Thermal Hydraulic Design Requirements – Steady State Design

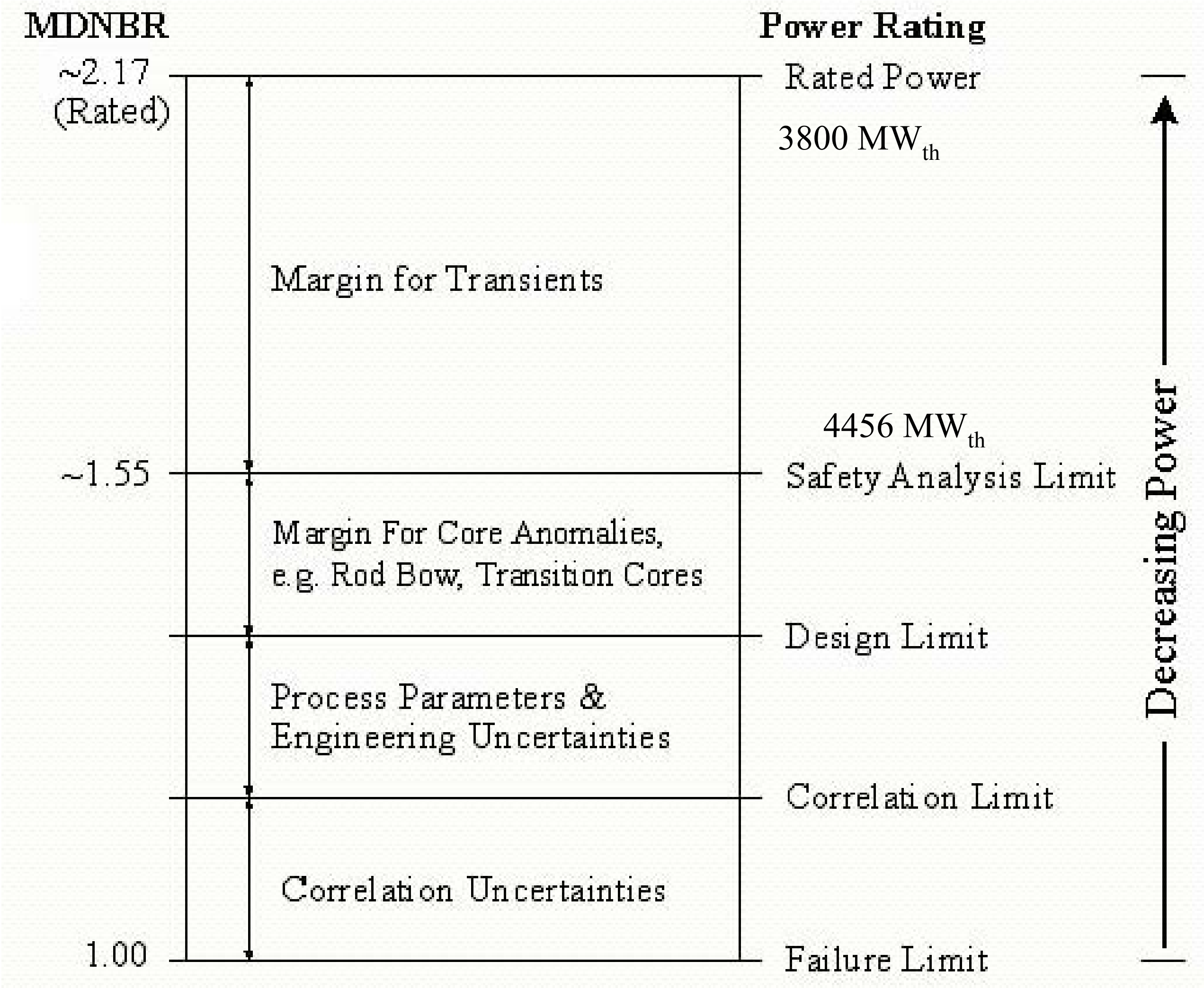
1. PWR Design
2. BWR Design

Course 22.39, Lecture 3

Professor Neil Todreas

PWR Design

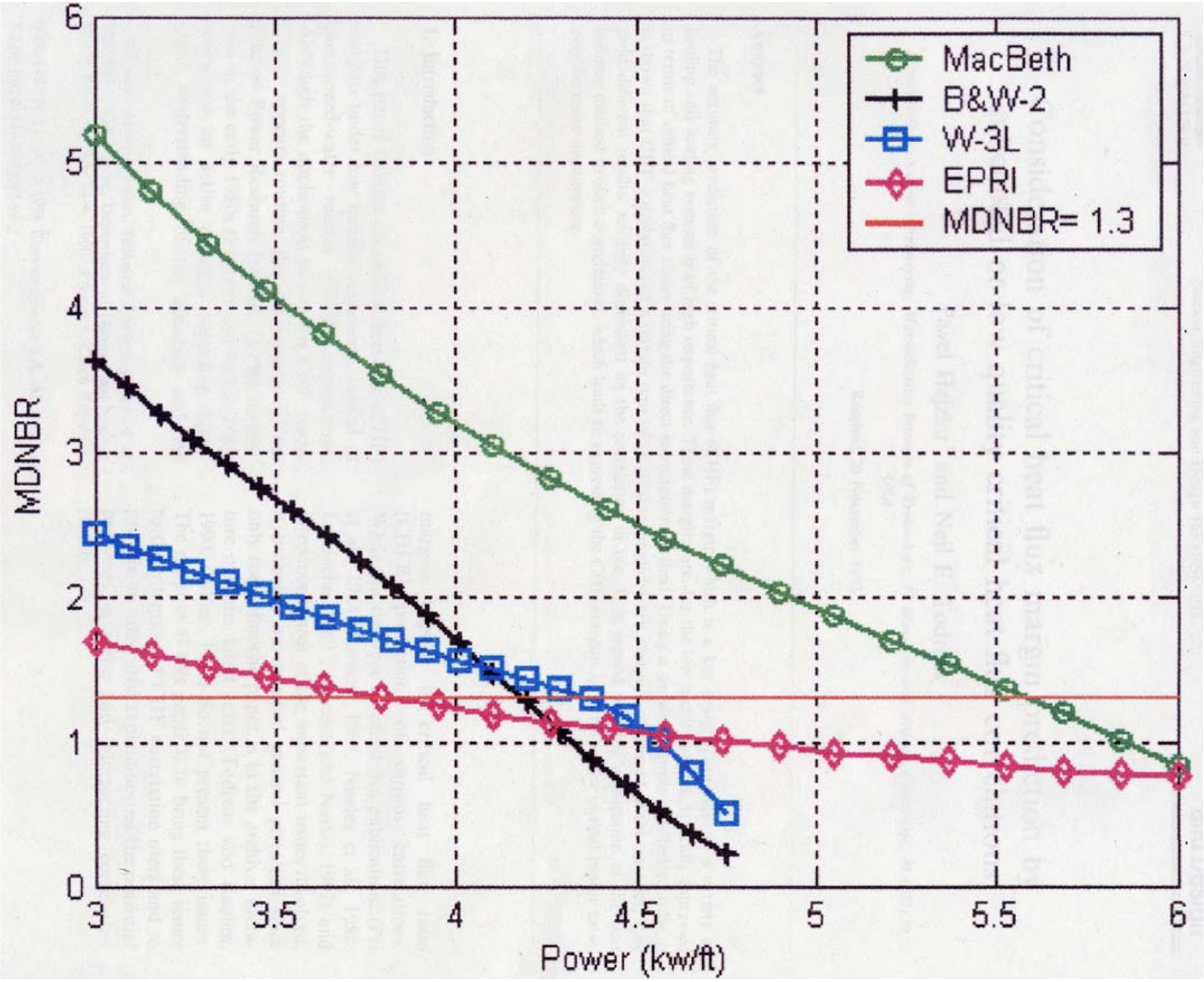
Components of Margin for MDNBR Overpower Transient



Summary of Steady-State Thermal Hydraulic Design Constraints

Design Constraints For:	*Constrained Parameters*	*Design Limit*	*Reference Equations*
Vortex-Shedding Lock-in	VSM_{lift}, VSM_{drag}	> 0.3	(3.18), (3.19)
Fluid-Elastic Instability	FIM	< 1	(3.21)
Fretting Wear	$\dot{W}_{fretting,new} / \dot{W}_{fretting,ref}$	$\leq T_{c,ref} / T_{c,new}$	(3.39)
Sliding Wear	$\dot{W}_{sliding,new} / \dot{W}_{sliding,ref}$	$\leq T_{c,ref} / T_{c,new}$	(3.44)
DNBR	MDNBR	> 2.17	
Pressure Drop	$\Delta P_{rod\ bundle}$	< 29 psia, 60 psia	
Fuel Temperature	$T_{centerline} - UZrH_{1.6}$ $T_{average} - UO_2$	< 750 C < 1400 C	

MDNBR vs Power



Source: Blair, S., and N.E. Todreas.
"Thermal Hydraulic Performance Analysis of a Small Integral Pressurized Water Reactor Core."
MIT-ANP-TR-099. Cambridge MA: MIT CANES, December 2003.

Flow-Induced Vibration Mechanisms

Flow-Induced Mechanism	*Design Concern*
Vortex-Induced Vibration	• Large amplitude vibrations occur when vortex shedding frequencies lock-in to the structural frequency of the rod
Fluid-Elastic Instability	• Large amplitude vibrations occur when cross-flows exceed the critical velocity for the rod bundle configuration
Turbulence-Induced Vibration in Cross and Axial Flow	• Small amplitude rod vibrations from turbulence generated pressure fields cause excessive fretting and sliding wear at the cladding/rod support interface

Vibrations Analysis Assumptions

- The fuel rod is modeled as a linear structure
- Changes to the fuel assembly structure over time are not considered
- Only the cladding structure is considered in the fuel rod model
- Only the first vibration mode is considered
- Core power is the only operating parameter affecting the vibrations performance of new designs

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Vortex Shedding

The vortex shedding margins in the lift and drag directions are defined as:

$$VSM_{lift} = \frac{|f_1 - f_s|}{f_s} > 0.3 \qquad (3.18)$$

$$VSM_{drag} = \frac{|f_1 - 2f_s|}{2f_s} \qquad (3.19)$$

where, f_1: *fundamental frequency of the rod*

The vortex shedding frequency is given by:

$$f_s = S \cdot \frac{V_{cross}}{D} \qquad (3.15)$$

where the Strouhal number, S, was found by Weaver and Fitzpatrick to depend on the P/D ratio and channel shape. For square arrays,

$$S = \frac{1}{2(P/D - 1)} \qquad (3.16)$$

and for hexagonal arrays,

$$S = \frac{1}{1.73(P/D - 1)} \qquad (3.17)$$

Fluid Elastic Instability

The ratio of the maximum effective cross-flow velocity in the hot assembly, V_{eff}, to the critical velocity for the bundle geometry $V_{critical}$:

$$FIM = \frac{V_{eff}}{V_{critical}} < 1 \qquad (3.21)$$

The most widely accepted correlation for estimating the critical velocity for a tube bundle is Connor's equation:

$$V_{critical} = \beta \cdot f_n \sqrt{\frac{2 \cdot \pi \cdot \zeta \cdot m_t}{\rho_{fl}}} \qquad (3.23)$$

where Pettigrew suggested a P/D effect on Connors' constant:

$$\beta = 4.76 \cdot \left(\frac{P}{D} - 1 \right) + 0.76 \qquad (3.24)$$

The critical velocity is constant for a fixed geometry and, with the exception of small changes in coolant density, does not depend on the power and flow conditions in the core.

Fretting Wear

$$\frac{\dot{W}_{fretting,new}}{\dot{W}_{fretting,ref}} = \frac{\left(f_1^3 \cdot m_t \cdot y_{rms}^2\right)_{new}}{\left(f_1^3 \cdot m_t \cdot y_{rms}^2\right)_{ref}} \leq \frac{T_{c,ref}}{T_{c,new}} \qquad (3.39)$$

where y_{rms} is turbulence induced vibration from axial and cross flow, m_t is total linear mass, and f_1 is fundamental frequency of fuel rod.

The wear rate ratio is the constrained parameter, and the ratio of the cycle lengths is the design limit.

If a new design has a shorter cycle length than the reference core, then it can safely accommodate a higher rate of wear.

The wear rate limit, due to its dependence on cycle length, will depend on both the power and the fuel burnup. The power, however, depends on the wear rate limit, and the burnup, when limited by fuel performance constraints, depends on the power.

Sliding Wear

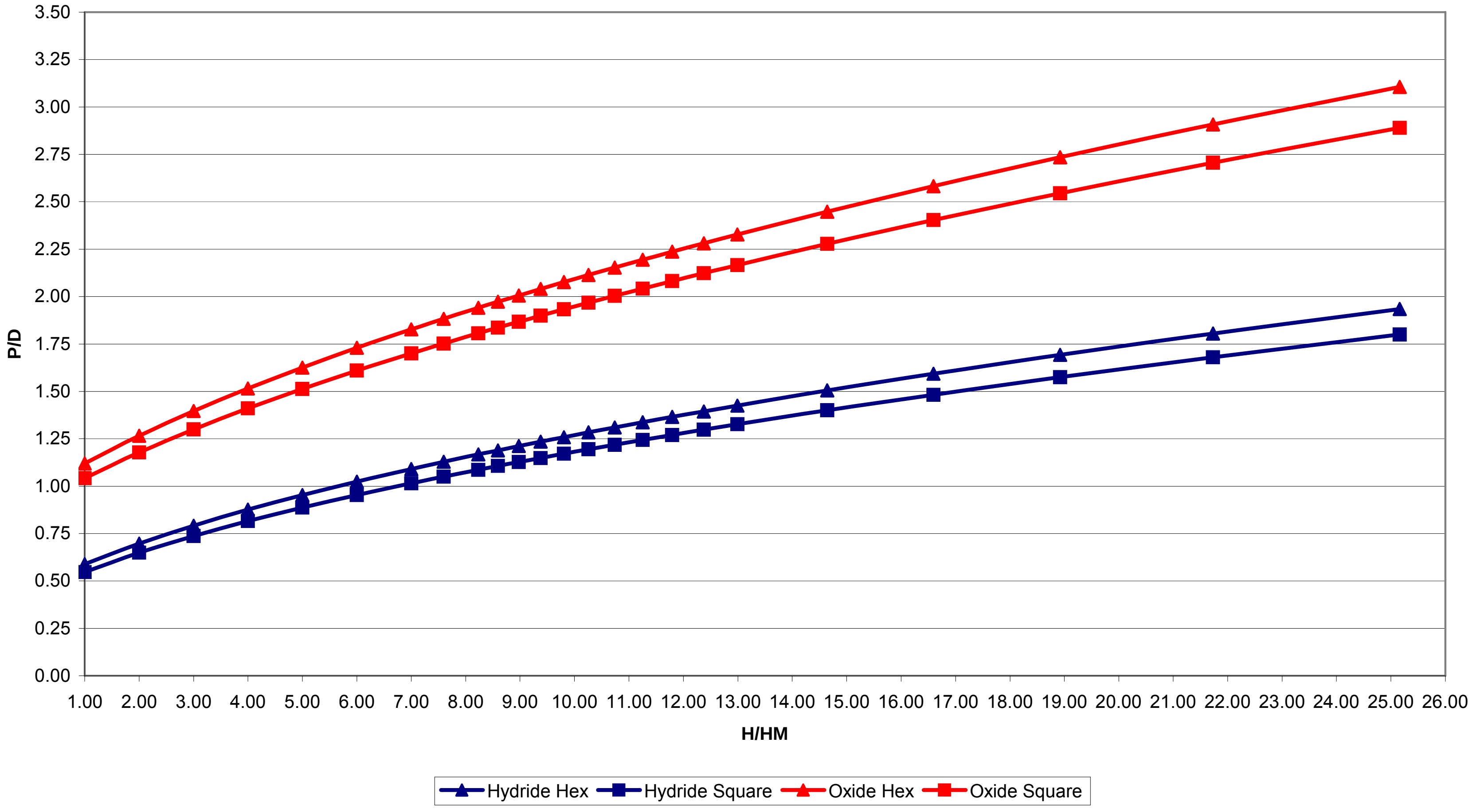
$$\frac{\dot{W}_{sliding,new}}{\dot{W}_{sliding,ref}} = \frac{\left(D \cdot y_{rms} \cdot f_1\right)_{new} \cdot \left(\frac{1}{A_{cl}} + \frac{D^2}{4I_{cl}}\right)_{ref}}{\left(D \cdot y_{rms} \cdot f_1\right)_{ref} \cdot \left(\frac{1}{A_{cl}} + \frac{D^2}{4I_{cl}}\right)_{new}} \le \frac{T_{c,ref}}{T_{c,new}} \qquad (3.44)$$

