Reactor Physics of NG CANDU

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Abstract

NG CANDU is the "Next Generation" CANDU® reactor, aimed at producing electrical power at a capital cost significantly less than that of the current reactor designs. A key element of cost reduction is the use of H_2O as coolant and Slightly Enriched Uranium fuel in a tight D_2O-moderated lattice. The improvements in economics are accompanied by enhancements in reactor licensability, controllability, and waste reduction. Full-core coolant-void reactivity in NG CANDU is less than one Beta (total delayed-neutron fraction). The power coefficient is substantially negative. Fuel burnup is about three times the current natural-uranium burnup.

1.0 Introduction

NG CANDU is the "Next Generation" CANDU reactor, aimed at producing electrical power at a capital cost significantly less than that of the current reactor designs. Cost reduction of the NG CANDU is achieved through the following innovations:

- reduce the inventory of D_2O by using H_2O as coolant and by using Slightly Enriched Uranium (SEU) fuel in a tight D_2O-moderated lattice,
- increase the maximum operating channel and bundle powers by using the CANFLEX® fuel bundle design,
- increase the thermal/electric conversion efficiency by operating at higher coolant pressure and temperature, and
- reduce the size of the reactor core and the reactor building.

The neutronic properties of the NG CANDU have been specifically designed to ensure the improvements in economics are also accompanied by the following improvements in reactor licensability, controllability, and waste reduction:

- a substantial enhancement of licensability by reducing the coolant-void reactivity to less than one Beta (i.e.< 5.6 mk), with the potential to achieve lower coolant-void reactivity if necessary,
- a significant increase in the reliability and effectiveness of the Emergency Core Cooling (ECC) system by simplifying the interface between the ECC and the Heat Transport (HT) system since they are both now light water,

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- a substantial enhancement in reactor control by operating with significantly negative feedbacks in reactor power, and
- a factor-of-three reduction in the quantity of spent fuel bundles per unit of electricity generated.

2.0 Lattice Pitch and Coolant-Void Reactivity

A CANDU reactor with H_2O coolant would have a high positive coolant-void reactivity at the current CANDU lattice pitch of 28.575 cm. The NG CANDU concept centers on adapting the fuel channel lattice to achieve a very modest value of coolant-void reactivity. The key parameter that determines this is the moderator-to-fuel volume ratio in the lattice cell. Therefore, an effective way of reducing the coolant-void reactivity is to reduce the lattice pitch until an under-moderated lattice condition is reached. The lattice becomes under-moderated when the D_2O moderator volume alone cannot provide sufficient moderation to achieve maximum reactivity. The H_2O inside the fuel channel then functions as both coolant and moderator. Coolant-void reactivity is determined by the net result due to the loss of absorption (a positive reactivity change) and the loss of moderation (a negative reactivity change). Spatial and spectral changes of the neutron flux in the lattice cell due to voiding of the coolant, as well as the nuclide composition in the fuel, also affect the coolant-void reactivity to a lesser extent. A survey study of the relationship between coolant-void reactivity and fuel enrichment as a function of lattice pitch was conducted using the lattice code WIMS-AECL version 2-5d with the ENDF/B-VI library (Reference 1). The results are shown in Figure 1. A moderator-to-fuel volume ratio of about 7.1 is calculated to lead to coolant-void reactivity less than one beta.

Coolant-void reactivity in the NG CANDU is a design parameter; lower values can be achieved mainly by reducing the lattice pitch. However, the space requirements between feeders in adjacent fuel channels determine the minimum lattice pitch that is permissible. A detailed engineering assessment performed later in the conceptual study concluded that it is practical to reduce lattice pitch to the range of 22 to 23 cm. Figure 1 shows that the coolant-void reactivity at a lattice pitch of 22 cm with the standard calandria tube is about 25 mk, indicating that further measures to reduce core void reactivity should be considered. However, enough moderator can be displaced from this lattice to achieve the required moderator-to-coolant volume ratio of 7.1 by using a large calandria tube of outside radius 7.8 cm. This calandria tube diameter retains the necessary tube-sheet ligament strength, and the separation between adjacent calandria tubes required for the installation of interstitial in-core reactivity control devices, required for a robust core mechanical design.

Table 1 summarizes sample calculations of fuel burnup and coolant-void reactivity for SEU fuel with 1.3 wt%, 1.5 wt%, 2.0 wt% and 2.5 wt% ^{235}U, based on a simple lattice model with moderator-to-fuel ratio of 7.1. The amount of natural uranium feed stock required to produce one kg of SEU at each enrichment level is also given in the table. A 0.2 wt% ^{235}U content in the tailing is assumed. The relative fuel efficiency is indicated by the natural-uranium utilization, obtained by dividing the SEU fuel burnup by the NU feed stock required for the enrichment process. Coolant-void reactivity for each fuel enrichment level is calculated at mid-burnup.

The enrichment level of 1.5 wt% SEU was initially chosen as a reference for further scooping studies for the following reasons:

- the average fuel burnup is about 20 MW.d/kg(U), which is within the high burnup limit achieved by a small number of CANDU fuel bundles,
- the coolant-void reactivity is about 5 mk, which is below one Beta, and
- natural-uranium utilization is similar to that for NU CANDU, but it is better than that for Light Water Reactors (LWRs).

3.0 Parametric Study of NG Lattice Configurations and Fuel Designs

Table 2 summarizes the results of a parametric study using the WIMS-AECL lattice code for different combinations of fuel-bundle designs and calandria-tube sizes to achieve different coolant-void reactivities for the NG lattice pitch of 22 cm. The results indicate the variation of coolant-void reactivity as calandria-tube size is changed. It can be seen that the coolant-void reactivity at this lattice pitch can be further reduced by using depleted uranium in the inner eight pins, or by using a small amount of burnable poison, such as dysprosium in the central pin.

Based on the results of engineering and safety assessments, it was concluded that the maximum size of the calandria tube should be as small as possible. There was also a consensus that uniform fuel enrichment without burnable poison is the preferred fuel-bundle design option, since this minimizes fuel fabrication cost, and maximizes fuel burnup and uranium utilization. The current reference NG CANDU concept has a lattice pitch of 22 cm, a 0.65-cm-thick pressure tube with an inside radius of 5.17 cm, and a 0.3-cm-thick calandria tube with an outside radius of 7.8 cm. The thicker pressure tube allows the NG CANDU to operate at coolant pressure and temperature similar to those in the LWR. Because of the use of slightly enriched fuel as a reference design approach, core performance, and fuel burnup, are not very sensitive to pressure-tube thickness, enabling this design change to be readily accommodated. The space between calandria tubes in the NG CANDU, although narrower than in traditional designs, is sufficient to accommodate control and safety devices using neutron-absorbing plates.

The internal element design of the CANFLEX fuel bundle was optimized for the higher burnups in NG CANDU, which resulted in slightly lower uranium mass per bundle (17.8 kg compared to the current value of 18.6 kg), requiring an increase in fuel enrichment from 1.5 wt% ^{235}U to 1.65 wt% ^{235}U in order to achieve the target fuel burnup of 20 MW.d/kg(U). The uranium utilization for this design in the NG CANDU is about the same as that for the current natural-uranium reactors. Detailed full-core calculations using the fuel-management code RFSP version IST-REL_300HP (Reference 2) confirmed that the core-average fuel burnup is 20.0 MW.d/kg(U) and the full-core coolant-void reactivity is 5.0 mk. The current reference NG CANDU has 256 fuel channels inside a 5.06-metre-diameter calandria shell. Figure 2 compares the size of the NG CANDU core with those for other CANDU designs. It is clear that the NG

CANDU achieves a large capital-cost reduction by replacing the D_2O coolant with H_2O and by reducing the inventory of the D_2O in the moderator system using a smaller lattice pitch.

