Assessment of a Transuranic Mixed Oxide fuelled CANDU Reactor

A. C. Morreale*,J. C. Luxat and D. R. Novog
McMaster University, Hamilton, Ontario, Canada
(*morreaac@mcmaster.ca, luxatj@mcmaster.ca, novog@mcmaster.ca)

Abstract

The extraction of transuranic actinides from spent fuel and usein current thermal reactors is an important step to providing an intermediary option before use in fast reactor fuel cyclein order to remove actinides from the nuclear waste stream. A transuranic mixed oxidefuel can provide a high level of burnup and actinide reduction in a current CANDU®* reactor.The effects of this fuel change on operations and performance must be assessed to ensure the reactor still operates within its designed envelope. Operational evaluations of this fuel/reactor combinationare made and compared to a standard natural uranium configuration detailing a similar performance envelope.

1. Introduction

Nuclear power is a clean and efficient component of the world's energy mix but the issue of long-term waste management must be dealt with to support sustainable carbon free nuclear power generation. The closing of the nuclear fuel cycle and reduction of the long-term monitoring issues hinges on the reprocessing and removal of actinide elements from the spent fuel waste stream. Partitioning the spent fuel produces three streams: uranium, transuranic actinides and fission product waste. The uranium stream can be directly recycled into current once through systems by re-enriching or blending with natural or depleted uranium stockpiles to produce a tailored composition nearly identical to standard new fuel. The actinides include plutonium, neptunium, americium and curium and are the primary sources of long-term radiotoxicity and decay heat load in spent fuel. The actinides can be group extracted or separated and burned in mixed oxide or inert matrix formats in fast and thermal reactors. The fission product waste that is left can be vitrified and stored in a long-term storage facility.

Reprocessing the actinides reduces the longevity of the waste material decreasing the time until it reaches the natural radioactivity levels in the ground from 100,000 years down to approximately 500 years. The latter value isthe time it takes for the fission products to decay below thelevel ofradiotoxicity of naturally occurring uranium ore. The actinides can be fully burned in fast reactor systems but, due to the increased complexity of fast reactors and limited operation success, it is prudent to explore an intermediate step or alternative approach of burning some of the actinides in thermal reactors first. This multi-stage approach reduces the number of fast reactors needed and uses current thermal systems to dispose of a significant portion of the actinides. One method of actinide burning in thermal systems extracts the grouped transuranic actinides from spent fuel and combines them with natural uranium

*CANadian Deuterium Uranium (CANDU) is a registered trademark of Atomic Energy of Canada Limited (AECL)

(NU)producing a mixed oxide(MOX) fuelthat can be used in current thermal reactor systems [1,2,3].Numerous studies have been performed of MOX-type fuel production and use in current thermal reactor designs, originating in response to the desire to reprocess excess nuclear weapons material, including studies on the feasibility of plutonium disposition in CANDU reactors [4, 5]. Currently pressurized water reactors (PWRs) in France, Belgium, Switzerland and Japan operate with a portion of MOX fuel (10-20% of core fuel load). Full core simulations and feasibility studies of transuranic mixed oxide(TRUMOX) fuels have been performed for CANDU systemsand the results show appreciable actinide conversion with safe operation within the standard envelope [6, 7, 8].

The detailed physics simulations utilized in previous studies used a multi-stage analysis to produce a full core diffusion model of a TRUMOX fuelled CANDU design. The analysis begins with a fuel design that selects the specific fuel blend and bundle geometry using successive simulations of the lattice cell in a neutron transport code (WIMS-AECL in this case, [9]). Upon completion of a suitable fuel design that meets the burnup requirements a set of 3D super-cell calculations are performed to obtain the necessary incremental cross sections which detail the local reactivity changes caused by interactions between the control devices and the lattice cell (the DRAGON 3D transport code is used in this case,[10]). Upon completion the full burnup homogenized macroscopic lattice cell cross sections, along with the set of homogenized incremental cross sections from the super-cell calculations for all the control devices, are passed along to the full core modelling code and provide the cross sections of the lattice cell building blocks of the full core diffusion solution (RFSP-IST code is used, [11], note that RFSP fuel tables are generated from the WIMS-AECL model using the WIMS-Utilities code to produce the micro-depletion tables). The full core model is a detailed 3D representation of the reactor core and all its internal structural components using the homogenized lattice and super-cell cross sections as building blocks to reproduce the core configuration and solve the diffusion equation to determine the neutron flux distribution within the core.

Full core modellingis used first to determine an optimal “equilibrium” core configuration that will be suitably within the operational envelope of the core. The key inputs used to determine this envelope are the time-average properties at each bundle location in the core (average bundle depletion, average coolant, fuel and moderator temperatures and densities). This provides important information about the fuel design including fissile content and burnup levels to determine if the fuel will be sufficiently active to maintain operations while maintaining the necessary constraints on the flux shape and power levels defined for the reactor system. The CANDU reactor system uses a continuous online fuelling scheme in order to maintain the reactivity in the core, in contrast to light water reactors (LWRs) which are batch fuelled. Therefore, the equilibrium or “time-average” calculation is used to define suitable specific irradiation levels and fuelling scheme and frequencies to achieve the desired fuel burnup level while maintaining the proper core reactivity and operational power and flux profiles. The specific characteristics of the full core model including the responses to changes in conditions such as temperature and moderator composition are evaluated along with the full core responses to the different control devices present in the core.

Upon the completion of a suitable "time-average" model the specific effects of instantaneous snapshot cores with random channel ages are then evaluated to ensure the design will remain within the desired operational envelope. Specifically, the online fuelling nature of the CANDU reactor means that the core at each instant in time will show small deviations from the time-average conditions described earlier. The online fuelling of the CANDU design puts specific demands on the control system and fuelling events must be studied in detail to ensure that the reactor remains within the operational envelope during fuelling. The finalized model can then be evaluated for specific scenarios of normal and accident operations to determine the response of the system and ensure acceptable behaviour under the defined conditions.

Detailed descriptions of the full core modelling process as applied to TRUMOX fuels in CANDU are available in reference [8].This paper focuses on evaluation of a full core model to assess the ability of the combined reactor/fuel system to maintain a standard operational envelope. This includes the effects of coolant voiding, short-term fuelling simulations and fuel ramp assessments along with modal analysis and core responsiveness. All comparisons in this study are performed for the 480 channel CANDU-900 (900MWe output) reactor design with 13 fuel bundles in each channel (similar to the Bruce and Darlington units). The standard reference fuel of the CANDU-900 to which the TRUMOX design is compared is the 37 element NU fuel. The NU fuelled CANDU-900 is referred to as NU-CANDU-900 while the TRUMOX fuelled CANDU-900 is referred to as TRUMOX-CANDU-900.

2. Fuel Design and Full Core Model

The TRUMOX fuel design evaluated in this paper is detailed in reference [8] and is a blended oxide of actinidesand NU. A43-elementfuel bundle design is used with a central pin of burnable neutron absorber (BNA) composed of dysprosium-zirconium. The BNA element is 17.4mm thick and is surrounded by concentric rings of 7, 14, and 21 fuel pins which have a common diameter of 11.4 mm. This bundle design is different from the standard 37 element CANDU bundle used with NU fuel which has a consistent diameter of 13.1 mm for each pin and does not contain a burnable absorber. The two fuel designs are compared in Figure 1.

