Long-Term Performance Of The CANDU-Type Of Vanadium Self-Powered Neutron Detectors In NRU

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Abstract

The CANDU®-type of in-core vanadium self-powered neutron flux detectors have been installed in NRU to monitor the axial neutron flux distributions adjacent to the loop fuel test sites since 1996. This paper describes how the thermal neutron fluxes were measured at two monitoring sites, and presents a method of correcting the vanadium burn-up effect, which can be up to 2 to 3% per year, depending on the detector locations in the reactor. It also presents the results of measurements from neutron flux detectors that have operated for over eight-years in NRU. There is good agreement between the measured and simulated neutron fluxes, to within ± 6.5%, and the long-term performance of the CANDU-type of vanadium neutron flux detectors in NRU is satisfactory.

1. Introduction

The NRU reactor at Chalk River, which is one of the oldest research reactors in the world, is celebrating its 50th anniversary of operation this year. The NRU reactor is heavy water cooled and moderated, with on-line refuelling capability. It is licensed to operate at a maximum power of 135 MW, and has a peak thermal flux of approximately 4.0×10^{18} $n.m^{-2}.s^{-1}$. Figure 1 shows a NRU core lattice, with rows (1 to 31) and 18 columns (A to S, with no column "I"). The hexagonal lattice pitch between adjacent rod assemblies is 19.685 cm.

In order to provide data for validating the simulated flux distributions from code calculations, in-core flux detectors were installed in NRU in 1996 to monitor the axial neutron flux distributions adjacent to the NRU loops. The NRU reactor loops [1] are high temperature, high pressure test facilities, designed mainly for fuel bundle testing.

One of the long-term problems of the vanadium detectors is the significant reduction in output signals due to burn-up, which can be up to 2 to 3% per year, depending on the detector locations in the reactor. This paper describes how the thermal neutron fluxes were measured at two monitoring sites using vanadium flux detectors, and presents a method of correcting the vanadium burn up effect. It also presents the results of measurements from flux detectors that have operated for over eight-years in NRU, and the comparisons with simulated fluxes from code predictions.

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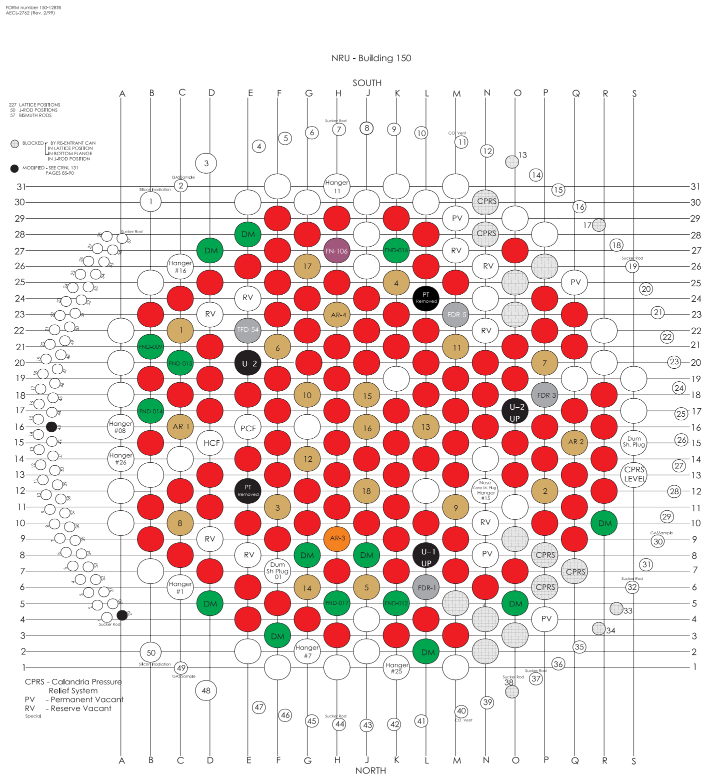

Figure 1. The NRU Core Lattice

2. The NRU Flux Detector Rods

There is a flux detector rod in each of the flux monitoring sites P18 and L06. The flux detector rod contains a smaller centre tube of 0.58 cm outer diameter with flux detectors tightly wound around it. The small centre tube also provides a passage for the Traveling Flux Detector (TFD) scans to re-calibrate the in-core flux detectors, if required.

