Final Results:
PWR MOX/UO_2 Control Rod Eject Benchmark

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Benchmark Description

- Background
  - Proposed by U.S. NRC / RES in 2001 as part of Pu Disposition Research
  - Sponsored by U.S. NRC (Purdue) and OECD/NEA
- Motivation
  - Assessment of heterogeneous transport and nodal diffusion transient methods for MOX RIA
  - Comparison of MOX/UO_2 and UO_2 core transient response to CEA
- Numerical Benchmark
  - Based on 4-loop Westinghouse PWR reactor
  - Steady-state at HZP and HFP conditions
  - Transient Rod Eject from HZP conditions
  - Heterogeneous Reference Solution (DeCART 47G MOC)

Benchmark Description (Cont.)

- Group constants provided
  - 2G assembly homogenized XS with ADF and pin power form functions
  - 4G assembly homogenized XS with ADF and pin power form functions
  - 8G assembly homogenized XS with ADF and pin power form functions
  - Number densities for heterogeneous calculation

- Benchmark conditions
  - Reactivity insertion problem (important for Weapons Pu transient w/ small B-eff)
  - Initial HZP conditions, critical boron concentration, CR ejected from the full core

- Compare:
  - Eigenvalue
  - Assembly and Pin Power distribution
  - CR worth
  - Transient power, reactivity and fuel temperature

OECD/NRC MOX Rod Ejection Benchmark: Core Loading Pattern

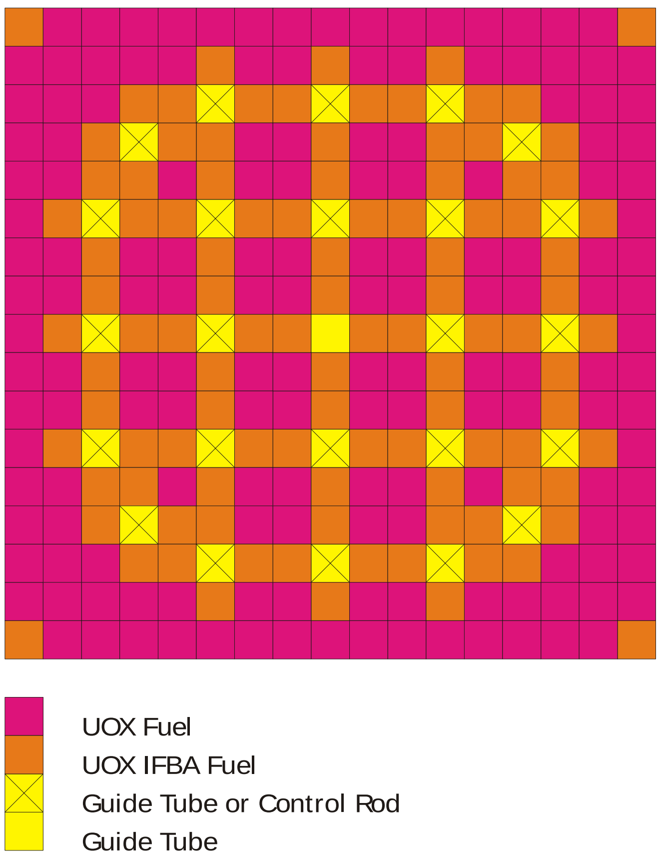
	1	2	3	4	5	6	7	8
A	U 4.2% (CR-D) 35.0	U 4.2% 0.15	U 4.2% (CR-A) 22.5	U 4.5% 0.15	U 4.5% (CR-SD) 37.5	M 4.3% 17.5	U 4.5% (CR-C) 0.15	U 4.2% 32.5
B	U 4.2% 0.15	U 4.2% 17.5	U 4.5% 32.5	M 4.0% 22.5	U 4.2% 0.15	U 4.2% (CR-SB) 32.5	M 4.0% 0.15	U 4.5% 17.5
C	U 4.2% (CR-A) 22.5	U 4.5% 32.5	U 4.2% (CR-C) 22.5	U 4.2% 0.15	U 4.2% 22.5	M 4.3% 17.5	U 4.5% (CR-B) 0.15	M 4.3% 35.0
D	U 4.5% 0.15	M 4.0% 22.5	U 4.2% 0.15	M 4.0% 37.5	U 4.2% 0.15	U 4.5% (CR-SC) 20.0	M 4.3% 0.15	U 4.5% 20.0
E	U 4.5% (CR-SD) 37.5	U 4.2% 0.15	U 4.2% 22.5	U 4.2% 0.15	U 4.2% (CR-D) 37.5	U 4.5% 0.15	U 4.2% (CR-SA) 17.5	
F	M 4.3% 17.5	U 4.2% (CR-SB) 32.5	M 4.3% 17.5	U 4.5% (CR-SC) 20.0	U 4.5% 0.15	M 4.3% 0.15	U 4.5% 32.5	
G	U 4.5% (CR-C) 0.15	M 4.0% 0.15	U 4.5% (CR-B) 0.15	M 4.3% 0.15	U 4.2% (CR-SA) 17.5	U 4.5% 32.5		
H	U 4.2% 32.5	U 4.5% 17.5	M 4.3% 35.0	U 4.5% 20.0				