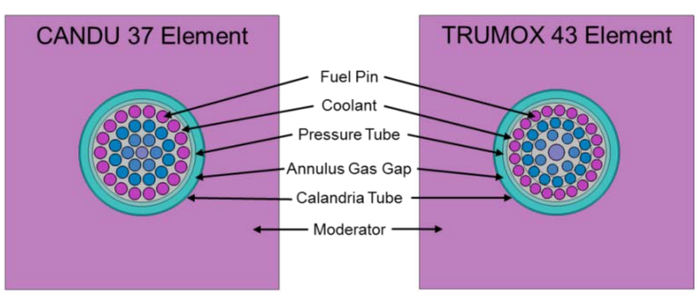

Figure 1 2D Lattice Cell Models for 37 element CANDU and 43-element TRUMOX.

The TRUMOX fuel is designed for a burnup level of 30 MWD/kgand is a mixture of 3.10wt% actinide oxide and 96.90wt% NUoxide with a mass of 17.38 kgHE/bundle. This specific blend is referred to as TRUMOX-30 fuel. The fresh fuel fissile content of TRUMOX-30 is 2.53 wt% (includingPu-239, Pu-241, and U-235). The burnup and fissile content is much higher than standard NU fuel, fresh fuel fissile content of 0.71 wt% (U-235 only) and a burnup level of 9.0 MWD/kg. The actinide composition (Np, Pu, Am and Cm) is proportional to the composition of actinide isotopes extracted from cooled spent LWR fuel (in this case, a prototypical PWR fuel irradiated to 45 MWD/kgHE and cooled for 30 years). The details of the actinide mixture are available in reference [8].

2.1 Full Core Time average model

The full core time average model evaluated herein has a similar evolution to that of the core designed in reference [8] but it has been modified to achieve a more even and optimised burnup. The full core model is of a CANDU-900 reactor system and contains all the relevant control devices, in-core instrumentation and structures [12]. Thus the combined fuel/reactor system explored here is referred to as the TRUMOX-30-CANDU-900. The 480 channels of the CANDU-900 were grouped based on geographic location and power levels into 12 regions over the core. Each region has a definitive fuelling scheme and irradiation level. The regions of the core and their associated fuelling schemes are provided in Figure 2.

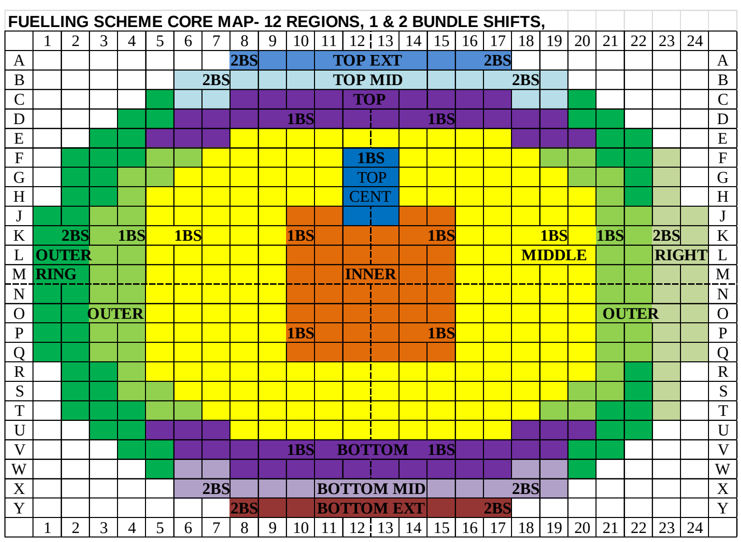

Figure 2Full Core TRUMOX-30-CANDU-900 Time-Average Region Definitions.

The fuelling scheme in the TRUMOX-30-CANDU-900 has six regions (in the inner core area) using a one-bundle-shift fuelling scheme encompassing 344 channels. The remaining 136 channels (in the outer core area) are made up of six regions fuelled using a two-bundle-shift scheme.This is lower than the 4 to 8 bundle shifts used in an NU core. The irradiations for the 12 regions used in the time average simulations are provided in Table 1 and the time average model characteristics are given in Table 2.

Table 1Time-average Exit Irradiation and Burnup Values

Region	Average Exit Irr. (n/kb) [Burnup (MWD/kgHE)]	Region	Average Exit Irr. (n/kb) [Burnup (MWD/kgHE)]
TOP EXT	3.12 [27.58]	TOP CENT	3.54 [30.26]
TOP MID	3.17 [28.07]	MIDDLE	3.82 [31.69]
TOP	3.40 [29.48]	INNER	3.82 [31.69]
OUTER	3.61 [30.60]	BOTTOM	3.32 [29.05]
OUTER RING	2.90 [26.45]	BOTTOM MID	3.09 [27.63]
RIGHT	2.87 [26.27]	BOTTOM EXT	3.03 [27.13]

Table 2Time-average Model Characteristics

Characteristic	TRUMOX-30 Value	NU-CANDU-900 Value [13]
k-effective	0.99909	~1
Max Bundle Power (BP in kW)	778	700-800
Max Channel Power (CP in kW)	6320	6400-6500
Whole Core Exit Burnup (MWd/kgHE)	29.98	9.1
Maximum Exit Burnup (MWd/kgHE)	31.69	~ 11.3
Radial Form Factor (Avg CP/ Max CP)	0.874	0.85-0.87
Axial Form Factor (Max CP/(Max BP x13 bundles)	0.625	0.625
Overall Form Factor (Average BP/Max BP)	0.546	0.54

The time-average full core system achieved a full core average burnup of 29.98 MWD/kgHE resulting in an actinide destruction level of 34.76% or 180 g/bundle as detailed in Table 3. The actinides are consumed with the exception of Cm which is produced due to neutron capture in Am and Pu. However, this is not of concern Cm isotopes (98% of which are Cm-244 and lower) are a small portion of the fuel and do not affect long-term heat load. Although it is an actinide, the long term radiotoxicity and heat load behaviour of Cmis similar to fission products. Thus both contributions become insignificant in the long-term (>100 years).

Table 3Actinide Destruction (Burnup = 29.98 MWD/kgHE)

Conc. (g/bundle)	U 235	Np Total	Pu Total	Am Total	Cm Total	Total Actinides
Initial	119.88	24.43	439.23	55.48	0.45	519.58
Final	24.55	13.47	293.09	20.80	11.62	338.99
Final-Initial	-95.34	-10.96	-146.13	-34.68	11.17	-180.59
% change	-79.53%	-44.86%	-33.27%	-62.51%	2491.04%	-34.76%

The time-average performance was checked using several instantaneous snapshot models with channel ages assigned based on operational simulations. A patterned random channel age distribution (PRCAD) was used[8, 14]. This snapshot assessment ensuredthe channel and bundle powers remained below CANDU limits (BP < 935 kW and CP <7.3 MW). The following sections evaluate the finalized time average design to assess the operational performance of the TRUMOX-30-CANDU-900and compare it to an NU-CANDU-900.

3. Full Core Model Assessment and Operational Simulations

The full core TRUMOX-30-CANDU-900 model was assessed in terms of performance and compared to a standard NU-CANDU-900 for various common operational events. The evaluations on the time average nature of the core include flux shape, control device worth and modal analysis. Operational transients are then assessed such as loss of coolant events and fuelling and fuel ramp modelling.

