Assessment of Pellet-Clad Interaction Indicators in Watts Bar Unit 1, Cycles 1-3 Using VERA

- Shane Stimpson¹ Jeffrey Powers¹ Kevin Clarno¹ Roger Pawlowski² Ryan Bratton³
- ¹Oak Ridge National Laboratory ²Sandia National Laboratories ³Pennsylvania State University

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Outline

Motivation

- What is VERA? _
- Why do we want to use BISON?
- **Generating BISON Input Files** ullet
 - BISON Template File
 - XML2MOOSE Preprocessor —
 - Input Data from VERA-CS _
 - Output Data Available from BISON _
- Watts Bar Unit 1
- Results •
- Conclusions and Future Work



What is VERA?





Motivation

- Why are we using BISON (INL)?
 - More attention to additional physics with MPACT/CTF becoming more mature
 - Provides high-fidelity, finite element-based fuel performance simulations built on the MOOSE framework [1,2]
 - Swelling, densification, relocation, gap closure, etc.
 - Provides insights into fuel behavior that VERA-CS does not directly take into account
 - Already being used in several applications within CASL:
 - Tiamat provides fully coupled simulations with MPACT/CTF/BISON [3,4]
 - Is being used to generate more accurate fuel temperatures for VERA-CS
 - Ongoing work to tackle the pellet-clad interaction (PCI) challenge problem
- The work covered here pertains to streamlining standalone BISON usability
 - Generate individual BISON cases for each rod using VERA-CS neutronics/TH output
 - Potentially as a screening tool for further analysis
 - This is not considered BISON V&V
 - Merely showing one of the directions being pursued in CASL



Generating BISON Inputs

- VERA simulations start of an ASCII input file, which is converted to XML
- The XML2MOOSE preprocessor creates an input for each rod
 - Uses a BISON template as the starting point
 - Updates the values in the template based on the parameters in the extended markup language (XML) file
 - Reads the VERA-CS output hierarchical data format (HDF5) file and populates input files that BISON can process
 - Normalized Axial Power Distribution
 - Rod Power History
 - Moderator Temperature Distribution
 - Shuffles fuel as appropriate by linking up data



Output Data

- BISON outputs a CSV and an EXODUS file
- CSV
 - typically Max/Min/Avg quantities of interest
 - Max/Min/Avg Fuel/Clad Temperature •
 - Max/Min Clad Hoop Stress
 - Min. Gap Thickness
 - Rod Power, Burnup, Internal Pressure
- EXODUS
 - more finely resolved data (such as axial distributions)
 - more complicated to access (currently in progress)
- A postprocessor has been developed that reads appropriate data from the CSV file and consolidates that data onto the HDF5 file produced by VERA-CS
- This can then be visualized with VERAView



Watts Bar Unit 1 [5]



- Began operating in 1996
- Operating 14th cycle now
- 3,411 MWth with 1.4% uprate in 2001
- 193 Westinghouse fuel assemblies
 - 17x17 _
 - 264 fuel rods
 - 25 guide/instrumentation
 - 12' tall
- 8 spacer grids
 - 2 Inconel
 - 6 Zircaloy
- Cycles 1-12 have been simulated with VERA-CS
 - Tomorrow Morning 8 am



Cycle 1 Core Layout and Rod Banks

	Н	G	F	Е	D	С	В	А
8	2.1	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 12
9	2.6 20	2.1	2.6 24	2.1	2.6 20	2.1	3.1 24	3.1
10	2.1	2.6 24	2.1	2.6 20	2.1	2.6 16	2.1	3.1 8
11	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 16	3.1
12	2.1	2.6 20	2.1	2.6 20	2.6	2.6 24	3.1	
13	2.6 20	2.1	2.6 16	2.1	2.6 24	3.1 12	3.1	
14	2.1	3.1 24	2.1	3.1 16	3.1	3.1		•
15	3.1 12	3.1	3.1 8	3.1	Enrichm Number	ent of Pyrex F	Rods	





Cycle 1 Power History





Results – Cycle 1 Maximum Centerline Fuel Temperature (K)

1.23 GWd/MT

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15.3 GWd/MT

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					1421.20-	
					1326.05-	
					1020.00	
					1230.91-	
					1125 76-	
					1130.70	
				100 C	1040.61-	
				N: : : /		
					945.00-	
					850 00-	
	124444				755.00-	
					660.00-	
					000.00	
					565.00	
1.1.1						