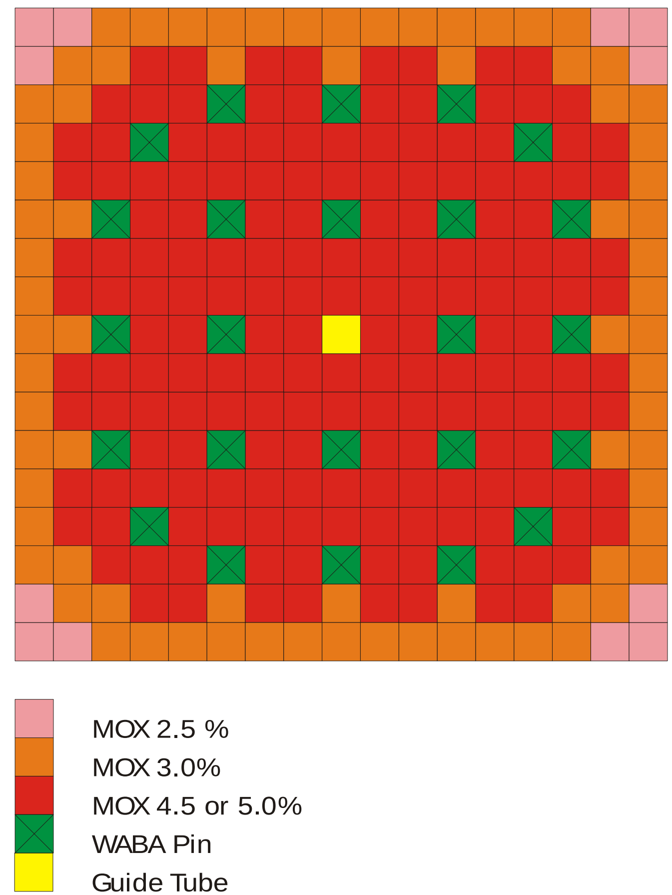
Assembly Type
CR Position
Burnup [GWd/t]

Fresh
Once Burn
Twice Burn

Note: 27% of the assemblies are MOX

Assembly Design





Refueling Strategy

Assembly Type	Fresh Fuel 0 GWd/tHM	Once Burned 20.0 GWd/tHM	Twice Burned 35.0 GWd/tHM
UOX 4.2%	28	28	17
UOX 4.5%	24	24	20
MOX 4.0%	8	8	4
MOX 4.3%	12	12	8
Total	72	72	49

Note: 27% of the assemblies are MOX

Fuel Composition

Assembly Type	Density [g/cm^3]	HM Material	
UOX 4.2%	10.24	U-235: 4.2 w/o, U-238: 95.8 w/o	
UOX 4.5%	10.24	U-235: 4.5 w/o, U-238: 95.5 w/o	
MOX 4.0%	10.41	Corner zone: 2.5 w/o Pu-fissile	Uranium vector: 234/235/236/238 = 0.002/0.2/0.001/99.797 w/o Plutonium vector: 239/240/241/242 = 93.6/5.9/0.4/0.1 w/o
		Peripheral zone: 3.0 w/o Pu-fissile	
		Central zone: 4.5 w/o Pu-fissile	
MOX 4.3%	10.41	Corner zone: 2.5 w/o Pu-fissile	
		Peripheral zone: 3.0 w/o Pu-fissile	
		Central zone: 5.0 w/o Pu-fissile	

Sample Fuel Number Densities Format

HELIOS

Identifier	0.0	17.5	20.0	22.5	32.5	35.0	37.5
42595	9.99999E-21	1.76830E-05	2.10532E-05	2.43736E-05	3.70448E-05	4.00530E-05	4.29970E-05
43599	9.99999E-21	2.40933E-05	2.73519E-05	3.05554E-05	4.27999E-05	4.57139E-05	4.85671E-05
46608	9.99999E-21	2.01585E-06	2.51039E-06	3.04915E-06	5.62129E-06	6.36298E-06	7.14199E-06
54631	9.99999E-21	1.06985E-05	1.20328E-05	1.33047E-05	1.77608E-05	1.87169E-05	1.96103E-05
55633	9.99999E-21	2.61076E-05	2.96475E-05	3.31193E-05	4.62932E-05	4.94008E-05	5.24312E-05
92235	9.71492E-04	5.80775E-04	5.36589E-04	4.94761E-04	3.49384E-04	3.18203E-04	2.88980E-04
92236	9.99999E-21	7.11583E-05	7.86753E-05	8.56486E-05	1.08470E-04	1.12982E-04	1.17044E-04
92238	2.18794E-02	2.16336E-02	2.15964E-02	2.15585E-02	2.13988E-02	2.13569E-02	2.13140E-02
94238	9.99999E-21	5.08451E-07	7.13536E-07	9.62084E-07	2.42733E-06	2.91468E-06	3.44917E-06
94239	9.99999E-21	1.07858E-04	1.14067E-04	1.19049E-04	1.30075E-04	1.31236E-04	1.31952E-04
94240	9.99999E-21	2.21196E-05	2.60945E-05	3.00003E-05	4.43591E-05	4.75380E-05	5.05287E-05
94241	9.99999E-21	1.09779E-05	1.37246E-05	1.64876E-05	2.67336E-05	2.89421E-05	3.09761E-05
94242	9.99999E-21	1.26448E-06	1.86575E-06	2.60137E-06	6.85451E-06	8.22176E-06	9.69682E-06
95241	9.99999E-21	1.76423E-07	2.49678E-07	3.33089E-07	7.19747E-07	8.17423E-07	9.11165E-07
8001	4.57018E-02	4.57018E-02	4.57018E-02	4.57018E-02	4.57018E-02	4.57018E-02	4.57018E-02
44601	9.99999E-21	2.19801E-05	2.51017E-05	2.82139E-05	4.05465E-05	4.35951E-05	4.66278E-05
45603	9.99999E-21	1.19458E-05	1.37890E-05	1.55849E-05	2.22112E-05	2.37128E-05	2.51478E-05
45605	9.99999E-21	4.57383E-08	4.84212E-08	5.09780E-08	6.02870E-08	6.24351E-08	6.45223E-08
46605	9.99999E-21	7.71152E-06	9.18176E-06	1.07211E-05	1.74893E-05	1.93171E-05	2.11929E-05
46607	9.99999E-21	3.32193E-06	4.08714E-06	4.91198E-06	8.76228E-06	9.85276E-06	1.09907E-05
47609	9.99999E-21	1.21185E-06	1.49268E-06	1.79259E-06	3.14995E-06	3.52120E-06	3.90237E-06
49615	9.99999E-21	9.92244E-08	1.11432E-07	1.23041E-07	1.63316E-07	1.71839E-07	1.79758E-07
54634	9.99999E-21	3.25852E-05	3.71928E-05	4.17910E-05	6.00974E-05	6.46538E-05	6.92024E-05
60643	9.99999E-21	1.97780E-05	2.21845E-05	2.44529E-05	3.21512E-05	3.37326E-05	3.51775E-05
60645	9.99999E-21	1.48964E-05	1.68123E-05	1.86793E-05	2.56639E-05	2.72896E-05	2.88670E-05
61647	9.99999E-21	5.80911E-06	6.27491E-06	6.67053E-06	7.69046E-06	7.83361E-06	7.94163E-06

