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*Resolution of Proliferation Issues
for a Sodium Fast Reactor Blanket*

TITLE

Resolution of Proliferation Issues For a Sodium Fast Reactor Blanket

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Abstract:

Breeding blankets are of interest for a SFR (Sodium Fast Reactor) as they allow for small cores to have positive breeding gains. However, because they breed very high quality plutonium, core designers are not currently encouraged to employ blankets. After verifying that the ERANOS code was in good agreement with BGcore, a Monte Carlo based depletion system, it was shown that a SFR blanket design could breed less attractive plutonium than Light Water Reactor (LWR) bred plutonium for making a nuclear explosive device. Minor actinide (MA) doping and moderator addition were the two options studied. This study shows that it is possible to build a sodium fast reactor with a secure blanket with minor actinide addition: at steady state MAs from approximately 1.5 LWRs are required per SFR (both rated at 1 GW(e)).

1. Introduction

The Sodium Fast Reactor (SFR) is seen as the most realistic Gen-IV reactor to be built in the near future. France and the US are still developing their designs; these will require improved safety, competitive economics, and also proliferation resistance. To meet this last requirement, both French and American designers hesitate on using breeding blankets. Fast reactor blankets are known to breed very high quality plutonium in large amount and are necessary for a small reactor to reach a breeding gain larger than one. Since the US and France won't need blankets to breed plutonium in their near term SFR designs, as they already have large amounts of plutonium from their LWR fleet (Light Water Reactor) to start a SFR fleet, SFR blankets are of current interest mainly for minor actinide burning. In contrast, India and China express a great interest in using blankets for their SFR designs, to reach a high breeding ratio: for example, the latest Indian PFBR design (Prototype Fast Breeder Reactor), a 500 MW(e) oxide-fueled SFR with a breeding ratio of 1.05[1].

The goal of this paper is to show how breeding weapon grade plutonium in a SFR blanket can be prevented by adding moderating materials and minor actinides (MAs). A methodology to conceive a blanket design meeting proliferation requirements was developed. Every mixture of plutonium isotopes can in principle be used to make a nuclear explosive device. Thus, the goal will be to breed less attractive plutonium in the SFR blanket than that

from 50 MWd/kg spent LWR fuel. A criterion[2] based on Pu238 and Pu240 content was chosen to rank plutonium quality.

The European ERANOS calculation code[3] was employed, and its performance compared to the MCNP based code BGCore[4]. After a description of the reference core studied, calculation tools will be analyzed. The methodology developed to render a blanket design secured will then be described and applied to the reference core.

2. Reference core description

The reference core is a sodium fast reactor designed by A. Nikiforova and E. Shwageraus[5]. It is a 2400 MW(t) self-sustaining core (conversion ratio of one), employing metallic fuel, obtained using ABR1000[6] as the initial reference design. As displayed in Fig 1., the core has 360 fuel assemblies, separated in 3 fueled zones (inner, middle and outer) and 19 control assemblies. Composition of the three fuel zones is displayed in Table I. Note that within the three zones, the enrichment in TRU remains constant and has a value of 15.2%. However, the quantity of diluent (zirconium) decreases to offset the increase of leakage in the outer zones. This way of diluting the fuel helps to prevent power shifting with burnup.

Each fuel assembly has a total of 271 pins. Homogeneous and heterogeneous compositions of the core zones are described in Table II and III. Axial description of the core is displayed in Fig 2. These pins are fueled with natural uranium (described in table XI)[7], zirconium as diluents, and with a

TRU vector described in Table IV. Assembly parameters are gathered in Table V.

The fuel temperature is 630 °C and the structure and coolant mean temperature is 427 °C. Sodium density was 0.85 g/cm^3. HT-9 steel was employed as the reference material for both cladding and structures.

3. Analysis tools and benchmark calculations

This design was modeled with both the MCNP, specifically MCNP4C[8], based code BGcore[9] and the ERANOS code.

