Burning Weapons Grade Plutonium in Thorium and Uranium with Silicone-Carbide Cladding

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Presentation Overview

- Motivation
- Metrics for core comparison
- Methods
- Terms and nomenclature
- Results to date
  - PuO_2 in ThO_2 fuel (PuTh)
  - PuO_2 in UO_2 fuel (MOX)
  - All weapons grade plutonium
- Comparison of cores developed
- Necessity for safety analysis

Motivation

Country	Non-civilian Pu (MT)	Civilian Pu (MT)
United States	87.0	0
Russia	128	50.1
France	6.0	57.5
United Kingdom	3.5	91.2
China	1.8	0.014
Japan	0	47.1

- Large amounts of excess weapons and civilian plutonium can be found in various countries
- Taken for the *International Panel on Fissile Materials*

Metrics for Comparison

- Is SiC an improvement over Zircaloy for the burning of excess weapons Plutonium in PWRs?
  - Once-through burning, using the same reload pattern and the same core power rating
    - Weapons Pu disposition in MOX
    - Weapons Pu disposition in thorium
- Metrics
  - Fissile fraction (vector) of the discharged Pu
  - Fraction of Pu remaining in fuel at discharge
  - Proliferation – multiples of critical mass for fissile isotopes

Analysis Method

1

- Neutronic Analysis (Core Design)
  - CASMO/SIMULATE
  - Serpent

2

- Fuel Performance Analysis
  - FRAPCON

3

- Accident Analysis
  - S3K

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Initial Isotope Comparison

Weapons Grade

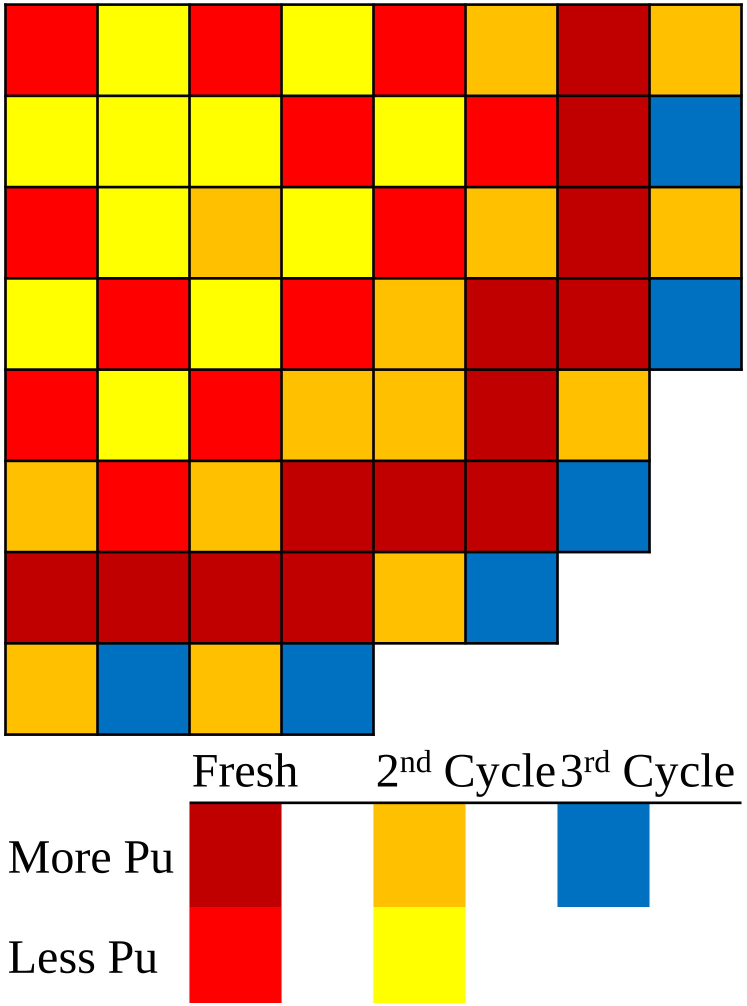
Isotope	Weight Percent
Pu-238	0.012
Pu-239	93.8
Pu-240	5.8
Pu-241	0.23
Pu-242	0.022
Am-241	0.13

Reactor Grade (~50MWd/kg)

