

3.3. India

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3.3.1. Introduction

The objective of this CRP is to look for thorium based fuel cycles that will reduce the quantity of plutonium in the world and also create less long-lived actinide wastes. This means examining different fuel cycles in which plutonium can be recycled with thorium to burn this plutonium or replace the plutonium with materials that are less unacceptable to the public. Thorium cycles are feasible in all types of reactors from LWRs to ADS. All reactors types have their own special advantages, but the major characteristic of thorium as the fuel of future comes from its superior fuel utilization. From this perspective, it turns out that the best system (barring the source driven system) is the molten salt breeder reactor, with the heavy water reactors coming in the second best. The molten salt technology is not yet commercially established, so it can be said that the present strategy would be to put the accent on thorium cycles in heavy water reactors. There are many advantages of using thorium as carrier for plutonium. The ^{233}U obtained from ^{232}Th could be used as future energy resource. The ^{233}U would be safeguarded in the spent fuel, with all the proliferation-resistant features. Moreover, the radiation fields caused due the presence of ^{232}U and its daughter products provide a high degree of self-protection and render ^{233}U unattractive as a weapons material. The option of using plutonium-thorium cycle in heavy water reactors has the highest merit in terms of plutonium destruction and has the highest energy yield because of good neutron economy even without recycling the ^{233}U . Recycling the ^{233}U would increase the energy yield many fold. To achieve these objectives, the CRP has been divided into 3 stages. The first stage is the code verification, second stage is the evaluation of the potential of plutonium incineration in different reactor systems and we have chosen the 200 MWe PHWR for this purpose. The third stage is the assessment of the effect of plutonium incineration on waste toxicity.

3.3.2. Benchmarks

The purpose of this stage is to verify the calculational methodology for establishing a consistent basis and to check whether the accuracy range of the reported results is adequate for the comparison of different conceptual thorium-based cycles.

As a beginning, the pin level calculations were verified. The various parameters like, multiplication factor, total neutron flux, average energy per fission, isotope densities and cross sections as a function of burnup were compared for a (Th,Pu)MOX fuelled light water reactor pin.

In the later stage, these parameters were compared for an LWR fuel assembly consisting of 17×17 fuel box lattice with the water gaps. The calculations required were assembly and core criticality curves, fuel composition, pin-by-pin power distribution and various temperature coefficients and boron worth.

3.3.2.1. Cell burnup calculations

For the pin level verification, the benchmark given was a LWR cell made of three coaxial cylindrical regions-fuel pellet, clad and the coolant moderator. Their dimensions, isotopic composition and other relevant data is as given in Section 2.1.1. Our analysis was done using

the WIMSD/4 code with 69 groups WIMS library. The methodology adopted was a heterogeneous infinite lattice cell calculation followed by a homogenous leakage calculation.

The detailed results are given in Section 2.1.1. We give here the results of two of the important parameters i.e. the integral quantity k_{inf} and a differential quantity, the one group microscopic cross sections of ^{232}Th , ^{233}U and ^{239}Pu (Tables 3.3.1 and 3.3.2).

3.3.2.2. Lattice calculations for LWR

The benchmark lattice consisted of an LWR fuel assembly consisting of 17×17 array of fuel rods, including 25 “water hole” positions. Burnup calculations were done with the given constant specific power of 37.7 w/g. The lattice calculations were done using the WIMS 69-group lattice code as before. Water holes were distributed among the adjacent pin cells. So the lattice parameters were calculated for three types of cells i.e., fuel cell sharing no water cell, sharing one water cell and sharing two water cells. These parameters were used in a diffusion theory code to perform the supercell calculations to obtain k_{eff} and pin power distributions, assuming zero current boundary conditions.

Assembly criticality is as shown in the Table 3.3.3 and that of fuel composition of the actinides in Table 3.3.4.

3.3.3. Evaluation of the potential of HWRs for plutonium incineration

For this purpose, it was agreed that each CRP participant will choose a particular reactor system. India has chosen a typical 200 MWe Indian PHWR (RAPS). The details of this reactor system are given below. This is a pressure tube type reactor that is moderated by heavy water and cooled by pressurized heavy water. The pressure tubes are 306 in number, are made of zircalloy and are arranged horizontally in a square lattice of pitch 22.86 cm inside a large cylindrical vessel referred to as calandria vessel. A description of this reactor is given in Table 3.3.5. No drastic modifications are envisaged for the introduction of thorium cycles into this reactor core.

The thorium/plutonium open cycle with direct disposal of the entire spent fuel has been chosen. In this cycle, we take 5.0% plutonium in thorium. Two varieties of plutonium were used in these studies. One was the standard LWR plutonium whose isotopic composition was supplied by IAEA. The other one was weapon grade plutonium. The two compositions are given in Table 3.3.6. The thorium/plutonium cycle with LWR plutonium is referred to as reactor-grade plutonium (RG), and with weapons-grade plutonium (WG).

The fuel is in the form of short fuel bundles of 49.53 cm length stacked along the length of the pressure tube. There are 10 such bundles in the active portion of the core, with one bundle each on either side outside the core. The fuel bundle is a 19-rod cluster. Each rod has a zircalloy tube as canning, containing a number of short ThO_2 fuel pellets with a small air gap filled with a mixture of helium and argon. A description of the fuel bundle is given in Table 3.3.7.

Lattice level calculations have been performed using the WIMS-D/4 code that gives the actinide composition as a function of burnup apart from k_{inf} and k_{eff} . The time average burnup calculations were performed using the TAQUIL code for the optimization of burnup and power distribution. The analysis details are given in Section 3.3.5.

