Utilizing the IRF for CANDU Fuel Bundle Irradiations

by

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Abstract

This paper reports a design study of power and reactivity trade-offs for the expected range of CANDU® bundles that will be tested in AECL's new Irradiation Research Facility (IRF). The study tracked peak driver-fuel ratings, test-fuel bundle powers and ratings as a function of burnup, and excess reactivity relative to the reference configuration of nine natural 37-element bundles (three per channel) with a uniform burnup of 3.5 MWd/kgU. The driver-fuel burnup distribution represented "Day 2" of an IRF operating cycle. The study provides a first-order parametric assessment of HTF behaviour, and establishes the need for lower-flux HTF positions that will limit the power of low-burnup, high-fissile-content test bundles to acceptable levels.

Background

To ensure the ongoing viability of the Canadian nuclear industry, a successor to Chalk River's NRU facility is needed to perform the fuel and materials testing that is prerequisite to developing advanced CANDU fuel cycles and future CANDU reactor designs, and for supporting existing CANDU stations. Accordingly, AECL is planning to build the Irradiation Research Facility (IRF) [1]. Based upon MAPLE technology, the IRF will employ a tank-in-pool reactor assembly with low-enrichment (19.75% ^{235}U) driver-fuel rods, mixed H_2O and D_2O moderation, and D_2O reflection. The unique split-core design features a set of three full-diameter horizontal CANDU channels with independent D_2O cooling systems in a D_2O-moderated region located between the two vertical H_2O-cooled driver-core halves (see Figure 1). These CANDU loops comprise the Horizontal Test Facility (HTF) and are intended primarily for the testing of up to nine full-size CANDU fuel bundles plus associated pressure and calandria tubes under realistic power-reactor conditions.

A major design challenge stems from the high fissile content of many advanced CANDU bundles relative to standard natural-UO_2 fuel. The IRF must compensate for anticipated HTF power and reactivity variations by deploying a system to vary the concentration of ^{10}B in a segmented annular D_2O channel located around the middle horizontal test section. This will reduce local power up to 15-20%, at a reactivity cost of up to ~15 mk, to limit de-rating of the IRF from full power during the irradiation of high-fissile-content test bundles.

This paper reports a design study of power and reactivity trade-offs for the expected range of CANDU test bundles. The study tracked peak driver-fuel ratings, test-fuel bundle powers and ratings as a function of burnup, and excess reactivity relative to the reference configuration of nine natural 37-element bundles (three per channel) with a uniform burnup of 3.5 MWd/kgU. The driver-fuel burnup distribution represented day 2 of an operating cycle.

Test Cases

Test bundle geometry was 37-element, unless noted below. Fuel compositions studied included: uniformly enriched 1.0, 1.2, and 1.5 wt% UO_2 fuel, Low Void Reactivity Fuel (LVRF), and "Parallex" MOX fuel. The "Parallex" MOX fuel (for weapons-grade plutonium disposition) used dysprosium poisoning, depleted uranium, and plutonium in selected fuel rings. The LVRF cases used 43-element (CANFLEX) geometry with dysprosium poisoning and ^{235}U enrichment in selected fuel rings.

CANDU bundle burnups covered the likely test range for each advanced CANDU fuel type, and included "bi-directional" shuffling in adjacent channels. Extreme cases of bundle power and excess reactivity were represented by low-burnup bundles positioned in the centre (highest power) HTF position. The boron shim control needed to reduce the excess reactivity to about the same as the reference case was also studied.

The burnup distribution in the driver core represented "Day 2" of an equilibrium operating cycle, calculated with reference mid-burnup, natural UO_2 CANDU fuel in the test loops. This distribution was not modified throughout the study and thus represents an approximation to the actual distribution that would be attained in each case.

Codes Used

The full-core power and flux distributions, including that of the CANDU test bundles, were calculated with the three-dimensional diffusion code 3DDT [2]. The driver-fuel burnup distribution was calculated using 3DDT and FULMGR (an in-house utility for fuel burnup and shuffling).

Few-group diffusion cross-sections for the driver fuel and CANDU fuel bundles were provided by WIMS-AECL [3] using supercells to represent the environments of driver-fuel and CANDU-fuel cells.

Results and Discussion

Table 1 presents the main results for the reference case and twenty-eight test configurations, normalized to a total driver-core power (i.e., excluding CANDU test fuel) of 30 MW. Cases where the reactivity relative to the reference case is labelled "B-10" indicate the simulation of boron shim, and establish the extent (0.9-1.8 %/mk) to which the excess reactivity associated with high fissile content and low burnup may be used to reduce the maximum test-bundle power.

The study provides a first-order assessment of HTF behaviour versus enrichment, fissile content, burnup distribution, boron shim level, and bundle position. Although approximate, it suggests the performance envelope within which advanced CANDU bundle testing will be constrained, and highlights certain areas of concern. In particular, since the IRF is designed to be operated at a power level that generates ~1000 kW in a mid-burnup natural UO_2 bundle, the high relative powers in the last column of Table 1 establish the need for an HTF position running at 60-70% of the highest-flux (middle) test section to limit the power of high-fissile-content bundles to 1000 kW.

As a measure of the reliability of the results, the first 1.5 wt% U-235 case in Table 1 was compared with a more accurate Monte Carlo calculation made with MCNP [4]. The diffusion result for relative reactivity is in agreement with MCNP, and the results for driver and test-fuel pin ratings are in reasonable agreement (4-5%) given the approximations in the WIMS-AECL/3DDT methodology. However, both the absolute k_{eff} value and the maximum CANDU bundle power are about 10% higher in the diffusion results, the latter being the more serious of the discrepancies in terms of interpretation of the current results. This is an area that will be improved as more rigorous analyses with WIMS-AECL/3DDT are performed for specific cases in the future.

