

3 Description of the Benchmark

3.1 Geometrical Model

The benchmark core is based on the Russian BN-800 new reactor design with 2100 MW thermal power. It is an axial heterogeneous oxide-fueled fast reactor. Its main core data are collected in Table 2. Figure 1 shows a full core cross-section and Figure 2 illustrates the axial and radial dimensions of the system in a RZ scheme without pointing out the absorbers.

The 18.2 cm thick internal breeder slice is located around core mid-plane and it is limited to the inner 211 out of a total of 565 fuel subassemblies (S/A) for reasons of radial power flattening. The height of the fissile columns including the internal breeder zone is 91 cm. The upper axial blanket has been replaced by a sodium plenum which contains the wrapper steel and sodium. The fissile columns and the plenum are separated by a 4 cm layer of the fuel pin steel plugs. The core has a 40.5 cm thick lower blanket and a single row of radial breeder S/As.

Table 2: Main parameters of the benchmark core

Thermal power	MW	2100
Core concept	–	ax. heterog.
Number of fuel S/As	–	565
Fissile height (incl. int. breeder)	cm	91
Internal breeder height	cm	18
Fuel and breeder residence time	cycles	3
Cycle length	efpd	150
Fuel pin: diameter	mm	6.90/6.96*
clad thickness	mm	0.55/0.555
number per S/A	–	127
Blanket pin: diameter	mm	14.0
clad thickness	mm	0.40
number per S/A	–	37
Wrapper : outside flat-to-flat	mm	96.0/96.58
wall thickness	mm	2.0/2.02
Gap between wrappers	mm	4.0/4.02
S/A lattice pitch	mm	100.0/100.6
Fuel smear density	g/cm ³	8.6
Maximum burnup	%	12.0

* values at full power conditions

The reactor has two shutdown systems. The eighteen compensating rods have the functions of burnup compensation, power control and shutdown. They are partly inserted at beginning of cycle and fully withdrawn at end of cycle. The benchmark configuration corresponds to an end of cycle configuration. The twelve safety rods are permanently withdrawn during operation due to their sole function of shutdown.

The oxide fuel is characterized by a maximum burnup of 12 % which corresponds to an average end of cycle burnup of 4.6 % and an average discharge burnup of 6.9 % for the fissile plus internal fertile zones.

The seven different types of S/As are subdivided in 41 sub-zones according to Figure 3. For these sub-zones the atomic densities are given in Table 3 for the homogeneous calculations together with the fuel temperatures.

The heterogeneous model of the fuel S/As is shown in Figures 4 and 5 and the atomic densities of the corresponding cells are collected in Table 4.

3.2 Tasks to be Performed

Six different void configurations should be considered, which are in detail described in Table 5:

1. Core plus internal breeder zone
2. Core plus internal breeder zone plus pin steel plugs and sodium plenum
3. Core plus internal breeder zone, pin steel plugs, sodium plenum and upper axial shield
4. Like 1 plus void in followers within fissile height
5. Like 2 plus void in followers plus absorber parts within pin steel plugs and plenum height
6. Like 3 plus void in followers and absorber parts within pin steel plugs, plenum and axial shield height.

**Table 3: Nuclear concentrations and fuel temperatures in axial sub-zones
(the numeration of sub-zones is the same as shown in Fig. 3)**

