Optimization of UO_2 Fueled PWR Core Design

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Presentation Outline

- Objective
- Approach
- Reference PWR and assumptions
- Neutronics
- Thermal hydraulics
- Clad mechanical integrity
- Vibration and wear
- Economics
- Conclusions

NERI 02-189 Project Objectives

- *Assess the feasibility of improving the* **performance** *of PWR and BWR by using hydride fuel instead of oxide fuel:*
  - *Economics*
    - *Higher power per given volume core*
    - *Higher HM loading (with Th hydride) → more energy per batch and longer cycles*
  - *Safety*
    - *Additional prompt negative reactivity insertion mechanism*
    - *Additional delayed negative reactivity insertion mechanism*
    - *Not so negative void coefficient for BWR*
    - *More uniform BWR assembly composition and pinwise power*

Project Objectives (2)

- *Assess the feasibility of improving the* ***environmental friendliness*** *of PWR and BWR by using hydride fuel instead of oxide fuel:*
    - *Higher discharge burnups*
    - *Pu disposition using fertile-free fuel*
    - *Pu (MA) multi-recycling in LWR*
    - *Use of Th as fertile fuel*

Observation

- *Maximum permissible power density using hydride fuel far exceeds that contemporary oxide fueled PWR cores are designed to operate at*

- *Optimal lattice geometry:*
  - *fuel rod outer diameter – D*
  - *Pitch-to-diameter ratio – P/D*

is highly different from the geometry range in present use by industry

Present Study Objective

Optimize the design of UO_2 fueled PWR core using same methodology we adopted for the search of optimal hydride fueled PWR cores

Study Approach

- *Search for that core design that gives the minimum Cost of Electricity (COE) in a retrofitted PWR*

  Need:
  - *Attainable power*
    - *Thermal hydraulic analysis*
    - *Transient analysis*
    - *Vibration analysis*
  - *Attainable discharge burnup*
    - *Neutronic analysis*
    - *Clad mechanical integrity analysis*

Study Approach (2)

- *Design variables:*
  - *Outer fuel diameter – D*
  - *Pitch-to-diameter ratio – P/D (square lattice)*
  - *Uranium enrichment – 5%, 7.5%, 10%*
  - *Coolant pressure drop across core – 29 psia or 60 psia*
  - *Type of fuel rod support – grid spacers or wire wraps*
- *Design constraints:*
  - $K_{\infty} > 1.05$
  - *Negative Doppler, moderator temperature and void* ρ *coef.*
  - *MDNBR*
  - *Peak fuel temperature*
  - *Coolant inlet and outlet temperatures fixed*
  - *Coolant pressure drop fixed*

Study Approach (3)

- *Design constraints (cont.)*
  - *Clad internal pressure*
  - *Clad strain*
  - *Clad water-side corrosion*
  - *Constraints imposed by 5 vibration and wear mechanisms:*
    - *Vortex induced vibration*
    - *Fluid elastic instability*
    - *Turbulence induced vibration in cross and axial flow*
    - *Fretting wear*
    - *Sliding (or adhesive) wear*

Reference PWR and Assumptions

South Texas Project Electric Generating Station

Parameter	Value
Effective core radius	~1.83 m (72”)
Active fuel length	4.26 m (168”)
Fission gas plenum length	17.8 cm (7”)
Clad outer diameter, D	*9.5 mm*
Square lattice pitch, P	*12.6 mm*
Pitch-to-diameter ratio	*1.326*
Number fuel rods per core	*50956*
Power level[*]	*3800 MWt*

Parameter	Value
Inlet temperature	294 C
Core enthalpy rise	204 kJ/kg
System pressure	2250 psia
Radial peaking factor	1.65
Axial peaking factor	1.55
Average linear heat rate	*174 W/cm*
Average specific power	*38.38 W/gU*
Average discharge burnup	*60 GWD/tHM*

[*] *Parameters in Italics are variables of this study*. The other parameters are fixed

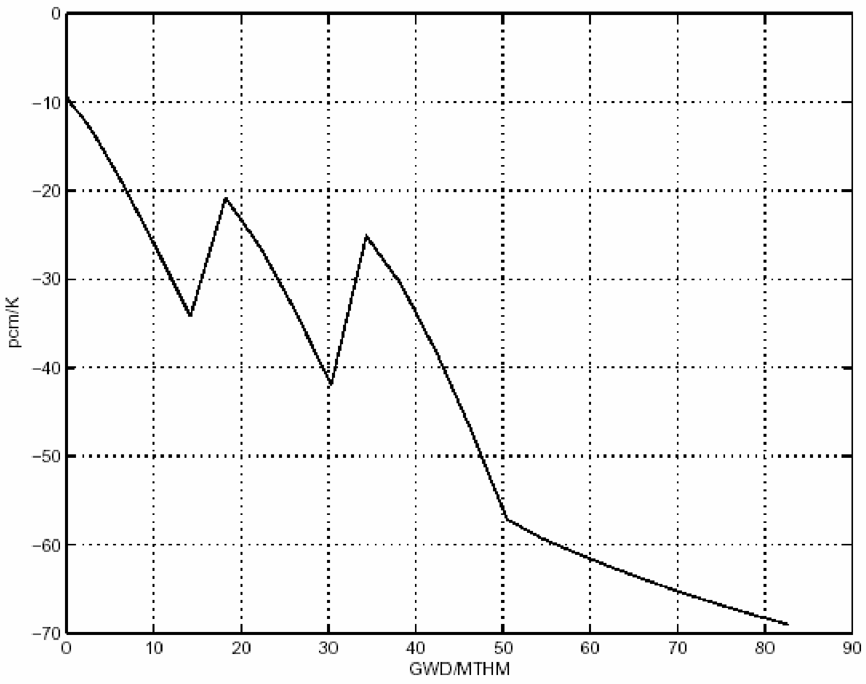
Outer diameter (mm)	Clad thickness (mm)	Gap thickness (mm)
D < 7.747	0.508	0.0635
D > 7.747	0.508 + (D – 7.747) * 0.0362	0.0635 + (D – 7.747) * 0.0108