where A_{cl} is cladding cross-sectional area,

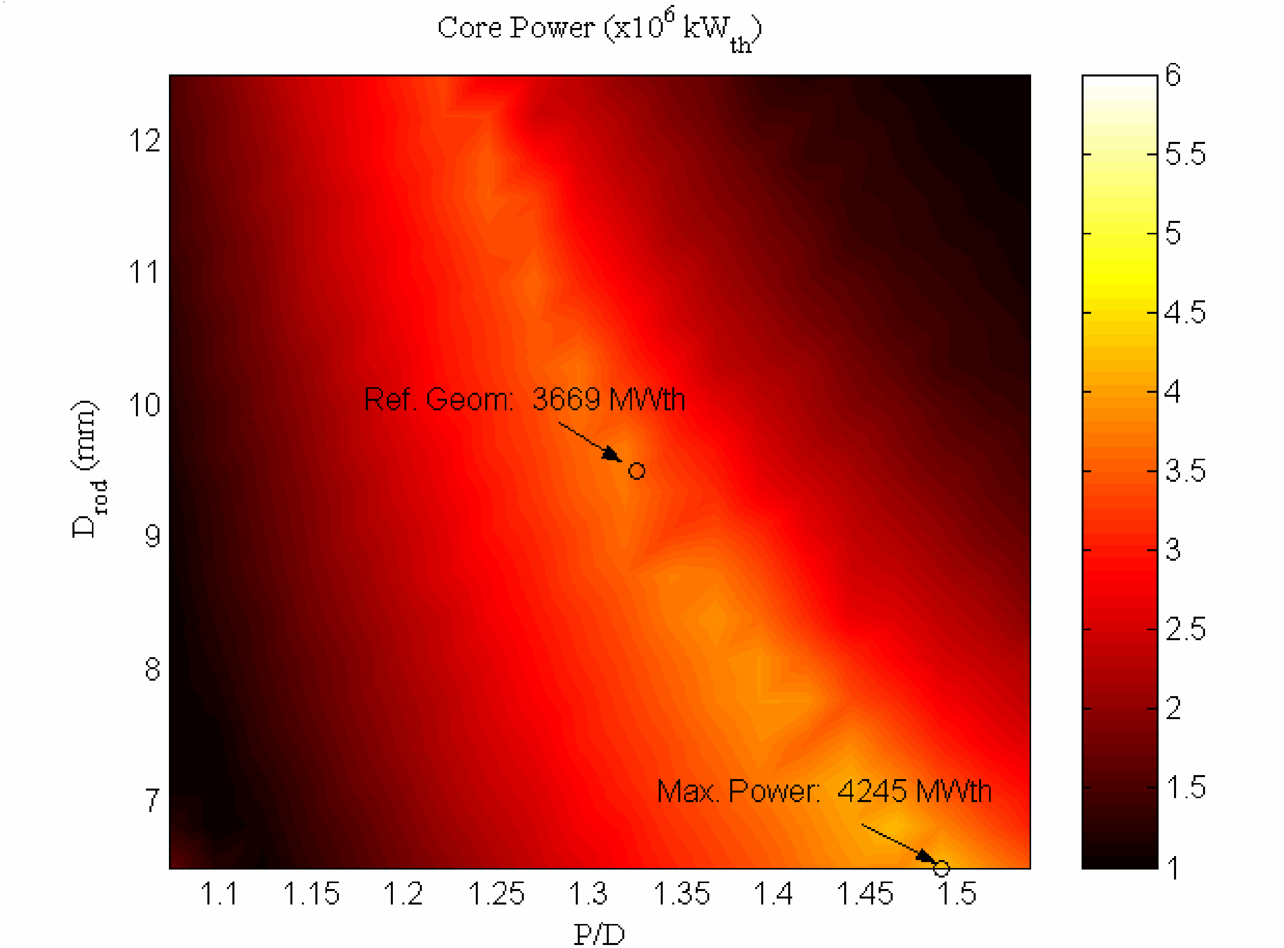
I_{cl} is cladding moment of inertia,

D is cladding outside diameter

P/D vs H/HM for Square and Hexagonal arrays of $UZrH_{1.6}$ and UO_2

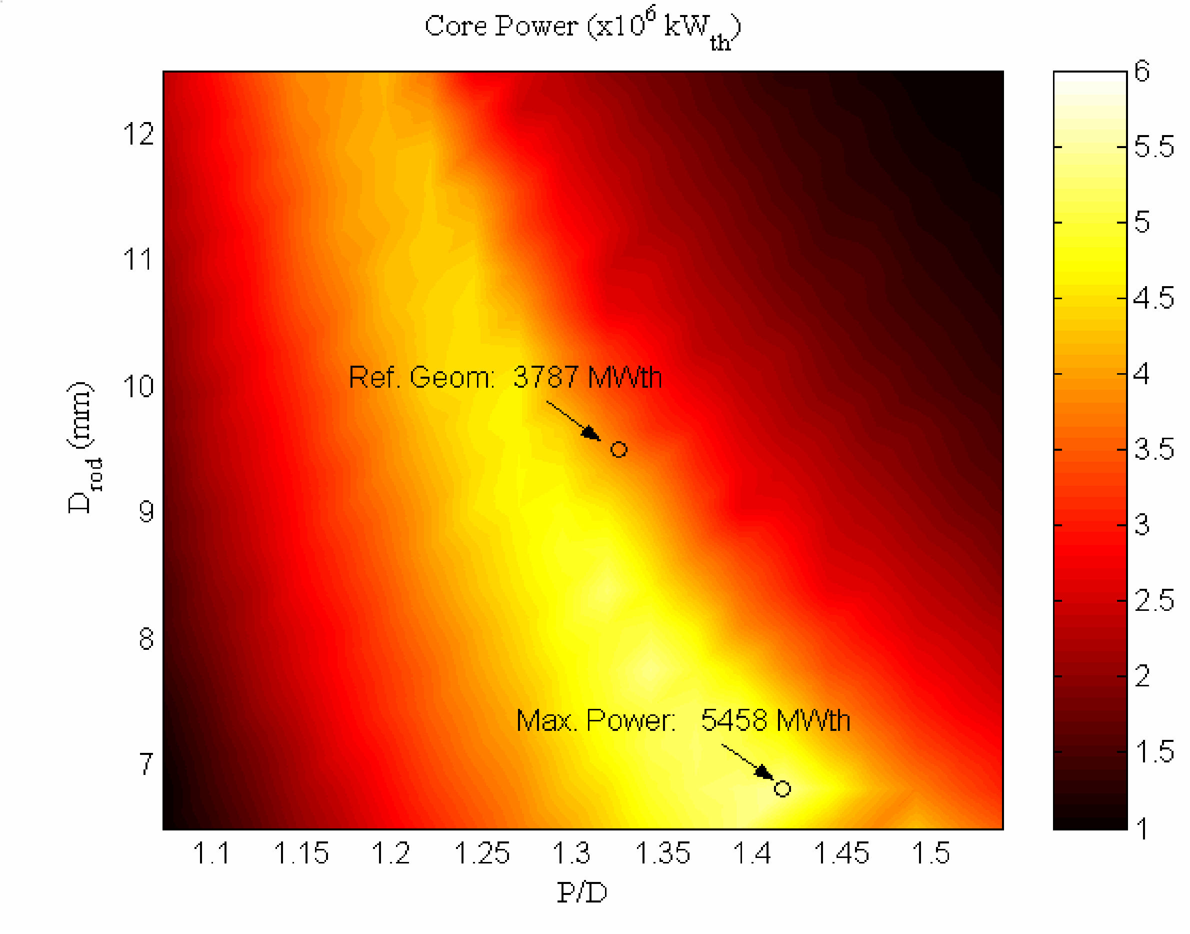


Maximum Achievable Power for Square

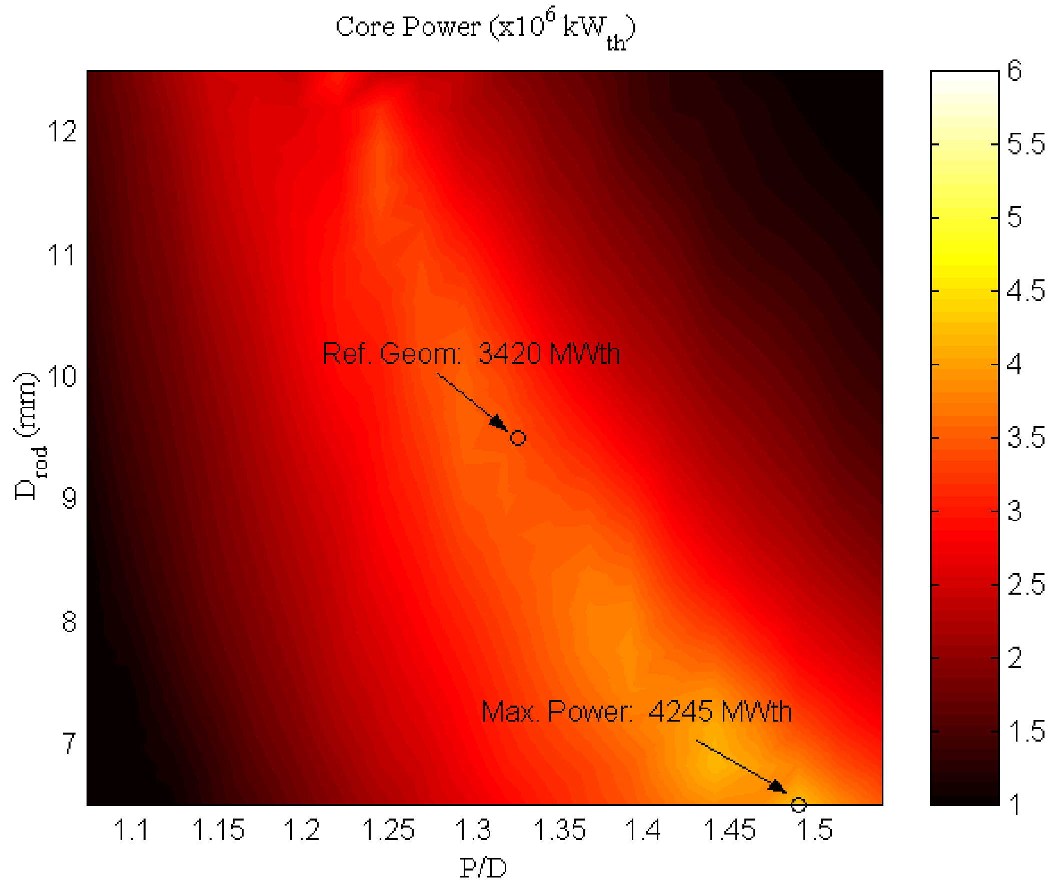


Note: The following figures, slides 14-19, came from the paper, E. Greenspan, N. Todreas, et al, "Optimization of UO_2 Fueled PWR Core Design," Proceedings of ICAPP '05, Seoul, Korea, May 15-19, 2005, Paper 5569

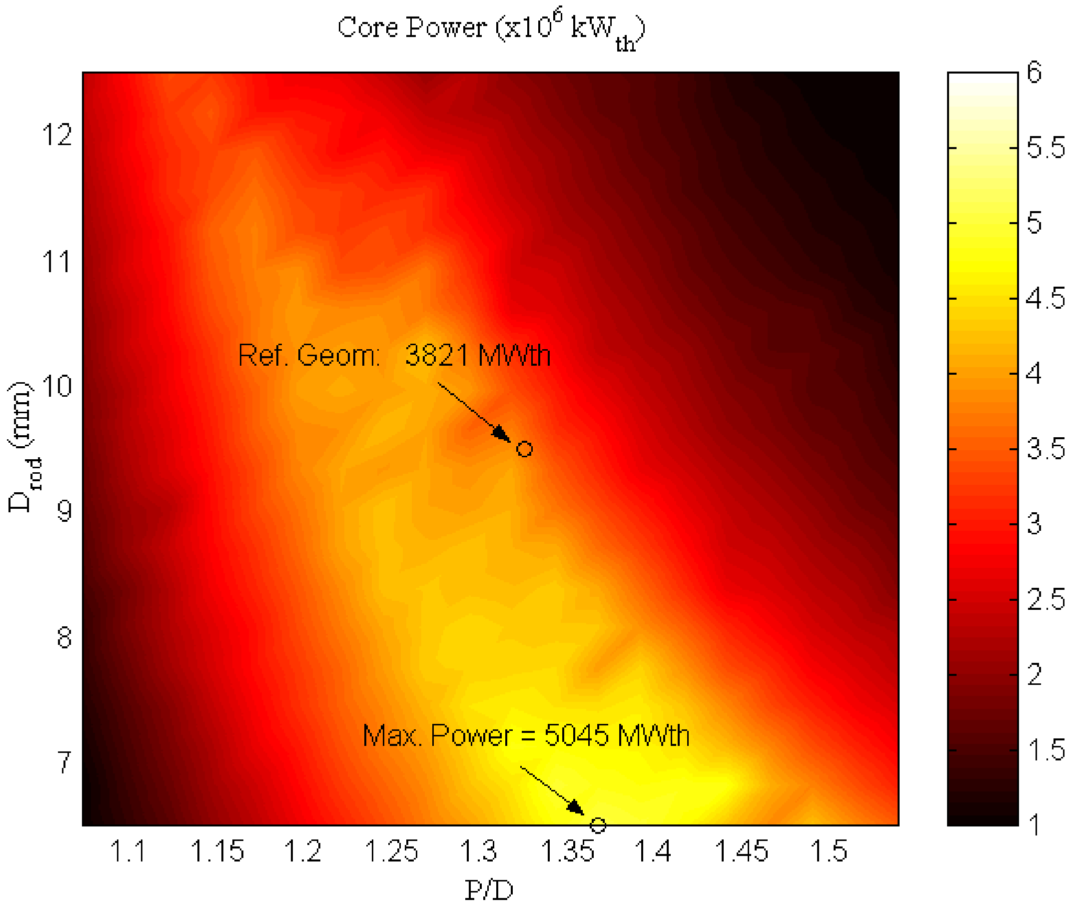
Maximum Achievable Power for Square Arrays of UO_2 at 60 psia



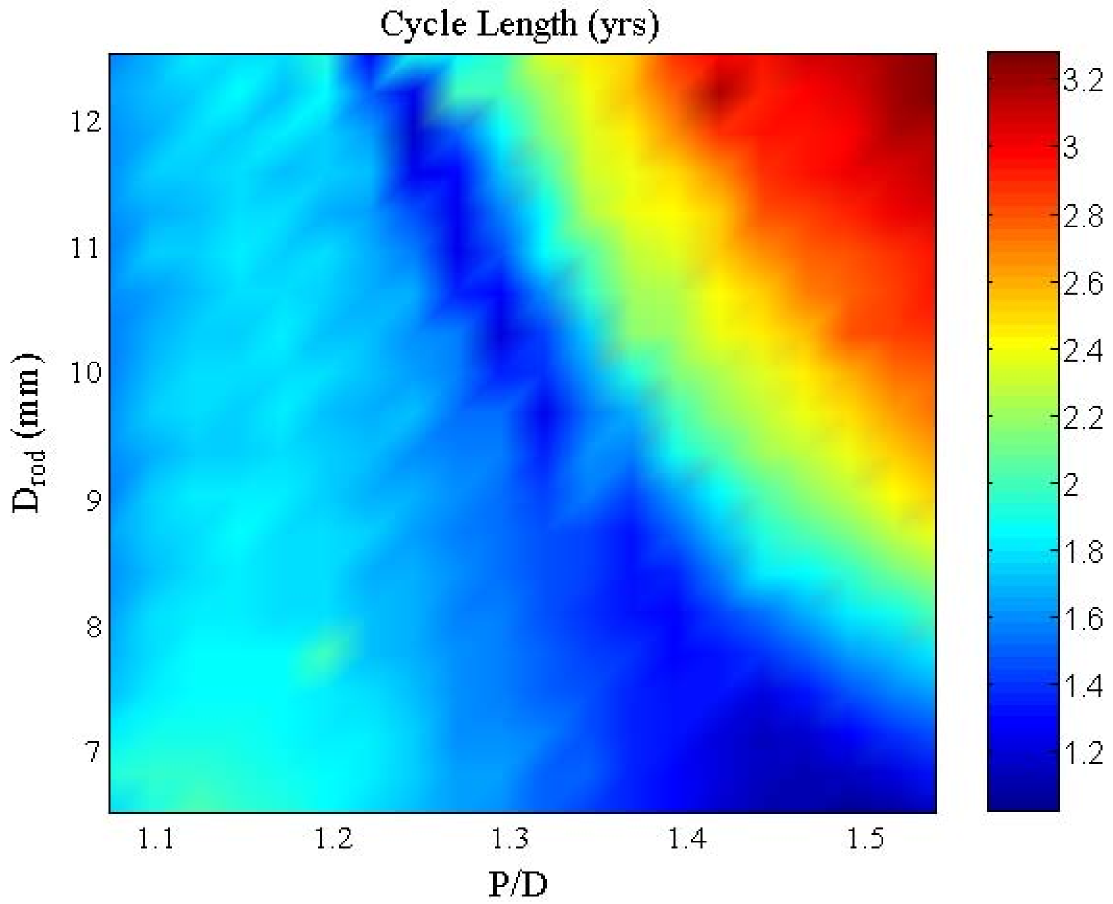
Maximum Achievable Power at 29 psia Accounting for Fuel Rod Vibration and Wear



