EPJ Web of Conferences **247**, 20003 (2021)
PHYSOR2020

https://doi.org/10.1051/epjconf/202124720003

RESULTS OF VERA APPLICATION TO THE AP1000® PWR STARTUP

F. Franceschini[1], D. Salazar[2], and A. Godfrey[3]

[1]Westinghouse Mangiarotti
Via Timavo 59, 34074 Monfalcone (Gorizia) Italy

[2]Westinghouse Electric Company LLC
1000 Westinghouse Drive, 16066 Cranberry Township (Pennsylvania) USA

[3]Oak Ridge National Laboratory
1 Bethel Valley Rd, 37830 Oak Ridge (Tennessee) USA

francef@westinghouse.com; salazada@westinghouse.com; godfreyat@ornl.gov

ABSTRACT

This paper describes the application of the Virtual Environment for Reactor Applications, VERA, under development by the Consortium for Advanced Simulation of LWRs (CASL) to the core physics analysis of the AP1000 PWR.

The AP1000 PWR features an advanced first core with radial and axial heterogeneities which provides significant enhancements compared to traditional first cores, allowing best fuel usage and short transition to the equilibrium cycle with subsequent fuel reloads. These core advanced features can pose some challenges to the core physics tools making application of VERA to the AP1000 PWR first core especially relevant to qualify VERA performance.

This paper focuses on the qualification efforts at hot zero power conditions, where Monte-Carlo reference solutions have also been established. In particular, the paper focuses on the comparison of the predictions obtained with VERA for the four AP1000 units that recently started up with the measured values. It is shown that there is excellent agreement between VERA and the key reactor physics parameters measured during the AP1000 startup.

KEYWORDS: AP1000, CASL, VERA

1. INTRODUCTION

This paper describes the application of the Virtual Environment for Reactor Applications, VERA, under development by the Consortium for Advanced Simulation of LWRs (CASL), to the core physics analysis of the AP1000 PWR. The AP1000 PWR has a low-leakage 18-month cycle advanced first core [1] featuring five fuel regions with intra-assembly enrichment zoning and a combination of burnable absorbers: the Westinghouse Integral Fuel Burnable Absorber (IFBA) a ZrB_2 coating on the pellet surface, and the Wet Annular Burnable Absorber (WABA), an insert employed at selected guide thimble locations. The core loading pattern is depicted in Figure 1. Figure 1 also shows the assembly loading pattern for Region D fuel, featuring radial enrichment zoning (3 enrichments), 68 IFBA rods, 8 “long” and 4 “short” WABA inserts.

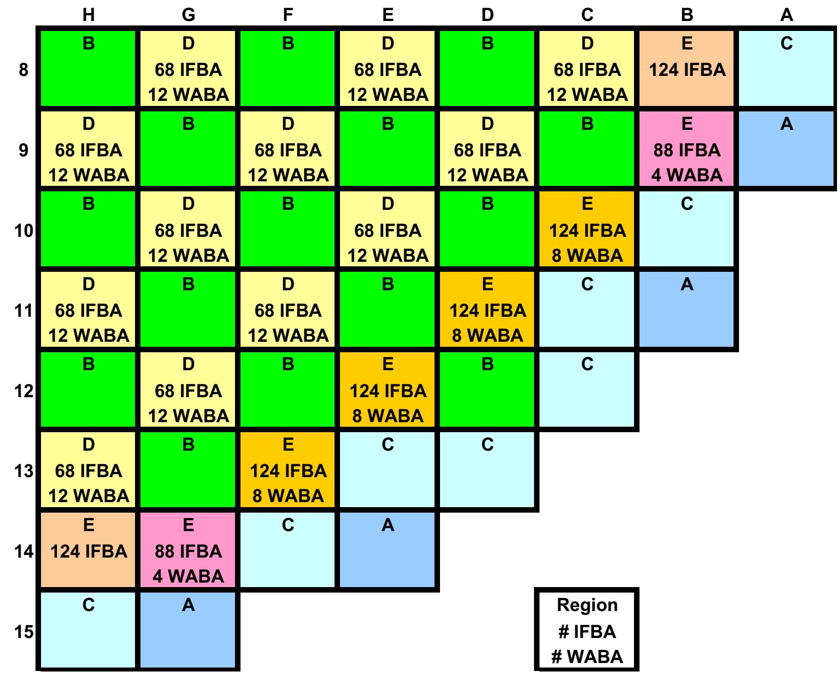
The long and short WABA inserts differ in the axial length (longer or shorter) of the poisoned-bearing region (see Figure 2), with the top plena and lower Zr spacer varying accordingly. Region E fuel assemblies are similarly characterized by enrichment zoning, IFBA rods and, when present, axially heterogeneous WABA inserts. Lower-enriched axial blankets are employed for Regions C, D and E; the blankets for the IFBA rods consist of annular fuel with a central void to accommodate He release from ^{10}B neutron absorptions in ZrB_2. For the various fuel regions, Table 1 provides the average enrichment at the core mid-plane, the number of assemblies in the core (out of 157 total) pertaining to each region, the blanket enrichment when present and the burnable absorbers specification.