It will be important to validate the WIMS-AECL/RFSP code suite in predicting the fuel burnup and coolant-void reactivity for the NG CANDU configuration. However, the results in Table 2 show that uncertainties in these parameters can be compensated by appropriate adjustments in the fuel enrichment and fuel design, if necessary, to meet the design targets for a given lattice pitch. While the absolute accuracies of WIMS-AECL and RFSP will have some impact on the fuelling cost, they will not affect the feasibility of the NG CANDU design.

4.0 Comparison of NG CANDU with Other Reactor Designs

Figure 3 compares the NG CANDU reference lattice with the NU CANDU lattice, the Japanese FUGEN reactor lattice, and the UK SGHWR lattice. The NG CANDU, the FUGEN reactor and the SGHWR are all channel-type reactors that use H_2O as coolant and D_2O as moderator. FUGEN and SGHWR are vertical reactors with boiling H_2O coolant. NG CANDU is a horizontal reactor with pressurized H_2O coolant. All three reactor-designs suppress the coolant-void reactivity by reducing the moderator-to-fuel volume ratio. Furthermore, all three designs use relatively large calandria tubes to fine-tune this ratio.

FUGEN and the SGHWR use different methods to achieve slightly negative coolant-void reactivity. The SGHWR used interstitial floodable moderator-displacing tubes to achieve a very low moderator-to-fuel volume ratio at a relatively large lattice pitch of 26 cm. FUGEN uses Mixed Oxide (MOX) fuel, with sufficient plutonium content to give a slightly negative coolant-void reactivity at a lattice pitch of 24 cm.

5.0 MCNP Simulations

The WIMS lattice code was originally designed for H_2O cooled and D_2O moderated lattice. Various versions of the WIMS lattice code have been used successfully to design the SGHWR and the FUGEN reactor. Therefore, it is expected that WIMS-AECL will be adequate for the design of the NG CANDU. While precise experiments will be required to determine the absolute accuracy of the coolant-void reactivity calculated by WIMS-AECL, it is desirable to confirm, at least qualitatively at the conceptual design stage, the WIMS-AECL results by comparing them against results obtained from a more vigorous code, such as the Monte Carlo code MCNP (Reference 3).

Figure 4 shows the neutron spectra averaged over the fuel and coolant regions inside the pressure tube with and without the H_2O coolant. These results were calculated with MCNP using nuclide densities calculated by WIMS-AECL for the NG CANDU lattice cell at mid-burnup. The neutron spectrum "hardens" when the coolant is lost and the dips at low epithermal neutron energies become more pronounced. Figure 5 shows a general increase in the fast and epithermal neutron flux in the moderator region as a result of increased escape of fast neutrons from the voided channel, and an associated decrease in the thermal neutron flux due to the lack of moderation.

The dips in the spectra in Figure 4 are attributed to absorption effects in different isotopes at specific neutron energies. Figure 6 shows the large resonance absorption cross section of ^{238}U between 1 eV and 1 keV, while Figure 7 shows the prominent broad resonance of ^{239}Pu fission cross section centred at 0.3 eV. The behaviours of these cross sections have a major influence on the coolant-void reactivity in the NG CANDU lattice.

The MCNP results show that the NG lattice is under-moderated at the nominal operating conditions. Voiding of the H_2O coolant removes its moderation effect, which renders the lattice even more under-moderated. The shift in neutron spectrum upon coolant voiding increases the absorption in ^{238}U in the resonance region. There is also a significant reduction of the fission-yield in ^{239}Pu due to the decrease in neutron flux near 0.3 eV. These negative reactivity effects reduce the overall coolant-void reactivity in the lattice cell that would be expected from the loss of substantial absorption in the H_2O coolant.

These MCNP simulations are in good qualitative agreement with WIMS-AECL results (not shown). It is not possible to compare WIMS-AECL and MCNP results quantitatively at this stage because some of the WIMS-AECL nuclides cannot be represented in the present MCNP model. Detailed comparisons between WIMS-AECL and MCNP will be conducted at a later stage.

6.0 Reactivity Effects in NG CANDU

Table 3 summarizes the major reactivity effects in the preliminary NG CANDU core. Each ppm of natural boron in the moderator is worth about -2.1 mk. The fuel-temperature and moderator-temperature reactivity coefficients are -0.0144 mk/ ^{o}C, and -0.0238 mk/ ^{o}C, respectively. The coolant-temperature coefficient is slightly positive, about 0.0284 mk/ ^{o}C. The reactivity change due to an increase in reactor power is the net result due to the increase in coolant temperature (positive reactivity change) and the increase in fuel temperature (negative reactivity change). A thermalhydraulic code was used to calculate the core-averaged coolant temperature (including density effect) and fuel temperature at various power levels using the time-average power shape. The reactivities corresponding to these power levels were calculated by WIMS-AECL for the mid-burnup fuel lattice using the appropriate fuel and coolant temperatures. The reactivity change from 0% power to 100% power in NG CANDU is estimated to be about -7.0 mk. Between 95% and 105% power levels, the power coefficient is about -0.05 mk/% full power. Detailed coupled neutronic-thermalhydraulic simulations will be conducted at a later stage to determine the power coefficient accurately. However, the magnitude of the negative power coefficient is sufficient to guarantee smooth power control during normal reactor operation, but it is not strong enough to interfere with the reactor control system.

Flooding the gap between the calandria tube and the pressure tube with H_2O coolant will result in a reactivity injection of -0.24 mk per channel. Therefore, a leaking pressure tube will cause a noticeable power reduction. In-core LOCA will not cause a power excursion in the NG CANDU. Instead, it could shut down the reactor automatically. However, flooding the gap between the calandria tube and the pressure tube with D_2O moderator will result in a reactivity injection of +0.08 mk per channel. This will cause a small increase in reactor power, which will be quickly terminated by the control system. Full-core coolant-void reactivity is about 5.0 mk.

This small positive coolant-void reactivity will result in modest LOCA power transients. The shutdown systems in NG CANDU are based on traditional CANDU systems, designed to quickly terminate much more severe power transients.

Figure 8 shows the effect of coolant voiding on the radial thermal neutron flux distribution in NG CANDU. The NG CANDU lattice is under-moderated in the core region. Fast neutrons born in fission in the core region may have to travel a long distance before they are adequately thermalized to initiate another fission cycle. However, fast neutrons born in fission in the peripheral channels can be thoroughly thermalized by the reflector, creating a large pool of thermal neutrons. Many of these thermal neutrons are reflected back into the core region. Consequently, the flux and power distributions in the NG core are naturally flat and stable. Voiding of coolant in the core region further reduces the moderation effect in the core and increases the migration of fast neutrons towards the reflector region. The increase in neutron flux in the reflector during a LOCA increases the reactor leakage and results in reduced coolant-void reactivity. Reducing the reflector thickness enhances the leakage effect, resulting in further reduction. Hence, the reflector thickness is another independent parameter, which can be used to fine-tune the coolant-void reactivity at the conceptual design stage.

7.0 Characteristics of Preliminary NG CANDU

Table 4 summarizes some of the major characteristics of the preliminary NG CANDU design. The stable flat radial flux profile enables the NG CANDU to operate at a very high radial power form factor of 0.93. Figure 9 shows that the NG axial power shape is flat, and is slightly skewed towards the inlet end. This results naturally from the chosen characteristics of the core, coupled with bi-directional fuel management, retaining the traditional simple CANDU fuelling scheme (in this case, a two-bundle shift). Thermalhydraulic assessments show that the NG axial power shape gives higher Critical Channel Powers (CCP) than those for a center-peaked power shape in an NU CANDU. The NG CANDU is expected to operate with a maximum instantaneous channel power of 7.8 MW(th) and a maximum bundle power of 875 kW(th), while retaining acceptable margin to dryout. The CANFLEX fuel design allows NG CANDU to operate at these power levels with relatively low fuel element ratings, significantly lower than in current CANDU designs.

