Loading Blended, Low-enriched Uranium Fuel in Browns Ferry Units 2 and 3

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Abstract

This paper summarizes fuel and cycle design results for the Tennessee Valley Authority (TVA) / Department of Energy (DOE) program to burn blended, low-enriched uranium (BLEU) material in the Browns Ferry Nuclear Units 2 and 3.

The BLEU material typically has about 60 times the allowed limit of U-236 in what would be defined as commercial, i.e., virgin, uranium. U-236 in particular is a strong neutron absorber.

Also included is a comparison of cycles using commercial uranium versus BLEU to determine the impact on key core design parameters of the high U-236 content in the BLEU.

Finally, there is a short discussion of the economic advantages of BLEU fuel.

1.0 Introduction

In 1995, President Clinton declared 174 metric tons (MT) of highly enriched uranium (HEU) out of the US weapons program as surplus material. In 1997, the Tennessee Valley Authority (TVA) signed a letter of understanding with the Department of Energy (DOE) to take 39 MT of the HEU to be downblended (thus becoming blended low enriched uranium—BLEU) for use as fuel to generate electricity. A consortium of AREVA NP[a], Fuel America, Siemens Power Corp., and Nuclear Fuel Services (NFS) was chosen to process the BLEU material into fuel. In 2001 a TVA interagency agreement with DOE and contracts with AREVA were signed to use BLEU at the Browns Ferry Nuclear Plant in Alabama.

In April 2005 TVA put its first reload of blended, low-enriched uranium fuel in Browns Ferry Unit 2. This was a key milestone in TVA's successful program to recycle surplus weapons-grade, highly enriched uranium in nuclear power plants. This project, a partnership venture between TVA and the DOE, provides benefits of saving the Federal government more than a half billion dollars as a lower-cost alternative for disposing of highly enriched uranium, and saving TVA 25 percent in nuclear fuel costs. One of the dominant characteristics of reprocessed, weapons-grade uranium is a high U-234 and U-236 content compared to commercially supplied uranium. The presence of these isotopes in relatively high amounts presents an interesting challenge to the reactor core designer.

This paper deals with the core physics aspects of designing boiling-water reactor (BWR) cores to use BLEU fuel. These aspects include the impact of BLEU on fuel bundle lattice enrichment, kinetic parameters, control rod worths, and reactivity, as well as core batch size, core monitoring (measured versus calculated results) and uranium savings.

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[a] AREVA NP Inc. is an AREVA and Siemens company.

2.0 BLEU Material Characteristics

As part of the overall program TVA contracted with AREVA/NFS to downblend HEU and to convert downblended aqueous uranyl nitrate UNH to uranium oxide powder. The down-blended U(4.95)NH comes from DOE in South Carolina and NFS in Tennessee to the AREVA conversion facility in Erwin, Tennessee, where it is converted through an ADU (ammoniumdiuranate) process from UNH to uranium oxide powder. The powder is then shipped to the AREVA Fuel Fabrication Facility in Richland, Washington, to be pelletized and loaded into BWR fuel assemblies. These assemblies are in turn shipped to the Browns Ferry Nuclear Plant in Alabama for use in the Browns Ferry Units 2 and 3.

2.1 BLEU Material Make-up

The BLEU material meets the commercial grade uranium (CGU) specification (Ref. 1) with the exception of the uranium isotopes, i.e., U-232, U-234, and U-236. (There is not a significant amount of U-234, which occurs naturally in uranium, and builds-in with exposure. U-236 does not occur naturally and builds-in with exposure only.) The primary effect of these isotopes in BLEU fuel is to decrease reactivity, due primarily to the parasitic absorption of neutrons in U-236. The impact of U-236 on light-water reactor fuel reactivity is not new. In CGU at fuel burnups beyond 25 GWd/MTU there is a build-in of U-236 in concentrations of about one-third those expected in BLEU. Table 1 gives a comparison of BLEU to CGU.

2.2 BLEU Material Reactivity Characteristics

Table 2 summarizes key cycle design core parameters. Fig. 1 and Table 3 compare reactivity (k-inf) and kinetic parameters for CGU and BLEU fuel lattices, respectively. From a reactivity standpoint there is a lattice average enrichment difference between CGU and BLEU of about 0.3 wt% U-235. For lattices of similar reactivity, there is little difference in kinetic parameters important to transient response of the fuel.

