TRANSURANIC MIXED OXIDE FUEL USE IN CANDU

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Abstract

Advanced fuel cycles that move beyond once-through strategies are important methods of dealing with spent fuel inventories minimizing demand for long term depositories. Fast reactor technology provides a solution to close the fuel cycle but is costly and complicated. There is a potential for current thermal spectrum reactors, such as CANDU[1], to provide an initial step in the utilization of spent fuel and reduce the fast reactor infrastructure required. A popular method is the extraction of actinides (e.g. Np, Pu, Am, Cm, etc.) from spent fuel and combining them with natural uranium in a mixed oxide format to be utilized in current thermal reactors. The burning of actinide-based mixed oxide fuel in CANDU is explored herein. The TRUMOX fuel type has actinide contents of 4.75wt% and 3.10wt% and target burnup levels of 45 and 30 MWd/kgHE. The lattice is modeled in 2D with WIMS-AECL v3.121 and 3D super-cell calculations are performed in DRAGON v3.06. The 2-group homogenized cross section data is then utilized for full core simulations in RFSP. Time-average and instantaneous fuel ripple simulations were performed along with short-term refueling and an evaluation of reactor coefficients and control device worth. The TRUMOX fuel designs were found to operate within the standard CANDU safety limits and provided a suitable level of actinide destruction (between 35-42%). These simulations illustrate the potential for the CANDU reactor to be an initial step for the utilization of spent fuel and contributing to a more sustainable and efficient nuclear fuel cycle using proven reactor technologies.

1. Introduction

Increased interest in nuclear energy as a clean-air, non-carbon emitting energy generation system has driven research into closing the fuel cycle and addressing the issue of spent fuel. The reprocessing and recycling of spent fuel is being heavily investigated and employed in several countries, such as France and Japan [1]. There are many avenues of reprocessing involving both fast and thermal spectrum reactor systems. A popular method involves extracting the transuranic actinides from spent fuel and utilizing them current thermal reactor systems. Currently France and Japan, among others, have employed as much as 20% reprocessed fuel in their light water reactors (LWRs). CANDU heavy water reactors, with their compact and flexible fuel bundle design and higher neutron economy afforded by heavy water are well suited to employ similar methods with high levels of actinide burning. The actinides can be placed in an inert matrix or mixed with natural uranium (NU) to create a mixed oxide fuel. The large stockpiles of spent fuel from 50 years of nuclear power plant operations provide an abundant supply of actinides for this purpose. Methods to close the fuel cycle such as this are central to the sustainable future of nuclear power generation and allow more efficient use of fuel and deal with the issue of large volumes of spent fuel.

Utilizing reprocessed fuel in current thermal systems provides an intermediate step in the full fuel cycle that reduces the amount of fast reactor infrastructure needed to burn the spent fuel material. Spent fuel from a once-through fuel cycle still contains significant amounts of usable fissile and

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

fertile material which can be separated into streams for recycle and reuse with fission product waste being put into long-term storage and disposal. In particular, uranium and useful actinides such as neptunium, plutonium, americium and curium can be extracted from the spent fuel and reused. The total end waste is the remaining fission products present in the fuel which accounts for ~3-5wt% of the original heavy metal (HM) mass, depending on initial enrichment and burnup lifetime [2]. These recycle methods are beneficial since several actinide isotopes have long lasting radioactive loads and are primary contributors to the spent fuel heat load. Reprocessing significantly reduces the amount of waste, activity level and heat load demands on long term nuclear waste storage facilities.

The minor actinide concentration increases with each recycling operation, affecting the fuel neutronics and complicating the spent fuel separation efforts. Thermal power reactors are in widespread use throughout the world today but are unable to cope with more than a few iterations of actinide recycle before safe operation concerns arise [3]. Fast breeder designs are somewhat more complex, have higher capital and operational costs and only a limited number of demonstration plants are in operation around the world (e.g. BN-600 in Russia, MONJU in Japan, etc.). However, fast breeder reactors are able to perform repeated and continuous recycle of fuel. There is potential for synergy between the two reactor types by using thermal reactors in the first couple of iterations to reduce the volume of waste as well as the amount of fast reactor infrastructure required.

1.1 Benefits and Challenges of Reprocessing and Recycling

The reprocessing and recycling of spent fuel and movement away from a once-through fuel cycle provides benefits related to reduction of overall waste and the more efficient utilization of the energy in fuel. The current once-through nuclear generation cycle in the United States outputs about 100 GWe resulting in 2200 tons of heavy metal (THM) of spent fuel per year [4]. The proposed long-term repositories have specific storage and temperature limits, which in turn dictate the load of spent fuel that can be accommodated. The Yucca Mountain project had an administrative maximum capacity of 70,000THM and a temperature limit between adjacent waste rows of 96°C, the local boiling point of water [3, 4]. Using these limits as a guideline, and assuming the current rate of nuclear power production remains constant, a repository of the size of Yucca Mountain would need to be opened every 32 years. Considering the swell of interest in nuclear energy as a clean-air, low-carbon emission power production strategy, this is likely an underestimate of the repository needs. For a once-through cycle there is still significant energy retained in the spent fuel, making it a potential future resource.

Actinide extraction, along with other recycle operations, can reduce the total end waste to only the fission products which make up a small portion (3-5 wt%) of spent fuel and a smaller fraction of the heat load. Proper use of this strategy could increase the repository loading by a factor of 200 [3], reducing the demand for large repository facilities and avoiding disposing of useful material. These estimates rely on the use of a continuous recycle strategy to attain maximum benefit. A limited recycle strategy only reduces the repository demands by half due to the fact that actinide based spent fuel requires 10 to 20 times more repository space due to increased heat load [3]. The other benefit of a closed cycle is the fact that current inventories of spent fuel become an important commodity which supplements freshly mined sources; thus allowing the nuclear industry to cope better with increased demand. In general, actinide fuels tend to have a higher fissile content allowing for increased burnup levels and more efficient energy utilization.

Reprocessing despite its efficiency and economic benefits presents unique challenges. The partitioning and transmutation activities required to extract the actinides from spent fuel are complex. There is also extensive chemical handling involved and at all times criticality and radiation protection concerns must be addressed combining the hazards of large scale chemical processing and nuclear fuel production as well as the associated waste streams generated. Current methods require stringent controls and have high costs which are important issues in determining the viability of reprocessing. Specific reprocessing methods are not explored here as the focus of this work is on the feasibility of utilizing reprocessed spent fuel not its fabrication.

1.2 Reactor Technology for Actinide Burning

The use of water moderated thermal reactors as a first stage in improved utilization allows 1 to 2 iterations of reprocessed spent fuel to be burned before requiring fast breeder reactors to close the cycle. This significantly reduces the fast breeder infrastructure needed, if used for the first cycle alone the actinide inventory in spent fuel is reduced as the production of one actinide MOX bundle requires the actinide content of 13.5 regular spent fuel bundles [3]. The remaining materials in these bundles can be recycled (e.g. uranium) while the waste fission products are sent to long term disposal. In addition, these thermal reactors are a proven and safe technology currently available and can be utilized with a full core of MOX bundles or with only a portion of the fuel being MOX without major changes to design or operations. Efforts of reprocessing nuclear weapons material and early trials of recycled spent fuel have been employed in current reactors with 10-20% of the fuel in the core being MOX. The logical first step of thermal reactor utilization can be performed using the MOX designs currently employed in pressurized water reactors (PWR), boiling water reactors (BWR) or pressurized heavy water reactor (PHWR) designs such as CANDU.

