

3. INDIVIDUAL CONTRIBUTIONS OF THE VARIOUS COUNTRIES

3.1. China

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3.1.1. Study of thorium fuel cycles burning weapons-grade and civil-grade plutonium in the MODULE- HTR

3.1.1.1. Introduction

Since development work on the 200 MW-MODULE Pebble Bed reactors began in 1979 in Germany, the HTR module is considered as one kind of the advanced nuclear reactors with completely passive safety properties [1,2]. At any accident the release of radioactivity in HTR module is prohibited, without putting technical safety equipment into operation.

The coating of the coated particle embedded in the fuel elements does not permit any radioactivity, radioactive gaseous 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 accidental conditions by means of passive heat transfer processes based on natural laws, such as heat conduction and radiation. HTR Module has negative reactivity temperature coefficient. Therefore the core temperature raise can offset reactivity increase as a result of reactivity accidents.

The spherical fuel elements are used for the HTR Module. Because fuel elements are able to receive a very great variety of fuel cycles, that ball permits really a wide flexibility in the conception of the reactor.

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, Pu(239 and 241) is used for thorium fuel cycle as fissile material in HTR Module.

3.1.1.2. HTR Module and calculation

Main design data are of the HTR-Module listed in Table 3.1. Power density 3 MW/m³ and reactor dimensions have been harmonized to provide sufficiently high passive removal of the decay heat at 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 negative temperature coefficient.

Under normal operation the temperature for spectrum calculation is listed Table 3.2. The VSOP code [3] 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.

TABLE 3.1.1. MAIN DESIGN DATA OF THE HTR MODULE

Reactor core	
Thermal power, MW	200
Power density, MW/m ³	3
Core height/diameter, m	9.43/3.0
Heating of helium, °C	250→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 ³	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 ₂ -ThO ₂
Density of the kernel, g/cm ³	10.5
Isotopic composition of weapons-grade plutonium, %	Pu-239/Pu-240 = 94/6
Isotopic composition of civil-grade plutonium, %	Pu-239/Pu-240/Pu-241/Pu-242 = 62.63/24.24/8.08/5.05
Coating layers	C/C/SiC/C
Density, g/cm ³	1.05/1.90/3.18/1.90
Thickness, cm	0.009/0.004/0.0035/0.0035

TABLE 3.1.2. 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<250 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

3.1.1.3. Calculation results

The equilibrium core is calculated for the case of the different heavy metal loading and enrichment.

3.1.1.3.1. Burning weapons-grade plutonium

The pebble bed reactor operates by continuous loading and discharging of fuel elements. Therefore a little excess reactivity is required in normal operation.

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, and 13 g are given in Tables 3.1.3 and 3.1.4.

Table 3.1.3 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 3.1.3. MAIN PERFORMANCE FOR DIFFERENT HEAVY METAL LOADING

Heavy metal loading	g/ball	7	9	11	13
Enrichment	%	9.6	10	11	12
Burnup	MWd/T _{HM}	100003	100140	100201	100173
Fuel element residence time	Days	1258	1618	1977	2337
Conversion ratio		0.513	0.529	0.542	0.560
Power peaking max./average		4.15	3.54	3.09	2.85
Max. power per ball	KW/ball	2.31	1.97	1.72	1.59
Core leakage	%	9.93	8.95	8.27	7.89
Neutron flux	E+14/(cm ² ×s)				
Average thermal flux	(<1.86ev)	0.4068	0.2662	0.1720	0.1247
Average fast flux	(>0.1Mev)	0.2384	0.2358	0.2340	0.2353
Average total flux		1.1896	1.0336	0.9260	0.8748
Temperature coefficient	(Δk/k/°C)				
Fuel	(10 ⁻⁵)	-1.82	-2.25	-2.62	-2.99
Moderator	(10 ⁻⁵)	5.10	1.73	-0.876	-1.99
Reflector	(10 ⁻⁶)	2.79	2.36	2.00	1.79