The AP1000 PWR operates following the MSHIM™ core control strategy, an advanced operational strategy that entails operation with multiple control rod banks inserted in the core, including light tungsten banks and standard Ag-In-Cd banks [2-3]. The control banks configuration is shown in Figure 3. The banks used for MSHIM maneuvers are the M-banks, typically the light tungsten banks MA through MD, with the AO bank used for controlling the axial power distribution.
The AP1000 PWR advanced core design and operational features make application of an advanced core simulator like VERA especially relevant for the analysis.

2. CODES EMPLOYED

The simulations performed for this analysis have been developed employing VERA [4]. VERA is an advanced package for reactor analysis which performs direct whole-core neutronic calculations coupled with sub-channel T/H feedback, thereby eliminating the inaccuracies involved in the traditional two-step process adopted for reactor analysis. The reactor core simulator of VERA, MPACT [5], provides an advanced pin-resolved transport capability within VERA. The key characteristics of the MPACT code include the subgroup method and the embedded self-shielding method (ESSM) for resonance treatment, depletion capability based on the ORIGEN [6] exponential matrix method, and a whole core solver with a 2-D/1-D synthesis method on the frame of a 3-D coarse mesh finite difference (CMFD) method for which axial and radial correction factors are obtained from 2-D method of characteristics (MOC) and 1-D Simplified PN. COBRA-TF (CTF) [7] is the T/H component of VERA. CTF is a quality controlled, state-of-the-art version of the COBRA-TF sub-channel thermal-hydraulic code. In VERA, CTF is directly coupled to MPACT and is executed in full for each neutronics-T/H feedback iteration until convergence is reached between the two codes. With these features, VERA provides direct and fully coupled solutions at the sub-channel level for T/H and intra-rod level for neutronics without requiring any homogenization, hence does not require application of approximate power/flux reconstruction techniques, like in typical industrial reactor physics toolkits.

Given the fresh fuel and uniform temperature conditions it has also been possible to establish Monte-Carlo Continuous Energy (CE) reference solutions for selected cases. In particular, the Monte-Carlo tool SHIFT has also been employed to model the AP1000 core for the startup simulations. SHIFT [8] is a general purpose radiation transport code that performs stochastic modeling of particle physics using the Monte Carlo method; it uses the Multiple-Set-Overlapping-Domain (MSOD) parallel scheme that allows full domain replication, domain decomposition, and domain decomposition with overlap and multiple sets.