The CANDU design offers extensive flexibility due to high neutron economy, a simple compact fuel bundle design and online fueling capability. The neutron economy produced by the combination of heavy water coolant and moderator along with low-neutron absorbing materials provides for efficient harnessing of the fuel at various levels of enrichment. Online fueling reduces the need for poison loading (i.e. Boron in the moderator) to counteract fresh fuel reactivity and provides constant management of the flux profile in the core. The fuel design of elements in a circular multi-ringed arrangement is simple, allows for the inclusion of integrated poison and various fuel contents and enrichments. Bundles can be optimized for linear power rating, coolant void reactivity or differential burnup. The adaptability and flexibility of the design make CANDU an excellent choice for the employment of reprocessed actinide fuel.

2. Fuel Designs and Lattice Cell Modelling

This study involves examining the use of transuranic actinides combined with natural uranium in a mixed oxide fuel configuration in a standard 600MWe CANDU (CANDU-6) reactor. The full core is fuelled with the transuranic mixed oxide fuel (referred to as TRUMOX) designed for high burnup levels and significant actinide destruction.

2.1 Design Description

Neptunium, plutonium, americium and curium, are extracted from 30 year cooled spent LWR fuel and blended with natural uranium to produce the actinide based TRUMOX fuels. Two fuel designs are explored with different levels of actinide concentration and different burnup targets. The burnup targets for the two fuel designs are 30 and 45 MWd/kgHE. These are 4 to 6 times the burnup level of standard natural uranium CANDU fuel (~7.5 MWd/kgHE). In order to evaluate a fuel design there is a four phase procedure to be followed. The first phase is fuel composition and bundle design to meet specific burnup, fissile content and reactivity properties and is performed using a lattice physics code. The second phase uses a 3D transport super-cell model to determine the necessary incremental cross sections used to model the control devices. The third phase uses a 3D, two group neutron diffusion core physics code to examine implementation of the fuel design into a CANDU core that meets current regulatory limits. The fourth phase evaluates the operational behaviour and physics characteristics of the design including reactor coefficients, control system responses and short-term fueling effects. Figure 1 shows a flow chart of the design and analysis.

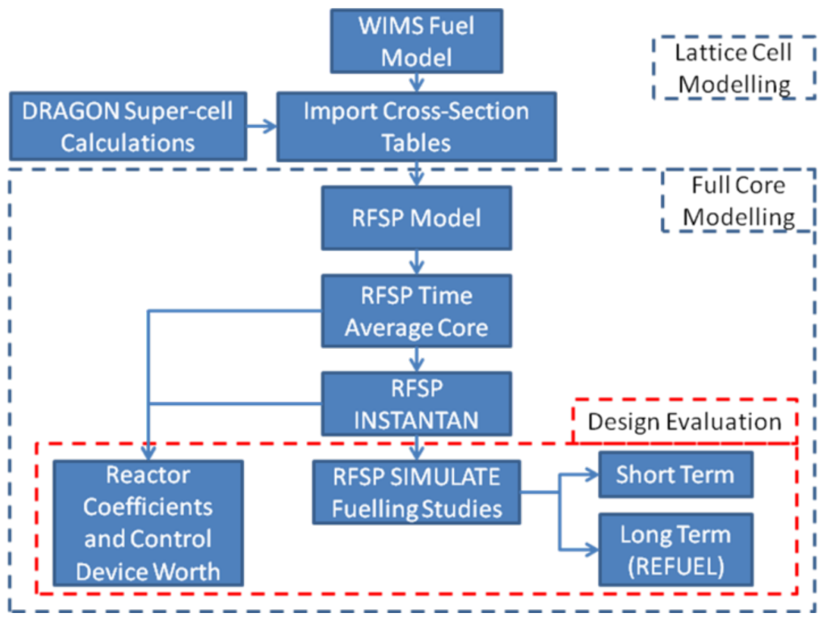

Figure 1 Flow Chart of TRUMOX Design and Analysis

The design utilized is a 43-element bundle with mixed actinide fuel in all elements except the center pin which contains a burnable poison that is used to reduce coolant void reactivity (CVR) effects. The lattice cell calculations are performed using WIMS-AECL v3.1.2.1. WIMS-AECL is a 2D multi-group neutron transport code and, for this study, was used with the ENDF/B-VI library modified with patches for dysprosium (used as a burnable neutron absorber) and curium (a minor actinide). The super-cell calculations are performed in the DRAGON 3D transport code with all the relevant control devices using the ENDF/B-VII library. A standard CANDU design (i.e. 6 m diameter calandria, 6 m long fuel channels, 21 adjusters and 380 fuel channels) was used in the study and modeled using the RFSP-IST 2-group neutron diffusion code. WIMS-AECL, DRAGON and RFSP are part of the industry standard tool (IST) set for reactor analysis in Canada [5] The design limits include burnup targets of 30 and 45MWD/kgHE, a mean CVR target of < +5 mk (Note: 1 mk = 100 pcm = 0.001 $\Delta k/k$) and power limits of 935kW/bundle and 7.3MW/channel (the administrative limits for CANDU).

There are two separate fuel designs with different burnup targets to test the ability of the CANDU design to handle fuels of different reactivity. The longer burnup TRUMOX-45 fuel provides a very high level of actinide destruction but contains a large amount of actinides resulting in a high fissile content. The reactivity of this fuel is approximately five times as much as natural uranium which can cause problems with control during fuelling shuffles. Additionally, the large amount of actinides reduces the effectiveness of the control devices and the long burnup time increases the probability of fuel failure. The lower burnup TRUMOX-30 fuel is designed for a more reasonable level of burnup that is closer to the predicted levels for the Advanced CANDU reactor (ACR-1000), [6], lowering the probability of fuel damage and reducing the reactivity needed in the fuel. This design has less of a fuelling ripple and should be easier to control, however this is at the expense of actinide destruction.

2.2 WIMS-AECL Fuel Design

The fuel bundle design is common for both fuel designs and is based off of the 43 element CANFLEX design with dysprosium burnable poison in the central element. The design has one thick central pin and 42 smaller elements of the same size. The central pin is about 1.5 times thicker than the other pins which are arranged in three rings of 7, 14 and 21 elements around the central pin. Figure 2 provides a depiction of the bundle arrangement.

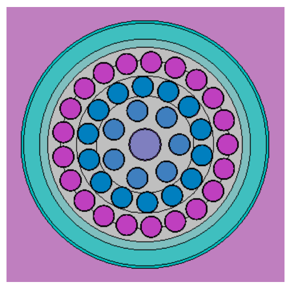

Figure 2 TRUMOX 43 Element Bundle Design

The WIMS-AECL transport models used 89 energy groups with a meshing of 53 lines and 11 angles within the calandria tube [7]. The numerical accuracy of this meshing was explored and for meshing from 50 to 5000 lines and 11, 13, 23, and 31 angles, the K-infinity value stays within 0.65 mk of the original mesh which is accurate enough for this feasibility study. The actinide composition is based on data from Oak Ridge National Laboratories that predicts the probable yields of actinides from spent fuel reprocessing [8]. The two fuel designs only differ by the amount of actinide material mixed into the natural uranium matrix. The actinide concentrations are optimized to achieve the burnup targets of 30 MWD/kg and 45 MWD/kg. The two fuel types are referred to according to their burnup targets as TRUMOX-30 and TRUMOX-45. The composition of the actinide mixture and the uranium matrix along with the central burnable absorber material is provided in Table 1.