Sub-zone number															
Element	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15,16 17
U-235	⁴ 161*	⁴ 155	⁴ 169	⁴ 154	⁴ 163	⁴ 198	⁴ 266	⁴ 274	-	-	-	⁴ 391	⁴ 363	⁴ 381	⁴ 436
U-238	² 527	² 524	² 530	² 524	² 528	² 741	² 774	² 776	-	-	-	¹ 117	¹ 116	¹ 117	¹ 119
Pu-239	³ 929	³ 919	³ 941	³ 919	³ 932	³ 329	³ 128	³ 110	-	-	-	³ 244	³ 321	³ 273	³ 121
Pu-240	³ 435	³ 437	³ 434	³ 438	³ 435	⁴ 202	⁵ 372	⁵ 274	-	-	-	⁵ 844	⁴ 155	⁴ 108	⁵ 233
Pu-241	³ 153	³ 149	³ 157	³ 149	³ 154	⁶ 920	⁶ 120	⁷ 860	-	-	-	⁶ 246	⁶ 592	⁶ 344	⁷ 516
Pu-242	⁴ 728	⁴ 731	⁴ 724	⁴ 732	⁴ 727	⁷ 296	⁸ 150	⁹ 338	-	-	-	⁸ 416	⁷ 140	⁸ 666	⁹ 461
Fission products	³ 353	³ 396	³ 307	³ 400	³ 345	³ 134	⁴ 201	⁴ 168	-	-	-	⁴ 514	⁴ 766	⁴ 609	⁴ 127
O	¹ 1446	¹ 1446	¹ 1446	¹ 1446	¹ 1446	¹ 1583	¹ 1583	¹ 1583	-	-	-	¹ 2414	¹ 2414	¹ 2414	¹ 2414
Na	² 799	² 799	² 799	² 799	² 799	² 799	² 799	² 799	² 799	¹ 198	² 958	² 542	² 542	² 542	² 542
Fe	¹ 146	¹ 146	¹ 146	¹ 146	¹ 146	¹ 146	¹ 146	¹ 146	¹ 208	² 529	² 964	² 956	² 956	² 956	² 956
Cr	² 337	² 337	² 337	² 337	² 337	² 337	² 337	² 337	² 474	³ 941	² 216	² 245	² 245	² 245	² 245
Ni	² 181	² 181	² 181	² 181	² 181	² 181	² 181	² 181	² 250	⁴ 179	³ 898	² 168	² 168	² 168	² 168
Mo	³ 319	³ 319	³ 319	³ 319	³ 319	³ 319	³ 319	³ 319	³ 435	⁴ 474	³ 118	³ 243	³ 243	³ 243	³ 243
B-10	-	-	-	-	-	-	-	-	-	-	² 674	-	-	-	-
B-11	-	-	-	-	-	-	-	-	-	-	¹ 269	-	-	-	-
C	-	-	-	-	-	-	-	-	-	-	² 841	-	-	-	-
Temperature, K	1500	1500	1500	1500	1500	1200	1200	1200	-	-	-	1200	1200	1200	1200

* ⁴161 means $0.0000161 \cdot 10^{24}$ nuc/cm³

Sub-zone number															
Element	18	19	20	21	22	23	24	25	26,27 28	29, 30,31 38*)	32,33 34*)	35,36 37	39	40	41
U-235	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
U-238	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pu-239	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pu-240	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pu-241	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pu-242	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fission products	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Na	² 799	² 542	¹ 148	¹ 183	¹ 214	-	¹ 172	¹ 110	¹ 114	¹ 205	¹ 114	¹ 114	² 799	² 799	² 619
Fe	¹ 146	² 956	¹ 194	¹ 111	-	¹ 560	¹ 112	¹ 308	¹ 110	² 526	¹ 110	¹ 110	¹ 383	¹ 383	² 787
Cr	² 337	² 245	² 546	² 312	-	¹ 157	² 315	² 674	² 283	² 130	² 283	² 283	¹ 104	¹ 104	² 162
Ni	² 181	² 168	² 395	² 226	-	¹ 115	² 229	² 340	² 172	³ 785	² 172	² 172	² 508	² 508	³ 659
Mo	³ 319	³ 243	³ 308	³ 176	-	³ 880	³ 176	³ 766	² 202	³ 132	³ 202	³ 202	-	-	³ 201
B-10	-	-	-	-	-	-	-	-	² 485	-	² 485	¹ 208	-	-	¹ 101
B-11	-	-	-	-	-	-	-	-	¹ 194	-	¹ 194	² 180	-	-	¹ 403
C	-	-	-	-	-	-	-	-	² 606	-	² 606	² 565	-	-	¹ 126

*) Number 32, 33, 34, 38 are not needed in the benchmark

Table 4: Nuclear concentrations and fuel temperatures in axial sub-zones of the heterogeneous cell model (the numeration of sub-zones is the same as shown in Fig. 4)

