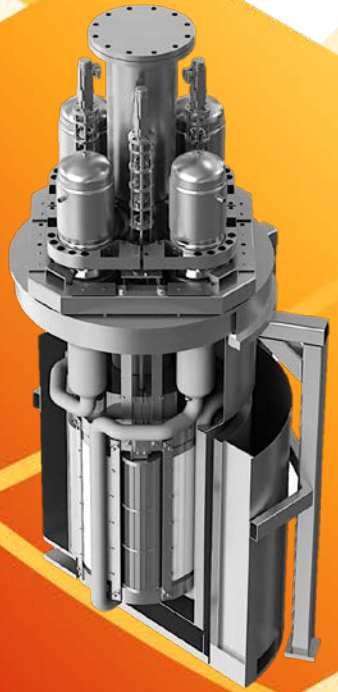
(Microreactor Applications Research, Validation & EvaLuation),

MARVEL Technology Review

10/19/2022



Fuel & Core System

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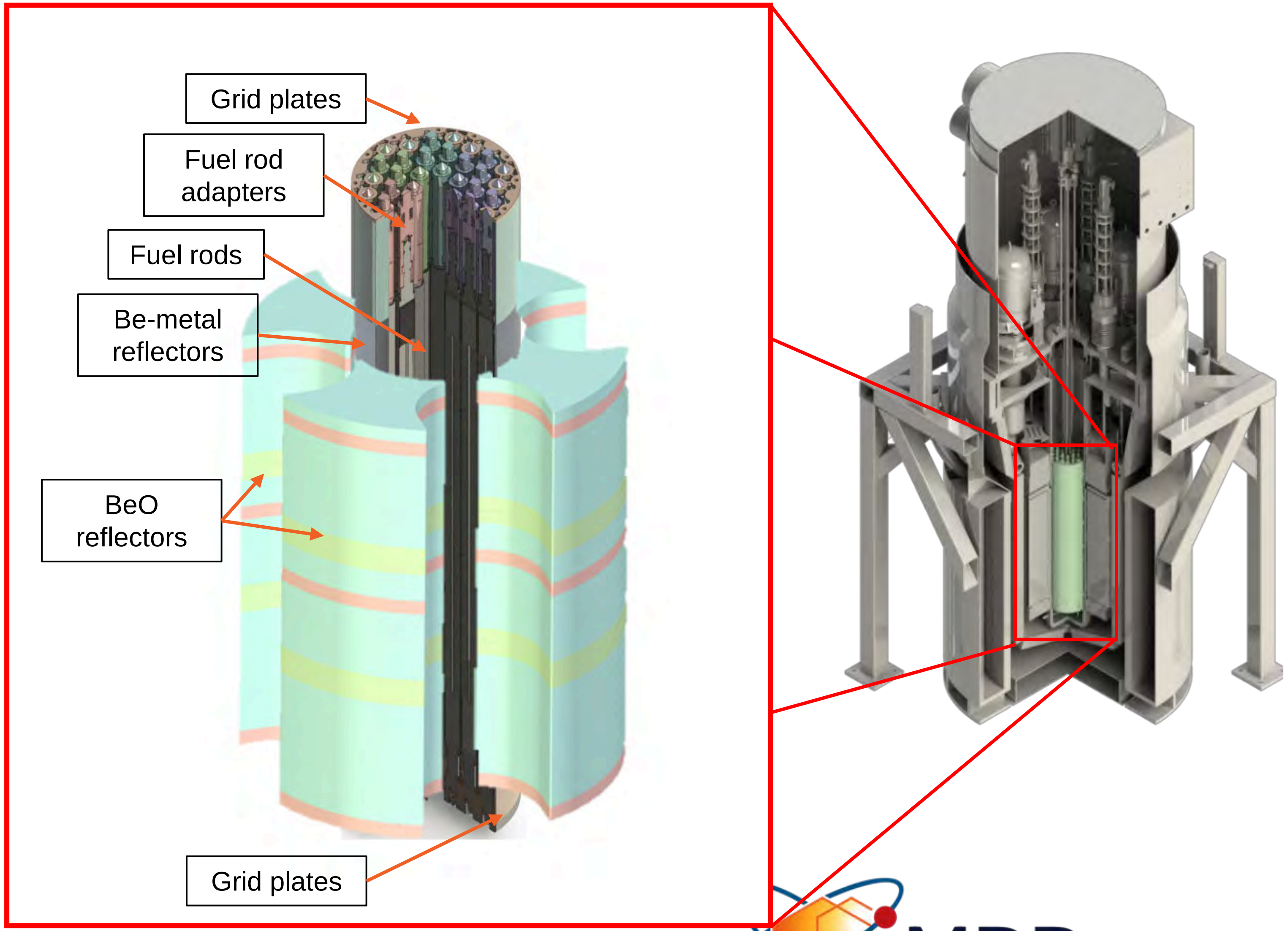
Outline

- Fuel and Core System Overview
- Fuel and Core System Description
  - Fuel Subsystem Design Description
- Fuel and Core System Analysis
  - Power Peaking, Reactivity Coefficients, Control Element Reactivity Worths, Shutdown Margin, Irradiation Damage
- Conclusion
- Questions

MRP Microreactor Program

Fuel and Core System (FCS) Overview

- Consists of:
  - Fuel Subsystem (FS): fuel rods
  - Core Structures Subsystem (CSS): grid plates, fuel rod adaptors, internal Be-metal reflectors
  - Stationary Core Reflector Subsystem (SCR): BeO reflector plate stacks