Table 1: Fuel Composition, Actinide Uranium and Dysprosium Zirconium Oxide

Actinides			**Uranium Mix**			**Dysprosium Zirconium Oxide**		
Isotope	**Type**	**Wt %**	**Isotope**	**Type**	**Wt %**	**Isotope**	**Type**	**Wt %**
Np-237	Actinide	4.698	U-234	U Mix	0.0054	Dy-160	Absorber	1.346
Pu-238	Actinide	1.301	U-235	U Mix	0.7110	Dy-161	Absorber	10.943
Pu-239	Actinide	56.243	U-238	U Mix	99.2836	Dy-162	Absorber	14.858
Pu-240	Actinide	20.099				Dy-163	Absorber	14.597
Pu-241	Actinide	3.040	**Actinide Oxide (AOX)**			Dy-164	Absorber	16.633
Pu-242	Actinide	3.800	Actinides	88.207	wt %	Zr-90	Zr Mix	12.388
Am-241	Actinide	9.907	Oxygen	11.793	wt %	Zr-91	Zr Mix	2.732
Am-243	Actinide	0.763				Zr-92	Zr Mix	4.221
Cm-243	Actinide	0.001	**Uranium Oxide (UO2)**			Zr-94	Zr Mix	4.371
Cm-244	Actinide	0.072	Uranium	88.150	wt %	Zr-96	Zr Mix	0.719
Cm-245	Actinide	0.012	Oxygen	11.850	wt %	O-16	Oxygen	17.192
Cm-246	Actinide	0.001						

The final design for the TRUMOX-45 fuel uses 95.25 wt% UO_2 and 4.75 wt% AOX, while the TRUMOX-30 fuel contains only 3.10 wt% AOX. In order to meet the high burnup targets the fissile elements in the fuels (Pu^{239}, Pu^{241}, and U^{235}) make up 3.50 wt% and 2.53 wt% for the TRUMOX-45 and TRUMOX-30 designs respectively. This is much higher than the 0.71 wt% U-235/U in natural uranium CANDU fuel. The average full core exit burnup achieved in the designs were 42.54 MWD/kgHE and 27.55 MWD/kgHE. The level of actinide burnup for both fuel types is provided in Table 2.

Table 2: Actinide Burnup for TRUMOX-45 and TRUMOX-30 Fuel designs

TRUMOX-45: Average full core burnup = 42.54 MWD/kgHE						
Concentration	**U 235**	**Np Tot**	**Pu Tot**	**Am Tot**	**Cm Tot**	**Actinides**
Initial	2.380	0.756	13.600	1.720	0.0139	16.100
Final	0.433	0.390	7.960	0.658	0.347	9.350
(Final-Initial)	-1.950	-0.364	-5.630	-1.070	0.329	6.720
% Change	-81.79%	-48.44%	-41.45%	-61.64%	2405.31%	41.82%

TRUMOX-30: Average full core burnup = 27.55 MWD/kgHE						
Concentration	**U 235**	**Np Tot**	**Pu Tot**	**Am Tot**	**Cm Tot**	**Actinides**
Initial	2.420	0.493	8.870	1.120	0.00906	10.500
Final	0.586	0.301	5.970	0.447	0.234	6.950
(Final-Initial)	-1.830	-0.192	-2.900	-0.673	0.225	3.540
% Change	-75.80%	-38.97%	-32.72%	-60.06%	2486.60%	33.75%

2.3 DRAGON 3D Super-cell Design

In order to determine the effects of control devices on the lattice cell cross sections an incremental cross section calculation is needed. Unlike other reactor designs where the control devices act in parallel to the fuel channels, the CANDU control devices are arranged perpendicular and hence require a full 3D transport simulation to determine the incremental cross sections. The 3D super-cell and contains two fuel channels with a control device in between the channels, see Figure 3.

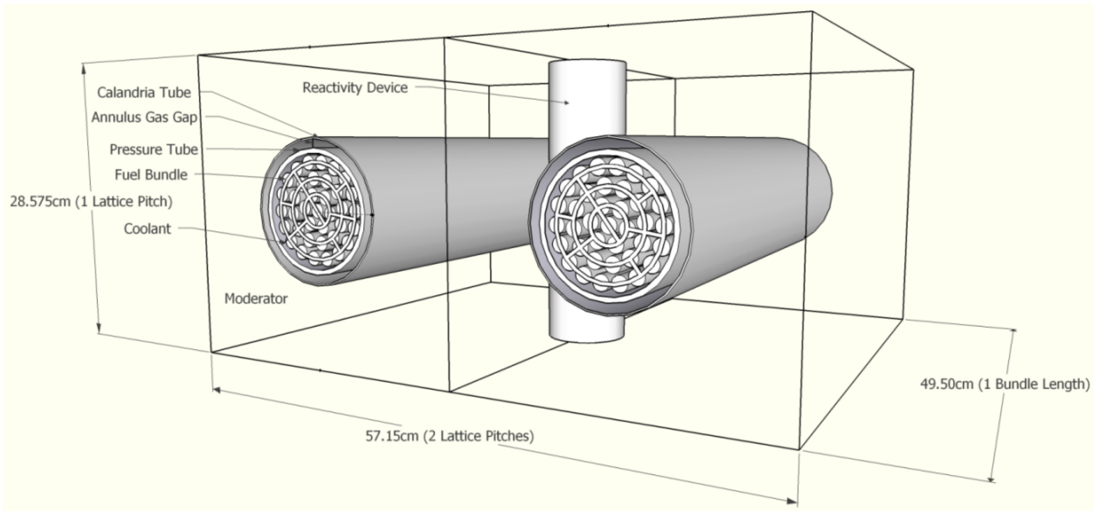

Figure 3 DRAGON 3D Super-cell Model

The DRAGON simulation was performed for each fuel type with all standard CANDU control devices. The control devices simulated include the liquid zone controllers, mechanical absorbers, adjuster rods and the shutdown system #1 control rods. The simulations are performed with the control devices at 0% and 100% inserted and the 2 group homogenized cross sections are computed. The incremental cross sections of Σ_T, Σ_a, $\Sigma_{s1,\ 2}$, $\Sigma_{s2,\ 1}$, and Σ_f are computed for both the fast and thermal energy groups[2]. These incremental cross sections are supplied to the diffusion simulation along with the cross sections generated by WIMS to produce the full core model.

3. Reactor Core Physics Modelling

The reactor core physics modelling of the CANDU-6 with TRUMOX fuel bundles was performed with the Reactor Fuelling Simulation Program, Industry Standard Toolset (RFSP-IST) [9]. RFSP is a 2-group diffusion code that is capable of modelling neutron spatial and temporal behaviour. The main inputs to RFSP include core geometry, fuel and moderator 2-group homogenized macroscopic cross sections and fuel burnup effects from WIMS-AECL (processed by WIMS Utilities v2.0), online fuelling patterns and irradiation targets as well as incremental cross sections for reactivity control devices from DRAGON. The CANDU model contained the in-core structures, reactor control and safety systems as well as the standard fuel channel and calandria geometry. The study was restricted to a typical CANDU with no reactor design modifications. The full core simulations are designed with as few internal control devices in the core as possible to allow maximal burnup.

In order to accommodate the TRUMOX fuels, fuelling patterns, target exit irradiations for fuelling and control devices changes were considered. The fuel designs contain an integral burnable poison in the central pin which produces a flat flux profile across the bundle and in general provides a flatter axial profile along each channel. Therefore, the adjuster rods used to flatten the flux for

[2] The 3D super-cell calculations were performed with fresh fuel, the effects of burnup will be accounted for in future work.

standard natural uranium fuel were not needed and the models were run with the adjusters out of the core. In the interest of easy transition to TRUMOX, efforts were made to maintain standard operating characteristics of a natural uranium fuelled CANDU as much as possible.