ERANOS is a neutronic code developed by CEA for fast neutron reactors in the framework of a European collaboration. It uses the ECCO code for cell calculations, which is based on the sub-group method combined with a fine group transport calculation (1968 groups). It is a deterministic code, which has been benchmarked with French fast reactors (Phenix), and also using the YALINA-Thermal facility[3]. Results show good agreement between calculation and measurements. Calculations were done in the present study using 1968 energy-groups for the cell calculation to model the self-shielding, and condensed into 33 energy-groups for all calculations. The transport equation was solved employing the ERANOS code, with both homogeneous and heterogeneous models. BGcore is an MCNP based code. MCNP is a transport calculation code using the Monte Carlo methodology to simulate neutron, photon or electron transport, employing point-wise cross sections. BGcore is a linkage program, which combines the continuous energy code

MCNP and the SARAF depletion and decay code[4]. For both the ERANOS and BGcore codes, the European library JEFF3.1 was used.

A difference of 0.27% in k_{eff} was calculated between the ERANOS heterogeneous model and MCNP at the beginning of cycle: this represents 280 pcm[*], as displayed in Fig 3. Differences between MCNP and ERANOS can be explained in part by the differing energy treatment of the two codes and the exactness of the spatial representation used in the deterministic code ERANOS. A comparison of the homogeneous calculation between ERANOS and MCNP at the beginning of cycle was also done to remove the differences due to geometric approximations. A reactivity difference of 130 pcm was calculated.

Safety coefficients were also compared at the beginning of the cycle. Results are displayed in Table VI. There is less than 3% of difference for delayed neutron fraction (ßeff) calculation, and less than 15% of differences for Doppler, sodium expansion and radial expansion coefficients calculations. These differences are within the uncertainties calculated by MCNP and displayed in Table VI.

Isotope mass evolution was also compared between both codes. Very good agreement was obtained. Fig 4. displays the atomic concentration evolution for plutonium 239. After 1200 efpds (equivalent full power days), there are less than 1% of differences between ERANOS and BGcore. This comparison was also done for all TRU isotopes, including Cm, and shows very good

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[*] percent millirho = $1 \times 10^{-5} \, \Delta k/k$

agreements (less than 0.5% of differences for Cm244 isotope after 1200 efpds).

Power maps were also compared and once again showed good agreement. This comparison between ERANOS models and BGcore validates the model generation procedure, and hence the study that will be described later using the ERANOS code.

4. Methodology explanation

4.i. Introduction about blankets

A breeding blanket is a number of low–fissile content fuel assemblies (depleted, natural, reprocessed uranium or thorium), situated in the core (which consists of two fuel types: blanket and enriched driver fuel). They can be situated above/under the driver fuel region of the core (axial blanket), or around it (radial blanket); internal blankets have also been studied in the past. This paper will focus on radial and axial blankets.

A blanket has five goals :

- To enable the reactor to have a positive breeding gain, as most of the excess of Pu is produced in the blanket. A positive breeding gain is difficult[10] to reach with a small core, high volume power and no blanket. A breeding gain is the most important goal of a blanket.

- To reflect neutrons back into the core and to reduce neutron losses to the unfueled reflector; this can reduce the critical mass of the core significantly.

- To provide gamma and neutron shielding.

- To flatten the power density profile of the core.

- To produce some power (around 10% of the power of the core at the end of the cycle).

The economic objective of a blanket is to maximize the net blanket fissile revenue, that is the quantity of plutonium produced, and thus to reduce fuel fabrication and reprocessing costs.

4.ii. Proliferation issues of a blanket

The main disadvantage of a blanket is that it produces high quality plutonium in large amounts. Few designers are using breeding blankets in the core of a fast reactor today mainly because of this reason.

All plutonium material can be used to make a nuclear warhead. However, one can derive a criterion that will take into account the difficulty to make a weapon with some mixtures of Plutonium. The criterion developed by M. Saito[2] was used to calculate plutonium-bred attractiveness. The fuel cycle irradiation time was chosen to be 1200 efpds. The radial blanket is irradiated during 3 driver fuel cycles for economic and proliferation resistance reasons (its quality decreases with time). After 3600 efpds in the core, blanket bred plutonium is composed of approximately 94% Pu239 and 5% Pu240. After 3

cycles, each blanket assembly has bred more than 7 kg of weapon grade plutonium, as displayed in Fig 5., which is enough to build a nuclear explosive device.