In each flux detector rod there are twelve flux detectors: six vanadium detectors and six Pt-clad Inconel detectors. The former type is designed to measure neutron fluxes in steady state, and the latter to measure rapidly changing neutron fluxes. The detectors are placed in a dry, leak-tight helium gas environment to reduce corrosion of the detectors. Details of the flux detector rods in NRU are described in a previous CNS paper [2].

3. Vanadium Flux Detectors

The in-core flux detectors used in the NRU reactor are the CANDU-type of self-powered neutron flux detectors [3]. This type of detector is essentially a coaxial cable consisting of an inner emitter and an outer collector, separated from each other by an annular insulator (see Figure 2). The self-powered flux detector does not require an external power supply to generate its output current signals. The vanadium flux detectors in NRU have a metallic vanadium emitter, an Inconel-600 (Ni-Cr-Fe alloy) collector or sheath, and magnesium oxide insulation. The outside diameter and wall thickness of sheath are 3.00 mm and 0.45 mm, respectively. The diameter of the vanadium emitter is 1.44 mm. The flux detectors are coiled to reduce the axial length over which they measure flux in the reactor. The coiled length of the vanadium emitter is 3.05 cm, and the uncoiled length is 28.60 cm.

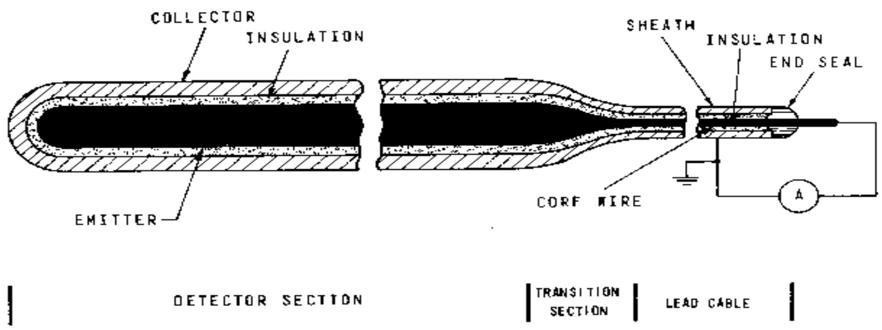

Figure 2. Schematic Diagram of a Self-powered Neutron Flux Detector

The current produced by a vanadium detector consists of two components:

(a) (n,γ,e) prompt contribution, which is about 8% of the total signal, and

(b) (n,β) delayed contribution, which is about 92% of the total signal. The current induced by the (n,β) reaction has a slow response with a 5.45-minute time constant determined by the 3.75-minute half-life of the nuclide, V-52.

The vanadium detectors were initially calibrated in a known thermal flux in the ZED-2 reactor at Chalk River. The sensitivities (output currents per unit neutron flux) of the vanadium detectors were determined with a precision of better than 1%. The typical sensitivity for the vanadium detectors was ~8.9 x10^{-21} A/ n. cm^{-2} s^{-1}. After the detectors had been installed in the NRU reactor, they were again calibrated, in-situ, by Traveling Flux Detector (TFD) scans, with the reactor operating at constant power. The TFD is a small pre-calibrated fission chamber, which can be driven through the central tube of the flux monitoring site to perform an axial flux scan to provide the correct output current signals for the vanadium detectors.