Figure 10 shows the element ratings versus element burnup for every fuel element in the NG CANDU using an instantaneous power distribution. The maximum fuel burnup in the core is about 25 MW.d/kg(U) and occurs at the outermost fuel elements in the CANFLEX bundle. A benefit of the flat NG CANDU core flux shape is therefore a low ratio of maximum to average burnup for the fuel. This enables increased confidence in fuel performance. The current Stress Cracking Corrosion (SCC) defect threshold curve is also shown in this figure. The flattened axial power shape and the use of CANFLEX significantly reduce the fuel-element ratings in NG CANDU. The maximum element rating is about 48 kW/m, which is about 15% lower than that experienced by NU fuel elements in the current standard 37-element bundles. This lower rating is achieved even with peak channel power more than 10% greater than that in current CANDUs.

The current SCC defect methodology predicts no fuel failure during a power ramp unless the power rating of the fuel exceeds thresholds for both the ramped (final) power, and the power-boost. Good fuel performance is expected for the NG fuel design because,

- the maximum linear element rating is significantly below the SCC defect threshold curve for the ramped power, and
- the maximum power-boost is expected to be lower than the SCC power-boost threshold curve because of the use of the 2-bundle-shift refuelling scheme.

Moreover, subtle design changes have been made to the fuel to assure good performance at extended burnup. The target fuel burnup in NG CANDU is 20 MW.d/kg(U), about three times the current NU burnup. This burnup requires a uniform fuel enrichment of 1.65 wt% ^{235}U using the CANFLEX fuel bundle design optimized for NG CANDU. The fuelling requirement is 5.4 bundles per full power day, or 2.7 channel-visits per full power day using a 2-bundle-shift refuelling scheme. The NG CANDU fuel handling system can easily meet this requirement.

8.0 Preliminary Control and Safety Systems in NG CANDU

The current NG reactor concept includes nine mechanical zone control assemblies, arranged in three symmetrical rows of three assemblies each. The central row is on the reactor axial centreline. Each assembly is divided into two independently movable segments. The SDS2 consists of eight liquid poison injection tubes, four in the upper reflector region and the other four in the bottom reflector region. The end-view and the plane-view of the zone control assemblies and liquid-poison injection tubes are shown in Figures 11 and 12, respectively. The layout of SDS1 has not been determined at this stage. There are no adjuster rods in the current NG CANDU design.

The tight neutronic coupling in a small core results in exceptional stability in the NG CANDU. Table 5 gives the sub-criticalities of the first 15 harmonic modes in NG CANDU. The sub-criticalities of some of these harmonics in an NU CANDU 6 reactor are also shown for comparison purposes. It is clear that NG CANDU is more stable than NU CANDU 6 for all harmonics except the first axial mode. The small sub-criticality for the first axial mode is due to the flattened axial flux distribution in NG CANDU. However, the equilibrium xenon load is only 26 mk and preliminary analysis has shown that all harmonic modes, including the first axial mode, are stable at 100% power in NG CANDU.

The current zone control system layout has a total reactivity worth of 9 mk. Assuming that the zone controllers operate nominally at 50% insertion, approximately ± 3 mk will be available for the following operations:

- perform bulk- and spatial-control functions,
- provide about 12 minutes of xenon override time,
- reduce power from 100% to 80% and hold indefinitely, and
- provide reactivity for about 7 full power days without refuelling.

Not all of the zone controllers are needed for bulk and spatial control purposes at any given time. For example, the three assemblies in the middle row will be used mainly for bulk reactivity control. Most of the spatial-control functions can be accomplished by using the four corner assemblies. The current layout can be configured in many ways to optimize the operation of the control system. The final layout of the zone control system will be determined at a later stage depending on the design specifications of the control system.

The liquid-poison injection tubes in the NG CANDU traverse the calandria in the upper and lower reflector regions only. These are the ideal locations for the liquid-poison injection tubes because the neutron flux level is high and the locations are easily accessible. The SDS2 system is designed to inject enough liquid poison (concentrated gadolinium nitrate solution) to blanket the entire reflector region within one second after actuation. RFSP calculations indicate that this is equivalent to the injection of -50 mk within one second, sufficient to quickly shut down all postulated accidents. SDS2 contains enough poison to guarantee a system reactivity lower than -200 mk after thorough mixing of the poison with the entire moderator system. This is more than sufficient to keep the reactor shut down under all foreseeable conditions.

The layout of SDS1 has not been finalized. However, it will also be designed to inject -50 mk within one second after actuation. Because of the smaller size of the NG CANDU core, conventional shutoff rod drives can readily achieve this. The number and the locations of the SDS1 assemblies will be optimized to meet this modest requirement in the most efficient way.

Figure 13 shows sample power transients for several LOCA scenarios in NG CANDU using very conservative assumptions. The peak power is below 2 times full power for all cases and there is no risk of failure for both the pressure tube and the fuel.

9.0 Conclusions

NG CANDU achieves substantial reduction in capital cost by using H_2O coolant, SEU fuel, and a tight D_2O-moderated lattice. A substantial enhancement to the licensing case is achieved by reducing the full-core coolant-void reactivity to less than one Beta. The use of the CANFLEX fuel-bundle design and the flat flux and power distributions enable NG CANDU to operate at higher fuel channel and bundle powers with no risk in fuel failure. The tight neutronic coupling in a small core results in exceptional stability, which is further enhanced by a substantial negative power coefficient. Fuel burnup in NG CANDU is selected at 20 MW.d/kg(U), resulting in a significant reduction in spent fuel volume per unit of energy produced.

References:

1. J.V. Donnelly, "WIMS-CRNL, A User's Manual for the CRNL Version of WIMS", AECL-8955, 1986 January
2. B. Rouben, "Overview of Current RFSP-Code Capabilities for CANDU Core Analysis", Transactions of the American Nuclear Society, TANSAO 72, 339, 1995
3. J.F. Briesmeister, " MCNP- A General Monte Carlo N-Particle Transport Code", LA-12625-M, Version 4B, 1997 March

Table 1 : Fuel Enrichment, Fuel Burnup and Coolant Void Reactivity for 20.7 cm Lattice Pitch and Standard Pressure and Calandria Tubes

Fuel Enrichment (wt.% ^{235}U)	Void Reactivity (mk)	Fuel Burnup (MW.d/kg (U))	NU (kg of feed stock) per kg of SEU	Uranium Utilization MW(th).d/kg(NU)
1.3	7.0	15	2.16	6.9
1.5	5.0	20	2.55	7.8
2.0	0	30	3.53	8.5
2.5	-3.0	39	4.51	8.6

current NU CANDU uranium utilization ~ 7.5 MW(th).d/kg(NU)

Table 2 : Void Reactivity (mk) vs. Calandria-Tube Size and Fuel Bundle Design for 22 cm Lattice Pitch with Standard Pressure Tube

CT (cm OR)	SEU(1.5%) 43 pins	SEU(2%) DU (8 pins)	SEU(1.7%) Dy 2% (1 pin)	SEU(1.7%) Dy 4% (1 pin)	SEU(1.7%) Dy 6% (1 pin)
6.6	22.7	16.9	16.0	10.8	6.5
7.3	12.6	6.6	4.6	0.2	-3.4
7.8	4.0	-1.9	-3.8	-8.1	-12.5
*	(19.2 MW.d/kg(U))	(21.1 MW.d/kg(U))	(20.5 MW.d/kg(U))	(18.5 MW.d/kg(U))	(17.0 MW.d/kg(U))
**	(7.5)	(7.9)	(7.0)	(6.3)	(5.8)
8.3	-7.7	-13	-14.5	-20	-24

Note: * Core-Average fuel burnup in MW.d/kg(U)