Benchmark Calculations

- **Part 1**: Fixed T/H conditions: HZP ARO and HZP ARI, 1000 ppmB (2D)
  - k_{eff}
  - assembly and pin power distribution
  - rod worth
- **Part 2**: Operating conditions: HFP, ARO (3D)
  - critical boron concentration
  - assembly and pin power distribution
- **Part 3**: Beginning of transient conditions: HZP, partly rodded (3D)
  - critical boron concentration
  - assembly and pin power distribution
- **Part 4**: Rod ejection transient (3D)
  - Ejection of the highest worth rod from conditions calculated in Part 3

Benchmark Conditions

- **HFP**
  - 100.0 % rated power (3565 MW)
  - inlet coolant temperature of 560 K
  - inlet pressure of 15.5 MPa

- **HZP**
  - 1.0e-4 % rated power (3565 W)
  - inlet coolant temperature of 560 K
  - inlet pressure of 15.5 MPa

- **Transient**
  - ejection of highest worth rod at HZP ARI, critical boron concentration
  - rod fully ejected in 0.1 sections
  - no reactor scram after the ejection
  - boron concentration in the position of the other control rods are constant.

Benchmark Participants and Submitted Homogeneous Solutions

Nodal solutions

Code, unique solution label	Organization (Country)	Solution method	Groups/ Homogenization	Cross section library
CORETRAN 1/FA	PSI (Switzerland)	Nodal diffusion	2G Nodal	2G benchmark library
CORETRAN 4/FA	PSI (Switzerland)	Nodal diffusion	2G Nodal	2G benchmark library
EPISODE	Osaka University (Japan)	Nodal diffusion	2G Nodal	2G benchmark library
NUREC	KAERI (Korea)	Nodal diffusion	2G Nodal	2G benchmark library
PARCS 2G	Purdue Univ. (USA)	Nodal diffusion	2G Nodal	2G benchmark library
PARCS 4G	Purdue Univ. (USA)	Nodal diffusion	4G Nodal	4G benchmark library
PARCS 8G	Purdue Univ. (USA)	Nodal diffusion	8G Nodal	8G benchmark library
SKETCH	JNES (Japan)	Nodal diffusion	2G Nodal	2G benchmark library

Benchmark Participants and Submitted Heterogeneous Solutions

Heterogeneous solutions

Code, unique solution label	Organization (Country)	Solution method	Groups/ Homogenization	Cross section library
BARS	Kurchatov Inst. (Russia)	Lambda matrix	5G Cell hom	UNK generated
DeCART	SNU/KAERI (Korea)	MOC	47G Cell het	HELIOS based
DORT	GRS (Germany)	S_N	16G Cell hom	HELIOS generated
MCNP	Kurchatov Inst. (Russia)	Monte Carlo	Continuous Cell het	ENDF/B-VI with NJOY

Part 1, 2D fixed T/H
Eigenvalue and Assembly Power Comparison

	Eigenvalue		Todal Rod Worth [dk/k]	Assembly Power Error			
				ARO		ARI	
	ARO	ARI		%PWE	%EWE	%PWE	%EWE
nodal							
CORETRAN 1/FA	1.06387	0.99202	6808	1.06	1.69	2.01	2.52
CORETRAN 4/FA	1.06379	0.99154	6850	0.96	1.64	1.67	2.18
EPISODE	1.06364	0.99142	6849	0.96	1.64	1.66	2.16
NUREC	1.06378	0.99153	6850	0.96	1.63	1.64	2.16
PARCS 2G	1.06379	0.99154	6850	0.96	1.63	1.67	2.18
PARCS 4G	1.06376	0.99136	6865	0.90	1.42	1.61	2.26
PARCS 8G	1.06354	0.99114	6868	0.86	1.25	1.65	2.49
SKETCH	1.06379	0.99153	6850	0.97	1.67	1.67	2.16
heterogeneous							
BARS	1.05826	0.98775	6745	1.29	1.92	3.92	10.30
DeCART	1.05852	0.98743	6801	ref	ref	ref	ref
DORT	1.06036	-	-	0.86	1.12	-	-
MCNP	1.05699	0.98540	6873	0.67	1.26	1.33	3.67
Max. difference	688	662	128				

