ALTERNATIVE CONCEPT FOR A FAST ENERGY AMPLIFIER ACCELERATOR DRIVEN REACTOR

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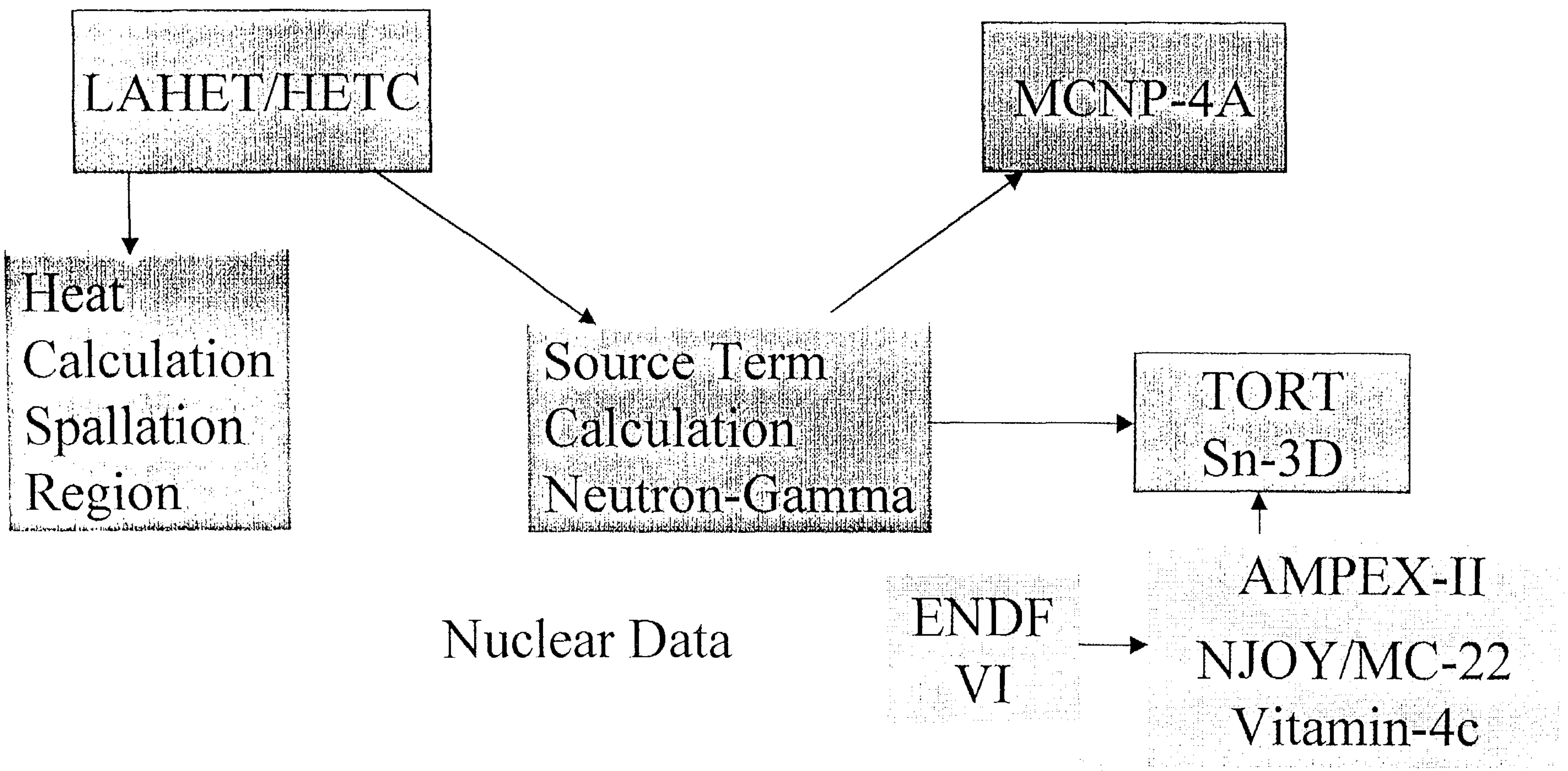
ABSTRACT

Recently Rubbia et alii [1] introduced a conceptual design of a Fast Energy Amplifier (EA) as an advanced innovative reactor which utilizes a neutron spallation source induced by protons as an external source in a subcritical array imbibed in a molten lead coolant which, besides being breeder and waste burner, generates energy. This paper introduces some qualitative changes in the Rubbia's concept such as more than one point of spallation, in order to reduce the requirement in the energy and current of the accelerator, and mainly to make a more flat neutron distribution. The subcritical core which in the Rubbia's concept is an hexagonal array of pins immersed in a molten lead coolant is replaced by a concept of a solid lead calandria with the fuel elements in channels cooled by Helium, allowing on line refueling or shuffling, and the utilization of a direct thermodynamic cycle (Brayton), which is more efficient than a vapor cycle. Although the calculations to demonstrate the feasibility of the EA alternative concept are underway and not yet finished, these ideas do not violate the basic physics of the EA, as showed in this paper, with evident advantages in the fuel cycle (on line refueling); reduced requirements in the accelerator complex which is more realistic and economical in today accelerators technology; and finally the utilization of He as coolant compared with molten Pb is more closed of the proved technology given the know how of gas cooled reactors and more efficient from the thermodynamic point of view, allowing simplification and the utilization in other process, besides electricity generation, as hydrogen generation .

ADS CALCULATION METHODOLOGY



Benchmark Calculation:LCS vs FLUKA for Rubbia FEA-ADS

	FLUKA	LCS
Thermal Power	1500 MW	1576 MW
k eff	0,98	0,967
Specific Power	52,8 W/g	53 W/g
Power Density	523 W/cm3	527 W/cm3
$\varepsilon = N_{233} / N_{232}$	0,11	0,107
Cladding Maximum	707 °C (Pb)	706 °C (Pb)
Temperature	--------	883 °C (He)