** Uranium Utilization expressed in MW(th).d/kg(NU)

Higher number means better fuel economy

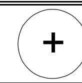
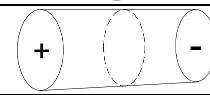
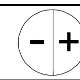
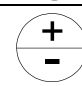
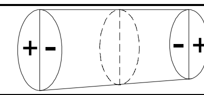
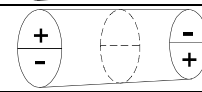
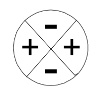
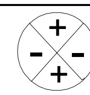
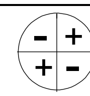
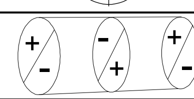
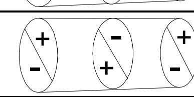
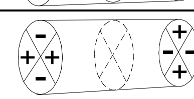
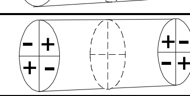
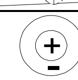
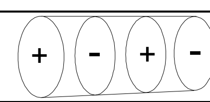
Table 3: Reactivity Effects in Preliminary NG CANDU

Parameter	Value
Moderator Temperature (including density) effect	-0.0238 (mk/°C)
Coolant Temperature (including density) effect	+0.0284 (mk/°C)
Fuel Temperature effect (from 687 to 787 °C)	-0.0144 (mk/ °C)
Boron increased from 0 to 5 ppm in Moderator	-2.1 (mk/ppm)
Power Coefficient (95% -105% full power)	-0.05 mk/% power
Reactivity change from 0% to 100% full power	-7.0 mk
CT and PT gap filled with H_2O Coolant	-0.24 mk/channel
CT and PT gap filled with D_2O Moderator	+0.08 mk/channel
Full-core Coolant-Void Reactivity	+5.0 mk

Table 4: Characteristics of Preliminary NG CANDU

Parameter	Value
Number of fuel channels	256
Reactor thermal power output	1786 MW(th)
Gross Electrical Power output	~ 650 MW(e)
Lattice Pitch (square)	22 cm
Coolant	H_2O (300 ^{o}C)
Moderator	D_2O (80 ^{o}C)
Enrichment of CANFLEX SEU fuel	1.65 wt% ^{235}U
Core-Average fuel burnup	20 MW.d/kg(U)
Maximum fuel element burnup	25 MW.d/kg(U)
Fuel bundles required per full power day	5.4
Channel visits per full power day (2-bundle-shift scheme)	2.7
Maximum Time-Average channel power	7.5 MW(th)
Maximum Time-Average bundle power	850 kW(th)
Maximum Instantaneous channel power	7.8 MW(th)
Maximum Instantaneous bundle power	875 kW(th)
Maximum Instantaneous linear element rating	48 kW/m

Table 5 : NG CANDU (256 Channels) - Harmonic Modes

Mode No.	Description	NG CANDU k-effective	NG CANDU Reactivity (mk)	CANDU 6 Reactivity (mk)	Harmonic Mode (Pictorial)
1	Fundamental	0.999960	0.0	0.0	
2	1st Axial	0.982343	-17.9	-26.25	
3	1st Azimuthal (A)	0.975186	-25.4	-16.19	
4	1st Azimuthal (B)	0.973743	-26.9	-17.06	
5	1st Azimuthal, 1st Axial (A)	0.956723	-45.2	-46.72	
6	1st Azimuthal, 1st Axial (B)	0.955345	-46.7	-46.09	
7	2nd Azimuthal (A)	0.941414	-62.2	-43.97	
8	2nd Azimuthal (B)	0.941208	-62.4	-46.70	
9	2nd Azimuthal (C)	0.928199	-77.3	--	
10	1st Azimuthal, 2nd Axial (A)	0.919847	-87.1	--	
11	1st Azimuthal, 2nd Axial (B)	0.919808	-87.1	--	
12	2nd Azimuthal, 1st Axial (A)	0.918988	-88.1	-76.14	
13	2nd Azimuthal, 1st Axial (B)	0.911245	-97.4	-79.39	
14	1st Radial	0.905745	-104.0	--	
15	3rd Axial	0.901008	-109.8	--	

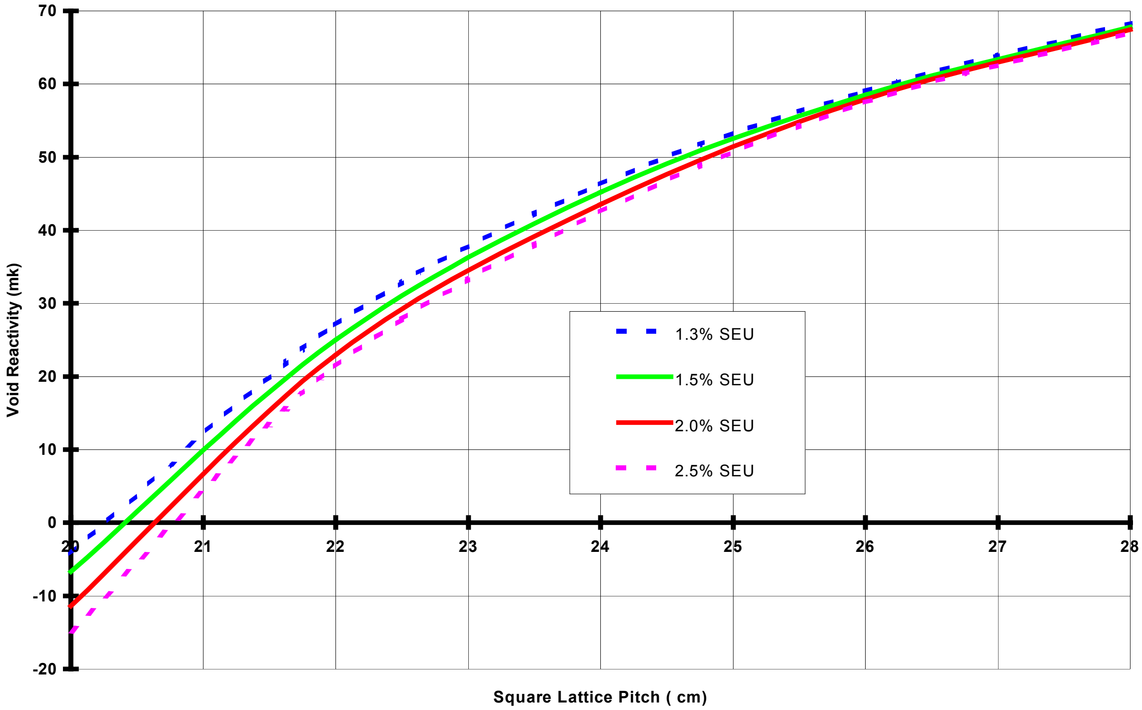


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Figure 1: Coolant (H_20) Void Reactivity Vs Fuel Enrichment and Lattice Pitch with D_2O Moderator and Current Pressure Tube and Calandria Tube Dimensions