3.3.3.1. Results of calculations

Assembly criticality curves for reactor- and weapons-grade plutonium are plotted in Fig. 3.3.1. Core criticality curves are shown in Fig. 3.3.2. Typical bundle power distributions at the core axial mid-plane at 0 and 600 FPD's, selected local power peaking factors as well as fuel and cladding temperatures in the hottest bundle in the core for some selected cases are given in Section 3.8.4. They are within the operating limits.

Table 3.3.8 gives the amount of initial and discharged total plutonium masses. One can note that about 65% of the initial reactor-grade plutonium is burnt in this core while 86% of the initial weapons-grade plutonium is burnt in the same core. The initial reactor-grade plutonium that is loaded into the burner is equivalent to nearly 4.5 times the discharged plutonium from a single 1 GWe LWR.

3.3.4. Assessment of the effect of plutonium incineration on waste toxicity

3.3.4.1. Benchmark calculation for typical LWR fuel

This benchmark aimed at standardizing the calculational methods of different participants in predicting the plutonium toxicities as a function of time, starting from the same actinide vector for a conventional LWR discharge fuel. First the activity of the various actinides was calculated using ORIGEN code with the initial composition (mass) as given for the discharged LWR fuel. These activities were later converted to toxicities by multiplying the DCI values (supplied by IAEA) of the corresponding actinides. Then they were summed up at each chosen time intervals for the decay time of 10 years up to 10^6 years to give the total toxicity of the spent fuel. Table 3.3.9 gives the total toxicity of the actinides in water and air with 100% plutonium and 99% plutonium-removed.

3.3.4.2. Assessment of the effect of plutonium burning on the waste toxicity

In this part of the study, the efficiency of the plutonium burner (with reactor-grade plutonium) is compared to that of the conventional LWR. First the individual masses, activities and the toxicities were calculated in one ton of fuel using ORIGEN code. The initial composition of the fuel is given in Table 3.3.10. Then the discharged masses (at 46 000 MWD/t for reactor-grade plutonium) and activities obtained were normalized to 1 Gwe. These activities were used to calculate the individual toxicities and the total toxicity at specified times from 10 years to 10^6 years after discharge. The individual toxicities are given in Table 3.3.11. For comparing the toxicity of the plutonium burner with that of the conventional LWR, a scheme was worked out at the last RCM in Taejon. The calculational methodology proposed is as follows:

- Let the initial charge of plutonium for the plutonium burner be X kg, and the plutonium discharged from the conventional LWR be 245 kg, per GWe per year.
- If the fraction of toxicity of the plutonium burner is T, then it is estimated from:
$$X/245 = (1-T)/T.$$
- This T% of the plutonium burner (toxicity.a) is added to the (1-T)% of the conventional LWR toxicity with 99% plutonium removed (toxicity.b).
- This total is called toxicity2 that is compared to the toxicity of conventional LWR with 100% plutonium-toxicity1.

Following the above method, we get $T = 18\%$ taking the plutonium charged per year as 1098 kg. Thus to get toxicity₂, 18% toxicity of the plutonium burner is added to 82% toxicity of conventional LWR with 99% plutonium removed.

The results of total toxicities from the evaluations are given in Table 3.3.12a for ingestion (water) and in Table 3.3.12b for inhalation (air). In the last column of these tables the decontamination factor (DF) is given which is the ratio of Toxicity₂ and Toxicity₁ for LWRs given in Table 3.3.9 without plutonium separation.

The results show that the DF is less than unity and decreases up to 10 000 years, but goes beyond 1 to as high as 2.3 (water) or 2.5 (air). This sudden jump at large times show that at first look the burner concept is not effective in reducing plutonium toxicity as a means of burning plutonium. The sudden increase beyond 10 000 years is not due to plutonium per se but due to the daughter isotopes of U-233 and U-234. Almost equivalent quantities of U-233 are also produced from the decay chains from Pu-241 and Am-241 that are produced from plutonium isotopes during burnup. But since the intermediate isotope Np-237, has a large half-life (2.11×10^6 years), the U-233 produced in the chain do not appear in these time periods of interest). The U-233 chain contributes to nearly 83% and U-234 chain nearly 12% to the total activity at 10^5 years. As can be seen from Tables 3.3.11a and 3.3.11b, the major contribution to toxicity at 10^5 years is due to Th-229, which is nearly 53 and 67% in water and air, respectively. The decay of U-233 with half-life of about 1.6×10^5 years to Th-229 dictates the toxicity values.

We noticed that the U-233 mass at discharge evaluated by ORIGEN with the same specific power as employed in WIMS are about 30% larger than those evaluated by the WIMS-D4 lattice code. For the actinide masses of discharged fuel as estimated from WIMS, we performed only the decay calculation with ORIGEN. This will be also consistent with the exercise in LWR benchmark analysis (Section 3.3.4.1.) where masses were supplied and one performed only the decay calculations. These results are given in Tables 3.3.13a and 3.3.13b. The DF factors are much lower. However the toxicity values at initial times would not be correct, since decay of actinides beyond Am-241 have a major contribution to toxicity in these periods. This limitation is due to our present version of WIMS library (of 1986 vintage) that does not contain actinides beyond Am-241, which was the reason why we did the analysis with ORIGEN.

Our present ORIGEN-2 code uses the cross sections generated from PHWR spectrum, which may not be the correct set for enriched thorium systems, where the spectrum is harder.

