THORIUM-BASED FUEL DESIGN FOR INCINERATION OF EXCESS WEAPON GRADE PLUTONIUM IN EXISTING PWRs*

A. GALPERIN
Ben-Gurion University of the Negev,
Israel

M. TODOSOW
Brookhaven National Laboratory,
New York, United States of America

Abstract. The main objective of the present design is to use thorium based fuel for an efficient incineration of excess weapon grade plutonium. A heterogeneous, seed-blanket (SBU) fuel assembly design was adopted. The main design approach is to use plutonium as a seed fuel providing neutrons to a subcritical blanket loaded mainly with thorium. The seed subassembly fuel consists of Pu/Zr metal alloy and the blanket subassembly fuel consists of Th-Pu-U mixed oxide. The plutonium provides a fissile component, while natural uranium part is added to denature (dilute) the ^{233}U built-up in thorium. This design is usually designated as the Radkowsky Thorium Fuel (RTF). A simulation of an "equilibrium" cycle demonstrated the feasibility of the RTF design with an efficient plutonium incineration. Advantages of thorium-based SBU assembly design in compliance with the standard PWR control system requirements are also demonstrated.

Why thorium-based fuel and SBU geometry?

The efficiency of incinerating the excess weapon grade stockpiles by utilization of the mixed oxide fuel (MOX) is significantly reduced by the production of the "new" or the second generation plutonium. For the MOX fuel based on natural uranium, residual plutonium in discharged fuel amounts to 60-70% of the initial plutonium load. Thus, using the MOX fuel is equivalent to a transformation of the pure weapon grade plutonium into reactor grade plutonium contained within the discharged fuel. Replacing the uranium by thorium as a fertile material for plutonium incinerating cycle is investigated in this work in order to improve the efficiency of the plutonium incineration cycle.

A well known design problem associated with heavy plutonium loading required in the plutonium incinerating cycles is the reactivity control problem. The higher thermal absorption cross-section of plutonium, as compared with uranium, causes reduction of the reactivity worth of all LWR control mechanisms: control rods, burnable poisons and soluble poison, by approximately a factor of two. Several solutions were proposed and investigated, such as using enriched boron, gadolinium (Gd), or even additional control rods to compensate this effect.

An alternative approach is offered by a heterogeneous, SBU fuel assembly geometry. The SBU geometry allows separate lattice optimization for the seed and blanket parts. The seed region is well moderated ($V_m/V_f = 3.5$) while the blanket part lattice is similar to a standard PWR ($V_m/V_f = 1.7$). In the present design the control rods and burnable poisons are concentrated in the seed region with a high moderator content. Thus, the reactivity worth of the control mechanisms is increased.

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Fuel Management Scheme.

The fuel management scheme is based on two separate material flows for the seed and blanker fuels. The seed part of the core (consisting of all seed sub-assemblies) is managed in three batches, each residing 300 full power days (FPD's). Thus, the seed in-core residence time is 900 FPD's. The blanket is managed as a single batch residing for 6 seed cycles, i.e. 1800 days. This fuel management scheme is designed to assure an efficient utilization of thorium, in terms of natural uranium savings. In addition, a 3-batch seed reload scheme was chosen to provide an "optimal" balance between two different performance parametors: the plutonium incineration rate and the residual plutonium content in the discharged fuel. The first one should be maximized and the second one should be minimized. The Th-based fuel cycle proposed and investigated in this work was designated for a standard PWR core, similar to Westinghouse and/or EPR design. The design description is given below and in Figure 1:

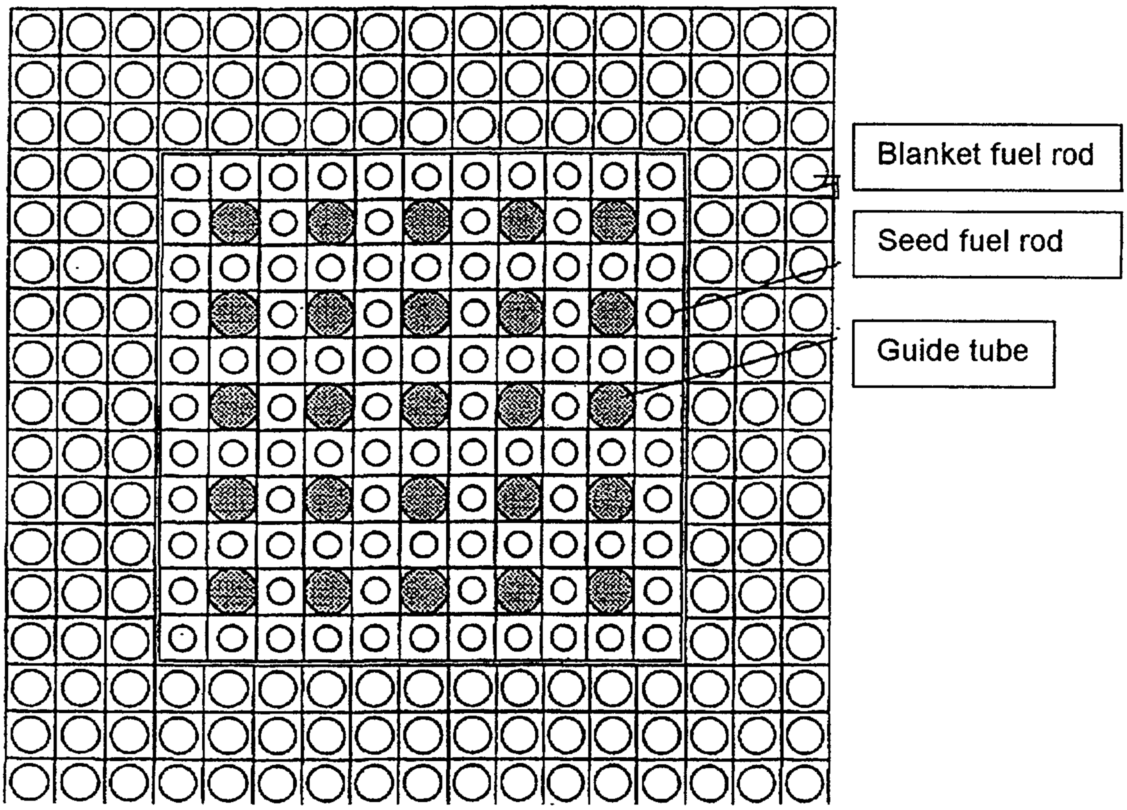

Figure 1. A Schematic View of a Seed-Blanket Unit (1/4 assembly)

Core Design Parameters

Power output (MW(th)) = 3,400
Number of fuel assemblies (SBU's) = 193
Average Power Density (w/c^3) = 104
Total coolant flow (kg/s) = 194X0

Seed Design Parameters:

Assembly Volume fraction (%) = 40.1
Composition: 7.0 weight % Weapon grade Pu
93.0% weight % Zr alloy.
Number of fuel rods = 96
Number of guide tubes = 24 (+ one central)
Moderator to Fuel Volume Ration = 3.535
Lattice (cell positions): 11x11
Cell Geometry: fuel pellet radius (cm) = 0.310
clad outside radius (cm) = 0.350 (no gap)
lattice pitch (cm) = 1.205
Average Fuel temperature (°C) = 470.0
Average Cladding temperature (°C) = 340.0
Average Moderator temperature (°C) = 306.0
Average Specific Power (MW/t) = 186.0

Blanket Design Parameters:

Assembly Volume fraction (%) = 59.9
Composition: O.8% weapon grade Pu oxide +
8.2% Natural U oxide +
91.0% Th oxide.
Cell Geometry: fuel pellet radius; (cm) = 0.4095
clad outside radius (cm) = 0.475
lattice pitch (cm) = 1.258
Average Fuel temperature (°C) = 750.0
Average Cladding temperature (°C) = 340.0
Average Moderator temperature (°C) = 306.0
Number of fuel rods = 168
Number of guide tubes = 0
Moderator to fuel volume ratio = 1.659
Average Specific Power (MW/t) = 30.0

Results of calculations (equilibrium cycle).

A full simulation of the proposed cycle involves the calculation of a single blanket life-time, which is equivalent to 6 seed replacement cycles. In this work this full simulation is approximated by a calculation of the "equilibrium" cycle assuming that its performance parameters are representative of a complete simulation, i.e. 6 seed cycles.

The equilibrium cycle for a 3-batch fuel management scheme is represented by a core which includes three seed fuel types - fresh, once-burned, and twice-burned, and a single blanket fuel type with an averaged burnup value of 900 FPD's. Burnup dependent reactivity and power sharing between seed and blanket are summarized below. The hot channel power density and a summary of the mass flow for all important isotopes are in the following tables.

Reactivity, power sharing, and fuel temperature summary:

days	Keff	seed (MW)	blanket (MW)
0	1.06931	507.0	343.0
20	1.06460	503.4	346.6
100	1.04S01	490.6	359.4
160	1.03633	481.2	368.8
200	1.02S45	474.7	375.3
260	1.01613	464.6	3H5.4
300	1.00745	457.5	392.5
310	1.00522	455.6	394.3

Reactivity Control.