Maximum Achievable Power at 60 psia Accounting for Fuel Rod Vibration and Wear



Maximum Permissible Cycle Length. 29 psia



Maximum Permissible Cycle Length. 60 psia

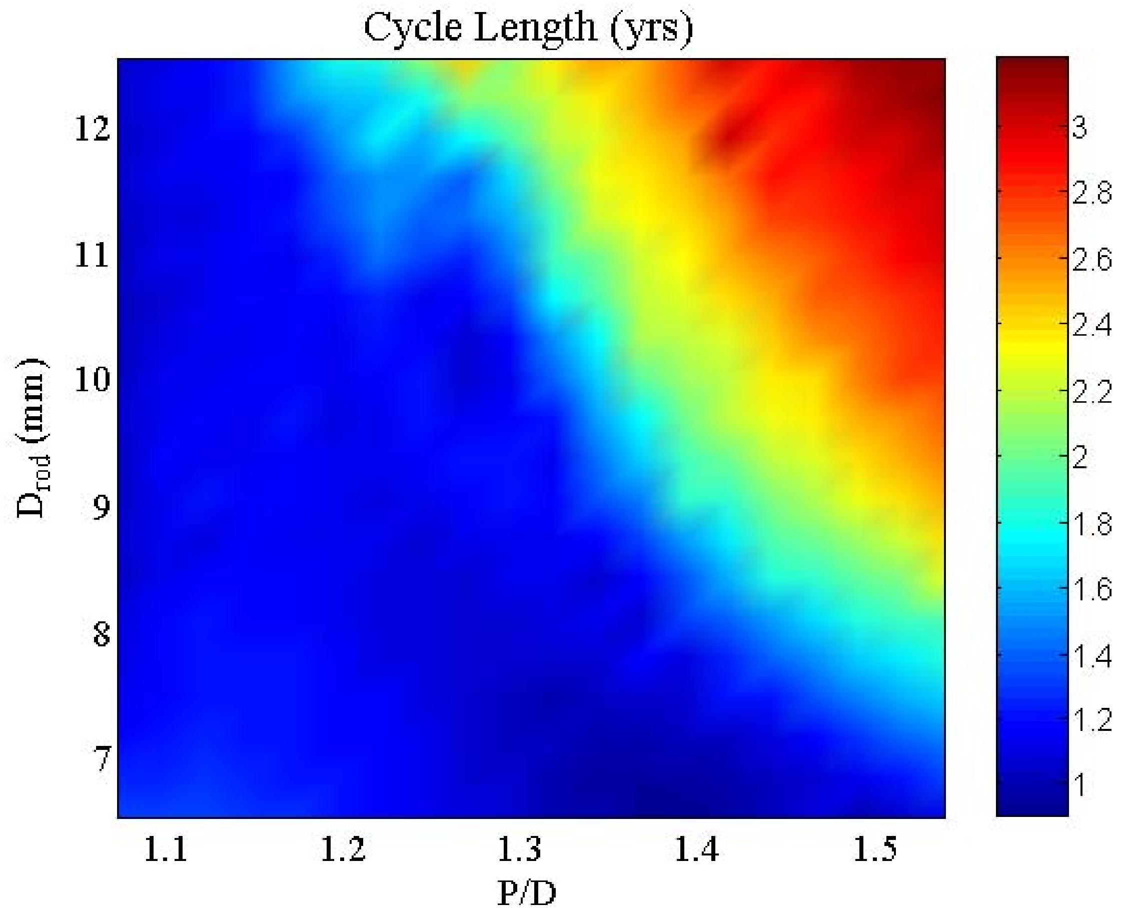
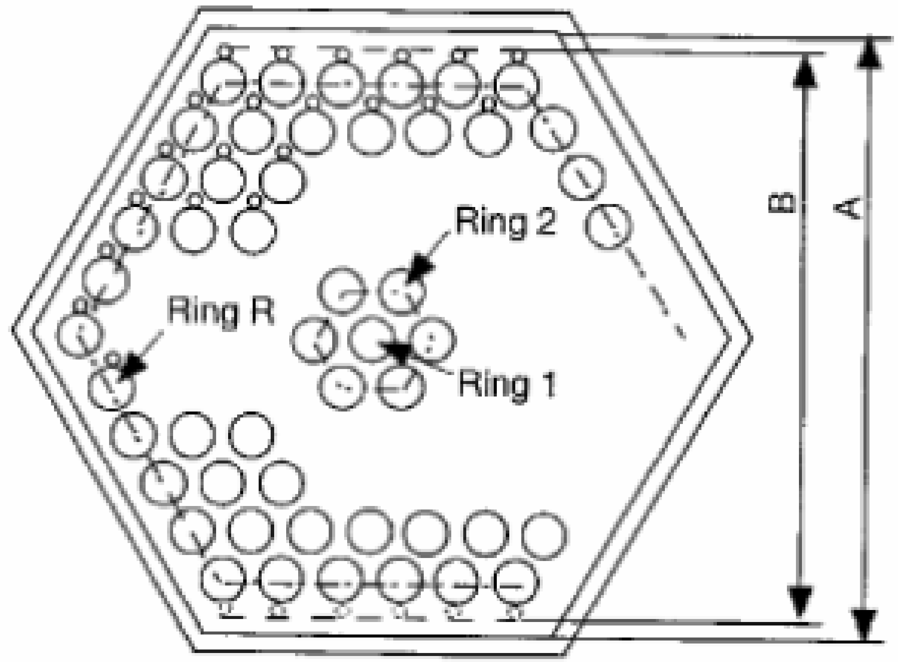


Illustration of Porosity in a Wire-Wrapped Bundle



Porosity = A - B Porosity / Ring = (A - B) / R

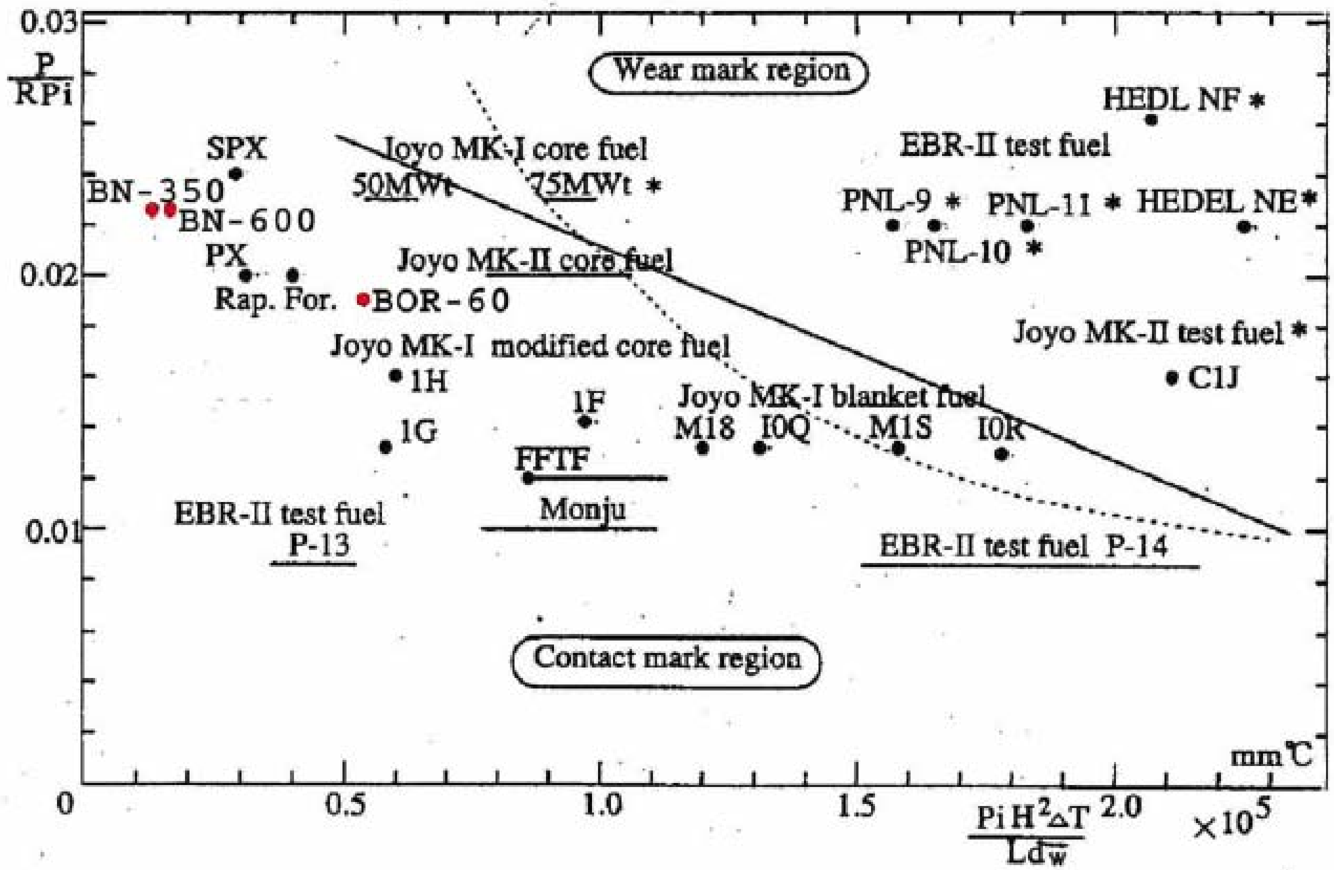
A : Distance betweern two wrapper tube walls

$B = 2(R - 1)(D + d_w)\cos 30^\circ + D + 2d_w$

D : Fuel pin diameter

d_w : Spacer wire diameter

THV-Induced Wear Data with Otsubo's Wear Constraint

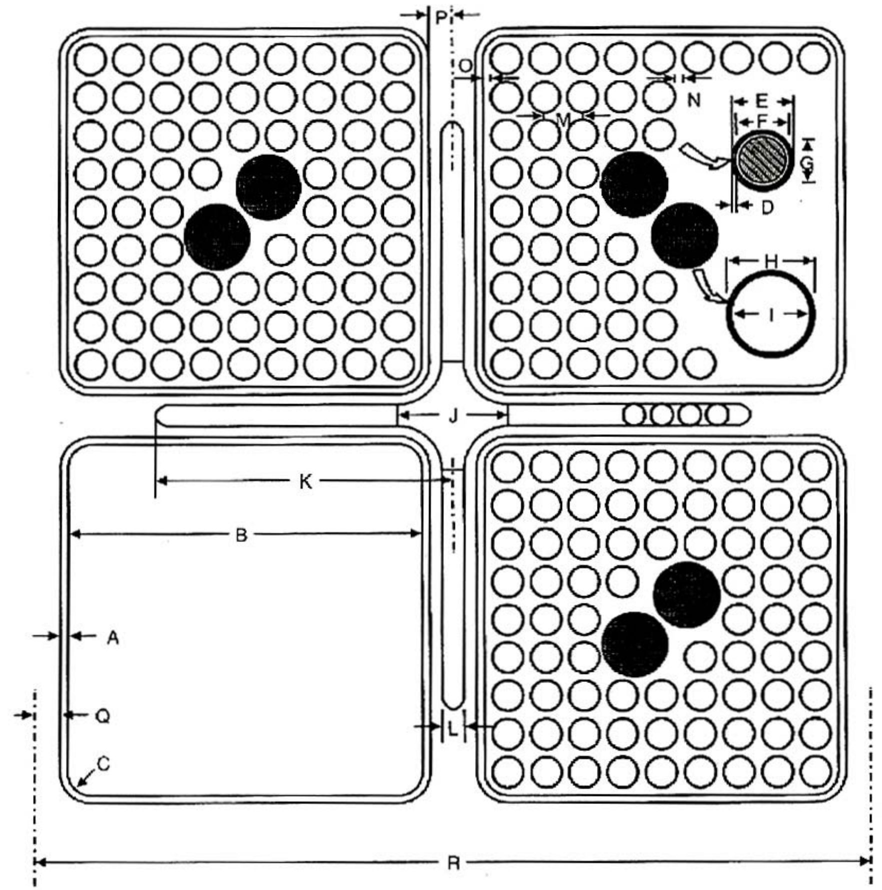


where P_i is the pitch, P is the porosity, d_w is the wire diameter, R is the number of rings in the bundle, ΔT is the temperature drop across the bundle in °C, H is the axial pitch, and L is the length of the assembly.

The region above this line (labeled wear mark region) is the region where Otsubo's constraint predicts that wear will occur. In the region below the dotted line, Otsubo's constraint predicts that no significant wear will occur. The points marked with a • represent reactors in which no wear has been observed, while the points marked with a * represent reactors in which wear marks occurred. The horizontal lines identify the range over which the subject fuel tests were conducted. The red dots, •, used for BN-350, BN-600, and BOR-60, represent Russian fast reactor data not used by Otsubo.

BWR Core Design

GE9×9 Fuel Bundle



	Channel			Fuel Rod			Pellet	Water Rod	
I.D.	A	B	C	D	E	F	G	H	I
Inches	0.100	5.215	0.380	0.028	0.440	0.384	0.376	0.980	0.920

	Control Rod			Bundle Lattice			Cell		
I.D.	J	K	L	M	N	O	P	Q	R
Inches	1.560	4.902	0.328	0.562	0.122	0.139	0.2925	0.2925	12.000

Thermal-Hydraulic Constraints

Table 2.3: Thermal-Hydraulic Constraints							
Case	Fuel centerline T (°C)	Fuel avg T (°C)	Core pres. drop (psi)	MCPR	$\dot{Q}/\dot{m}$ (kW/(kg/s))	Clad surface T (°C)	Vibration ratio
0	2805	1400	Output*	Output*	Input*	349	0.021
Ox-Backfit-5	2805	1400	24.5 36.0	1.015	243.07		
Ox-Backfit-ES	2805	1400	11.0	1.018	449.87		
Hyd-Backfit-5 Hyd-NewCore-5	750	N.A.	24.5 36.0	1.015	243.07		
Hyd-NewCore-ES	750	N.A.	11.0	1.018	449.87		

N.A. ≡ Not Applied

* Case 0 is used to obtain the minimum allowed CPRs as well as the core pressure drop limits. Core power and coolant flow rate are entered as input data.

The Hench-Gillis correlation has the general form:

$$x_C = \frac{AZ}{B+Z}(2-J)+F_P$$

Where:

$A = 0.5G^{-0.43}$

$B = 165 + 115G^{2.3}$

$Z = \frac{boiling\_heat\_transfer\_area}{bundle\_flow\_area}$

$F_P = f(pressure)$

$J = f(G, J_1)$

→ $J_1 = f(\text{bundle geometry, rod peaking factors})$

Pin-by-Pin Power-to-Average Power Ratio at BOL for a BWR GE 9×9 Single Bundle – No PLFRs, with Gd

1.15	1.26	1.25	1.22	1.21	1.22	1.25	1.26	1.16
1.26	1.12	1.01	0.44	0.87	0.44	1.01	1.14	1.26
1.26	1.01	0.42	0.87	1.00	0.92	0.43	1.02	1.26
1.22	0.44	0.87	1.14			0.93	0.45	1.22
1.21	0.87	1.00				0.99	0.87	1.20
1.23	0.45	0.94			1.11	0.85	0.44	1.21
1.27	1.01	0.43	0.93	1.00	0.87	0.43	1.00	1.24
1.25	1.14	1.01	0.44	0.89	0.44	1.00	1.12	1.26
1.14	1.25	1.25	1.23	1.21	1.22	1.25	1.24	1.15

J_1 Factors

J1 factors. BOL for a BWR GE9x9, no PLFRs, with Gd								
1.115	1.196	1.167	1.119	1.106	1.119	1.167	1.197	1.123
1.197	1.114	0.971	0.647	0.871	0.650	0.974	1.123	1.198
1.174	0.971	0.597	0.815	0.855	0.779	0.577	0.982	1.175
1.120	0.647	0.815	0.893			0.786	0.658	1.120
1.107	0.873	0.857				0.847	0.870	1.098
1.128	0.659	0.793			0.879	0.801	0.643	1.110
1.181	0.976	0.578	0.786	0.856	0.814	0.601	0.963	1.158
1.190	1.120	0.974	0.652	0.879	0.647	0.964	1.111	1.194
1.106	1.188	1.167	1.126	1.107	1.119	1.164	1.181	1.113