Power-Weighted Error (PWE)

$$PWE = \frac{\sum_i |e_i| ref_i}{\sum_i ref_i}$$

Error-Weighted Error (EWE)

$$EWE = \frac{\sum_i |e_i||e_i|}{\sum_i |e_i|}$$

$$e_i = \frac{calc_i - ref_i}{ref_i} \times 100$$

Part 1, 2D fixed T/H
Pin Power Comparison

ARO

	Assembly Position					
	(A,1)	(B,2)	(C,3)	(D,4)	(E,5)	(F,6)
nodal						
CORETRAN 1/FA	0.85	1.05	0.91	2.37	1.38	4.89
CORETRAN 4/FA	-	-	-	-	-	-
EPISODE	0.25	0.23	0.42	1.37	0.47	4.04
NUREC	0.24	0.22	0.31	0.67	0.32	0.87
PARCS 2G	0.28	0.21	0.29	0.54	0.32	0.51
PARCS 4G	-	-	-	-	-	-
PARCS 8G	-	-	-	-	-	-
SKETCH	0.22	0.22	0.32	0.71	0.32	1.05
heterogeneous						
BARS	0.26	0.45	0.55	0.40	0.33	0.61
DeCART	ref	ref	ref	ref	ref	ref
DORT	1.52	0.59	0.92	0.33	1.64	0.41
MCNP	-	-	-	-	-	-

Part 1, 2D fixed T/H
Pin Power Comparison

ARI

	Assembly Position					
	(A,1)	(B,2)	(C,3)	(D,4)	(E,5)	(F,6)
nodal						
CORETRAN 1/FA	6.22	1.31	5.95	3.26	7.75	3.99
CORETRAN 4/FA	-	-	-	-	-	-
EPISODE	2.44	0.28	2.32	1.35	2.37	3.83
NUREC	-	0.33	-	0.66	-	0.77
PARCS 2G	-	0.63	-	0.65	-	0.50
PARCS 4G	-	-	-	-	-	-
PARCS 8G	-	-	-	-	-	-
SKETCH	2.63	0.33	2.67	0.79	2.97	1.19
heterogeneous						
BARS	0.42	0.30	1.55	0.33	1.96	0.66
DeCART	ref	ref	ref	ref	ref	ref
DORT	-	-	-	-	-	-
MCNP	-	-	-	-	-	-

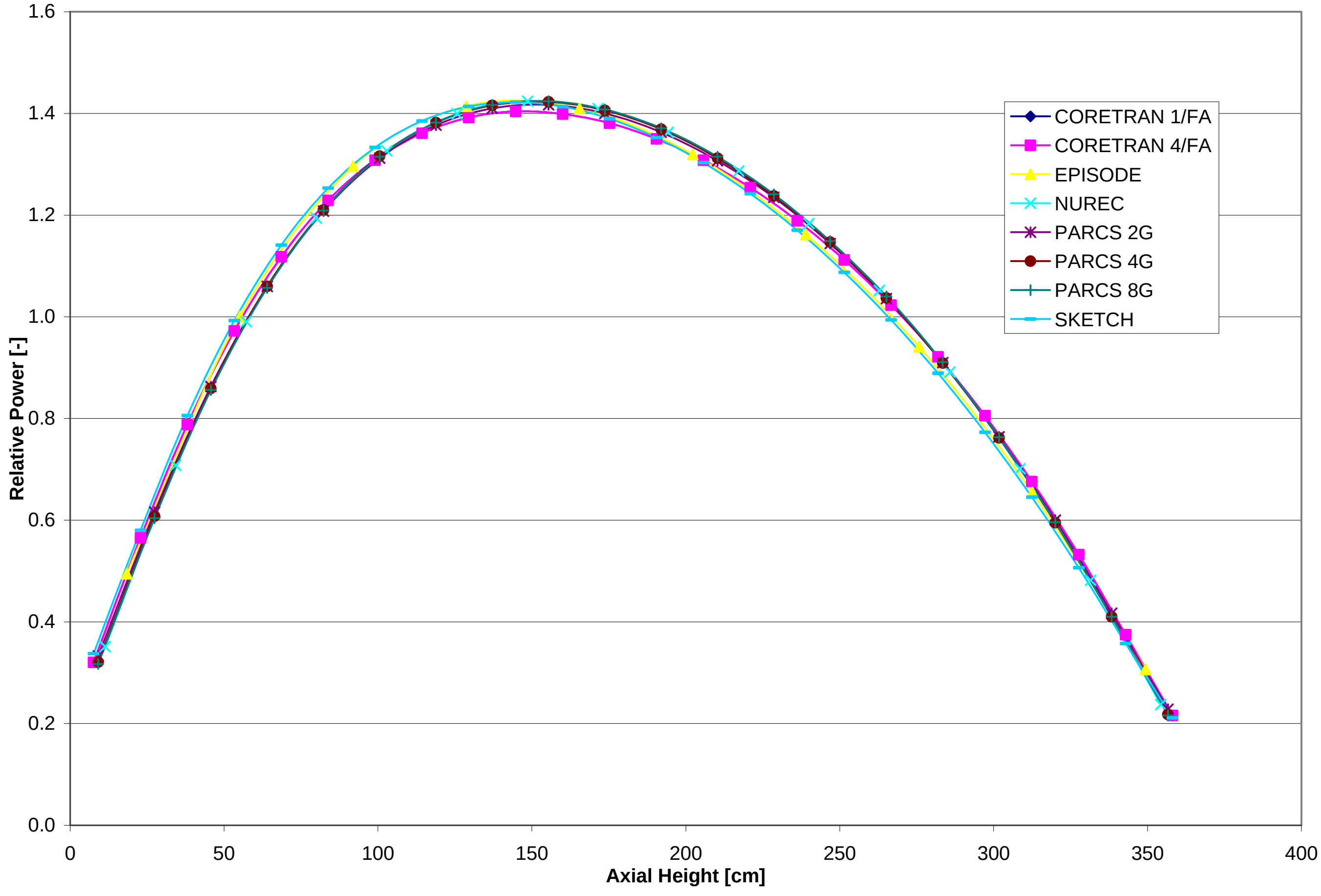
Part 2, 3D Hot Full Power
Eigenvalue, Assembly Power, T/H Conditions