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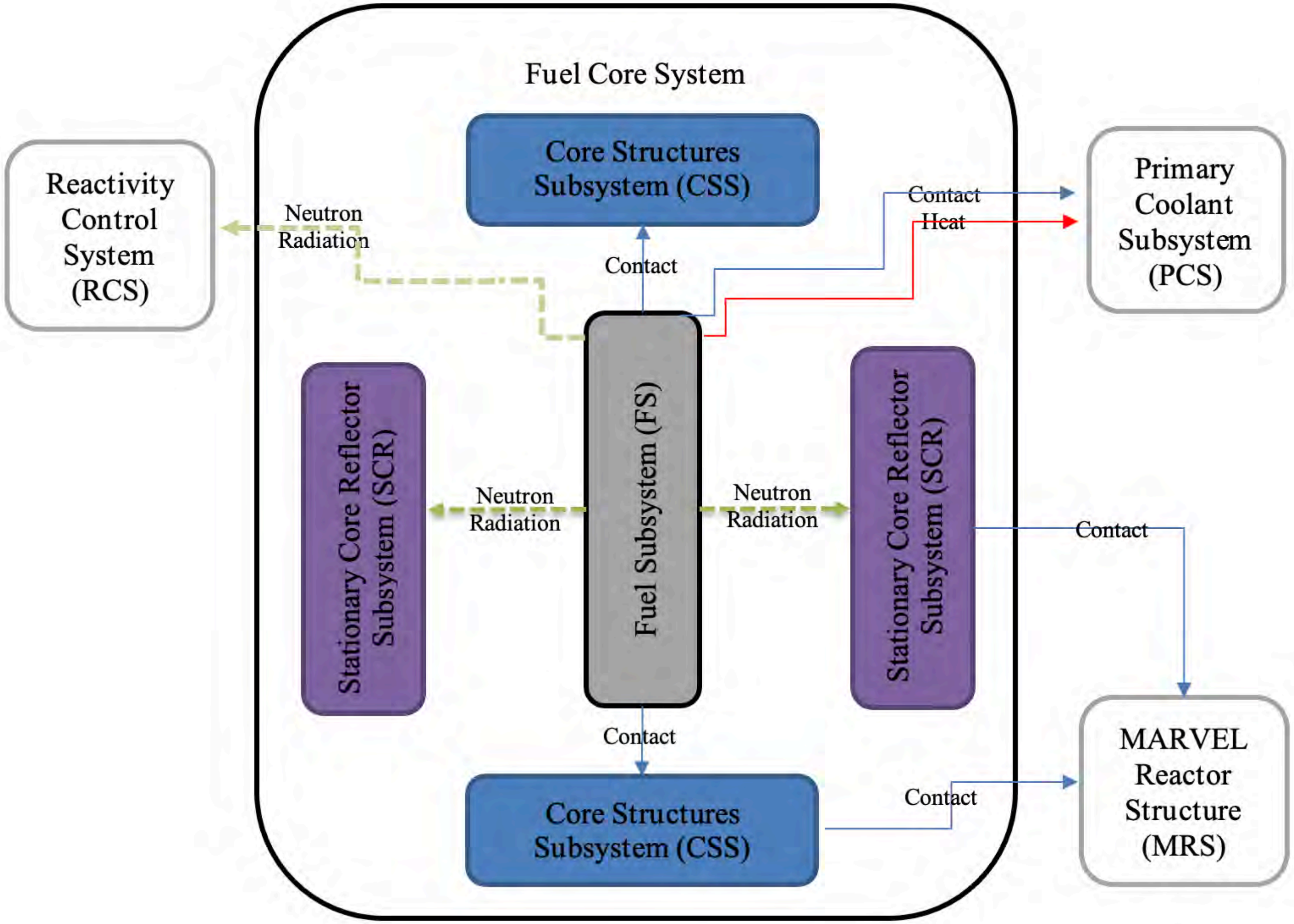
FCS Interfaces

- Internal interfaces:
  - CSS supports and holds FS in place
  - SCR interacts with FS through neutron radiation
- FCS interfaces with other systems
  - MARVEL Reactor Structure through structural support and load transfer
  - Primary Coolant Subsystem through heat transfer
  - Reactivity Control System through neutron radiation



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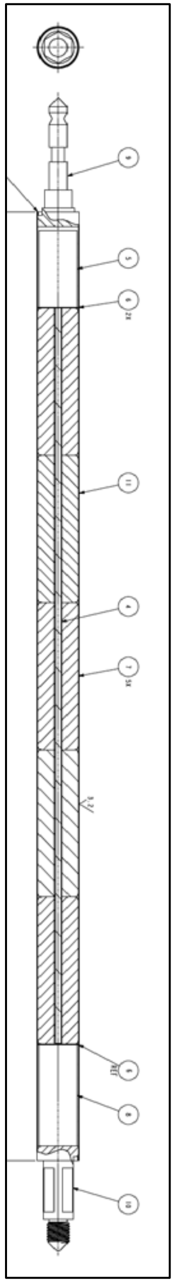
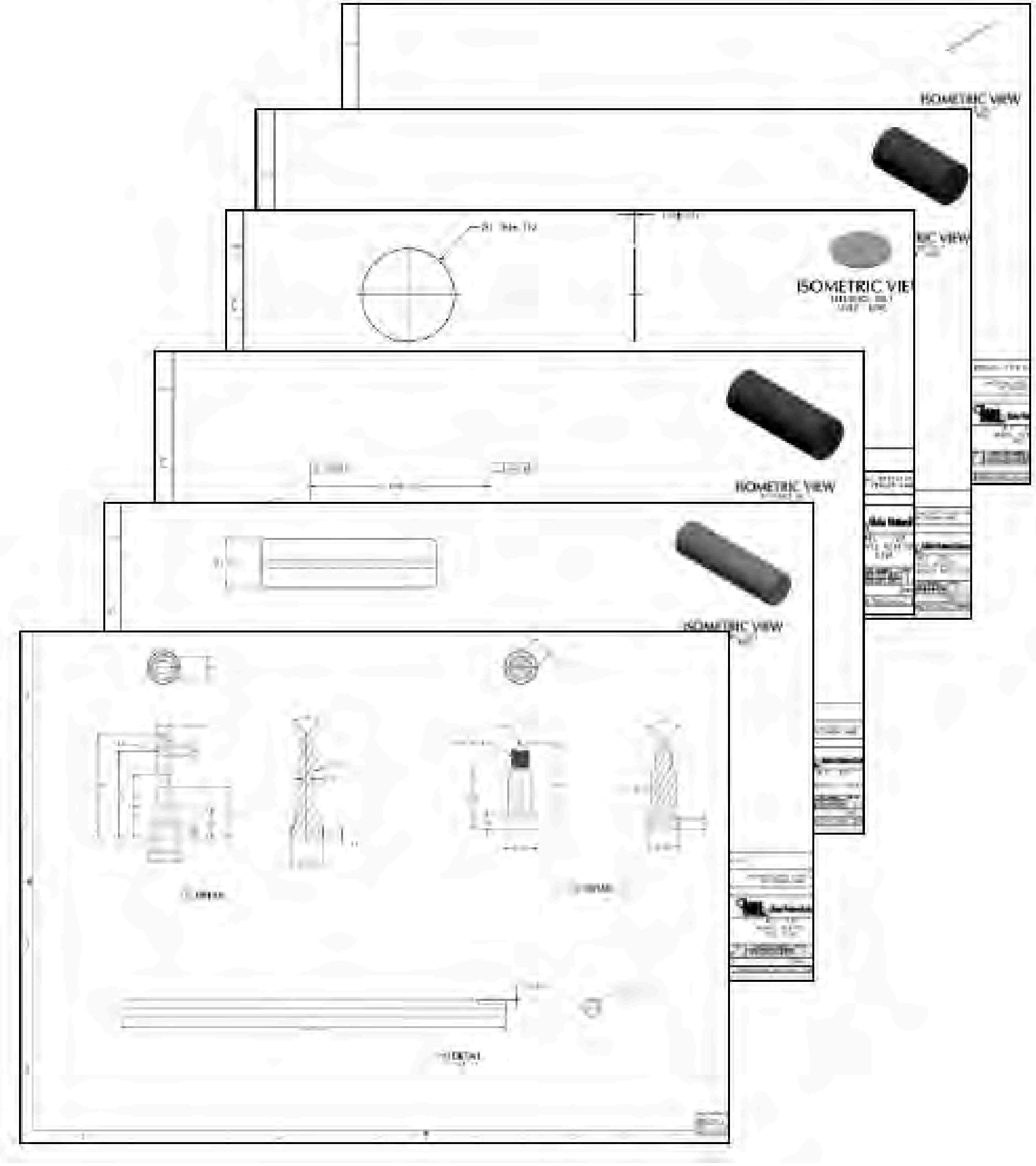
Fuel Subsystem Description

- Fuel purchased by external supplier: TRIGA International
  - GA and CERCA in France
- MARVEL fuel is modified “off the shelf”
  - with 5 fuel pellets instead of 3