Neutronics - methodology

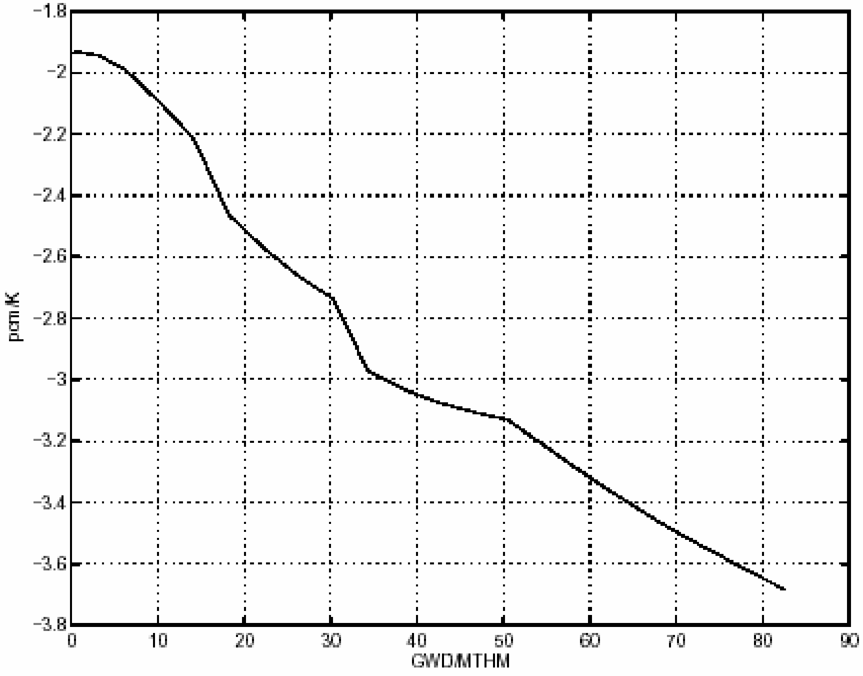
- *Unit cell analysis using SAS2H sequence of SCALE4.4*
  - *Good agreement with OECD/NEA MOX benchmarks*
- *Assuming 3 batches*
  - *Same power density*
  - *Core* $k_\infty(\alpha)$ *is arithmetic average of batch* $k_\infty(\alpha)$
- *Accounting for non-linearity of* k_∞ *with BU*
  - $k_\infty(EOC)=1.05$
- *Finding boron concentration in water required to bring* k_∞ *to 1.05 at any point in time*
- *Calculating Doppler, MTC and reactivity effect due to 5% voiding – as a function of BU*
- *Amount of IFBA - 0.2D(cm)/0.95 mg/cm* ^{10}B

Neutronics – illustration

Reference geometry

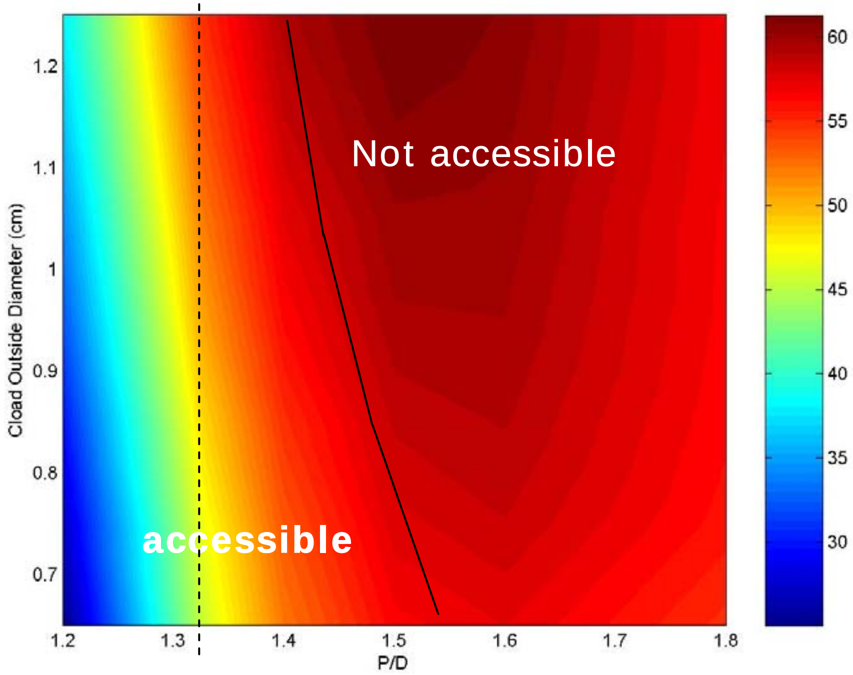


MTC

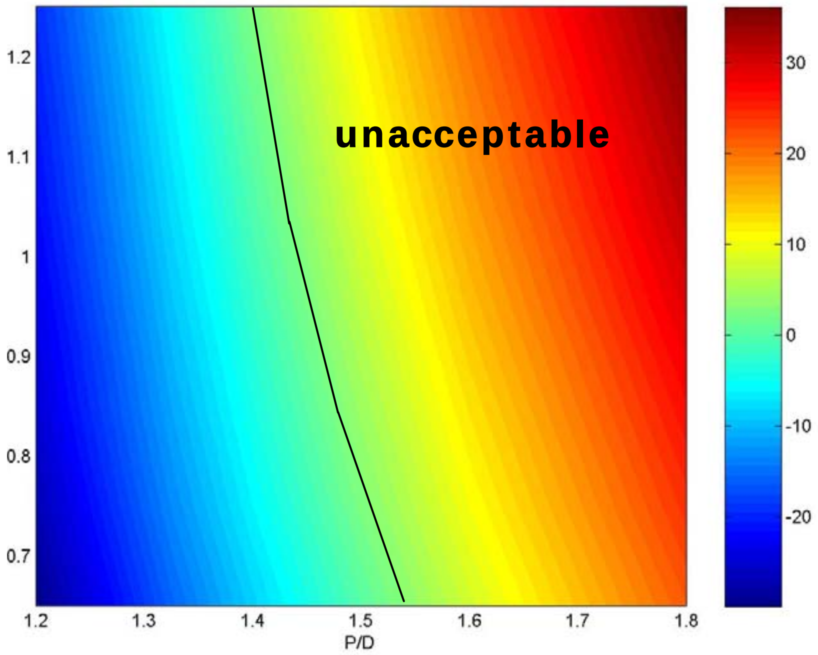


Doppler

Neutronics – results; 5% enriched U



Discharge BU (GWD/tHM)