The TRUMOX-30 fuel with its high concentration of actinides and smaller fuel bundle shifts has a much flatter axial flux profile than NU. In an NU-CANDU-900, the adjuster rods are held in the core during operations to provide axial flattening. However, in the TRUMOX core the flux is flattened by the large actinide content in the fuel thus allowing the adjusters to be left out of the core. Even with the adjusters out of the core, the TRUMOX-30-CANDU-900 has a much flatter thermal flux. The actinide content introduces a large amount of material that absorbs thermal flux and burns up as the fuel passes through the core. Thus the flux is lower inthe TRUMOX-30 case than for an NU case and the axial flux is also flatter along the channel as the actinides absorb the flux and are depleted at a similar rate to the fissile material. The axial flux profile for TRUMOX is provided in Figure 3 and compared with that ofNU-CANDU-900 (with adjusters inserted) for a central channel in the core (M12).

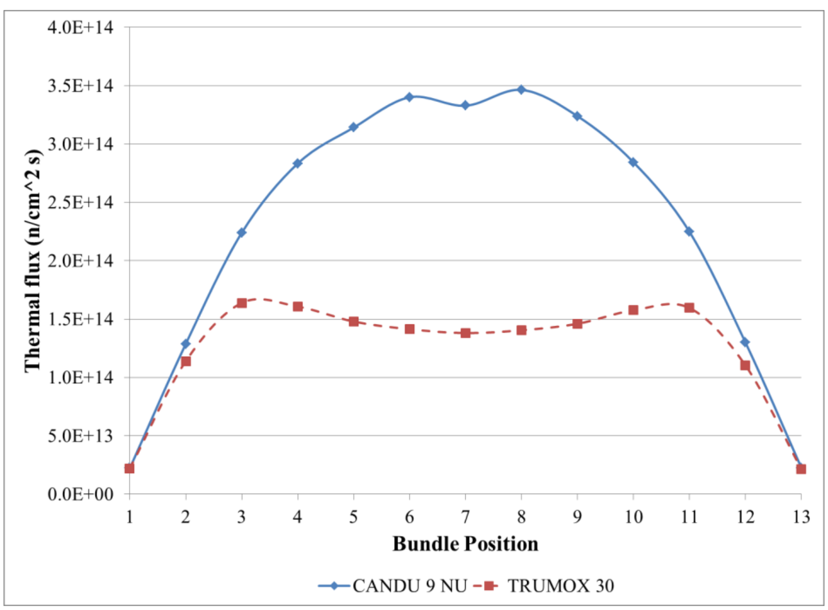

Figure 3 Axial Thermal Flux Profile (lattice cell averaged flux) in centre of core (chan. M12)

The flattened axial profile and lower flux level in the core has implications on the controllability and responses of the core to certain situations. The effects of the flat axial profile are seen in the control device worth assessment and in the harmonic mode analysis.

3.1 Control Device Reactivity Worth

The response of the reactor control system is important for determining the fuel compatibility with the reactor design and will determine if the operational envelope can be maintained. For the CANDU-900 reactor the control devices include adjuster rods, mechanical control absorbers (MCAs), liquid zone controllers (LZCRs) and shutdown system 1 rods (SDS1). Simulations model the insertion and/or removal of the devices into a time average core to determine the reactivity worth of the device. The LZCRs are designed for fine control and consist of 14 vessels of H_2O distributed throughout the core. Altering the water levels controls neutron absorption in the core and their distributed nature allows for both bulk and spatial control. The adjuster rods are 24 neutron absorbing rods arranged in (typically) 7 banks and for the TRUMOX-30-CANDU-900 configuration are held out of the core (for an NU core, the adjusters are usually left inserted in the core to produce a flat flux profile and to provide a positive reactivity reserve to counteract xenon buildup). The MCAs are 4 neutron absorbing rods normally positioned outside the core and driven in to provide additional negative reactivity. The adjusters and MCAs are coarse control supplements to the fine control of the LZCRs. SDS 1 is a set of 32 neutron absorbing rods deployed in 4 banks poised above the core ready to be released to initiate reactor shutdown. These rods are arrayed across the core and are designed to provide rapid shutdown even if the two strongest rods are unavailable. The time-average reactivity worths of the control devicesare presented for the TRUMOX-30-CANDU-900 in Table 4 along with standard NU-CANDU-900 values.

Table 4Approximate reactivity worth of control devices.

Device	**TRUMOX Worth (mk), ($)**	**NU fuel Worth[13] (mk), ($)***
LZCRs 0% to 100% Full	3.90, $1.01	~7.00, $1.20
LZCRs0% to 42% Full	2.01, $0.52	~3.40, $0.59
LZCRs42% to 100% Full	1.89, $0.49	~3.60, $0.61
Adjuster Rods	3.14, $0.81	~ 15.00, $2.58
Mechanical Absorbers (MCAs)	4.38, $1.13	~ 10.00, $1.72
Shutdown System (SDS 1)	55.01, $14.25	~80.00, $13.75

*Approximate, slight variations between reactors. **Note:**Only NU runs with adjusters in core, TRUMOX does not. Exit burnup for TRUMOX = 30.0MWd/kgHE, NU fuel =9.0MWd/kgHE

The absolute reactivity worth for each of the control devices is considerably lower than the typical values for CANDU with NU fuel. The TRUMOX fuel with its high fissile content and actinides has a higher ratio of $\upsilon\Sigma_f/\Sigma_a$ at thermal energies effectively increasing the number of fissions to be controlled by the control device and reducing the absolute reactivity worth. The TRUMOX fuel has a lower delayed neutron fraction, β value, than NU (~34%)due to the larger plutonium content. The full core delayed neutron fractions for the two core types are NU-CANDU-900$\beta_{FC} = 5.82\ mk$ [15]; TRUMOX-30-CANDU-900$\beta_{FC} \sim 3.86\ mk$. Using the delayed neutron fractions, the relative dollar worth, ($\Delta\rho/\beta$ in \$), of the control devices was also computed and provided in Table 4. The relative worth values are much closer for the LZCRs and MCAs as the differences in delayed fraction offset the lower absolute worth.

The flatter axial flux profile of the TRUMOX fuel has displaced the flux in some areas of the core where the control devices interact, reducing their effectiveness.This is most visible in the worth of the adjusters which are designed to act in the locations of peak flux in the NU-CANDU-900 system (between bundles 5 and 8). Due to the flat axial profile, seen earlier in Figure 3, the flux in this region is lower resulting in a lower worth for the adjusters (relative worth is more that 65% lower than NU). The flux where the adjusters interact is lower, having already been flattened by the presence of the actinides in the fuel. However, since the adjusters are now designed to be positioned outside the core during operations they can be repurposed to provide negative reactivity to supplementthe LZCRs and MCAs. Therefore, the combined relative worth of the adjusters and MCAs in the TRUMOX case can be compared to the MCA worth in the NU case. The combined worth of inserting the adjusters and absorbers into the TRUMOX core is approximately \$1.78 which is quite comparable to the NU core absorber worth of \$1.72. The more distributed systems such as the LZCRs and SDS rods see smaller decreases as they are still acting in areas of significant flux.

