------4---------5---------6---------7---------8
NUCIRC
FUELTEMP
```

spatial-bulk-trumox.txt (parameters to be written into RFSP input file)

```
$-------------------------------------------------------------------------------
$  SPATIAL AND BULK CONTROL CARDS
$---v----1----v----2----v----3----v----4----v----5----v----6----v----7----v----8
AA           20    1   20   14    1    3    1
BB           0.00001     0.003   1.00100      1.00      0.00      0.95      0.05
CC        ZCR01     ZCR02     ZCR03     ZCR04     ZCR05     ZCR06     ZCR07
CC        ZCR08     ZCR09     ZCR10     ZCR11     ZCR12     ZCR13     ZCR14
DD        ZCR**          300.0
EE        ZCR**     2.0
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
$** FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF FF
FF        ZCR01      0.93078     353607082241   354009102241   354211122241
FF        ZCR01      0.93078     354413132241   354514152241   354616202241
FF        ZCR01      0.93078     354721272241
$....................
FF        ZCR02      0.99791     354728342241   354635392241   354540412241
FF        ZCR02      0.99791     354442422241   354243432241   354044452241
FF        ZCR02      0.99791     353646462241
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
FF        ZCR03      1.02231     193407202241
$....................
FF        ZCR04      1.08288     193421342241
$....................
FF        ZCR05      1.03140     193435462241
$....................
FF        ZCR06      0.97592     171807082241   131809102241   111811122241
FF        ZCR06      0.97592     091813132241   081814152241   071816202241
FF        ZCR06      0.97592     061821272241
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
FF        ZCR07      0.94864     061828342241   071835392241   081840412241
FF        ZCR07      0.94864     091842422241   111843432241   131844452241
FF        ZCR07      0.94864     171846462241
```

```
$*********************************************************************
FF        ZCR08      0.94474     171807080121   131809100121   111811120121
FF        ZCR08      0.94474     091813130121   081814150121   071816200121
FF        ZCR08      0.94474     061821270121
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
FF        ZCR09      1.00656     061828340121   071835390121   081840410121
FF        ZCR09      1.00656     091842420121   111843430121   131844450121
FF        ZCR09      1.00656     171846460121
$...................
FF        ZCR10      1.02693     193407200121
$...................
FF        ZCR11      1.07283     193421340121
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
FF        ZCR12      1.03346     193435460121
$...................
FF        ZCR13      0.97476     353607080121   354009100121   354211120121
FF        ZCR13      0.97476     354413130121   354514150121   354616200121
FF        ZCR13      0.97476     354721270121
$...................
FF        ZCR14      0.95089     354728340121   354635390121   354540410121
FF        ZCR14      0.95089     354442420121   354243430121   354044450121
FF        ZCR14      0.95089     353646460121
$*********ZONE_NAME FLUXLEVEL    X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2   X1X2Y1Y2Z1Z2*******
$---v----1----v----2----v----3----v----4----v----5----v----6----v----7----v----8
GG        ZCR**     1.00      0.00      0.95      0.05
$-------------------------------------------------------------------------------
$C         ZCR**           0.50
$C         ADJ** *      -1000.0
$--------1---------2---------3---------4---------5---------6---------7---------8
E    2  10 2651000.0   0.95500   0.00001       1.5     1.000      0.01 0     999
$  print out POWERS, FUELBURNUP and FUEL TYPES for subsequent verification
$
*PRINT    POWERS
*PRINT    FUELBURNUP
```