

# STUDY OF THORIUM FUEL CYCLES BURNING PLUTONIUM IN THE MODULE- HTR\*

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**Abstract.** The advantages of HTR module pebble bed reactor and thorium fuel cycles are discussed in this paper. In order to reduce plutonium stockpiles, the thorium fuel cycles are used for HTR module, and plutonium is used as fissile material. The equilibrium core is calculated and analysed for the case of the different heavy metal loading and enrichment. For the case of more than 11 g heavy metal per sphere has a negative temperature coefficient, and the maximum temperature of fuel elements under regular operation and loss of coolant accident is lower than 1500°C. Therefore the feasibility of above scheme is studied.

## 1. INTRODUCTION

Since development work on the 200 MW-MODULE Pebble Bed reactor began in 1979 in Germany, the HTR module is considered as one kind of the advanced nuclear reactors with completely passive safety properties [1]. Under any accident the release of radioactivity in HTR module is not possible even without technical safety equipment in operation. The coating of the coated particle embedded in the fuel elements does not permit any radioactive gas or metallic fission products to escape from intact fuel particles up to a temperature of 1600°C.

Residual heat can be removed from the core, even under extreme accident conditions, by means of passive heat transfer processes based on natural laws, such as heat conduction and radiation. The HTR Module also has a negative reactivity temperature coefficient. Therefore a core temperature rise can offset any reactivity increase as a result of reactivity accidents.

The spherical fuel elements are used for the HTR Module. Because these fuel elements are able to receive a very great variety of fuel cycles, this fuel permits a wide flexibility in the design of the reactor. A thorium-based fuel cycle in the HTR Module would produce a small amount of toxic fuel waste or long-lived radiotoxic waste. In order to reduce plutonium stockpiles, plutonium is used for thorium fuel cycle as fissile material in HTR Module.

## 2. HTR MODULE AND CALCULATION

The layout of HTR Module is shown in Fig. 1. Main design parameters are listed in Table I. The power density is 3MW/m<sup>3</sup> and reactor dimensions have been optimized to provide sufficiently high passive removal of the decay heat under loss of coolant, thus keeping the fuel temperature below 1600°C. The weight of heavy metal and enrichment in the sphere are optimized for burning as much plutonium as possible, and keeping a negative temperature coefficient. Under normal operation the temperature for the spectrum calculation is listed Table II.

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\* 1998 meeting.