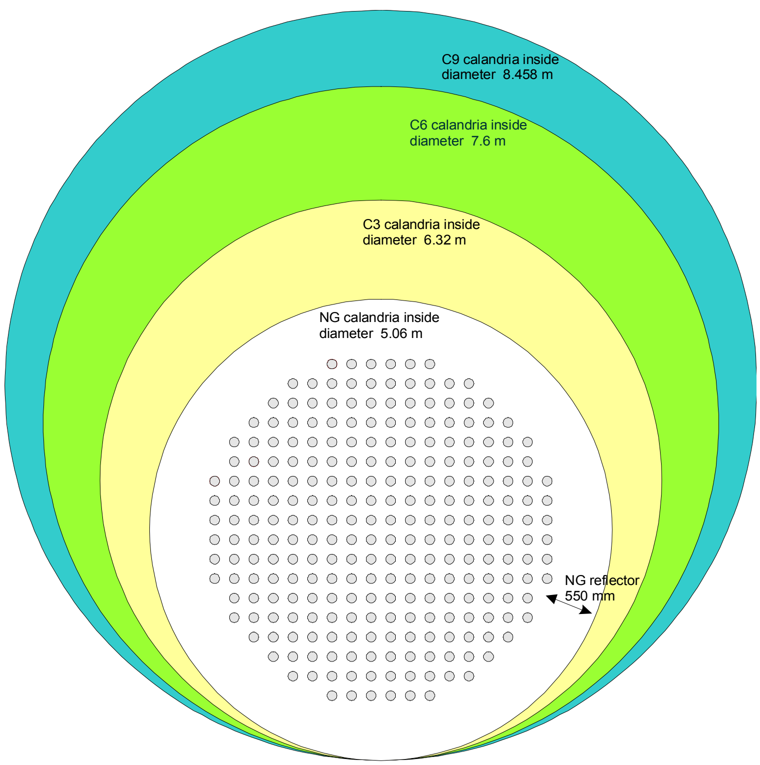
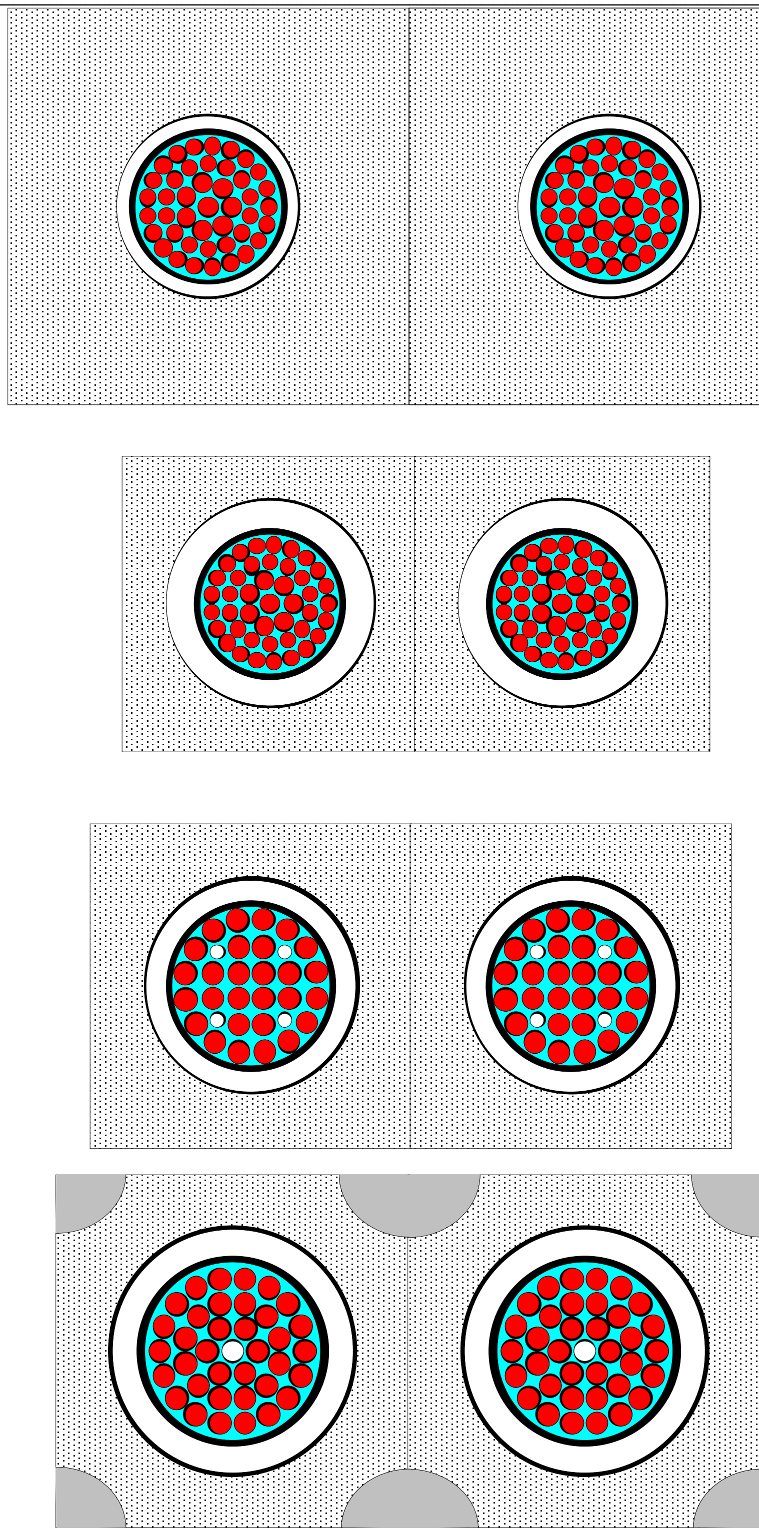


Figure 2 Comparison of Calandria Sizes



NU CANDU Lattice
LP = 28.575 cm.
PT_{OR} = 5.6 cm.
CT_{OR} = 6.6 cm.
V_M / V_F = 16.4

NG CANDU Lattice
LP = 22.0 cm.
PT_{OR} = 5.6 cm.
CT_{OR} = 7.8 cm.
V_M / V_F = 7.1

FUGEN Lattice
LP = 24.0 cm.
PT_{OR} = 6.3 cm.
CT_{OR} = 8.0 cm.
V_M / V_F = 7.7

SGHWR Lattice
LP = 26.0 cm.
PT_{OR} = 7.0 cm.
CT_{OR} = 9.2 cm.
V_M / V_F = 5.7
(with moderator displacing tubes)

Figure 3 Lattice Configurations for NU CANDU, NG CANDU, FUGEN and SGHW Reactors

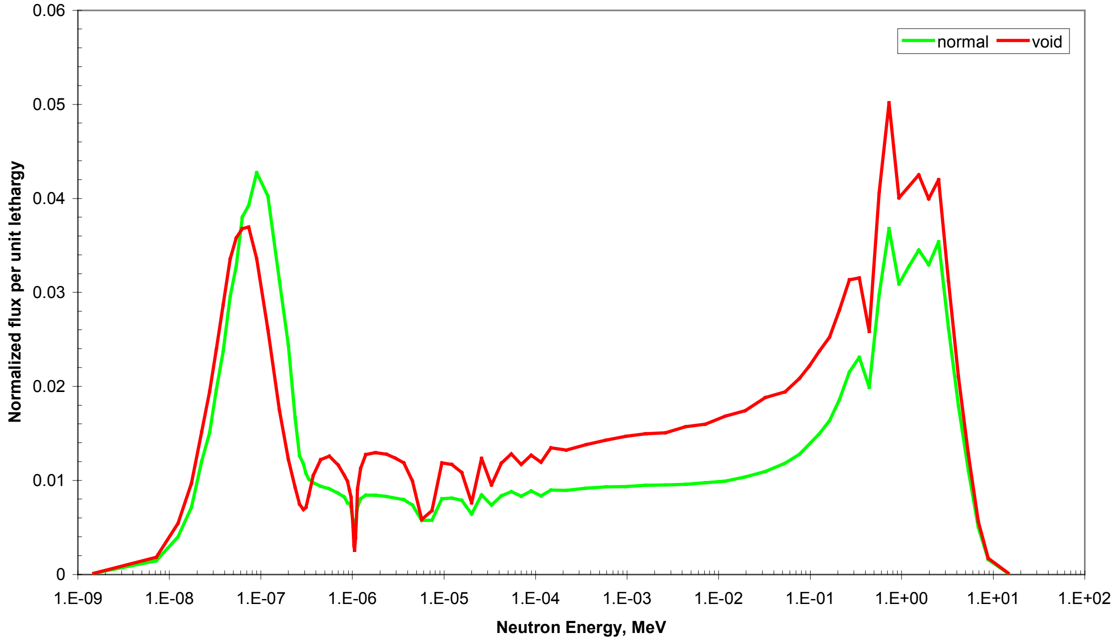


Figure 4 Neutron Flux Averaged over Fuel and Coolant within the Pressure Tube (MCNP Model)