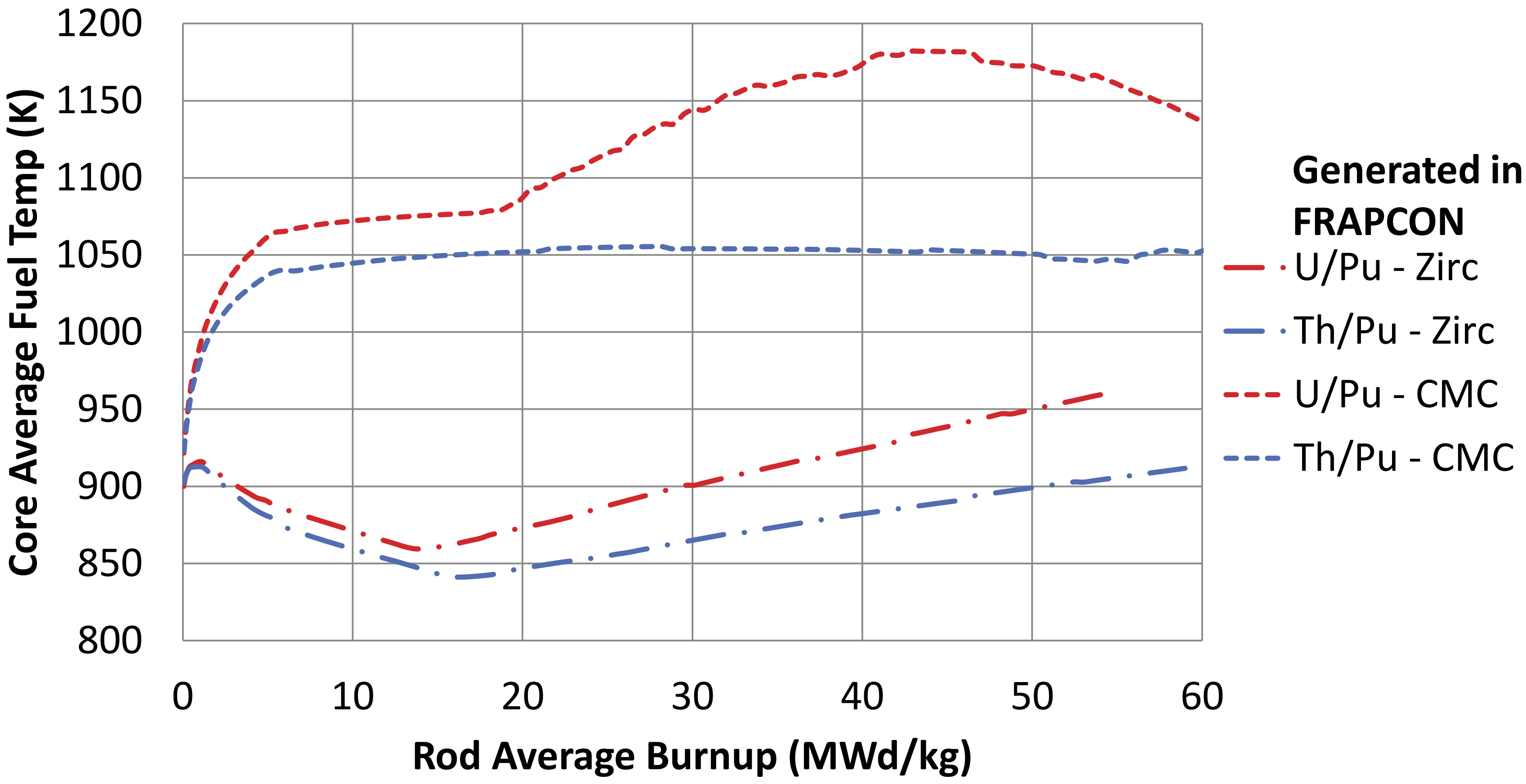
Isotope	Weight Percent
Pu-238	1.3
Pu-239	60.2
Pu-240	24.3
Pu-241	8.3
Pu-242	5.1
Am-241	0.8

Thorium Cores with Weapons Pu

- Assemblies designed and modeled in CASMO
- Core loading pattern developed using SIMULATE
- Designed to meet:
  - FdH: 1.55
  - F_Q: 2.0
  - Cycle burnup: ~492 EFPD
  - MTC: <+5 pcm/F at HZP, <0 pcm/F at HFP
  - SDM > 1300 pcm with B_4C rods
- Contains two different assembly types
  - Shapes power peaking in the core