3.1 RFSP Model Design

The model portion of RFSP-IST allows the partitioning of the core into regions and to define the fuelling scheme for these regions. The TRUMOX fuels are much more active than standard fuel (due to their higher fissile contents) and hence require a modified fuelling scheme with 1 to 2 bundle shifts over 12 defined regions, compared to the 7 region, 4 to 8 bundle shift strategy normally used with natural uranium (NU) fuel [10]. The TRUMOX-30 and TRUMOX-45 fuel designs use the same model where six regions use one-bundle shifts (264 channels) and six use two-bundle shifts (116 channels). The region and fuelling information for the TRUMOX core is provided in Figure 4.

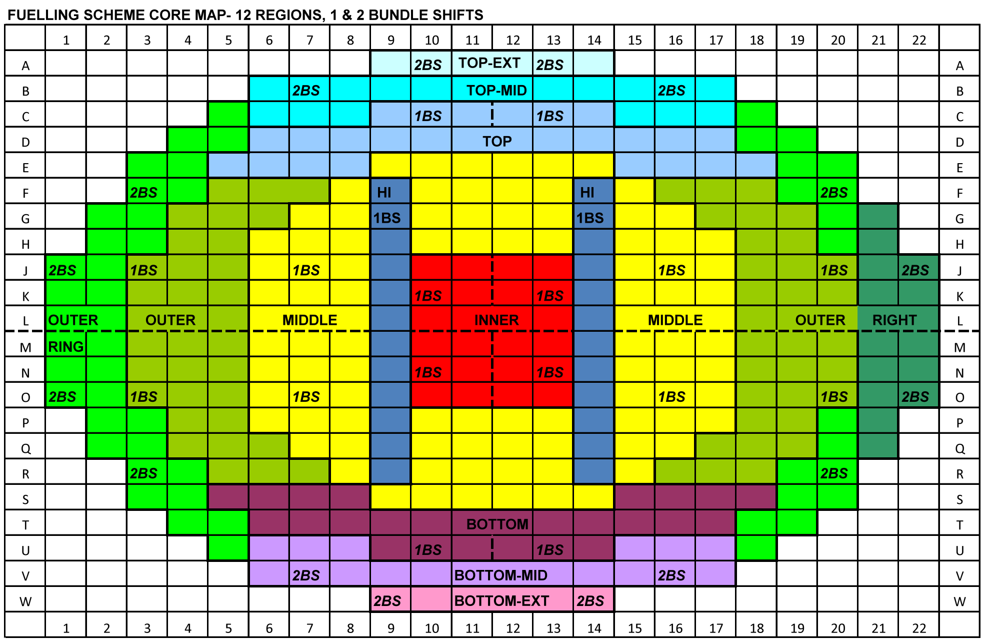

Figure 4 TRUMOX CANDU, Fuel irradiation regions and associated fuelling scheme

3.2 RFSP Time Average

The time-average module determines the total core power distribution in the radial and axial directions and can be used to refine the fuelling and burnup patterns such that the bundle and channel power limits of the TRUMOX fuel mimic those of standard NU fuel. The options include the control of long term reactivity control device positions such as the adjuster rods, and the liquid control zone levels. The time average module was finalized with all the adjuster rod banks removed from the core. The final average burnup reached was 42.54 and 27.55 MWD/kgHE for the TRUMOX-45 and TRUMOX-30 fuel designs respectively. The removal of the adjusters left the liquid zone controllers as the only in core reactivity devices considered. This allowed the core to achieve the maximum burnup possible. The integral burnable neutron poison in the fuel provided flux flattening, allowing the adjusters to be left out of the core. The irradiation characteristics for each region for the two fuels are provided in Table 3 and the 3-D channel power profiles are shown in Figure 5. A plot of the axial thermal flux for the fuels is provided in Figure 6 and the characteristics of the time average core are provided in Table 4.

Table 3: Time-Average exit irradiation values, TRUMOX-45 and TRUMOX-30 in CANDU

TRUMOX-45				TRUMOX-30			
Region	**Avg Exit Irr (n/kb)**	**Region**	**Avg Exit Irr (n/kb)**	**Region**	**Avg Exit Irr (n/kb)**	**Region**	**Avg Exit Irr (n/kb)**
TOP EXT	3.555	BOTTOM	3.798	TOP EXT	2.794	BOTTOM	2.894
TOP MID	3.565	BOT- MID	3.545	TOP MID	2.804	BOT-MID	2.774
TOP	3.818	BOT- EXT	3.535	TOP	2.915	BOT- EXT	2.764
MIDDLE	4.444	OUTER	4.191	MIDDLE	3.528	OUTER	3.296
INNER	4.444	OUT- RING	3.255	INNER	3.528	OUT-RING	2.563
HI	4.565	RIGHT	3.249	HI	3.598	RIGHT	2.557

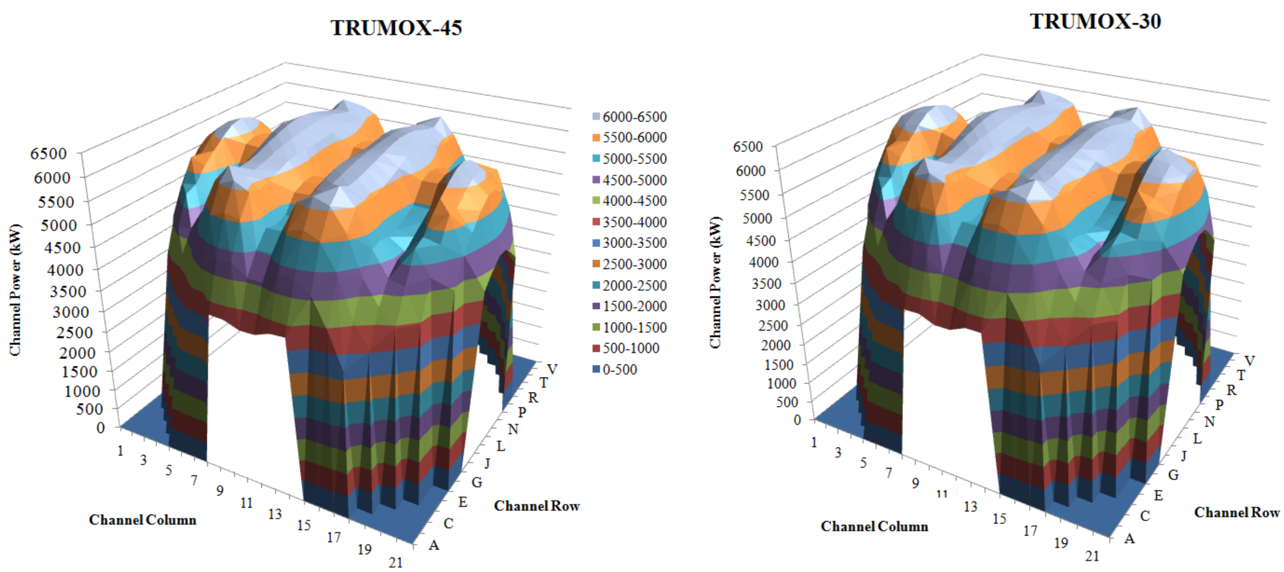

Figure 5 Time-Average Core Channel Powers for TRUMOX-45 and TRUMOX-30 in CANDU

Table 4: TRUMOX CANDU Time-Average characteristics

Characteristic	TRUMOX-45	TRUMOX-30	CANDU-6 NU Value [10]
k_{eff}	0.999393	0.999380	~1
Max BP	807 kW	744 kW	800-820 kW
Max CP	6473 kW	6409 kW	6500-6600 kW
Avg Whole Core Exit Burnup	42.54 MWd/kgHE	27.55 MWd/kgHE	7.5 MWd/kgHE
Maximum Exit Burnup	46.49 MWd/kgHE	30.43 MWd/kgHE	~ 8.00 MWd/kgHE
Radial Form Factor*	0.838	0.846	0.824
Axial Form Factor**	0.668	0.718	0.684
Overall Form Factor***	0.560	0.607	0.564