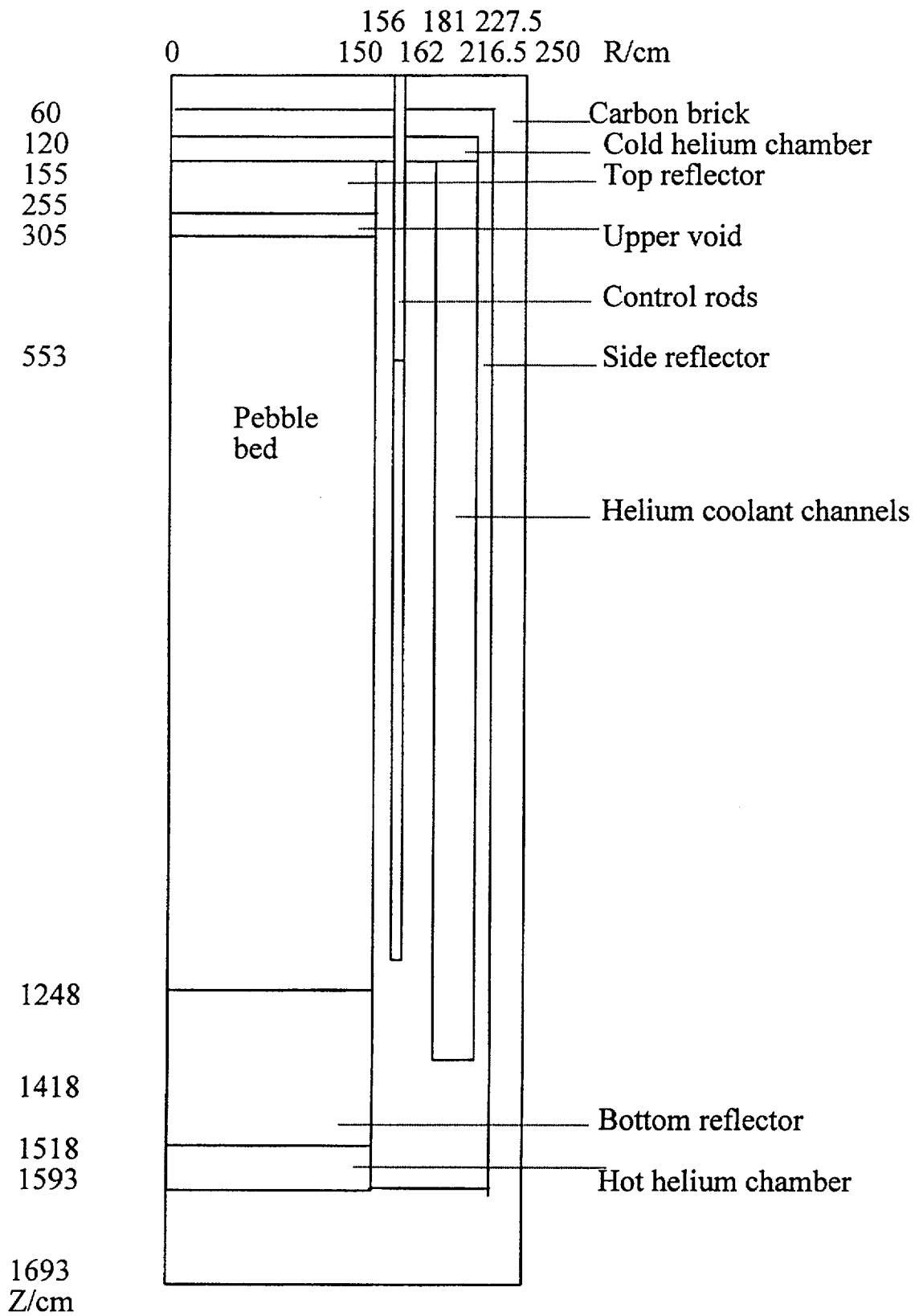


Figure 1. The layout of HTR module.

Table I. Main design data of the HTR module

Reactor-Core	
Thermal power MW	200
Power density MW/m <sup>3</sup>	3
Core height/diameter m	9.43/3.0
Heating of helium °C	200→700
Helium pressure bar	60
Helium mass flow rate kg/s	85.4
Fuel element	
Diameter of pebble cm	6
Diameter of fuel zone cm	5
Density of graphite in the matrix and outer shell g/cm <sup>3</sup>	1.75
Volumetric filling fraction of elements	0.61
Number of passes of spheres through the core	10
Coated particle	
Radius of the kernel cm	0.025
Fuel composition	PuO <sub>2</sub> -ThO <sub>2</sub>
Density of the kernel g/cm <sup>3</sup>	10.5
Isotopic composition of plutonium %	Pu-239/Pu-240=94/6
Coating layers	C/C/SiC/C
Density g/cm <sup>3</sup>	1.05/1.90/3.18/1.90
Thickness cm	0.009/0.004/0.0035/0.0035

Table II Temperature for spectrum calculation

Zone(cm)	Temperature(°C)
0<R<150 305<Z<1428	Fuel:586 moderator:576
0<R<255 0<Z<255	203
0<R<150 255<Z<305	265
150<R<162 155<Z<1248	430
162<R<250 155<Z<1248	250
0<R<150 1248<Z<1518	748
0<R<150 1518<Z<1693	320
150<R<250 1248<Z<1693	320

The VSOP code [2] is used for calculation of HTR Module. The reactor is divided into eleven spectrum zones. The pebble bed is divided into five spectrum zones. The thorium absorption cross sections of resolved and unresolved resonances are generated by ZUT-DGL code basing on resonance data.

### 3. Calculation results

The equilibrium core is calculated for the case of the different heavy metal loadings and enrichments. The main results for a heavy metal loading of 7g/sphere are given in the Table III.