CONCEPTUAL BASES

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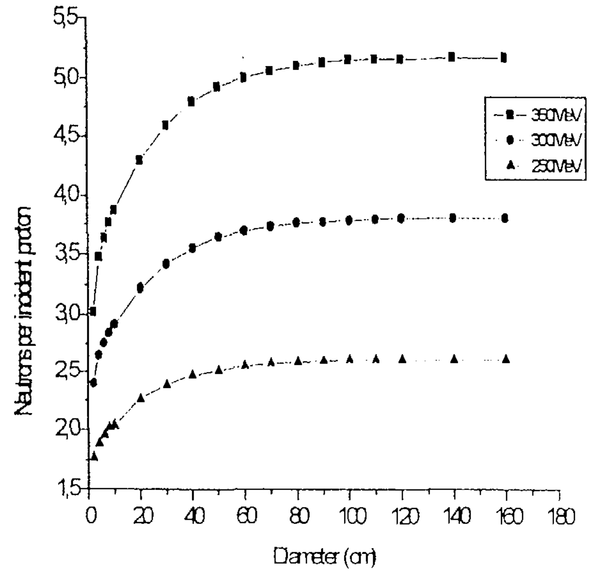
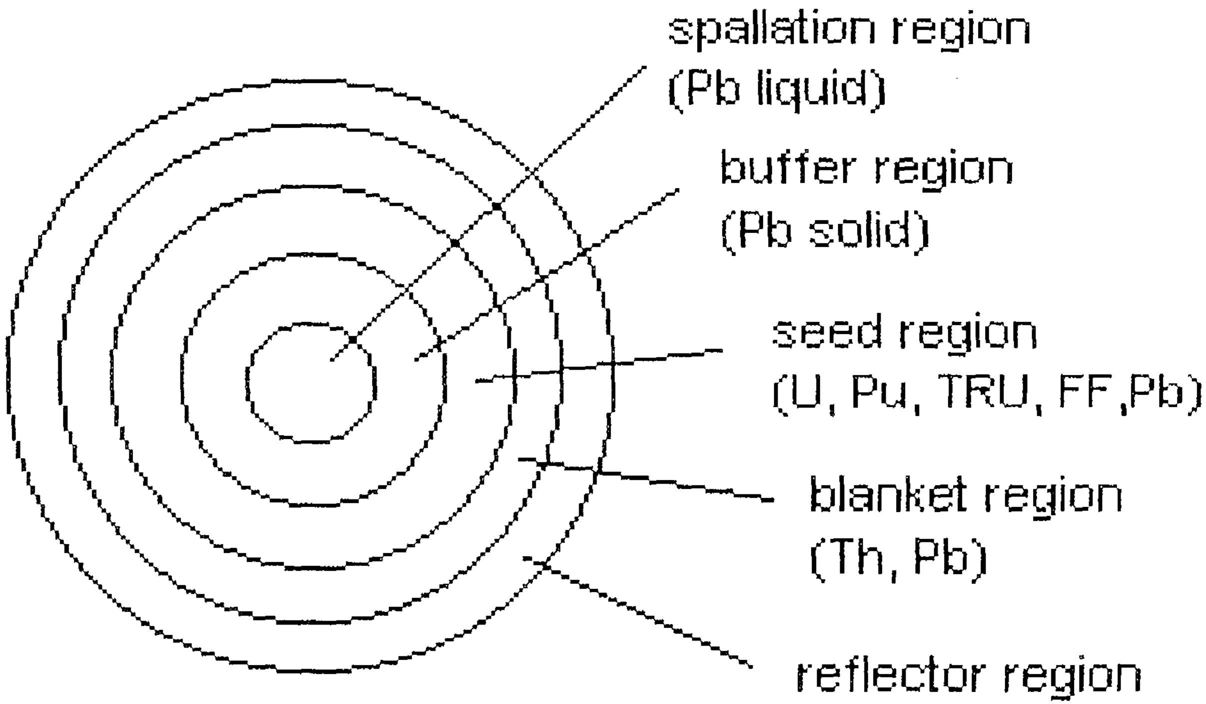
Proton Energy (MeV)	Multiplicity n_0, (n/p)		Integrated Yield S_0, (n/sec.mA)	
	FLUKA	LCS	FLUKA	LCS
100	0,399	0,321	2,49E+15	2,00E+15
150	0,898	0,835	5,61E+15	5,21E+15
200	1,788	1,627	1,12E+16	1,02E+16
250	2,763	2,664	1,73E+16	1,66E+16
300	4,156	3,883	2,60E+16	2,42E+16
350	5,291	5,272	3,31E+16	3,29E+16
400	6,939	6,784	4,34E+16	4,23E+16
1000	----	28,76	----	1,79E+17

Neutron Yield for Spallation Process Induced by high Energy Protons Calculated by LAHET and FLUKA

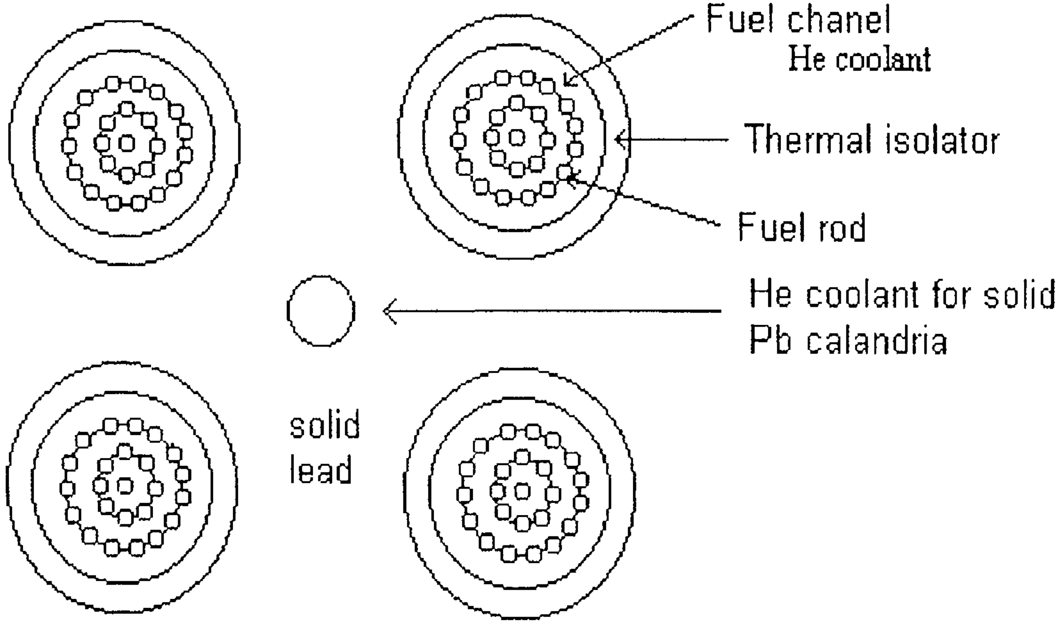
- Total Leakage Production



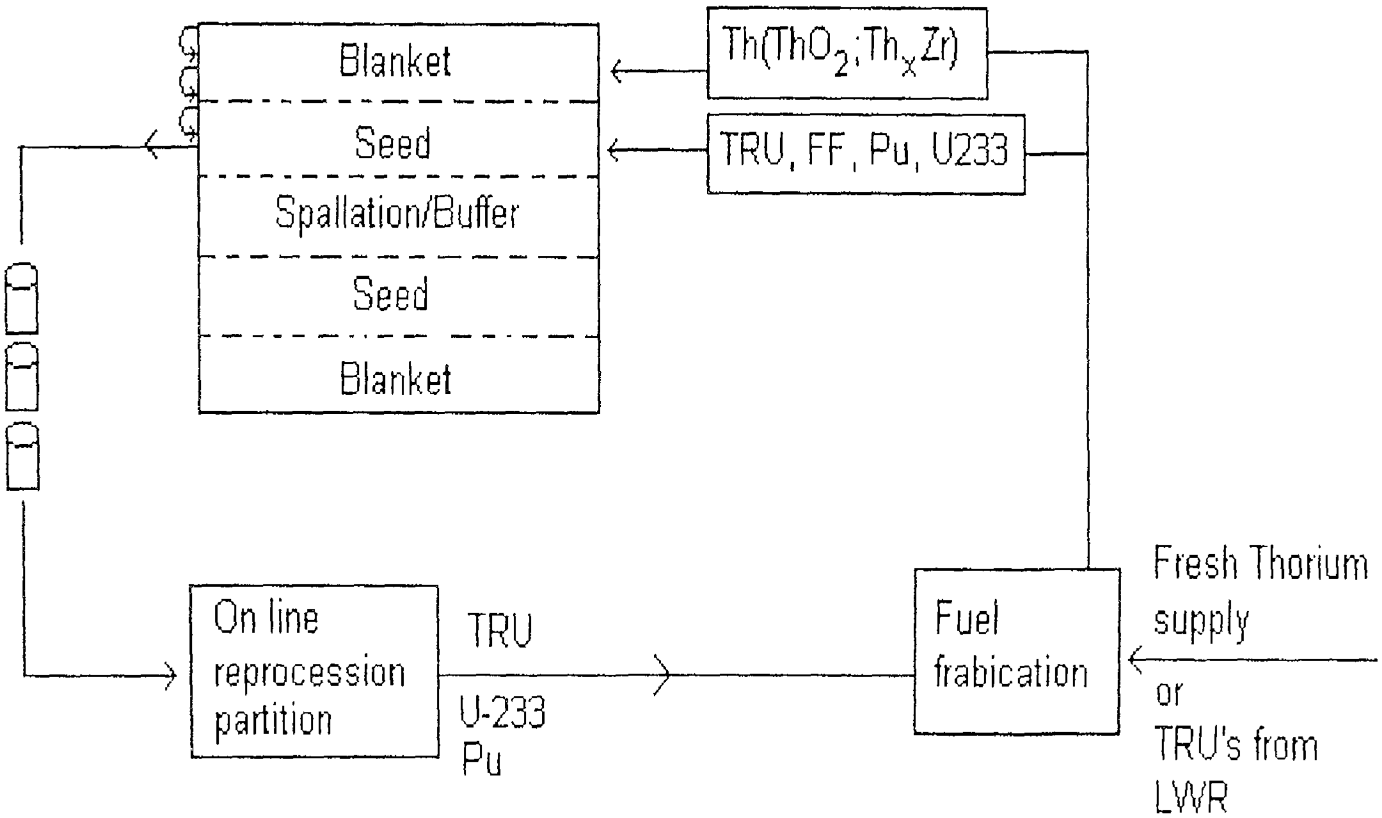
Schematic Regions for the Modified Energy Amplifier ADS