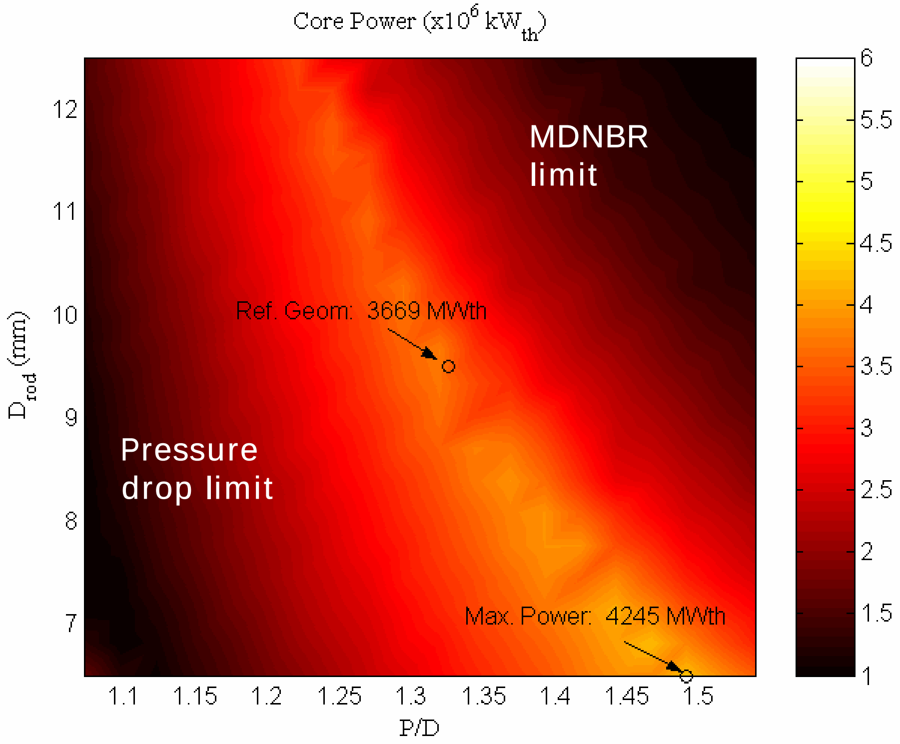
MTC (pcm/k)

Thermal hydraulics - methodology

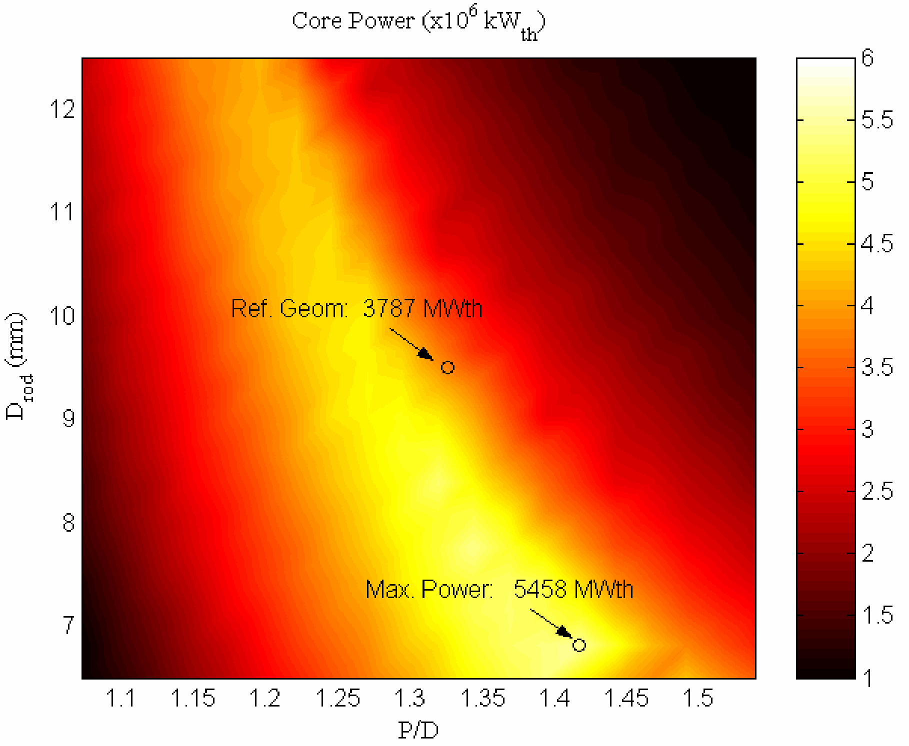
- *Using VIPRE-EPRI subchannel analysis*
- *Verified against VIPRE full-core analysis*
- *MATLAB scripts to automate VIPRE execution*
- *W3-L correlation for MDNBR*
- *Constraints:*

Constraint	Value
MDNBR	2.17
Peak/average fuel temperature (^oC)	1400/2800
Present/future Core pressure drop (Psia)	29/60