TABLE 3.1.4. INVENTORY, SUPPLY AND DISCHARGE OF MAIN ISOTOPE

Heavy metal loading	g/ball	7	9	11	13
Inventory	(kg/GWth)				
U-233		137.19	192.99	253.96	322.10
Pu-239		232.32	383.72	686.99	1077.73
Pu-241		101.48	158.62	243.05	327.11
Th-232		11050.10	14119.23	17030.09	19838.69
Pu-240		133.80	162.28	203.70	243.68
Pu-242		45.64	52.89	53.71	53.98
Supply-Discharge	(kg/GWDth)				
U-233		0-0.1890	0-0.2065	0-0.2244	0-0.2405
Pu-239		0.9873-0.0055	1.0278-0.0156	1.1298-0.0533	1.2314-0.1128
Pu-241		0-0.0447	0-0.0655	0-0.1089	0-0.1441
Th-232		8.9632-8.6098	8.9150-8.5488	8.8032-8.4311	8.6889-8.3002
Pu-240		0.0633-0.0249	0.0659-0.0258	0.0724-0.0364	0.0789-0.0454
Pu-242		0-0.0663	0-0.0621	0-0.0557	0-0.0493
Consumption of Pu-239	(kg/GWDth)	0.9818	1.0122	1.0765	1.1186

Table 3.1.4 shows that with increment of heavy metal loading per sphere weight of U-233 and Pu-239 in equilibrium code increases, weight of U-233 and Pu-239 in discharged spheres increases, consumption of Pu-239 increases.

3.1.1.3.2. Burning civil-grade plutonium

The computational results of heavy metal loading 7 g sphere for enrichment 10, 11, and 12% are given in Tables 3.1.5 and 3.1.6.

TABLE 3.1.5. MAIN PERFORMANCE FOR DIFFERENT ENRICHMENT WITH CIVIL-GRADE PLUTONIUM

Enrichment	%	10	11	12
k_{eff}		1.00027	1.00528	1.00707
Burnup	MWd/T _{HM}	100116	100117	100095
Fuel element residence time	days	1258	1258	1258
Conversion ratio		0.599	0.598	0.598
Power peaking max./average		2.52	2.34	2.22
Max. power per ball	KW/ball	1.40	1.30	1.23
Core leakage	%	8.66	8.38	8.17
Neutron flux				
Average thermal flux	E+14/(cm ² s)	0.2532	0.2146	0.1880
Average fast flux	(<1.86ev)	0.2425	0.2411	0.2405
Average total flux	(>0.1M eV)	1.0462	1.0015	0.9716
Temperature coefficient	($\Delta k/k/^\circ\text{C}$)			
Fuel	(10 ⁻⁵)	-1.62	-1.58	-1.54
Moderator	(10 ⁻⁵)	-0.598	-1.63	-2.31
Reflector	(10 ⁻⁶)	2.28	2.08	1.95

TABLE 3.1.6. INVENTORY, SUPPLY AND DISCHARGE OF MAIN ISOTOPE WITH CIVIL-GRADE PLUTONIUM

Enrichment	%	10	11	12
Inventory	(kg/GWth)			
U-233		127.32	123.31	119.94
Pu-239		354.46	458.24	564.94
Pu-241		262.92	306.76	345.70
Th-232		10576.15	10404.79	10230.77
Pu-240		281.23	323.56	364.03
Pu-242		141.13	143.75	147.34
Supply-discharge	(kg/GWDth)			
U-233		0-0.1871	0-0.1839	0-0.1807
Pu-239		0.9098-0.0419	0.9993-0.0804	1.0895-0.1288
Pu-241		0.1182-0.1534	0.1300-0.2054	0.1417-0.2529
Th-232		8.5523-8.2621	8.4067-8.1352	8.2615-8.0037
Pu-240		0.3533-0.0854	0.3884-0.1165	0.4235-0.1471
Pu-242		0.0742-0.1431	0.0816-0.1449	0.0890-0.1464
Consumption	(kg/GWDth)			
Pu-239		0.8670	0.9189	0.9607
Pu-241		-0.0352	-0.0754	-0.1112