3.0 Use in Browns Ferry Units 2 and 3

Table 4 summarizes experience to-date of ATRIUM™-10[a] fuel and BLEU in Browns Ferry Units 2 and 3. Also included are beginning-of-cycle (BOC) cold shutdown demonstration results for each of the cycles. These cycles were designed with the CASMO-4 bundle code (Ref. 2) and MICROBURN-B2 reactor simulator code (Ref 3). The cores are monitored with the POWERPLEX®III[b] Core Monitoring Software System. Fig 2 shows calculated versus monitored core k-eff as a function of cycle exposure for BLEU cycles to date versus the normal range of the same core data for CGU cycles. Fig 3 through 5 summarize calculated versus monitored axial traversing in-core probe (TIP) traces for results to date.

These results indicate very good agreement between calculated and monitored results, and that

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[a] ATRIUM is a trademark of AREVA NP.

[b] POWERPLEX® is a trademark of AREVA NP registered in the United States and various other countries.

the CASMO-4/MICROBURN-B2 code system (which is an integral part of POWERPLEX III) is doing a very good job modeling the BLEU for these cycles.

4.0 BLEU Economics

The material used in the BLEU program comes from a variety of sources and is stored in a variety of forms by the DOE. Original plans for this material included down-blending to low-enrichment, conversion to a uranium oxide, and eventual disposal of the oxide as waste. This method would have resulted in 2,500 metric tons of oxide waste and taken approximately 15 years to complete at an estimated cost to the United States taxpayer of $1B. Instead, the BLEU program converts this potential waste to a resource with net savings of $500M, clearly a win for both the government and the taxpayer.

TVA accepted a significant amount of the risk in starting this program including approximately $100 million in startup costs associated with building HEU dissolution, purification, downblending and LEU oxide conversion facilities in Erwin, Tennessee, and a storage and pelletizing facility in Richland, Washington. The initial proceeds from the program are applied to return the startup capital with the overall benefit shared with DOE on a 50/50 basis. The BLEU material will be available for reloads in TVA reactors for approximately 10 years. Clearly a win for TVA, the Tennessee Valley ratepayers, and, again, the US taxpayer.

As noted previously, the U-236 isotope absorbs neutrons and therefore decreases the reactivity of BLEU fuel compared to commercial-grade Uranium fuel. Fig. 1 depicts the impact of this parasitic absorption on the required enrichment to achieve the same effective reactivity. A BLEU lattice with the average U-236 content of the surplus material has an effective reactivity defect equivalent to ~0.3 percent reduction in U-235 content. This means that BLEU reloads have to offset this impact by increasing the average enrichment or the number of bundles being loaded in order to achieve the same total energy.

Commercial reactor fuel in the United States is limited to a maximum of five wt% U-235 content. In reality, the actual bundle average enrichment is lower since uniform enrichment cannot be achieved due to peak pin-power constraints. Current reactor reloads are already at or near this upper effective bundle enrichment limit, which means that the BLEU reloads generally require higher batch sizes. Table 4 shows that a batch size increase of 16 bundles was required for Unit 3 Cycle 13 even though the total cycle energy was slightly smaller than the previous cycle. Batch size increases of 16-24 bundles are typical for comparable BLEU versus CGU reloads at Browns Ferry.

The cost of these batch size increases are negligible when compared to the savings in uranium and enrichment components of the fuel. The net savings to TVA after benefit sharing is approximately 25 percent overall fuel cost reduction. The actual fuel cost differences are dependent upon prevailing market conditions with BLEU use becoming more beneficial with increases in uranium and enrichment costs.

5.0 Conclusions

The concept conceived in the early 1990’s of taking the excess highly enriched uranium out of the weapons program and converting the material for use to generate electricity in the TVA

Browns Ferry commercial BWRs has come to fruition. By all accounts the technical aspects of the program are doing well as indicated by the results presented in this paper. This program has and continues to be a financial winner for the US Government, TVA and US electricity ratepayers.