One of our immediate efforts would to update both the WIMS and ORGEN libraries.

TABLE 3.3.1. k_{inf} OF PIN CELL

Burnup (GWd/T)	0.0	30.0	40.0	60.0
k_{inf}	1.112	0.889	0.851	0.822

TABLE 3.3.2a.. CROSS SECTIONS AT BURNUP = 0.0 MWd/kg & 60.0 MWd/kg

	X-sections (barns) at burnup	
	0.0 MWD/kg	60.0 MWD/kg
		Th-232
Fission	0.0259	0.0237
Absorption	0.8664	1.170
		U-233
Fission	35.7	58.9
Absorption	41.3	66.2
		Pu-239
Fission	44.1	120.9
Absorption	68.5	189.0

TABLE 3.3.3. k_{inf} OF THE LATTICE

Burnup (GWd/t)	k_{inf}
0.0	1.1852
0.5	1.1735
20.0	1.0372
40.0	0.9104
60.0	0.8294

TABLE 3.3.4. FUEL COMPOSITION (ACTINIDES) AS A FUNCTION OF BURNUP

Burnup (MWD/t)	Number density (atom/barn×cm)	
	Th-232	Pu-239
0.0	2.059E-2	7.478E-4
20.0	2.036E-2	2.993E-4
60.0	1.970E-2	0.479E-4
	U-233	Pu-240
0.0	-	2.903E-4
20.0	1.596E-4	2.846E-4
60.0	3.191E-4	0.670E-4
	U-234	Pu-241
0.0	-	1.534E-4
20.0	0.9627E-5	1.545E-4
60.0	6.195E-5	0.539E-4
	Pu-238	Pu-242
0.0	2.29E-5	0.5010E-4
20.0	1.829E-5	0.7203E-4
60.0	7.488E-6	1.1624E-4

TABLE 3.3.5. DESCRIPTION OF PHWR REACTOR

Number of fuel channels	306
Lattice pitch, cm	22.86
Calandria inner radius, cm	299.8
Calandria length, cm	500.0
Number of bundles per channel inside the active portion of the core	10
Extrapolated core radius, cm	303.3
Extrapolated length, cm	508.5
Number of absorber rods (xenon override)	4
Number of regulating rods (for reactor regulation)	2
Total thermal power to coolant, MWth	655
Maximum channel power, MW	2.9
Maximum bundle power, KW	440
Maximum coolant outlet temperature, °C	297
Coolant inlet temperature, °C	249
Average fuel temperature, °C	625
Average coolant temperature, °C	271
Specific power, KW/kg	19.2

TABLE 3.3.6. PLUTONIUM COMPOSITION

Isotope	Reactor-grade plutonium initial %	Reactor-grade plutonium at discharge %	Weapons-grade plutonium initial %	Weapons-grade plutonium at discharge %
Pu-238	1.0	0.9	-	-
Pu-239	62.0	16.3	94.0	29.7
Pu-240	24.0	45.0	6.0	35.3
Pu-241	8.0	12.7	-	14.4
Pu-242	5.0	25.0	-	20.5

TABLE 3.3.7. DESCRIPTION OF THE 19 ROD ELEMENT FUEL ASSEMBLY

Fuel material (normal)	Nat UO ₂
Fuel material (CRP)	ThO ₂ (5% Pu)
Number of fuel rods in a fuel bundle	19
Sheath material	Zr-4
Diameter of the fuel rod, mm	14.4
Outer diameter of the sheath, mm	15.2
Clad thickness, mm	0.38
Diameter of the first ring (6 pins), cm	3.3
Diameter of the second ring (12 pins), cm	6.36
Bundle mass (ThO ₂), kg	12.0
Pressure tube (zircalloy) ID, cm	8.26
OD, cm	9.1
Air gap thickness, mm	8.5
Calandria tube (zircalloy) ID, cm	10.8
OD, cm	11.1

TABLE 3.3.8. MASS BALANCES [kg/Gwe year)]

	Reactor-grade plutonium	Weapons-grade plutonium
U ²³³ charged	-	-
U ²³⁵ charged	-	-
Pu charged	1098	725
Pu-discharged	405	141
Pu-burned	693	584
Ratio Pu-burned/Pu-charged	0.63	0.81
²³³ U produced	286	204
Average Mwd/kg	46	70

TABLE 3.3.9. TOXICITY OF CONVENTIONAL LWR

Time (years)	Ingestion		Inhalation	
	100% Pu (toxicity1)	99% Pu-removed	100% Pu (toxicity1)	99% Pu-removed
10 ¹	1.42E+9	1.60E+8	2.78E+11	4.11E+10
10 ²	1.16E+9	5.27E+7	2.24E+11	1.07E+10
10 ³	4.02E+8	1.36E+7	7.27E+10	2.56E+9
10 ⁴	1.28E+8	4.68E+6	2.14E+10	8.04E+8
10 ⁵	7.56E+6	1.14E+6	1.11E+9	8.86E+7
10 ⁶	1.25E+6	7.19E+5	1.44E+8	5.26E+7

TABLE 3.3.10. ISOTOPIC COMPOSITION IN 1 t OF FUEL (INITIAL) OF THE PLUTONIUM BURNER

Isotope	Quantity (kg)
Th-232	834.847
Pu-238	0.439
Pu-239	27.24
Pu-240	10.55
Pu-241	3.52
Pu-241	2.2