Because weight of ^{240}Pu and ^{241}Pu in reactor with civil-grade plutonium is more than that with weapons-grade plutonium, its physical performance is different. Table 3.1.5 shows that the moderator temperature coefficient is negative, with increment of enrichment its absolute value increases. Table 3.1.6 shows that with increment of enrichment weight of ^{239}Pu and ^{241}Pu in equilibrium core increase, weight of ^{239}Pu and ^{241}Pu in discharged spheres increase, consumption of ^{239}Pu increases.

3.1.2. Physics studies of energy production and plutonium burning in pebble-bed type High Temperature gas cooled Module Reactor (HTMR)

3.1.2.1. Introduction

Physics studies were done for two HTMRs, one of which is a Current Energy-producing Reactor (CER) with 200 MW of thermal power used to burn uranium, the other is a Plutonium Burning Reactor (PBR) with the same power of that of the CER. For PBR, the compositions of the isotopes of plutonium in the fresh fuel element are the same as those in the discharged fuel of CER.

3.1.2.2. Calculation model of HTMR

For CER and PBR, most designed parameters are the same. The differences consist only in the choices of fissile and fertile materials for the two cases.

For the two reactors, the geometric parameters are the same (Section 3.1.1, Fig. 3.1.1). The main data are according to Section 3.1.1, Table 3.1.1. The heavy metal load of the fuel elements is different for CER (7 g) and for PBR (7.33 g). The total power and average power density for both reactors are the same. Under normal operation the temperature for spectrum calculation is listed in Section 3.1.1, Table 3.1.2. The code VSOP [3] were used for the calculations. The reactor was divided into eleven spectrum zones among which five spectrum zones were used for the core region.

The thorium absorption cross sections of resolved and unresolved resonance were generated by code ZUT-DGL [3].

3.1.2.3. Calculation results

For the CER, ^{235}U was chosen as fissile material and ^{238}U as fertile material. For the PBR, ^{232}Th was chosen as fertile material because thorium based fuel cycle has less HLW compared with uranium/plutonium fuel cycle and can not produce extra plutonium. Because the PBR is used to burn the isotopes of plutonium from the discharged fuel of CER, we did the two designs in this way, firstly the CER, secondly the PBR.

TABLE 3.1.7. PARAMETERS OF FUEL PARTICLE

	CER	PBR
Radius of the kernel, cm	0.025	
Fuel composition	UO ₂	(^{233}U -Pu-Th)O ₂
Density of the kernel, g/cm ³	10.5	10.5
Weight composition of fissile material	^{235}U	$^{233}\text{U}/^{239}\text{Pu}/^{241}\text{Pu} =$ 0.261/0.538/0.20
Weight fractions fissile/fertile	$^{235}\text{U}/^{238}\text{U} =$ 0.077/0.923	($^{233}\text{U}+^{239}\text{Pu}+^{241}\text{Pu}$)/ ($^{232}\text{Th}+^{240}\text{Pu}+^{242}\text{Pu}$) = 0.172/0.828
Weight compositions of fertile materials	^{232}Th	$^{232}\text{Th}/^{240}\text{Pu}/^{242}\text{Pu}$ = 0.889/0.077/0.034
Coating layers		C/C/SiC/C
Density, g/cm ³		1.05/1.90/3.18/1.90
Thickness, cm		0.009/0.004/0.0035/0.0035

For the convenience of comparison, the data for both reactors are listed in the same table, e.g., Table 3.1.7. This does not mean that the data, e.g. the weight compositions of fissile materials of PBR can be defined at the same time of the definition of those of CER. In fact, the compositions were defined according to those in the discharged fuel of CER listed in Table 3.1.8.