Thermal hydraulics - results



29 psia

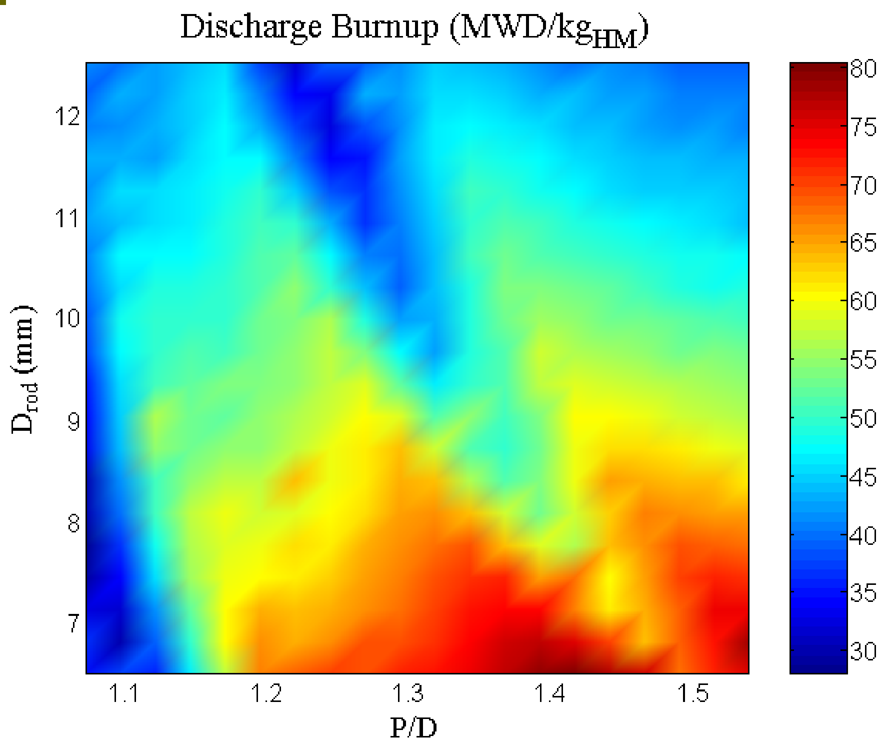


60 psia

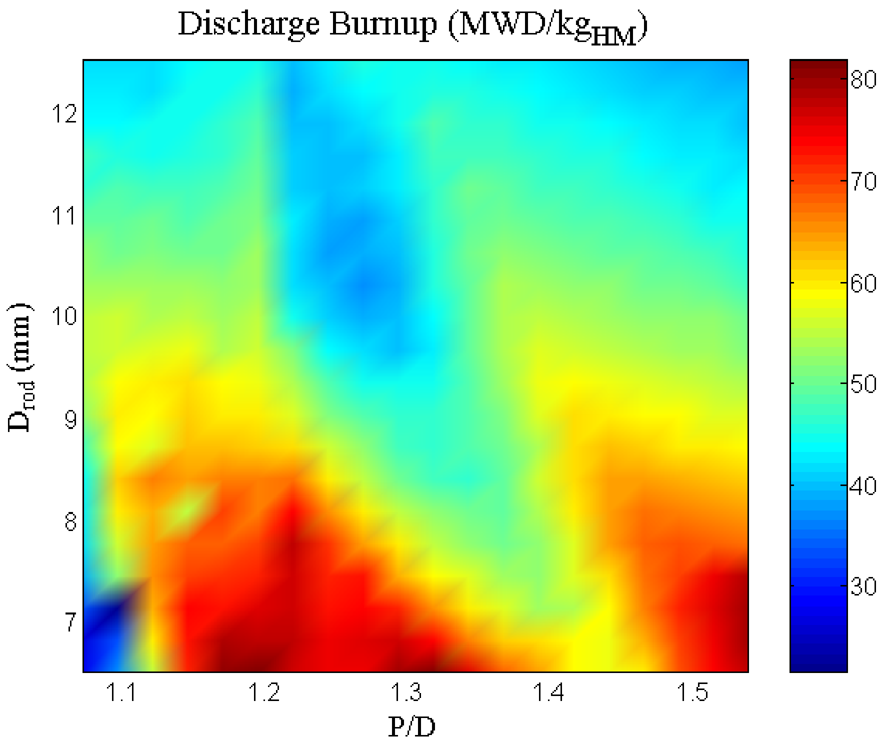
Clad integrity - methodology

- *Using FRAPCON*
- *Constraints:*
    - *Clad corrosion, water side: < 0.1 mm, independent of D*
    - *Clad strain: < 1% in tension*
        - *External coolant pressure*
        - *Thermal expansion (fuel and clad)*
        - *Fuel swelling*
    - *Clad internal pressure: < 2500 psia*
        - *Gaseous fission products*
        - *Helium from ^{10}B of IFBA*

Clad integrity - results



29 psia

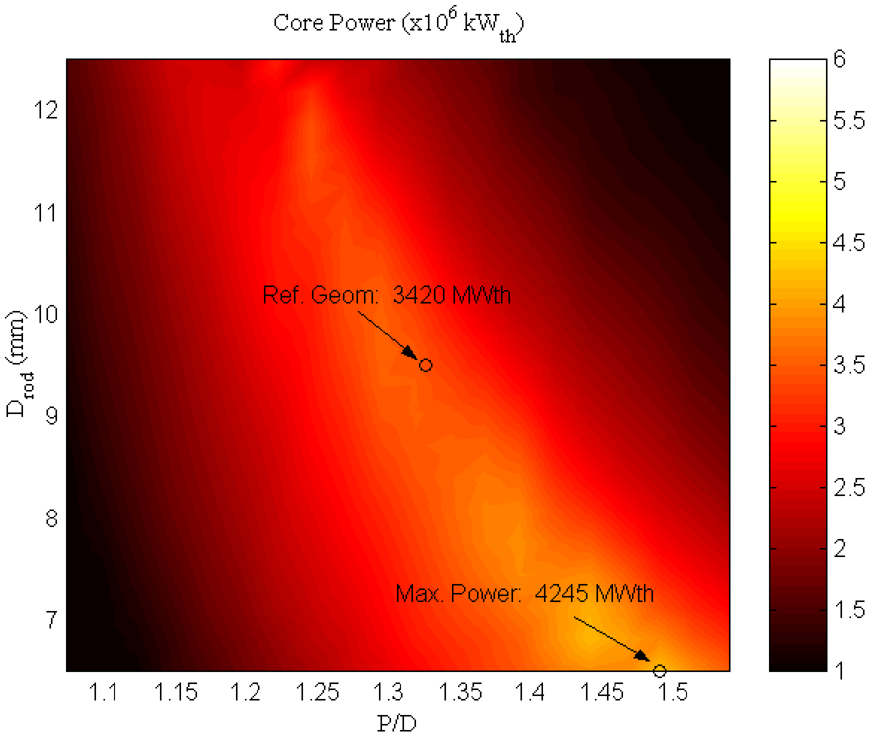


60 psia

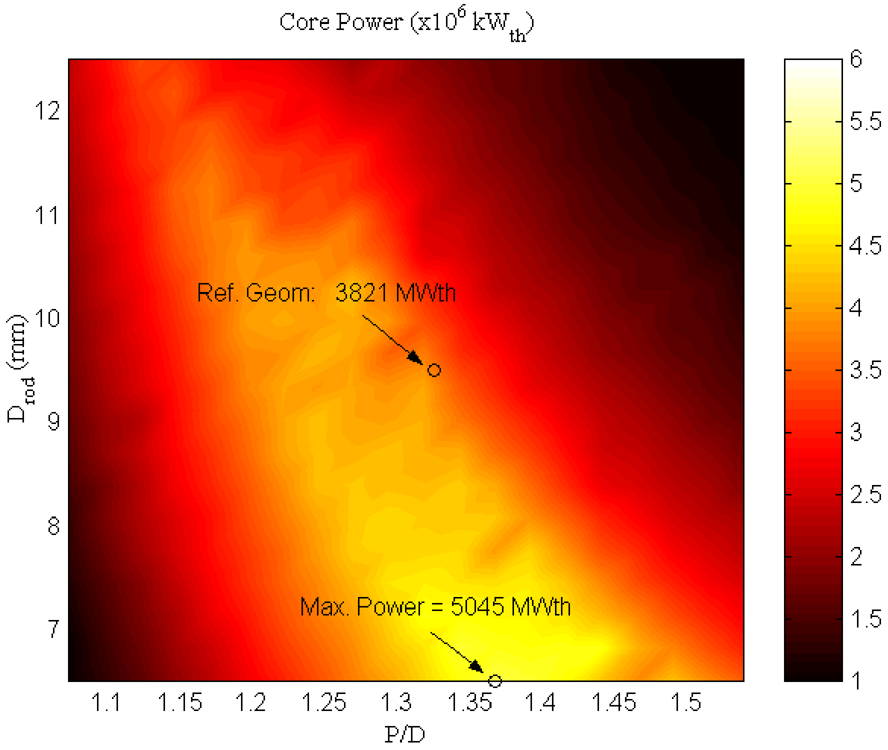
Fuel rod vibration - methodology

- *Vibration mechanisms:*
  - *Fluid elastic instability*
  - *Vortex shedding lock-in*
  - *Turbulence induced vibration in cross and axial flow*
- *Cladding wear mechanisms:*
  - *Sliding wear*
  - *Fretting wear*