4. Detector Burnup Correction

When a vanadium detector is exposed to a neutron flux for a long period of time, there is a gradual loss of output current signal due to burnup of vanadium. The change in the current response of the vanadium detector was corrected on the basis of the thermal neutron absorption cross section of vanadium and the thermal fluence (accumulated flux over time) that the detector was exposed to.

$$I(t) = I(0)\exp(-\sigma_0 \phi_0 t) \tag{1}$$

where $I(t)$ is the total current of the vanadium detector,
$I(0)$ is the initial current of the vanadium detector at zero burnup,
t is the total irradiation time,
ϕ_0 is the mean measured thermal flux over the irradiation time, and
σ_0 is the thermal neutron absorption cross section of vanadium (V-51), 4.9 barns.

Using Eq. (1), the burnup correction factor for a detector, i, in NRU, $C_i(j, j+1)$, between two successive measurements, or scans, j and $j+1$, is:

$$C_i(j, j+1) = \exp(\sigma_0 \phi_{i,j} \Delta t_j), \tag{2}$$

where $\phi_{i,j}$ is the flux reading for detector i for the j^{th} scan, and
Δt_j is the irradiation time between two successive scans, j and $j+1$.

For longer irradiation periods with more scans in-between, the combined correction factor is just the product of the correction factors between all the successive scans within that period.

$$C_i(j, j+n) = C_i(j, j+1) * C_i(j+1, j+2) * C_i(j+2, j+3) * ....C_i(j+n-1, j+n) \tag{3}$$

In NRU, typical thermal neutron fluxes at the reactor centre, and near the top or bottom of the reactor near loop sites, are 3.0 x 10^{18} n. m^{-2} s^{-1} and 1.2 x 10^{18} n. m^{-2} s^{-1}, respectively. Using Eq. (1), the burnup correction factors, $I(0)/I(t)$, at these locations for 30 days of irradiation are 1.0038 and 1.0015, respectively. In general, the burnup correction factors in NRU are 1 to 3% per year, depending on the detector locations.

Table 1 shows the burnup correction factors for the detectors at the P18 and L06 sites in the beginning of the year 2005, after about eight-years of operation. In this Table, the largest correction factor is 1.27 for the detector located at the centre high-flux region of the reactor. The uncertainties of the burnup correction factors are also listed in the last column of Table 1, assuming about $\pm$5 % in the flux measurement error.

Table 1. Burnup Correction Factors for Vanadium Detectors in the Beginning of Year 2005

Monitoring Sites	Vanadium Detectors	Date of First Calibration (yyyy-mm-dd)	Axial Location, Distance from Centre of Reactor, mm	Burnup Correction Factors in the Beginning of Year 2005
P18	282V	1996-08-28	1140	1.170 $\pm$ .009
P18	284V	1996-08-28	640	1.243 $\pm$ .012
P18	286V	1996-08-28	140	1.270 $\pm$ .014
P18	288V	1996-08-28	-360	1.251 $\pm$ .013
P18	290V	1996-08-28	-860	1.223 $\pm$ .011
P18	292V	1996-08-28	-1360	1.122 $\pm$ .006
L06	262V	1997-03-14	1140	1.136 $\pm$ .007
L06	264V	1997-03-14	640	1.197 $\pm$ .010
L06	266V	1997-03-14	140	1.215 $\pm$ .011
L06	268V	1997-03-14	-360	1.202 $\pm$ .010
L06	270V	1997-03-14	-860	1.172 $\pm$ .009
L06	272V	1997-03-14	-1360	1.091 $\pm$ .005

5. Calculation of Axial Flux Distributions

The axial flux distributions at the flux monitoring sites were obtained from the calculation results of a three-dimensional diffusion code, TRIAD3 [4], using the finite difference method. The code was based on a neutronic model of the NRU reactor, made up of 301 reactor sites at a 19.685 cm hexagonal pitch. Each of the various types of rods in NRU was modeled as 18 axially stacked cells. The homogeneous two-group neutron cross sections for each cell were prepared by version 2-5d of the WIMS-AECL [5] cell code, with its associated ENDF/B-V derived database. WIMS-AECL is a multi-group transport code with two-dimensional capabilities using the 'Pij' collision probability method. For a fixed reactor power level, the simulated axial fluxes at 18 different elevations of a flux detector rod site were calculated by the TRIAD3 code using two energy groups, and the axial boundary conditions were set with zero fluxes at $\pm$182.0 cm from the centre of the reactor. The fluxes at the detector locations were then calculated by linear interpolation of the thermal fluxes at the appropriate axial cell locations.