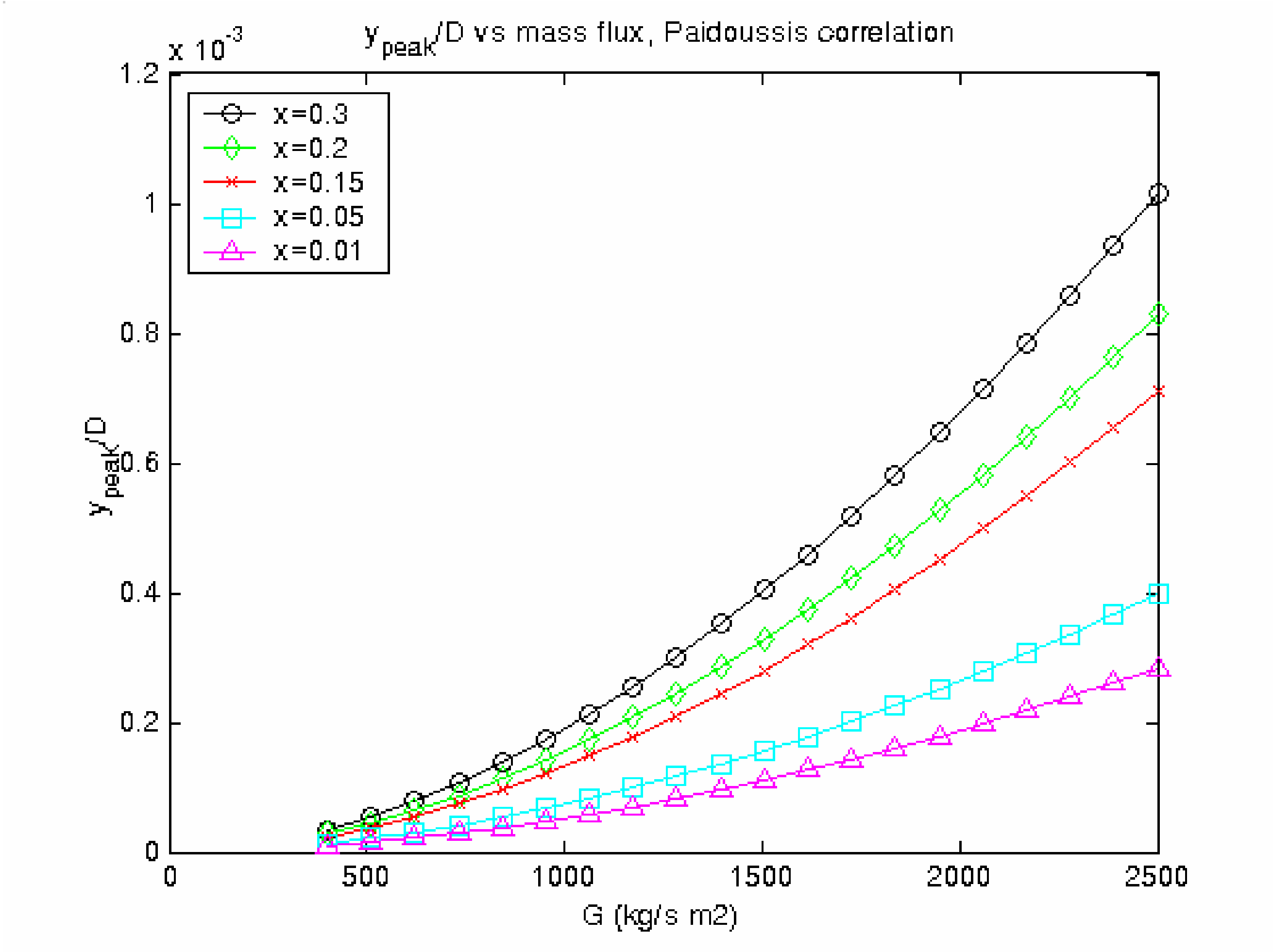
Bundle Loss Coefficients

Table E.1: Bundle Loss Coefficients			
Type of form loss	*Normalized Value*	*Axial Location (in)*	
		BWR/5	ESBWR
Central region orificing	$C_{central}^{10in^2} = 10.12$	0	0
Peripheral region orificing	$C_{peripheral}^{10in^2} = 87.36$	0	0
Lower tie plate	$C_{ltp}^{10in^2} = 4.54$	7.3[70]	7.3[70]
Grid spacers[71]	Absolute value directly computed using In's correlation (see Appendix H)	19.5; 39.0; 58.5; 78.0; 97.5; 117.0; 136.5. (From [24])	17.7; 33.7; 49.7; 65.7; 81.7; 97.7; 106.1; 113.7
Upper tie plate form	$C_{utp}^{10in^2} = 0.18$	145.3[72]	118[72]

Coefficients for Frictional Pressure Drop Correlations

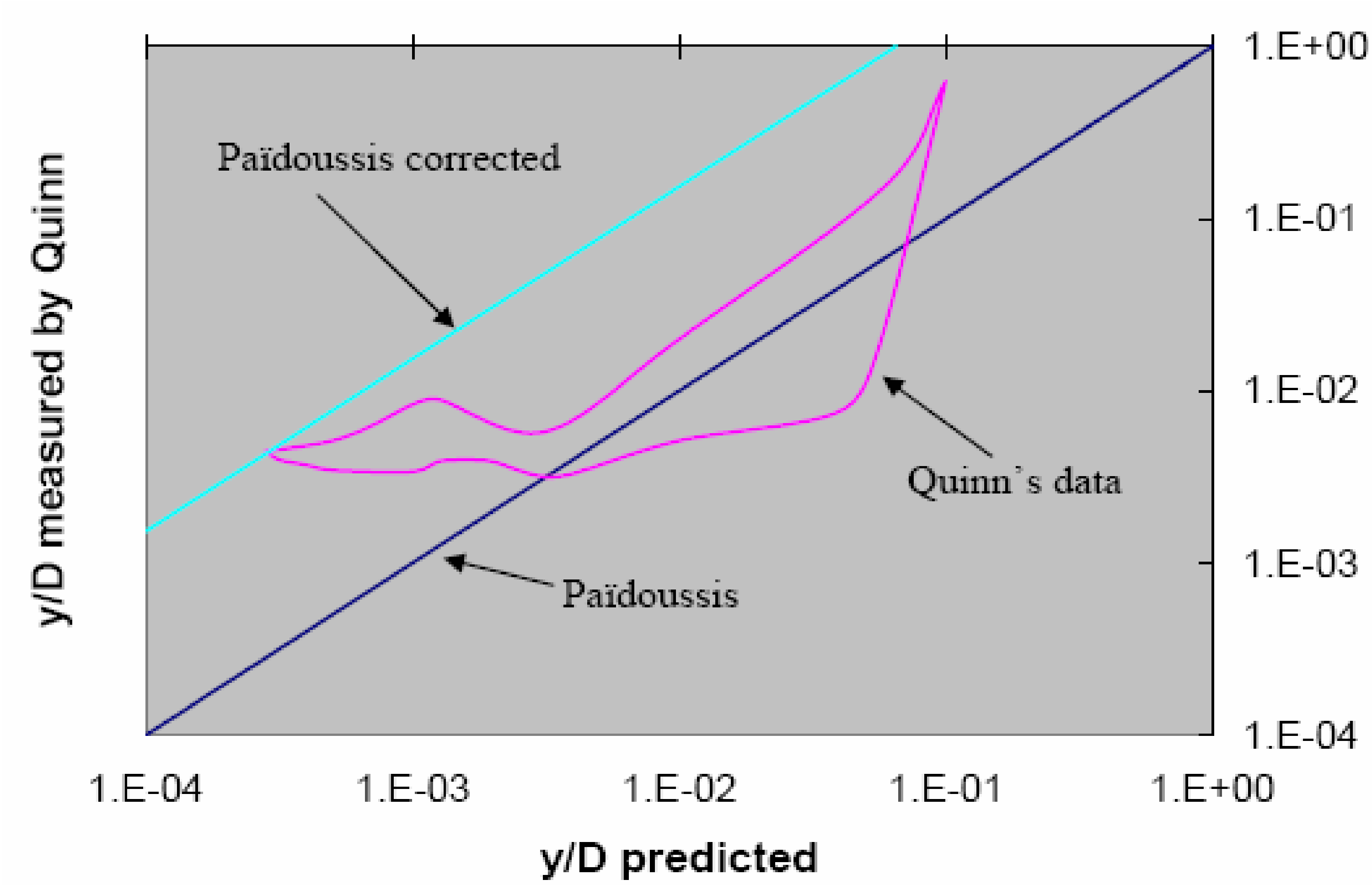
Channel type	a_L	b_L	a_T	b_T
Bundles (Cheng&Todreas)	$35.55+263.7\cdot\left(\frac{P}{d}-1\right)-190.2\cdot\left(\frac{P}{d}-1\right)^2$	-1	$0.1339+0.09059\cdot\left(\frac{P}{d}-1\right)-0.09926\cdot\left(\frac{P}{d}-1\right)^2$	-0.18
Bypass channels	64	-1	0.184	-0.2

Peak Vibration Ratio Dependence on Quality and Mass Flux, Païdoussis Correlation

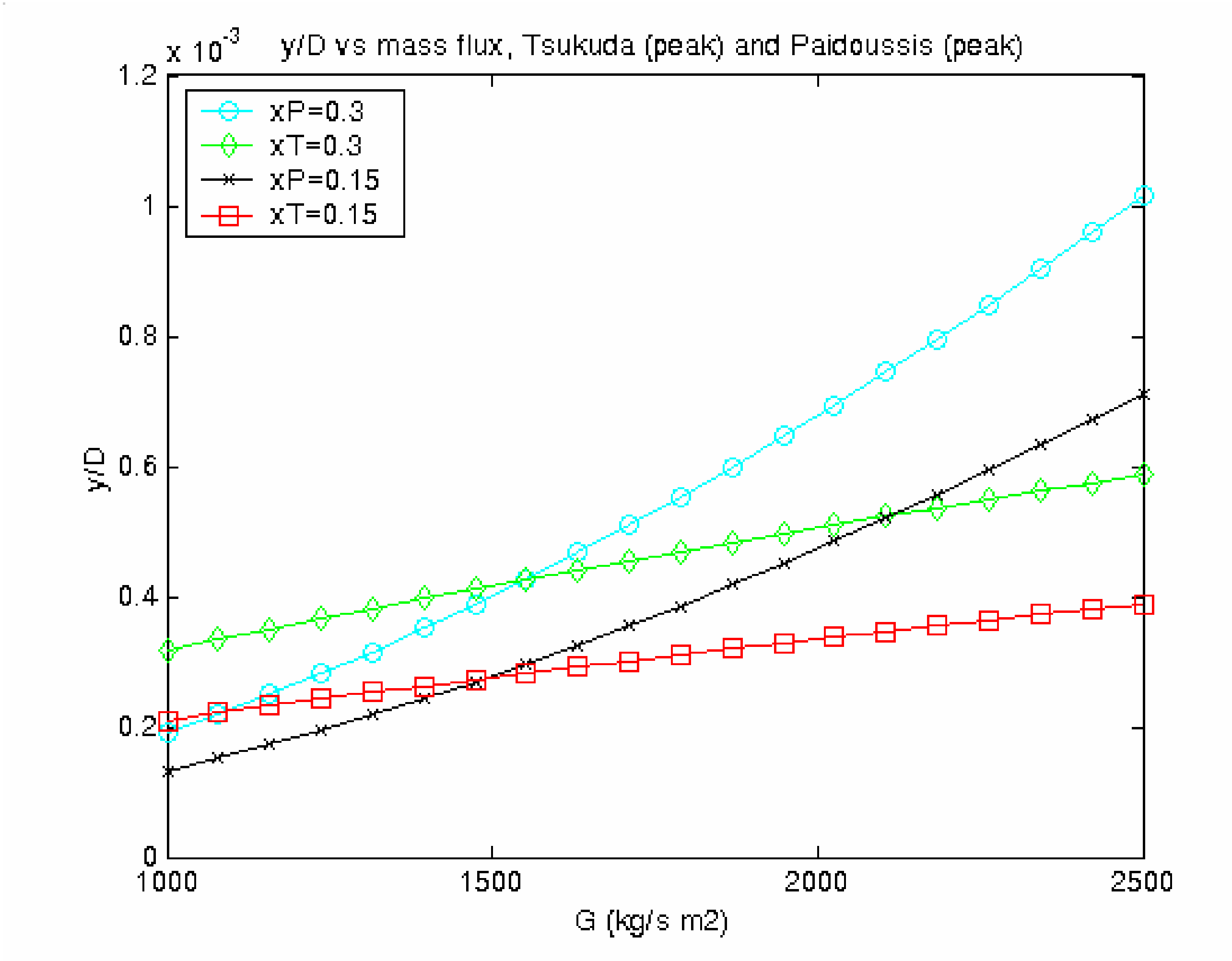


Source: Ferroni, P., and N. E. Todreas.
"Thermal Hydraulic Analysis of Hydride Fueled BWRs" *MIT-NFC-TR-079.*
Cambridge, MA: MIT CANES, February 2006. Courtesy of MIT CANES.
Used with permission.

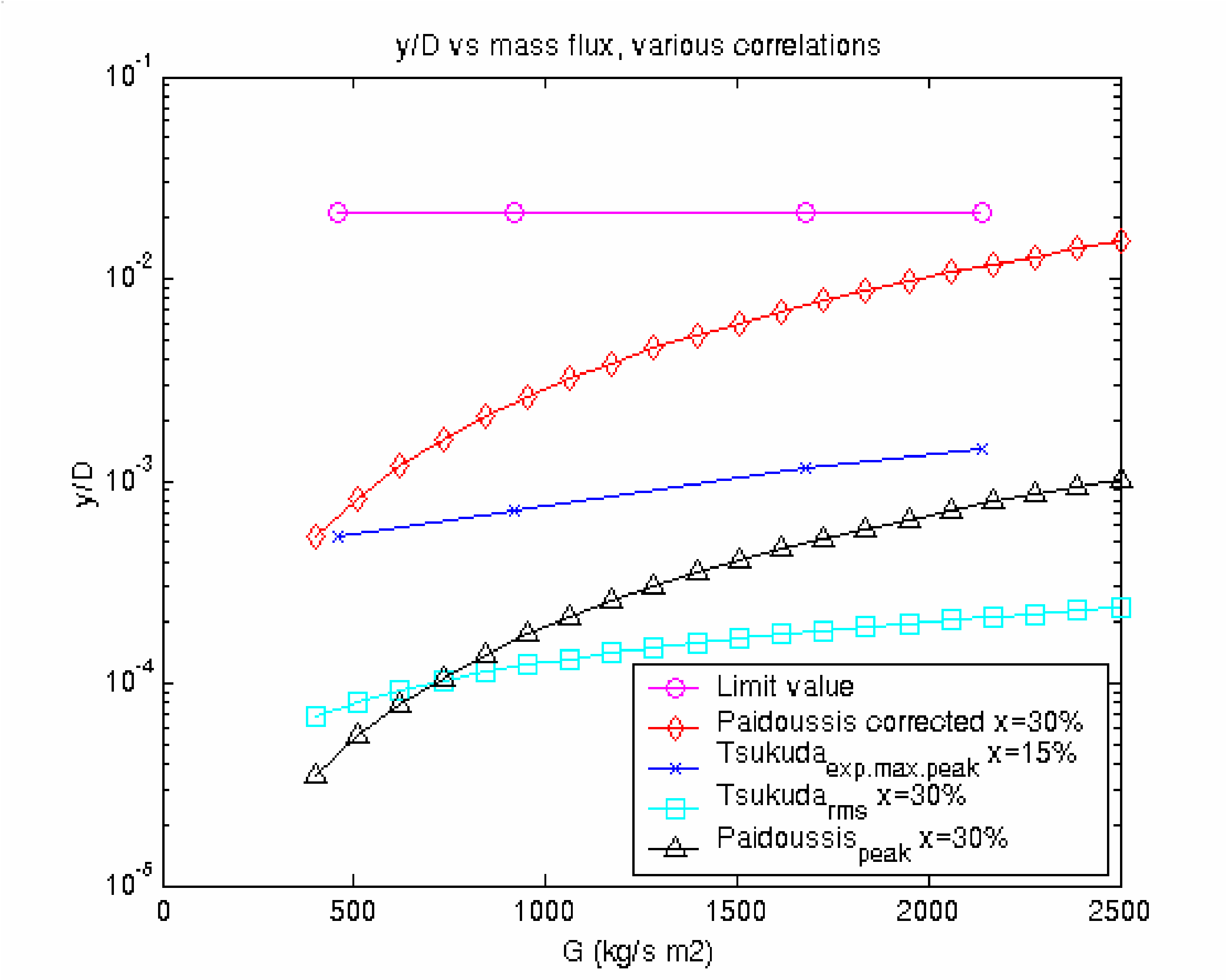
Païdoussis Correlation – Quinn's Data Comparison



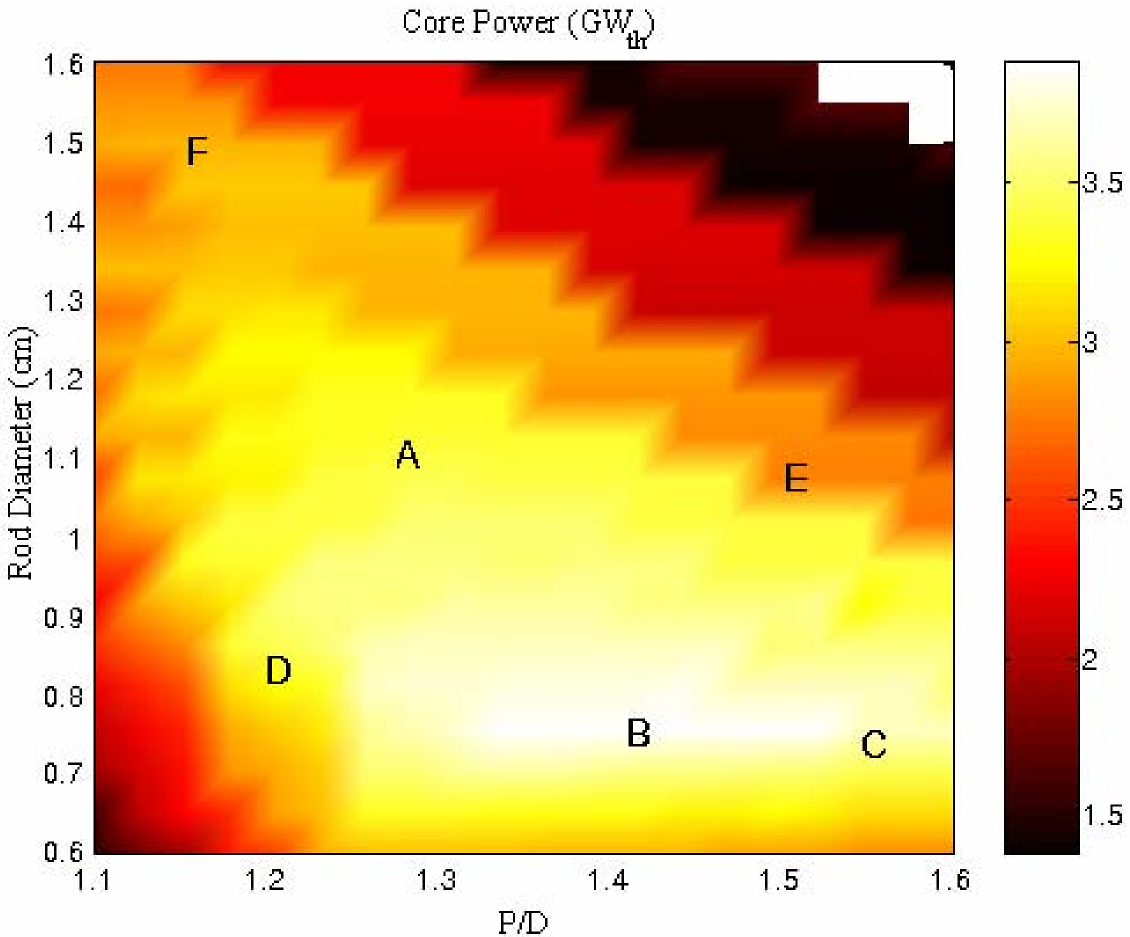
Païdoussis - Tsukuda Peak Vibration Ratio Comparison (Restricted G Range)