TABLE 3.3.11a. TOXICITY OF REACTOR-GRADE PLUTONIUM IN WATER (Sv/GWe)

Time (years)	0	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵	10 ⁶
Tl-209	0.567E+00	0.187E+01	0.148E+02	0.138E+03	0.913E+03	0.105E+04	0.565E+02
Pb-209	0.315E+01	0.104E+02	0.822E+02	0.766E+03	0.507E+04	0.585E+04	0.314E+03
Pb-210	0.101E+01	0.212E+01	0.181E+03	0.260E+05	0.102E+07	0.783E+07	0.133E+07
Pb-212	0.198E+06	0.301E+06	0.129E+06	0.572E+03	0.550E+03	0.550E+03	0.550E+03
Pb-214	0.268E-03	0.137E-02	0.446E-01	0.371E+01	0.146E+03	0.112E+04	0.190E+03
Bi-210	0.144E-02	0.303E-02	0.258E+00	0.371E+02	0.146E+04	0.112E+05	0.190E+04
Bi-212	0.991E+04	0.150E+05	0.645E+04	0.286E+02	0.275E+02	0.275E+02	0.275E+02
Bi-213	0.105E+02	0.346E+02	0.274E+03	0.255E+04	0.169E+05	0.195E+05	0.105E+04
Bi-214	0.268E-03	0.137E-02	0.446E-01	0.371E+01	0.146E+03	0.112E+04	0.190E+03
Po-210	0.301E+00	0.606E+00	0.517E+02	0.742E+04	0.292E+06	0.224E+07	0.379E+06
Po-213	0.462E+02	0.152E+03	0.121E+04	0.112E+05	0.744E+05	0.858E+05	0.461E+04
Po-214	0.241E-02	0.123E-01	0.401E+00	0.334E+02	0.131E+04	0.101E+05	0.171E+04
Po-216	0.297E+05	0.451E+05	0.193E+05	0.858E+02	0.825E+02	0.825E+02	0.825E+02
Po-218	0.241E-02	0.123E-01	0.401E+00	0.334E+02	0.131E+04	0.101E+05	0.171E+04
At-217	0.473E+02	0.156E+03	0.123E+04	0.115E+05	0.760E+05	0.877E+05	0.471E+04
Rn-220	0.991E+03	0.150E+04	0.645E+03	0.286E+01	0.275E+01	0.275E+01	0.275E+01
Rn-222	0.804E-04	0.410E-03	0.134E-01	0.111E+01	0.438E+02	0.336E+03	0.569E+02
Fr-221	0.473E+02	0.156E+03	0.123E+04	0.115E+05	0.760E+05	0.877E+05	0.471E+04
Ra-224	0.231E+07	0.351E+07	0.150E+07	0.667E+04	0.642E+04	0.642E+04	0.642E+04
Ra-225	0.525E+04	0.173E+05	0.137E+06	0.128E+07	0.845E+07	0.974E+07	0.523E+06
Ra-226	0.804E+00	0.410E+01	0.134E+03	0.111E+05	0.438E+06	0.336E+07	0.569E+06
Ra-228	0.287E+05	0.502E+05	0.642E+05	0.642E+05	0.642E+05	0.642E+05	0.642E+05
Ac-225	0.105E+04	0.346E+04	0.274E+05	0.255E+06	0.169E+07	0.195E+07	0.105E+06
Ac-228	0.164E+02	0.287E+02	0.367E+02	0.367E+02	0.367E+02	0.367E+02	0.367E+02
Th-228	0.231E+07	0.351E+07	0.150E+07	0.667E+04	0.642E+04	0.642E+04	0.642E+04
Th-229	0.263E+05	0.864E+05	0.685E+06	0.639E+07	0.422E+08	0.487E+08	0.262E+07
Th-230	0.419E+03	0.712E+03	0.384E+04	0.394E+05	0.375E+06	0.223E+07	0.379E+06
Th-232	0.183E+05	0.183E+05	0.183E+05	0.183E+05	0.183E+05	0.183E+05	0.183E+05
Pa-233	0.148E+07	0.217E+02	0.485E+03	0.312E+04	0.392E+04	0.381E+04	0.285E+04
U-233	0.708E+07	0.708E+07	0.708E+07	0.705E+07	0.679E+07	0.465E+07	0.257E+06
U-234	0.898E+06	0.912E+06	0.101E+07	0.110E+07	0.107E+07	0.831E+06	0.649E+05
U-236	0.358E+02	0.586E+02	0.288E+03	0.248E+04	0.159E+05	0.243E+05	0.237E+05
Np-237	0.360E+03	0.242E+04	0.539E+05	0.346E+06	0.436E+06	0.423E+06	0.316E+06
Np-239	0.119E+06	0.119E+06	0.118E+06	0.109E+06	0.467E+05	0.996E+01	0.298E-03
Pu-238	0.223E+10	0.213E+10	0.105E+10	0.894E+06	0.133E-12	0.000E+00	0.000E+00
Pu-239	0.104E+09	0.104E+09	0.104E+09	0.103E+09	0.853E+08	0.696E+07	0.112E+00
Pu-240	0.512E+09	0.515E+09	0.517E+09	0.470E+09	0.181E+09	0.130E+05	0.763E+00
Pu-241	0.269E+10	0.174E+10	0.229E+08	0.113E+04	0.543E+03	0.352E+00	0.000E+00
Pu-242	0.284E+07	0.284E+07	0.284E+07	0.283E+07	0.278E+07	0.237E+07	0.473E+06
Am-241	0.744E+09	0.198E+10	0.376E+10	0.896E+09	0.222E+05	0.148E+02	0.000E+00
Am-243	0.299E+08	0.298E+08	0.296E+08	0.272E+08	0.117E+08	0.249E+04	0.744E-01
Cm-242	0.580E+09	0.170E+06	0.112E+06	0.186E+04	0.280E-14	0.000E+00	0.000E+00
Cm-244	0.124E+10	0.882E+09	0.281E+08	0.308E-07	0.000E+00	0.000E+00	0.000E+00
Total	0.815E+10	0.741E+10	0.553E+10	0.152E+10	0.344E+09	0.918E+08	0.715E+07