6.0 References

1. Standard Specification for Uranium Hexafluoride Enriched to Less Than 5% U - 235, American Society for Testing and Materials (ASTM) C996-96, September 1996.
2. D. Knott, BH Forssen, M Edenius, "CASMO-4, A Fuel Assembly Burnup Program Methodology", STUDSVIK/SOA-95/2, Studsvik Proprietary, September 1995.
3. H. Moon, Siemens Power Corporation Methodology for Boiling Water Reactors: Evaluation and Validation of CASMO-4/MICROBURN-B2", EMF-2158(P)(A), Siemens Power Corp., October, 1999.

Table 1: Characteristics of Blended, Low-Enriched Uranium (BLEU)

Parameter	Commercial-Grade Uranium (CGU)	Blended, Low-Enriched Uranium (BLEU)	Comment
Chemically	---	Same as CGU	Within fuel fab. process isotopes are inseparable from BLEU feed.
U-235 Enrichment Limit, wt% U-235	4.95	4.95	Fuel Fab. Plant limit.
U-234, wt% U-234 in 4.95 wt% U-235 BLEU	0.05 (ASTM limit)	0.07 (~1.4 times the ASTM limit)	ASTM limit as defined in Ref. 1 for CGU
U-236, wt% U-236 in 4.95 wt% U-235 BLEU	0.025 (ASTM limit)	1.5 (~60 times the ASTM limit)	ASTM limit as defined in Ref. 1 for CGU

Table 2: Key Core Design Parameters

Parameter	Value	Comments
Reactor-Browns Ferry 2/3	BWR/4, D-Lattice, 764 FA 3458 MWt, 51 kW/l	Planned uprates in 2007/08 to 3952 MWt, 58.5 kW/l
Fuel type/co-resident fuel	ATRIUM-10/GE-13,-14	
Loading Strategy	Scatter load	
Cycle Length, months	24	

Table 3: Kinetic Parameters Comparison

Parameter	Browns Ferry 2 Cycle 14	
	AT-10 Comm. U	AT-10 BLEU
EOC Doppler Reactivity Coefficient, Δk/k/°F	-1.3×10^{-5}	-1.4×10^{-5}
EOC Delayed Neutron Fraction, βeff	.0053	.0052
EOC Control Rod SCRAM Worth, Δk/k	-0.22	-0.22
EOC Void Reactivity Coefficient, Δk/k/%VF	-0.11	-0.10

Table 4: Operating Experience of ATRIUM-10 Fuel in Browns Ferry Units 2 and 3

Parameter	Browns Ferry 3 Cycle 12	Browns Ferry 2 Cycle 14	Browns Ferry 3 Cycle 13
Cycle Length, EFPD (GWd)	699 (2,417)	676 (2,338)	680 (2,351)
Reload Fuel Type	ATRIUM-10	ATRIUM-10	ATRIUM-10
Fuel Material Type	CGU	BLEU	BLEU
Batch Average Enrichment, % U-235	4.08 *	3.92 **	4.17
Reload Batch Size, # Assemblies	280 (37%) *	280 (37%) **	296 (39%)
Predicted BOC Cold Shutdown Margin, %Δk/k	1.3	1.5	1.4
Measured BOC Cold Shutdown Margin, %Δk/k	1.4	1.6	1.6

* The actual Unit 3 Cycle 12 loading also included a batch of 16 bundles at 1.62 % U-235 to replace damaged, exposed, low-reactivity assemblies. These bundles are not included in the reload batch size or enrichment since they were effectively equivalent to the exposed assemblies they replaced.

** The Unit 2 Cycle 14 core had high carryover reactivity from the previous cycle, consequently the batch fraction and enrichments are lower than typical for a BLEU reload.