Fuel rod vibration – results: attainable power

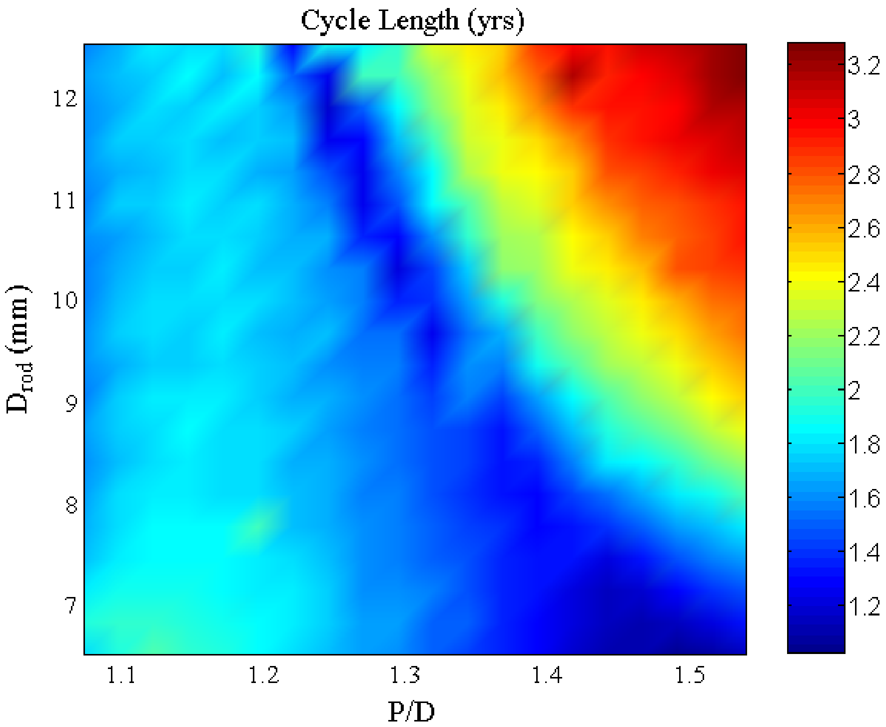


29 psia

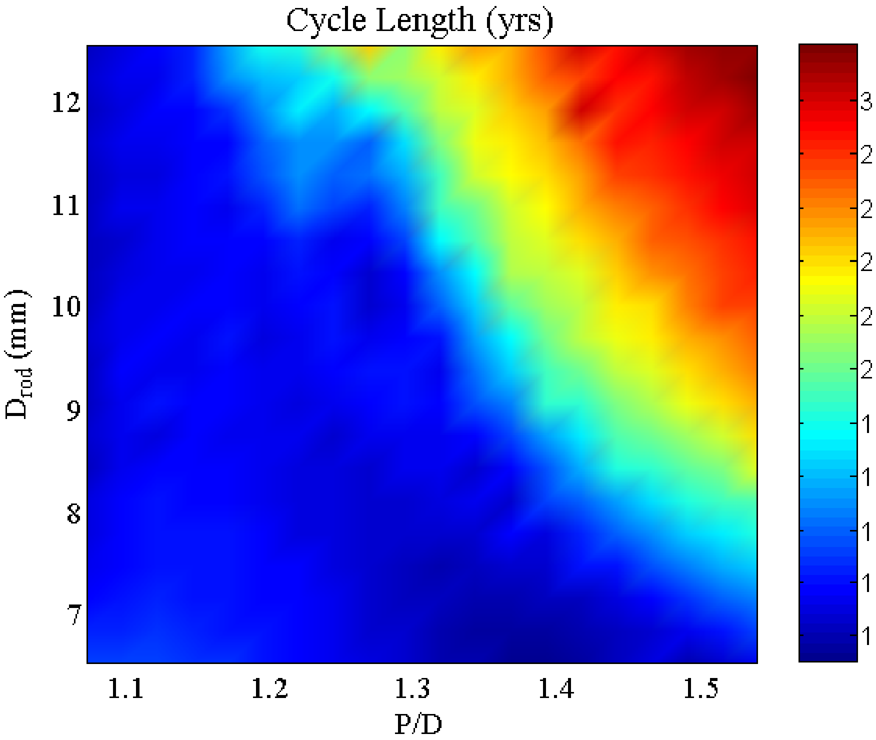


60 psia

Fuel rod vibration – results: cycle length



29 psia



60 psia

Accidents and transient analysis (limited) – methodology & results

- *Using VIPRE-EPRI subchannel analysis*
- *MATLAB scripts to automate VIPRE execution*
- *Considering:*
  - *An overpower transient due to control rod bank withdrawal at full power – DNB should not occur*
  - *A large break LOCA – peak clad temperature < 2200^{o}F*
  - *A complete LOFA – DNB should not occur*
- *Findings:*

Pressure drop	Peak power MW$_{th}$	D (mm)	P/D
29 psia	4104 (vs. 4245)	7.1	1.47
60 psia	4990 (vs. 5045)	6.5	1.39

Economics - methodology

- *“Major backfit” scenario; replacement of:*
  - *Steam generators*
  - *High pressure turbine*
  - *Pressure vessel head and core internals*
- *OECD/NEA cost data and costing methodology*
- *Fuel assembly fabrication cost:*
  - *50% of reference proportional to U loading*
  - *50% of reference proportional to # of fuel rods per assembly*
- *Outage time of reference plant is 20 days:*
  - *13 days for refueling – fixed*
  - *7 days for maintenance – scales with cycle length (same per year)*

Economics – costing assumptions

Cost Component	Unit Price
Mining/Ore	\$41/kg_{HM}
Conversion	\$8/kg_{HM}
Enrichment	\$108/kg_{SWU}
Fabrication	\$275/kg_{HM}
Spent Fuel Storage	\$250/kg_{HM}
Waste Disposal	1 mill/kWh

Transaction Time	Value
Fuel Fabrication	1 yr
Uranium Enrichment	1.5 yr
Uranium Conversion	1.5 yr
Uranium Ore Purchase	2 yr
Spent Fuel Storage	- T_C*

* T_c is the cycle length. A negative sign implies that the storage costs need to be referred back in time to the reference date

Mass Loss Fraction	Value
Mining/Ore	0
Conversion	0.005
Enrichment	Varies
Fabrication	0.01