The usable/unusable limit in Fig. 5. was benchmarked with LWR 50 MWd/kg bred plutonium and represents all the points with the same attractiveness. The attractiveness function is defined by Equation (1):

$$ATTR = \frac{\dfrac{\alpha_\infty}{\alpha_{\infty\,239}}}{\dfrac{DH}{DH_{238}} + \dfrac{SN}{SN_{238}}} \qquad (1)$$

where DH stands for Decay Heat; SN for Spontaneous Neutron emission and α is the α-Rossi function. It is the ratio of the α-Rossi function[11] which is the ratio of super-criticality over prompt neutron lifetime and defines the criteria of the explosive yield, to characteristics of technical difficulties in manufacturing explosive devices, given by the decay heat (DH) and the spontaneous fission neutron (SN).

The objective of this paper is to show how the use of moderator and minor actinides in the blanket will breed plutonium that is less attractive for someone seeking fissile materials to build a nuclear explosive device, than LWR bred plutonium. The Pu quality evolution is displayed in Fig 5. In this figure, plutonium quality must be in the *practically unusable* domain to be less attractive than LWR bred plutonium. Resolving proliferation issues for an SFR blankets will consist of spoiling the composition of plutonium bred in the blankets.

It has also been verified that in the driver fuel, because of the initial amount of minor actinides and use of reactor grade plutonium, the plutonium quality at the end of the cycle does not change significantly.

4.iii. Possible strategies to render a blanket fuel secure.

The blankets used in these studies involved radial and axial blankets with fuel design shown in Tables IX and X and on Figure 6.

<u>Moderated blanket</u>

The first way to decrease blanket bred plutonium quality is to use moderator. Adding moderator in a blanket softens the spectrum, favoring Pu240 production over Pu239 fission. Hydride moderators were used since their moderation power is the highest. However, their maximum acceptable temperature is quite low. The moderator chosen is $ZrH_{1.6}$[12]. This material cannot stand a temperature higher than 800°C. That is acceptable for a blanket-moderated fuel, especially if heterogeneous moderation is chosen. The quantity of moderator used was 30% by volume of the blanket assembly fuel. This represents one pin out of three. Having a higher amount of moderator would decrease even more the quality of plutonium bred, but would have only small additional contribution to the reduction of plutonium attractiveness, as displayed in Fig 7. However, it would replace uranium, which breeds plutonium, thus decreasing the breeding ratio of the blanket. A 30% of $ZrH_{1.6}$ by volume is an acceptable compromise.

However, moderator is not sufficient by itself, as displayed in Fig 7. In addition, it increases power peaking in the pins next to the moderator, as they receive large quantities of thermal neutrons. This will be further discussed in 5.iii.

Moderated reflector

Reflector materials were studied at MIT by K. Yu[13] and their albedo compared. BeO was chosen for the reflector of the blanket because of its high albedo (greater than 0.9) and because of its moderation power. However this option gives only a slightly noticeable improvement of plutonium self-protection quality. As for the moderated blanket, 80% of BeO within the reflector steel was chosen to be a good compromise. While this option is not very efficient, it is of interest to evaluate because adding reflector to a thin axial or radial blanket reduces minor actinide fraction needed to add to blanket to spoil plutonium vector, as explained next.

MA (Minor Actinide) doping

Some researchers[14, 15] found that adding MAs in a SFR blanket increases MA burning while helping proliferation resistance. Because if is difficult to separate Am, Cm and Cf, this study assumes no separation of individual minor actinides and keeps all transplutonium isotopes together. The minor actinide vector added in the blanket is given in Table VII. It was shown that MAs had very desirable impact on plutonium composition with respect to proliferation issues. Adding two percent of the blanket fuel mass as MA yielded plutonium bred with a quality meeting non-proliferation requirements. This can be explained theoretically, as Np237 will result in Pu238 following a capture and a beta decay of Np238 with a 2.1 days half-life. Am241 will also,

due to a capture and an alpha decay of Cm242, give Pu238. These two capture reactions are favored by a moderated spectrum.