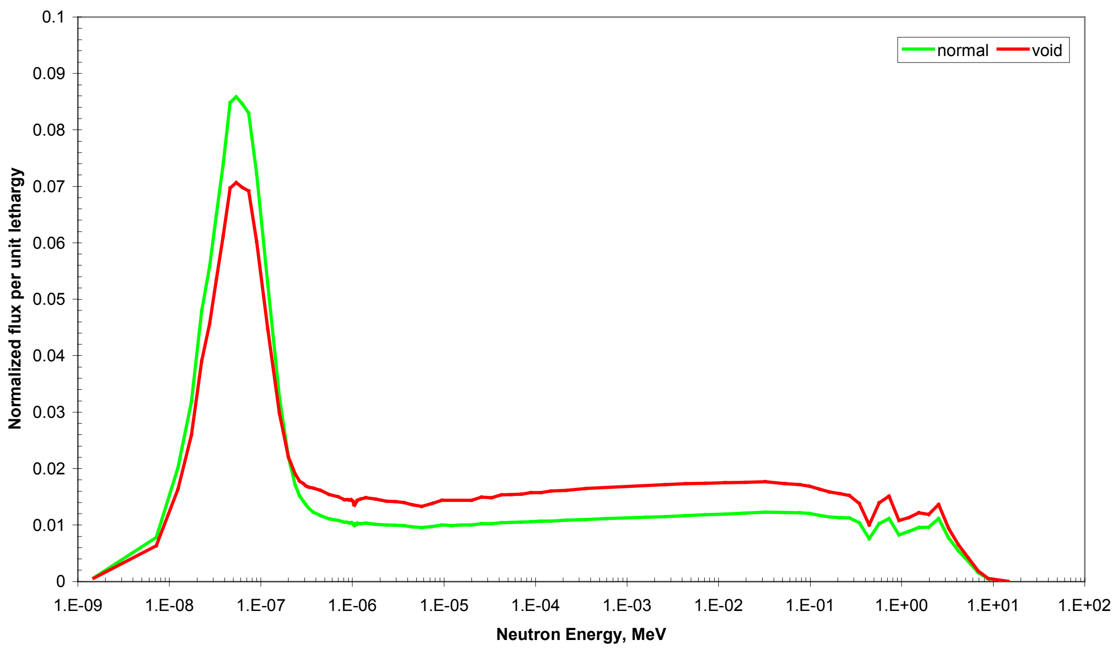


Figure 5 Neutron Flux Averaged over D_2O Moderator Region (MCNP Model)