O&M function

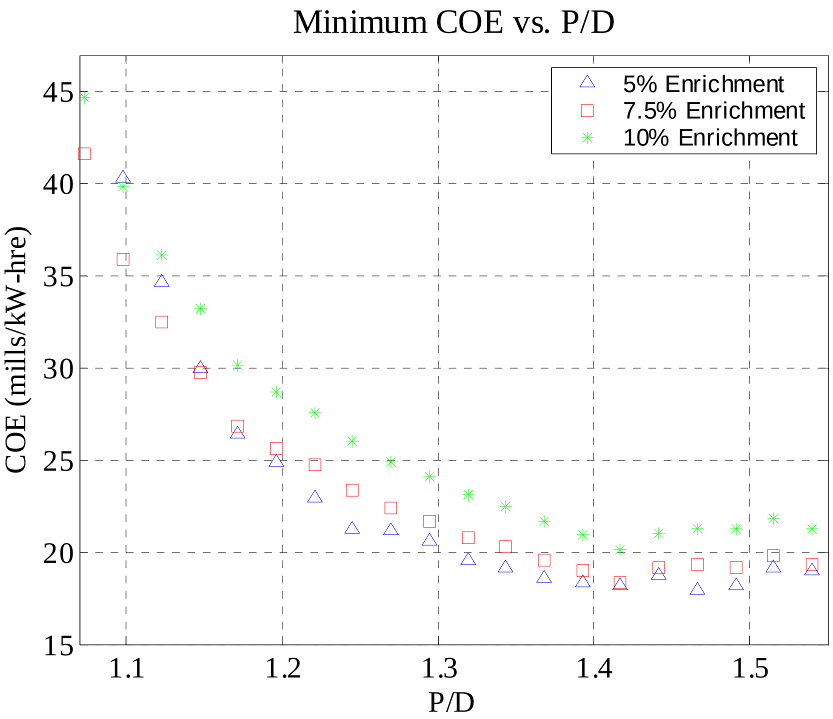
Variable	Cost
Refueling Outage	\$800,000/day
Forced Outage	\$100,000/day
Replacement	30 mills/kWh
Fixed	
Personnel	\$150,000/person-yr
Number Personnel	600
Refueling Outage	20 days/cycle
Forced Outage	1%
Availability	99%

Economics – costing assumptions

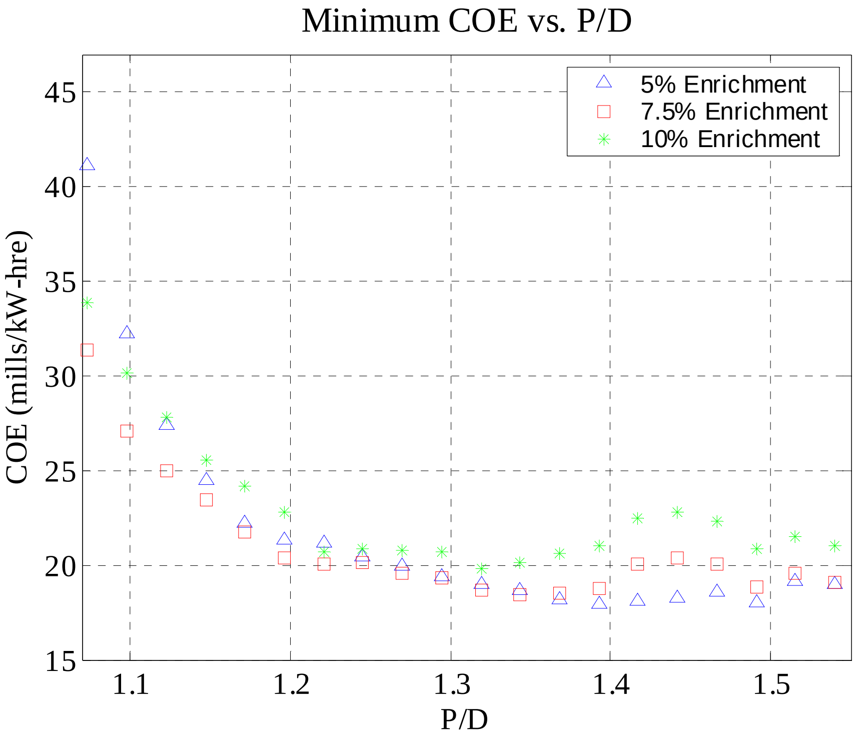
Characteristic	Value
Thermal Efficiency	0.33
Number of Batches	3
Plant Life Extension	20 yrs

Component	Price ($\$10^6$)	Scaling Factor
Steam Generators	100	0.6
Vessel Head	25	-
Core Internals	25	-
Turbine Generator	338	0.8
Existing Fuel Value	67	-