Another factor in controllability is the prompt neutron generation time, Λ, which together with the delayed neutron fraction, β, provides information on the reactor kinetics of the core.The values for delayed fraction and generation time in the TRUMOX core are lower than for an NU core. The point kinetics equations, shown below with 6 delayed neutron groups, help to estimate the kinetic response of a specific core configuration [16].

$$\frac{dn}{dt} = \left[\frac{\rho(t)-\beta}{\Lambda}\right]n(t) + \sum_{i=1}^{6}\lambda_i C_i \quad where, \quad \frac{dC_i}{dt} = \frac{\beta}{\Lambda}n(t) - \lambda_i C_i(t), \quad i = 1,\dots,6 \qquad [16]$$

From the point kinetics equations it is evident that the ratio of β/Λ is an important factor in the kinetics response of the core. Thus a comparison of the ratios for the NU and TRUMOX-30 cores is prudent. For NU, the delayed fraction of 5.82 mk and generation time of 0.688 ms results in a β/Λ ratio of 8.46 mk/ms. In the case of TRUMOX-30, the delayed fraction of 3.86 mk and generation time of 0.427 ms results in a β/Λ ratio of 9.04 mk/ms. Thus the β/Λ ratio is only approximately 6.9% higher for the TRUMOX-30 case than for NU, indicating a similar kinetic response which is slightly faster in the TRUMOX core.An interesting comparison in response can be made using the point kinetics equation for a static reactivity injection or for a common event such as a draining of the liquid zones. In both cases we can examine the $n(t)$ multiple in the point kinetics equation [$(\rho(t)-\beta)/\Lambda$] to compare the response of the NU and TRUMOX cores. For a static reactivity injection of 2mkthe resultant multiple value is -4.36 mk/ms for TRUMOX and -5.55 mk/ms for NU. For a liquid zone drain from steady state, the reactivity injection is 2.01mk for TRUMOX and 3.40 mkfor NU.

Thus the multiple is -4.33mk/ms for TRUMOX and -3.52 mk/ms for NU.The effects of the worth of the reactivity devices on neutron overpower characteristics are of interest as is the xenon behavior of the TRUMOX-30-CANDU-900 and are suitable for future studies.

3.2 Harmonic Mode Analysis

The effects of the change in axial flux profile are also seen in an analysis of the harmonic modes of the neutron diffusion equation. These are powerful tools for evaluating and comparing the flux shapes and neutronics behaviour of different reactor configurations. The lowest level harmonic or “Fundamental” mode is the flux shape calculated by solving the neutron diffusion equation as a critical system and has the largest value of k-effective and hence the smallest eigenvalue for the given set of nuclear properties. The higher harmonics have smaller k-effective values (larger eigenvalues) and thus represent sub-critical flux shapes. These cannot exist as a “self-standing” reactor state due to the regions of negative flux (which is non-physical). The modes also provide insight on the sensitivity of the core to tilting in various directions. The flatter axial profile of the TRUMOX-30-CANDU-900 alters the response to axial tilting compared to an NU-CANDU-900.Lower sub-criticality in a mode is a sign that the core will be more susceptible to tilting in that mode. The first 10 harmonic modes for the TRUMOX-30 case were calculated and compared to NUreference values [17]. The sub-criticalities for the modes of both designs are compared in Figure 4.

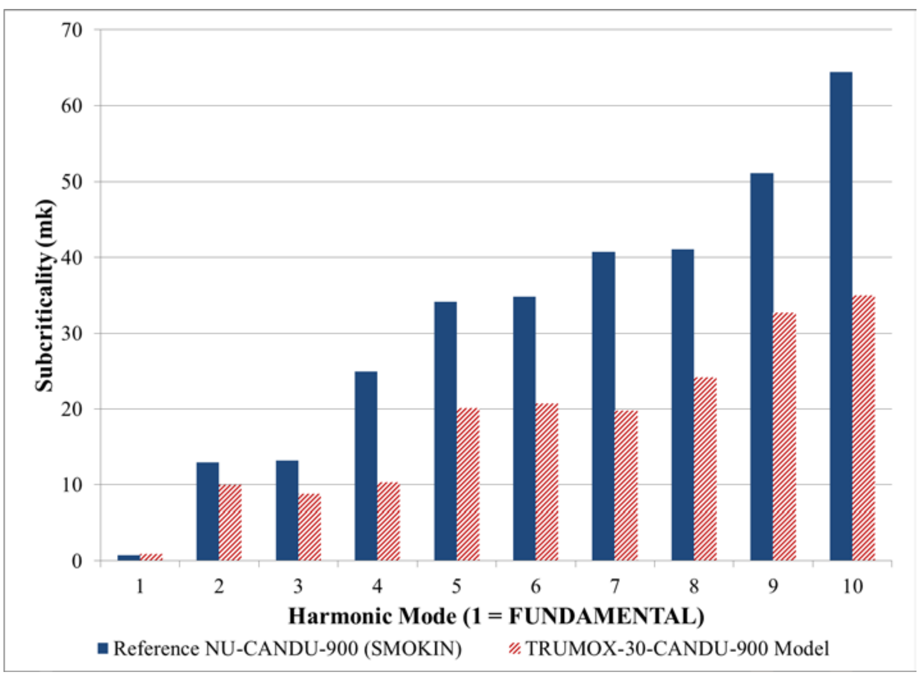

Figure 4Sub-criticalities for the Harmonic Modes for CANDU-900 fueled with TRUMOX-30 and NU [17]

The TRUMOX core sub-criticalities are lower than for NU but follow a similar trend for most of the modes. The lower modes (1, 2 and 3) are affected by the increased radial flattening as the radial form factor of this core is 0.874 compared to approximately 0.85 for the NU reference core. The flatter the channel power profile is, the lower the sub-criticalities of the higher modes. The axial modes (4 and 7) are significantly different due to the flatter axial flux in TRUMOX caused by the fuel composition. Examining the change in sub-criticality from mode to mode for these cases can help to further detail the differences in the axial modes. The sub-criticality of higher modes builds on the lower modes thuschanges from one mode to the next provide information on how a mode affects the core.

The changes in sub-criticality from mode to mode for the primary axial modes are significantly lower for TRUMOX than NU. The change from mode 3 to 4 is 1.46 mk for TRUMOX and 11.75mk for NU while the change for mode 6 to 7 is -0.93 mk for TRUMOX and 5.88 mk for NU. These differences surrounding the main axial modes indicate an increased susceptibility to tilting in the axial direction for TRUMOX. This susceptibility to tilting is due to the flatter axial flux profile in TRUMOXcaused by the 1 or 2 bundle shift fuelling scheme and minor actinide presence in the fuel. This effect is somewhat mitigated by the fact that the liquid zone controllers are better able to balance the flatter axial flux and dampen the tilting. Overall the lower sub-criticalities in the modes for the TRUMOX case indicate that these modes can be more easily excited. This may result in a core that is more susceptible to tilting than an NU core. The response of the control systems and reactor to accident conditions such as loss of coolant is another important area of investigation.