Schematic Cell of a Modified Concept Fast Energy ADS



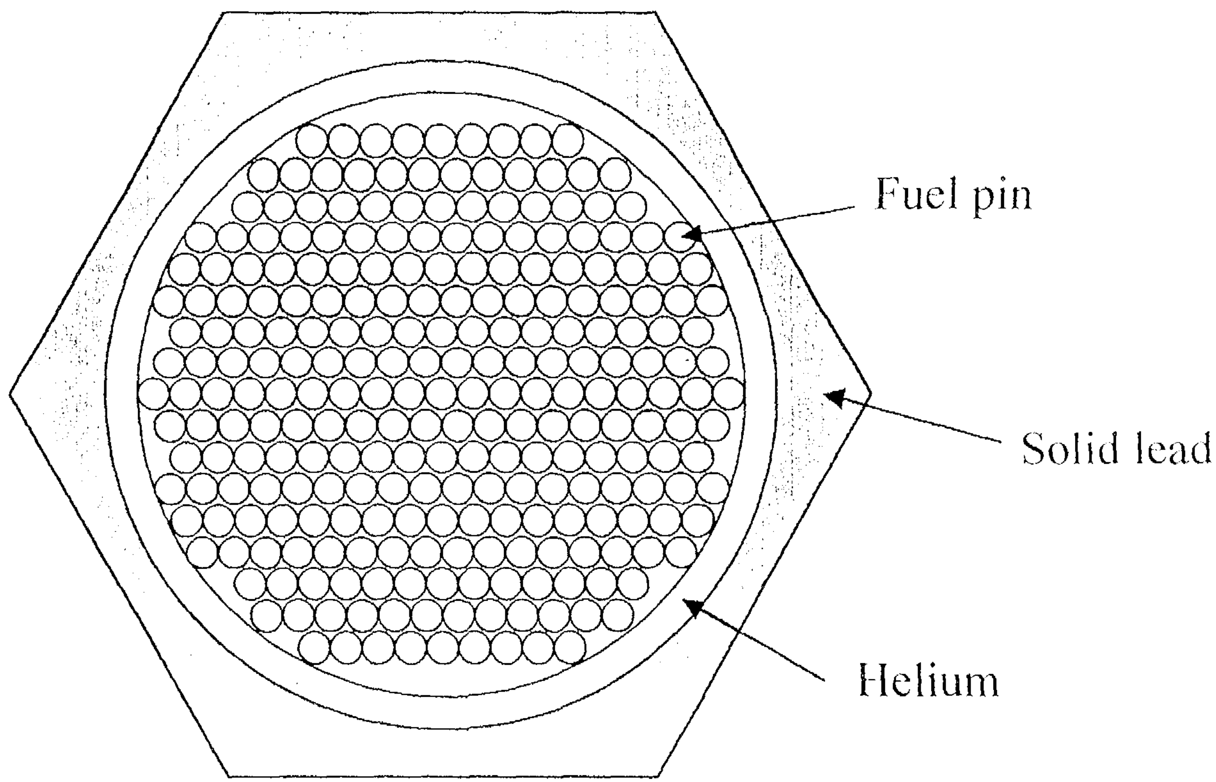
Fuel Cycle for the Modified Concept(FEA-ADS)

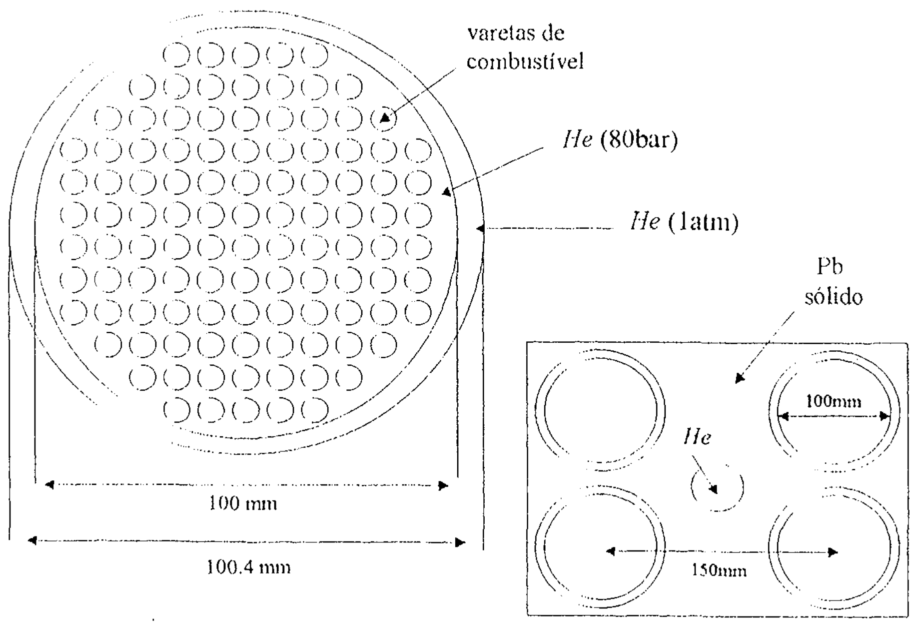


Reactor Description-MFEA-ADS 2

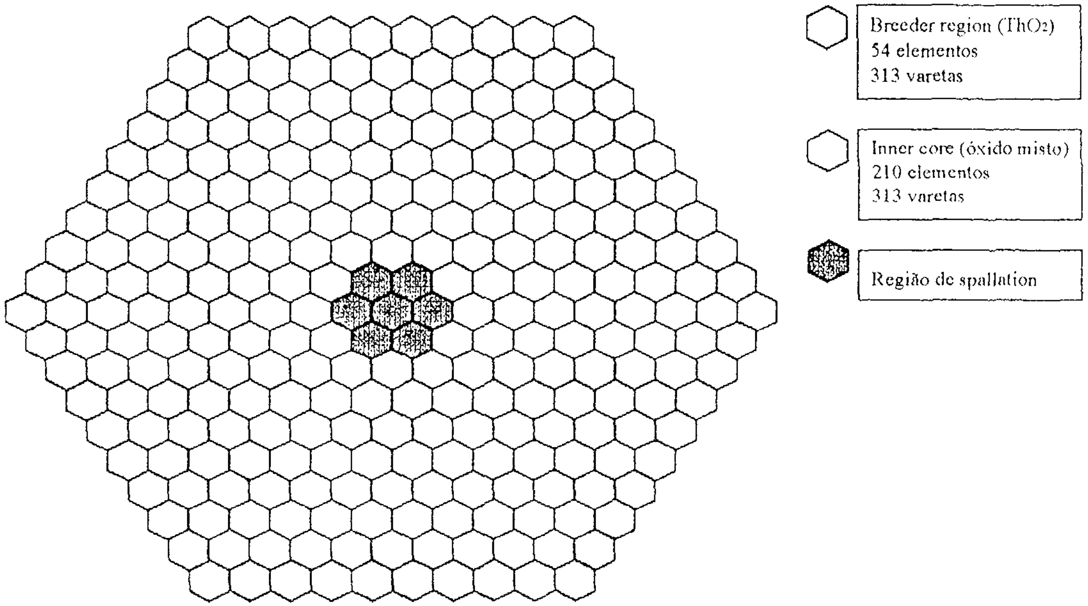
Geometry:Hexagonal with pin
Coolant:He
Keff=0.96
<u>Seed Region</u>
$(ThO_2 + 0.1\ U_{233}O_2)$/HT-9
<u>Blanket Region</u>
<u>(ThO_2)/HT-9</u>
Spallation Target :Liquid Pb
Pin Pitch:1.138 cm
FE Pitch:28.45 cm
H=200 cm