A series of assembly level calculations were carried out to evaluate the reactivity worth of the different control mechanisms and the moderator temperature coefficients. It should be noted that the values generated on the assembly level represent a "core averaged" evaluation and are applicable only for the comparison of different cycle options. Several U-Pu based cycle options were considered in order to obtain a clear picture of the reactivity controllability issue. The cycle options considered are designated as follows:

PWR - A standard slightly enriched U fuel,
MOX - A mixed oxide fuel (U-Pu oxide, reactor grade plutonium),
MOX239 - A mixed oxide fuel (U-Pu oxide, weapon grade plutonium),
TMOX - A thorium based homogeneous mixed oxide fuel (Th-Pu oxide reactor grade Pu),
TMOX239 - A thorium based homogeneous mixed oxide fuel (Th-Pu oxide weapon grade plutonium),
RTF239 - Radkowsky thorium fuel seed-blanket (weapon grade plutonium).

Summary of Performance Parameters.

A seed-blanket heterogeneous fuel assembly design combined with a Th-based fuel offers an attractive option for a plutonium-incineration cycle. Two main problems associated with plutonium incineration in LWR's: an overall efficiency of the plutonium destruction and the reactivity control issue are addressed adequately by the flexibility of the SBU geometry. A preliminary design analysis indicated that approximately 700 kg of plutonium per year may be incinerated and the residual plutonium "quality" is sufficiently deteriorated to reduce the danger of its diversion to weapon material. A set of assembly level calculations also shows that only 10% reduction in the reactivity worth of control rod and soluble boron reactivity control mechanisms for the RTF design, compared with approximately 50% reduction for all other fuel cycles options.

Hot Channel Power Density Summary:

Axial average power density: seed: 1240.3 (w/c^3 in fuel)
blanket: 247.6 (w/c^3 in fuel)
SBU: 126.46 (lattice)

Cycle Mass flow Summary (kg)

Core charge	Core inventory		Core discharge
seed fresh(64)	BoC seed fresh(64)	EoC seed once(64)	
Pu239 873.07 Pu240 55.73	Pu239 873.07 Pu240 55.73	Pu238 0.05- Pu239 546.37 Pu240 125.09 Pu241 32.50 Pu242 2.15	
	seed once(65)	seed twice(65)	
	Pu238 0.04 Pu239 565.82 Pu240 128.33 Pu241 29.10 Pu242 1.80	Pu238 0.25 Pu239 276.51 Pu240 165.34 Pu241 53.91 Pu242 9.26	
	seed twice(64) Pu238 0.21 Pu239 278.72 Pu240 163.40 Pu241 52.95 Pu242 8.60	seed out(64) Pu238 0.83 Pu239 91.54 Pu240 154.35 Pu241 57.67 Pu242 21.97	seed out(64) Pu238 0.83 Pu239 91.54 Pu240 154.35 Pu241 57.67 Pu242 21.97
Initial Load	blanket(193)		
47,484.0	Th232 46098.16	Th232 45629.82	
-	Pa231 3.95	Pa231 4.38	
-	U232 2.62	U232 3.73	
-	U233 633.70	U233 708.64	
-	U234 81.19	U234 115.20	
33 .4	U235 20.32	U235 26.09	
4,664.8	U238 4376.22	U238 4279.75	
-	Pu238 1.33	Pu238 2.10	
475.0	Pu239 63.09	Pu239 59.82	
30.3	Pu240 42.91	Pu240 29.95	
	Pu24i 43.78	Pu241 33.94	
	Pu242 35.12	Pu242 40.78 1	

Weapon grade plutonium incineration.
Summary

	Total plutonium incinerated (kg/a)	Pu239 incinerated (kg/a)	Residual Fraction
seed	602	778	0.35
blanket	95	79	0.24
TOTAL	**697**	**857**	

Summary of Reactivity worth values.

Fuel Cycle Option	Soluble Boron ($\Delta\rho$/ppm B)	Control rods worth (all rods inserted)
PWR	-6.50e-03	-0.3332
MOX	-2.97e-03	-0.2157
MOX239	-3.21e-03	-0.2217
TMOX	-3.05e-03	-0.23 IX
TMOX239	-2.97e-03	-0.223
RTF239	-5.X2e-03	-0.2936

Conclusion: The Radkowsky thorium fuel seed-blanket design demonstrated an efficient weapon grade plutonium incineration: high destruction rate and relatively low residual content. In addition, the reactivity control system of existing PWR cores seems adequate for the Radkowsky thorium fuel (RTF) plutonium -incinerator design.