3.3 Response to Loss of Coolant

The pressure tube design of CANDU separates the coolant from the moderator and thus a loss of coolant is not also a loss of moderator. Thus the response of the reactor to the loss of coolant is important in a CANDU system as the coolant void reactivity (CVR) is generally positive. There are two sets of changes when the core moves into a state where the moderator is present but the coolant is not. For neutrons born from fission in the fuel the lack of coolant means less of the neutrons are slowed into the resonance region resulting in more opportunities for fast fission and a higher probability of escaping resonance capture producing two positive effects on reactivity. For thermalized neutrons re-entering the channel from the moderator there is no hot coolant present and thus less up-scatter into resonance energies occurs, this leads to less resonance capture for U-238 but also reduces the resonance fission in Pu-239 producing both a positive and negative reactivity effect. The net result of these four bulk effects within the lattice cell (3 positive and 1 negative) is the CVR. In addition to the bulk physics effect in the lattice, there is a flux effect local to the fuel channels. Upon voiding of the coolant, the thermal flux increases in the center of the fuel channel and decreases at the outer edge and in the moderator. This flux displacement increases absorption (and fission for fuel material) in the center of the channel. If there is a BNA located in the center, this flux displacement will produce a negative effect on the reactivity. The TRUMOX-30 fuel,as described in Section 2, contains a strong BNA in the central element that impacts the CVR.

Coolant void effect is computed by comparing a normal simulation with one where the coolant density is reduced by a factor of $\rho_{liquid} / \rho_{vapour} \approx 1000$. The voiding can occur in every channel in the core at once or more realisticallyin only one side of the core or in checkerboard pattern across the core.The concept of instantaneous uniform full core coolant voiding is not physically plausible due to the primary heat transport system (PHTS) design but it provides a means of comparison between the two reactor designs (TRUMOX and NU). The half core voiding event is more realistic with one side of the core voiding while the other side of the core remains fully cooled. The CANDU-900 PHTS has a two loop design where each half of the core (240 channels) is serviced by a separate system of a large header connected to each channel by a feeder pipe and to two steam generators with the flow driven by two heat transport pumps. A large loss of coolant in a CANDU-900 system is consistent with a single header break which quickly voids one coolant loop and the 240 associated fuel channels on that side of the core (e.g. the LHS). The other side of the core (e.g. the RHS), which is fed by the other coolant loop that is still intact, experiences a small break loss of coolant through the loop interconnect piping that is a much slower transient. The result is one side of the core being fully voided while the other still contains a nearly full coolant load.In all cases the TRUMOX-30 core has a much lower instantaneous CVR than the NU core as seen in Table 5. This is due to the strong BNA in the central pin of the TRUMOX fuel bundles which causes an injection of negative reactivity during voiding that mitigates the positive reactivity effects caused by the loss of coolant.

Table 5Response to Coolant Voiding.

Event	**TRUMOX Response (mk), ($)**	**NU Response (mk), ($)**
Instantaneous full core void	1.79, $0.46	12.57, $2.16
Instant left half of core void	0.97, $0.25	8.81, $1.51
Checkerboard void	0.80, $0.21	6.30, $1.08
Note: $\beta_{\text{Full Core TRUMOX}}$ = 3.86 mkand $\beta_{\text{Full Core NU}}$ = 5.82 mk		

The CVR for a left half voiding will be larger than 50% the full core CVR due to the flux tilt caused from the coolant imbalance (the cooled side of the core has increased fission). This flux tilt effect of the half core voiding is lower in TRUMOX (half core void is 54% of full core CVR) than NU (half core void is 70% of full core CVR).The checkerboard voiding scenario is not technically possible in the CANDU-900 design as the PHTS is a 2-loop configuration servicing each half of the core. However, other proposed CANDU configurations, such as the ACR, have the PHTS loops service alternating channels within the core such that if one loop fails a checkerboard pattern of voiding will occur in the core. The ACR design uncovered that checkerboard void resulted in a substantially different void coefficient mostly due to the smaller lattice pitch and light water coolant used in the design. Both the NU and TRUMOX cases have the larger CANDU-900 lattice pitch (28.575 cm) and use a heavy water coolant and moderator so the effects of the checkerboard void event elicits less response than a left half voiding and is not of specific concern.

These instantaneous simulations are not realistic and do not include any reactor control or shutdown system action. In a loss of coolant accident (LOCA)a break may be nearly instantaneous but the voiding transient for the loop and thus the reactivity transient within the core takes time to propagate before it reaches such a point where half the core is voided.However, these simulationsprovide information on general core behaviour and allow comparison between the designs.

A more realistic comparison can be made using a density transient that simulates a loss of coolant event more closely. A density transient for a 100% pump discharge LOCA in a CANDU reactor loop is utilized for this study to simulate a voiding transient in the left half of the core. The right half of the core will experience a depressurization through the loop interconnect piping but this transient is much slower so the voiding transient will run almost completely through on the left hand side of the core while the right hand side channel coolant densities remain near nominal values, resulting in a voiding of one half of the core. The density transient for the first 2.5 seconds the event was used to simulate the loss of coolant event in RFSP for both the TRUMOX-30-CANDU-900 and NU-CANDU-900 configurations[18]. This simulated transient does not include any power change effects or shutdown system actions. The coolant void reactivity response is presented in Figure 6 for both cases. The left hand side of the core experiences the density transient in the figure while the right hand side of the core maintains the nominal coolant density (~0.8 g/cm^3).

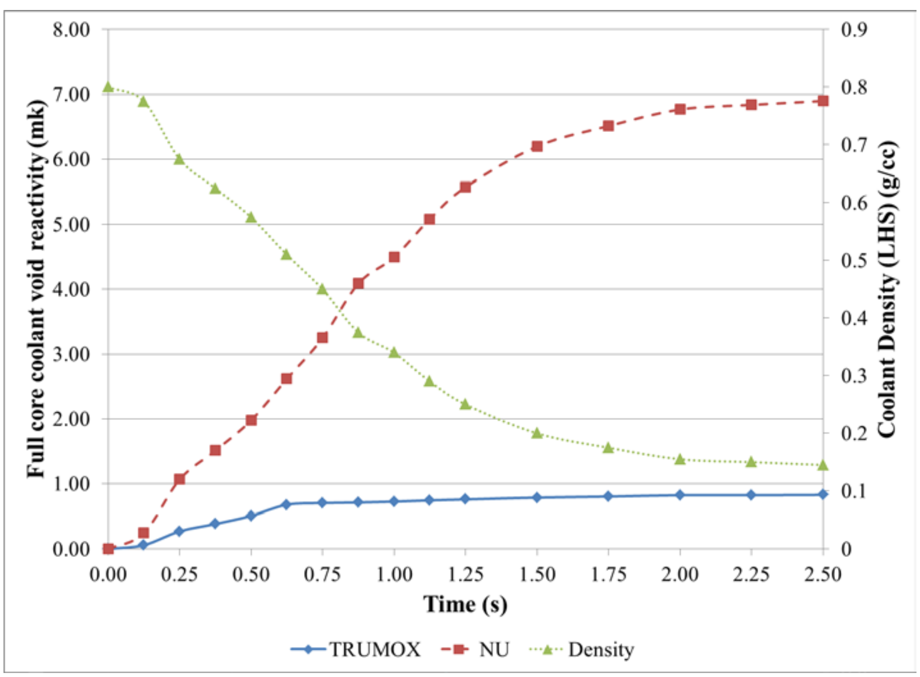

Figure 6 LOCA Density Transient Effects for TRUMOX-30 and NU (LHS of Core isVoided)

As expected from the previous results, the response of the TRUMOX fuel is more favourable for this case than NU. The peak void reactivity is 0.83 mk ($0.21) for TRUMOX and 6.90 mk ($1.18) for the NU case. It should also be noted that the TRUMOX void reactivity transient plateaus much faster than the NU case resulting is a smoother response. As discussed earlier, the inclusion of the BNA in the TRUMOX fuel bundle is the main cause of the reduced CVR response. Overall the TRUMOX core has CVR values that are more than 80% lower than NU-CANDU-900. These represent a potential improvement in LOCA response since lower CVR will lead to lower predicted fuel centerline and sheath temperatures. However, full coupled-code accident analysis was not performed in this study.