Results – Cycle 1 Minimum Gap Thickness (m)

1.23 GWd/MT

			,	

1

15.3 GWd/MT

Negative gap thickness indicate mesh overlap in BISON



Results – Cycle 1 Maximum Clad Hoop Stress (Pa)

1.23 GWd/MT

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	2005	2003	2005	2005		2005	2000
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15.3 GWd/MT

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8. 2010s.	2000	100	14.14	41.8			2.65e+07-
			1.4.2	4 66			2.20e+07-
1996		100	688b				1.75e+07-
22 Mitz	1000		STTN.	1222			1.30e+07-
6 (iii)	200 B	1993	111				8.46e+06-
	6.00.6					· · · · ·	3.95e+06-
		1.2					-5.69e+05-
							-5.08e+06-
							-9.60e+06-
					1		-1.41e+07

Stress spiking after coming back to full power, though values are still low



Cycle 2 Core Layout

_	Н	G	F	Е	D	С	В	А	
8	H-14	N-13	128*	R-8	128	N-8	L-15	F-11	
9	N-3	104	A-9	104 8	B-11	128*	48	C-4	
10	128*	G-15	E-15	D-7	104 8	B-7	48	G-10	
11	H-1	104 8	J-12	128*	N-2	128	48	F-13	
12	128	E-14	104 8	P-3	A-6	104 4	B-4		Batch 1 - 2.11%
13	H-3	128*	J-14	128	104 4		P-6		Batch 2 - 2.619%
14	R-5	48	48	48	M-14	K-2			Batch 3 - 3.1%
15	L-10	M-13	F-9	C-10	IFBA W Previous	/ABA or s Cycle 1	Location		Batch 4 - 3.709%

* 132 inch IFBA (All others 120 inch)

NOTE: These results were obtained before IFBA capability (He production) was available in BISON (as of March 2016). Ongoing and future analysis includes IFBA.



Cycle 2 Power History





Results – Cycle 2 Maximum Centerline Fuel Temperature (K)

0.142 GWd/MT

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16.3 GWd/MT

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				100			611 E	1221.73-	
	8.13	100	2002	202		100	2007	1127.89-	
	11. C						<u> (111)</u>	1034.05-	
	1. S.	1	2008	10.00	100		SHEEK.	940.00-	
								846.00-	
								753.00-	
								659.00-	
		3.14						565.00-	
					1.1.2				



Results – Cycle 2 Minimum Gap Thickness (m)

0.142 GWd/MT

100	10.00	100	1.1.1	

16.3 GWd/MT

								7.65e-05
:::	2005	/110	2005	2005	·::::	2005	2000	6.87e-05⁻
	100	100	100	100		100	100	6.08e-05-
	400 B	2003 B	2003 B	2003 B		2003 B	2003 B	5.30e-05-
	N	N /	N. 17	N	•••••	N /	2007	4.51e-05⁻
	2000 B	::::::	2002 B	::::::		2003 C	2000 C	3.73e-05⁻
	2007	2012	2007	2012	·	2002	2007	2.94e-05-
								2.15e-05-
		•••••	· · · · · ·	•••••	•••••			1.37e-05-
								5.83e-06-
	2008	2008	2008	2008				-2.02e-06
						-		



Results – Cycle 2

Maximum Clad Hoop Stress (Pa)

0.142 GWd/MT

	100	S	100	1.1.1	415		S
	2000 B	18	2003 B	12		2003 1997	
	2007	198	2007	2.3	2007	2007	100
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	1	10.00	· · · · · ·			2011	
2							

16.3 GWd/MT

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	1.1.1	1.1.1	1.1.1	1.1.1	1.1.1	10.07	1.1.1	2.54e+08	
: : .	2002	2005	2002	2002	2005	2005	2005	2.27e+08⁻	
	S	· · · · ·	·	·		1.1.1	1.1.1	2.00e+08-	
						2003 2003	2003	1.73e+08-	
	·	·	·	·	·	Sec. 17	5117	1.47e+08⁻	
	::::::	2002 B	2003 B	::::::		<u> </u>	<u> </u>	1.20e+08-	
	N /	2007	N	N /	·	2007	2007	9.31e+07-	
	::::::		::::::	::::::		2002) 1997		6.64e+07-	
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								1.30e+07-	
•••	•••••	•••••	•••••	•••••	•••••	11111		_1 38e+07-	
								-1.500-07	
1.14	10.00	2012	10.00	10.00	2007				
	2003 B		2003 1						