	Critical Boron Concent. [ppm]	Assembly Power Error		Core Average T/H Properties				
		%PWE	%EWE	Doppler Temp. [K]	Moderator Density [g/cm3]	Moderator Temp. [K]	Outlet Mod Density [g/cm3]	Outlet Mod. Temp. [K]
nodal								
CORETRAN 1/FA	1647	0.31	0.51	908.4	706.1	581.0	658.5	598.6
CORETRAN 4/FA	1645	0.26	0.46	908.4	706.1	581.0	658.5	598.6
EPISODE	1661	0.40	0.64	846.5	701.8	582.6	697.4	585.5
NUREC	1683	0.31	0.44	827.8	706.1	581.1	661.5	598.7
PARCS 2G	1679	ref	ref	836.0	706.1	581.3	662.1	598.8
PARCS 4G	1674	0.31	0.50	836.1	706.1	581.3	662.1	598.8
PARCS 8G	1672	0.55	0.86	836.2	706.1	581.3	662.1	598.8
SKETCH	1675	1.04	1.39	836.6	705.5	580.9	659.6	598.9
Max. difference	38			81	4	2	39	13

Part 2, 3D Hot Full Power
Pin Power Comparison

	Assembly Position					
	(A,1)	(B,2)	(C,3)	(D,4)	(E,5)	(F,6)
nodal						
CORETRAN 1/FA	1.07	0.92	0.90	2.62	1.38	4.60
CORETRAN 4/FA	-	-	-	-	-	-
EPISODE	3.08	2.67	3.01	3.47	3.44	10.47
NUREC	0.08	0.17	0.24	0.32	0.13	0.89
PARCS 2G	ref	ref	ref	ref	ref	ref
PARCS 4G	-	-	-	-	-	-
PARCS 8G	-	-	-	-	-	-
SKETCH	0.09	0.11	0.18	0.58	0.22	0.87

