Validation of RFSP-IST/WIMS-IST Time-Average Fuel Discharge Burnup Calculation*

M.A. Shad
Atomic Energy of Canada Limited
2251 Speakman Drive
Mississauga, ON, Canada L5K 1B2

Abstract

At the design stage, the average exit burnup achieved in a CANDU core is predicted by performing a time-average calculation with certain assumed nominal operating conditions. The major physics design code RFSP-IST is often used for such calculations. At an operating CANDU® plant, power production and refuelling histories are routinely tracked by suitable three-dimensional diffusion neutronic codes, including RFSP-IST. Since daily operating conditions vary and would not be the same as those assumed in the time-average design calculation, there is considerable interest in ascertaining the accuracy of the time-average burnup prediction. Aside from exit burnup prediction, the time-average model is also used to assess core performance and behaviour, such as operation under different device configurations, fuel management schemes, adjuster loadings, etc. Therefore, the accuracy of the time-average flux shape prediction is also of interest.

This paper assesses the accuracy of the burnup calculations, by comparing the predicted discharge burnup with the discharge burnup obtained from the actual one-year period of reactor fuelling history at the Point Lepreau Generating Station (PLGS). It also covers the accuracy of the time-average flux shape calculation.

1.0 INTRODUCTION

AECL and the utilities have committed to the Canadian Nuclear Safety Commission (CNSC) to validate Industry Standard Tools (IST) employed to capture various phenomena at play in normal reactor operation as well as in safety analysis. This study is part of a series of validation exercises for the Reactor Fuelling Simulation Program RFSP-IST. It presents validation of the time-average exit discharge burnup calculation, using the WIMS-IST/DRAGON/RFSP-IST suite of codes. The version of RFSP-IST used for this study was “rfsp-ist.REL_3-01HP”, and the WIMS-IST version used in was “WIMS-AECL 2-5d”, with the ENDF/B-VI data library, version “u2x.1-0d.hpux10”.

This validation of the time-average calculation made use of the two-group lattice properties based on the Simple-cell Methodology (SCM)[1]. The incremental cross sections for various reactivity devices and structural materials were calculated with the transport code DRAGON.

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The validation was done against site data from the Point Lepreau Generating Station (PLGS) over the time period of 1994 March 30 (FPD 3857) to 1995 April 14 (FPD 4215). The accuracy of the time-average-calculation methodology as embodied in the *TIME-AVER module in RFSP was assessed by comparing the computed average discharge burnup against actual average discharge burnup obtained over the one-year of reactor operation and by comparing the computed fluxes at detector locations against actual averages from detector measurements.

2.0 METHODOLOGY

The actual achieved average discharge burnup was inferred from site data over the one-year period. The total power generated by the reactor (in terms of thermal energy transferred to the coolant) during this period was 17 718 084 MW.h(t). With a nominal full thermal power at 2061.4 MW(t), the total power generated corresponded to 358.13 FPD. Given the total number of bundles discharged (5486), the "measured" average discharge burnup was readily inferred.

The core operating history was tracked by a total of 123 RFSP "production simulations". In addition to the channel refuelled, the records from these simulations provided the variations in core conditions such as moderator poison level, zone fill levels, moderator purity and temperature etc. Four of the production simulations were excluded from consideration for the reason of "irregularity". These "irregular" simulations did not include any fuelling and had small time steps. Most of the refuelling operations done in the one-year period used the 8-bundle-shift refuelling scheme. Two channels were refuelled with a 4-bundle-shift refuelling scheme, and one channel was refuelled with a 2-bundle-shift refuelling scheme.

The "measured" average discharge burnup was compared to the "time-average" calculation discharge burnup. The time-average calculation required:

(a) Assumed core parameters, which were taken as the average values over the one-year period. These parameters included zone fills, coolant D_2O purity, moderator D_2O purity, moderator temperature, moderator poison concentration and coolant temperature. These parameters were obtained by averaging the values of each parameter from the production simulation records, weighted by the incremented energy corresponding to each burnup step. The average values are given in Table 1

(b) A target k-eff value that represented a critical core state, and a target channel power distribution. These quantities would be the averages from the production simulations. However, these simulations from site were performed using the PPV-based methodology. Therefore the core-follow simulations were repeated independently, using the SCM lattice-cell properties. Based on the simulation results, an average core reactivity bias value (-2.5 milli-k) and an average channel power map (shown in Figure 1) were established.

In the time-average calculation, the exit irradiation of each channel was adjusted to match the channel power distribution and the overall k-eff value. The predicted average discharge burnup was then compared to the measured average discharge burnup.

3.0 RESULTS

"Measured" average discharge burnup and feed rate

During the one-year period, three fuel types, namely ZTFU01-NAT, ZTFU02-NAT and GEFU01-NAT, were either fuelled into the core or discharged from the core. The actual uranium mass per bundle in these fuel types varied from 19.08 to 19.35 kg(U). A summary of the fuel types resident in core and discharged from the core is shown in Table 2. An average uranium mass of 19.19 kg per in a bundle was used in the WIMS-IST model to generate the lattice-cell properties for the time-average calculation. The core-follow simulations, however, modelled the three different fuel types explicitly.