Fuel Element

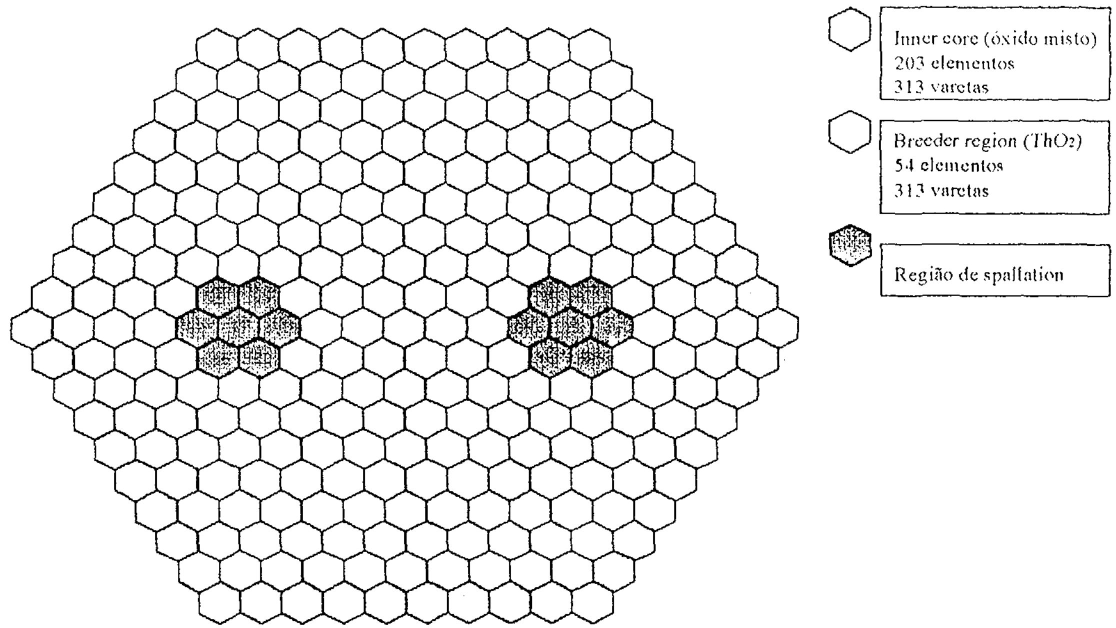




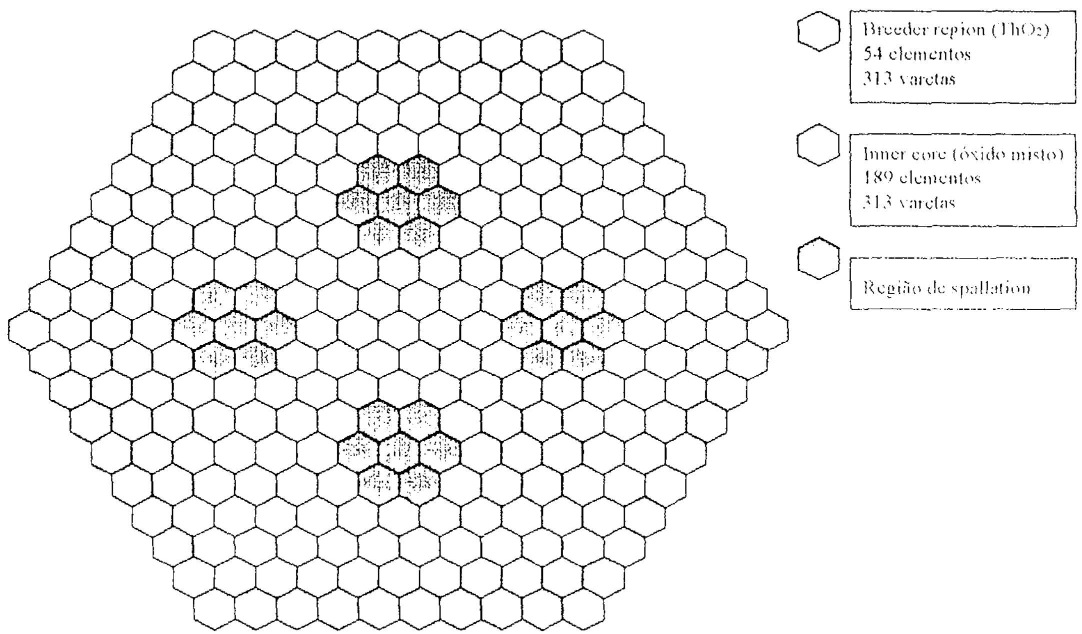
Modified Scheme of the FE with He circulating through Fuel Pins
Solid Pb ; Channel of He(to keep Pb Solid)