Part 2, 3D Hot Full Power
Axial Power



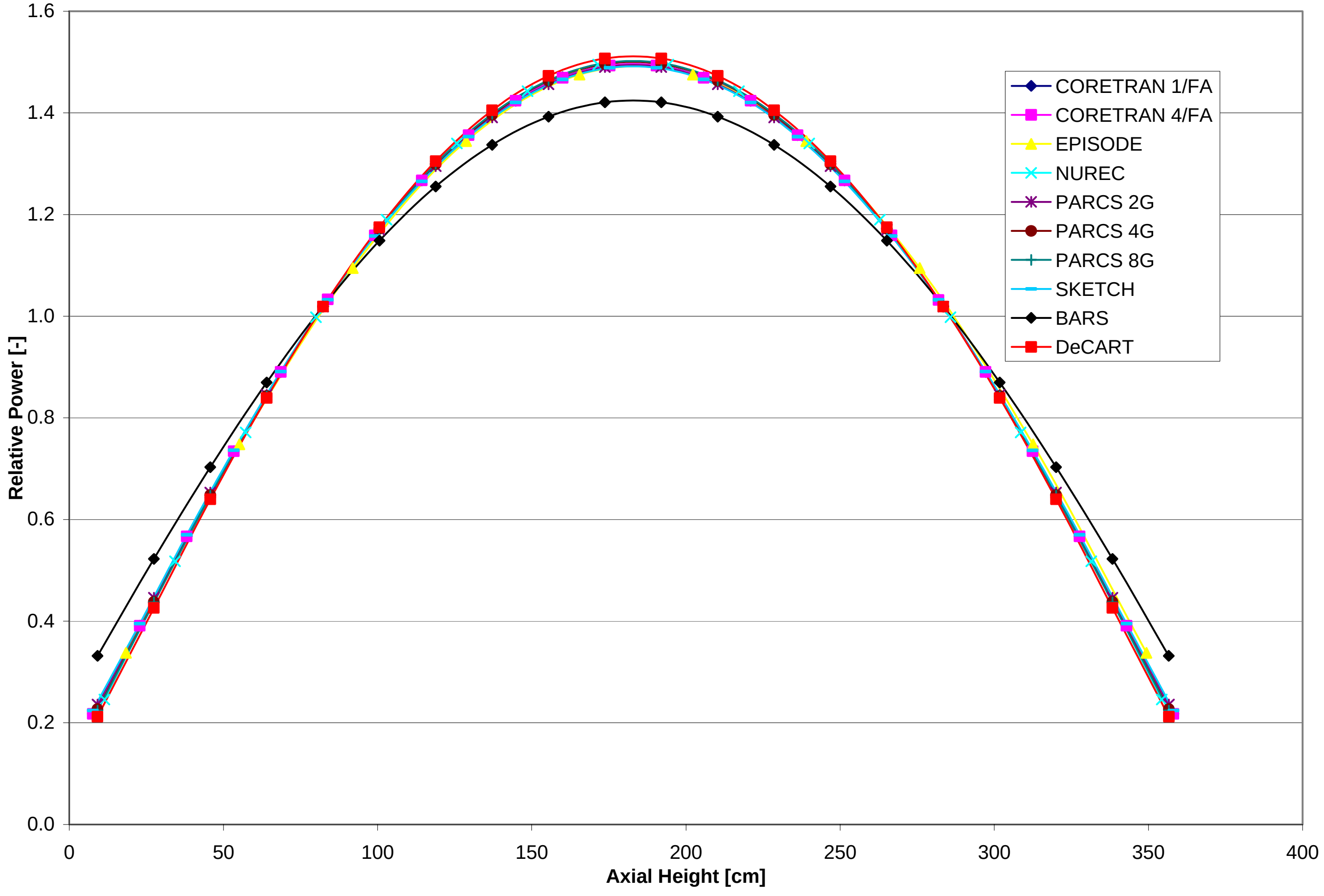
Part 3, 3D Hot Zero Power
Critical Boron Concentration, Delayed Neutron Fraction and Assembly Power Comparison

	Critical Boron Concent. [ppm]	Delayed Neutron Fraction [pcm]	Assembly Power Error	
			%PWE	%EWE
nodal				
CORETRAN 1/FA	1351	568	1.26	4.10
CORETRAN 4/FA	1346	568	1.09	3.72
EPISODE	1340	579	1.05	3.42
NUREC	1343	576	1.05	3.43
PARCS 2G	1341	579	1.05	3.49
PARCS 4G	1337	579	1.11	3.06
PARCS 8G	1334	580	1.20	2.85
SKETCH	1341	579	1.06	3.77
heterogeneous				
BARS	1296	579	2.65	5.66
DeCART	1265	-	ref	ref
Max. difference	86	12		

Part 3, 3D Hot Zero Power Pin Power Comparison

	Assembly Position					
	(A,1)	(B,2)	(C,3)	(D,4)	(E,5)	(F,6)
nodal						
CORETRAN 1/FA	6.46	0.81	6.66	3.44	6.71	4.81
CORETRAN 4/FA	-	-	-	-	-	-
EPISODE	2.51	0.57	2.33	1.41	2.39	3.88
NUREC	2.38	0.68	2.14	0.64	2.33	0.80
PARCS 2G	-	0.82	-	0.62	-	0.46
PARCS 4G	-	-	-	-	-	-
PARCS 8G	-	-	-	-	-	-
SKETCH	2.65	0.70	2.65	0.80	2.79	1.09
heterogeneous						
BARS	0.38	0.60	1.83	0.33	0.41	0.45
DeCART	ref	ref	ref	ref	ref	ref