Table 5: BLEU Fuel Cycle Relative Economic Impacts

Negative	
Increased Batch Size	Higher Fabrication Costs - (~16-24 bundles / cycle) Additional Dry Storage Costs (~1 cask every 3 cycles)
Increased Complexity	U-236 variation in BLEU requires specific modeling - included as part of the design process
Positive	
Reduced Uranium and Enrichment Requirements	BLEU material replaces most enriched U in bundle CGU still used for some rods (e.g. gadolinia rods). Natural U used for blending

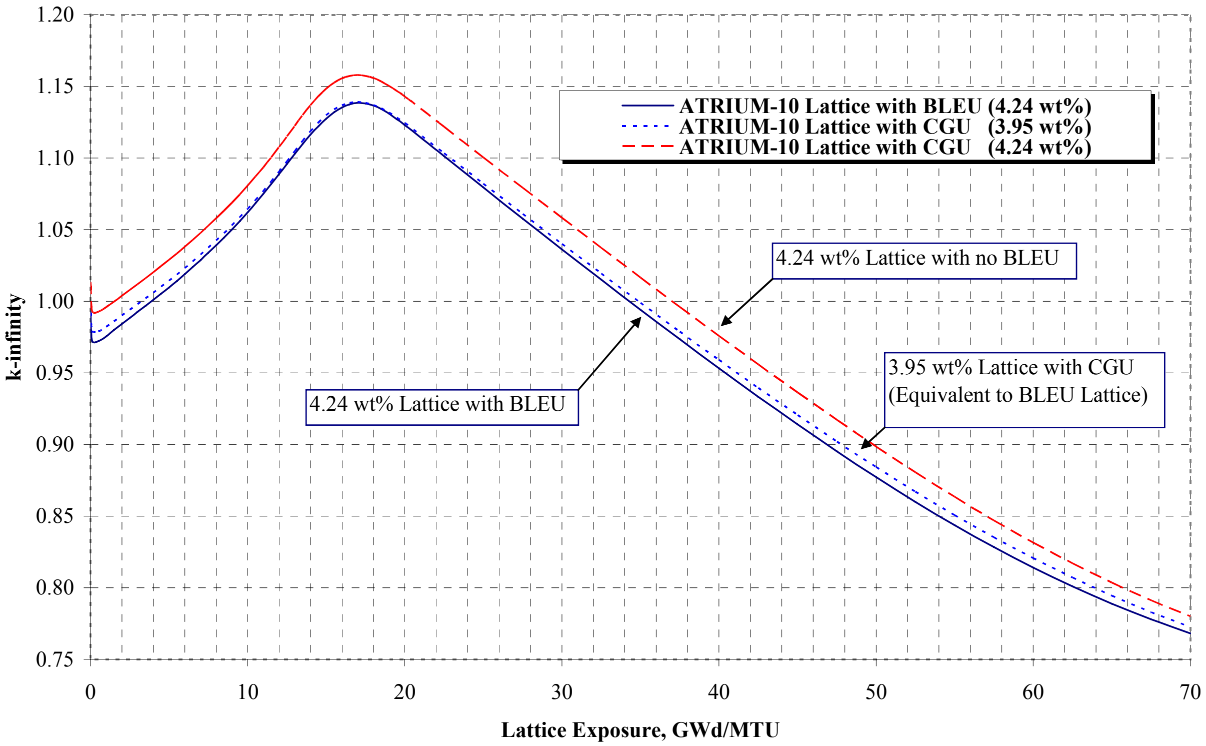


Figure 1 CGU and BLEU Hot Operating, Uncontrolled, 40% Voids, k-inf versus Exposure