Final Vibration Ratio Comparison



Locations of the Assembly Configurations Examined for Power/Flow Ratio Investigation



Comparison between "Relative" Maximum Power and "Overall" Maximum Power

Table C.2 : Comparison between "Relative" Maximum Power and "Overall" Maximum Power

Assembly configuration	$\dot{Q}_{max}^{rel}$ ($\dot{Q}/\dot{m}$ =243.07 kW/(kg/s)) (MW_t)	$\dot{Q}_{max}$ (MW_t)	n_{i_max} (kW/(kg/s))	$\Delta Q\%$ (%)	$\Delta p\%$ (%)
A	3324	3482	200	+4.7	+42.6
B	3875	3898	240	+0.6	+3.2
C	3777	3834	250	+1.5	-1.6
D	3459	3500	250	+1.2	-1.7
E	3377	3482	200	+3.1	+41.6
F	2938	3084	200	+5.0	+41.5

Core Radial Power Distribution

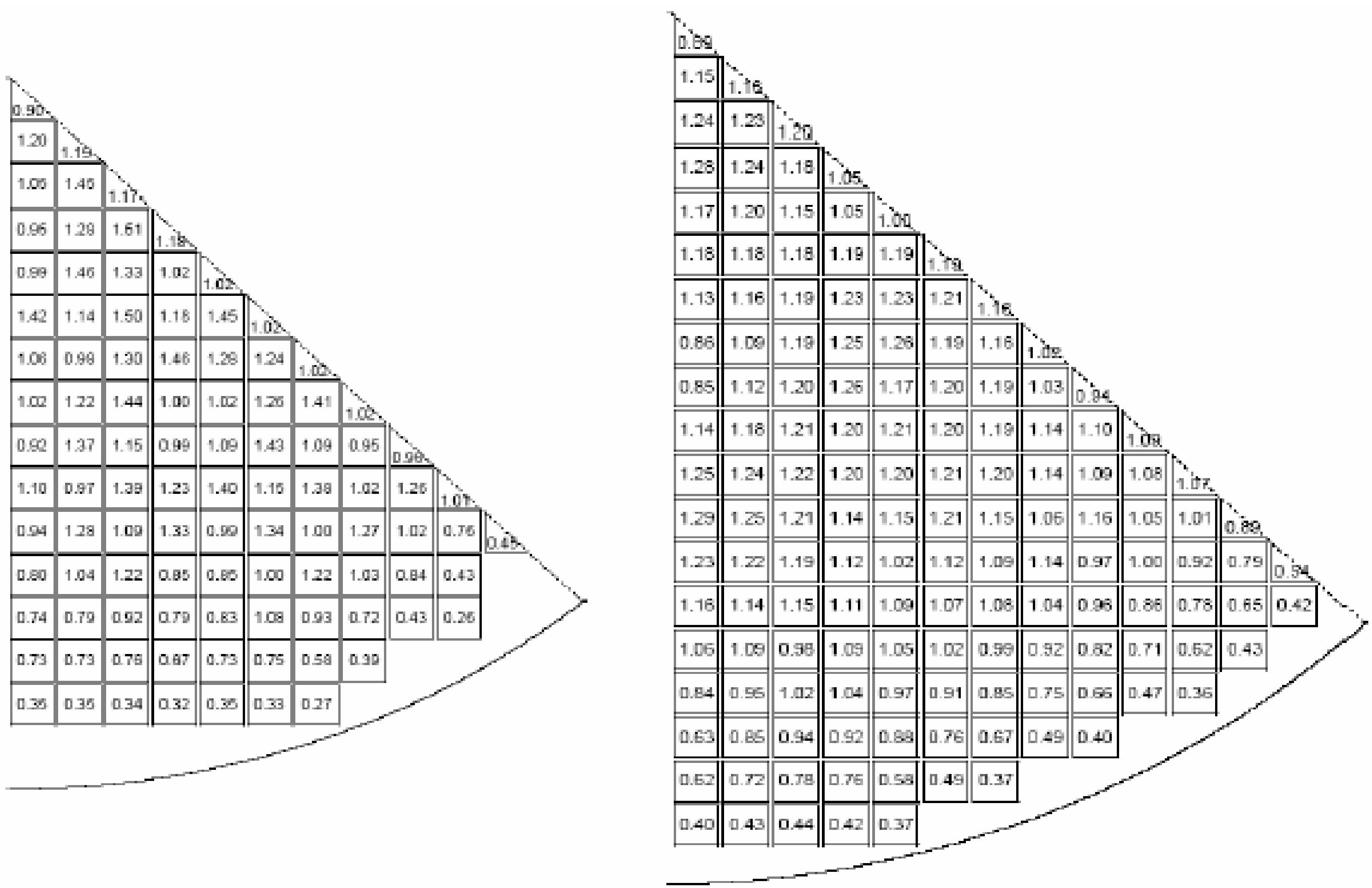


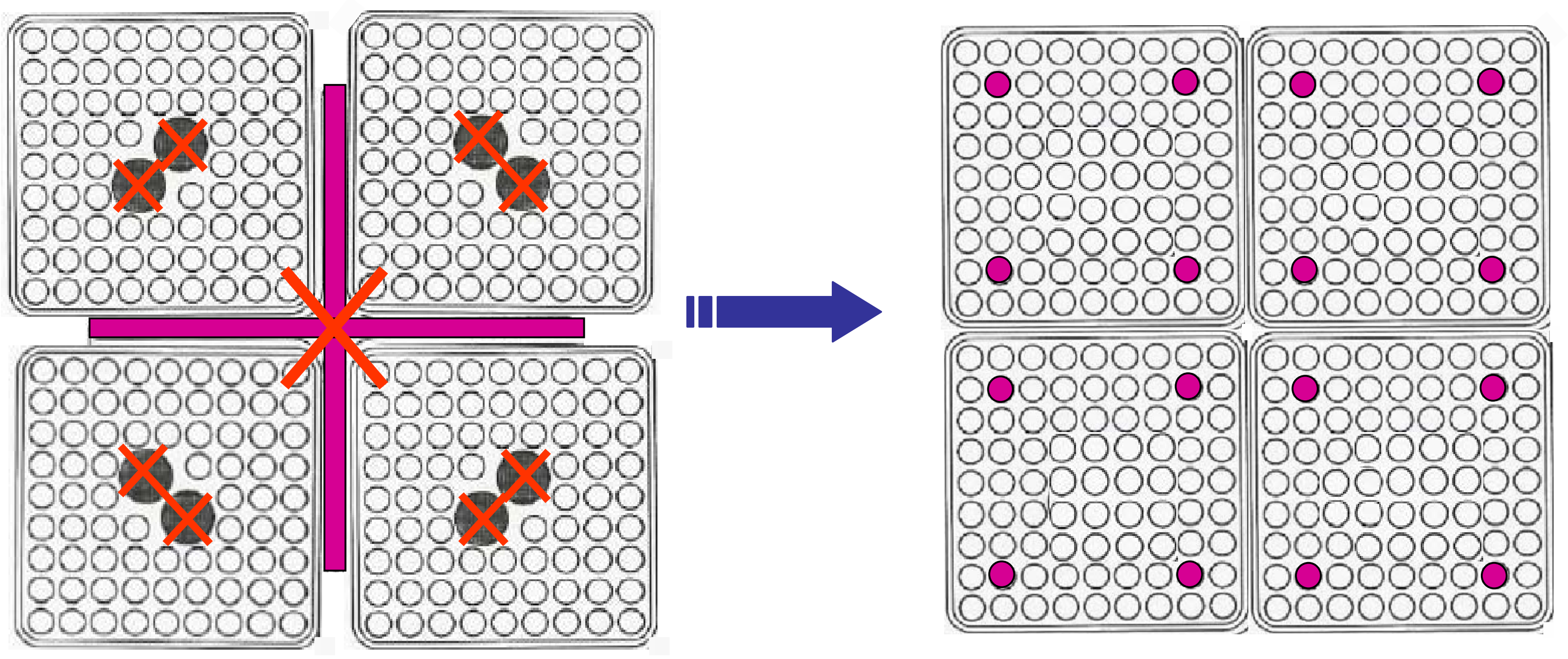
Figure 3.4: Core Radial Peaking Factors for Ref. BWR/5 and Ref. ESBWR

5 core types are considered*:

1) Ox-Backfit-5: existing BWR/5 vessel (D_{core}= 5.2 m), UO_2 fueled, crucif.CRs, WRs, fixed fuel channel size.
2) Hyd-Backfit-5: existing BWR/5 vessel (D_{core}= 5.2 m), U-$ZrH_{1.6}$ fueled, crucif.CRs, no WRs, fixed fuel chan. size.
3) Hyd-NewCore-5: existing BWR/5 vessel (D_{core}= 5.2 m), U-$ZrH_{1.6}$ fueled, control fingers, no WRs, variable fuel chan. size.
4) Ox-Backfit-ES: ESBWR vessel (D_{core}=6.1 m), UO_2 fueled, crucif. CRs, WRs, fixed fuel channel size.
5) Hyd-NewCore-ES: ESBWR vessel (D_{core}=6.1 m), U-$ZrH_{1.6}$ fueled, control fingers, variable fuel channel size.

*Each core type has been modeled 400 times, i.e. each time with a different assembly configuration.

Core structural changes resulting from the implementation of U-$ZrH_{1.6}$…



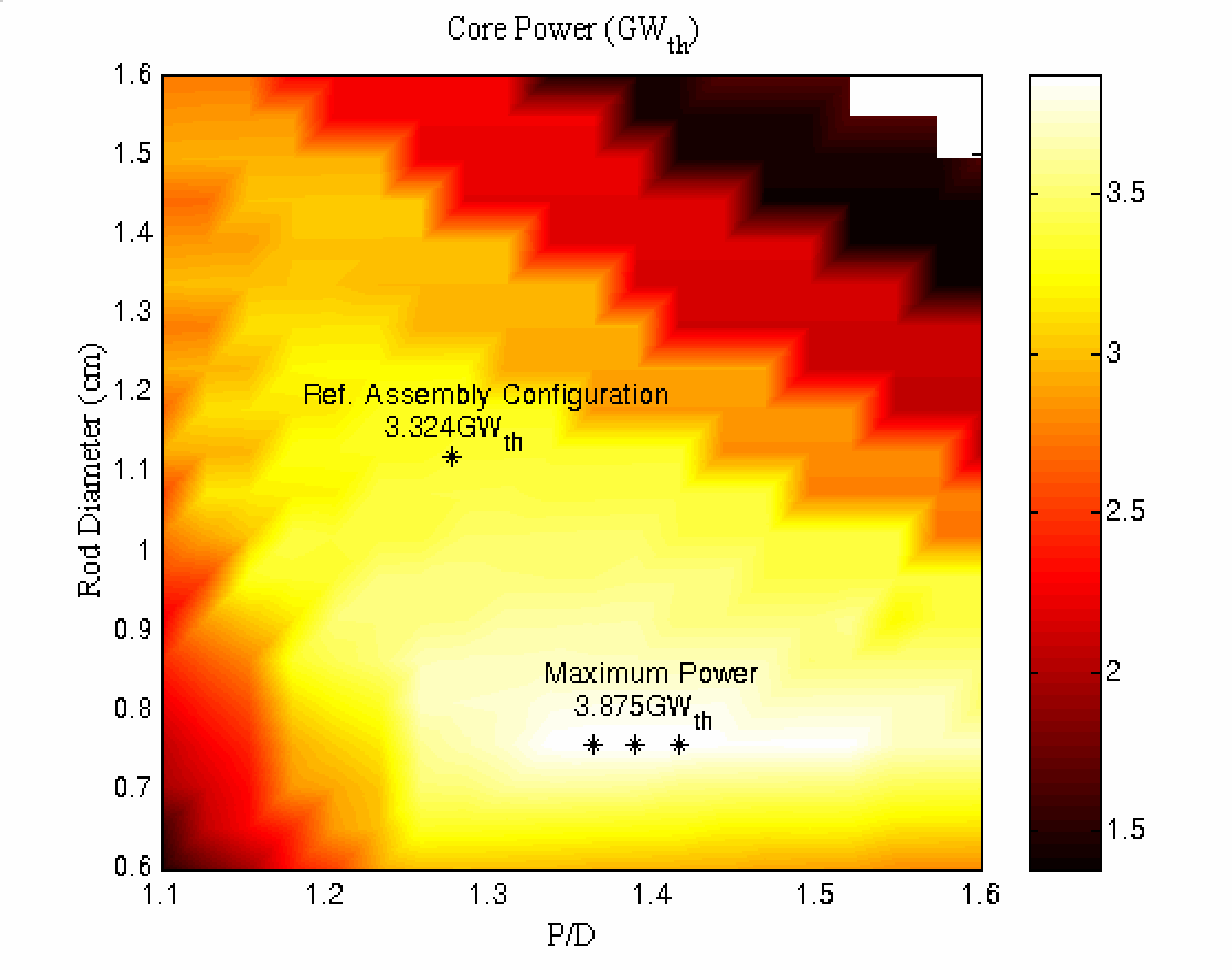
The greater design freedom for the hydride cores is limited by the application of 2 Structural Constraints:

	Structural Constraints	
	Maximum Number of Assemblies*	Maximum Assembly Weight**
Hydride Backfit Core	$1.6N_{ref}$ (1222)	$1.4M_{ref}$ (361kg)
Hydride NewCore	$1.6N_{ref}$ (1222)	Not Applied

* to limit the refueling time.

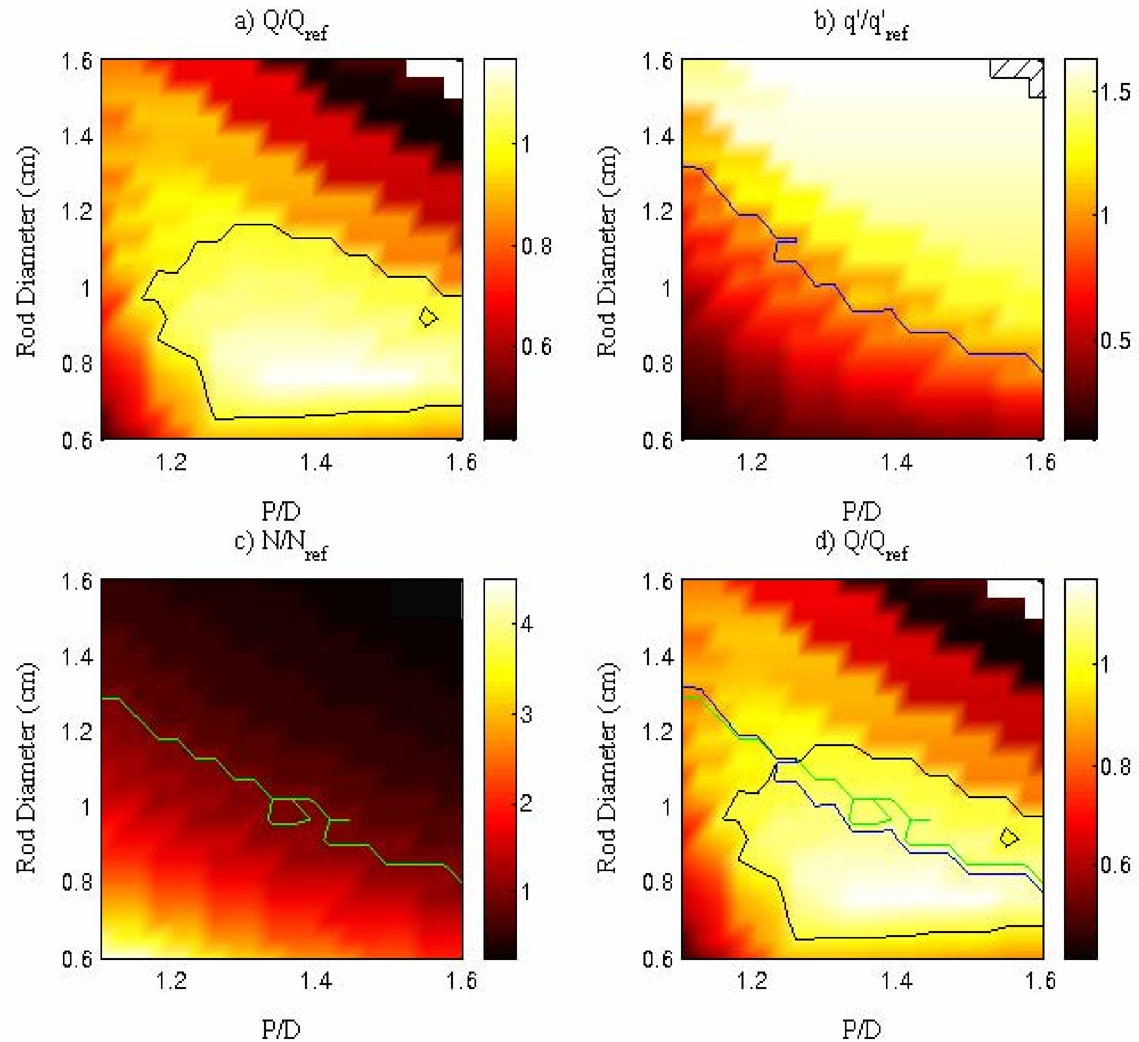
** due to the limited load capacity of the crane in an existing plant. Not applied to the Hydride New Core since a reactor designed specifically to utilize U-$ZrH_{1.6}$ is assumed to be provided with a crane of sufficient load capacity.