The drawback of this option is that it increases the cost of blanket fabrication because of the decay heat and the neutron-gamma emission of these minor actinides. It will also increase the cost of blanket assembly reprocessing, especially if they contain large amounts of Pu238, which is a strong neutron emitter. This is why it is of interest to keep the quantity of MAs in the blanket as low as possible while still meeting non-proliferation requirements. In addition, as moderator cannot be an answer by itself for proliferation resistance, MA doping will be needed. It is also desirable to decrease the dependency on LWR bred minor actinides, in case the LWR nuclear fleet is eventually completely replaced by a fast reactor nuclear fleet.

For a non-moderated blanket (radial blanket with two rows around the driver fuel core), it was proven that 2% of MAs by mass of heavy metal fuel were required to secure the bred plutonium, as displayed in Fig. 8. In this chart the quality evolution of the blanket bred plutonium was calculated employing several levels of MA doping.

This methodology to determine the lowest MA percentage needed to meet the proliferation requirements was applied also to a moderated blanket (radial blanket with two rows of reprocessed uranium fuel and $ZrH_{1.6}$ moderator around the driver fuel core), and to a non-moderated blanket employing a moderating reflector (radial blanket of 1 row of depleted uranium around the core). Minimum amounts of MA needed for each option are displayed for both axial and radial blankets in Table VIII. It is interesting to note that, while a

moderated blanket might not be an answer by itself, it decreases MA requirements significantly.

5. Design description and performance

5.i. Design description

Three secured radial blankets (A, B and C) and two secured axial blankets (D1 and D2) were designed. Table IX summarizes each blanket's characteristics. The axial blanket was kept for one cycle in the core (1200 efpds), as it is part of the driver fuel assembly. Thus, the axial blanket lattice description is the same as the driver fuel description. Only one axial blanket, situated under the core, was studied. A gas plenum was kept on the top of the core as in the benchmarked core. The radial blanket design has been derived from the S-PRISM blanket assembly design[16], described in Table X, and was kept during 3 cycles in the core (3600 efpds). It was verified that after this irradiation time, both fluence and burnup limits of the blanket fuel were not reached. Both axial and radial blankets were fueled with reprocessed uranium[17] (Table XI), which is less expensive than natural and depleted uranium but more radioactive. This last point is made unimportant because of minor actinide doping.

5.ii. Design performance comparisons

The three radial blanket designs described in the previous section were compared in a core employing each of the two axial designs. Their performance was compared at steady state. Table XII displays, for each axial and radial design, three factors of interest. The first one is the number of 1 GW(e) LWRs that will be required at steady state to generate enough minor actinides to fuel the blanket to keep it secured. The second one is the number of 1 GW(e) LWRs whose minor actinides are burned in the blanket at steady state if the amount of MA loaded in the blanket corresponds to the first column. It was assumed that a typical amount of 20 kg of minor actinides is generated by a 1 GW(e) LWR every year. The last figure of merit is the doubling time for the SFR. It is the time required, in equivalent full power years, to breed 4000 kg of plutonium in the blanket, which is the quantity of the blanket plutonium needed to start a new 1GWe SFR.

This comparison shows that, depending on the SFR goals (high breeding ratio, MA burning, low MA dependency), secure blanket designs are possible.

5.iii. Description and performance of the selected design

Design C/D1 (see Table XII) was selected for further studies. Even though it doesn't have the shortest doubling time nor burn the most MAs, the main advantage of this design is that it employs a one row radial blanket. Thus this design has a smaller core for nearly the same doubling time, which reduces blanket assembly fabrication and reprocessing costs.

 A 70 equivalent full power year long irradiation of successive cores was calculated. Driver fuel plutonium was reprocessed and sent back to the core

with a cooling time of 5 years and a reprocessed time of 2 years. This could be done because of its internal breeding ratio of 1.0. A once through minor actinide management strategy was applied for the blankets and its plutonium was accumulated to start a new fast reactor. During all the lifetime of the plant, plutonium quality in the core (blanket and driver fuel) was studied and is displayed in Fig 9. For both axial and radial blankets, and for the driver fuel, plutonium quality meets proliferation resistance requirements. It was also verified that the quality of the driver fuel plutonium is always more proliferation resistant than the LWR bred plutonium. Plutonium isotopic composition in both blankets and in the driver fuel, at the end of the life of the core, is displayed in Table XIII.