TABLE 3.3.11b. TOXICITY OF REACTOR-GRADE PLUTONIUM IN AIR (Sv/GWe)

Time (years)	0	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵	10 ⁶
Tl-209	0.567E+01	0.187E+02	0.148E+03	0.138E+04	0.913E+04	0.105E+05	0.565E+03
Pb-209	0.158E+01	0.518E+01	0.411E+02	0.383E+03	0.253E+04	0.292E+04	0.157E+03
Pb-210	0.144E+01	0.303E+01	0.258E+03	0.371E+05	0.146E+07	0.112E+08	0.190E+07
Pb-212	0.991E+06	0.150E+07	0.645E+06	0.286E+04	0.275E+04	0.275E+04	0.275E+04
Pb-214	0.134E-01	0.684E-01	0.223E+01	0.185E+03	0.730E+04	0.559E+05	0.948E+04
Bi-210	0.116E+00	0.242E+00	0.207E+02	0.297E+04	0.117E+06	0.895E+06	0.152E+06
Bi-212	0.132E+07	0.200E+07	0.860E+06	0.381E+04	0.367E+04	0.367E+04	0.367E+04
Bi-213	0.210E+04	0.691E+04	0.548E+05	0.511E+06	0.338E+07	0.390E+07	0.209E+06
Bi-214	0.536E-01	0.273E+00	0.891E+01	0.742E+03	0.292E+05	0.224E+06	0.379E+05
Po-210	0.451E+01	0.909E+01	0.775E+03	0.111E+06	0.438E+07	0.336E+08	0.569E+07
Po-213	0.154E+04	0.507E+04	0.402E+05	0.375E+06	0.248E+07	0.286E+07	0.154E+06
Po-214	0.803E-01	0.410E+00	0.134E+02	0.111E+04	0.438E+05	0.336E+06	0.569E+05
Po-216	0.991E+06	0.150E+07	0.645E+06	0.286E+04	0.275E+04	0.275E+04	0.275E+04
Po-218	0.804E-01	0.410E+00	0.134E+02	0.111E+04	0.438E+05	0.336E+06	0.569E+05
At-217	0.158E+04	0.518E+04	0.411E+05	0.383E+06	0.253E+07	0.292E+07	0.157E+06
Rn-220	0.231E+04	0.351E+04	0.150E+04	0.667E+01	0.642E+01	0.642E+01	0.642E+01
Rn-222	0.188E-04	0.957E-04	0.312E-02	0.260E+00	0.102E+02	0.783E+02	0.133E+02
Fr-221	0.158E+04	0.518E+04	0.411E+05	0.383E+06	0.253E+07	0.292E+07	0.157E+06
Ra-224	0.991E+08	0.150E+09	0.645E+08	0.286E+06	0.275E+06	0.275E+06	0.275E+06
Ra-225	0.315E+06	0.104E+07	0.822E+07	0.766E+08	0.507E+09	0.585E+09	0.314E+08
Ra-226	0.536E+02	0.273E+03	0.891E+04	0.742E+06	0.292E+08	0.224E+09	0.379E+08
Ra-228	0.123E+06	0.215E+06	0.275E+06	0.275E+06	0.275E+06	0.275E+06	0.275E+06
Ac-225	0.420E+06	0.138E+07	0.110E+08	0.102E+09	0.676E+09	0.779E+09	0.418E+08
Ac-228	0.123E+04	0.215E+04	0.275E+04	0.275E+04	0.275E+04	0.275E+04	0.275E+04
Th-228	0.132E+10	0.200E+10	0.860E+09	0.381E+07	0.367E+07	0.367E+07	0.367E+07
Th-229	0.525E+07	0.173E+08	0.137E+09	0.128E+10	0.845E+10	0.974E+10	0.523E+09
Th-230	0.838E+05	0.142E+06	0.768E+06	0.788E+07	0.749E+08	0.447E+09	0.759E+08
Th-232	0.367E+07	0.367E+07	0.367E+07	0.367E+07	0.367E+07	0.367E+07	0.367E+07
Pa-233	0.660E+07	0.966E+02	0.216E+04	0.139E+05	0.174E+05	0.169E+05	0.127E+05
U-233	0.127E+10	0.127E+10	0.127E+10	0.127E+10	0.122E+10	0.837E+09	0.463E+08
U-234	0.162E+09	0.164E+09	0.182E+09	0.198E+09	0.193E+09	0.150E+09	0.117E+08
U-236	0.573E+04	0.938E+04	0.462E+05	0.397E+06	0.255E+07	0.389E+07	0.378E+07
Np-237	0.721E+05	0.483E+06	0.108E+08	0.693E+08	0.872E+08	0.847E+08	0.633E+08
Np-239	0.149E+06	0.149E+06	0.148E+06	0.136E+06	0.584E+05	0.124E+02	0.372E-03
Pu-238	0.446E+12	0.426E+12	0.210E+12	0.179E+09	0.266E-10	0.000E+00	0.000E+00
Pu-239	0.174E+11	0.174E+11	0.173E+11	0.171E+11	0.142E+11	0.116E+10	0.186E+02
Pu-240	0.854E+11	0.858E+11	0.861E+11	0.783E+11	0.302E+11	0.216E+07	0.127E+03
Pu-241	0.483E+12	0.313E+12	0.412E+10	0.203E+06	0.977E+05	0.634E+02	0.000E+00
Pu-242	0.567E+09	0.567E+09	0.567E+09	0.566E+09	0.557E+09	0.474E+09	0.946E+08
Am-241	0.149E+12	0.396E+12	0.752E+12	0.179E+12	0.444E+07	0.297E+04	0.000E+00
Am-243	0.597E+10	0.597E+10	0.592E+10	0.544E+10	0.233E+10	0.498E+06	0.149E+02
Cm-242	0.290E+12	0.850E+08	0.562E+08	0.928E+06	0.140E-11	0.000E+00	0.000E+00
Cm-244	0.373E+12	0.265E+12	0.844E+10	0.925E-05	0.000E+00	0.000E+00	0.000E+00
Total	0.185E+13	0.151E+13	0.109E+13	0.284E+12	0.585E+11	0.146E+11	0.946E+09