3.4 Fuelling Simulations and Fuel Ramp Assessments

The CANDU design uses continuous online fuelling of the channels during operation and thus the effects of fuelling transients on the behavior of the control systems and the bundle powers must be assessed. These fuelling operations can cause local power peaking and spatial variances in the core reactivity.The reactivity insertion from fuelling is controlled by adjusting the liquid zone controller levels in the core to compensate for the local reactivity insertion and maintain the desired bulk power level in the core while avoiding local power spikes that exceed the prescribed limits. The effects of fuelling the core on the control system are very important in determining if the capabilities of the controllers are adequate to handle the fuel, and the power ramp rate that the fuel undergoes. The bundle and channel powers are monitored, along with the fill levels of the liquid zone controllers and power ramps to ensure the reactor remains within operational limits with the TRUMOX fuel.The fuelling of the TRUMOX-30-CANDU-900 is more complicated than for NU-CANDU-900 as the fuel is more active and uses smaller bundle shifts.

An NU-CANDU-900 has a reactivity decay rate of -0.42 mk/full power day (FPD) requiring a fuelling rate of approximately 15-16 bundles/FPD, usually accomplished by fueling 3 to 4 channels with 4 to 8 bundle shifts [13]. The TRUMOX fuel is much more reactive and requires fewer bundles to be fuelled but since fuelling is accomplished by 1 and 2 bundle shifts the fueling rate, in terms of channels visited per day, is higher. The reactivity decay rate of TRUMOX fuel is lower at -0.37 mk/FPD resulting in a fuelling rate of 5.33 bundles/FPD (approximately 1/3 of the daily fuel bundle requirement for NU). Using 1 and 2 bundle shifts this fuelling rate is approximately 4.63 channel visits/FPD. The reactivity of the fuel dictates the small sized fuelling shifts as a TRUMOX bundle has an average reactivity of 0.069 mk/bundle compared to only 0.026 mk/bundle for NU fuel (reactivity decay rate/fuelling rate in bundles). Considering that the TRUMOX fuel bundle has 2.65 times the average reactivity of the NU bundle the 1 and 2 bundle shift scheme is appropriate. Additionally, the 2 bundle shifts are restricted to the low power channels on the periphery of the core (136 channels in this case). These basic time-average properties are used to produce a realistic single full power day simulation that will evaluate the fuelling effects in TRUMOX-30-CANDU-900.

The detailed fuelling simulation begins from an instantaneous snapshot and tests the response of the core, fuel and LZCRs. This evaluation is different from instantaneous snapshot studies as it looks at the direct control responses of the liquid zones to a fuelling event in the core and the ramp rates on the fuel. From the initial snapshot core a time dependent RFSP simulation is performed wherein fuel is inserted into a channel and the direct changes on channel and bundle power and the liquid zone levels across the core are observed. The simulation performed here is one full power day (24 hours) of operation from 9 am to 9 am with 4 fuelling actions that load 5 bundles of TRUMOX into the core.

The fuellings are conducted at the beginning of the day and the channels are fuelled at 3 hour intervals (9 am, 12 pm, 3 pm and 6 pm). The first shift is a 2 bundle movement into channel P24 followed by three consecutive one-bundle movements into channels E6, M16 and R4. The average zone level for the day is tracked in Figure 7.

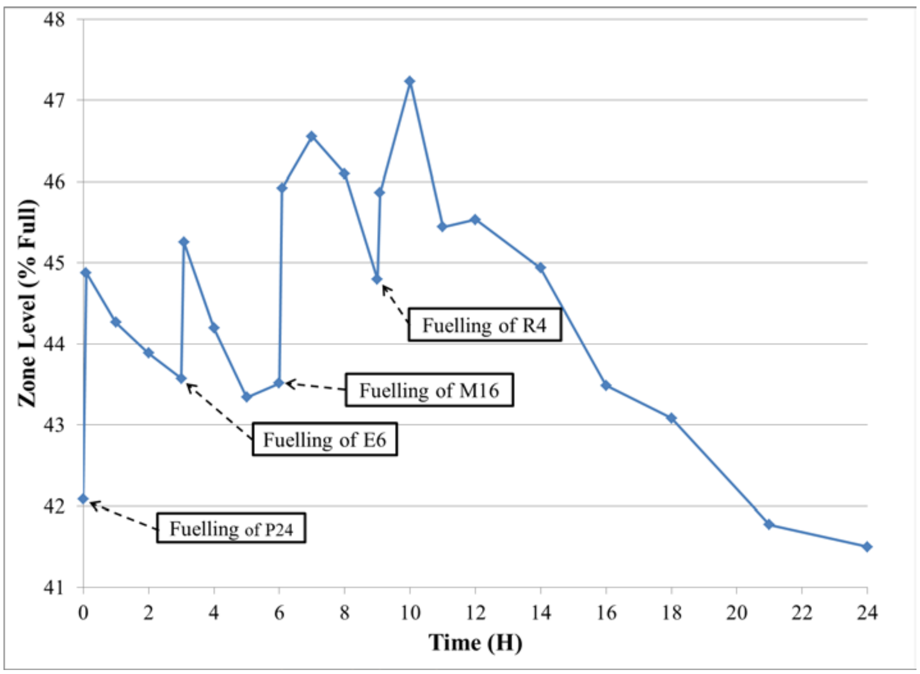

Figure7Average zone level responses for 1FPD of fuelled operations in TRUMOX-30-CANDU-900

The average zone level fluctuates between 41.5% and 47.2% which is relatively small but the maximum and minimum zone levels achieved are 78.0% and 20.0%, a spread of 58.0%. The four individual fuelling events have different effects on the average zone level. The fuelling of M16 has the largest effect increasing the average zone level by 3.04% full or approximately 0.119 mk of reactivity even more than P24 which, despite being a two bundle shift, affects the average zone level by 2.80% full (0.109mk) since it is in the outer region. The fuelling of E6 has an effect of 1.68% full or 0.066 mk and the fuelling of R4 has an effect of 2.44% full on average liquid zone level (0.095 mk). The bundle and channel powers were maintained below the limits during the full simulation with the maximum channel power of 6.91 MW and the maximum bundle power of 844 kW. The average zone level falls at the end of the simulation as it will soon be time to start fuelling again.

Although caution should be taken to avoid excessive fuelling in one zone and fuelling induced flux tilts must be monitored, the control system is able to handle the reactivity inputs from fuelling. This fuelling simulation proved that the TRUMOX-30-CANDU-900 was able to handle day-to-day fuelling within the prescribed operational envelope.