Ox-Backfit-5 Powermap (Δp_{lim}=36 psia)



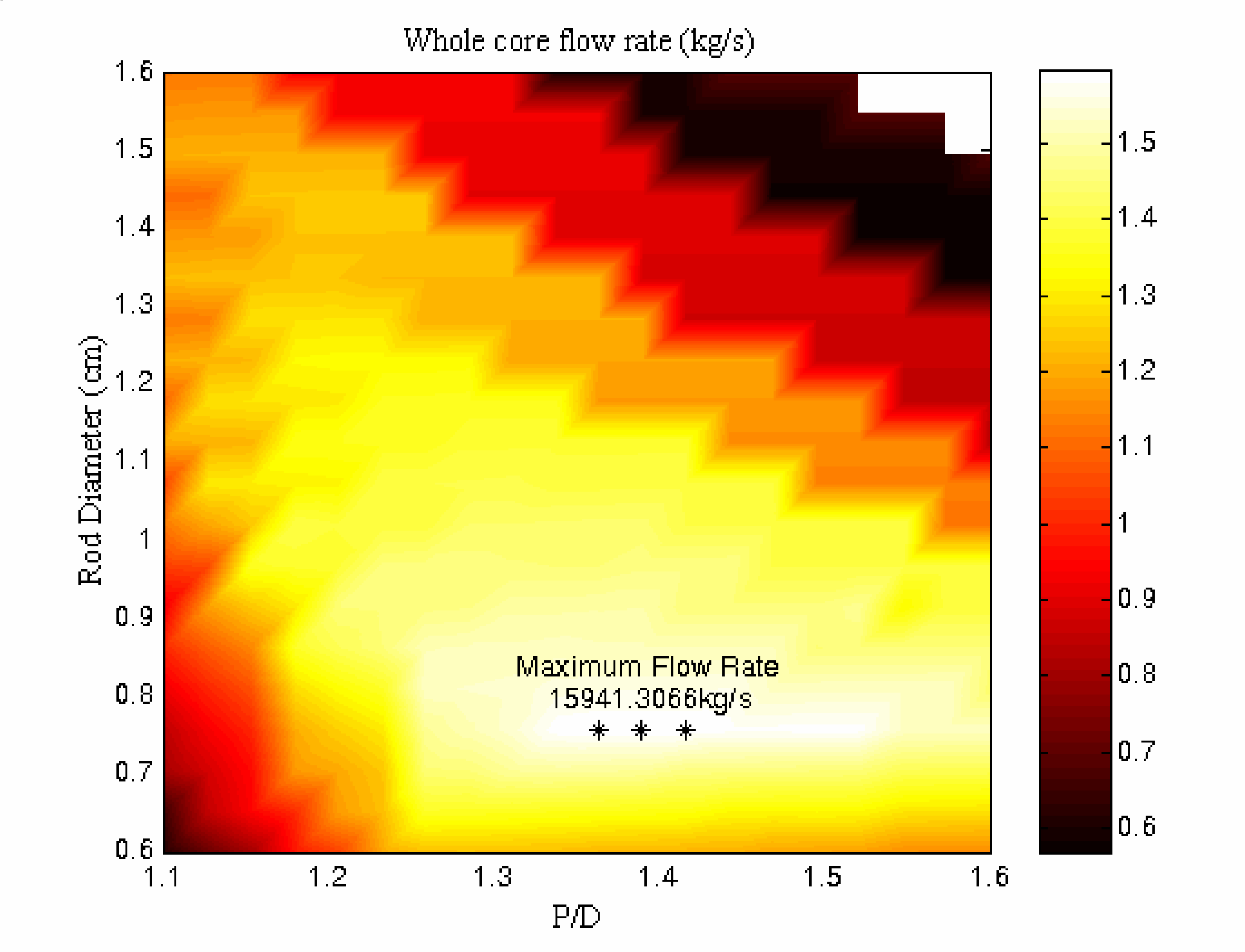
Power, LHGR and Number of Rod Ratios Between the Examined Ox-Backfit-5 Core Configuration and the Ref. Core, Δp_{lim}=36 psia

(the lines represent unity ratios)

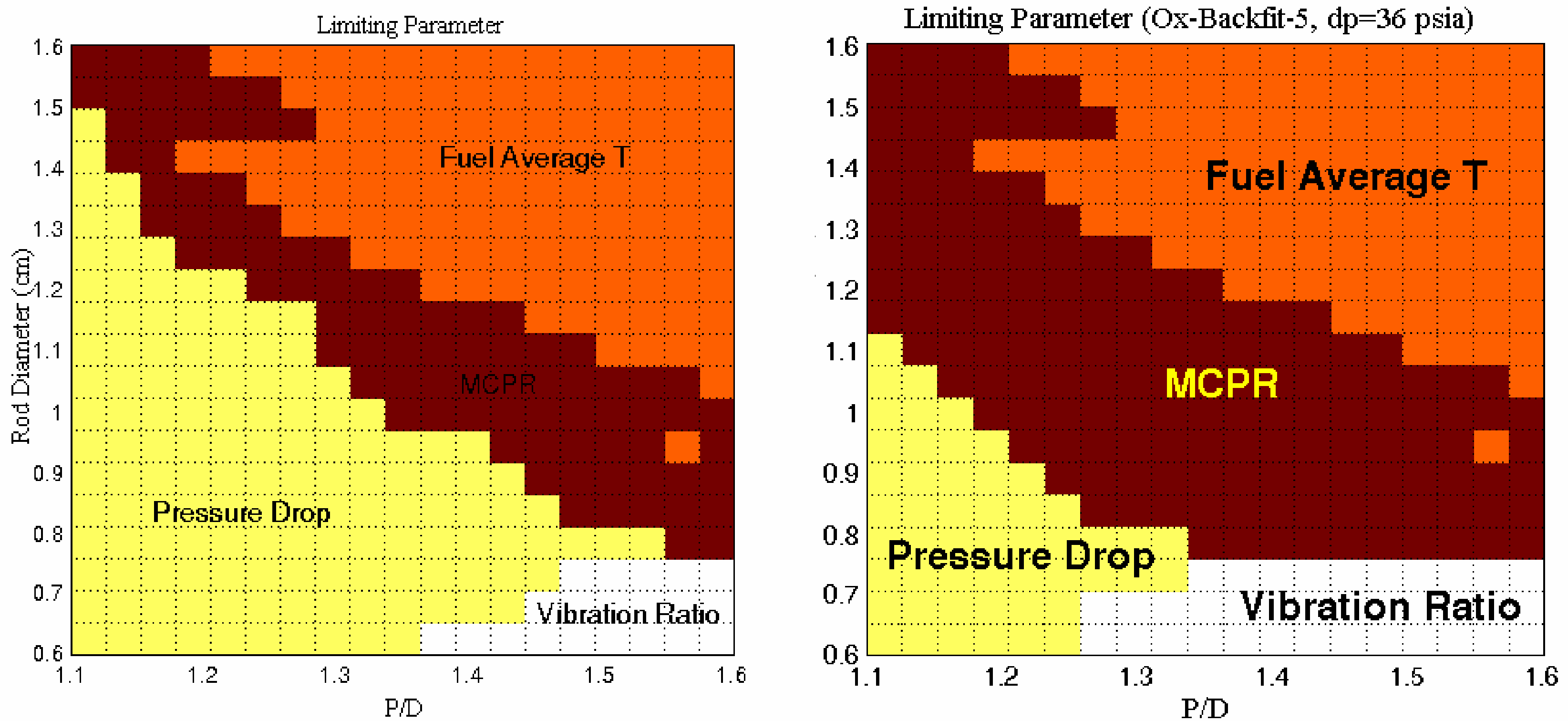


Professor Neil Todreas

Whole Core Flow Rate (Ox-Backfit-5, Δp_{lim}=36 psia)



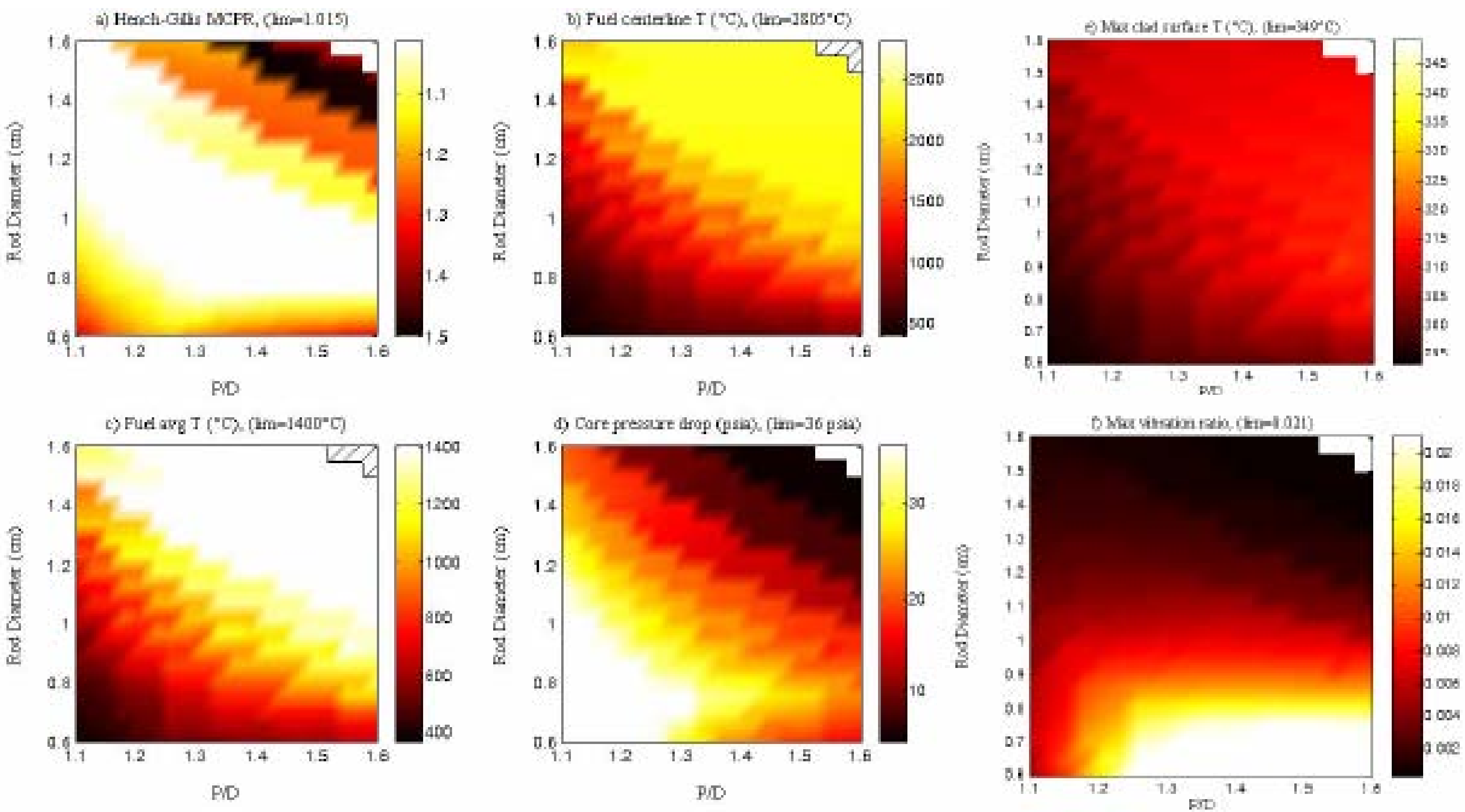
Case Ox-Backfit-5: What are the limiting parameters and where do they apply



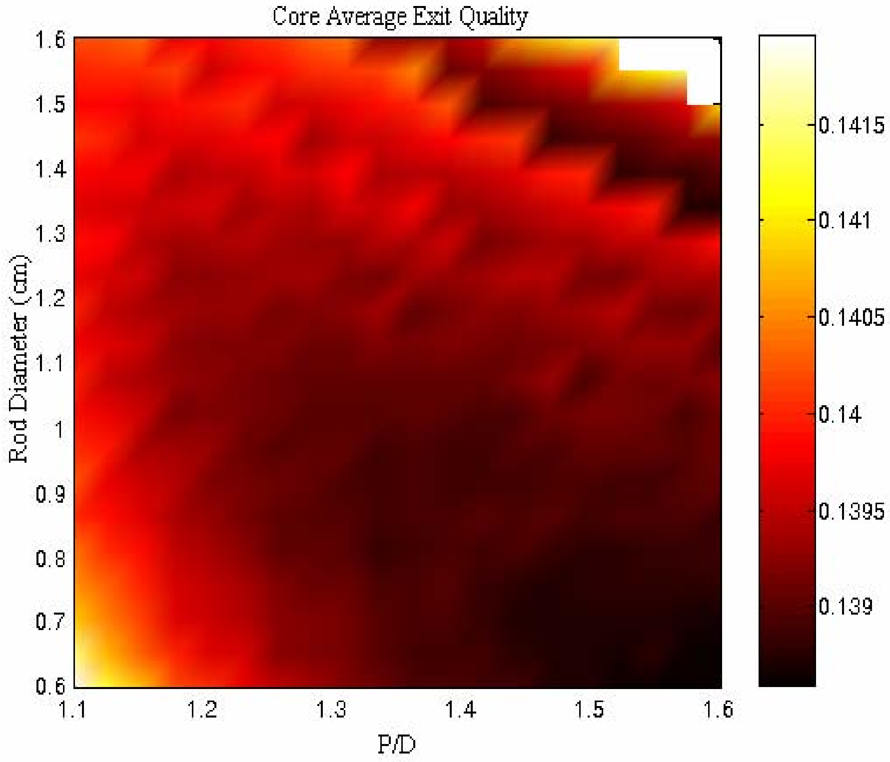
Ox-Backfit-5 (p_{lim}=24.5 psia) Ox-Backfit-5 (p_{lim}=36 psia)

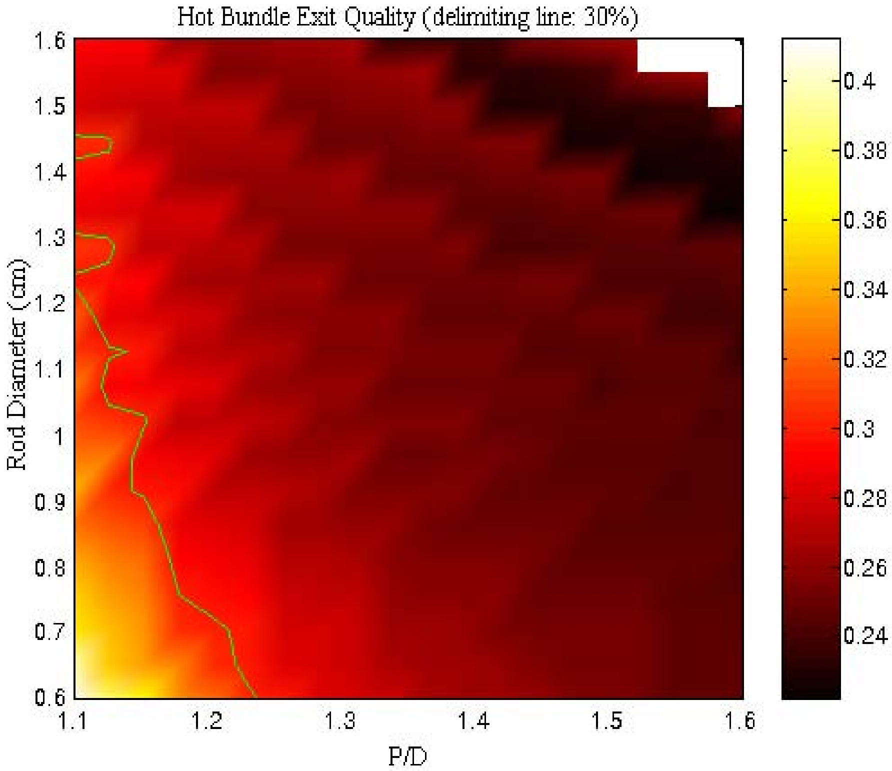
NOTE: Clad Surface T and fuel centerline T are never limiting.