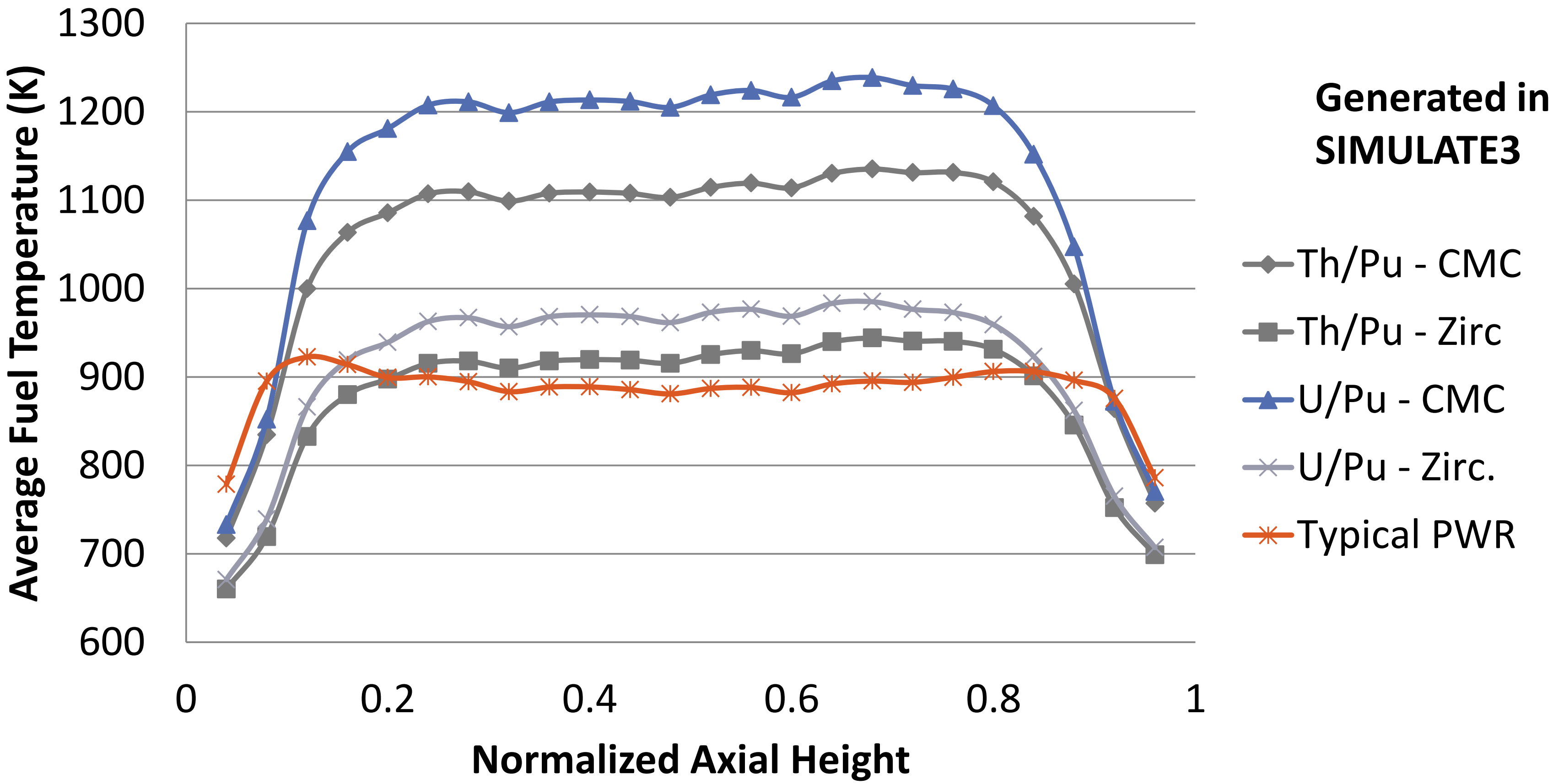
Fuel Temperature Dependence on Burnup



Zirc: Temperature initially decreases due to gap closure and then increases due to decrease in fuel thermal conductivity and fission gas release.

CMC: Temperature initially increases due to decrease in cladding thermal conductivity and continues to increase due to presence of an open gap filled with fission gases.

Volume-Averaged Fuel Temperature at EOL



Fuel Pin Specifications

SiC tri-layer tubes are thicker than Zr tubes

Geometry	Zircaloy	SiC
Fuel Pellet Outer Diameter (cm)	**0.819**	**0.781**
Cladding Inner Diameter (cm)	0.836	0.798
Cladding Outer Diameter (cm)	0.950	0.950
Pitch (cm)	1.26	1.26
Density (g/cm^3)	6.55	2.85

Reactor Conditions

Parameters	4-Loop PWR
Core thermal power (MW)	3587.0
Power density (kW/L)	109.9
Core Coolant flow rate (MT/hr)	67047
System pressure (MPa)	15.5
Core inlet temperature (K)	565.71
Number of fuel assemblies	193
Active Fuel Length (m)	3.66