Sub-zone number												
Element	1	2	3	4	5	6	7	8	9	10	11	12
U-235	-	-	⁴ 314	⁴ 183	⁴ 234	⁴ 190	-	-	-	-	-	-
U-238	-	-	² 914	² 619	² 875	² 623	-	-	-	-	-	-
Pu-239	-	-	³ 151	² 109	³ 389	² 110	-	-	-	-	-	-
Pu-240	-	-	⁵ 440	³ 516	⁴ 239	³ 514	-	-	-	-	-	-
Pu-241	-	-	⁶ 142	³ 176	⁵ 109	³ 181	-	-	-	-	-	-
Pu-242	-	-	⁸ 177	⁴ 864	⁷ 350	⁴ 860	-	-	-	-	-	-
Fission products	-	-	⁴ 237	³ 468	³ 158	³ 417	-	-	-	-	-	-
O	-	-	¹ 187	¹ 171	¹ 187	¹ 171	-	-	-	-	-	-
Na	¹ 148*	² 741	² 741	² 741	² 741	² 741	² 741	¹ 214	² 934	¹ 183	¹ 214	-
Fe	¹ 194	¹ 110	¹ 110	¹ 110	¹ 110	¹ 110	¹ 183	-	² 513	¹ 111	-	¹ 560
Cr	² 546	² 287	² 287	² 287	² 287	² 287	² 449	-	² 144	² 312	-	¹ 157
Ni	² 395	² 212	² 212	² 212	² 212	² 212	² 293	-	² 104	² 226	-	¹ 115
Mo	³ 308	³ 321	³ 321	³ 321	³ 321	³ 321	³ 458	-	⁴ 834	³ 176	-	³ 880
B-10	-	-	-	-	-	-	-	-	² 796	-	-	-
B-11	-	-	-	-	-	-	-	-	¹ 318	-	-	-
C	-	-	-	-	-	-	-	-	² 994	-	-	-
Temperature, K	-	-	1200	1500	1200	1500	-	-	-	-	-	-

* ¹148 means $0.0148 \cdot 10^{24}$ nuc/cm³

Sub-zone number											
Element	13	14,15	16	17	18	19,20	21	22	23	24	25
U-235	-	-	-	-	-	-	-	⁴ 324	⁴ 193	⁴ 182	⁴ 200
U-238	-	-	-	-	-	-	-	² 917	² 624	² 619	² 626
Pu-239	-	-	-	-	-	-	-	³ 130	² 110	² 109	² 111
Pu-240	-	-	-	-	-	-	-	⁵ 324	³ 514	³ 517	³ 513
Pu-241	-	-	-	-	-	-	-	⁶ 102	³ 182	³ 176	³ 185
Pu-242	-	-	-	-	-	-	-	⁸ 111	⁴ 859	⁴ 865	⁴ 855
Fission products	-	-	-	-	-	-	-	⁴ 198	³ 408	³ 473	³ 363
O	-	-	-	-	-	-	-	¹ 187	¹ 171	¹ 171	¹ 171
Na	¹ 172*	¹ 219	¹ 219	¹ 219	¹ 219	¹ 214	-	² 741	² 741	² 741	² 741
Fe	¹ 112	-	-	-	-	-	¹ 703	¹ 110	¹ 110	¹ 110	¹ 110
Cr	² 315	-	-	-	-	-	¹ 125	² 287	² 287	² 287	² 287
Ni	² 229	-	-	-	-	-	³ 238	² 212	² 212	² 212	² 212
Mo	³ 176	-	-	-	-	-	³ 630	³ 321	³ 321	³ 321	³ 321
B-10	-	-	-	-	-	-	-	-	-	-	-
B-11	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	-	-	-	-
Temperature, K	-	-	-	-	-	-	-	1200	1500	1500	1500

Table 5: Definition of the voided states of the IAEA/CEC void benchmark

<i>no.</i>	<i>voided zones</i>	<i>voided sub - zones</i>
1	fissile + internal breeder	1 - 6
2	fissile + int. breeder + plugs + plenum	1 - 6, 9 - 10
3	fissile + int. breeder + plugs + plenum + axial shield	1 - 6, 9 - 11
4	fissile + int. breeder + followers	1 - 6, 29
5	fissile + int. breeder + plugs + plenum + followers + absorbers	1 - 6, 9 - 10, 28, 29, 37
6	fissile + int. breeder + plugs + plenum + ax. shield + followers + absorbers	1 - 6, 9 - 11, 27 - 29, 36, 37

Based on these definitions the following parameters should be calculated:

1. Effective multiplication factors for the reference state with sodium in all cells and for the six voided states. Convergence criteria should also be given.
2. Sodium void effect values for all steps and cases calculated as

$$\Delta\rho \text{ [\%]} = \left[\frac{1}{k_{eff}(\text{with Na})} - \frac{1}{k_{eff}(\text{without Na})} \right] \times 100$$

3. For the maximum void state no. 6 a perturbation breakdown by components (spectrum, leakage, capture) should be done zone-wise.
4. For the void state no. 6 the heterogeneity effect when voiding the total sodium or only the flowing sodium should be calculated.
5. Maximum linear power [W/cm] in the core with sodium in all sub-zones based on a flux normalization via fission rates

and 200 MeV per fission, e.g. the gamma power is globally included:

- radial distributions in the middle of the upper and lower part of the core
 - two axial distributions in the central subassembly and in a peripheral core subassembly as indicated in Figure 1.
6. Control rod worth ($\% \Delta \rho$) separately for the 18 compensating rods and for the 12 safety rods with sodium in all sub-zones. When the rods are inserted, their lower boundary is at the core lower boundary and their upper boundary is at the pin steel plugs upper boundary.
7. Breeding ratios for all reactor sub-zones with sodium:

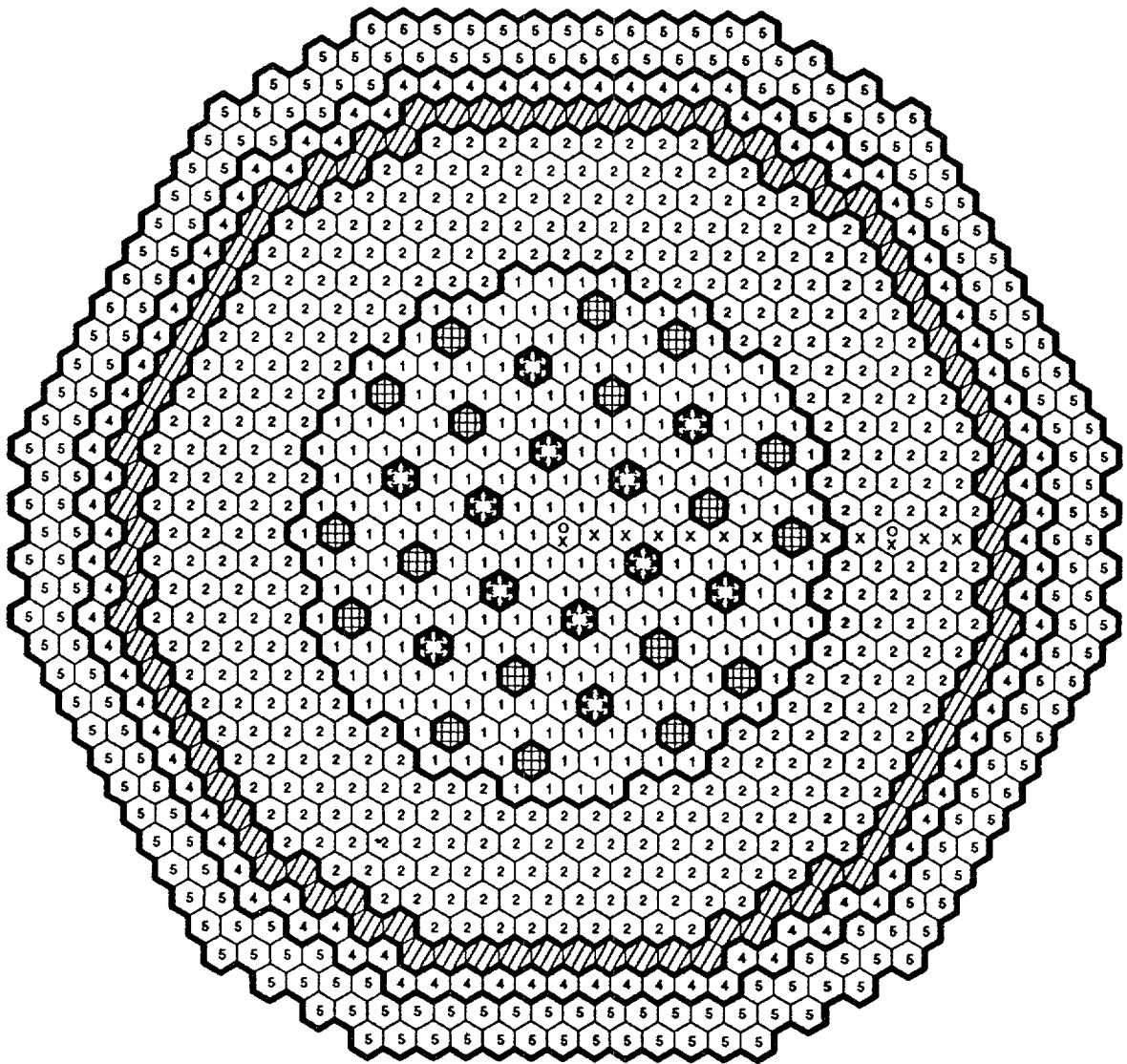
- core
- internal breeder zone
- lower axial breeder
- radial breeder
- reactor.