Limiting Effect Exerted by Constraints (Ox-Backfit-5, Δp_{lim}=36 psia)

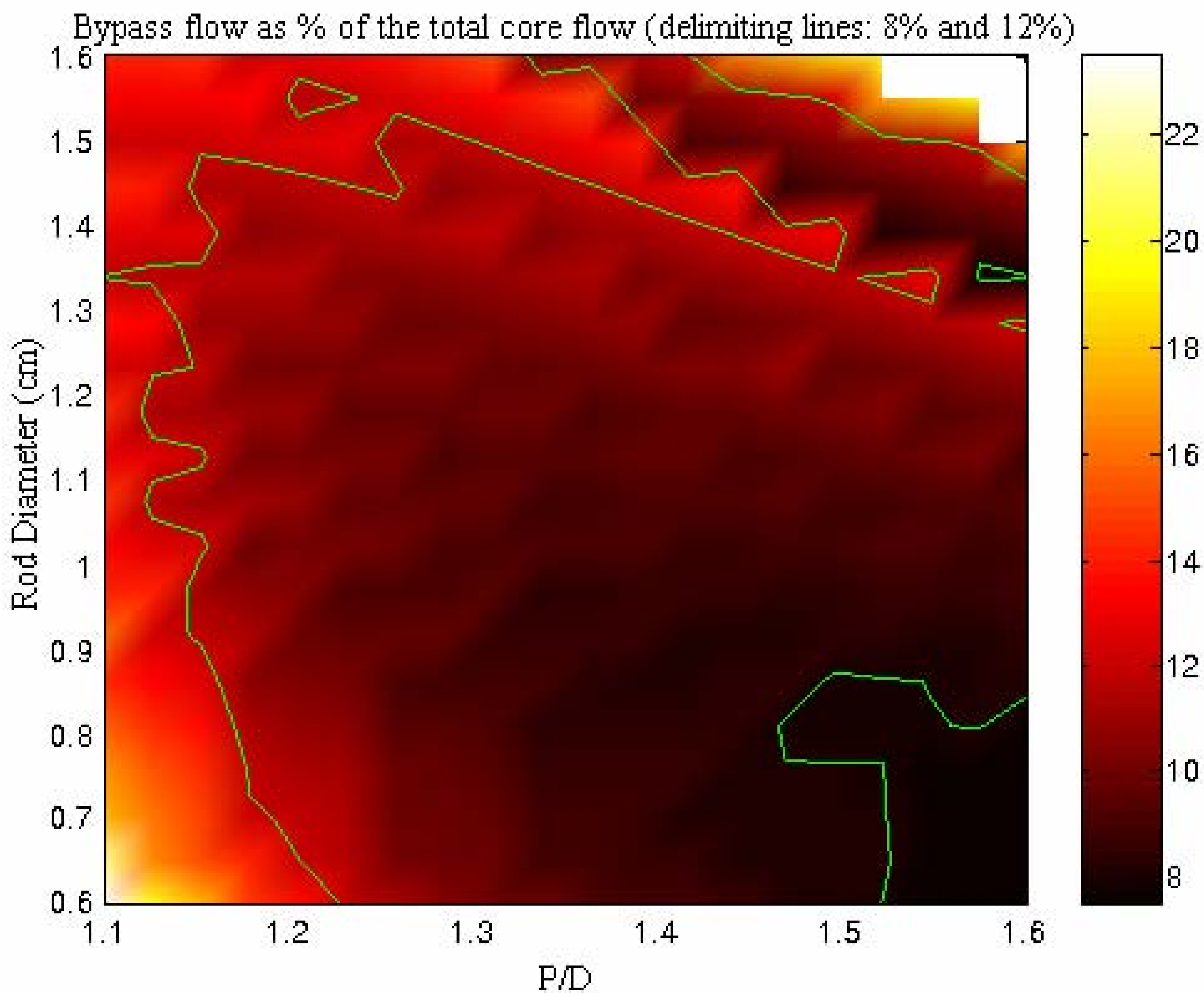


Core Average Exit Quality and Hot Bundle Exit Quality (Ox-Backfit-5, Δp_{lim}=36 psia)



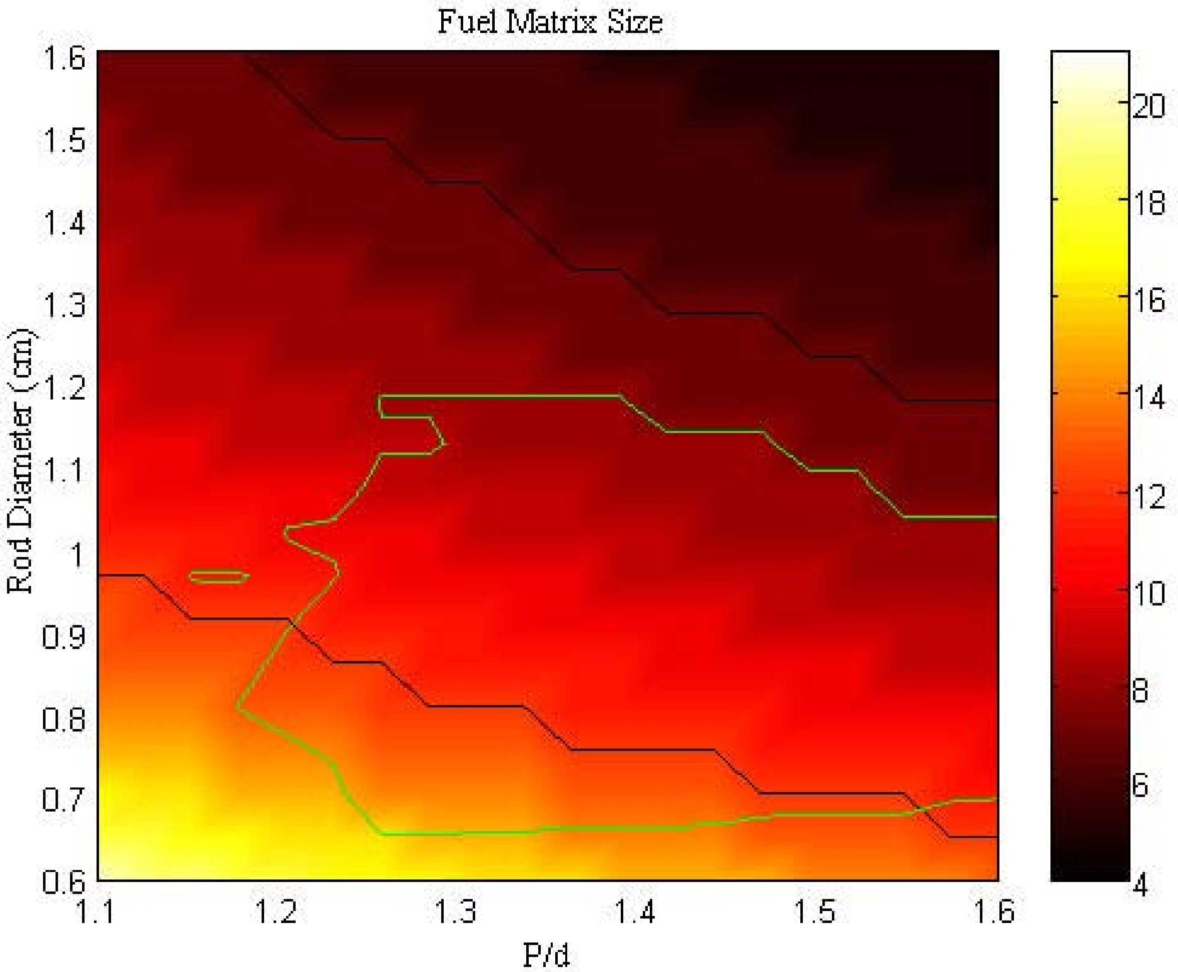


Bypass Flow Percentage (Ox-Backfit-5, Δp_{lim}=36 psia)

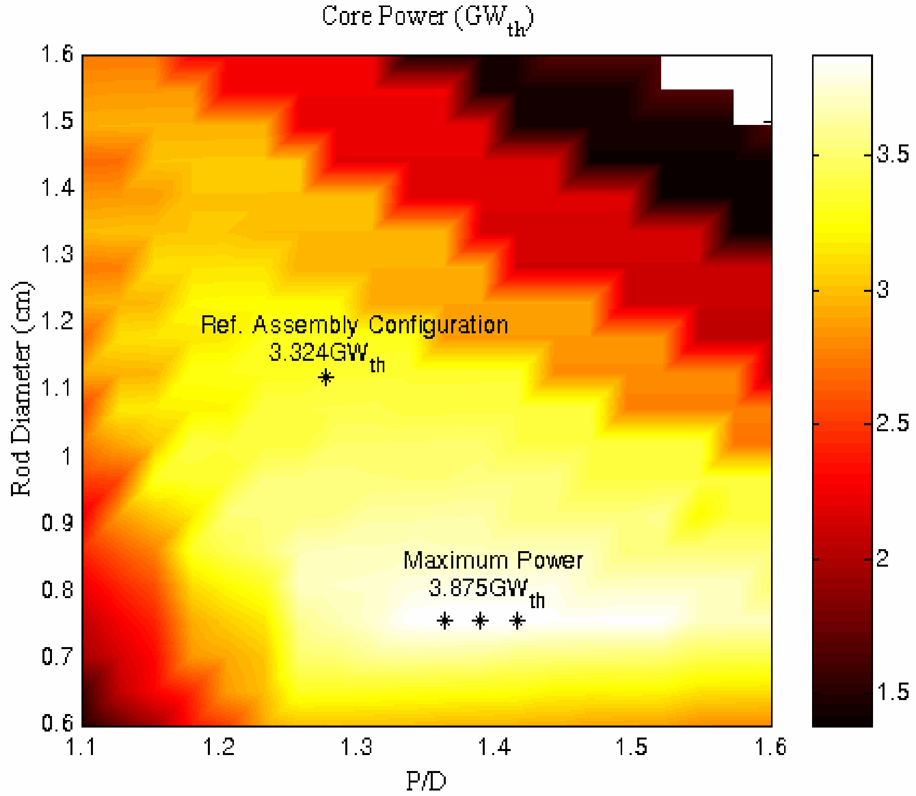


Oxide Core Fuel Matrix ($n \times n$) Size

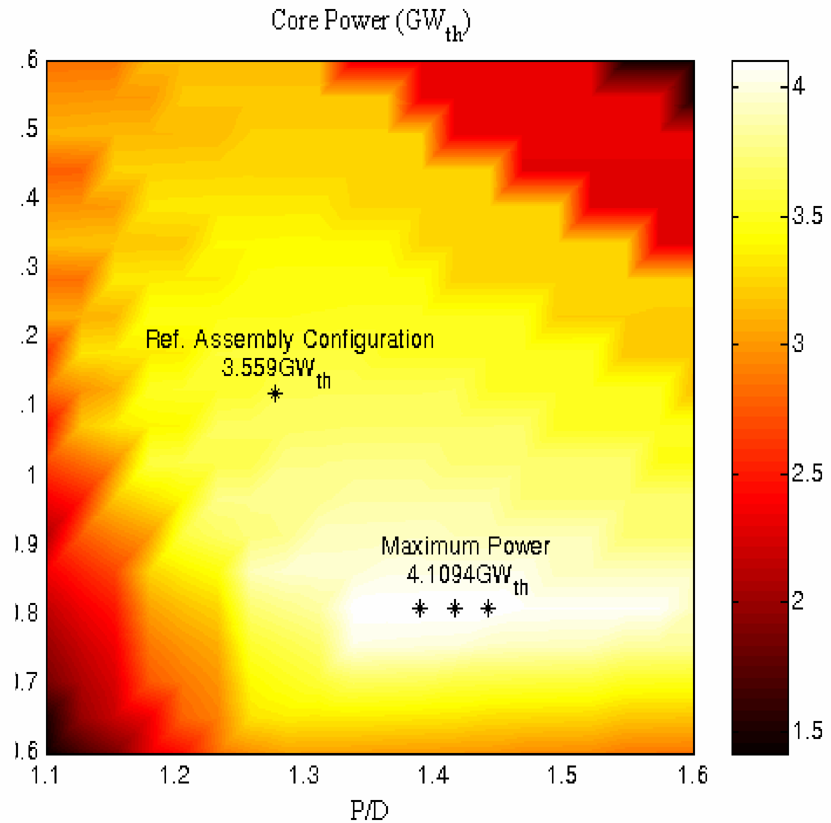
(the colored scale indicates the matrix index n; black upper line: n=7, black lower line: n=12; green line: high power region)



Power comparison: Ox-Backfit-5 vs Hyd-Backfit-5 (Δp_{limit} =36 psia)



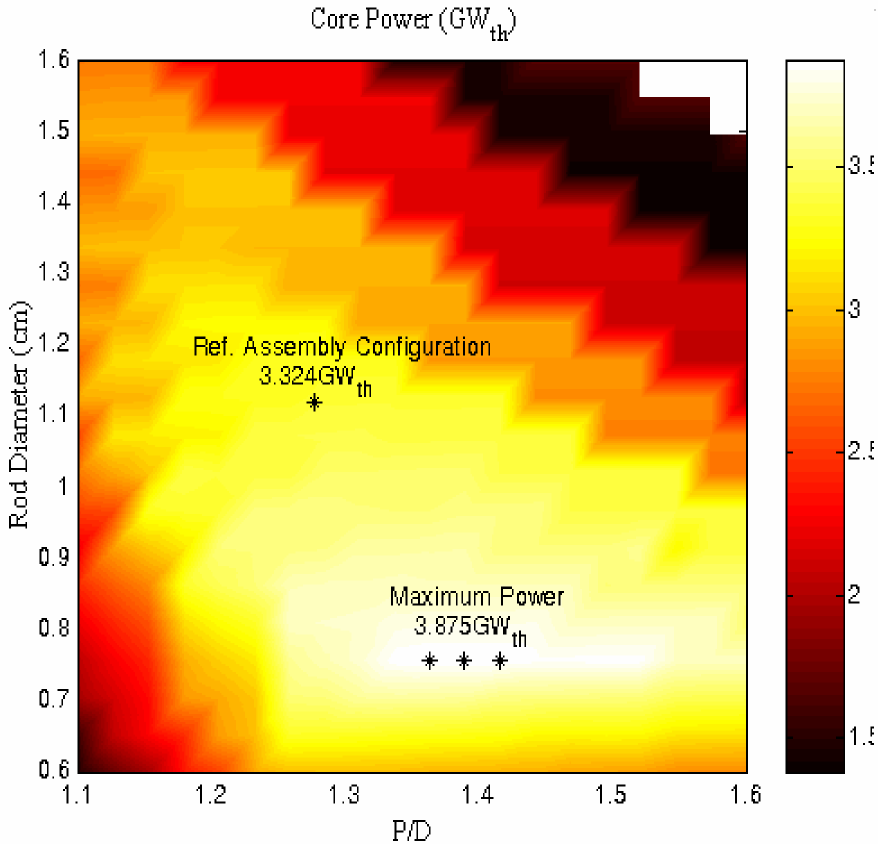
Ox-Backfit-5



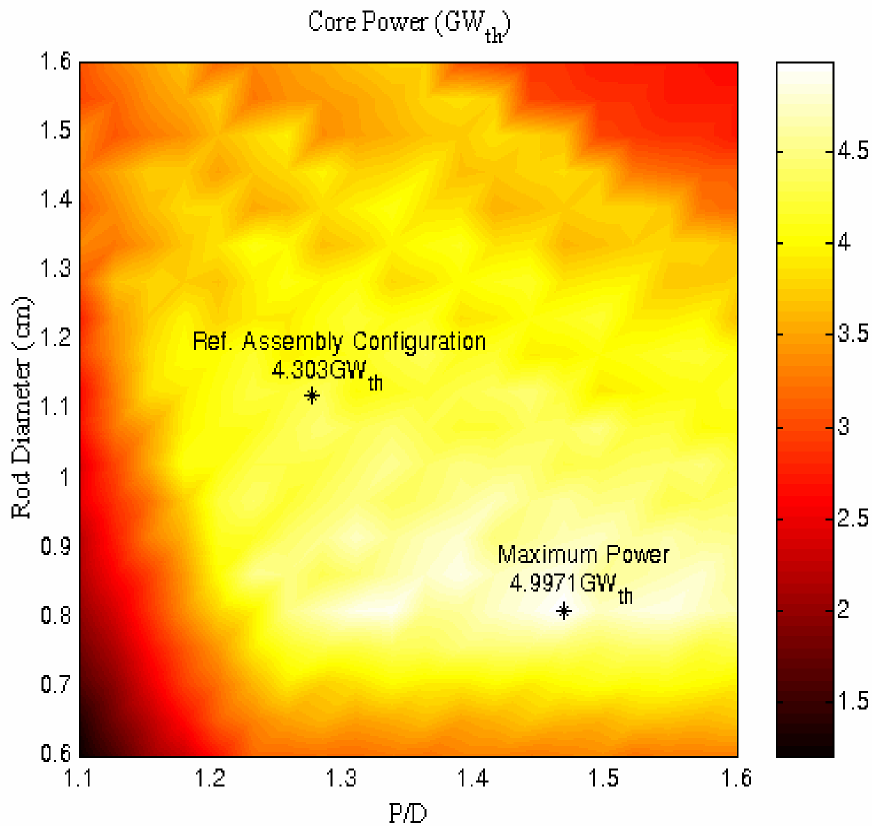
Hyd-Backfit-5

By comparing the two cores for the same D-P/D pair, the Hydride Backfit Core delivers around 6-9% more power.