Fuel Element Design Data	Specification
Number of fuel elements	36
Fuel type	U-$ZrH_{1.6}$
Zirconium rod diameter, in.	0.225
Fuel meat outer diameter, in.	1.370
Fuel meat length, in.	25.0
Clad thickness, in.	0.020
Clad material	304 SS
Total uranium, wt%	30.0
Uranium density, g/cm^3	2.14
Uranium enrichment, %	19.75
Nominal hydrogen/zirconium ratio	1.6





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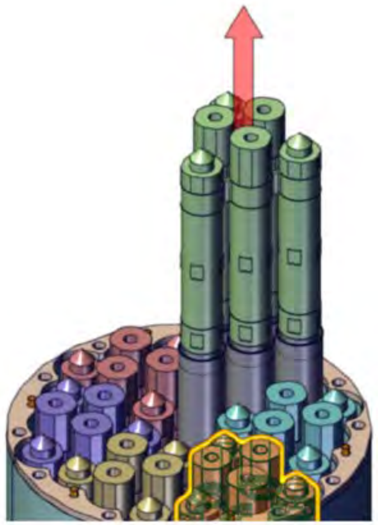
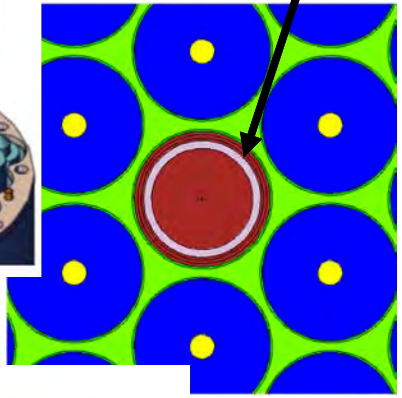
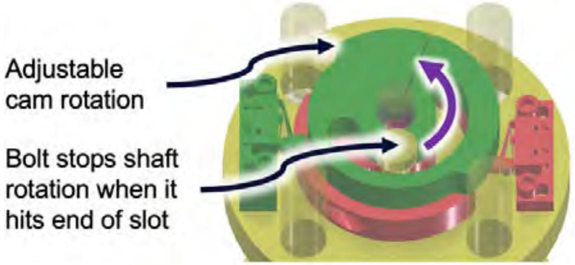
Innovative Reactivity Management for Uncertainties

- Uncertainties:
  - U-235 loading, hydrogen moderator loading, modeling uncertainties
- Core designed to lower end of tolerances to ensure sufficient reactivity
  - Allows for the potential of too much excess reactivity at BOL
- 3 methods to manage excess reactivity
  - ”Course” tuning of BOL excess reactivity through the replacement of a fuel rod(s) with a dummy rod(s). Could be solid stainless steel, ZrH filled, etc.
  - “Fine” tuning of BOL excess reactivity through the burnable absorber (gray tube) composition that can be swapped for the desired poison loading
  - Mechanical hardstops that will set limits on the reactivity accessible to the control drums (40¢/CD)



Burnable absorber (gray tube)





Mechanical Hardstops

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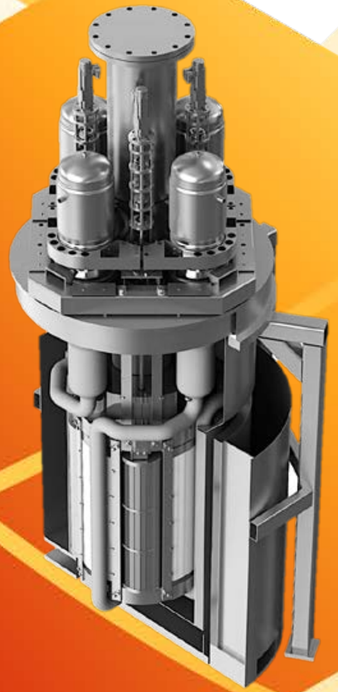
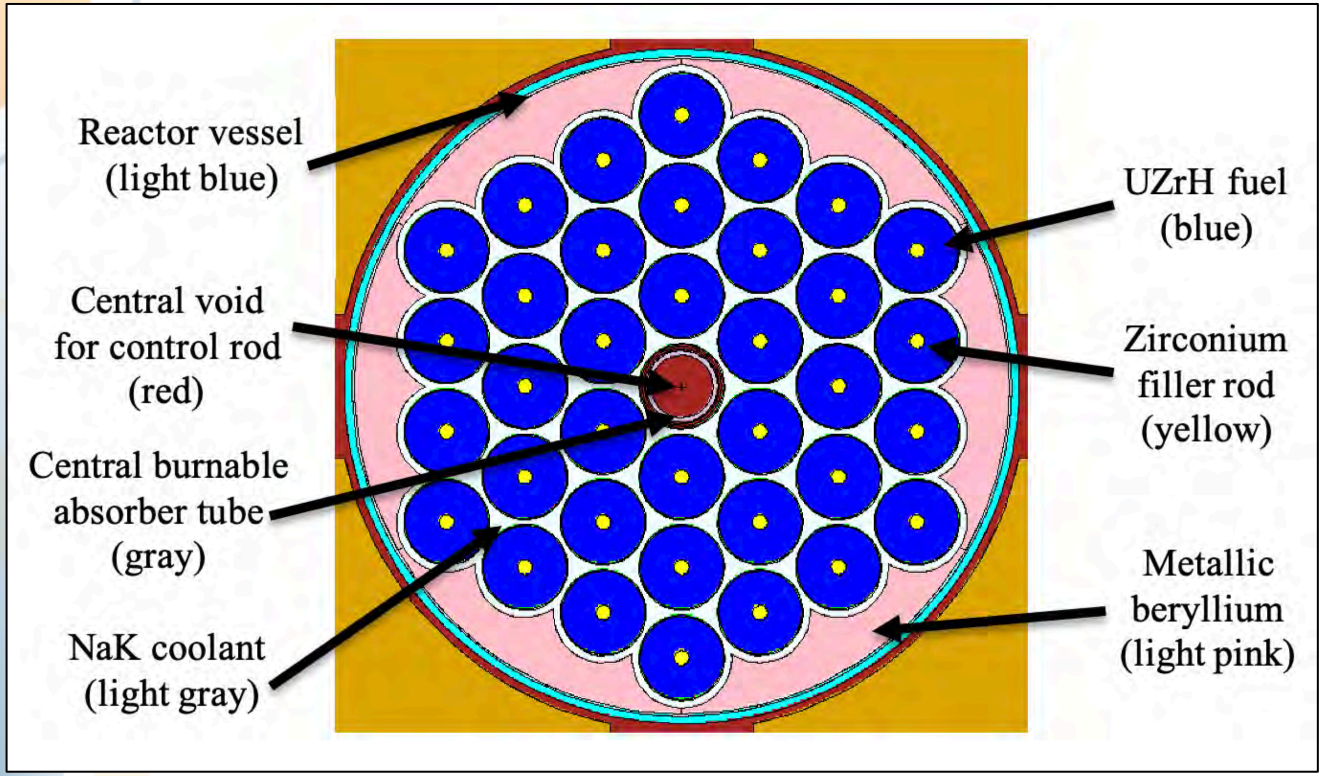
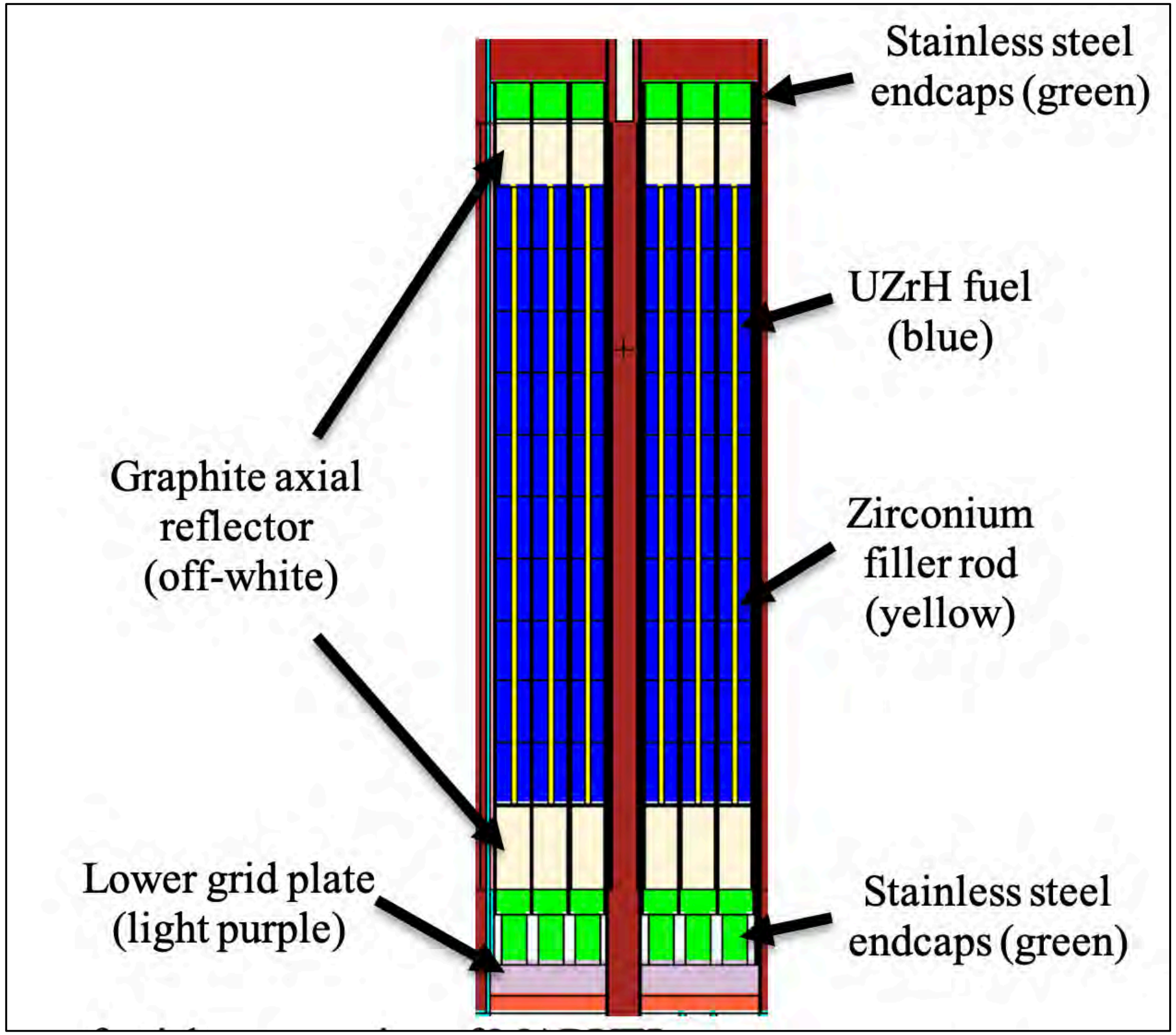