*Radial Form Factor = Average Channel Power / Maximum Channel Power
**Axial Form Factor = Max Channel Power / (Max Bundle Power x # of bundles)
***Overall Form Factor = Average Bundle Power / Maximum Bundle Power

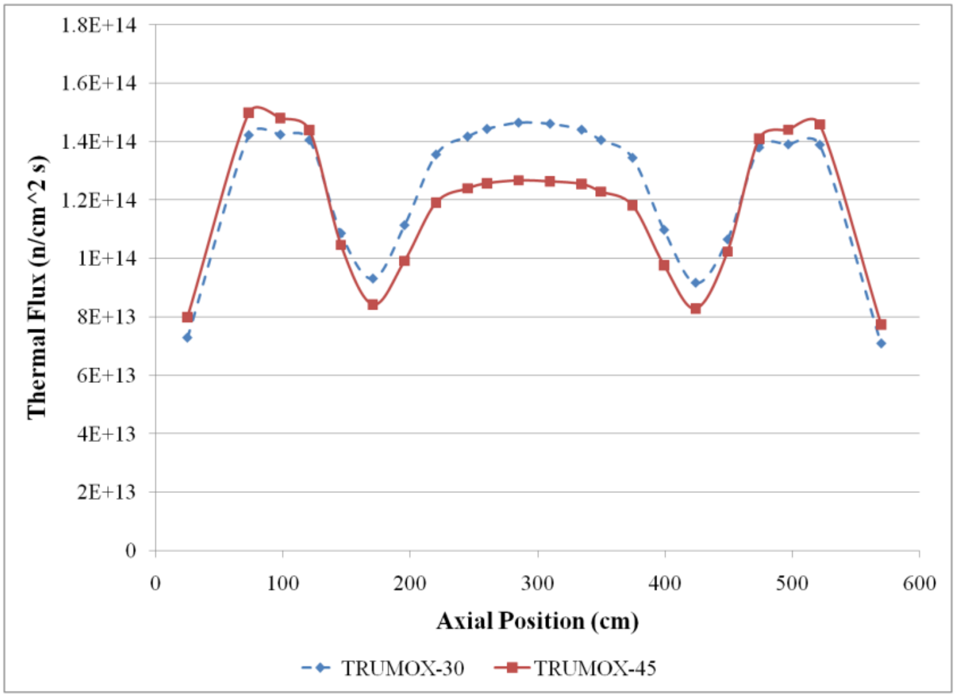

Figure 6 Time-Average Axial Thermal Flux in the Vertical Mid-plane (X=390cm, Y=397cm) for the TRUMOX Fuel Designs

The time-average results provide the mean channel power behaviour but do not include local spikes which may occur due to periodic on-line refueling. As a result, channel and bundle powers must be investigated at random times during potential fuelling operations to ensure the instantaneous power profiles conform to existing license constraints. This is defined as the ripple effect and is analyzed using the INSTANTAN module, which predicts core behavior accounting for online fueling effects.

3.3 RFSP INSTANTAN Simulations

The INSTANTAN module in RFSP allows the production of a random snapshot of the core at a given time with some channels recently fuelled, some in the middle of the fuelling cycle and some high burnup channels that are to be fuelled soon. A random aging pattern is provided which dictates the stage in the fuelling cycle for each channel. This type of analysis simulates a random core configuration in time and ensures that the fuelling and irradiation parameters are able to maintain the criticality of the core. Furthermore, these simulations provide data to ensure the bundle and channel power limits are met for a given set of random channel ages. To realistically simulate random ages for the channels that would arise after a long period of online fuelling, the following procedure is applied. A 7x7 matrix of random ages (between 0 and 1) is generated and referred to as a "pattern random channel distribution" (PRCAD) matrix. One of the 49 (7x7 = 49) elements in the matrix is assigned the highest number and is hence next to be fuelled. The values within this "patterned" matrix are not just random numbers they are based on an operating history to realistically represent the ages of channels near each other [11]. In the absence of a fuel history one could use a uniform random distribution over the interval (0, 1) with a different value for each channel. However, this method will frequently produce exaggerated maximum bundle and channel powers compared to a more accurate core history. The random number generator may place several channels of the same age together, while a fuelling engineer avoids fuelling adjacent channels at the same time especially for higher power regions of the core. Therefore, the 49 elements of the PRCAD matrices utilized in this study were based off of a real fuelling history for the group of channels to provide a more realistic pattern of channel aging and avoid unrealistically excessive bundle and channel powers. The 7x7 PRCAD matrix pattern is repeated across a 22x22 array that encompasses all of the channels in the CANDU core. Adjacent matrices are the transpose of those next to them. A sample channel age map is provided in Figure 7 showing the PRCAD matrix (E12 to L18) applied over the core and would be considered one "snapshot" of the channel burnup profile at an instant in time.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A	0	0	0	0	0	0	0	0	0.96	0.02	0.48	0.84	0.30	0.76	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0.28	0.82	0.16	0.42	0.64	0.86	0.38	0.56	0.22	0.96	0.42	0.08	0	0	0	0	0
C	0	0	0	0	0.20	0.94	0.12	0.70	0.08	0.18	0.32	0.92	0.10	0.68	0.02	0.64	0.18	0.52	0	0	0	0
D	0	0	0	0.78	0.74	0.40	0.62	0.36	0.90	0.52	0.78	0.50	0.80	0.26	0.48	0.86	0.32	0.78	0.74	0	0	0
E	0	0	0.92	0.50	0.98	0.60	0.34	0.72	0.58	0.20	0.74	**0.98**	**0.24**	**0.66**	**0.84**	**0.38**	**0.92**	**0.50**	0.98	0.60	0	0
F	0	0	0.10	0.80	0.24	0.46	0.88	0.06	0.28	0.94	0.40	**0.60**	**0.46**	**0.04**	**0.30**	**0.56**	**0.10**	**0.80**	0.24	0.46	0	0
G	0	0.22	0.68	0.26	0.66	0.04	0.14	0.44	0.82	0.12	0.62	**0.34**	**0.88**	**0.14**	**0.76**	**0.22**	**0.68**	**0.26**	0.66	0.04	0.14	0
H	0	0.96	0.02	0.48	0.84	0.30	0.76	0.54	0.16	0.70	0.36	**0.72**	**0.06**	**0.44**	**0.54**	**0.96**	**0.02**	**0.48**	0.84	0.30	0.76	0
J	0.16	0.42	0.64	0.86	0.38	0.56	0.22	0.96	0.42	0.08	0.90	**0.58**	**0.28**	**0.82**	**0.16**	**0.42**	**0.64**	**0.86**	0.38	0.56	0.22	0.96
K	0.70	0.08	0.18	0.32	0.92	0.10	0.68	0.02	0.64	0.18	0.52	**0.20**	**0.94**	**0.12**	**0.70**	**0.08**	**0.18**	**0.32**	0.92	0.10	0.68	0.02
L	0.36	0.90	0.52	0.78	0.50	0.80	0.26	0.48	0.86	0.32	0.78	**0.74**	**0.40**	**0.62**	**0.36**	**0.90**	**0.52**	**0.78**	0.50	0.80	0.26	0.48
M	0.72	0.58	0.20	0.74	0.98	0.24	0.66	0.84	0.38	0.92	0.50	0.98	0.60	0.34	0.72	0.58	0.20	0.74	0.98	0.24	0.66	0.84
N	0.06	0.28	0.94	0.40	0.60	0.46	0.04	0.30	0.56	0.10	0.80	0.24	0.46	0.88	0.06	0.28	0.94	0.40	0.60	0.46	0.04	0.30
O	0.44	0.82	0.12	0.62	0.34	0.88	0.14	0.76	0.22	0.68	0.26	0.66	0.04	0.14	0.44	0.82	0.12	0.62	0.34	0.88	0.14	0.76
P	0	0.16	0.70	0.36	0.72	0.06	0.44	0.54	0.96	0.02	0.48	0.84	0.30	0.76	0.54	0.16	0.70	0.36	0.72	0.06	0.44	0
Q	0	0.42	0.08	0.90	0.58	0.28	0.82	0.16	0.42	0.64	0.86	0.38	0.56	0.22	0.96	0.42	0.08	0.90	0.58	0.28	0.82	0
R	0	0	0.18	0.52	0.20	0.94	0.12	0.70	0.08	0.18	0.32	0.92	0.10	0.68	0.02	0.64	0.18	0.52	0.20	0.94	0	0
S	0	0	0.32	0.78	0.74	0.40	0.62	0.36	0.90	0.52	0.78	0.50	0.80	0.26	0.48	0.86	0.32	0.78	0.74	0.40	0	0
T	0	0	0	0.50	0.98	0.60	0.34	0.72	0.58	0.20	0.74	0.98	0.24	0.66	0.84	0.38	0.92	0.50	0.98	0	0	0
U	0	0	0	0	0.24	0.46	0.88	0.06	0.28	0.94	0.40	0.60	0.46	0.04	0.30	0.56	0.10	0.80	0	0	0	0
V	0	0	0	0	0	0.04	0.14	0.44	0.82	0.12	0.62	0.34	0.88	0.14	0.76	0.22	0.68	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0.16	0.70	0.36	0.72	0.06	0.44	0	0	0	0	0	0	0	0