Power comparison: Ox-Backfit-5 vs Hyd-NewCore-5 (Δp_{limit} =36 psia)



Ox-Backfit-5

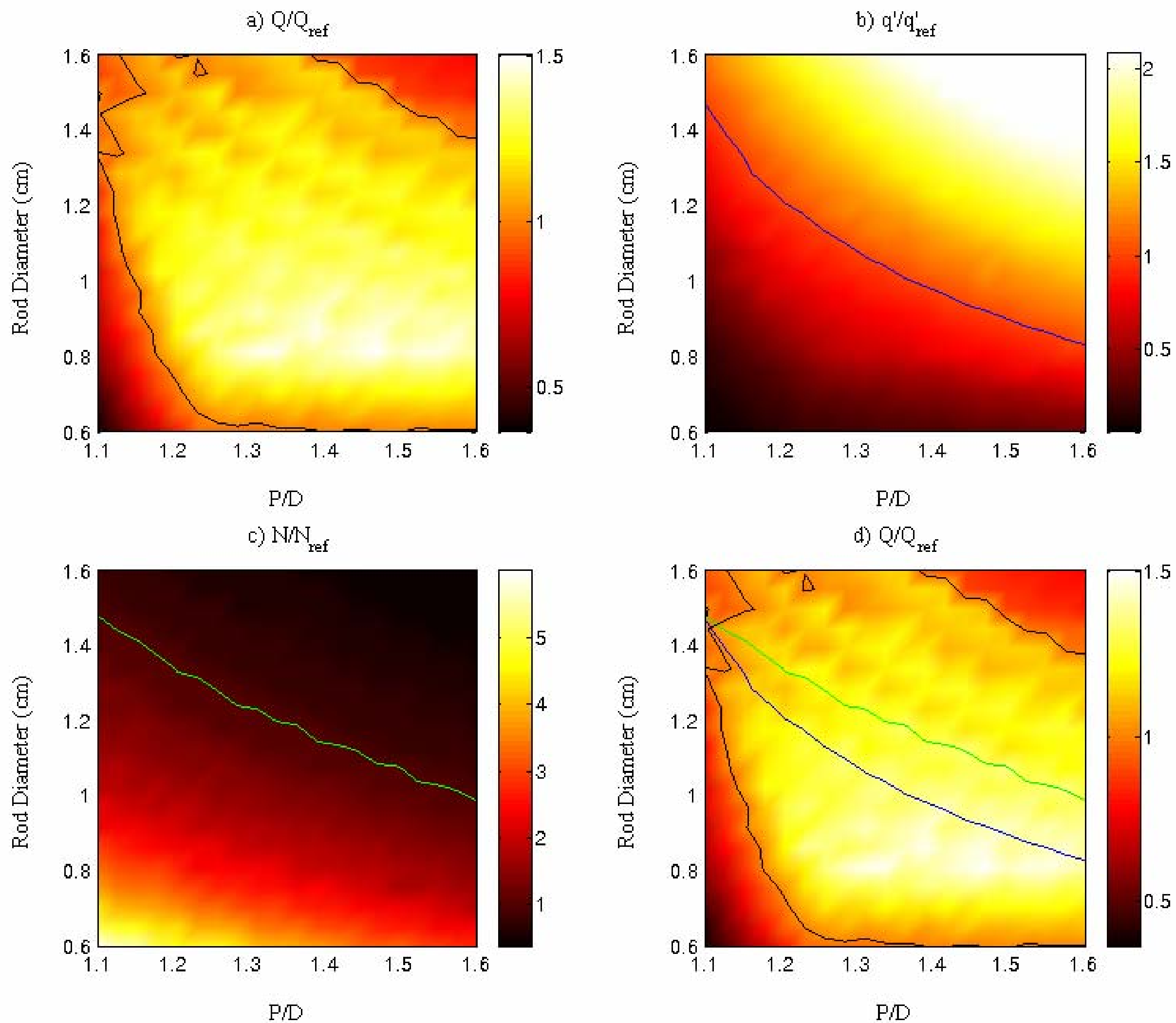


Hyd-NewCore-5

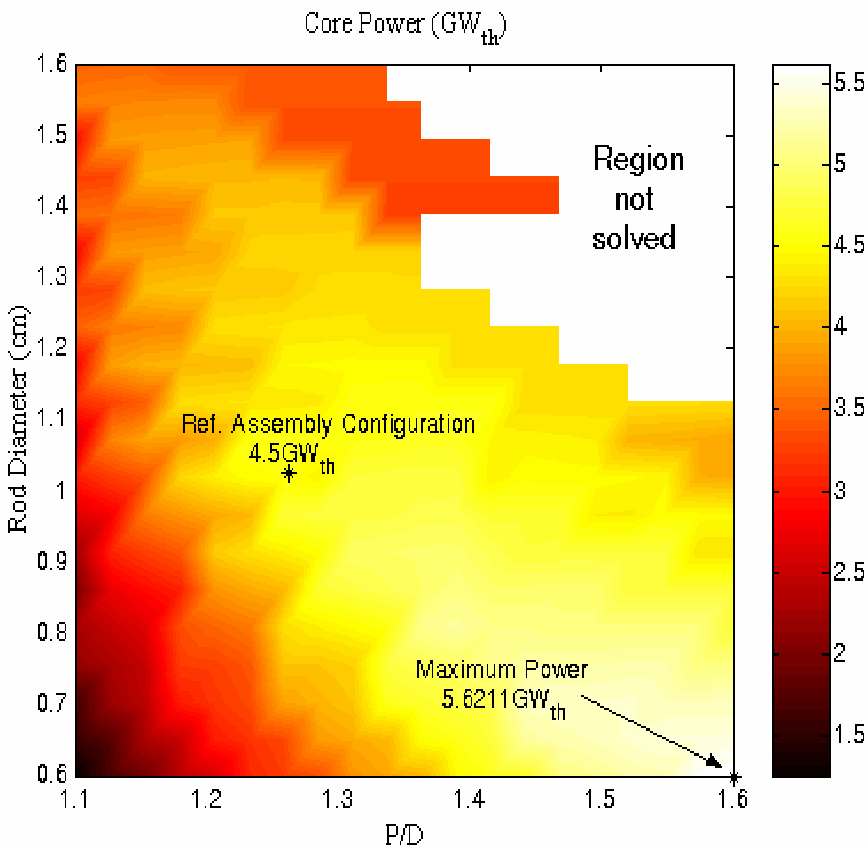
By comparing the two cores for the same D-P/D pair, the Hydride NewCore delivers around 25-30% more power

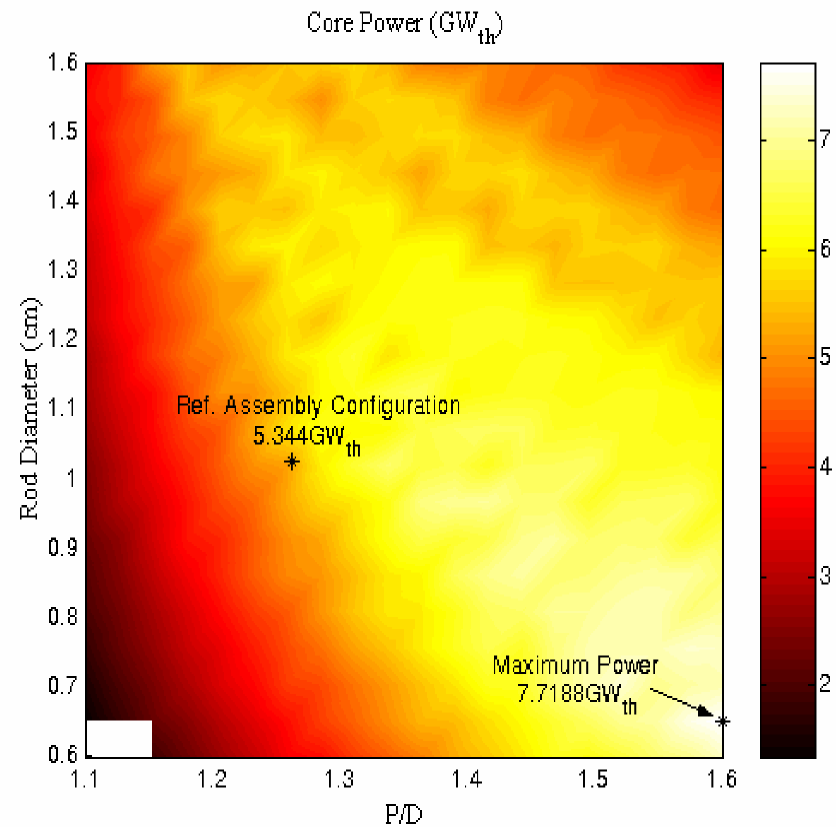
Power, LHGR and Rod Ratios Between Hyd-NewCore and Oxide

Ref. Core, Δp_{lim}=36 psia (continuous lines represent unity ratios)



Power comparison: Ox-Backfit-ES vs Hyd-NewCore-ES (Δp_{limit} =11 psia)

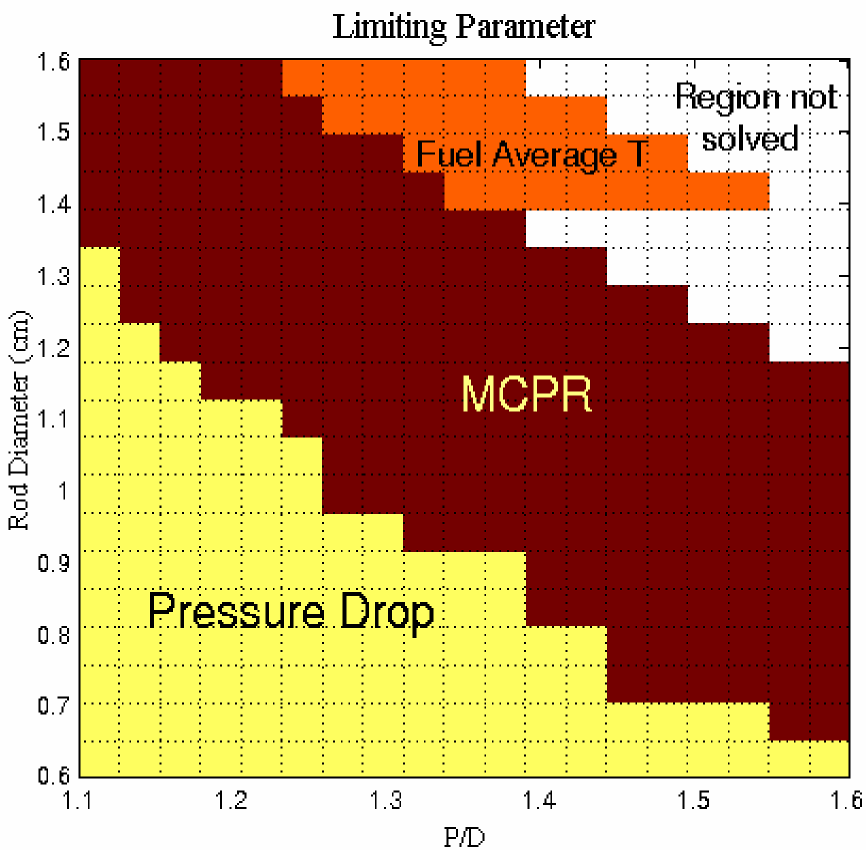


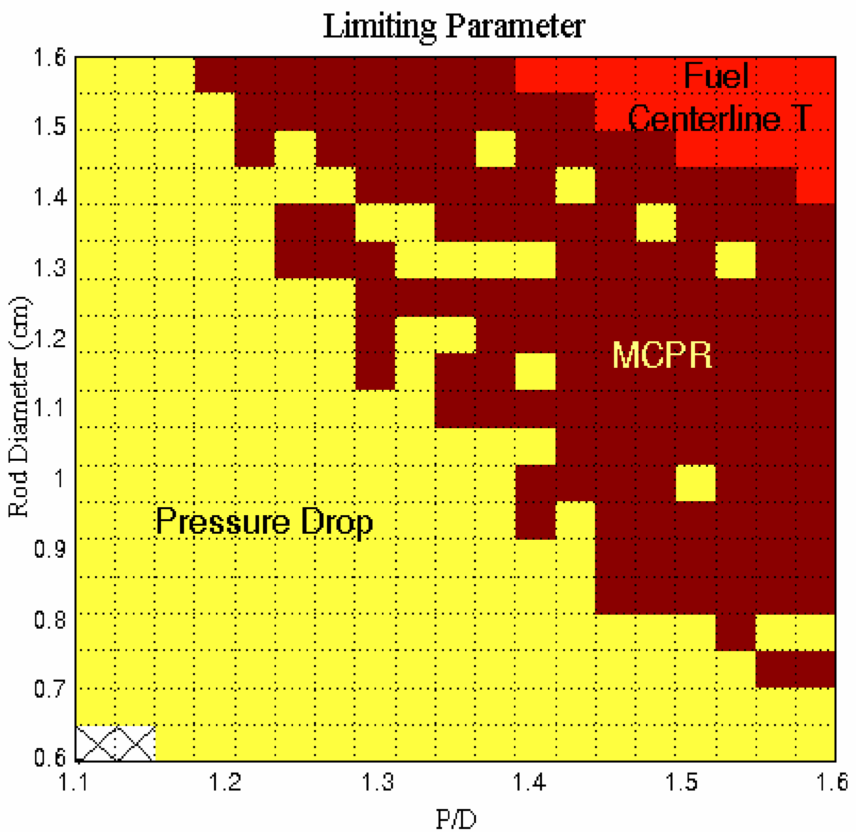


Power gain percentages: up to +37% for the same D-P/D pair, up to +70% with respect to the reference ESBWR (4500 MWt).

Reason for higher power gain % with respect to BWR/5 backfit-newcore comparison: smaller flow rate → vibrations are not limiting

Limiting Constraints for Ox-Backfit-ES and Hyd-NewCore-ES





NOTE: 1) vibrations are not limiting, 2) Δp more limiting for Hyd than Ox because of larger number of rods per bundle (Hyd does not contain WRs)

Overall Maximum Achievable Power Not Accounting for Neutronic Constraints									
Case	**Vessel Size**	**Core Structure**	**Fuel**	**Δp_{limit} (psia)**	***D* (mm)**	***P/D***	**n×n**	**Q_{core} (MW_t)**	**ΔQ_{core} %**
0 (Ref. BWR/5)	BWR/5	Backfit	Ox	NA	11.176	1.2773	9×9	3324	0
Ox-Backfit-5	BWR/5	Backfit	Ox	24.5	8.105	1.5737	10×10	3717	+11.8
				36	7.579	1.3632 1.3895 1.4158	12×12	3875	+16.6
Hyd-Backfit-5	BWR/5	Backfit	Hyd	24.5	8.105	1.6000	9×9	3910	+17.6
				36	8.105	1.3895 1.4158 1.4421	11×11	4109	+23.6
Hyd-NewCore-5	BWR/5	NewCore (2-mm gap between bundles)	Hyd	24.5 36	8.105	1.4684	11×11	4997	+50.3
0 (Ref. ESBWR)	ESBWR	Backfit	Ox	N.A.	10.260	1.2622	10×10	4500	0
Ox-Backfit-ES	ESBWR	Backfit	Ox	11	6.000	1.6000	13×13	5621	+24.9
Hyd-NewCore-ES	ESBWR	NewCore (2-mm gap between bundles)	Hyd	11	6.526	1.6000	14×14	7719	+71.5

Effect of Neutronic Constraints: feasibility regions for Hydride

- Feasible region: $1.1 \leq P/D \leq 1.2$. In this region there are no limitations due to the reactivity coefficients, and the theoretical burnup can be achieved.
- Feasible region but with limited burnup: $1.2 < P/D \leq 1.35$. These geometries can safely reach only a fraction of the theoretical burnup.
- Non feasible region: $P/D > 1.35$. These geometries are not feasible due to limitations on the reactivity coefficients.

Overall Maximum Achievable Power for Hydride NewCore Cases Accounting for Preliminary Neutronic Results and Larger Gap Between NewCore Bundles

Case	Vessel Size	Δp_{limit} (psia)	Neutronic feasibility region	*D* (mm)	*P/D*	n×n	Q_{core} (MW_t)	ΔQ_{core} %
0 (Ref. BWR/5)	BWR/5	N.A.	Feasible for sure	11.176	1.2773	9×9	3323	0
Hyd-NewCore-5 (5-mm gap between bundles)	BWR/5	24.5	Feasible	11.789	1.2053	8×8	3909	+17.6
			Feasible but BU limited	8.632	1.3368	11×11	4413	+32.8
		36	Feasible	9.684	1.2053	11×11	4149	+24.8
			Feasible but BU limited	8.105	1.3105	14×14	4764	+43.3
0 (Ref. ESBWR)	ESBWR	N.A.	Feasible for sure	10.260	1.2622	10×10	4500	0
Hyd-NewCore-ES (5-mm gap between bundles)	ESBWR	11	Feasible	14.947	1.2053	8×8	5625	+25.0
			Feasible but BU limited	10.211	1.3105	11×11	6250	+38.9