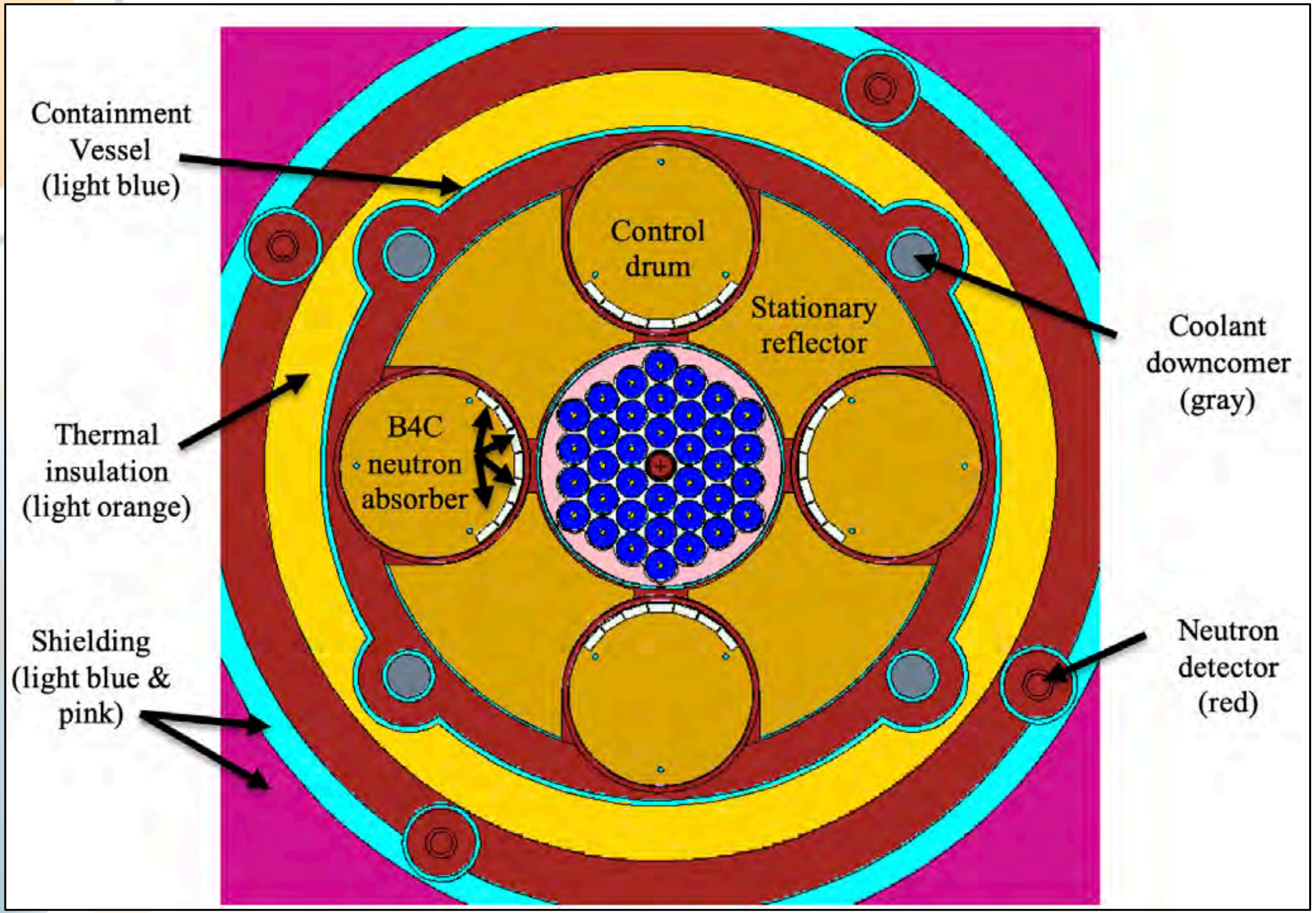
Fuel and Core System Neutronic Analysis

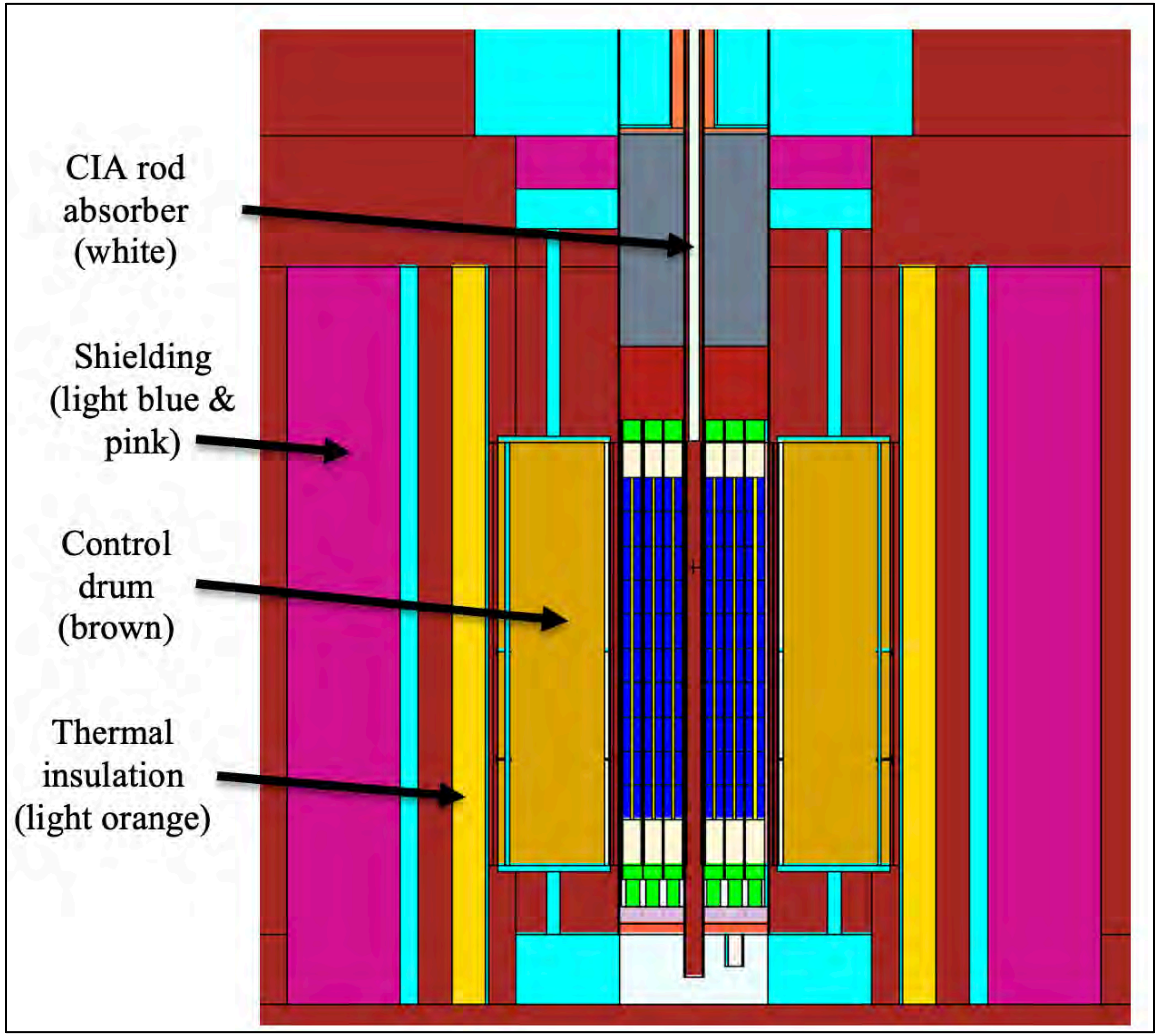
MARVEL MCNP Model





MARVEL MCNP Model