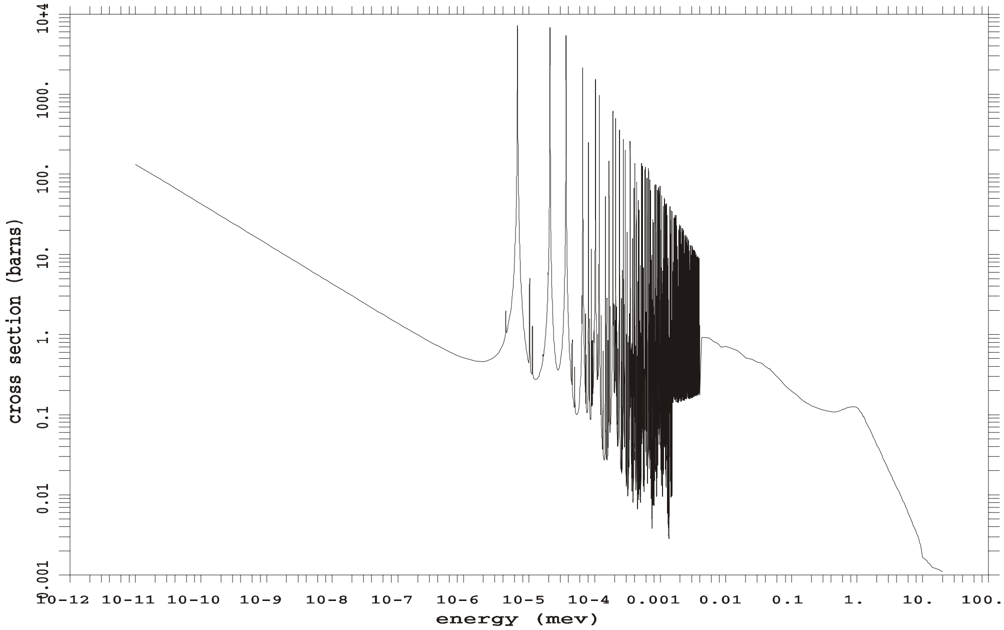


Figure 6 Absorption Cross Section of ^{238}U

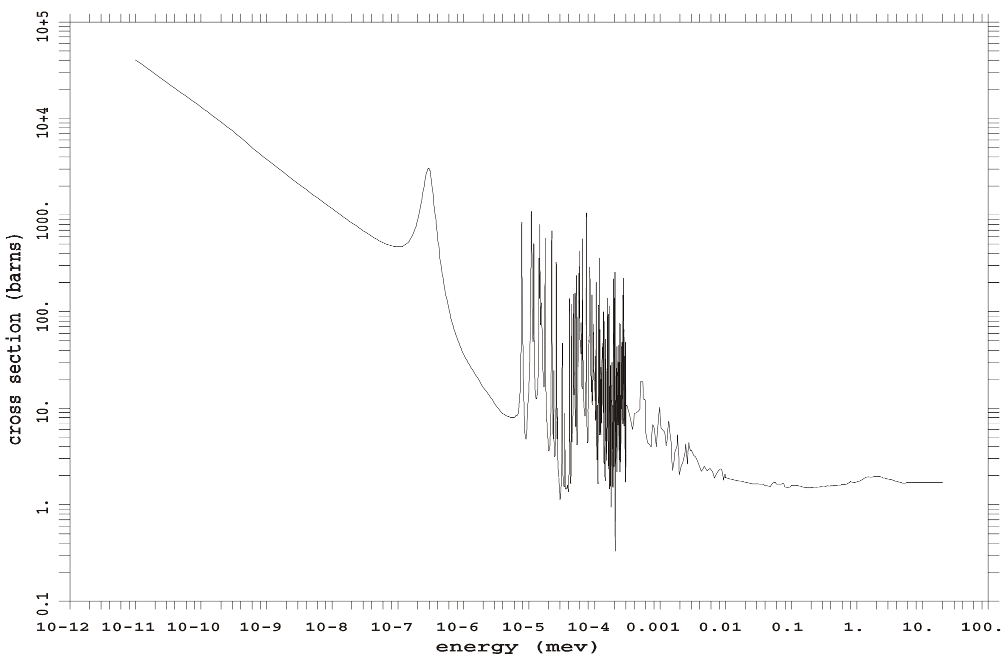


Figure 7 Fission Cross Section of ^{239}Pu

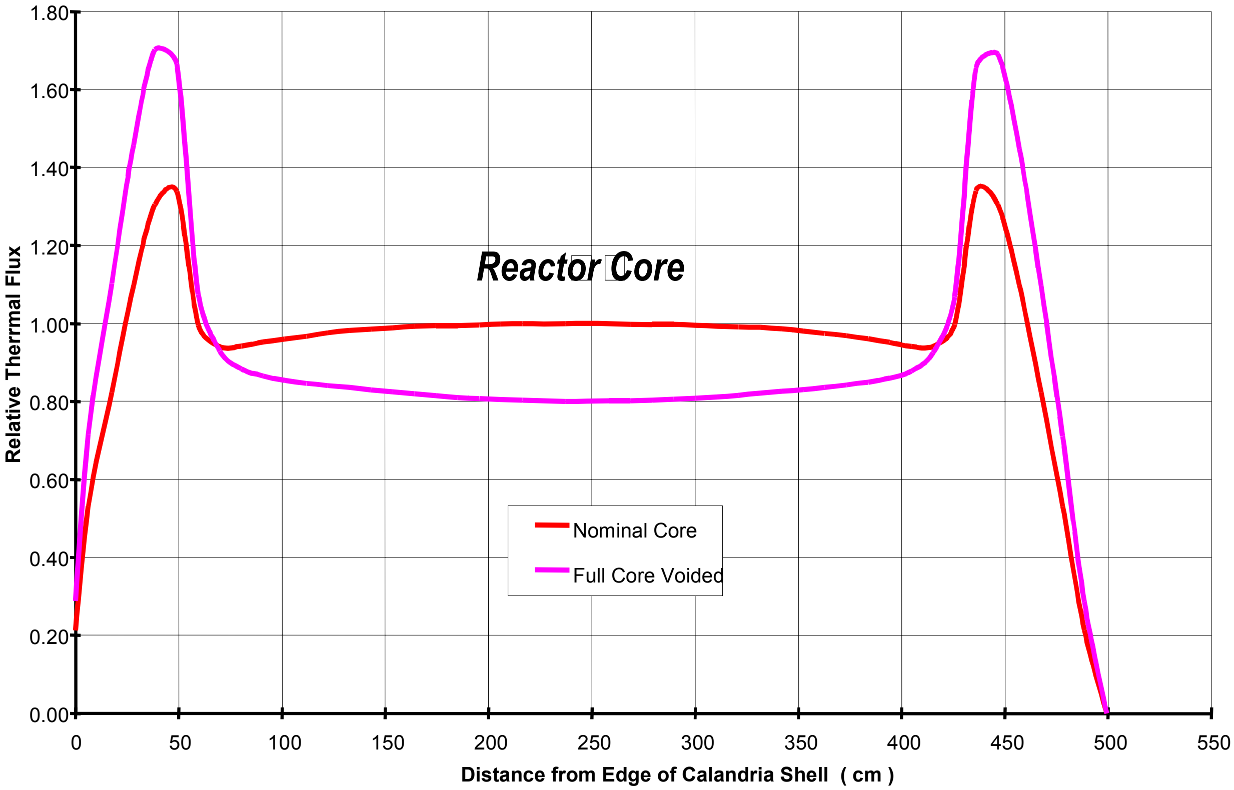


Figure 8 Effect of Coolant Voiding on Radial Thermal-Neutron-Flux Distribution in NG Core