The compositions of the isotopes of plutonium of CER discharged fuel in Table 3.1.4 show that the weight fraction of fissile materials including ^{239}Pu and ^{241}Pu is only 0.581 that is too low to be used as fresh fuel for PBR. Therefore we used plutonium produced by CER plus ^{233}U as fuel of PBR. The detailed data are listed in Table 3.1.3.

We defined Cn as the ratio of plutonium consumption of PBR to the plutonium production of CER, i.e.,:

Cn = consumption of plutonium in PBR / production of plutonium in PBR.

From Table 3.1.8, Cn = 1.036/0.153 = 6.77.

Tables 3.1.9 and 3.1.10, respectively, show the data of fractional fission of heavy metals and main characteristics of CER and PBR at equilibrium state.

According to Table 3.1.8, for PBR, the relative burnup in discharged fuel for plutonium isotopes is 37.5% and that for ^{233}U is only 5.81%. The reason why the consumption of ^{233}U is so low is that the conversion ratio of PBR has a high value of 0.62 (Table 3.1.10). From Table 3.1.9 we can see that the fission fraction of plutonium isotopes is 80.8% and about 4 times as much as that of ^{233}U .

TABLE 3.1.8. INVENTORY, SUPPLY AND DISCHARGE OF MAIN ISOTOPES

Reactor	CER	PBR
Inventory		
^{232}Th		9542.38
^{233}Pa		8.06
^{233}U		564.44
^{234}U		17.12
^{235}U	426.56	1.37
^{236}U	89.54	
^{238}U	11568.96	
^{239}Pu	57.53	764.53
^{240}Pu	29.66	617.63
^{241}Pu	13.91	578.32
^{242}Pu	6.54	353.96
^{237}Np	5.27	
^{243}Am		56.42
Total heavy metal	12197.97	12504.23
Supply-discharge		
^{232}Th		9.285-9.069
^{233}U		0.568-0.535
^{235}U	0.981-0.139	0.000-0.004
^{236}U	0.000-0.130	
^{238}U	11.747-11.253	
^{239}Pu	0.000-0.065	1.168-0.428
^{240}Pu	0.000-0.045	0.807-0.413
^{241}Pu	0.000-0.024	0.437-0.551
^{242}Pu	0.000-0.019	0.351-0.335
Production/consumption Of plutonium	Production 0.153	Consumption 1.036

In order to maintain the PBR at criticality, the fuel enrichment of PBR is higher than that of CER. This is because that there are ^{240}Pu and ^{242}Pu in PBR, which have larger neutron absorptive micro-cross sections than ^{238}U and also leads to larger magnitude of conversion ratio for PBR.

TABLE 3.1.9. THE FRACTIONAL FISSION OF HEAVY METALS, %

Heavy metal	CER	PBR
²³² Th		0.05
²³³ U		19.17
²³⁵ U	63.99	0.03
²³⁶ U	0.02	
²³⁸ U	0.32	
²³⁹ Pu	28.67	45.63
²⁴⁰ Pu	0.01	0.19
²⁴¹ Pu	6.99	34.87
²⁴² Pu		0.06

TABLE 3.1.10. MAIN CHARACTERISTICS OF CER AND PBR

Reactor		CER	PBR
Fuel enrichment	%	7.7	17.2
Average burnup of discharged fuel	MWd/t _{HM}	80000	80000
Fuel element residence time		1007	1040
Conversion ratio		0.45	0.62
Power peaking max./average		2.66	1.84
Max. power per ball	kW	1.46	1.02
Neutron flux	E+14/(cm ² ×s)		
Average thermal flux	(<1.86eV)	0.70	0.12
Average total flux		1.42	0.88

REFERENCES TO SECTION 3.1.

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- [3] RÜTTEN, H.J., TEUCHERT, E., V.S.O.P.(’94) Computer Code System for Reactor Physics and Fuel Cycle Simulation, Jül-2897, Forschungszentrum Jülich (1994).