6. Comparison of Measured and Simulated Fluxes

Thermal neutron fluxes at detector locations were measured with different fuel strings in the adjacent loop fuel test sites, and on some occasions, with no fuel strings but high-flow dummy fuel in the loop fuel test sites. The currents from each detector were taken through an appropriately chosen precision resistor to provide a voltage in the range of 0 to 50 millivolts for REDNET to monitor. REDNET, Reactor Data NETwork, is the data acquisition and processing system for the NRU reactor. After the flux measurement data were corrected for burnup of vanadium, they were compared with the simulated fluxes.

For the normalization of the fluxes, the simulated fluxes determined by the TRIAD3 code are first normalized to 1.0 at the flux peak. The measured fluxes are then normalized to the simulated fluxes such that the sums of the squares of the differences between the measured and simulated fluxes are minimized, i.e., the measured fluxes were least square fitted to the simulated fluxes. The normalization factor for the measured fluxes at the detector locations of the monitoring site, a_N, can be shown to be:

$$a_N = \sum_i (\phi^*_{sim,i})^2 / \sum_i \phi^*_{sim,i} * \phi_{mea,i} \ , \ i = 1,\dots k \tag{4}$$

where $\phi^*_{sim,i}$ is the normalized simulated fluxes at detector location, i ,
$\phi_{mea,i}$ is the measured fluxes at detector location, i , and
k is the number of detectors at the monitoring site.

The normalized measured flux at detector location, i, denoted by $\phi^*_{mea,i}$, is determined by:

$$\phi^*_{mea,i} = a_N * \phi_{mea,i} \tag{5}$$

Figures 3a to 3c show comparisons between the flux detector measurements and some calculated axial flux distributions for sites P18 and L06. In these figures, the axial thermal fluxes predicted by TRIAD3 at the 18 axial elevations and the fitted flux distributions are shown. These figures also show the measured fluxes at the vanadium detector locations, with a $\pm$ 3% error bar, which is the error for the reproducibility of the flux distributions.

In Figure 3a, the simulated axial flux distribution at site P18 on 2004 April 29, with fuel string S324 in the adjacent loop site is shown. The flux distribution was asymmetrical about the reactor centre. The fluxes were slightly depressed in the top half of the reactor. The largest discrepancy occurred in the second detector from the top, 3.4%. The agreement between the measured and simulated fluxes for the rest of the detectors was quite good, within $\pm$2.0%.

In Figure 3b, the simulated axial flux distribution at site P18 on 2004 October 25, with fuel string S325 in the adjacent loop site is shown. The flux distribution was asymmetrical about the reactor centre, with fluxes slightly depressed in the top half of the reactor. The agreement between the measured and simulated fluxes at all the detector locations was quite good, within $\pm$2.5%.