PWR with Weapons Grade Pu in MOX

- Two different claddings compared
    - SiC
    - Zircaloy
- IFBA used as a burnable poison (zirc. boride coating of 12 micron thickness on ~60% of the fuel pellets)
- Developed to meet the same criteria as the thorium cores
    - Cycle length
    - Safety

Comparison of MOX and Thorium Cores

Fuel	U – Pu	U - Pu	Th – Pu	Th - Pu
Cladding	SiC	Zirc	SiC	Zirc
Cycle Burnup (MWd/kg)	21.5	19.5	23.5	21.3
Plutonium Initial Wt% Heavy Metal	5.69	5.48	6.79	6.51
Pu mass change of a batch - kg	674	629	1452	1455
Percent Pu burned- %	32.7	28.8	64.7	61.4

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Percent Pu burned- %	32.9	28.8	**65.4**	62.0

Extending to a Higher Burnup

- Linear theory
    - Direct correlation between the amount of fissile material and the achievable burnup
- Higher burnups enabled by SiC and thorium combination
- Why SiC may extend cycle length
    - Possibly lower corrosion rate
    - Proper application of an EBC
- Currently limiting burnup
    - Zirc limited in terms of residence in water
    - At higher burnups, fuel less reactive due to fission products

Max Pin Burnup (MWd/kg)	Wt% Initial Pu	Percent of Initial Pu at Discharge
60	6.4	38.0
80	7.9	32.9
100	9.3	27.8

Comparison of MOX and Thorium

- Percent of Pu Burned
- Vector of Discharged Pu
- Proliferation
  - Multiples of critical mass

Fraction of Initial Plutonium Discharged

Fuel	Clad	Percentage (%)
Th - Pu	Zircaloy	38.0
	SiC	34.6
U -Pu	Zircaloy	71.2
	SiC	67.1

- A higher fraction burned is found with SiC
  - Proliferation benefit
  - Economic benefit
- A significant amount of Pu-239 is bred in MOX due to the presence of U-238
  - This decreases the fraction burned

Plutonium Discharge Vectors: Isotopic Percentage of total Pu and Am

Isotope	Initial	Pu - Th	U-Pu
Pu-238	0.012	0.7	0.5
Pu-239	93.8	32.8	52.0
Pu-240	5.8	34.5	27.0
Pu-241	0.23	22.7	15.7
Pu-242	0.022	8.0	3.9
Am-241	0.13	1.2	0.8

Critical Mass Multiples in a Discharged Assembly

Fuel	Clad	Pu	U-233
Th - Pu	Zircaloy	0.53	0.72
	SiC	0.46	0.66
U - Pu	Zircaloy	0.91	-
	SiC	0.80	-

- Critical mass
    - 20 kg of reactor grade Pu
    - 8.4 kg of U-233
- U-233 is inseparable from U-232, which emits strong gamma radiation
- Th-Pu plutonium vector is also preferable, since less fissile material

Safety Analyses, comparison to typical

- Different characteristics of the reactor necessitate new safety analyses
- Delayed neutron fraction is smaller in thorium – (Beta)
- Prompt neutron lifetime is smaller in Thorium
    - Larger if preferable since the reaction is more controllable

Parameter	Typical PWR	Th/Pu	U/Pu
Delayed Neutron Fraction -	0.0061	0.0029	0.0033
Prompt Neutron Lifetime – sec.	16×10^{-6}	7.9×10^{-6}	7.3×10^{-6}

Table parameters at HFP at BOC for CMC clad

Safety Analyses – Coefficients for SiC Cladding

- Fuel temperature coefficient and
  - Amount of negative reactivity feedback when temperature raises
- Moderator temperature coefficient
  - Should always be negative at full power
- Power coefficient is a combination of fuel and moderator feedback

Parameter	Typical PWR	Th/Pu	U/Pu
Fuel Temperature Coefficient - pcm/F	-1.43	-1.43	-1.30
Moderator Temperature Coefficient - pcm/F	-17.9	-18.1	-21.5
Power Coefficient pcm/%	-16.4	-19.5	-19.0

Table parameters at HFP at BOC for CMC clad

Acknowledgement

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Questions?

Backup Table

Fuel	U– Pu		Th– Pu	
Cladding	SiC	Zirc.	SiC	Zirc.
Cycle Burnup MWd/kg	21.5	19.5	23.5	21.3
Plutonium Initial Wt% Heavy Metal	5.69	5.48	6.79	6.51
Initial Loading Mass Pu - kg	2058	2183	2246	2369
Discharge Mass Pu – kg	1384	1553	793	914
Pu mass change - kg	674	629	1452	1455
Percent Pu burned - %	32.7	28.8	64.7	61.4