The breeding ratio for each sub-zone i is defined as

$$BR_i = \frac{(R_c^{U238} + R_c^{Pu240})_i}{\sum_j (R_{c+f}^{Pu239} + R_{c+f}^{Pu241})_j}$$

where R_c and R_f are the capture and fission rates of the given isotopes and sub-zones.

8. Burnup reactivity loss ($\% \Delta \rho$) for depleting the given core by additional 30 full-power days.



EXPLANATION








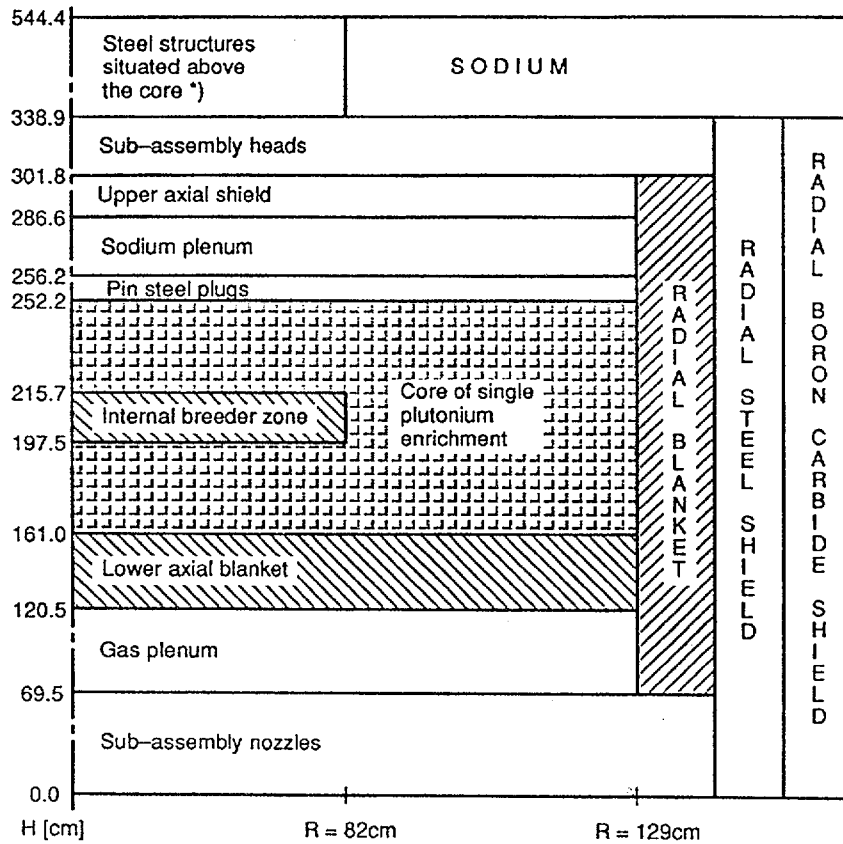
	: CENTRAL CORE	211		: RADIAL BORON CARBIDE SHIELD	210
	: PERIPHERAL CORE	354		: COMPENSATING ROD	18
	: RADIAL BLANKET	90		: SAFETY SYSTEM ROD	12
	: RADIAL STEEL SHIELD	96	X	: POSITIONS OF RADIAL POWER TRAVERSES	
			O	: POSITIONS OF AXIAL POWER TRAVERSES	

FIG. 1. Cross-section of the IAEA/CEC void benchmark core.



*) Above-core structures according to BN-type reactor design

FIG. 2. RZ scheme of the IAEA/CEC void benchmark.