Stresses spike after startup and relax by end of cycle



Results – Cycle 2

Cumulative Damage Index (%)







Cycle 3 Core Layout

_	Н	G	F	Е	D	С	В	А	
8	1A-10	H-6	128	L-5	N-13	D-8	104	J-9	
9	F-8	128 8	D-13	128 8	B-7	104	128	M-10	
10	128	C-12	L-2	N-11	128	G-11	128	M-2	Batch 1 - 2.11%
11	E-5	128 8	E-3	128	J-3	128	16	A-5	Batch 2 - 2.619%
12	N-3	J-14	128	N-7	E-2	128	P-10		Batch 3 - 3.1%
13	H-12	104	E-9	128	128	16	G-15		Batch 4 - 3.709%
14	104	128	128	16	F-2	A-9			Batch 5A - 3.807%
15	J-7	F-4	P-4	L-15	IFBA W Previous	/ABA or s Cycle 1	Location	Batch 5B - 4.401%	



Cycle 3 Power History





Results – Cycle 3 Maximum Centerline Fuel Temperature (K)

0.195 GWd/MT

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18.1 GWd/MT

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197				2008	80.8	18. J	80.07	1130.15-
						đ 🗄		1035.93-
	10.00	2	4005		-		1111	942.00-
			200					847.00-
								753.00-
8								659.00-
86.		400	6					565.00



Results – Cycle 3 Minimum Gap Thickness (m)

0.195 GWd/MT

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18.1 GWd/MT

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i.	2005	2005	2005	2005.	2000	2005	2005	6.86e-05-	
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	40.5		2018.		40N	2003		5.29e-05-	
	100	100	1.12	S	100	30.00	×	4.50e-05-	
	2003 B	(113)	2003 B	:##h	::::::	2003 B	2003 B	3.71e-05-	
24	2005	2004	2007	202	S	2007	2007	2.92e-05⁻	
	400 h	2003) 1993	<u>(112</u>)	::::::	::::::	2003) 1997		2.13e-05⁻	
	2016	2007	2015	N P	·	S		1 34e-05-	
Ì								5.48e-06-	
	2005	2005	2005		2000			-2.42e-06	
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Results – Cycle 3 Maximum Clad Hoop Stress (Pa)

0.195 GWd/MT

·	10.07	S	8a	10.00	10.07	•••••

18.1 GWd/MT

	1.1.1	1.11	1.11		1 (V			1.79e+08	
: :×.		2005					2005	1.60e+08-	
9						· · · · ·		1.40e+08⁻	
			-11 h		<u>den</u>			1.21e+08⁻	
	·	10.07		• • • •	1 . P	*****	2017	1.02e+08⁻	
	2002 B	2005 B	::::::	21 N		2002 B	<u> </u>	8.26e+07-	
12	2002	$A \cap M$	·	N. 19	S	100	2007	6.33e+07⁻	
			411					4.40e+07-	
	••	· · · · ·		•••••		•••••		2.48e+07−	
								5.51e+06-	
								-1.38e+07	



Results – Cycle 3

Cumulative Damage Index (%)







Conclusions

- Standalone Capability demonstrated for WBN1, Cycles 1-3
 - Better estimation of PCI indicators
 - Which rods are in contact?
 - How high are the clad stresses?
 - Which may need more detailed analysis?
 - Observed trends resulting from various fuel performance phenomena
 - Swelling, densification, clad creep
 - No rods were particularly concerning with respect to failure
 - No reported failures, so this is expected



Future Work and Application

- Developing Capability
 - Need IFBA modelling capability (already complete)
 - Processing more detailed results with EXODUS files
- Perform fuel temperature comparisons to existing simulations
- Future Application
 - Start-up simulation
 - Assess ramping speed and impact on hoop stress and damage
 - Assessing PCI in Watts Bar Cycles 6-7



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Questions?