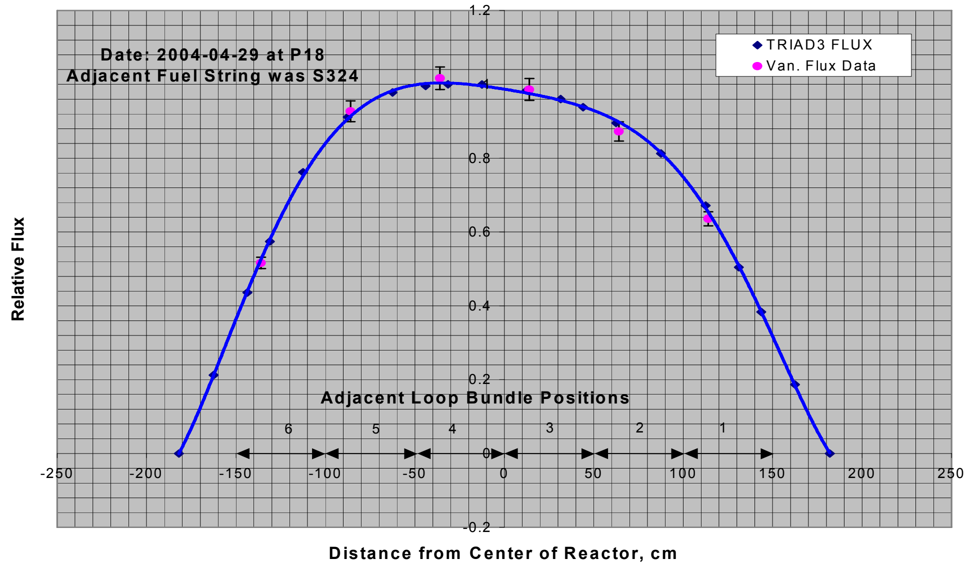

Figure 3a. Comparison of Measured-to-simulated Fluxes on 2004 April 29 at Site P18

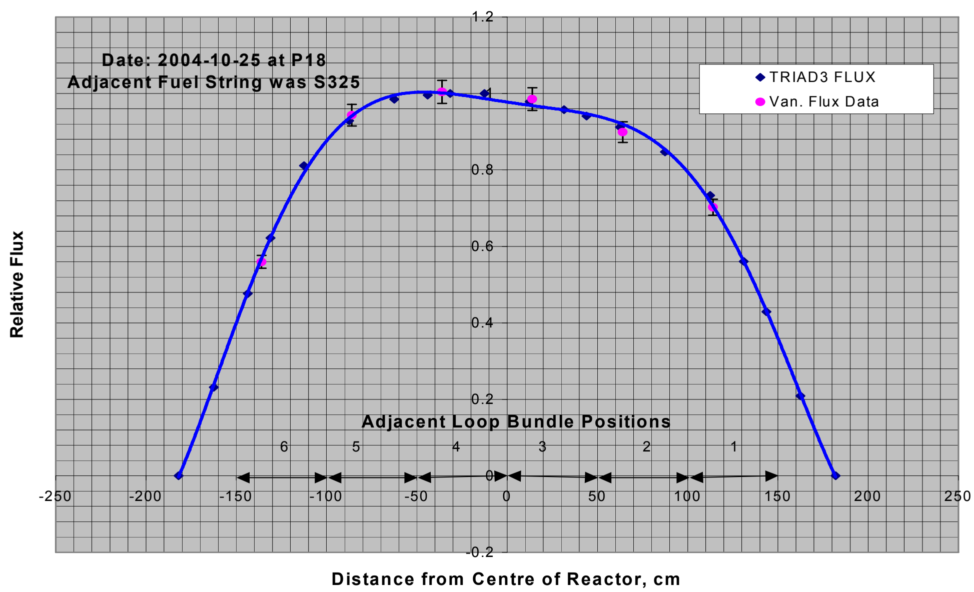

Figure 3b. Comparison of Measured-to-simulated Fluxes on 2004 October 25 at Site P18