Axial layer name	Axial layer thickness cm	Central core s/a	Peripheral core s/a	Radial blanket s/a	Radial steel shield s/a	Radial B ₄ C shield s/a	Compensating rod	Safety system rod
Steel structures situated above the core	150.0	24	22	22	22	22	24	24
	5.1	23	22	22	22	22	25	25
	25.5	22	22	22	22	22	25	25
	16.0	22	22	22	22	22	25	25
	9.0	22	22	22	22	22	26	35
Subassembly heads	37.0	21	21	21	39	40	26	35
Upper axial shield	15.2	11	11	17	39	40	27	36
Sodium plenum	18.4	10	10	16	39	40	28	37
	12.0	10	10	16	39	40	28	37
Pin steel plugs	4.0	9	9	16	39	40	28	37
Upper part of the core	36.5	1	3	12	39	41	29	29
Internal breeder zone	18.2	6	4	13	39	41	29	29
Lower part of the core	36.5	2	5	14	39	41	29	29
Lower axial blanket	40.5	7	8	15	39	40	30	30
Gas plenum	51.0	18	18	19	20	40	31	31
Subassembly nozzles	69.5	20	20	20	20	20	20	20

Number 32, 33, 34, 38 are not needed in the benchmark

FIG. 3. Axial description of the hexagonal subassemblies.

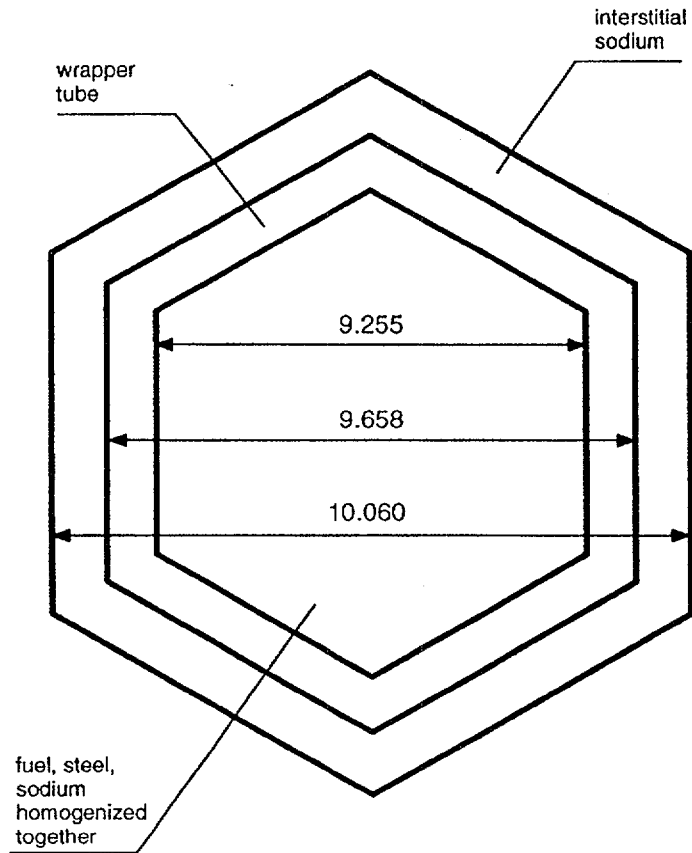


FIG. 4. Cross-section of the heterogeneous cell model (dimensions are given in cm).

Axial layer name	Axial layer number						Thickness cm
Steel structures situated above the core	13	13	13	13	13	13	150.0
	12	12	12	12	12	12	5.1
	11	11	11	11	11	11	50.5
Subassembly heads	10	10	10	10	10	10	37.0
Upper axial shield	20	21	9	21	20	20	15.2
Sodium plenum	19	21	8	21	19	19	30.4
Pin plugs	19	21	7	21	19	19	4.0
Upper part of the core	18	21	inner core 6	periph. core 25	21	18	36.5
Internal breeder zone	17	21	5	24	21	17	18.2
Lower part of the core	16	21	4	23	21	16	36.5
Lower axial blanket	15	21	3	22	21	15	40.5
Gas plenum	14	21	2	21	14	14	51.0
Subassembly nozzles	1	1	1	1	1	1	69.5

FIG. 5. Axial structure of the core subassemblies in the heterogeneous cell model.