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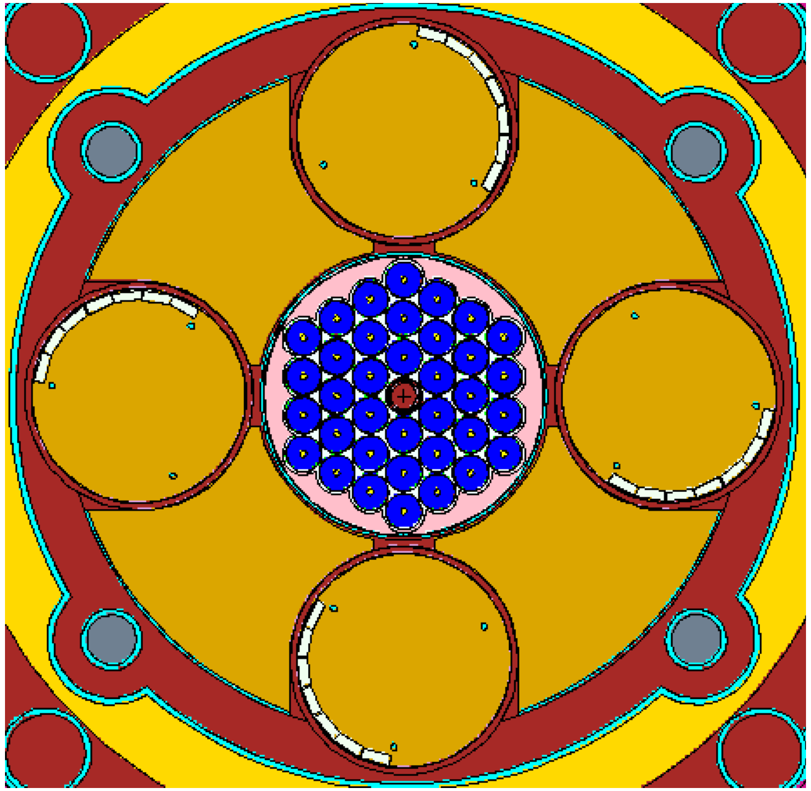
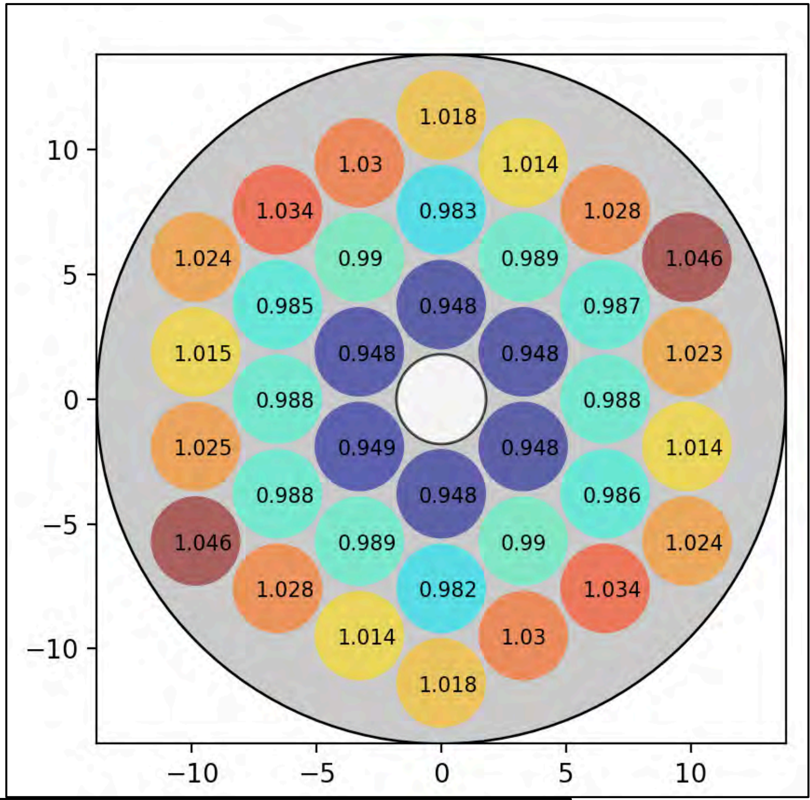
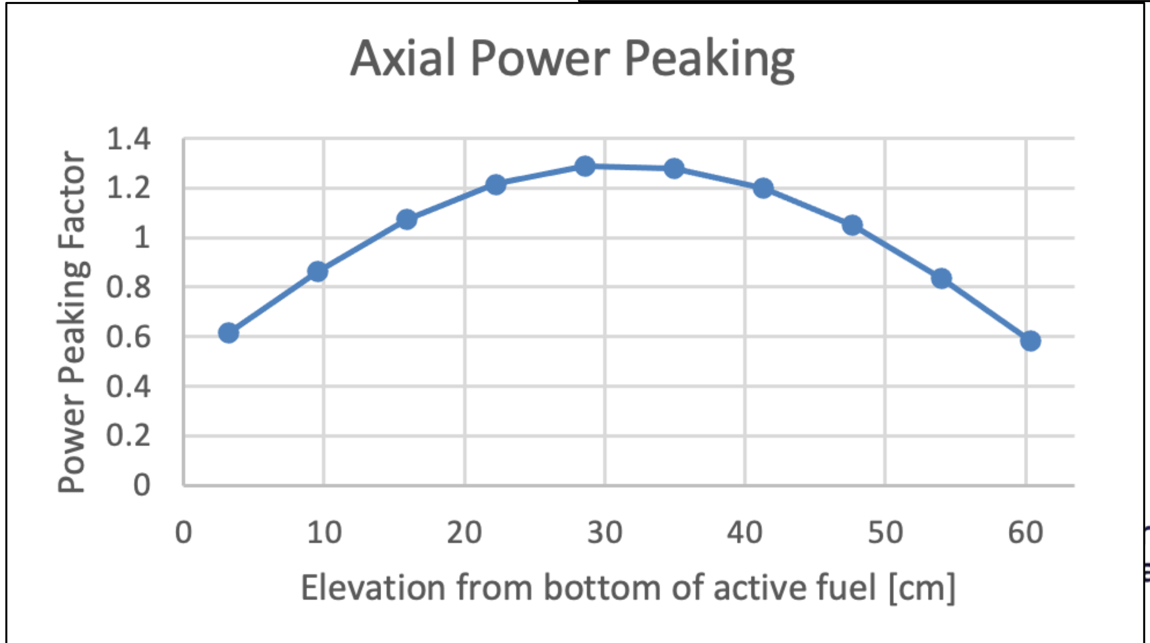
Normal Operations: Power Peaking