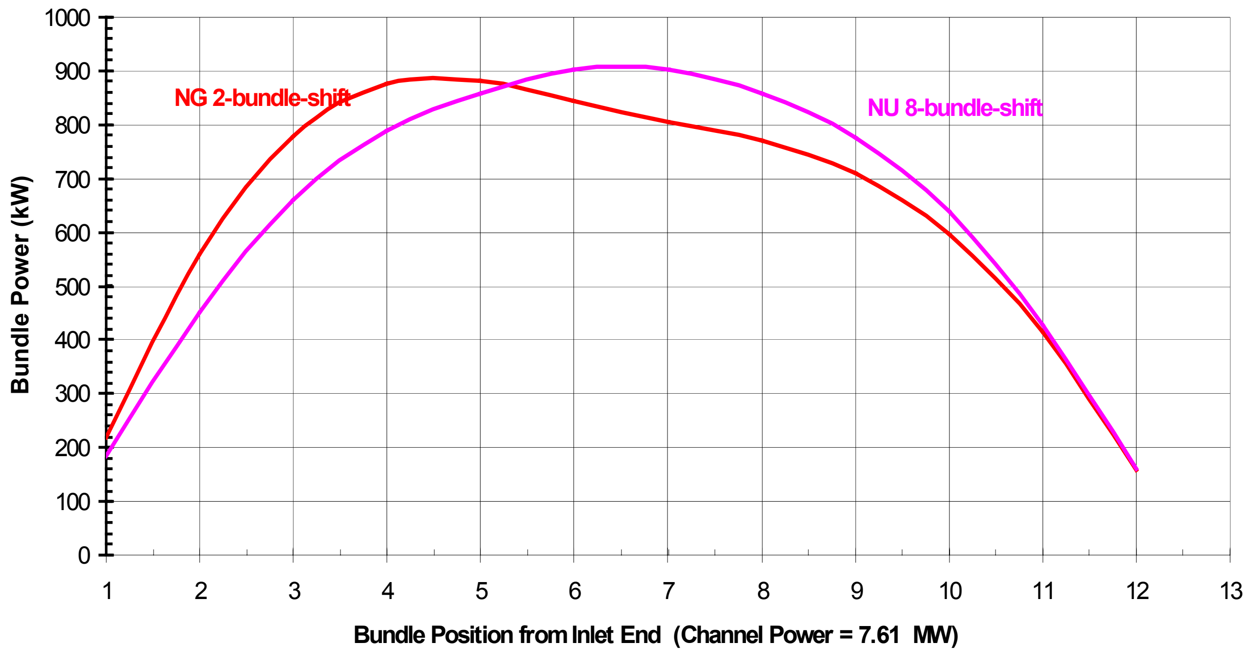


Figure 9 Instantaneous Bundle Power Profiles

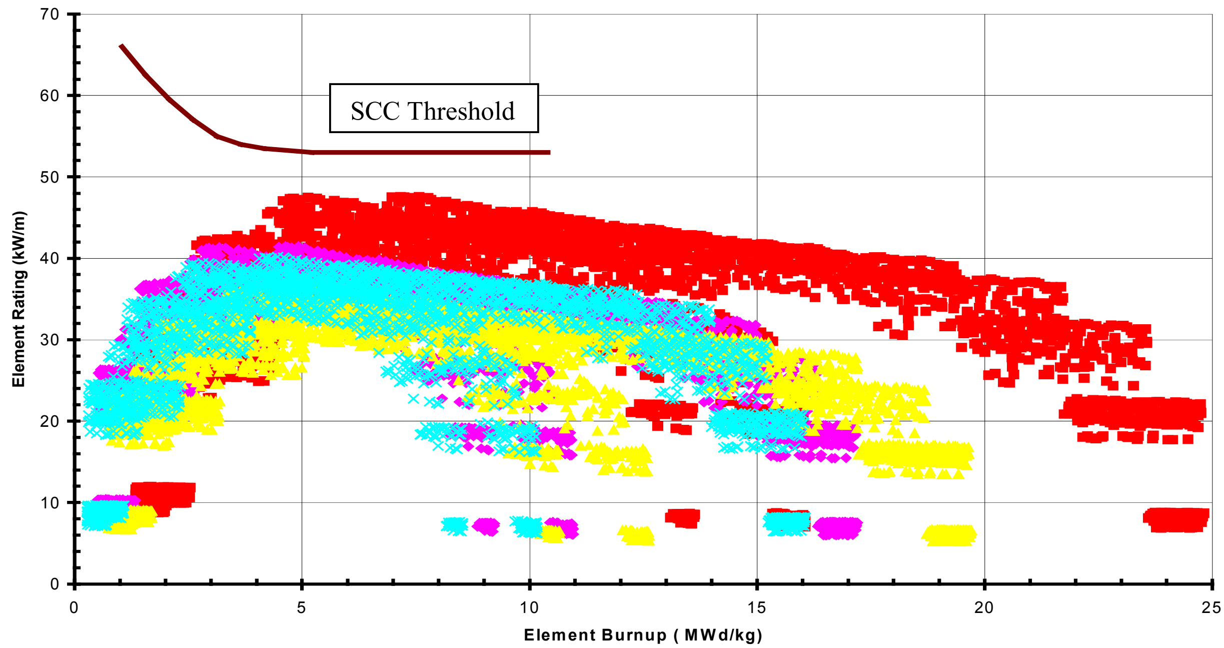


Figure 10 Fuel Element Ratings in NG CANDU

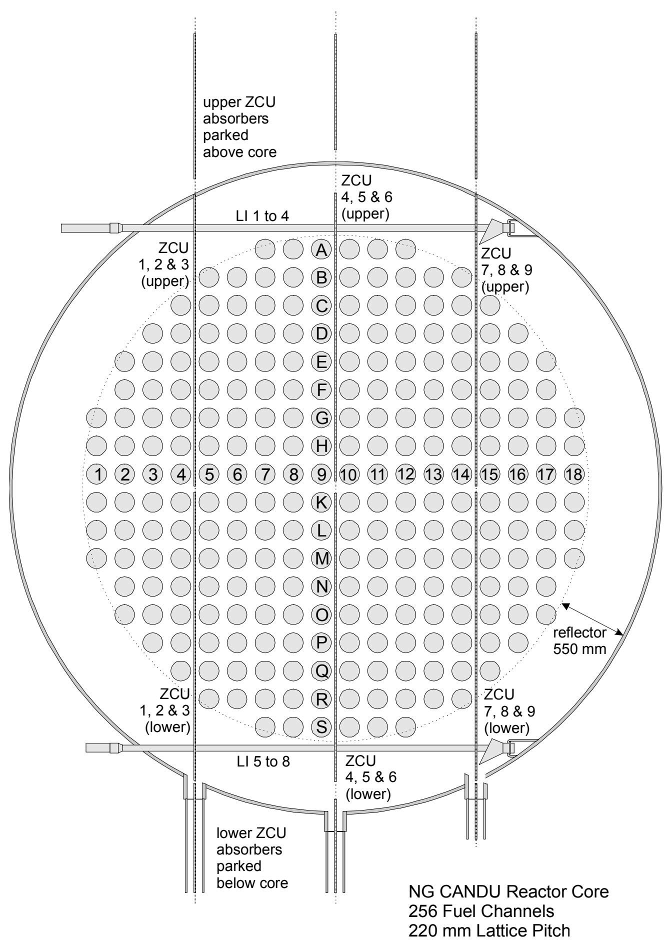


Figure 11 End-View of NG CANDU

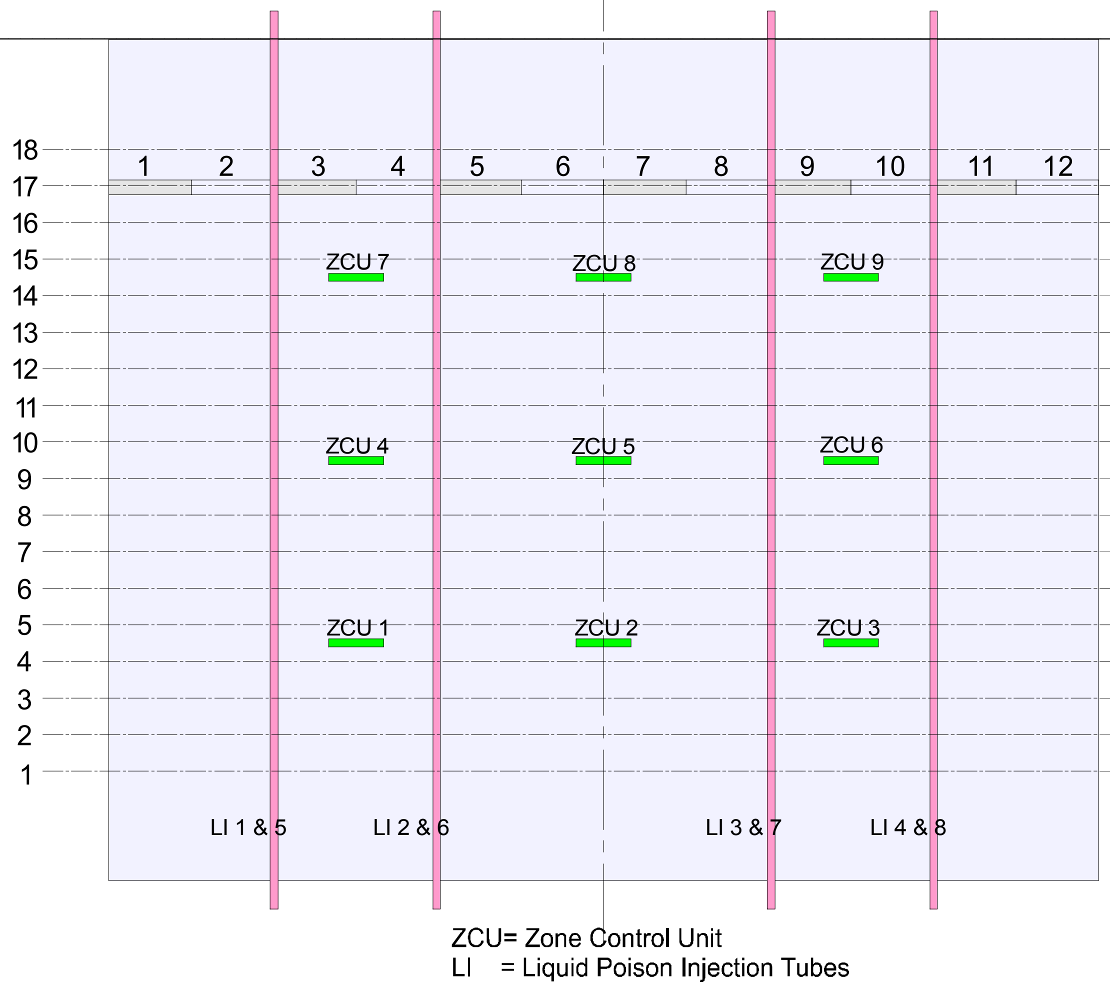


Figure 12 Plane-View of NG CANDU

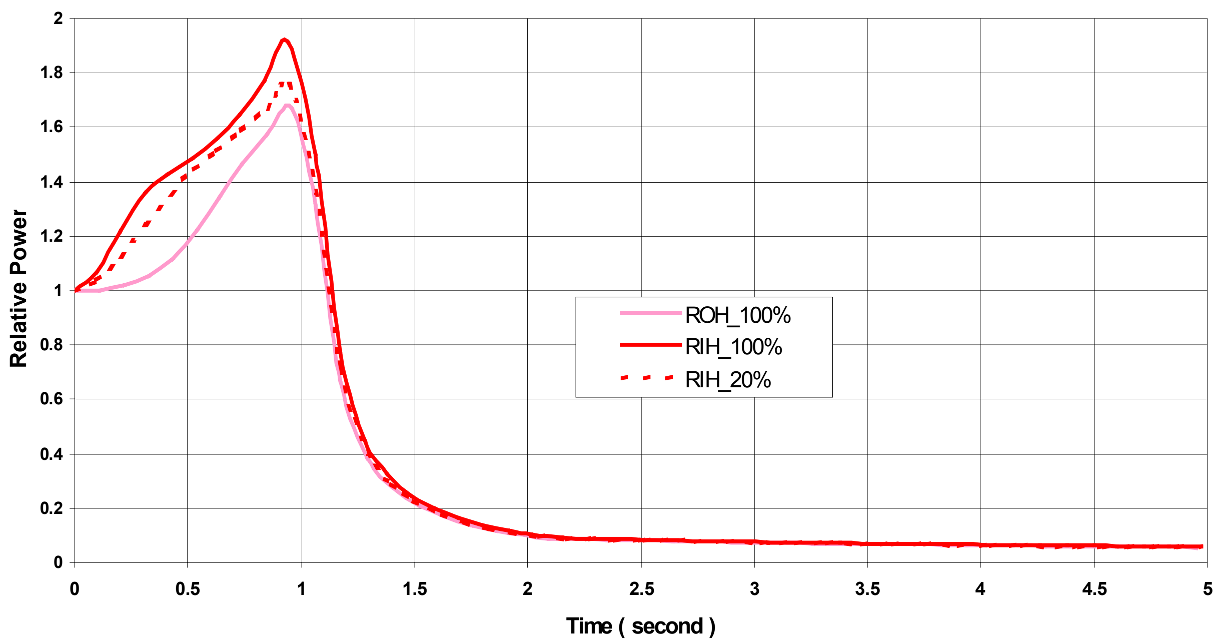


Figure 13 LOCA Power Transients in NG CANDU