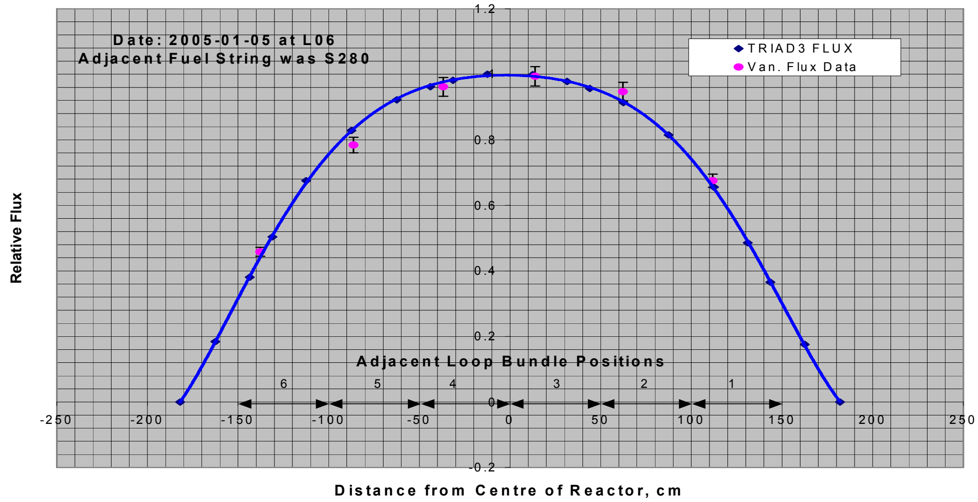

Figure 3c. Comparison of Measured-to-simulated Fluxes on 2005 January 05 at Site L06

In Figure 3c, the simulated axial flux distribution at site L06 on 2005 January 05, with fuel string S280 in the adjacent loop site is shown. The flux distribution was fairly symmetrical about the reactor centre, similar to a cosine distribution. The discrepancy between the measured and simulated fluxes for the second detector from the bottom was -6.0%, but a smaller discrepancy occurred for the rest of the detectors, within $\pm$5.2%.

7. Measured-to-simulated Flux Ratios at Detector Locations

The measured-to-simulated flux ratio, R_{ϕ_i}, is the ratio of the *normalized* measured and simulated fluxes at a detector location, i, at the time of flux measurement:

$$R_{\phi_i} = \phi^*_{mea,i} / \phi^*_{sim,i} \,. \qquad (6)$$

The mean value, $\mu_i = \overline{R}_{\phi_i}$, and standard deviation, σ_i, of the measured-to-simulated flux ratios at a detector location, i, are calculated by:

$$\mu_i = (\sum_{n=1}^{N} R_{\phi_{i,n}}) / N \,, \quad \text{and} \qquad (7)$$

$$\sigma_i = \sqrt{\frac{\sum_{n=1}^{N}(R_{\phi_{i,n}} - \mu_i)^2}{N-1}}, \tag{8}$$

where N is the number of data points for each detector location.

Figure 4 shows a typical histogram of the measured-to-simulated flux ratios for detector 286V for a 4-year period between 2000 and 2003. The histogram is compared with a normal (Gaussian) distribution. The normal distribution, $f_i(x)$ for the detector location, i, is defined as:

$$f_i(x) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(1/2)[(x-\mu_i)/\sigma_i]^2}, \tag{9}$$

where x is the measured-to-simulated flux ratio, R_{ϕ_i}, for detector location i. For this detector, the mean value for R_{ϕ_i} was 1.010 and the standard deviation was $\pm$0.011.