Outside of the control system responses, it is important to assess the effects of the fuelling transients on the bundle powers to ensure that they do not exceed their limits and compromise fuel sheath integrity. The fuelling process not only introduces fresh fuel into the core it also shifts low burnup fuel into the higher flux region in the center of the core. The fuelling shift thus produces a local power transient, having an effect on the power level of each of the bundles in the fuelled channel as well as the bundles in the adjacent channels. These local power changes are termed the fuel ramp rate, and if they exceed predetermined limits there may be a higher probability of fuel defects. The specific limits on power and the ramp rate are based on the linear element rating and changes with fuel burnup. It should be noted that due to the bi-directional fuelling design of CANDU, adjacent channels are fuelled from opposite ends and older fuel bundles with high burnup will be exposed to power transients from fuelling adjacent channels with new fuel.

The limits of the TRUMOX-30 fuel design are different from that of NU fuel as the bundle configuration (number of fuel pins, arrangement and pin diameters) is different, the fissile content is higher and the burnup levels are higher. Therefore, the standard NU limits for fuel ramps are not suitable for use in evaluating the TRUMOX-30 fuel.

However, the TRUMOX-30 fuel is quite comparable to the fuel design used for the Advanced CANDU Reactor (ACR).The development ACR included studies to prove the design adequacy of the ACR fuel [19] and to define the operational envelope for the fuel [20] along with simulating refueling transients [21]. The ACR and TRUMOX-30 design share a common bundle configuration, 43-elements with a larger diameter central BNA and similar fuel pin diameters. Additionally, the fissile contents are similar (~2.4%vs 2.53% for TRUMOX-30) along with the fuel burnup range (~20-35 MWD/kgHEvs ~30-35MWD/kgHE for TRUMOX-30) [19].

Given the similarities between the two fuel types it is logical to apply the ACR fuel envelope to the TRUMOX-30 fuel in order to determine if the fuelling shifts experienced in the TRUMOX-30-CANDU-900 are within acceptable limits. The ACR limit is given in terms of linear element rating (kW/m)and is translated into macroscopic bundle power to compare to the data provided by the RFSP simulations. The maximum linear element rating is converted to kW by multiplying by the bundle length (0.4953 m) and then scaled based on the maximum pin power factor of the fuel for that specific burnup. The TRUMOX-30 fuel experiences maximum pin powers in the outer ring with pin power factor (PPF) values of 1.136 to 1.445

over the burnup cycle of 30 MWD/kgHE. This power is then multiplied by the number of fuel elements to get the bundle power.

The ACR fuel operational envelope is for sustained power with a maximum linear rating limit of 58 kW/m. The maximum linear ratings during fuelling for ACR are 64 kW/m for fresh fuel and 69 kW/m for irradiated fuel [19]. Using the highest PPF encountered over the TRUMOX-30 fuel burnup cycle, 1.45, the limit on sustained bundle power is 832kW and the limits on bundle power during fueling are 918 kW and 989 kW for fresh and irradiated fuel respectively. These transient fuelling limits are only valid for a short time during and after the fuelling operation (<1 hour) after which the standard fuel envelope applies again.

For the TRUMOX-30-CANDU-900 fuelling events described earlier, the fuelling of a central channel in the core will likely cause the largest impacts on bundle power and is thus compared to the derived defect limits. This corresponds to the fuelling of channel M16 which fuels from the left end of the channel therefore bundle 1 is extracted and a new bundle is placed into position 13. The lowest burnup position is 13 while the highest burnup occurs in position 1. The transient resulting from the fuelling of channel M16 is compared to the ACR fuel operational envelope in Figure 8.

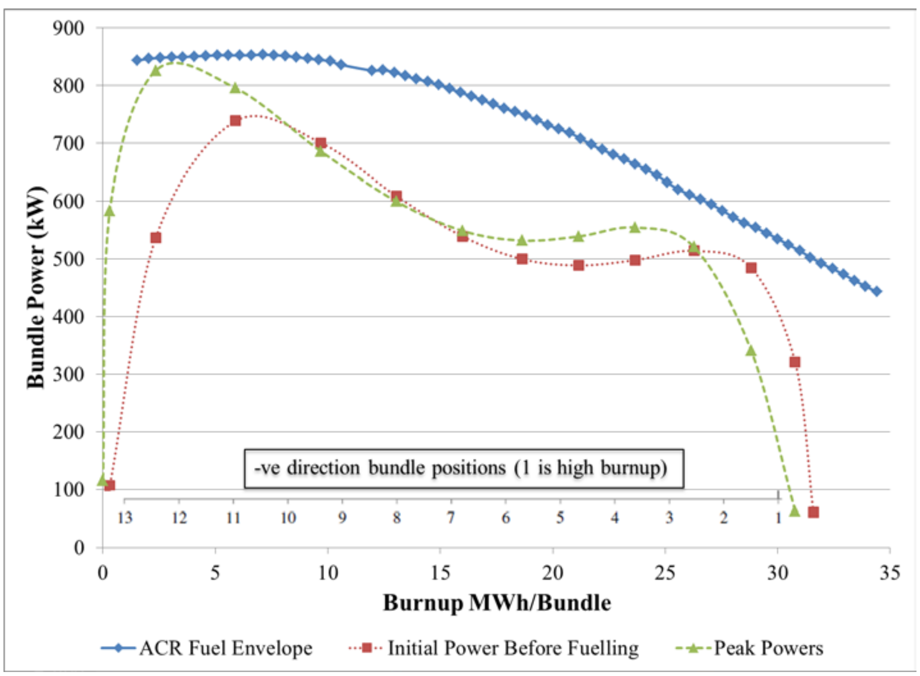

Figure 8Comparison of M16 Fuelling Transient to ACR Fuel Operational Envelope

The peak bundle powers in M16 during the transient come close to the limit but are still within the envelope. The initial bundle powers in M16 before the fuelling are well within the ACR fuel envelope.The peaking bundle powers are the result of two effects, the reactivity insertion from fuelling and the axial flux shape in the core. For TRUMOX, the axial flux shape is peaked at the ends of the core in positions 3 and 11, as discussed earlier in Section 3. This peaking in the ends of the channel means that the fresh fuel is being inserted into higher flux regions than would be the case for NU resulting in larger bundle power ramps.

The channels near the fuelled channel also experience a bundle power transient due to the fuelling. This is less than in the fuelled channel but due to the bi-directional nature of fuelling in CANDU the channels adjacent to the fuelled channel may experience the highest change bundle power in a high burnup bundle which can become limiting as the criteria decreases with burnup. The effect of the M16 fuelling transient on the surrounding channels was explored and despite the above concerns, the adjacent channels experienced smaller power changes and had large margins to the ACR limit.

The channels in the periphery of the core will experience similar transients but with lower initial powers. However, the use of two-bundle fuelling shifts in these channels may result in higher reactivity transients that couldproduce bundle powers that may exceed the limits. Thus thetwo-bundle-shift fuelling of Channel P24 is explored in a similar fashion to that of channel M16. The fueling transient in Channel P24 produces a large increase in the bundle powers in P24 and the adjacent channels. The changes in bundle powers due to the P24 fuel transient are larger than those encountered for the one bundle shift fuelling for channel M16 but the margin to the top of the fuel envelope is also much larger for the fuelling in the periphery channel P24. The channels adjacent to P24 have similarly large margin to the ACR limit. Since the periphery channels are at much lower powers than the central channels the large changes in bundle power produced by the two-bundle-shift fuelling can be accommodated without stressing the limits dictated by the ACR fuel envelope.The assessments made here show that for a fuelling transient in both a high power central channel and a lower power periphery channel, the bundle powers in the TRUMOX-30-CANDU-900 core remain within the ACR fuel operating envelope and the fuel defect probability is low.