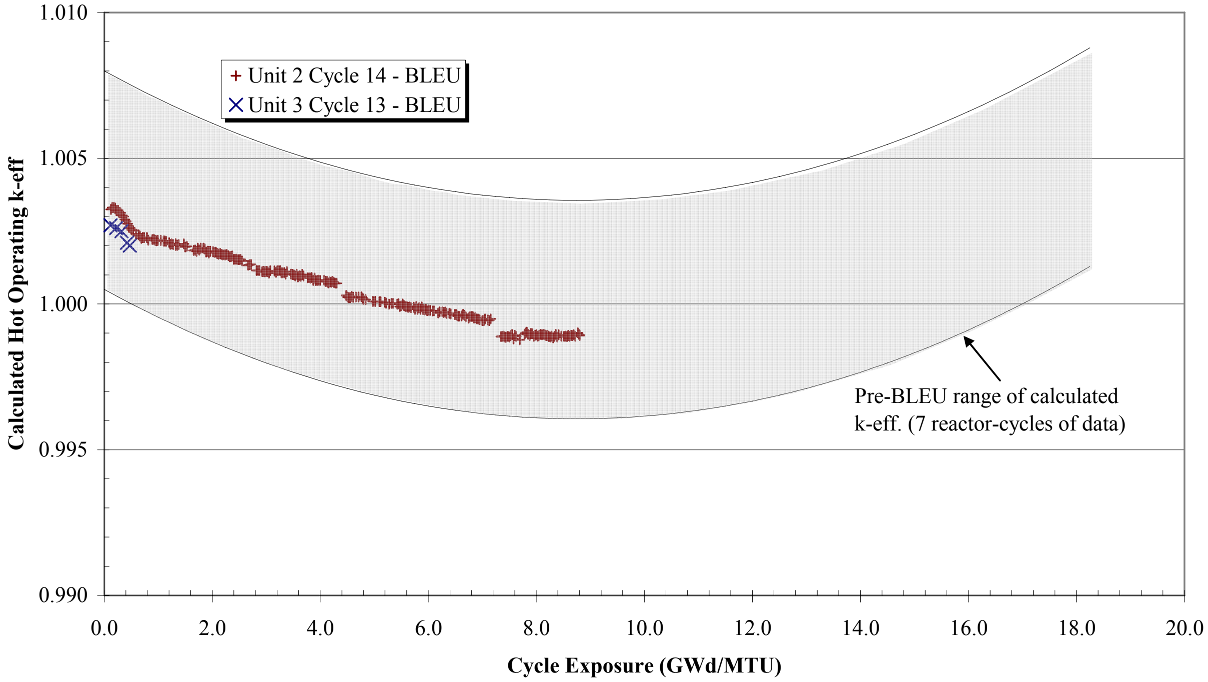


Figure 2 Comparison of Calculated Core Follow k-eff at Browns Ferry 2/3 for BLEU and Pre-BLEU Cycles