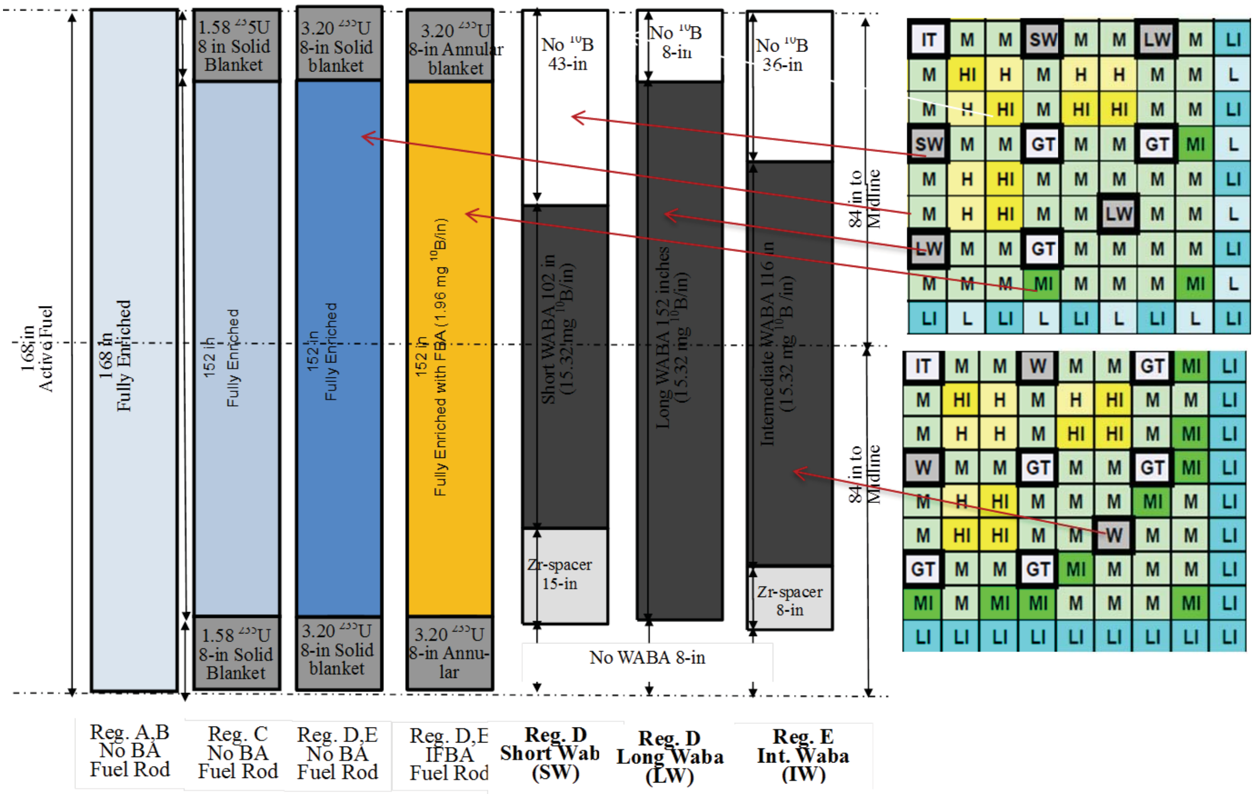
	H	G	F	E	D	C	B	A
8	B	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	E 124 IFBA	C
9	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	B	E 88 IFBA 4 WABA	A
10	B	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	B	E 124 IFBA 8 WABA	C	
11	D 68 IFBA 12 WABA	B	D 68 IFBA 12 WABA	B	E 124 IFBA 8 WABA	C	A	
12	B	D 68 IFBA 12 WABA	B	E 124 IFBA 8 WABA	B	C		
13	D 68 IFBA 12 WABA	B	E 124 IFBA 8 WABA	C	C			
14	E 124 IFBA	E 88 IFBA 4 WABA	C	A				
15	C	A						

Region
IFBA
WABA

Figure 1 AP1000 PWR First Core – Fuel Loading Pattern (Quarter Core Radial Map) and Region D Fuel Lattice Design (Quarter Assembly Radial Map)

Table 1 Fissile, IFBA and WABA Content for the AP1000 PWR First Core (“L”: Long WABA, “S”: Short-WABA, “I”: Intermediate WABA)

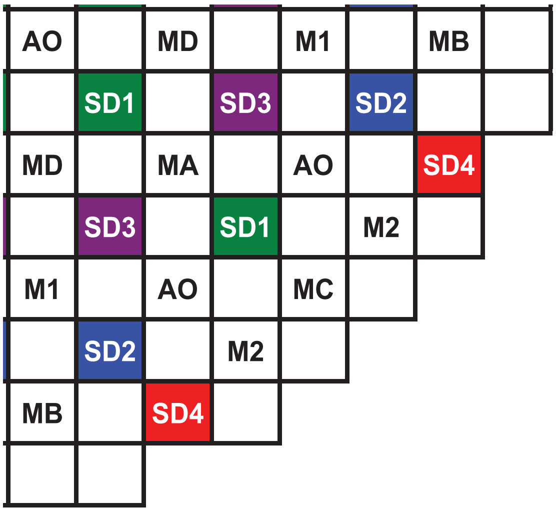
Region Identifier	Number of Assemblies	^{235}U Midplane	^{235}U Blanket	IFBA Rods	WABA Rods
A	16	0.740	Absent	0	0
B	49	1.580	Absent	0	0
C	28	3.200	1.580	0	0
D	36	3.776	3.200	68	8L+4S
E(1)	8	4.376	3.200	88	4I
E(2)	4	4.376	3.200	124	0
E(3)	16	4.376	3.200	124	8I