Figure 7 Sample Channel Age Map for INSTANTAN Simulation

Using multiple PRCAD matrices several random channel age patterns were produced which generated multiple core snapshots for the TRUMOX-45 and TRUMOX-30 fuels. These snapshots were used to evaluate and refine the irradiation times, and fuelling patterns as well as to assess the bundle and channel power limits. The result of these multiple random core snapshots obtained from RFSP are that an adequate K-effective value is maintained over these simulations and that the maximum bundle and channel powers are kept under the limits for typical existing CANDU. At this stage the completed designs satisfy the time average and fuelling ripple assessments with the specifications and constraints met to a reasonable degree. The next step is to evaluate the reactor control characteristics and the behaviour during normal operation situations for the two fuel designs.

4. Design Evaluation and Fuelling Simulations

The TRUMOX fuel designs described above were evaluated to determine the general reactor properties and behaviour. The full core reactivity changes produced by the insertion of the control devices are calculated along with the reactor coefficients. Additionally, the cores are subjected to a two day operational cycle that includes the fuelling of multiple bundles into the core.

4.1 Reactivity Control Device Worth

The worth of control devices are investigated using the time average model, the adjuster rods, mechanical absorbers (MCA), liquid zone controllers (LZCR) and shutdown system 1 (SDS1) were evaluated. The fine control of the reactor is accomplished with the LZCRs which consist of 14 vessels of H_2O distributed throughout the core. The water levels in the vessels are altered to control neutron absorption in the core and the distributed nature allows for both bulk and spatial control. The adjuster rods are 21 neutron absorbing rods arranged in 7 banks and are usually left inserted in the core to produce a flat flux profile and to provide a positive reactivity reserve to counteract Xenon buildup. These are coarse control devices meant to supplement the LZCRs. The MCAs are 4 neutron absorbing rods normally positioned outside the core and driven in to provide negative reactivity as a coarse control supplement to the LZCRs. SDS 1 is a set of 28 neutron absorbing rods deployed in 4 banks and are poised above the core ready to be released for shutdown purposes.

The only change made to normal operating procedures with respect to the control systems is the removal of the adjusters from the core. The TRUMOX fuel designs include an integrated burnable poison which along with the fuel composition produces a flat flux profile that peaks much closer to the edges of the core than regular fuel. Therefore, the adjusters are not needed to flatten flux and if held in would dampen the central flux in the core pushing it further out to the edges. On a device by device basis, reactor control and safety rods were manipulated in the time average core to determine the difference in core reactivity caused by each perturbation. The results for the TRUMOX design are presented in Table 5 along with the standard values for natural uranium fuel.

Table 5: Approximate reactivity worth of control devices

Device	**TRUMOX-45 Worth (mk)**	**TRUMOX-30 Worth (mk)**	**NU Fuel Worth (mk) [10]***
(LZCRs) 0% to 100% Full	3.93	4.43	~7
0% to 50% Full	2.27	2.56	n/a
50% to 100% Full	1.66	1.87	n/a
Adjuster Rods	3.07	3.17	~ 15.0
Mechanical Absorbers (MCAs)	4.00	3.91	~ 10.0
Shutdown System (SDS#1)	35.20	31.05	~ 80.0

*Approximate worth, slight variations between different reactors, n/a (not available)
Exit burnup (MWd/kgHE): TRUMOX-45 = 42.54, TRUMOX-30 = 27.55, NU fuel =7.50

The reactivity worth of all the control devices were shown to be considerably lower than the typical values for CANDU with natural uranium fuel. The primary reason for this is the harder neutron spectrum produced by the actinide fuel which has a higher fissile content and larger amounts of Plutonium-239. The harder spectrum drives up the average thermal neutron energy (i.e. neutron velocity, v) reducing the absorption in the control devices since at thermal energies the absorption cross-sections of the control device follow a 1/v relationship.

4.2 Reactivity Coefficients

The important reactivity coefficients of the TRUMOX-45 and TRUMOX-30 CANDU designs were analyzed including the coolant temperature, fuel temperature, moderator temperature and the moderator purity. The coolant void reactivity (CVR) of the fuel is also analyzed by reducing the coolant density by a factor of 1000 to simulate a bounding estimate of channel voiding. The full core CVR for both designs was low compared to the full core CVR for natural uranium fuel of approximately +10-15mk [10]. The TRUMOX-45 fuel has a CVR of +3.87 mk and the TRUMOX-30 fuel had a CVR of +1.01 mk. The lower CVR is mainly the result of the integrated burnable poison in the center pin of the fuel bundles. The TRUMOX-30 CVR is significantly lower than the TRUMOX-45 value since the actinide concentration is reduced by 35% while the burnable neutron absorber content is maintained. Therefore, TRUMOX-30 has the same amount of BNA acting in a design with much lower reactivity making relatively much stronger and reducing the CVR. This represents a potential improvement in loss of coolant accident (LOCA) response since lower CVR will lead to lower predicted fuel centerline and sheath temperatures. However, full accident analysis was not performed as part of this study.