- Critical CD position @ 113° withdrawn
  - Dependent on multiple factors
- 2D radial power peaking
  - Max:1.046
  - Min:0.948
- 2D axial power peaking
  - Max:1.29
  - Min:0.58
- Axial offset: -1.1%







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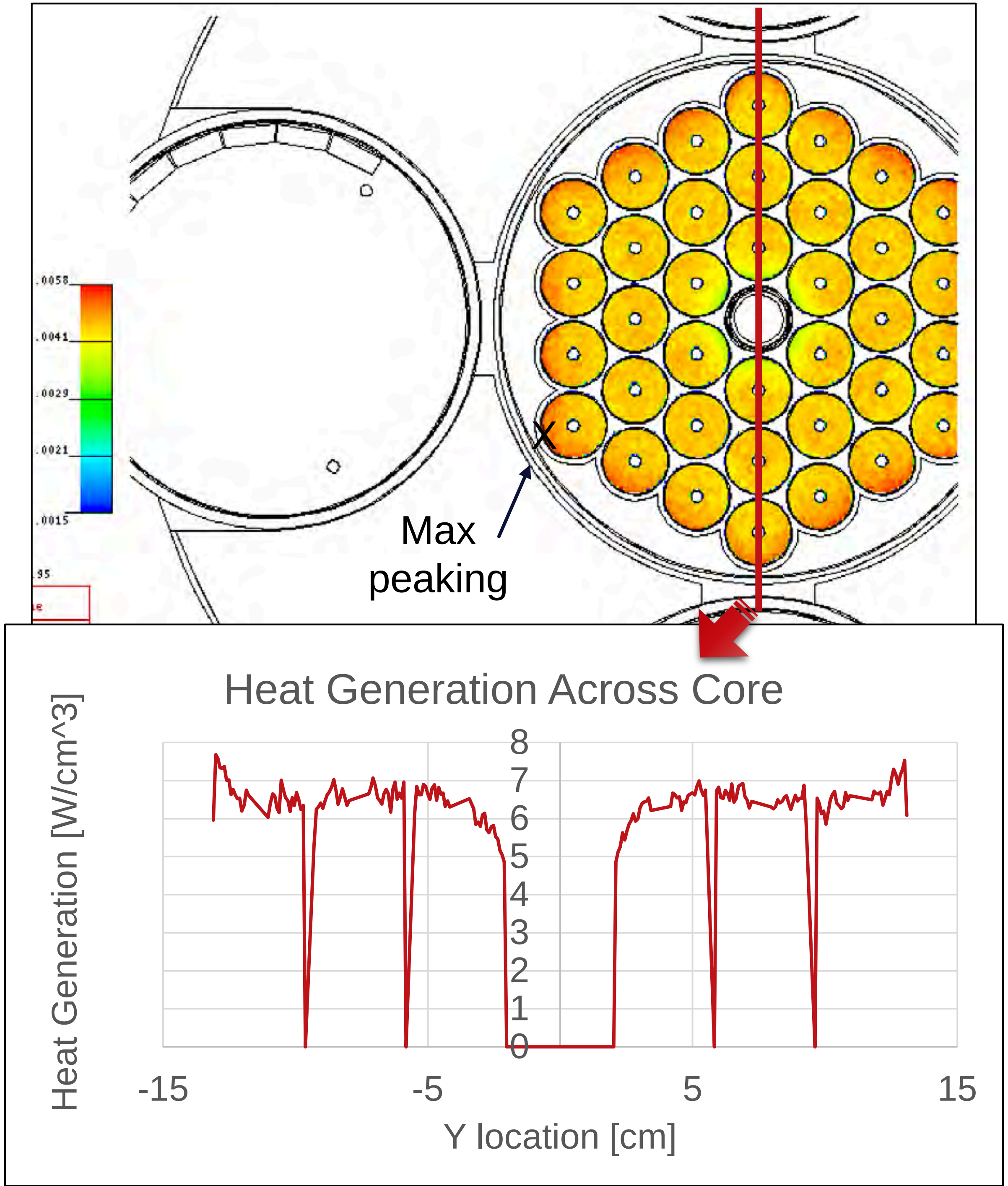
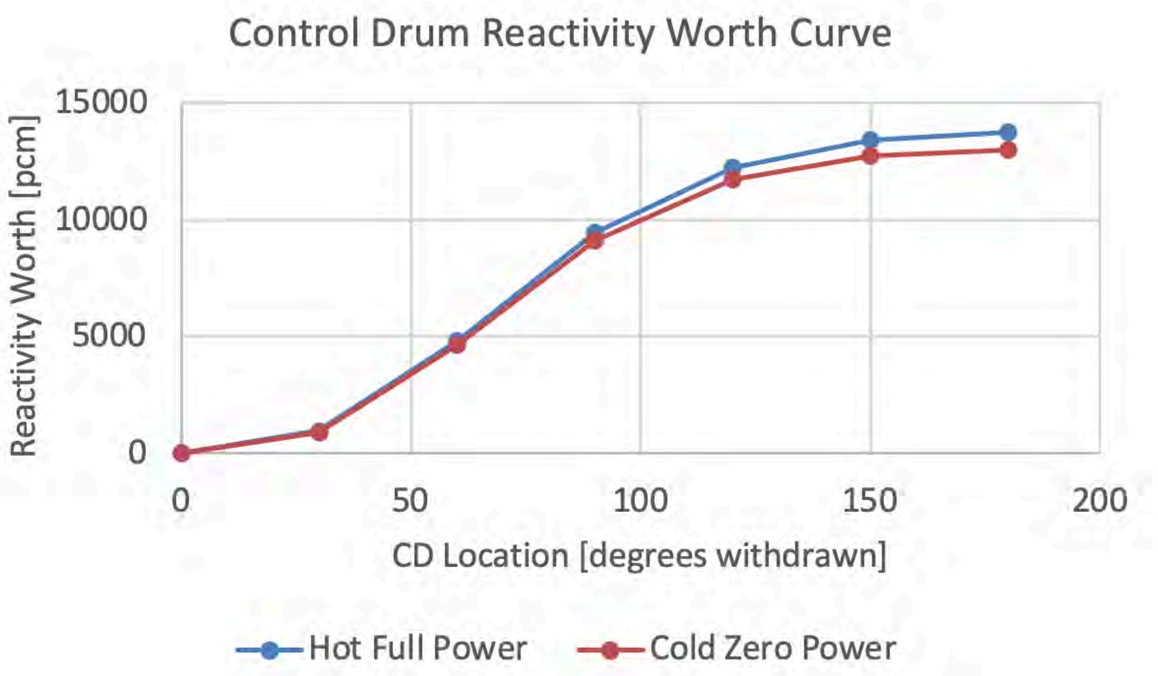
3D Power Peaking