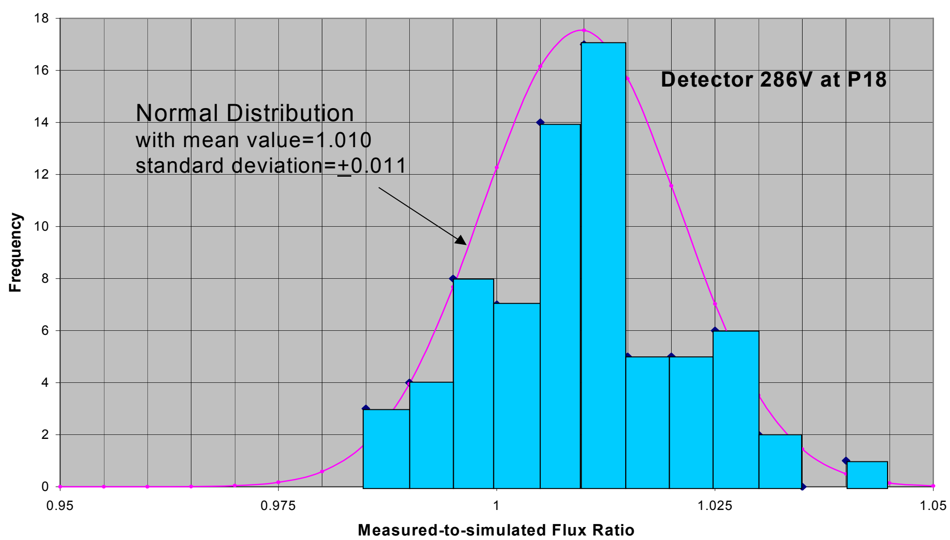

Figure 4. Histogram of the Measured-to-Simulated Flux Ratios for Detector 286V at Site P18.

Results of the mean values and standard deviations for the measured-to-simulated flux ratios, R_{ϕ_i}, at detector locations for the two monitoring sites are summarized in Table 2.

In this Table, the results covered a variety of fuel strings at the adjacent loop fuel test sites over a 4-year period from 2000 to 2003. For both monitoring sites, the agreement between the measured and simulated fluxes at detectors located at the centre region of the reactor was quite good, within ±1.5%, and it became poorer at detectors near the top and bottom of the reactor. In general, there is a better agreement between the measured and simulated fluxes at the detector locations of site P18 than those of site L06. At site P18, the $\overline{R}_{\phi_i}$ ratios varied only from 0.961 to 1.010, but at site L06, from 0.936 to 1.042. At the detector locations where the maximum discrepancy between the measured and simulated fluxes occurred at site L06, the simulation code TRIAD3 could over-predict the fluxes by 6.4% for detector 270V, but under-predict the fluxes by 4.2% for detector 264V.

At site P18, the uncertainty or standard deviation for the measured-to-simulated flux ratios may vary from ±0.011 to ±0.026, and at site L06, from ±0.013 to ±0.045.

Table 2. Mean Measured-to-simulated Flux Ratios at Detector Locations for Sites P18 and L06

Site	**Neutron Flux Detectors (Distance above or below centre of Reactor)**					
P18	**282V** **(1140 mm)**	**284V** **(640 mm)**	**286V** **(140 mm)**	**288V** **(-360 mm)**	**290V** **(-860 mm)**	**292V** **(-1360 mm)**
Mean, $\overline{R}_{\phi_i}$**, Standard Deviation**	0.988 ±0.026	1.003 ±0.014	1.010 ±0.011	1.005 ±0.012	0.994 ±0.020	0.961 ±0.025
	Neutron Flux Detectors (Distance above or below centre of Reactor)					
L06	**262V** **(1140 mm)**	**264V** **(640 mm)**	**266V** **(140 mm)**	**268V** **(-360 mm)**	**270V** **(-860 mm)**	**272V** **(-1360 mm)**
Mean, $\overline{R}_{\phi_i}$**, Standard Deviation**	1.033 ±0.029	1.042 ±0.027	1.012 ±0.013	0.993 ±0.015	0.936 ±0.018	0.985 ±0.045

8. Conclusions

Several conclusions can be drawn from this study:

1) After eight-years of operation in the NRU reactor, the burnup correction factors for the vanadium flux detectors can vary from 9% to as high as ~ 27%, depending on the detector locations in the reactor.

2) When both the measured and simulated fluxes were normalized to the same axial flux shape (i.e., the measured fluxes were least square fitted to the simulated fluxes), the agreement between the flux detector measurements and simulated fluxes for a variety of axial flux distributions at two of the monitoring sites of P18 and L06 was fairly good, within $\pm$6.5%.

3) The CANDU-type of vanadium self-powered neutron flux detectors after over eight-years of operation in NRU, is producing the expected output signals, and the overall long-term performance of the detectors is satisfactory.

9. References

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