During the plant lifetime, masses of plutonium bred and of minor actinides burned are displayed in table XIV. The doubling time calculated is 24.2 equivalent full power years. It is also interesting to check the quantity of minor actinides burned in the blanket (Table XV), which is between 20 and 30% of Np and between 50 and 60% of Am. However, Cm and Cf buildup will be an issue, as they are responsible for most of the decay heat and of the neutron emission, which drives blanket fuel reprocessing and refabrication costs.

Safety coefficients were calculated for this design at beginning of cycle and after 1200efpds. Results are compared for the reference core and for the C/D1 design in Table XVI. Both calculations were done using a heterogeneous model of the driver fuel assemblies but a homogeneous model of both blankets and structures. The main results show that adding blankets improves all the safety coefficients studied.

- Beta effective is improved thanks to the presence of U238 in the blankets, which emits a large amount of delayed neutrons.

- Doppler Coefficient is increased once again, thanks to the presence of U238, which has large and wide absorption resonances.

- Coolant void coefficient at beginning and at end of cycle is decreased, as some moderator has been added in the blanket, which reduces the hardening of the spectrum due to a loss of coolant.

However, for both axial and radial blankets, adding moderator materials or a moderated reflector generates an interfacial power peaking, which raises fuel performance issues, as displayed in Fig 10. However, these local peakings are typically small and occur at the core periphery where power is much lower than in the core center; hence peaking is expected not to be limiting. If these interfacial power peaking issues become limiting, they can be solved using a higher flow of coolant (by adjusting the assembly inlet orificing pattern to increase safety margins) and by fuel assembly shuffling and/or rotation to limit the exposure of pins.

6. Conclusions and recommendations

6.i. Conclusions

Blankets are used in SFR to increase the breeding ratio of the core, by breeding a significant amount of plutonium. This plutonium is generally of a high quality, making it useable for a nuclear explosive device.

The objectives of this paper were to determine if blanket design modifications could be made to spoil plutonium so that it would be less attractive to proliferators than plutonium in spent LWR fuel. It was shown that:

- Breeding plutonium that is less attractive than that of spent LWR fuel plutonium at 50 MWd/kg, in the metal-fuel blankets of a SFR, is feasible.

- Several breeding blanket designs were conceptualized to meet diverse goals (MA burning, short doubling time), that can breed plutonium that meets proliferation criteria.

- A breeding blanket design could be modified with the methodology developed in this work, to breed plutonium that is proliferation resistant.

- Minor actinide doping to about 2.0 weight percent is sufficient by itself to secure the bred plutonium, but using moderator materials decreases the dependency on minor actinides.

- Securing blanket plutonium needs minor actinides. It does not appear possible, current techniques considered, to build a sodium fast reactor, employing a secure blanket, without minor actinide input from a LWR. At steady state approximately 1.5 LWRs are required per SFR (both rated 1 GW(e)). This value could be further reduced to 0.8 if MAs from blankets are recycled.

- Reactivity coefficients can be improved using MA doped blankets with modest moderator addition

6.ii. Recommendations

The methodology developed to keep a breeding blanket secure requires MA separation, which generates some proliferation issues. Thus secure ways to do this separation, perhaps employing electrochemical reprocessing[18], could be developed. The issues of the blanket designs developed here are power peaking and Cm and Cf buildup. Interfacial power peaking issues using moderated materials are considered to be manageable but further studies will have to be done at the engineering stage. Cm and Cf buildup will increase fuel cycle cost; this is why their separation from the TRU vector should be studied.

Finally, this study of axial and radial blankets was done for a metal-fueled SFR. Internal blankets could also be of interest and a study like this could also be applied to oxide, carbide and nitride fueled SFR, or to other Gen-IV fast reactors such as the GFR (Gas Fast Reactor).