IT	M	M	SW	M	M	LW	M	LI
M	HI	H	M	H	H	M	M	L
M	H	HI	M	HI	HI	M	M	LI
SW	M	M	GT	M	M	GT	MI	L
M	H	HI	M	M	M	M	M	LI
M	H	HI	M	M	LW	M	M	L
LW	M	M	GT	M	M	M	M	LI
M	M	M	MI	M	M	M	MI	L
LI	L	LI	L	LI	L	LI	L	LI

IT	M	M	W	M	M	GT	MI	LI
M	HI	H	M	H	HI	M	M	LI
M	H	H	M	HI	HI	M	MI	LI
W	M	M	GT	M	M	GT	MI	LI
M	H	HI	M	M	M	MI	M	LI
M	HI	HI	M	M	W	M	M	LI
GT	M	M	GT	MI	M	M	M	LI
MI	M	MI	MI	M	M	M	MI	LI
LI	LI	LI	LI	LI	LI	LI	LI	LI

Figure 2 AP1000 PWR First Core – Fuel Axial Configuration



AO		MD		M1		MB	
	SD1		SD3		SD2		
MD		MA		AO		SD4	
	SD3		SD1		M2		
M1		AO		MC			
	SD2		M2				
MB		SD4					

Figure 3. AP1000 PWR Control Banks Configuration (Quarter Core Radial Map)

3. RESULTS

An extensive set of simulations has been performed with VERA for the AP1000 PWR, with past results presented in [9-12]. The results presented here are focused on Hot Zero Power (HZP) simulations (e.g. HZP critical boron, Isothermal Temperature Coefficient (ITC) and rod worth), and namely on the comparison between predicted values with the corresponding startup measured parameters at four AP1000 units that recently began commercial operation.

3.1. Main Modeling Assumptions

The results of the comparisons for each figure of merit are expressed as deltas between the predicted and measured value, indicating each of the four AP1000 units modeled as plant "A" through "D". The typical settings used in standard PWR core calculations have been employed, and namely transport-corrected scattering ("TCP0"), 0.05 cm ray spacing, three radial rings per fuel pellet with eight azimuthal angles. The impact of refining some of these settings has been assessed as well with results to be presented later.

SHIFT calculations employed 25 million particles per generation for a total of 2,000 generations with 500 inactive cycles, resulting in an eigenvalue statistical uncertainty typically of 0.5 pcm.

Thermal expansion at hot zero power temperature has been assumed for all calculations. IFBA and U as-built values have been modeled on a per region basis. The natural ^{10}B content of 19.90 a/o in B has been assumed.

The libraries used have been generated by the AMPX code system [13] based on ENDF/B-VII.0 CE cross section library for SHIFT (a continuous energy library has been used) and ENDF/B-VII.1 for MPACT (a 51-group cross-section library has been used).

3.2. HZP Critical Boron

Table 2 shows the delta in HZP critical boron for MPACT and SHIFT vs. the measured critical boron for each plant. As it can be seen, there is excellent agreement with the measured boron at the plants with both codes mildly underpredicting the critical boron, an average delta of -9 ppm with a standard deviation of 8 ppm for MPACT, and an average delta of -5 ppm with a standard deviation of 7 ppm for SHIFT. Note that while the behavior in the delta P-M critical boron for plant A, C and D is very consistent, plant B deviates from the observed trend.