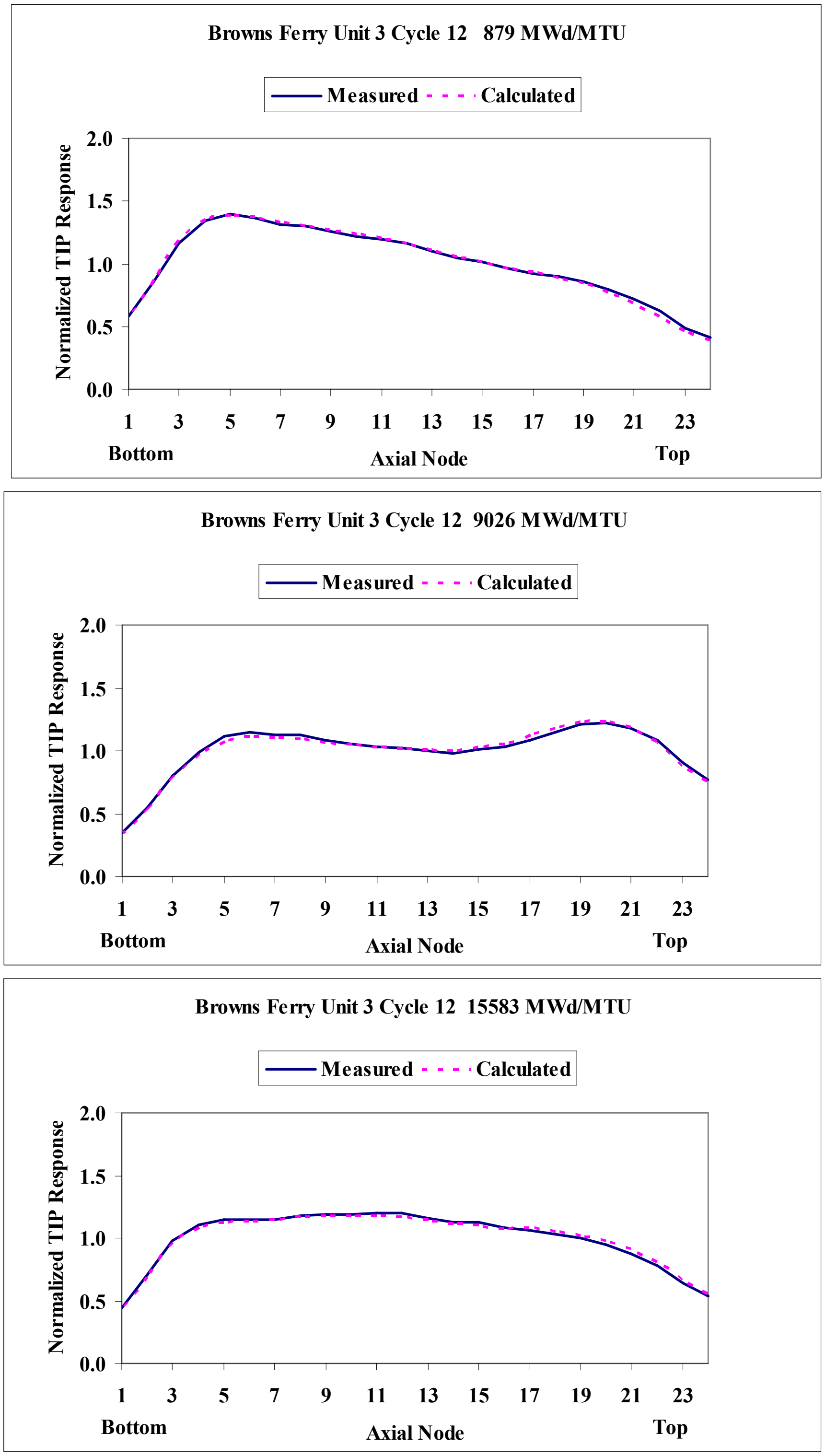
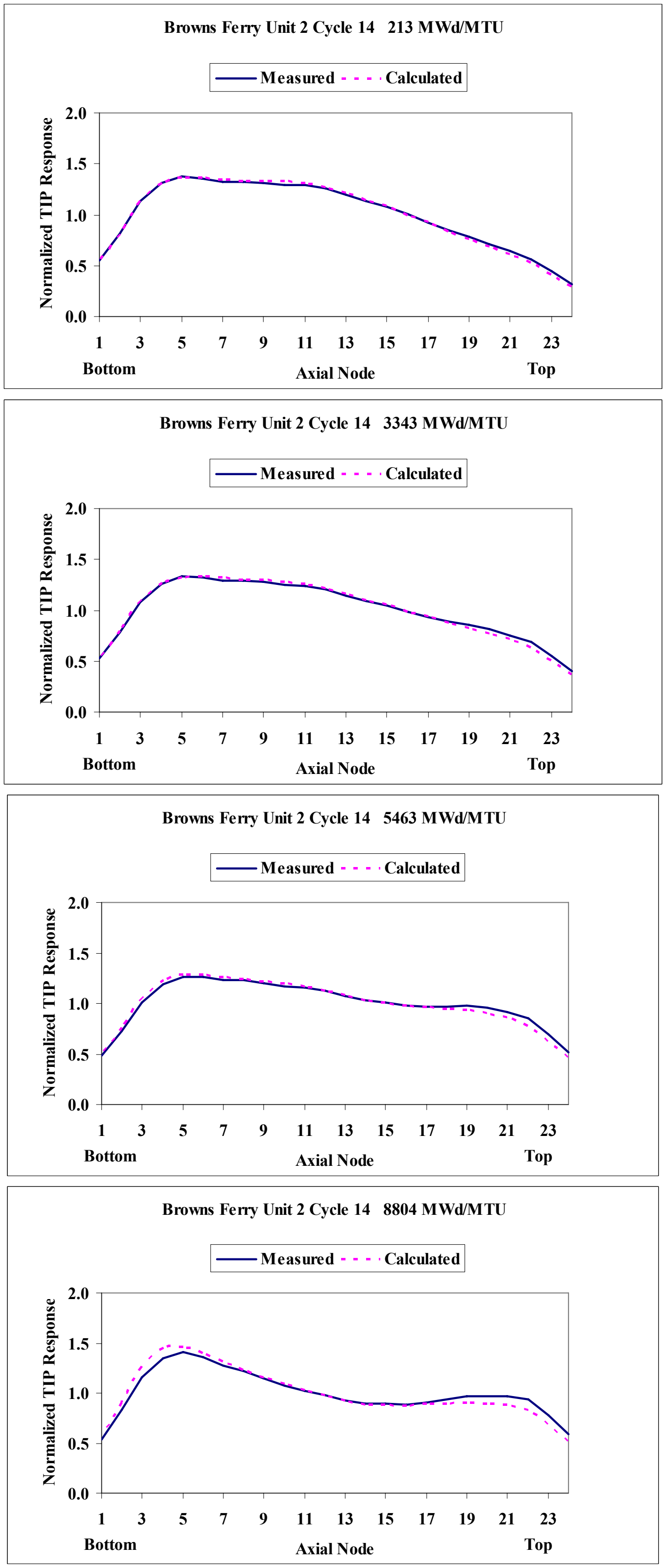