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	U (wt%)	TRU (wt%)	Zr(wt%)	Density (g/cm^3)	Number of assemblies
Zone 1: Inner core	67	12	21	13.7	54
Zone 2: Middle core	71.2	12.8	16	14.7	156
Zone 3: Outer core	76.3	13.7	10	16.1	150

Table I: Fuel Uranium-TRU-Zr composition

	Fuel	Na	HT9	B4C
lower grid	0	28.6	71.5	0
lower shielding	0	28.6	25.7	45.7
lower reflector	0	28.6	71.5	0
inner fuel	34.3	11.43 (bond) and 28.54	25.73	0
middle fuel	34.3	11.43 (bond) and 28.54	25.73	0
outer fuel	34.3	11.43 (bond) and 28.54	25.73	0
gas plenum	0	28.6	25.7	Helium : 45.7
upper assembly shield	0	28.6	25.7	45.7
radial reflector	0	8.5	91.5	0
radial shield		21.0	34.2	44.8
Sodium holes	0	29.0 (bond) and 38.3	32.7	0
rods	0	38.3	32.7	29.0

Table II: Homogeneous core model description in volume percentage.

	Fuel	Lower assembly reflector	Upper Gas plenum	Lower grid plate Shielding	Upper Shielding
Pellet radius (mm)	3.0				
Inner clad radius (mm)	3.6	3.6			
Outer clad radius (mm)	4.0	4.0			
Inner pin composition	U-TRU-Zr Na (Bond)	HT-9	Gas (He and fission products)	B_4C (natural Boron)	B_4C (natural Boron)
Clad composition	HT-9				
Pin pitch (mm)	8.7				
Number of pins per assembly	271				
Assembly duct	yes				

	Radial reflector	Radial Shield	Control rods	Hole
Pellet radius (mm)			2.77	
Inner clad radius (mm)		21.4	4.0	
Outer clad radius (mm)	9.8	26.7	4.4	
Inner pin composition	HT-9	B_4C (natural Boron)	B_4C (natural Boron) Na (Bond)	Na
Clad composition	HT-9			
Pin pitch (mm)	19.7	53.5	8.76	
Number of pins per assembly	61	7	271	
Assembly duct	No	No	yes	

Table III: Heterogeneous core model description

isotope	Wt %
Np237	3.33%
Pu238	2.74%
Pu239	48.80%
Pu240	23.06%
Pu241	6.95%
Pu242	5.08%
Am241	2.34%
Am243	0.74%
Cm244	0.25%
Cm245	0.02%

Table IV: Composition of the TRU vector loaded in the driver fuel (in wt%)

Assembly parameters	
hexagon pitch (mm)	161.4
inter-assembly gap (mm)	4.3
duct outside flat-to-flat (mm)	157.1
duct wall thickness (mm)	3.9
duct inside flat-to-flat (mm)	149.2

Table V: Assembly parameters

	units	ERANOS	MCNP	σ (%)
β_{eff}	pcm	372	380	3
Doppler coeff	pcm/K	-0.145	-0.13	20
Coolant temperature coeff	pcm/K	0.24	0.276	9
Radial expansion coeff	pcm/K	-0.155	-0.145	12

Table VI: Comparison of the safety coefficients calculated at beginning of life by MCNP (with σ uncertainties) and by ERANOS

Np237	49.87%
Am241	35.03%
Am243	11.01%
Cm243	0.04%
Cm244	3.72%
Cm245	0.28%
Cm246	0.05%

Table VII. Isotopic composition of the TRU vector added in the blanket assemblies (representative of LWR spent fuel at 50 MWd/kg(HM) burnup)

Radial Blanket designs	Lower Axial Blanket designs	Minimum wt% of MA in the fuel
2 rows, no moderator		2.0
2 rows, 30%ZrH1.6	20cm, 30%ZrH1.6	0.6
1 row, BeO reflector	20cm, BeO reflector	1.4

Table VIII: Minimal weight percent of minor actinides to add in each blanket to breed secured plutonium (percentage of fuel heavy metal)

Lower axial blanket designs	Design D1	Design D2
Height of the blanket	20 cm	20 cm
Moderator	30 volume % of ZrH1.6	None
Reflector	HT-9	BeO
Total mass of fuel (kg of Metal)	6624	9505
Minor Actinides	Yes	Yes
Concentration of MA (wt % of metal)	0.6	1.4