Table III. Main data of the equilibrium core under 7g(HM)/sphere

Enrichment(%)	8 9.6 11
$K_{eff}$	0.9430 1.0073 1.0402
Burnup $MW \cdot d/t_{HM}$	97325 100925 105595
Fuel element residence time days	1258 1258 1258
Conversion ratio	0.575 0.518 0.493
Inventory of $^{233}U$ (kg/GW(th))	151.5 138.74 131.26
Inventory of $^{239}Pu$ (kg/GW(th))	97.65 214.79 321.54
Inventory of $^{232}Th$ (kg/GW(th))	11249.92 11047.86 10896.41
Supply of $^{239}Pu$ (kg/GW(th))	0.8271 0.9875 1.1322
Discharge of $^{239}Pu$ (kg/GW(th))	0.0002 0.0035 0.0132
Consumption of $^{239}Pu$ (kg/GW(th))	0.8269 0.9840 1.1190
Utilization of the loaded $^{239}Pu$ %	99.98 99.65 98.83

Table IV. Main performance for different heavy metal loading

Heavy metal loading	g/sphere	7	9	11	13
Enrichment	%	9.6	10	11	12
Burnup	$MW \cdot d/t_{HM}$	100925	101828	102628	103783
Fuel element residence time	days	1258	1618	1977	2336
Conversion ratio		0.518	0.535	0.549	0.569
Power peaking max./avg.		4.44	3.54	2.86	2.61
Max. power per ball	kW /ball	2.47	1.97	1.59	1.45
Core leakage	%	10.04	8.97	8.21	7.84
Neutron flux	$E+14/(cm^2 \cdot s)$				
Avg. thermal flux	(<1.86ev)	0.4176	0.2745	0.1752	0.1277
Avg. fast flux	(>0.1Mev)	0.2402	0.2376	0.2357	0.2373
Avg. total flux		1.2060	1.0479	0.9345	0.8843
Temperature coefficient	( $\Delta k/k$ )				
Fuel	( $10^{-5}$ )	-1.59	-2.02	-2.35	-2.70
Moderator	( $10^{-5}$ )	3.68	0.883	-1.49	-2.48
Reflector	( $10^{-6}$ )	2.82	2.34	2.21	1.89

The equilibrium status is calculated for enrichment 8%, 9.6% and 11% respectively. With the enrichment increment,  $K_{eff}$  value increases, conversion ratio decreases, consumption of  $^{239}Pu$  increases and utilization ratio of the loaded  $^{239}Pu$  decreases.

The pebble bed reactor operates by continuative loading and discharging of fuel elements. Therefore little excess reactivity is required in normal operation. The case of enrichment 9.6% is also able to operate.

In order that the reactor has negative moderator temperature coefficient, heavy metal loading in sphere is increased gradually and enrichment is adjusted so that  $K_{eff}$  value of core is around 1.01. The results for heavy metal weight in sphere 7,9,11,13 g are given in Table IV and Table V.

Table IV shows that as heavy metal weight in sphere increases the enrichment should increase for retaining a close  $K_{eff}$  value, the conversion ratio increases, moderator temperature coefficient changes from positive to negative.

Table V. Inventory, supply and discharge of main isotope

Heavy metal loading g/ball	7	9	11	13
Inventory (kg/GW(th))				
U-233	138.74	194.5	254.82	322.48
Pu-239	214.79	359.60	664.28	1031.45
Pu-241	100.54	156.24	241.75	326.27
Th-232	11047.86	14115.14	17027.33	19835.31
Pu-240	133.19	161.14	203.33	243.55
Pu-242	48.29	56.18	56.32	57.81
Supply-discharge (kg/GWd(th))				
U-233	0-0.1903	0-0.2075	0-0.2269	0-0.2409
Pu-239	0.9875-0.0035	1.0279-0.0103	1.1300-0.0408	1.2315-0.0861
Pu-241	0-0.0400	0-0.0580	0-0.1015	0-0.1364
Th-232	8.9653-8.6071	8.9164-8.5441	8.8043-8.4241	8.6896-8.2976
Pu-240	0.0633-0.0219	0.0659-0.0219	0.0724-0.0319	0.0789-0.0399
Pu-242	0-0.0684	0-0.0646	0-0.0586	0-0.0532
Consumption of Pu-239 (kg/GWd(th))	0.9840	1.0176	1.0892	1.1454

Table V shows that with increment of heavy metal loading per sphere weight of U-233 and  $^{239}\text{Pu}$  in equilibrium code increases, weight of  $^{233}\text{U}$  and  $^{239}\text{Pu}$  in discharged spheres increases, consumption of  $^{239}\text{Pu}$  increases.