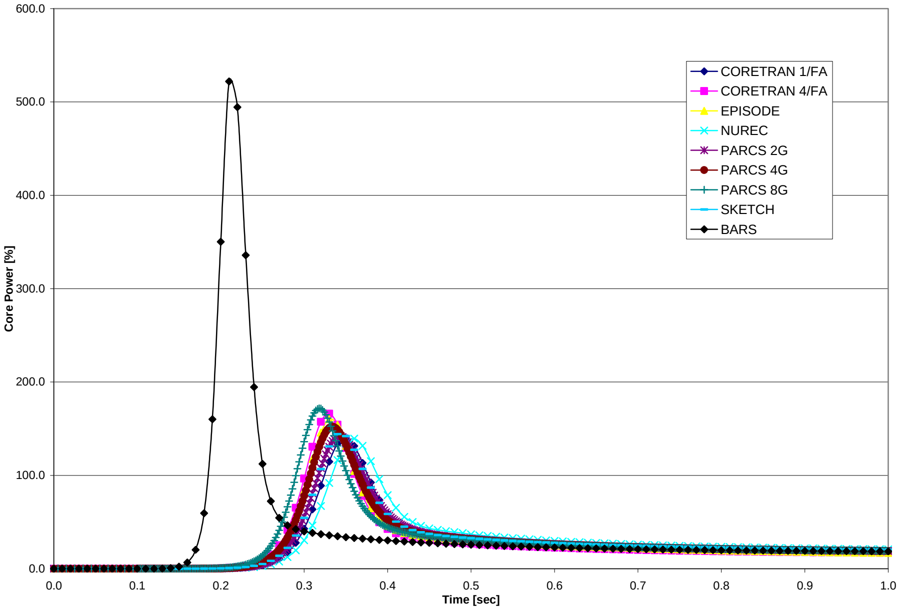
Part 3, 3D Hot Zero Power Axial Power

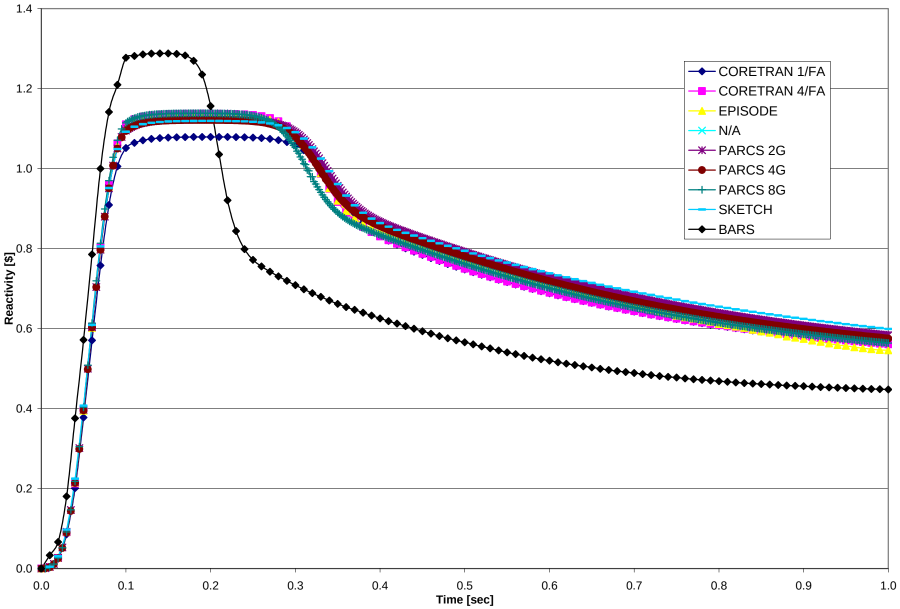


Part 4, 3D Transient
Integral Parameter Comparison

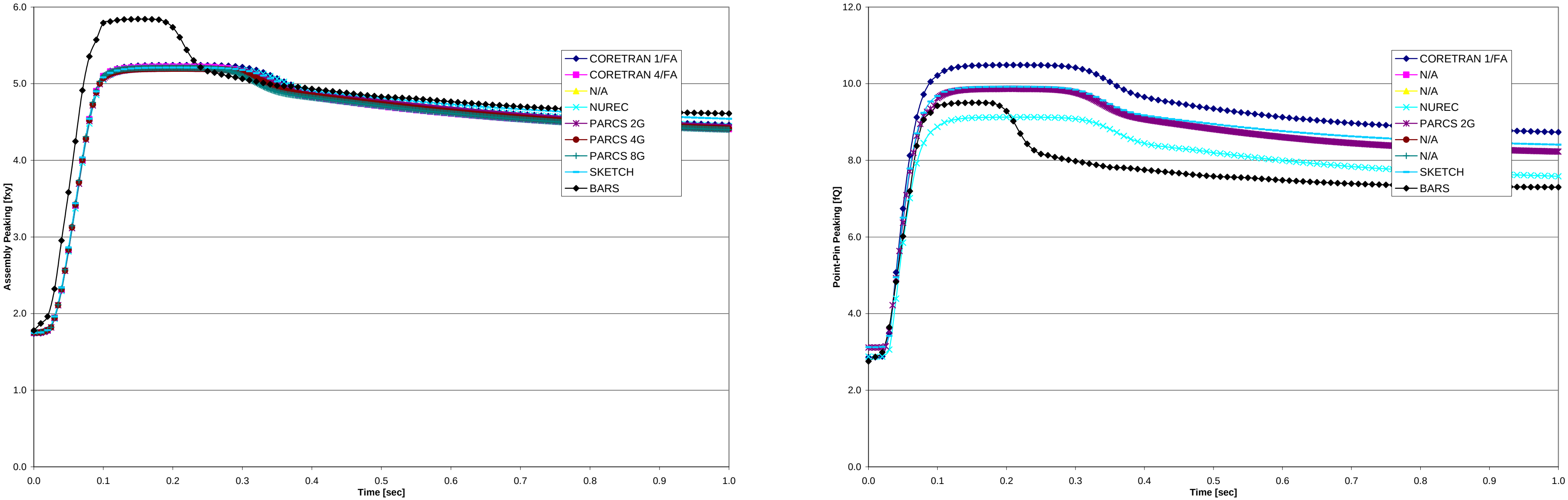
	Peak Time [sec]	Peak Power [%]	Peak Reactivity [$]	Power Integral [%-sec]
nodal				
CORETRAN 1/FA	0.35	140	1.08	24.8
CORETRAN 4/FA	0.33	166	1.14	26.4
EPISODE	0.33	160	1.13	26.9
NUREC	0.36	139	-	28.4
PARCS 2G	0.34	142	1.12	27.2
PARCS 4G	0.33	152	1.12	27.8
PARCS 8G	0.32	172	1.14	29.1
SKETCH	0.34	144	1.12	28.0
heterogeneous				
BARS	0.21	522	1.29	41.7
Max. difference	0.04	32	0.06	4.3