Radial blanket designs	Design A	Design B	Design C
Number of rows	2	2	1
Moderator	None	30 volume % of ZrH1.6	None
Reflector	HT-9	HT-9	BeO (80 volume %)
Total mass of fuel (kg of Metal)	24658	17178	11934
Minor Actinides	Yes	Yes	Yes
Concentration of MA (wt % of Metal)	2.0	0.6	1.4

Table IX: Description of the axial and radial blanket designs studied

Pin Count of a radial blanket assembly	127
Heterogeneous description	(mm)
Pin Outer Diameter	12.0 mm
Pin Clad Thickness	0.55 mm
Fuel outer diameter	10.05 mm
Homogeneous description	(%)
Fuel	44.6
Bond (Na)	7.9
Coolant	26.5
Structure	21.0

Table X: Radial blanket fuel homogeneous and heterogeneous description

	Natural Uranium[7]	Reprocessed Uranium[17]
U234	1.00E-10	0.02
U235	0.71	0.83
U236	1.00E-10	0.60
U238	99.29	98.5

Table XI: Composition (wt%) of natural uranium (in the driver fuel) and reprocessed uranium (in the blanket fuel)

| | Axial | LWR MA required to fuel the Blanket designed | | LWR MA burned in the Blanket designed | | Doubling time of the blanket designed (in efp years) | |
Radial		D1	D2	D1	D2	D1	D2
A : 2 rows, no moderator		2.3	3.8	0.8	1.1	20.8	23.2
B : 2 rows, 30 volume % of ZrH1.6		1.1	2.5	0.5	0.7	22.6	25.4
C:1 row BeO reflector		1.4	2.9	0.6	0.9	24.7	28.1

Table XII: Performance comparison for each design studied

Pu Quality	End of life of the core		
(% of isotopes)	Axial blanket (D1)	Radial Blanket (C)	Driver fuel
Pu238	5.6	6.3	2.2
Pu239	76.9	79.6	62.5
Pu240	10.0	12.3	29.0
Pu241	6.4	1.2	3.0
Pu242	1.1	0.6	3.3

Table XIII: Isotopic composition of plutonium at the end of the last cycle of the core (after 70 years)

(kg)	Axial blanket (D1)	Radial blanket (C)	Total blankets	Total driver fuel
Np produced	-3197	-156	-3353	-553
Pu produced	6499	5100	11600	1017
Am produced	-976	-229	-1206	-210
Cm produced	708	44	752	100
Cf produced	0.09	0.0007	0.09	0.03

Table XIV: Mass (in kg) of actinides produced and burned in the blanket and in the driver fuel during the total lifetime of the plant (70 years).

	Radial Blanket (C)	Axial Blanket (D1)
Cm	109%	181%
Np	-31%	-21%
Am	-50%	-62%

Table XV: Percentages of minor actinides produced per actinide loaded during the entire life of the reactor per initial quantities.

	Reference core	C/D1
β_{eff} beginning of cycle (pcm)	372	381
β_{eff} after 1200efpd (pcm)	337	345
Doppler BOC (c/K)	- 0.14	- 0.17
Doppler after 1200efpd (c/K)	- 0.13	- 0.17
Coolant void worth BOC ($)	+ 9.0	+ 7.2
Coolant void worth after 1200efpd ($)	+ 11.4	+ 10.5

Table XVI: Comparison of feedback coefficients and delayed neutron fraction for design C/D1 and for the reference core.