TABLE 3.3.12a. TOXICITY (WATER) OF PLUTONIUM-BURNER AGAINST CONVENTIONAL LWR (USING ORIGEN MASSES & ORIGEN DECAY)

Time (years)	Toxicity of the Pu-burner without Pu-separation	Toxicity.a = 0.82 of LWR with Pu-separation	Toxicity.b = 0.18 of the Pu-burner without Pu-separation	Toxicity2 = Toxicity.a + Toxicity.b	DF
10	7.41E+9	1.31E+8	1.33E+9	1.46E+9	1.03
10 ²	5.53E+9	4.32 ^E +7	9.95E+8	1.04E+9	0.89
10 ³	1.52E+9	1.11 ^E +7	2.74E+8	2.85E+8	0.71
10 ⁴	3.44E+8	3.84 ^E +6	6.19E+7	6.57E+7	0.51
10 ⁵	9.18E+7	9.35 ^E +5	1.65E+7	1.74E+7	2.3
10 ⁶	7.15E+6	5.89 ^E +5	1.29E+6	1.88E+6	1.5

TABLE 3.3.12b. TOXICITY (AIR) OF PLUTONIUM-BURNER AGAINST CONVENTIONAL LWR (USING ORIGEN MASSES & ORIGEN DECAY)

Time (years)	Toxicity of the Pu-burner without Pu-separation	Toxicity.a = 0.82 of LWR with Pu-separation	Toxicity.b = 0.18 of the Pu-burner without Pu-separation	Toxicity2 = Toxicity.a + Toxicity.b	DF
10	1.51E+12	3.37E+10	2.72E+11	3.06E+11	1.10
10 ²	1.09 ^E +12	8.77E+9	1.96E+11	2.05E+11	0.92
10 ³	2.84 ^E +11	2.09E+9	5.11E+10	5.32E+10	0.73
10 ⁴	5.85 ^E +10	6.59E+8	1.05E+10	1.12E+10	0.52
10 ⁵	1.46 ^E +10	7.27E+7	2.63E+9	2.70E+9	2.43
10 ⁶	9.46 ^E +8	4.31E+7	1.71E+8	2.14E+8	1.49

TABLE 3.3.13A. TOXICITY (WATER) OF PLUTONIUM-BURNER AGAINST CONVENTIONAL LWR (USING WIMS MASSES & ORIGEN DECAY)

Time (years)	Toxicity of the Pu-burner without Pu-separation	Toxicity.a = 0.82 of LWR with Pu-separation	Toxicity.b = 0.18 of the Pu-burner without Pu-separation	Toxicity2 = Toxicity.a + Toxicity.b	DF
10	3.62E+9	1.31E+8	6.52E+8	7.83E+8	0.55
10 ²	2.72 ^E +9	4.32E+7	4.89E+8	5.32E+8	0.45
10 ³	7.79 ^E +8	1.11E+7	1.40E+8	1.51E+8	0.38
10 ⁴	2.41 ^E +8	3.84E+6	4.34E+7	4.69E+7	0.37
10 ⁵	6.66 ^E +7	9.35E+5	1.19E+7	1.28E+7	1.69
10 ⁶	4.26 ^E +6	5.89E+5	7.67E+6	1.36E+6	1.09

TABLE 3.3.13b. TOXICITY (AIR) OF PLUTONIUM-BURNER AGAINST CONVENTIONAL LWR (USING WIMS MASSES & ORIGEN DECAY)

Time (years)	Toxicity of the Pu-burner without Pu-separation	Toxicity.a = 0.82 of LWR with Pu-separation	Toxicity.b = 0.18 of the Pu-burner without Pu-separation	Toxicity2 = Toxicity.a + Toxicity.b	DF
10	6.95E+11	3.37E+10	1.25E+11	1.59E+11	0.57
10 ²	5.26 ^E +11	8.77E+9	2.47E+11	1.04E+11	0.46
10 ³	1.41 ^E +11	2.09E+9	2.54E+10	2.75E+10	0.38
10 ⁴	4.10 ^E +10	6.59E+8	7.38E+9	8.04E+9	0.38
10 ⁵	1.08 ^E +10	7.27E+7	1.95E+9	2.02E+9	1.82
10 ⁶	5.47 ^E +8	4.31E+7	9.85E+7	1.42E+8	0.99