Part 4, 3D Transient
Core Power and Reactivity

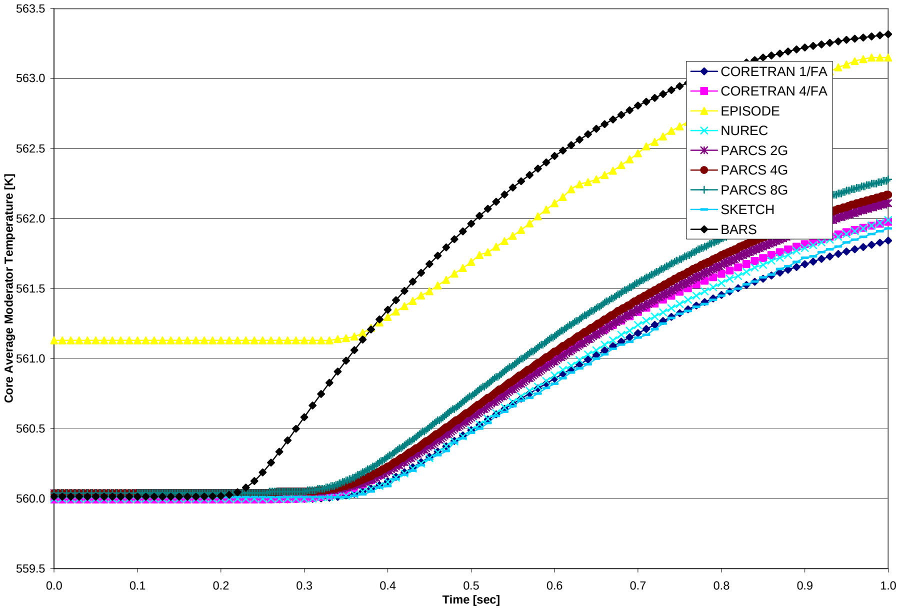


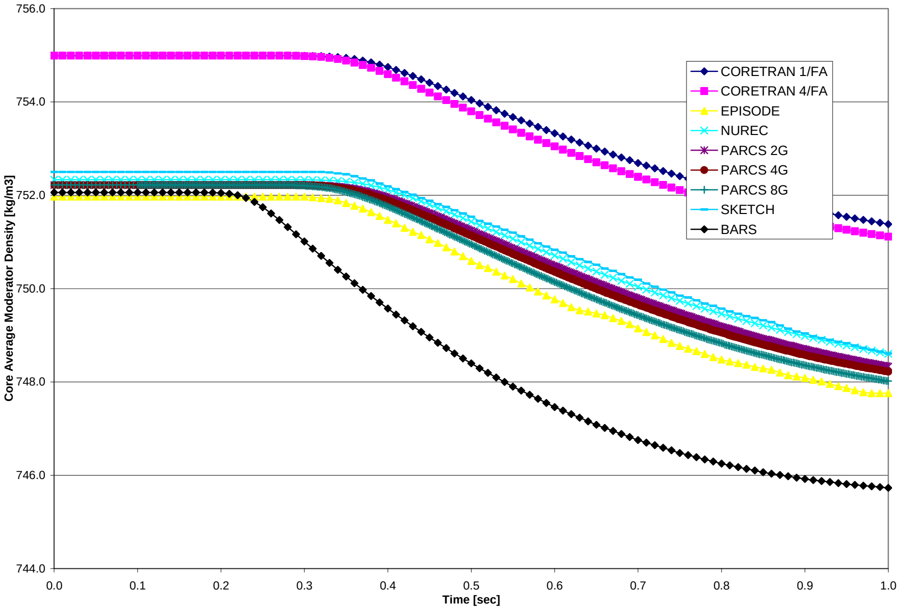


Part 4, 3D Transient
Assembly and Point Pin Peaking



Part 4, 3D Transient
Moderator Temperature and Density





Conclusions

- Nodal diffusion codes are **capable of modeling static MOX core**
  - 1-2% assembly and pin-power error at ARO
  - 2-4% assembly and pin-power error at ARI
- Nodal diffusion codes are **consistent in modeling transient MOX core**
  - Lack of high-order reference to assess absolute performance
- All nodal results almost identical, the only significant difference can be seen in pin power prediction **due to differences in pin power reconstruction methods**
- 1 node per FA discretization is not sufficient for MOX core even with advanced nodal methods (ANM)
  - The difference between 1/FA and 4/FA is small but noticeably improves results
- It was found that the **group effect is not very significant** for this problem
  - Negligible difference at static conditions
  - The difference between 2G diffusion and 8G diffusion is 17% for peak power and 7% for power integral
- Code improvement needs
  - High order heterogeneous transport transient capability

Benchmark Schedule

- December 2002: - Distribute first draft specifications
- February 2003: - Obtain participant's comments
- March 2003: - Implement participant's comments into specifications
- April 2003: - Recalculate benchmark
- May 2003: - Distribute final draft of the specifications
  - WPPR14: finalize specifications and schedule
- August 2003: - Provide any additional data for the benchmark
- December 2003: - Release 2nd revision with all comments
- February 2004: - Request preliminary results for WPPR meeting
- March 2004: - Prepare final 8 group xsec set
- August 2004: - Request for final results
- September 2004: - WPRS01: final results from 4 participants
- October 2004: - Request final results before end of the year
- December 2004: - Generate final DeCART reference
- **June 2005: - WPRS02: close benchmark**

- January 2006: - submit final report for participants review
- January 2006: - WPRS03: present final report
- December 2006: - publish final report