The thermal hydraulics evaluation in the case of a heavy metal loading per sphere of 13 g and an enrichment in the fresh element of 12%, is performed. The temperature distribution of the regular operation is calculated. The temperature of spectrum zones is listed Table VI. The temperature value in Table VI is close to that in Table II. The maximum temperature of fuel elements is 779°C. For the Loss of Coolant Accident (LOCA) residual heat can be removed from the core to surrounding graphite structures and then to the surface coolers through natural process. The variance of the relative decay power (relative to full power) is outlined in Fig. 2. The temperature transients of the core and pressure vessel are indicated in Fig. 3. The maximum temperature of core reaches at maximum value 1448°C at about 106 hours after shutdown.

Therefore a thorium fuel cycle, burning plutonium, in the HTR module is entirely feasible.

Table VI. Temperature of spectrum zones

Zone(cm)	Temperature(°C)
0<R<150 305<Z<493.6	Fuel:340.90 moderator:331.21
0<R<150 493.6<Z<682.2	Fuel:456.41 moderator:442.44
0<R<150 688.2<Z<870.8	Fuel:569.58 moderator:554.95
0<R<150 870.8<Z<1059.4	Fuel:658.30 moderator:645.94
0<R<150 1059.4<Z<1248	Fuel:711.62 moderator:703.37
0<R<255 0<Z<255	192.28
0<R<150 255<Z<305	264.71
150<R<162 155<Z<1248	427.62
162<R<250 155<Z<1248	260.30
0<R<150 1248<Z<1518	696.24
0<R<150 1518<Z<1693	342.28
150<R<250 1248<Z<1693	342.28

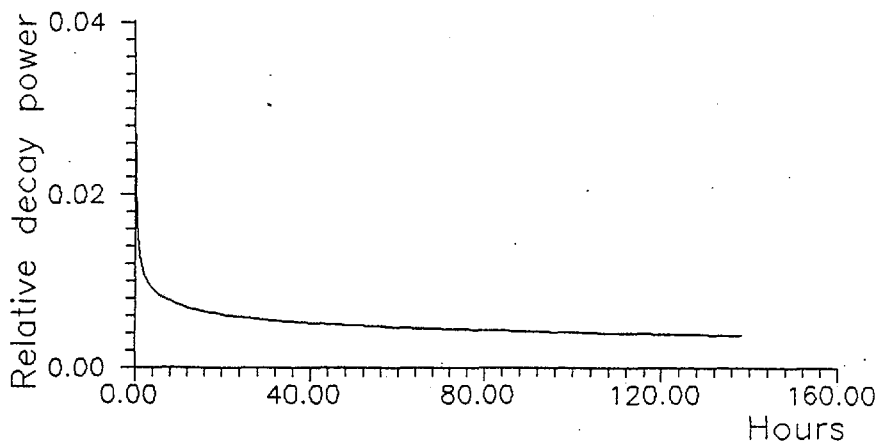


Figure 2. Variance of relative decay power.

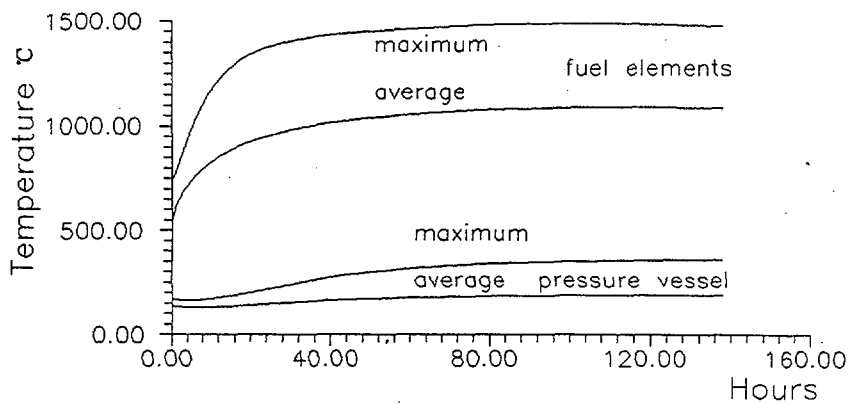


Figure 3. Temperature transients at loss of coolant.

### REFERENCES

- [1] TEUCHERT, E., HASS, K. A., " Features of Safety and Simplicity of Advanced Pebble Bed HTR's," (paper presented to the IAEA Technical Committee Meeting, 28-30 Nov. 1994).
- [2] TEUCHERT, E., HASS, K. A., RUTTEN, H. J., et al., V.S.O.P.( '94) Computer Code System for Reactor Physics and Fuel Cycle Simulation, Jul-2897 (1994).