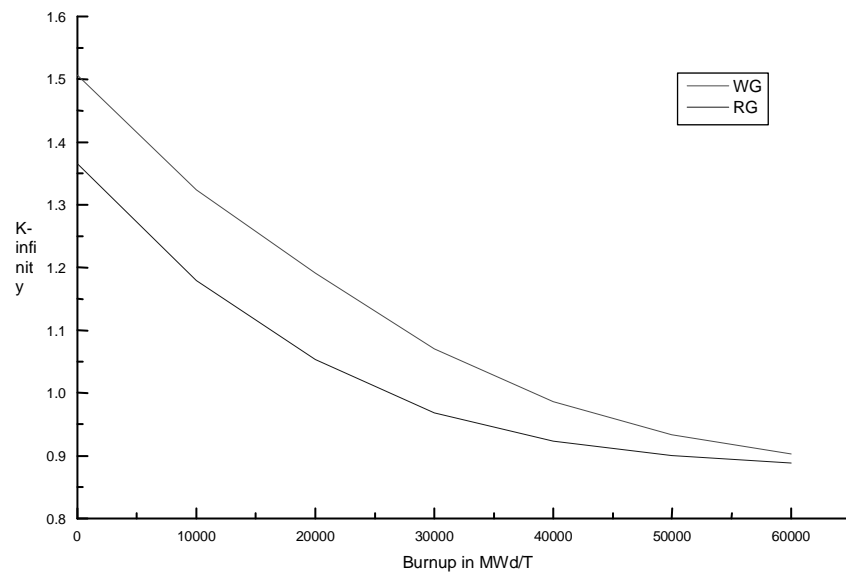


FIG. 3.3.1. Assembly criticality curves.

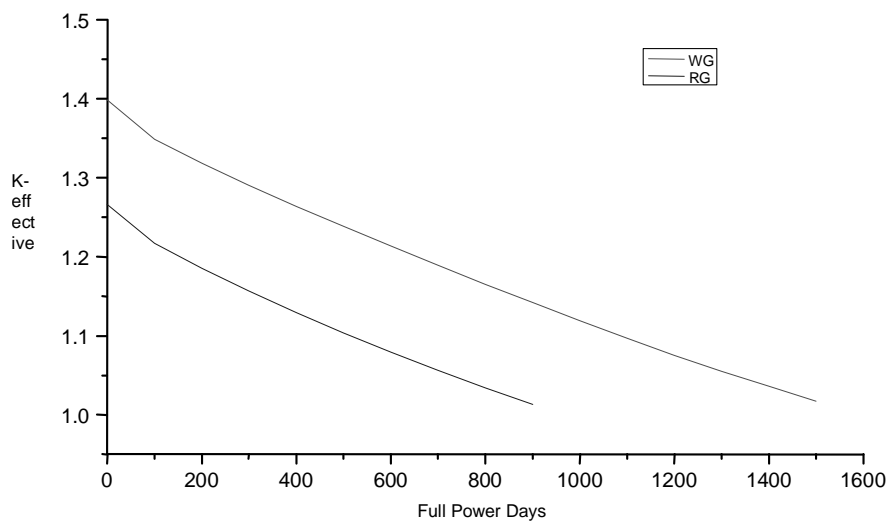


FIG. 3.3.2. Assembly criticality curves.

3.3.5. Details of reactor physics calculations for plutonium burner (PHWR)

Lattice level calculations have been performed using WIMS-D/4, a 69-group neutronics code that gives the actinide composition as a function of burnup apart from k_{inf} and k_{eff} , as well as two group parameters as a function of burnup. The time average code TAQUIL, takes these burnup dependent cross sections and estimates the equilibrium core for the nominal adjuster configuration, with multi-bundle shift options.

In TAQUIL, two-bundle shift scheme has been used and the maximum channel power and bundle power obtained are 2.9 MWth and 476 kWth. While the channel power satisfies the present operational limits of our 200 MWe PHWR, the bundle power is too high in time average simulation. The bundle power peak appears in the fresh bundle which goes into the second string position in the core. The maximum burnup before refueling is about 10 000 MWD/t at this position. Adding a suitable burnable poison to the fresh bundles, which will vanish around the above burnup, this could be controlled in principle. The design power limits of a thorium bundle also will be higher than natural uranium bundles, due to better thermal conductivity and stability properties of thorium fuel. The equilibrium channel power distribution is given in Table 3.3.14. The requirement of adjuster rod reactivity values has also been verified. The estimated core average exit burnup for reactor-grade plutonium and weapons-grade plutonium are 46 000 and 70 000 MWD/t, respectively. Based on these exit burnup the average daily refueling requirements are about 1.39 bundles for reactor-grade plutonium fuel and about 0.92 for weapons-grade plutonium fuel. The spent fuel compositions at this estimated discharge burnup and fueling rates were used as the starting point after normalizing them to 1 GW(e) assuming 300 FPDS/year of operation. This reactor produces a fission power of 690 MW(th) of which 655 MW(th) is delivered to the coolant and 200 MW(e) is generated. However the results have been normalized to 1 GW(e) as specified in the CRP. This amounts to about 22 t for reactor-grade plutonium and about 14.5 t for weapons-grade plutonium, of heavy metal requirement per year. The corresponding plutonium throughput requirements for 5% enrichment are 1098 and 725 kg, respectively.