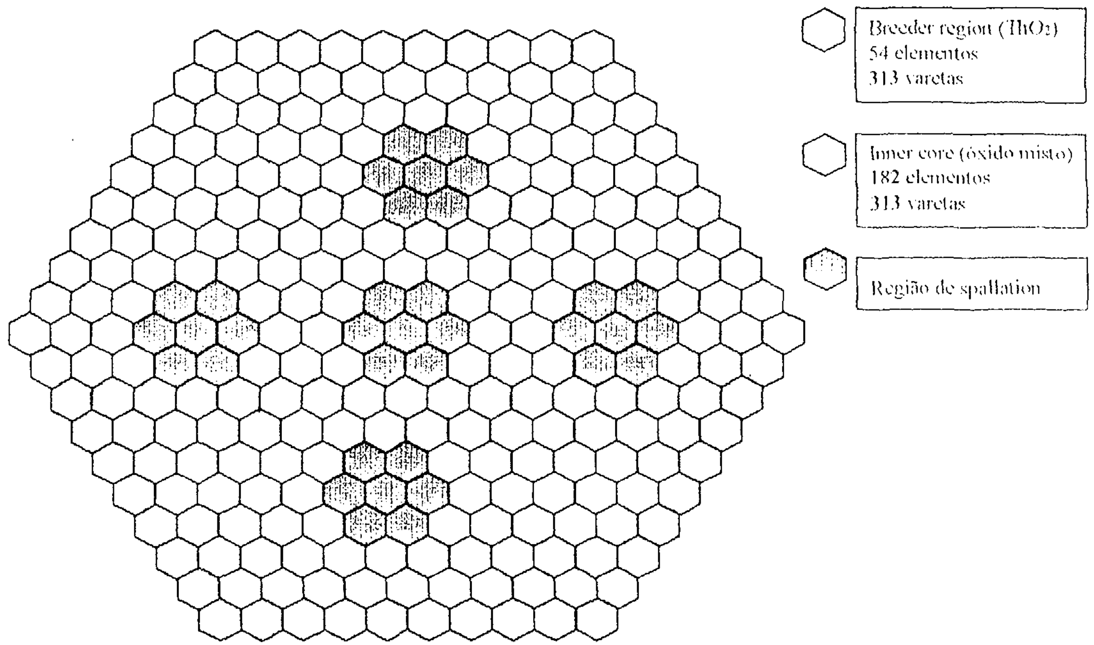
One Spallation Region



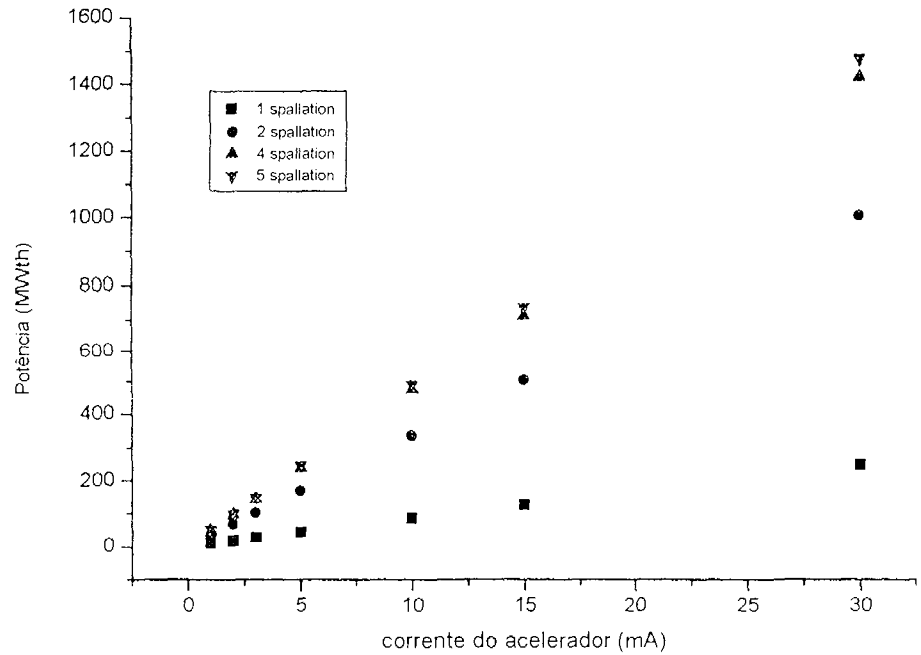
Two Spallation Regions



Four Spallation Regions



Five Spallation Regions

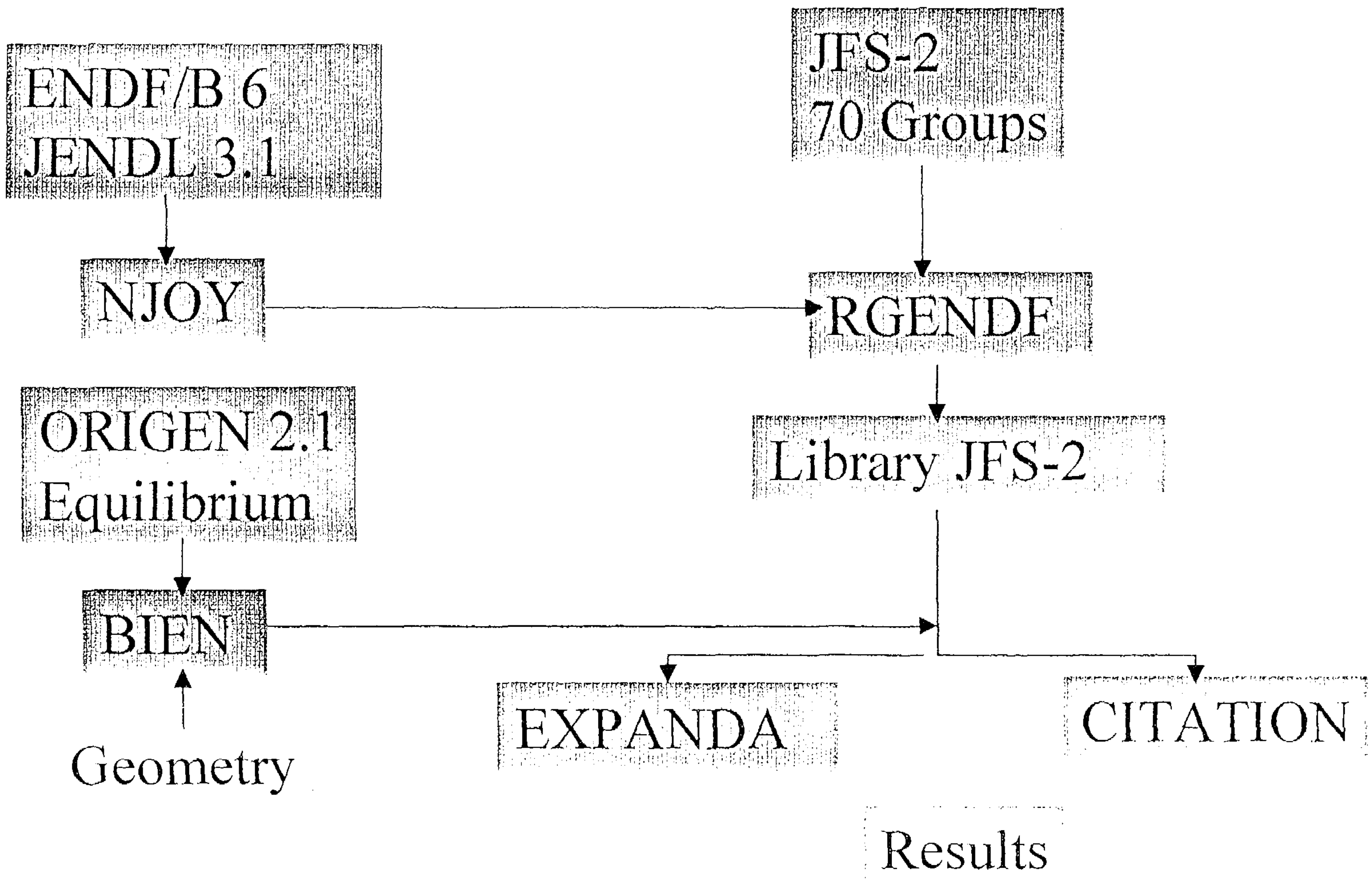


Total Power for 1,2,4 and 5 Spallation Sources vs Accelerator Current
Proton Energy=500 Mev

Corrente do acelerador (mA)	Potência (MWth) 1 região spallation	Potência (MWth) 2 regiões spallation	Potência (MWth) 4 regiões spallation	Potência (MWth) 5 regiões spallation
1	8	33	47	49
2	16	67	94	98
3	24.5	100	141	147
5	40.8	167	236	245
10	81.6	335	472	491
15	122	502	709	736
30	244	1004	1418	1473

Power Variation(MWth) for 1,2,4 and 5 Spallation Source vs Accelerator Current (Ep =500 MeV)