The results are nevertheless useful in indicating relative trends and defining extreme cases.

References

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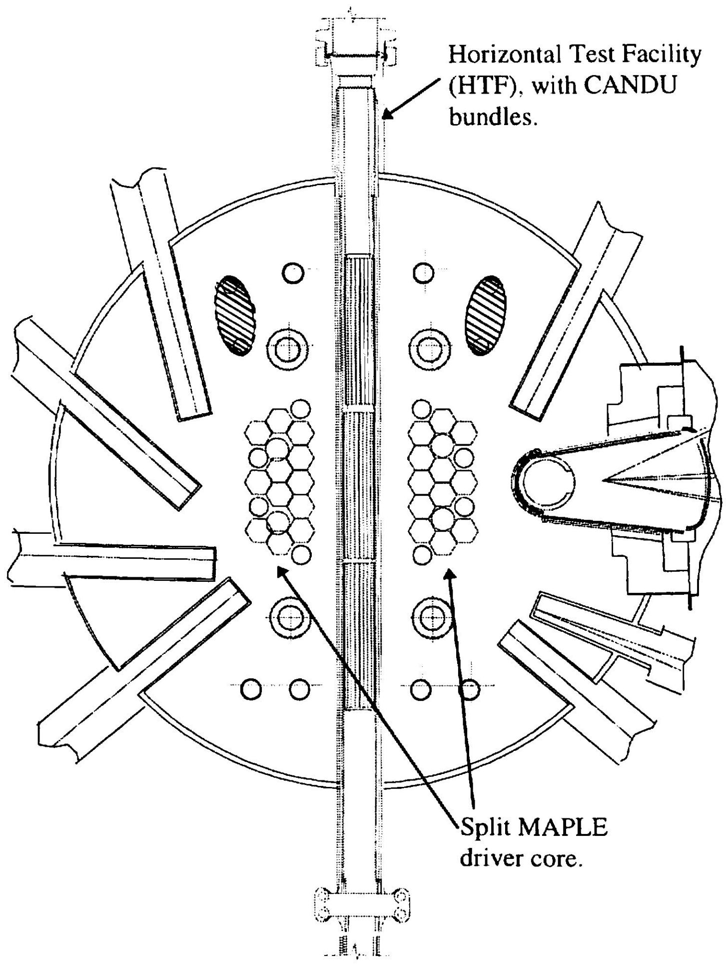

Figure 1. Plan view of proposed IRF, shown with three CANDU test bundles in one of three horizontal test channels (channels are stacked vertically between driver-core halves). Also shown are beam tubes and in-reflector irradiation sites.

Table 1. Summary of WIMS-AECL/3DDT Design Study Results for the IRF Horizontal Test Facility

Enrichment (wt% U-235)	Burnup of max. HTF bundle (MWd/kg)	ρ relative to ref. Case (mk)	Max. driver pin peak rating (kW/m)	Max. HTF element rating (kW/m)	Max. HTF bundle power (kW)	Relative Max. HTF bundle power
natural (ref.)	3.5	0.0	75.4	54.3	815	1
1.0	10	-0.1	75.6	56.7	853	1.047
1.0	8	+1.7	75.1	58.6	882	1.082
1.0	8	-1.7 (B-10)	75.9	55.6	836	1.026
1.5	10	+9.2	73.5	66.6	1005	1.233
1.5	10	-0.2 (B-10)	75.6	58.7	879	1.079
1.5	5	+13.4	72.3	75.3	1101	1.351
1.5	5	+0.5 (B-10)	75.1	64.4	936	1.148
1.5	2	+16.0	71.8	78.1	1143	1.402
1.2	10.5	+2.4	74.9	59.6	897	1.101
1.2	10.5	-0.9 (B-10)	75.5	57.1	858	1.053
1.2	5	+6.4	73.9	65.2	983	1.206
1.2	5	-1.3 (B-10)	75.2	59.6	895	1.098
1.2 (CANFLEX)	10.5	+2.6	74.9	48.0	890	1.092
1.2 (CANFLEX)	10.5	-0.7 (B-10)	75.6	46.0	851	1.044
1.2	2	+8.8	74.1	67.5	1018	1.249
1.5	14	+3.2	74.7	58.9	918	1.126
1.5	14	0.0 (B-10)	75.4	56.5	878	1.077
1.5	7	+6.4	73.3	71.8	1050	1.050
1.5	7	-0.4 (B-10)	75.3	63.2	919	1.128
1.5	2	+12.8	72.4	77.6	1134	1.134
LVRF (CANFLEX)	10.5	+0.3	75.6	55.8	956	1.173
LVRF (CANFLEX)	5	+3.8	74.7	63.2	1043	1.280
LVRF (CANFLEX)	5	+0.7 (B-10)	75.3	60.5	997	1.223
LVRF (CANFLEX)	2	+5.5	74.3	67.8	1083	1.329
Parallex MOX	4.75	+4.9	74.8	78.2	1106	1.357
Parallex MOX	4.75	+0.1 (B-10)	75.8	77.0	1054	1.293
Parallex MOX	2	+8.8	74.2	88.2	1211	1.486
Parallex MOX	2	+0.1 (B-10)	75.8	78.3	1071	1.314