- Power is relatively flat across core because of integrated moderator
- Power peaking in outer fuel rods
  - Expected from highly reflected system
- Power depression on interior surface of interior ring of fuel
  - Due to burnable absorber tube in central location
- Colorscale maximum is 9.12 W/cm^3 and minimum is 2.36 W/cm^3
- Max volumetric heat generation @ 30.9 cm elevation (marked with X)



Normal Operations: Control Drums Reactivity Worths

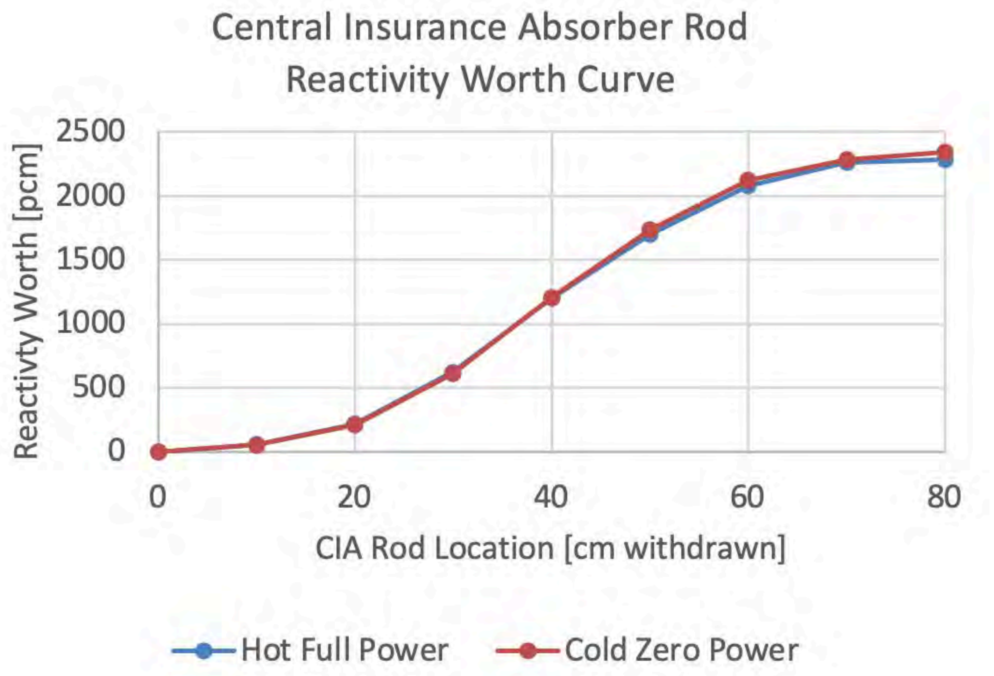
- Total reactivity worth:
  - $18.30 at HFP
  - $17.00 at CZP



HOT FULL POWER CONTROL DRUM WORTH CURVE			
CD LOCATION [DEGREES WITHDRAWN]	Keff	Reactivity Worth [pcm]	Reactivity Worth [$]
0	0.90279	0	0
30	0.91053	942	1.26
60	0.94386	4820	6.43
90	0.9868	9430	12.57
120	1.01468	12214	16.29
150	1.02721	13417	17.89
180	1.0305	13727	18.30

Normal Operations: CIA Rod Reactivity Worth

- Total reactivity worth:
  - $3.05 at HFP
  - $3.12 at CZP



Hot Full Power CIA Rod worth curve			
Location [cm withdrawn]	Keff	Reactivity Worth [pcm]	Reactivity Worth [$]
0	1.00414	0	0.00
10	1.00467	53	0.07
20	1.0063	214	0.29
30	1.01044	621	0.83
40	1.01641	1202	1.60
50	1.02159	1701	2.27
60	1.02556	2080	2.77
70	1.02749	2263	3.02
80	1.02773	2286	3.05

Normal Operations: Reactivity Coefficients

- UZrH fuel temperature reactivity coefficient
  - Strongly negative
  - Prompt (milliseconds)
- NaK Density, Metallic Beryllium
  - Small positive coefficients
  - Delayed (seconds to minutes)
- Pin Pitch Thermal Expansion
  - Small negative coefficient
  - Delayed (~minutes)
- Beryllium Oxide
  - Significant positive coefficient
  - Quite delayed (~1 minute – 10's of minutes)
  - Has been observed before (KRUSTY)

	Reactivity Coefficient [pcm/K]	1-sigma	Averaged over temperature range
UZrH Fuel	-5.22	0.15	293-1200 K
Beryllium oxide*	1.26	0.09	293-1200 K
Metallic beryllium*	0.30	0.06	293-1200 K
NaK Density	0.16	0.08	293-1000 K
Pin Pitch Thermal Expansion	-0.34	0.04	293-1200 K
Net Temperature Reactivity Coefficient	-3.84	0.42	293K-1200K

* Does not consider thermal expansion effects, which will cause the coefficients to be more negative