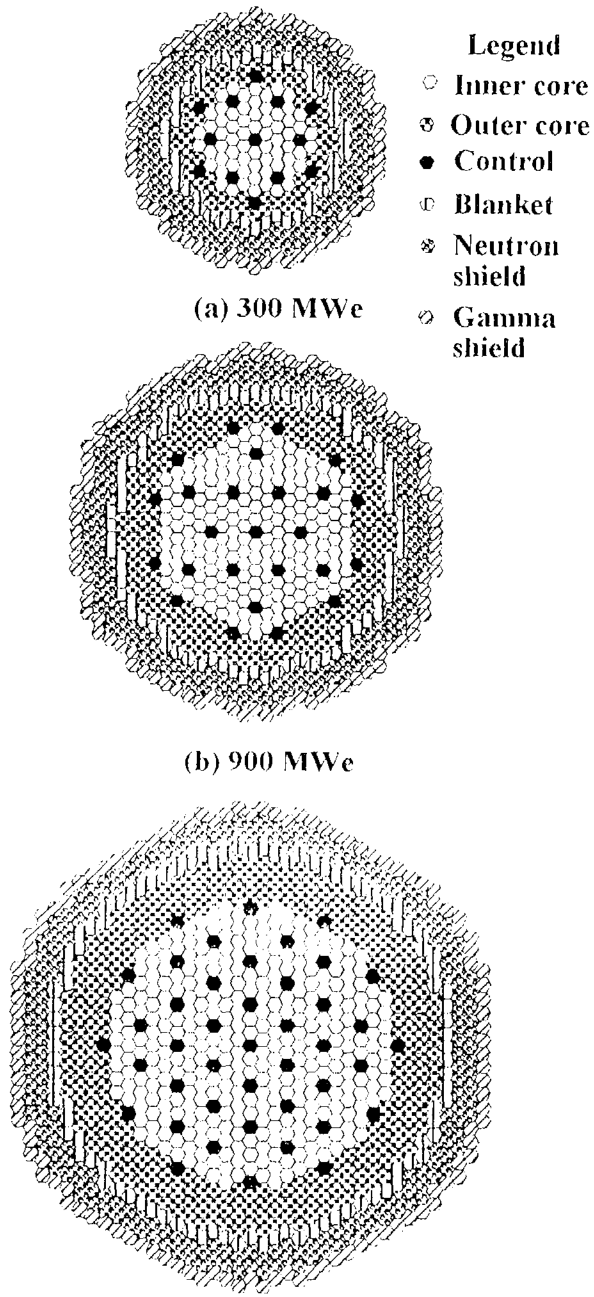
ILR Calculation Methodology



ILR Benchmark Calculation Results

Critical Assembly	Core Volume (ℓ)	Fertile/Fissile Ratio	k_{exp} 1.0000 (+/-)	k_{calc}*	k_{exp} - k_{calc}
		Plutonium Fuel			
VERA-11A	12	0.05	0.0030	0.9899	0.0101
ZEBRA-3	60	8.6	0.0030	0.9982	0.0018
SNEAK-7A	110	3.0	-	1.0036	-0.0036
SNEAK-7B	310	7.0	-	1.0027	-0.0027
ZPR-3-48	410	4.5	0.0010	1.0033	-0.0033
ZPR-3-56B	610	4.6	0.0014	0.9939	0.0061
ZPPR-2	2400	6.5	0.0006	1.0045	-0.0045
ZPR-6-7	3100	6.5	0.0010	1.0020	-0.0020
Mean		All Pu cases		1.0002	--
Mean | 1 - k |				--	0.0043
		Uranium Fuel			
VERA-1B	30	0.07	0.0028	1.0024	-0.0024
ZPR-3-6F	50	1.1	0.0015	1.0139	-0.0139
ZPR-3-12	100	3.8	-	1.0067	-0.0067
ZPR-3-11	140	7.5	0.0025	1.0061	-0.0061
ZEBRA-2	430	6.2	0.0020	0.9930	0.0070
ZPR-6-6A	4000	5.0	0.0005	0.9985	0.0015
Mean		All U cases		1.0014	--
Mean | 1 - k |				--	0.0063
Mean		All Pu + U cases		1.0008	--
Mean | 1 - k |				--	0.0051

ILR Core
Hexagonal Models



(a) 300 MWe

(b) 900 MWe

(c) 1500 MWe

Core Specifications

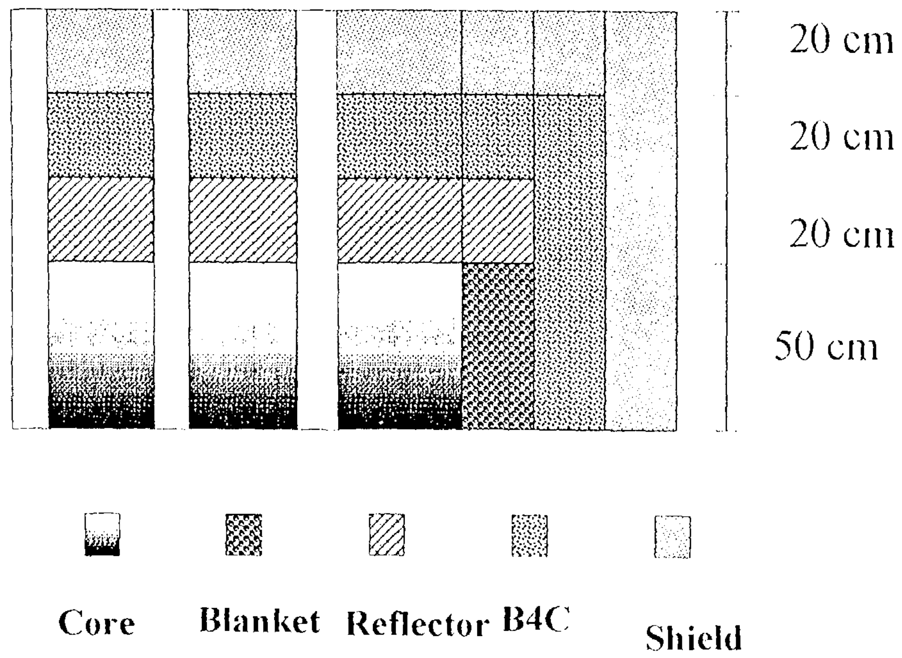
Power (MWe)	300	900	1500
Fuel pin numbers	34146	104064	170730
# Assemblies			
Inner core	66	204	342
Outer core	60	180	288
Control	13	25	43
Blanket	48	78	96
Neutron shield	114	174	210
Gamma shield	66	96	114

(*) Read as 3.409×10^6

Assembly Design Parameters, dimensions in mm

Pin diameter Cladding thickness	6.35 0.489			8.12 0.625			10.4 0.800		
P/D ratio	1.308	1.417	1.495	1.308	1.417	1.495	1.308	1.417	1.495
Lattice pitch	149.5	160.6	169.1	188.2	202.9	213.9	238.4	257.4	271.6
Fuel Assembly					Volume Fractions (%)				
Fuel	31.73	27.50	24.80	32.75	28.16	25.35	33.49	28.73	25.80
Structure	21.77	19.56	18.10	20.36	18.09	16.65	19.15	16.88	15.46
Coolant	46.50	52.94	57.10	46.89	53.75	58.02	47.36	54.39	58.74
Radial Blank./Shield.									
Fuel / B_4C / SS	42.97	37.02	33.31	42.97	37.02	33.31	42.97	37.02	33.31
Structure	17.46	15.54	14.31	17.46	15.54	14.31	17.46	15.54	14.31
Coolant	39.57	47.44	52.38	39.57	47.44	52.38	39.57	47.44	52.38
Axial Reflect./Shield.									
Pb / B_4C / SS	31.73	27.50	24.80	32.75	28.16	25.35	33.49	28.73	25.80
Structure	21.77	19.56	18.10	20.36	18.09	16.65	19.15	16.88	15.46
Coolant	46.50	52.94	57.10	46.89	53.75	58.02	47.36	54.39	58.74
Control Out									
Structure	6.00	←	←	4.50	←	←	3.50	←	←
Coolant	94.00	←	←	95.50	←	←	96.50	←	←