The reactor coefficient values for the TRUMOX-45 and TRUMOX-30 fuels are provided in Table 6 along with the standard natural uranium fuel values. The coefficient values computed are much different from the typical natural uranium results due to the much higher fissile content in the TRUMOX fuel, the harder neutron spectrum and the increased amount of Pu-239 present. The fuel temperature coefficient is only 20% of the typical value since Pu-239 which has a smaller fuel temperature reactivity response is the primary fissile element in TRUMOX. Moderator purity has a much lower effect for TRUMOX fuels due to the higher fissile content and greater fuel reactivity.

Table 6: Reactor Coefficients

Reactor Coefficient	**TRUMOX-45**	**TRUMOX-30**	**NU Value [10, 12]**
Coolant Temperature	0.028 mk/°C	0.022 mk/°C	~ 0.018 mk/°C
Fuel Temperature*	-0.003 mk/°C	-0.003 mk/°C	~ -0.015 mk/°C
Small perturbations (± 5°C)	-0.003 mk/°C	-0.004 mk/°C	N/A
Moderator Temperature**	-0.044 mk/°C	-0.062 mk/°C	~ -0.070 mk/°C
Small perturbations (± 5°C)	-0.026 mk/°C	-0.045 mk/°C	N/A
Moderator Purity	1.210 mk/atm%	1.336 mk/atm%	~ 34 mk/atm%
N. B. All temperature coefficients include the related density changes			

4.3 Fuelling Operations Analysis

As discussed previously, CANDU type reactor designs fuel on-line which may lead to local power peaking during these fuelling operations. These fluctuations during fuelling are referred to as the "fuelling ripple" factors in operating reactors and typically vary between 0.9 and 1.1. Hence it is necessary to study the effects of fueling the core on the bundle and channel powers and the control systems to ensure the reactor remains within operational limits with the TRUMOX fuels. Online fueling allows the addition of fuel as it is burnt up rather than the batch fueling process common in LWR designs which uses burnable neutron poisons to hold down the reactivity of fresh fuel and burn off as the fuel burns up and becomes less reactive. The standard CANDU with natural uranium fuel has a fuelling rate of about 15 bundles/full power day (FPD), fueling 2 to 3 channels with 4 to 8 bundle shifts [10]. The TRUMOX fuels are much more reactive and require less fueling but since it is accomplished by 1 and 2 bundle shifts the fueling rate, in terms of channels visited per day, is slightly higher. The reactivity decay rate of TRUMOX-45 is 0.275 mk/full power day (FPD) while TRUMOX-30 has a value 0.368 mk/FPD. The lower reactivity of the TRUMOX-30 fuel results in a higher reactivity decay rate and therefore a higher recommended fueling rate. The fuelling rate is about 2.5-3 bundles/FPD for the fuel designs. This means that given a full week of operations 17 to 18 channels are fueled with 20 bundles. The response to day to day fueling of channels was studied to test the short-term response of the core, fuel and LZCRs using a detailed two day fuelling simulation. This evaluation is different from the INSTANTAN studies as it looks at the direct short term control responses of the liquid zones to a fuelling event in the core. While the initial core used is one of the INSTANTAN snapshots, a time dependent RFSP simulation is performed wherein fuel is inserted into a channel and the direct change on channel power is observed. The key objective of these fuelling studies is to ensure that the control system is able to compensate for the fuelling operations as well as to ensure that the power limits are maintained.

Sample fuelling operations were conducted for two days using 16 consecutive simulations determining the core response in detail throughout the two days. The first day, involved three 1-bundle fuelling shifts in channels S05, L12 and E11. The fuelling began at 9:00am and each shift was spaced 3 hours apart and then the core was run normally until the end of the day. The second day involved the fuelling of 2 channels with 3 bundles beginning at 9:00am with a 1-bundle shift into channel M04 followed 3 hours later with channel D05 being fuelled with a 2-bundle shift. Throughout the 2-day simulation the LZCRs were able to properly maintain bulk and spatial control within their normal operating ranges. The changes in the average zone levels over the two-day operational cycle for both TRUMOX fuel types is provided in Figure 8.

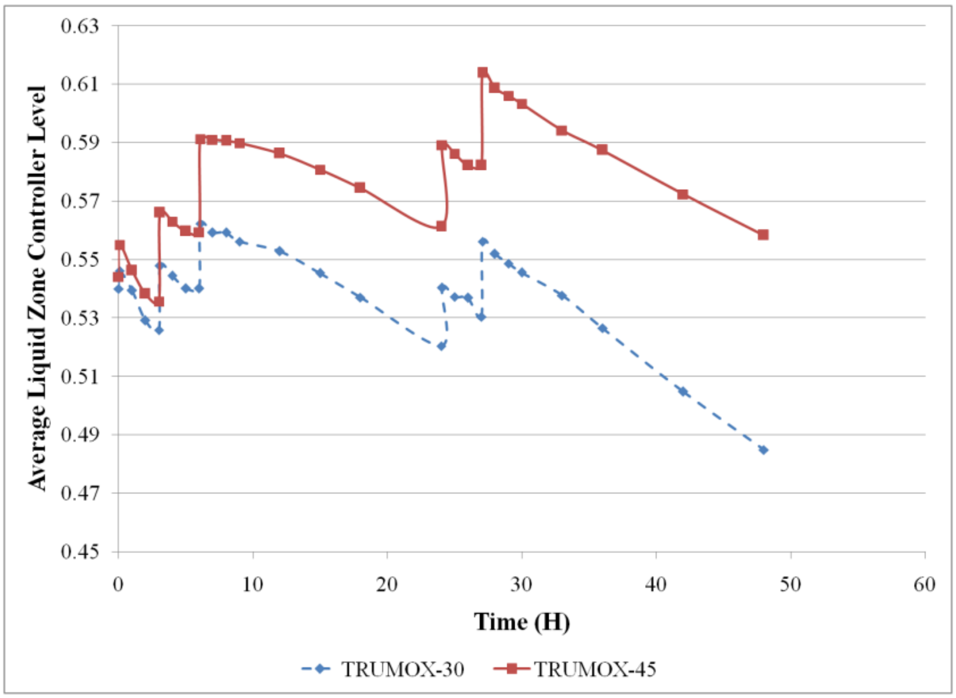

Figure 8 Average Liquid Zone Level, Two-day Fuelling Study

The average zone level fluctuates similarly for both designs. The TRUMOX-45 fuel is more active and has a larger impact on the LZCR level causing the average LZCR level to fluctuate between 53% and 62% (range of 7.8%) with the maximum and minimum levels achieved by a zone being 88.6% and 12.7% respectively. The TRUMOX-30 fuel has a similar fluctuation in average LZCR level between 48% and 56% (range of 7.7%) but the maximum and minimum levels achieved by a zone are not as extreme at 77.6% and 22.2% respectively. The bundle and channel powers were maintained below the limits for both fuels with the maximums being 845 kW and 6680 kW for TRUMOX-45 and 773 kW and 6620 kW for TRUMOX-30.

Single channel effects were measured on channel L12, the average zone levels and the specific LZCR (zone 11) levels were tracked with both fuel designs. A plot of the average zone level responses for the first day of fuelling simulation for both fuelling and not fuelling channel L12 at 3 hours is provided for both TRUMOX-45 and TRUMOX-30 in Figure 9. The change in the LZCR-11 fill level as a result of fuelling is displayed for both fuels in Figure 10.