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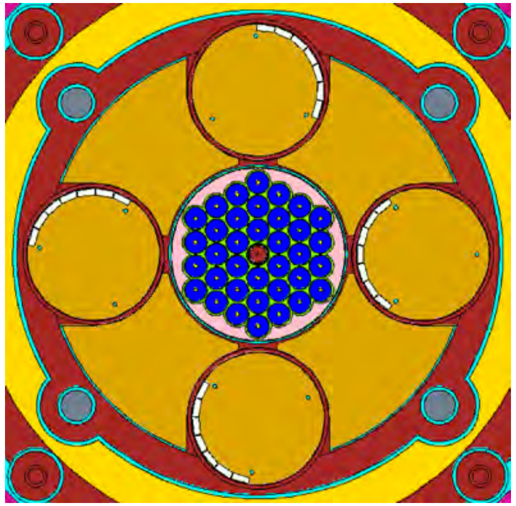
Excess Reactivity and Shutdown Margin

- 1 CD can bring MARVEL subcritical with 1 CD stuck out at HFP (2 other CDs @ critical)
- 1CD + any other control element can bring MARVEL shutdown and hold shutdown at CZP conditions
- MARVEL has sufficient shutdown margin under all scenarios 2/5 working control elements
  - Made possible by mechanical hardstops

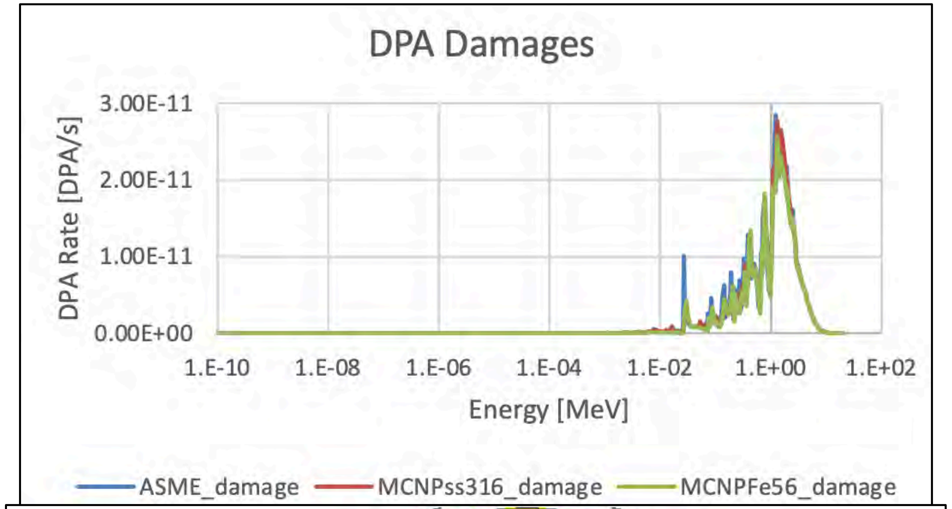


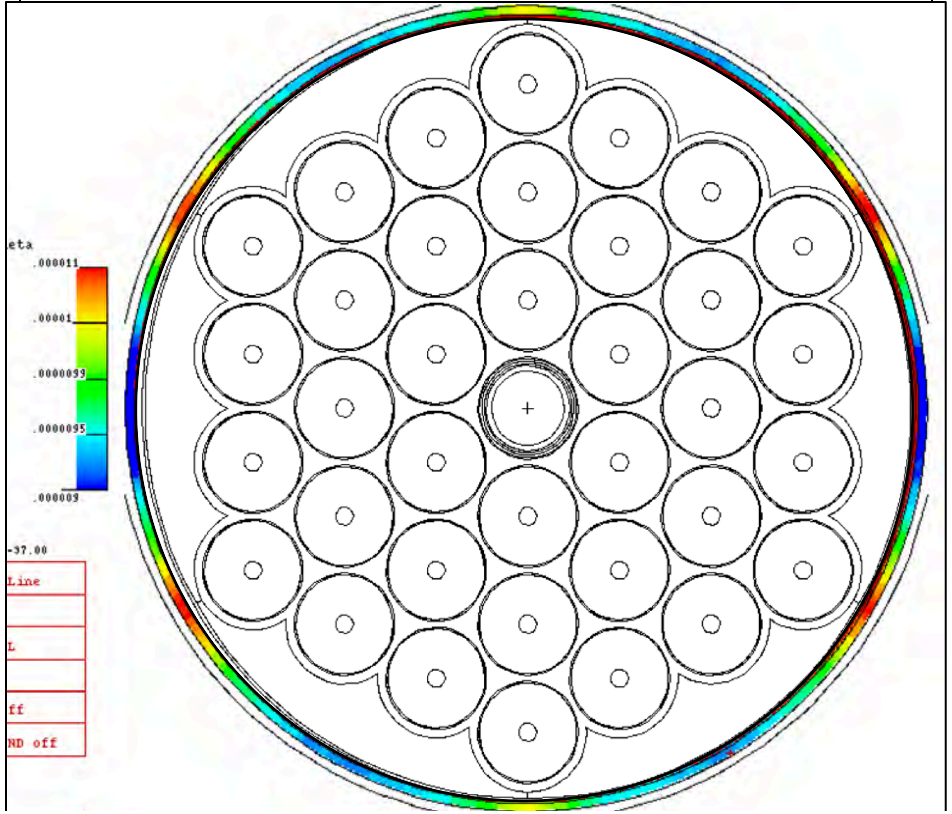
Excess Reactivity BOL			
	keff	1-sigma	Excess reactivity [pcm]
HFP	1.03654	0.00017	3525
CZP	1.0551	0.00015	5222

Scenario	Reactor conditions	Shutdown Margin [pcm]	Shutdown Margin [$]
1 CD stuck out @ hardstop limit 3 CDs fully inserted	HFP	7574	10.10
1 CD stuck out @ hardstop limit 3 CDs fully inserted	CZP	4903	6.54
Only CIA in 4 CD @ hardstop	HFP	1165	1.55
CIA + 1 CD in 3 CDs @ hardstops	HFP	4199	5.60
1 CD in 3 CDs @ hardstop CIA out	HFP	1626	2.17

Irradiation Damage to Core Barrel and Clad

- Used ASTM E693-17
  - "Standard Practice For Characterizing Neutron Exposures In Iron And Low Alloy Steels In Terms Of DPA"
- Core barrel irradiation damage plot
  - Taken at highest power elevation
  - Circumferential peaking factor of ~1.21
- Checked against "rule of thumb" correlation in NUREG/CR-7027
  - Agrees within 10%





Maximum scale: 0.0315 DPA/EFPY
minimum scale: 0.0258 DPA/EFPY

Average Irradiation Damage		
	1 EFPY	Lifetime (2 EFPY)
Core Barrel	0.026 DPA	0.052 DPA
"Hot Rod" Fuel Clad	0.049 DPA	0.098 DPA

Summary and Conclusions

- Fuel and Core System Design is mature with very few gaps
- FCS relevant uncertainties identified
  - Uncertainty management methodologies defined
- Neutronic analysis indicates acceptable operational and accident parameters
  - Significant negative inherent reactivity feedback contributing to a stable, safe design
  - Sufficient shutdown margin in all cases for normal and off-normal scenarios
  - Made possible by reactivity management strategies:
    - physical hardstops on control drums
    - “tunable” burnable poison loadings

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