Figure 3 Browns Ferry 3 Cycle 12
Core Average TIP Comparison
(No BLEU material)



Browns Ferry Unit 2 Cycle 14 213 MWd/MTU

Browns Ferry Unit 2 Cycle 14 3343 MWd/MTU

Browns Ferry Unit 2 Cycle 14 5463 MWd/MTU

Browns Ferry Unit 2 Cycle 14 8804 MWd/MTU

Figure 4 Browns Ferry 2 Cycle 14 Core Average TIP Comparison (Uses BLEU Material)

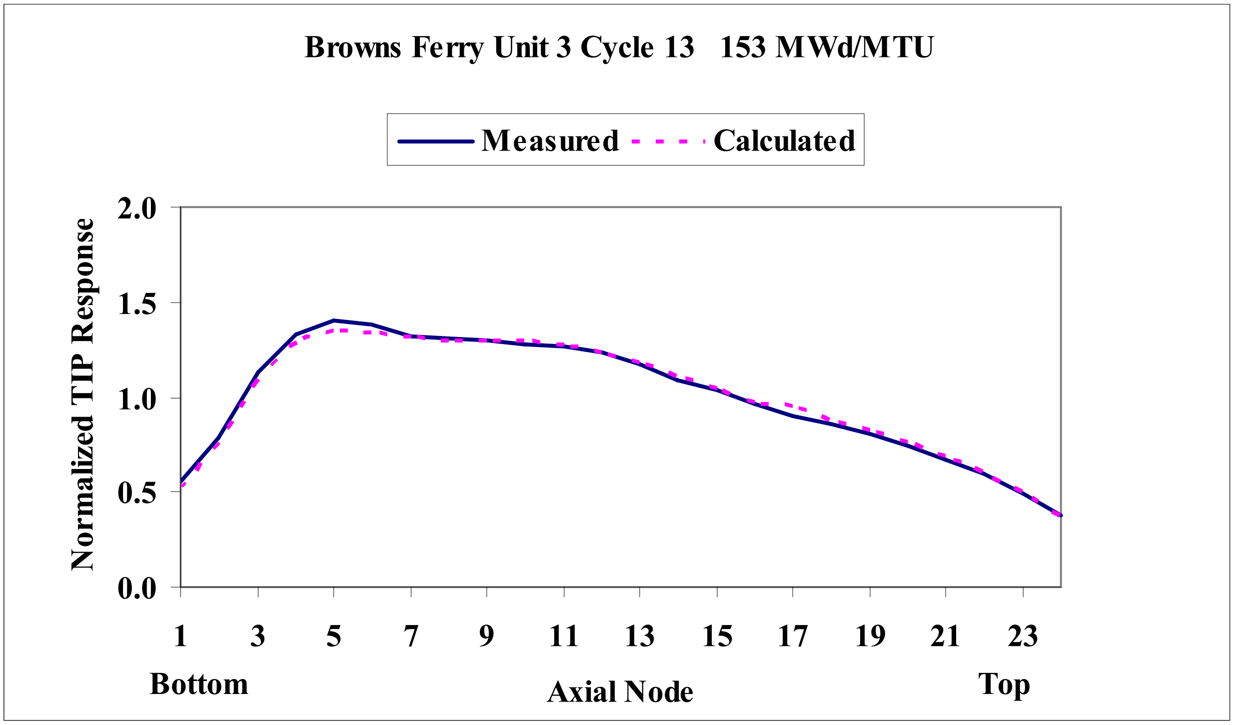


Figure 5 Browns Ferry 3 Cycle 13 Core Average TIP Comparison (Uses BLEU material)