However, the core follow-up calculations were also done using a two-group diffusion theory finite difference code ASPECT for the initial core. In the initial core flux flattening was introduced through loading of plain thorium bundles in the 40 selected channels. The k_{eff} as a function of core burnup i.e., the core criticality curve and the power distributions at 0 & 600 FPD's were obtained from code ASPECT. The core simulations were done only up to the start of refuelling. The transition to equilibrium from start of refuelling was not simulated explicitly.

Table 3.3.6 gives a breakdown of the plutonium isotopes in the loaded and disloaded charges, respectively, of the plutonium burner. Typical bundle power distributions at the core axial mid-plane at 0 and 600 FPD's are given in Tables 3.3.15 and 3.3.16. Selected local power peaking factors are given in Tables 3.3.17 and 3.3.18. Fuel and cladding temperatures in the hottest bundle in the core for some selected cases are given in Tables 3.3.19 and 3.3.20, which are within the operating limits.

cont'd

TABLE 3.3.16. POWER DISTRIBUTION IN MIDPLANE – WEAPONS-GRADE PLUTONIUM
(Bundle power distribution in KW 600 days)

						68	192	209	212	201	182								
					52	62	192	221	236	237	227	202	71	60					
		173	76	174	90	226	249	260	261	252	231	96	183	189	182				
	88	198	210	211	224	252	268	275	275	269	254	228	217	217	203	91			
	221	231	240	237	245	266	277	282	282	277	267	247	240	243	233	222			
	231	237	253	258	252	156	272	281	284	285	280	177	257	252	259	253	237	230	
	240	253	265	268	259	261	276	282	286	195	283	276	260	259	267	264	252	240	
228	242	261	271	274	267	270	185	284	285	287	283	278	268	168	273	271	261	241	227
227	247	266	276	181	276	277	282	286	287	287	285	281	179	275	276	275	266	247	226
231	251	269	276	278	277	279	284	196	289	288	287	281	278	276	279	278	268	250	230
230	250	269	277	279	178	280	284	289	289	290	197	284	180	278	279	278	268	249	229
235	247	266	276	279	176	279	285	289	292	291	290	283	278	175	278	276	266	246	235
	249	260	272	275	270	273	188	291	293	294	291	283	269	267	271	270	258	248	
	232	244	260	266	259	265	282	290	294	294	289	279	261	149	261	257	243	231	
	210	217	235	245	243	253	275	286	290	289	282	270	248	240	241	231	215	208	
		80	195	209	106	231	257	272	279	277	267	141	225	210	204	190	77		
		48	56	63	174	194	224	243	252	250	236	214	183	163	55	49	44		
				137	38	145	69	195	206	204	188	59	38	28	29				
					19	23	35	48	56	55	45	30	17	13					

TABLE 3.3.17. POWER PEAKING FACTORS – REACTOR-GRADE PLUTONIUM

Burnup (MWD/t)	Ring: 1	Ring: 2	Ring: 2
0.0 ⁺	0.49282	0.91676	1.08389
1000.0	0.51030	0.94761	1.06701
2000.0	0.52682	0.97611	1.05138
3000.0	0.54356	1.00350	1.03628
4000.0	0.56065	1.03012	1.02155
5000.0	0.57802	1.05584	1.00724
10000.0	0.66476	1.16276	0.94656
20000.0	0.81192	1.22673	0.90231
30000.0	0.90864	1.14804	0.93360
40000.0	0.95907	1.04187	0.98247
50000.0	0.95575	0.95873	1.02432
60000.0	0.91027	0.90978	1.05259

TABLE 3.3.18. POWER PEAKING FACTORS – WEAPONS-GRADE PLUTONIUM

Burnup MWD/t	Ring: 1	Ring: 2	Ring: 2
0.0 ⁺	0.45124	0.91362	1.08892
1000.0	0.46607	0.94457	1.07221
2000.0	0.47990	0.97408	1.05630
3000.0	0.49409	1.00340	1.04046
4000.0	0.50878	1.03275	1.02456
5000.0	0.52391	1.06197	1.00869
10000.0	0.60422	1.19874	0.93361
20000.0	0.76313	1.35345	0.84302
30000.0	0.89719	1.32900	0.84407
40000.0	1.01563	1.22327	0.88706
50000.0	1.10378	1.10116	0.94077
60000.0	1.12480	0.99509	0.99205

TABLE 3.3.19. MAXIMUM CLAD & FUEL TEMPERATURES – REACTOR-GRADE PLUTONIUM

Days	Bundle	Clad	Fuel temperature
0.0	384	389	1487
100.0	361	382	1415
200.0	356	381	1399
300.0	340	376	1348
400.0	323	371	1293
500.0	307	366	1245
600.0	295	362	1204
700.0	289	361	1188
800.0	285	359	1173
900.0	281	358	1162

TABLE 3.3.20. MAXIMUM CLAD & FUEL TEMPERATURES - WEAPONS-GRADE PLUTONIUM

Days	Bundle	Clad	Fuel temperature
0.0	385	390	1490
100.0	360	382	1409
200.0	352	380	1385
300.0	338	375	1340
400.0	321	370	1287
500.0	305	366	1237
600.0	292	362	1195
700.0	285	360	1175
800.0	280	358	1157
900.0	275	357	1142
1000.0	271	355	1130
1100.0	268	354	1120
1200.0	266	354	1113
1300.0	272	356	1134
1400.0	286	360	1175
1450.0	292	362	1196