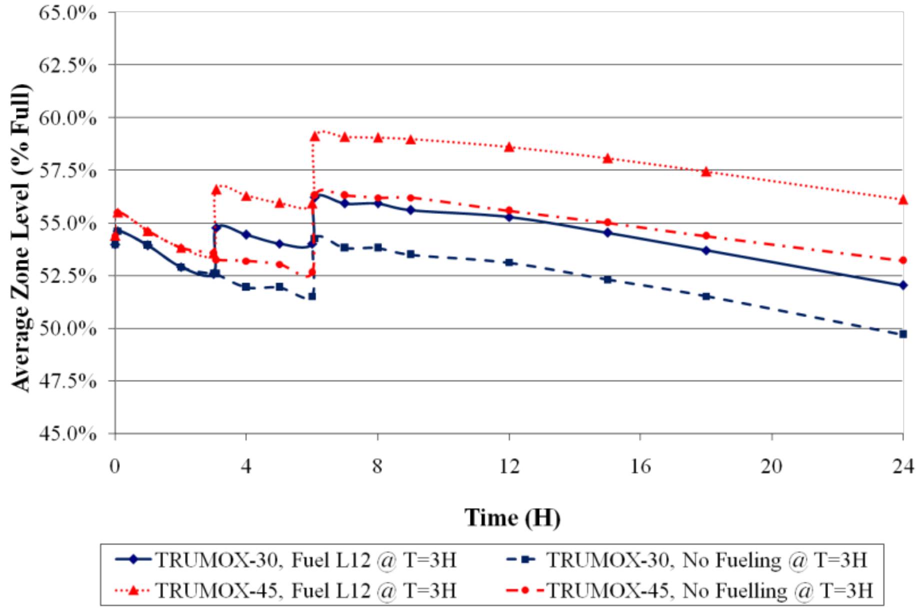

Figure 9 Effects of Fuelling L12 on Average Liquid Zone Level (Fuelling at T=3H)

The average zone response to fueling is similar for both the TRUMOX fuels the change in zone level is TRUMOX-45 = 6.5% and TRUMOX-30 = 4.4%. The reactivity change is about 0.255 mk and 0.195 mk full core for the TRUMOX-45 and TRUMOX-30 fuels respectively. The lower fissile content of TRUMOX-30 has less of an impact on reactivity and a smaller zone controller response.

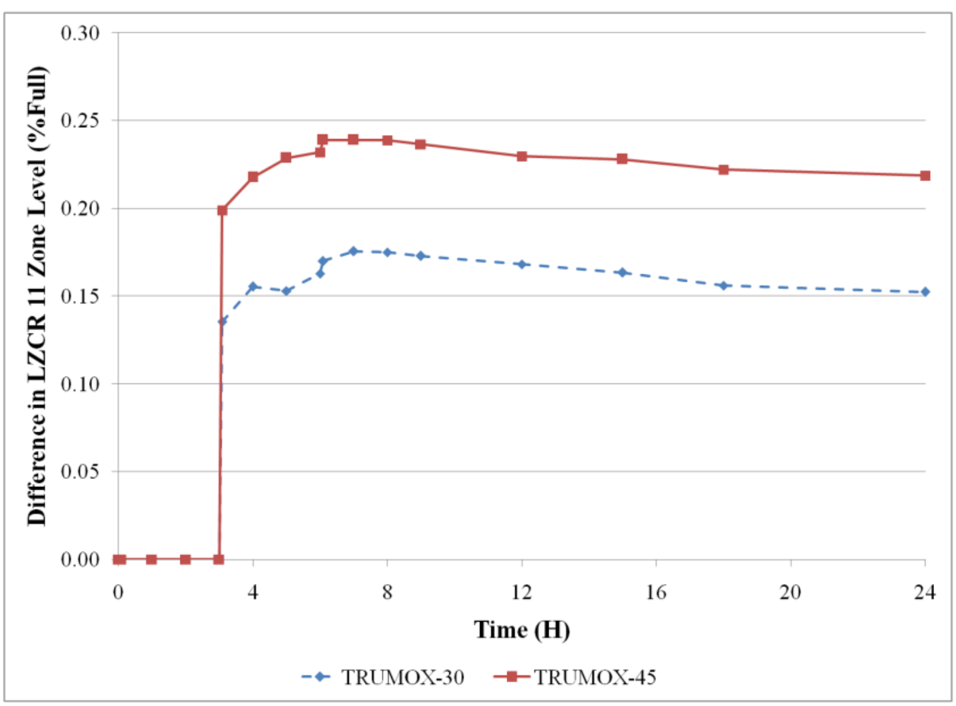

Figure 10 Effect of Fuelling L12 on LZCR-11 Level (Fuelling at T=3H)

The liquid level in LZCR-11 which is adjacent to channel L12 experiences peak zone level changes of 23.9% for the TRUMOX-45 fuel and 17.5% for the TRUMOX-30 fuel. The peak local reactivity change in the zone is approximately 0.94 mk and 0.78 mk for the TRUMOX-45 and TRUMOX-30 fuels respectively. Although caution should be taken to avoid fuelling too much in one zone, both the designs are able to handle the reactivity inputs from fuelling. This fuelling simulation proved that the TRUMOX CANDU was able to handle day-to-day fuelling and maintain the prescribed limits. The TRUMOX-30 fuel is a more mild fuel that the control system is better able to handle and hence the core is more controllable tempering the reduced actinide destruction level of this fuel.

A major finding in this phase was related to the fuelling strategy for the TRUMOX fuels. In particular, during portions of normal fuelling the reactivity inserted by fuelling caused some zone levels to depart from their normal operating envelope with the TRUMOX-45 fuels. It is unlikely that changes to the fuelling strategy itself could overcome these effects. The lower reactivity of the TRUMOX-30 fuel is better suited to the control systems with smaller reactivity insertions that allow the LZCRs to stay within their existing prescribed envelope. The TRUMOX-30 fuel has lower fuelling ripple and a larger LZCR worth, reducing the effects of the zone levels during fuelling.

While the target burnup of 45 MWd/kgHE is advantageous in terms of economic performance and the level of actinide destruction, the TRUMOX-30 fuel with its lower burnup is better accommodated in existing operating reactors. TRUMOX-30 is more easily controlled while still providing a significant level of actinide destruction and reducing the probability of fuel failure due to excessive burnup.

5. Conclusion

The use of Transuranic Mixed Oxide fuels in a CANDU reactor was proven feasible and the control of such a core has been thoroughly evaluated. The fuels, known as TRUMOX-45 and TRUMOX-30, were mixed oxide designs containing 4.75% and 3.10% actinides of neptunium, plutonium americium and curium with natural uranium. The actinides were reprocessed from spent LWR fuel that had cooled for 30 years. The TRUMOX fuels were combined with the proven CANDU pressurized heavy water reactor platform.

The desired burnup targets of 45 MWd/kgHE and 30 MWd/kgHE for the TRUMOX-45 and TRUMOX-30 designs were sufficiently met with the fuels achieving 95% and 92% of their burnup targets respectively. Both designs were able to maintain the bundle and channel power limits of 935 kW and 7.3 MW at all times. However, during the fuelling studies some abnormal liquid zone levels were observed with the TRUMOX-45 fuel that imposes potential limits on the enrichment/burnup target of the fuel design. The TRUMOX-30 fuel with its lower fissile content had a reduced impact on the liquid zone control system and proved to be more controllable. Both designs were feasible and safe under a wide variety of standard operational circumstances and required very minor changes to the CANDU platform. The TRUMOX_30 fuel despite its lower actinide destruction level (34% vas 42% for TRUMOX-45) is better suited to applications in CANDU due to the enhanced controllability and margins available with the lower reactivity fuel.

This reactor design will reduce fuel disposal costs and the increased costs of TRUMOX fuels 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.

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