Table 2 Delta in HZP Critical Boron Concentration for MPACT and SHIFT vs. Measurements

	MPACT Delta P-M (ppm)	**SHIFT Delta P-M (ppm)**
A	-13	-9
B	6	8
C	-14	-9
D	-14	-8
Avg.	-9	-5
Std. Dev.	8	7

3.3. Isothermal Temperature Coefficient

Table 3 shows the delta ITC predicted by MPACT and SHIFT vs. the measured ITC for each plant. It should be noted that the ITC simulation has been performed at the measured critical boron for the respective plant. While MPACT predicts the ITC with satisfactory accuracy, on average -0.21 pcm/F from the measurements with a standard deviation of 0.19, SHIFT mispredicts the ITC by nearly -1 pcm/F (only a single plant ITC has been calculated with SHIFT). The behavior from the SHIFT code, with respect to ITC calculations, is in line with past observations relative to the KENO code. This issue needs further investigation to understand the reason leading to this discrepancy.

Table 3 Delta in ITC for MPACT and SHIFT vs. Measurements

	MPACT Delta P-M (pcm/F)	**SHIFT Delta P-M (pcm/F)**
A	-0.27	
B	-0.46	
C	-0.19	
D	+0.07	-0.94
Avg Delta	-0.21	
Std Dev Delta	0.19	

3.4. Rod Worth

Table 4 shows the delta in rod worth for MPACT vs. the measured worth given both as delta pcm and delta % worth. There is remarkable accuracy in the predicted values across all plants and banks, with most of the banks predicted within 1% or 10 pcm accuracy.

Table 5 shows the delta in rod worth when P2 scattering is used instead of TCP0 and the delta in rod worth predicted by SHIFT vs. the measured rod worth for plant D. While the P2 scattering results only mildly improve the results, the agreement with the measured worth shown by the SHIFT code is outstanding.

Table 4 Delta in Rod Worth for MPACT vs. Measurements

Bank Name	**A: delta pcm**	**B: delta pcm**	**C: delta pcm**	**D: delta pcm**	**A: delta %**	**B: delta %**	**C: delta %**	**D: delta %**
MA	-1	-3	0	0	-0.5%	-1.2%	0.1%	-0.2%
MB	-2	-2	-4	-7	-1.2%	-1.1%	-1.7%	-3.5%
MC	-4	-8	-4	-10	-2.3%	-4.3%	-2.0%	-5.7%
MD	-3	-3	-2	-3	-1.5%	-1.3%	-0.7%	-1.4%
M1	15	11	6	5	2.3%	1.7%	1.0%	0.8%
M2	13	6	1	0	1.4%	0.7%	0.1%	0.0%
AO	52	14	-59	6	3.2%	0.9%	-3.8%	0.4%
S1	11	-1	34	-14	1.0%	-0.1%	3.1%	-1.3%
S2	29	23	7	-3	2.6%	2.1%	0.6%	-0.3%
S3	12	0	-4	-11	1.1%	0.0%	-0.4%	-1.0%
S4	4	5	3	-3	0.7%	0.9%	0.6%	-0.5%
Avg Delta	11	4	-2	-4	0.6%	-0.2%	-0.3%	-1.2%
Std Dev Delta	16	9	21	6	1.7%	1.7%	1.7%	1.8%

Table 5 Delta in Rod Worth for MPACT with TCP0 vs. P2 Scattering and Delta Rod Worth for SHIFT (Plant D)

Bank Name	**MPACT TCP0 delta pcm**	**MPACT TCP0 delta %**	**MPACT P2 delta pcm**	**MPACT P2: delta %**	**SHIFT delta pcm**	**SHIFT delta %**
MA	0	-0.2%	0	0.1%	0	0.0%
MB	-7	-3.5%	-6	-2.7%	-4	-1.8%
MC	-10	-5.7%	-9	-5.2%	-5	-2.9%
MD	-3	-1.4%	1	0.5%	1	0.4%
M1	5	0.8%	6	0.9%	6	0.9%
M2	0	0.0%	-3	-0.4%	2	0.3%
AO	6	0.4%	-2	-0.1%	1	0.0%
S1	-14	-1.3%	-9	-0.8%	-13	-1.3%
S2	-3	-0.3%	-8	-0.7%	-1	-0.1%
S3	-11	-1.0%	-4	-0.3%	-9	-0.8%
S4	-3	-0.5%	-5	-0.8%	1	0.2%
Avg Delta	-4	-1.2%	-3	-0.9%	-2	-0.5%
Std Dev Delta	6	1.8%	4	1.6%	5	1.1%

4. CONCLUSIONS

The results presented show excellent agreement in the MPACT and SHIFT predictions for the HZP critical boron concentration and rod worth for the AP1000 PWR. While the ITC predicted by MPACT shows satisfactory accuracy, SHIFT underpredicts the ITC by nearly 1 pcm/F, showing a recurring problem, to the authors' experience, with Monte Carlo tools in calculating this parameter.