Economics – results

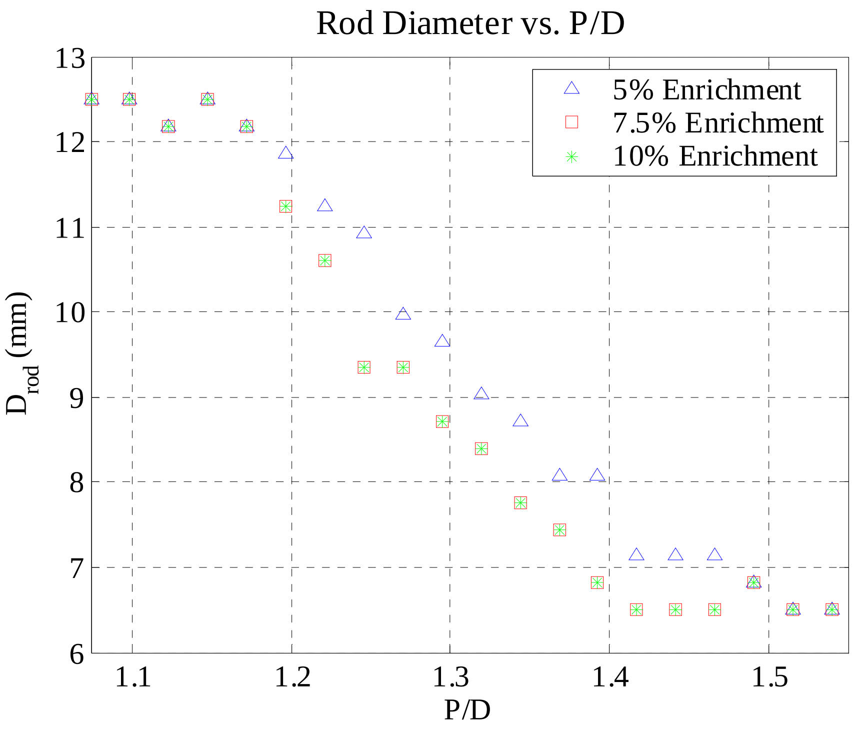


29 psia

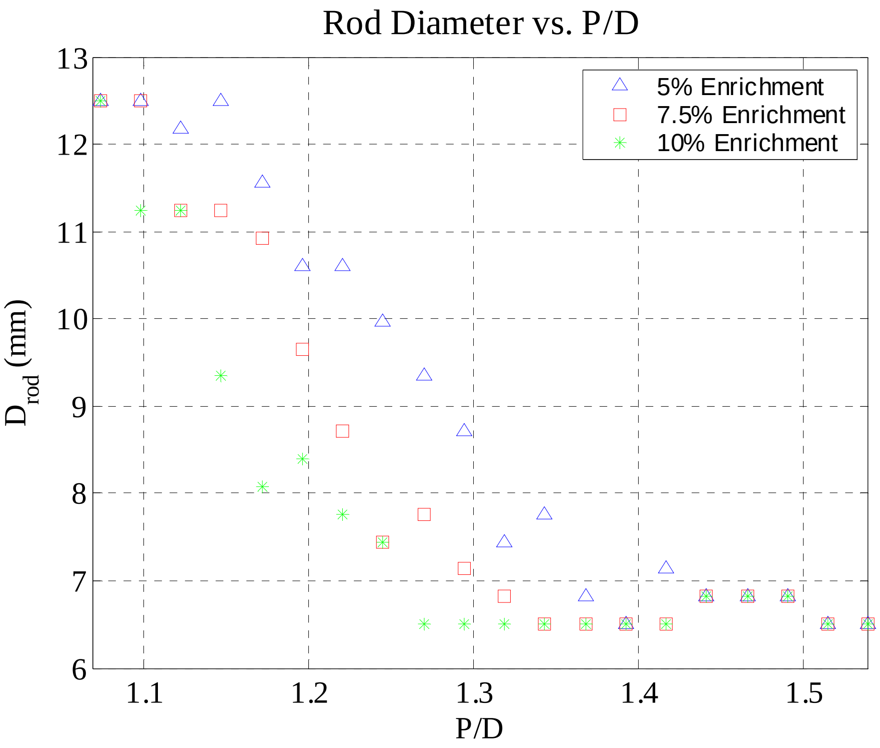


60 psia

Economics – results

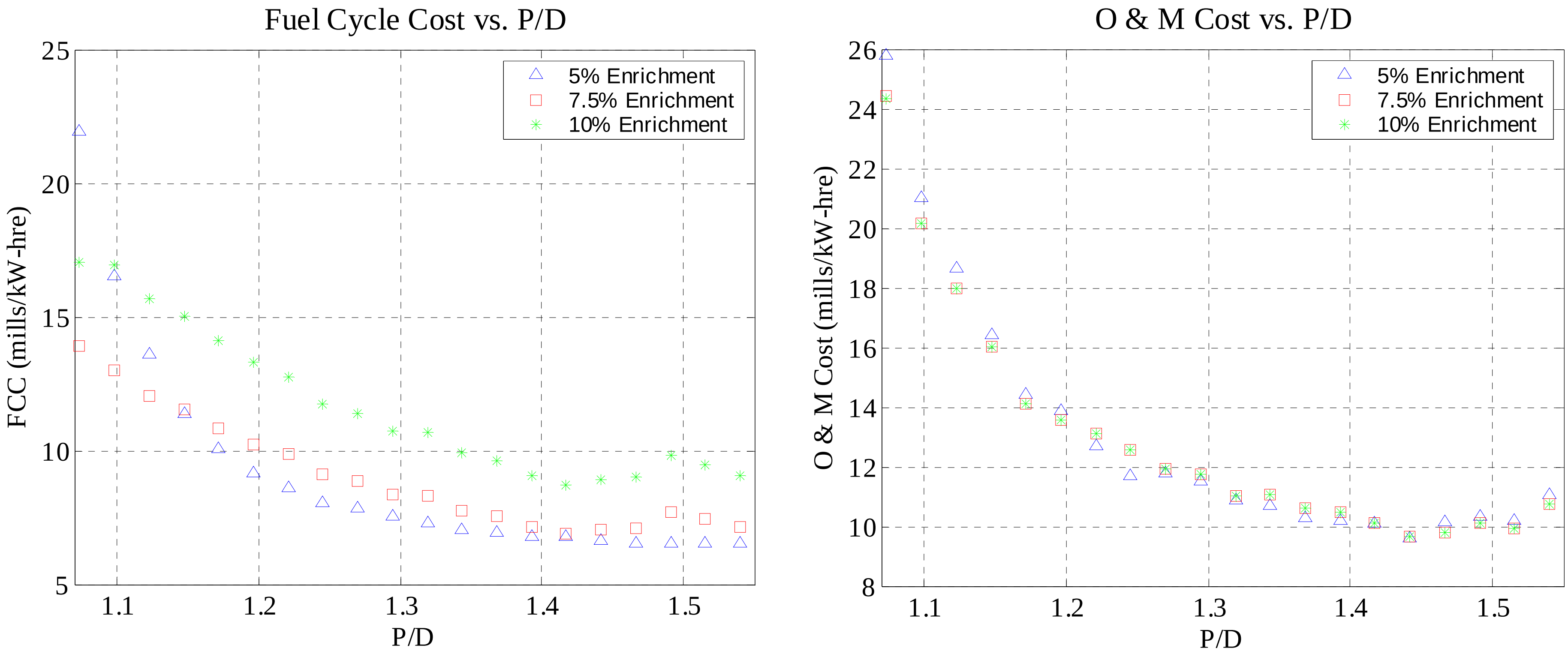


29 psia



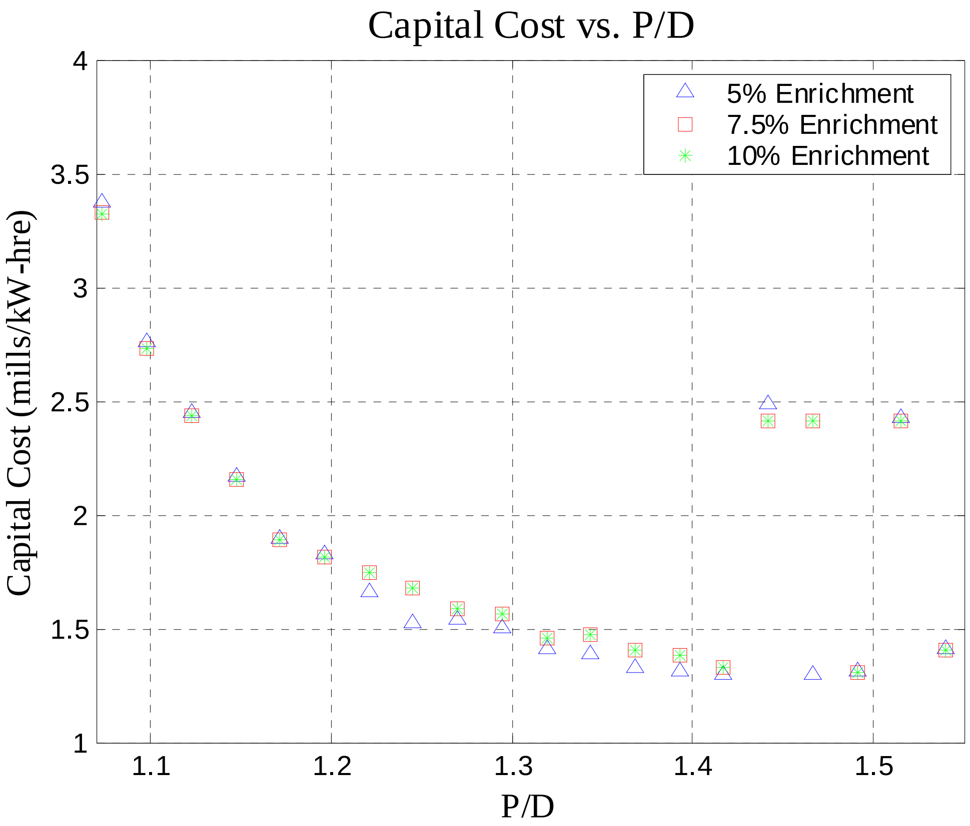
60 psia

Economics – results



29 psia

Economics – results



29 psia

Lowest COE designs

		Reference	29 psia	60 psia
COE (mills/kW-hre)		19.7	18.0	17.9
Power (MWth)		3800	3800	4929
Geometry:	D (mm)	9.5	7.13	6.5
	P/D	1.326	1.47	1.39
Rod Number		50,956	73,966	98,699
U Inventory (kg_HM)		99,010	81,581	87,104
Specific Power (kWth/kg_HM)		38.4	46.6	56.6
Linear Heat Rate (kW/ft)		5.30	3.67	3.56
Cycle Length (yrs)		1.5	1.17	0.9
Burnup (MWd/kg_HM)		60	56.55	52.3
MDNBR		2.17	2.17	2.65
Peak Fuel Temp (F)			1906	1879

Conclusions

Pressure drop	Reduction in COE	Increase in power density	Optimal /reference D (cm)	Optimal/ reference P/D
29 psia	12%	0%	0.71/0.95	1.47/1.326
60 psia	12.5%	30%	0.65/0.95	1.39/1.326