The thermal energy produced over the one-year period was 17 718 084 MW.h. The total number of fuel inserted in the core (and removed from the core) was 5486. The core conditions, in particular the average zone fills, were somewhat different at the beginning and at the end of the one-year period. Table 3 shows the instantaneous conditions of the core at 10:00 AM on 1994 March 30 and at 03:50 AM on 1995 April 14. The average zone water level at the end of the one-year period was higher than at the start by 9.15%, which was equivalent to 0.7 milli-k. Assuming a reactivity decay rate of 0.4 milli-k/FPD, the reactor could run for another 1.75 FPD without fuelling. This extended time would add 86 578.8 MW.h to the total energy production and consequently the total thermal energy produced was corrected by this amount. The corrected value of the thermal energy produced is thus 17 804 662.8 MW.h.

Burnup is defined as the time-integrated fission energy produced per unit mass of uranium. Assuming a ratio of thermal energy to the fission-energy of 0.95612 (the same ratio in RFSP-IST time average calculation), the total fission energy produced was 18 621 787 MW.h(fission). The year-average bundle mass of the fuel bundles resident in the core was 19.19 kg(U). The total fuel mass throughput for the period is 104 732.68 Kg(U). The average discharge burnup was 177.80 MW.h/kg(U). The "measured" fuelling rate (corrected for the zone level difference) for the one-year period was 15.24 bundles/FPD.

Time-Average Calculation Results

The *TIME-AVER module of RFSP-IST was used to simulate the time-average core, with a fuel type ZTFU02-NEW that represents the "average fuel bundle". The bundle mass was 19.19 kg(U). The exit irradiation in each channel of the core was adjusted to match the "production average channel powers" shown in Figure 1, and a core excess reactivity offset of -2.5 milli-k. The individual zone fills were also the "average" over the one-year period for each zone controller, and the average zone fill was 49.07%.

The computed discharge burnup was 3371.97 MW.h/bundle or 175.70 MW.h/kg(U). The computed average bundle feed rate was 15.34 bundles/FPD. Thus the time-average calculated discharge burnup is 98.8% of the "measured" burnup, the time-average bundle feed rate is 100.6% of the "measured" bundle feed rate.

<u>Flux-Shape Comparison</u>

The global flux shape is characterized by the vanadium detector readings at 102 location distributed throughout the core. During the one-year period of the operating history of PLGS, 114 sets of vanadium detector measurements were recorded. The set of average values over the 114 measurements at each detector location was representative of the average flux shape. For each detector, the variation of the measured signal over time was examined. The maximum value of the standard deviations was ±3.72%, while the minimum value of the standard deviations was ±1.29%.

The measured flux values were compared with the computed fluxes at the 102 detector locations from the time average calculation. Both sets of measured fluxes and computed fluxes were normalized such that the sum of the 102 flux values was 1.0. The maximum positive difference and the maximum negative difference between the detector-average of the “measured” values and the simulated time-average values were 9.26% and -9.91% respectively. The average difference was -0.35%, and the standard deviation of the difference was ±3.54%.

4.0 CONCLUSIONS

The time-average discharge burnup has been validated against the “measured” discharge burnup, which was extracted from the refuelling data for a one-year operating history of PLGS. The calculated time-average discharge burnup is 98.8% of the “measured” discharge burnup. The bundle feed rate predicted by the time-average calculation was 100.6% of the actual bundle feed rate. The close agreement confirmed the soundness of the “time-average” formulation and its accuracy. The underestimation of average discharge burnup is quite small (1.2%), and the associated underestimate in core-average instantaneous burnup would be much smaller still (about half of the discharge-burnup underestimate).

The fluxes at the 102 vanadium detector sites obtained from the time-average calculation were compared to the measured value average over the one-year period. The standard deviation of the differences was ± 3.54%.

5.0 REFERENCES

1. J.V. Donnelly, “Development of a Simple-Cell Model for Performing History-Based RFSP Simulations with WIMS-AECL”, in Proceedings of the International Conference on the Physics of Nuclear Science and Technology, Long Island, NY, 1998 October.