Calculation RZ Model



First Cycle Performance Characteristics, 300 MWe Core

Pin diameter (mm)	6.35			8.12			10.4		
Height/Diameter core ratio	0.54	0.50	0.48	0.43	0.40	0.38	0.34	0.31	0.30
P/D ratio	1.308	1.417	1.495	1.308	1.417	1.495	1.308	1.417	1.495
Enrichment IC/OC* (% HM)	16.8 / 28.2	17.9 / 30.0	18.8 / 31.4	15.3 / 24.1	16.4 / 25.9	17.3 / 27.2	14.2 / 20.8	15.3 / 22.5	16.2 / 23.7
Burnup swing (% Δk)									
Transmutation reactivity	4.03	4.33	4.50	3.79	4.30	4.59	3.01	3.71	4.11
Swelling reactivity	1.73	1.64	1.57	1.40	1.33	1.27	1.14	1.09	1.05
β_{ef} (10^{-3})	7.56 / 7.10**	7.48 / 7.08	7.43 / 7.06	7.61 / 7.00	7.53 / 6.99	7.47 / 6.98	7.67 / 6.95	7.57 / 6.95	7.51 / 6.95
Conversion Ratio (CR)	0.39 / 0.43	0.36 / 0.40	0.34 / 0.38	0.45 / 0.51	0.42 / 0.47	0.39 / 0.45	0.51 / 0.58	0.47 / 0.53	0.44 / 0.50
Breeding Ratio (BR)	0.50 / 0.55	0.46 / 0.51	0.44 / 0.49	0.56 / 0.63	0.52 / 0.58	0.49 / 0.55	0.62 / 0.69	0.57 / 0.64	0.54 / 0.60
Burnup - Aver/Peak (MWd/kg)									
Inner core	32.0 / 45.0	32.1 / 44.9	32.2 / 44.7	35.2 / 48.6	35.1 / 48.0	35.0 / 47.6	34.4 / 46.6	34.3 / 45.9	34.2 / 45.5
Outer core	32.3 / 49.5	32.2 /49.4	32.3 / 49.4	33.6 / 52.0	33.9 / 52.1	34.0 / 52.2	31.5 / 49.2	31.8 / 49.3	32.0 / 49.3
Radial blanket	0.98 / 2.35	0.89 /2.19	0.83 / 2.04	0.97 / 2.60	0.87 / 2.42	0.81 / 2.26	0.78 / 2.46	0.72 / 2.27	0.66 / 2.11
Fast fluence (10^{23} n/cm^2)									
Inner core	1.26	1.18	1.12	1.46	1.35	1.28	1.48	1.37	1.29
Outer core	0.94	0.88	0.84	1.13	1.06	1.01	1.19	1.11	1.06
Peak flux (10^{15} n/cm^2 s)									
Inner core	4.98 / 5.42	4.69 / 5.08	4.48 / 4.84	3.30 / 3.67	3.07 / 3.38	2.91 / 3.19	2.12 / 2.39	1.96 / 2.19	1.86 / 2.06
Outer core	3.51 / 3.80	3.30 / 3.59	3.15 / 3.44	2.45 / 2.65	2.28 / 2.49	2.18 / 2.38	1.68 / 1.79	1.56 / 1.68	1.48 / 1.61
Temperature effect									
Doppler (10^{-3})	-2.47	-2.36	-2.25	-2.93	-2.77	-2.60	-3.09	-3.03	-2.88
Expansion (% Δk)	-1.14	-1.26	-1.35	-0.98	-1.12	-1.20	-0.91	-1.00	-1.06
Power fractions (%)									
Inner core	51.4 / 51.0	51.7 / 51.1	51.8 / 51.1	52.5 / 52.7	52.6 / 52.4	52.6 / 52.1	53.3 / 54.2	53.4 / 53.7	53.4 / 53.4
Outer core	47.1 / 46.5	47.0 / 46.7	47.0 / 46.9	46.2 / 45.0	46.3 / 45.6	46.4 / 46.0	45.7 / 43.8	45.7 / 44.5	45.7 / 44.9
Power peaking factor	1.56 / 1.51	1.55 / 1.51	1.55 / 1.51	1.54 / 1.47	1.53 / 1.48	1.53 / 1.49	1.53 / 1.44	1.52 / 1.45	1.51 / 1.46
Core inventory									
^{235}U (t)	1.85 / 1.54	1.97 / 1.65	2.07 / 1.74	2.65 / 2.11	2.85 / 2.30	3.0 / 2.44	3.88 / 3.04	4.19 / 3.34	4.42 / 3.56
^{236}U (kg)	0 / 59.6	0 / 61.0	0 / 62.0	0 / 102.9	0 / 105.8	0 / 107.8	0 / 160.9	0 / 165.7	0 / 169.1
Pu (kg)	0 / 120	0 / 114	0 / 109	0 / 242	0 / 227	0 / 218	0 / 428	0 / 402	0 / 384
Blanket inventory									
^{238}U (t)	5.23	5.23	5.23	8.35	8.35	8.35	13.43	13.43	13.43
Pu (kg)	0 / 37.3	0 / 35.3	0 / 34.0	0 /65.2	0 / 62.3	0 / 60.1	0 / 99.7	0 / 95.1	0 / 91.8

(*) IC/OC = Inner Core/Outer Core; (**) 7.56 / 7.10 = Beginning Of Cycle / End Of Cycle results

First Cycle Performance Characteristics, 900 MWe Core

Pin diameter (mm)	6.35			8.12			10.4		
Height/Diameter core ratio	0.32	0.30	0.28	0.25	0.23	0.22	0.20	0.18	0.17
P/D ratio	1.308	1.417	1.495	1.308	1.417	1.495	1.308	1.417	1.495
Enrichment IC/OC (% HM)	14.3 / 21.0	15.4 / 22.6	16.3 / 23.7	13.7 / 18.5	14.8 / 20.0	15.7 / 21.1	13.1 / 16.5	14.3 / 18.0	15.2 / 19.0
Burnup swing (% Δk)									
Transmutation reactivity	3.18	3.79	4.16	2.77	3.64	4.15	2.01	3.04	3.62
Swelling reactivity	1.12	1.07	1.03	0.93	0.88	0.86	0.77	0.75	0.72
β_{ef} (10^{-3})	7.62 / 6.94*	7.53 / 6.94	7.48 / 6.93	7.67 / 6.83	7.57 / 6.85	7.51 / 6.86	7.71 / 6.81	7.61 / 6.84	7.55 / 6.85
Conversion Ratio (CR)	0.51 /0.58	0.47 / 0.53	0.45 / 0.50	0.56 / 0.64	0.52 / 0.58	0.48 / 0.55	0.61 / 0.68	0.56 / 0.63	0.52 / 0.59
Breeding Ratio (BR)	0.58 / 0.64	0.53 / 0.59	0.50 / 0.56	0.62 / 0.70	0.57 / 0.64	0.54 / 0.61	0.67 / 0.74	0.61 / 0.68	0.57 / 0.64
Burnup - Aver/Peak (MWd/kg)									
Inner core	33.5 / 45.6	33.4 / 45.1	33.3 / 44.7	36.7 / 49.7	36.4 / 48.5	36.3 / 47.9	35.6 / 48.3	35.1 / 46.6	35.1 / 46.2
Outer core	30.1 / 48.4	30.3 / 48.4	30.0 / 48.4	31.4 / 50.5	31.7 /50.7	31.9 / 50.7	29.6 / 47.5	30.2 / 47.8	30.3 / 47.8
Radial blanket	0.89 / 2.06	0.81 / 1.88	0.75 / 1.79	0.84 / 2.18	0.76 / 1.99	0.71 / 1.88	0.66 / 1.95	0.60 / 1.82	0.55 / 1.69
Fast fluence (10^{23} n/cm^2)									
Inner core	1.41	1.30	1.23	1.61	1.47	1.38	1.62	1.46	1.38
Outer core	1.14	1.07	1.02	1.32	1.24	1.18	1.36	1.27	1.21
Peak flux (10^{15} n/cm^2 s)									
Inner core	5.60 / 6.40	5.22 / 5.88	4.97 / 5.53	3.55 / 4.23	3.29 / 3.82	3.12 / 3.56	2.22 / 2.75	2.04 / 2.44	1.94 / 2.27
Outer core	4.48 / 4.77	4.18 / 4.50	3.97 / 4.30	3.03 / 3.18	2.80 / 2.99	2.65 / 2.87	2.01 / 2.06	1.86 / 1.95	1.76 / 1.86
Temperature effect									
Doppler (10^{-3})	-3.19	-3.02	-2.90	-3.43	-3.20	-3.06	-3.58	-3.36	-3.20
Expansion (% Δk)	-0.84	-0.94	-1.03	-0.75	-0.87	-0.95	-0.70	-0.81	-0.88
Power fractions (%)									
Inner core	54.7 / 55.9	54.8 / 55.4	54.9 / 55.1	55.5 / 57.7	55.5 / 56.8	55.6 / 56.3	55.7 / 59.0	55.6 / 57.7	55.8 / 57.2
Outer core	44.6 / 42.9	44.5 / 43.5	44.5 / 43.8	43.9 / 41.3	43.9 / 42.2	43.9 / 42.8	43.8 / 40.1	44.0 / 41.5	43.9 / 42.1
Power peaking factor	1.55 / 1.47	1.55 / 1.48	1.54 / 1.48	1.53 / 1.52	1.52 / 1.47	1.51 / 1.44	1.51 / 1. 57	1.51 / 1.49	1.50 / 1.45
Core inventory									
^{235}U (t)	4.44 / 3.52	4.77 / 3.83	5.02 / 4.07	6.61 / 5.04	7.16 / 5.55	7.58 / 5.93	10.02 /7.58	10.93 /8.41	11.58 /9.02
^{236}U (kg)	0 / 180	0 / 184	0 / 188	0 / 308	0 / 317	0 / 324	0 / 479	0 / 496	0 / 507
Pu (kg)	0 / 469	0 / 443	0 /424	0 / 890	0 / 835	0 / 798	0. / 1505	0 / 1409	0 / 1344
Blanket inventory									
^{238}U (t)	8.51	8.51	8.51	13.57	13.57	13.57	21.83	21.83	21.83
Pu (kg)	0 / 62.9	0 / 59.7	0 / 57.4	0 /104	0 / 99.7	0 / 96.2	0 /151	0 / 145	0 / 140