Our preliminary analysis indicates:

- *It may be possible to reduce COE by ~12% by going to thinner fuel rods of a larger P/D ratio*
- *It may be possible to increase core power density by ~ 30% by going to smaller D, larger P/D and ~60 psia coolant pressure drop*

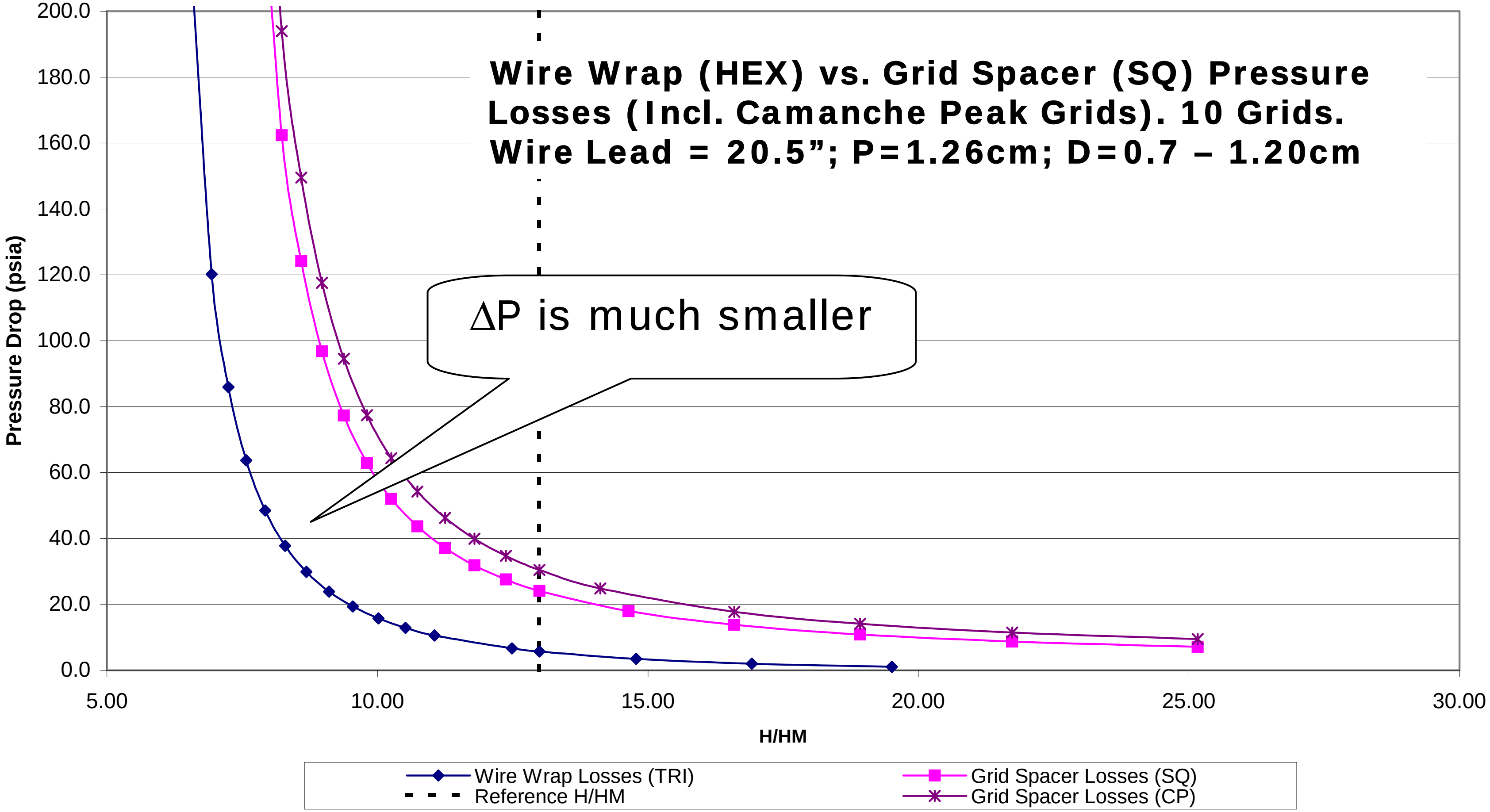
Conclusions (2)

- *It may be possible to design new PWR for nearly 2 GWe per unit using the same pressure vessel dimensions to be used for the 1500 MWe PWR*

Question:

Why industry is not using lower D, higher P/D, higher ΔP core designs???

An alternative promising design approach – wire wrap in hex lattice



An alternative promising design approach – wire wrap in hex lattice

Preliminary results:

Using hexagonal lattice with wire wraps instead of grid spacers, it may be possible to significantly increase core power density without increasing pressure drop above 29 psia. For example:

- *With D=0.65 cm and P/D = 1.42*
- *Power density can be increased by ~30%*