Table 1

Variation in Operational Parameters in PLGS Production Simulations

From 1994 April 04 to 1995 April 14

Parameter	Average Zone Fill (%)	Moderator Temperature (^0C)	Moderator D_2O (atom%)	Coolant D_2O (atom%)	Boron Conc. (mg/kg)	Core Excess Reactivity (mk)	
						PPV	WIMS-IST
Minimum Value	33.7	63.0	99.930	98.170	0.000	0.06	-12.77
Maximum Value	61.3	68.0	99.935	98.391	0.593	4.48	0.00
Mean Value	49.1	66.7	99.934	98.342	0.123	2.95	-2.50
Standard Deviation	±5.6	±2.2	±0.002	±0.077	±0.143	±0.57	±1.30

Table 2

Summary of Refuelling at PLGS

Fuel Type	ZTFU01-NAT	ZTFU02-NAT	GEFU01-NAT	Total U-Mass (kg(U))	Avg. U-Mass per Bundle (kg(U))
START 94/03/30 at 10:00 AM	3730	830	0	4560	19.3539
Fuelled Into the Core	94	5391	1	5486	19.0845
Discharged From the Core	3584	1901	1	5486	19.3010
END 95/04/14 at 03:50 AM	240	4320	0	4560	19.0957

Table 3

Instantaneous Core Conditions at Start and End of Analyzed Period

Date & Time → Parameter ↓	1994 March 30 @ 10:00 AM	1995 April 14 @ 03:50 AM
Cumulative Energy (MW.h)	190 799 674	208 517 758
FPD	3856.59	4214.72
Average Zone Level (%)	48.9	58.22
Boron Concentration. (mg/kg)	0.142	0.0
Moderator Temperature (^{0}C)	68.0	63.00
Moderator Purity (atom%)	99.935	98.170
HTS Purity (atom%)	98.391	98.170
Coolant Temperature (^{0}C)	288.5	288.1
Reactivity (milli-k)	-3.15	-2.53

Figure 1: Average Channel Power (kW) for PLGS Operating History For the Period 94/03/30 to 95/04/14

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									3311	3465	3601	3584	3453	3303									A
B						2928	3562	4161	4462	4656	4660	4615	4617	4408	4060	3582	2971						B
C					3213	3897	4607	5119	5431	5541	5495	5450	5539	5440	5166	4702	4056	3423					C
D				3330	4119	4734	5357	5799	6060	6133	6038	6010	6193	6133	5923	5492	5003	4256	3495				D
E			3218	4007	4780	5386	5866	6174	6296	6303	6207	6287	6348	6420	6320	6072	5638	5032	4248	3349			E
F			3905	4665	5311	5770	6145	6349	6335	6240	6202	6202	6302	6390	6541	6360	6022	5529	4903	4040			F
G		3415	4499	5183	5608	6000	6248	6378	6323	6351	6260	6319	6310	6356	6521	6392	6151	5802	5430	4626	3652		G
H		4048	4946	5470	5846	6113	6271	6306	6300	6294	6339	6356	6425	6386	6492	6415	6270	6004	5765	5005	4125		H
J	3218	4426	5313	5928	5988	6156	6260	6300	6243	6229	6246	6282	6335	6355	6393	6348	5909	6081	6036	5425	4504	3257	J
K	3522	4735	5613	6157	6125	6199	6281	6243	6142	6141	6137	6162	6237	6321	6388	6379	6241	6235	6249	5652	4804	3555	K
L	3703	4941	5800	6320	6392	6378	6346	6306	6206	6160	6041	6034	6206	6298	6405	6440	6482	6446	6328	5835	4878	3708	L
M	3707	4959	5885	6374	6491	6429	6387	6355	6301	6181	6008	6046	6208	6330	6429	6457	6522	6514	6424	5901	4964	3647	M
N	3535	4798	5780	6356	6539	6488	6470	6401	6329	6255	6120	6160	6296	6337	6416	6489	6568	6521	6400	5789	4716	3469	N
O	3240	4528	5573	6197	6421	6538	6475	6445	6379	6361	6319	6323	6361	6395	6462	6556	6548	6474	6248	5596	4554	3276	O
P		4103	5129	5882	6168	6399	6523	6493	6400	6292	6421	6442	6405	6425	6489	6553	6408	6163	5870	5154	4140		P
Q		3616	4476	5377	5793	6109	6373	6542	6440	6422	6418	6411	6414	6381	6452	6374	6112	5731	5378	4536	3602		Q
R			3881	4642	5249	5770	6167	6392	6418	6418	6368	6400	6409	6415	6393	6186	5723	5224	4698	3858			R
S			3152	3964	4659	5304	5897	6224	6359	6347	6276	6256	6396	6336	6211	5800	5215	4600	3971	3153			S
T				3179	3850	4615	5229	5687	5893	5932	5844	5810	5952	5881	5606	5124	4512	3821	3158				T
U					3000	3693	4258	4800	5075	5214	5122	5194	5192	5054	4643	4218	3535	2846					U
V						2475	3108	3664	4004	4222	4278	4243	4193	3933	3535	3028	2452						V
W									2729	2955	3066	3088	2912	2714									W
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	

```
MAXIMUM VALUE        =   6568.83     POSITION OF MAXIMUM VALUE = N 17
MINIMUM VALUE        =   2452.19     POSITION OF MINIMUM VALUE = V 17
MEAN VALUE           =   5424.73     STANDARD DEVIATION        = 1118.36
```