(*) IC/OC = Inner Core/Outer Core; (*)7.62 / 6.94 = Beginning Of Cycle / End Of Cycle results

First Cycle Performance Characteristics, 1500 MWe Core

Pin diameter (mm)	6.35			8.12			10.4		
Height/Diameter core ratio	0.25	0.23	0.22	0.20	0.18	0.17	0.15	0.14	0.13
P/D ratio	1.308	1.417	1.495	1.308	1.417	1.495	1.308	1.417	1.495
Enrichment IC/OC (% HM)	14.1 / 19.2	15.2 / 20.6	16.1 / 21.7	13.5 / 17.1	14.7 / 18.5	15.6 / 19.6	13.1 / 15.5	14.3 / 16.8	15.1 / 17.8
Burnup swing (% Δk)									
Transmutation reactivity	3.04	3.75	4.17	2.61	3.59	4.13	1.85	2.97	3.59
Swelling reactivity	0.99	0.94	0.91	0.82	0.80	0.78	0.67	0.58	0.56
β_{ef} (10^{-3})	7.63 / 6.87*	7.54 / 6.88	7.49 / 6.89	7.68 / 6.77	7.58 / 6.80	7.52 / 6.81	7.72 / 6.76	7.62 / 6.79	7.56 / 6.81
Conversion Ratio (CR)	0.55 / 0.61	0.50 / 0.57	0.47 / 0.54	0.59 / 0.67	0.54 / 0.61	0.51 / 0.58	0.64 / 0.71	0.58 / 0.65	0.54 / 0.61
Breeding Ratio (BR)	0.59 / 0.66	0.55 / 0.61	0.52 / 0.58	0.64 / 0.71	0.58 / 0.66	0.55 / 0.62	0.68 / 0.75	0.61 / 0.69	0.58 / 0.65
Burnup - Aver/Peak (MWd/kg)									
Inner core	34.4 / 47.1	34.3 / 46.5	34.2 / 46.1	37.5 / 52.1	37.2 / 50.8	36.9 / 49.9	36.2 / 51.8	35.7 / 49.8	35.4 / 48.9
Outer core	30.3 / 49.0	30.4 / 48.9	30.6 / 48.9	31.6 / 51.2	32.0 / 51.3	32.4 / 51.5	30.0 / 48.4	30.7 / 48.8	31.1 / 48.9
Radial blanket	0.86 / 1.96	0.79 / 1.78	0.73 / 1.70	0.81 / 2.04	0.73 / 1.87	0.68 / 1.78	0.62 / 1.80	0.57 / 1.69	0.53 / 1.59
Fast fluence (10^{23} n/cm^2)									
Inner core	1.47	1.36	1.28	1.67	1.55	1.45	1.74	1.56	1.46
Outer core	1.27	1.16	1.10	1.43	1.34	1.28	1.46	1.37	1.31
Peak flux (10^{15} n/cm^2 s)									
Inner core	5.76 / 6.85	5.40 / 6.24	5.13 / 5.83	3.67 / 4.58	3.40 / 4.10	3.21 / 3.80	2.30 / 3.05	2.12 / 2.67	2.02 / 2.46
Outer core	4.93 / 5.19	4.59 / 4.90	4.35 / 4.70	3.31 / 3.42	3.06 / 3.23	2.90 / 3.10	2.20 / 2.19	2.03 / 2.09	1.92 / 2.01
Temperature effect									
Doppler (10^{-3})	-3.43	-3.25	-3.14	-3.59	-3.39	-3.15	3.70	3.48	3.30
Expansion (% Δk)	-0.78	-0.87	-0.96	-0.71	-0.83	-0.91	0.65	0.77	0.84
Power fractions (%)									
Inner core	56.2 / 58.2	56.4 / 57.5	56.5 / 57.1	56.7 / 59.7	56.7 / 58.6	56.6 / 57.9	56.4 / 60.8	56.3 / 59.1	56.3 / 58.3
Outer core	43.3 / 41.0	43.1 / 41.7	43.1 / 42.1	42.9 / 39.6	42.9 / 40.7	43.0 / 41.4	43.3 / 38.6	43.4 / 40.3	43.4 / 41.2
Power peaking factor	1.55 / 1.52	1.54 / 1.47	1.53 / 1.46	1.53 / 1.60	1.52 / 1.53	1.52 / 1.48	1.53 / 1.71	1.53 / 1.59	1.52 / 1.54
Core inventory									
^{235}U (t)	6.84 / 5.32	7.36 / 5.81	7.76 / 6.18	10.32/ 7.72	11.21/ 8.53	11.87/ 9.15	15.83/11.78	17.27/13.10	18.32/14.07
^{236}U (kg)	0 / 299	0 / 308	0 / 314	0 / 511	0 / 529	0 / 540	0 / 797	0 / 826	0 / 845
Pu (kg)	0 /830	0 / 782	0 / 748	0 / 1547	0 / 1451	0 / 1386	0 / 2588	0 / 2422	0 / 2312
Blanket inventory									
^{238}U (t)	10.48	10.48	10.48	16.70	16.70	16.70	26.86	26.86	26.86
Pu (kg)	0 / 78.1	0 / 74.2	0 / 71.5	0 / 128	0 / 122	0 / 118	0 / 180	0 / 175	0 / 170

(*) IC/OC = Inner Core/Outer Core; (*)7.63 / 6.87= Beginning Of Cycle / End Of Cycle results