ACKNOWLEDGMENTS

The authors would like to dedicate this paper to the memory of their colleague, Jeff Secker, for the example that he set throughout his career at Westinghouse.

This paper contains results of research supported by the Consortium for Advanced Simulation of Light Water Reactors (www.casl.gov), an Energy Innovation Hub (http://www.energy.gov/hubs) for Modeling and Simulation of Nuclear Reactors under U.S. Department of Energy (DOE) Contract No. DE-AC05-00OR22725.
This research also made use of the resources of the High Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

REFERENCES

1. M. Hone et al., AP1000 Core Reference Report, Westinghouse Electric Company, March 2012 WCAP-17524-NP
2. T. Morita, et al., "Application of MSHIM Core Control Strategy for Westinghouse AP1000 Nuclear Power Plant", *International conference on global environment and advanced nuclear power plants GENES4/ANP2003*; Kyoto (Japan); 15-19 Sep 2003.
3. K. Drudy, etc., Robustness of the MSHIM Operation and Control Strategy in the AP1000 Design, *17th International Conference on Nuclear Engineering (ICONE 17)*, July 12-16, 2009, Brussels, Belgium
4. B. Kochunas, et al., "VERA Core Simulator Methodology for PWR Core Cycle Depletion," *Nucl. Sci. and Eng.*, **185**(1), 2017.
5. B. Kochunas, et al., "Overview of Development and Design of MPACT: Michigan Parallel Characteristics Transport Code," *Proc. Int. Conf. M&C 2013*, ANS, Sun Valley, ID, USA. May 5-9 (2013).
6. I. C. Gauld, O. W. Hermann, and R. M. Westfall, "ORIGEN-S: SCALE System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms," NUREG/CR-0200, Revision 7, Volume 2, Section F7, ORNL/NUREG/CSD-2/V2/R7 (2002)
7. R. Salko M. Avramova, "CTF Theory Manual", North Carolina State University (2017).
8. T. M. Pandya, S. R. Johnson, T. M. Evans, G. G. Davidson, S. P. Hamilton, A. T. Godfrey, "Implementation, capabilities, and benchmarking of Shift, a massively parallel Monte Carlo radiation transport code", *Journal of Computational Physics* **308** (2016) 239–272.
9. F. Franceschini et. al., AP1000® PWR Reactor Physics Analysis with VERA-CS and KENO-VI – Part I: Zero Power Physics Tests", *PHYSOR 2014 – The Role of Reactor Physics Toward a Sustainable Future,* Kyoto (Japan) , September 28 – October 3, 2014

10. F. Franceschini et. al., AP1000® PWR Reactor Physics Analysis with VERA-CS and KENO-VI – Part II: Power Distribution”, *PHYSOR 2014 – The Role of Reactor Physics Toward a Sustainable Future,* Kyoto (Japan) , September 28 – October 3, 2014

11. F. Franceschini et. al., AP1000 PWR Startup Core Simulations with VERA-CS”, *Advances in Nuclear Fuel Management V (ANFM 2015),* Hilton Head Island, South Carolina, (USA) March 29-April 1, 2015

12. D. Salazar et. al., “AP1000 PWR Cycle 1 HFP Depletion Simulations with VERA-CS”, *PHYSOR2016 - Unifying Theory and Experiments in the 21st Century*, Sun Valley, Idaho (USA) May 1-5, 2016

13. M.E. Dunn and N.M. Greene, “AMPX-2000: A Cross section Processing System for Generating Nuclear Data for Criticality Safety Applications,” Trans. Am. Nucl. Soc. 86, 118–119 (2002).