4. Conclusion

Theemployment of Transuranic Mixed Oxide (TRUMOX) fuel in the CANDU-900 reactor was shown to be feasible and several assessments of the full core model demonstrated an ability to operate within the standard CANDU envelope. The TRUMOX-30 fuel used in this study was a mixed oxide containing 96.9% NU blended with 3.1 wt% transuranic actinides (Np, Pu, Am and Cm). The actinides were reprocessed from spent LWR fuel that had cooled for 30 years.The TRUMOX-30-CANDU-900 design had a burnup of 30MWD/kgHE, maintained bundle and channel power limits at all times and achieved a significant actinide conversion (~35%). Assessments of the full core model included controllability and device worth, harmonic mode analysis, response to loss of coolant events and fuelling transients.

The controllability and device worth for the TRUMOX core were found to be similar to that of an NU core with a slightly faster core response. The harmonic mode analysis showed that the TRUMOX design may be more susceptible to axial tilting due to a flatter axial flux profile caused by the actinides in the fuel. The response to coolant voiding is more favourable in the TRUMOX core than NU due to the central burnable absorber pin in the TRUMOX fuel bundle. During the fuelling studies the TRUMOX fuel performed well and within the normal CANDU operating limits. The fuel ramp assessments found that the TRUMOX fuel stayed within the Advanced CANDU reactor fuel envelope for both high-power central core and low-power periphery fuelling events thus maintaining a very low probability of fuel defects. The simulations demonstrate that the TRUMOX-30 fuel is controllable by the current CANDU-900 control system and will remain within the standard operational envelope prescribed for CANDU. This reactor design will reduce fuel disposal costs and the increased costs of TRUMOX fuel can be offset by the efficiency gains of higher burnup. The use of reprocessed actinides increases the recycling and reuse of spent fuel producing a more efficient and sustainable fuel cycle.

5. Acknowledgements

The authors would like to thank the Computational Reactor Physics Branch at AECL Chalk River Labs especially B. Bromley, B. Hyland and G. McGee for their reviews and editorial comments. Funding and support for this research was provided by Atomic Energy of Canada Limited (AECL), The University Network for Excellence in Nuclear Engineering (UNENE), Nuclear Ontario, The Ontario Ministry of Research and Innovations and the National Science and Engineering Research Council (NSERC).

6. References

[1] L.H. Baetsle and Ch. De Raedt, “Limitations of actinide recycle and fuel cycle consequences, Part 2”, *Nuclear Engineering and Design*, **Iss. 168**, p. 203-210, (1997).

[2] R. A. Wigeland, et al, “Impact on Geologic Repository Usage from Limited Actinide Recycle in Pressurized Light Water Reactors”, *Nuclear Science and Technology*, **Vol. 44, No. 3**, p. 415-422, (2007).

[3] T. A. Taiwo, et al, “Assessment of a Heterogeneous PWR Assembly for Plutonium and Minor Actinide Recycle”, *Nuclear Technology*, **Vol. 155**, p. 34-54, (2006)

[4] P. Boczar, et al, “Global Warming and Sustainable Energy Supply with CANDU Nuclear Power Systems”, *Prog.inNucl.Energy***, Vol. 32, No. ¾,** p. 297-304, (1998).

[5] P. G. Boczar, J. R. Hopkins, H. Feinroth and J.C. Luxat, “Plutonium Disposition in CANDU”, *Proc. IAEA Technical Meeting on Recycling of Plutonium and Uranium in Water Reactor Fuels*, Windermere, U. K., July 1995.

[6] A. C. Morreale, et al, “The reactor physics characteristics of a transuranic mixed oxide fuel in a heavy water moderated reactor” *Nucl. Eng. and Des.*,**Vol. 241**, pp. 3768-3776 (2011).

[7] A. C. Morreale, et al., “The behaviour of Transuranic Mixed Oxide Fuel in a CANDU-900 Reactor” *Proc. PHYSOR 2012*, Knoxville, TN, USA., April 15-20, 2012.

[8] A. C. Morreale, et al., “The behavior of Transuranic Mixed Oxide Fuel in a CANDU-900 Reactor” *Nuclear Technology*, **In Press**, (July 2013).

[9] D. Altipamarkov, "New Capabilities of the Lattice Code WIMS-AECL", *Proc. PHYSOR-2008*, Interlaken, Switzerland, September 14-19, 2008.

[10] G. Marleau, A. Hebert and R. Roy, “A User Guide for DRAGON,” Report IGE-174 Rev.5, ÉcolePolytechnique de Montréal, April 2000.

[11] B. Rouben, “RFSP-IST, The Industry Standard Tool Computer Program for CANDU Reactor Core Design and Analysis”, *Proc. 13th Pacific Basin Nuclear Conference*, Shenzhen, China, October 21-25, 2002.

[12] V. G. Snell, J. R. Webb, “CANDU 9 – The CANDU Product To Meet Customer and Regulator Requirements Now and In the Future”, *Proc. 11th Pacific Basin Nuclear Conference*, Banff, Canada, May 3-7, 1998.

[13] B. Rouben, “Introduction to Reactor Physics”, [On-Line], Available: https://canteach.candu.org/Content%20Library/20040502.pdf (2002)

[14] Z. Xing Guan, et al., “Physics Codes and Methods for CANDU Reactor.”*Nuclear Power Engineering*.**1999-06** (1996)

[15] P. G. Boczar et al, “Plutonium Dispositioning in CANDU” *Proc. IAEA Technical Committee Meeting on Recycling of Plutonium and Uranium in Water Reactor Fuels*, Newby Bridge, U.K., July, 1995.

[16] J. J. Duderstadt, L. J. Hamilton, *Nuclear Reactor Analysis*, John Wiley and Sons, Inc. New York, NY, USA., 1976

[17] M. Gold, “SMOKIN-A Family of Codes for Reactor Space-Time Neutronics Calculations Based on Modal Kinetics – Theory Manual” **OH- 90133**, Ontario Hydro, Toronto (1990).

[18] “Plutonium Consumption Program CANDU Reactor Product, Appendix C: Supplementary Data and Licensing”, **DE-AC03-94SF20218**, AECL Technologies Inc., Rockville, MD, USA (1994).

[19] J. Chang, et al., “Proof of Design Adequacy for the ACR-1000 Fuel Bundle” *Proc. 10th CNS International Conference on CANDU Fuel*, Ottawa, Canada, October 5-8, 2008.

[20] J. Hood, F. Iglesias, “Construction of ACR-1000 Fuel Element Operating Envelopes”,*Proc. 10th CNS Intl. Conf. on CANDU Fuel*, Ottawa, Canada, October 5-8, 2008.

[21] J. Hu, I. Martchouk, R. Robinson, “RFSP-IST Simulation of Fuel Transient During Refuelling the ACR-1000 Reactor”,*Proc. 29th Annual Conference of the Canadian Nuclear Society*, Toronto, Canada, June 1-4, 2008.