Shielding

Reflector

Zone 3

Zone 2

Zone 1

Control Rods
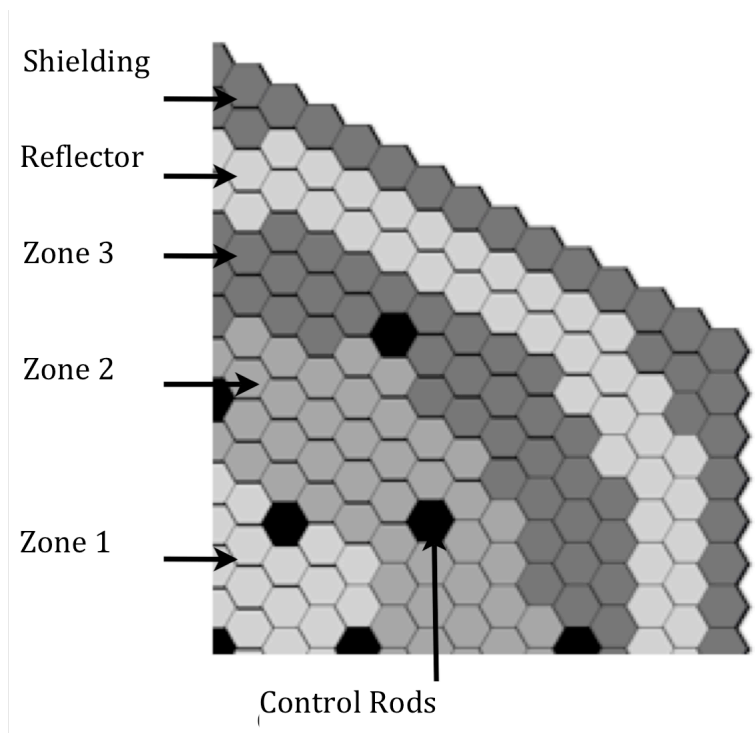
Fig 1.: 2400 MW(t) Core layout
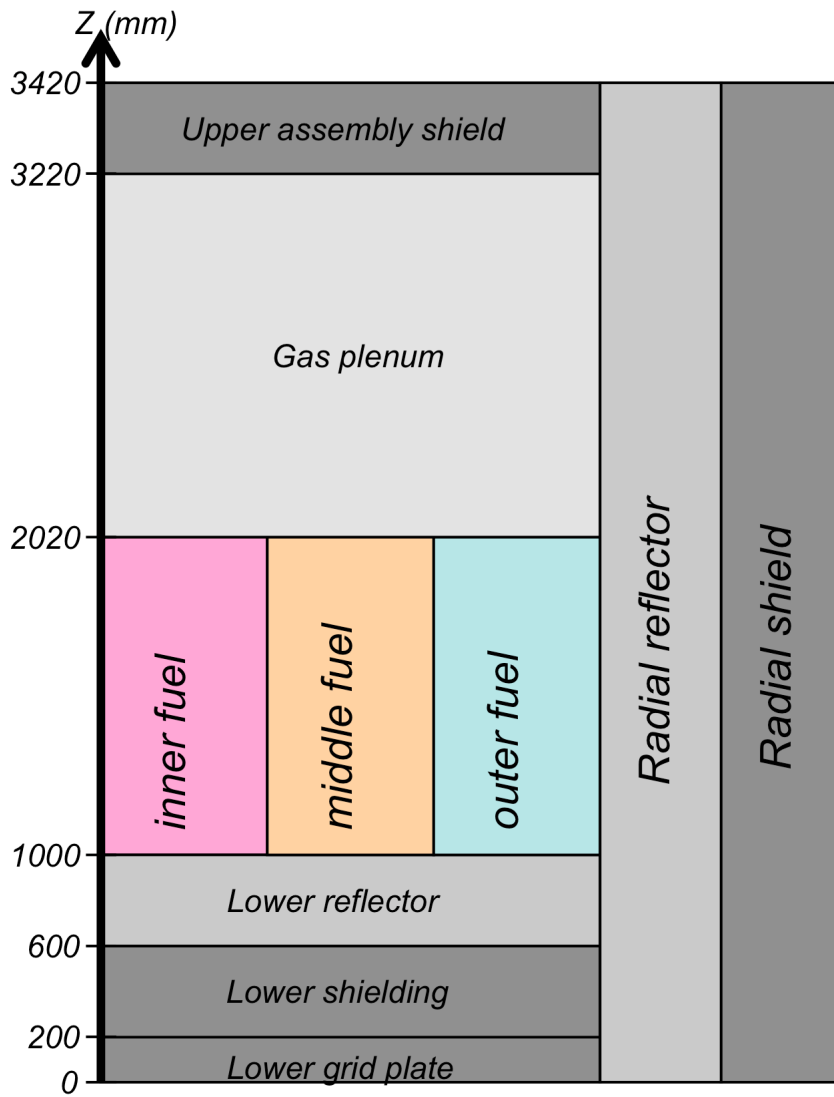
Fig 2. : Axial layout of the core
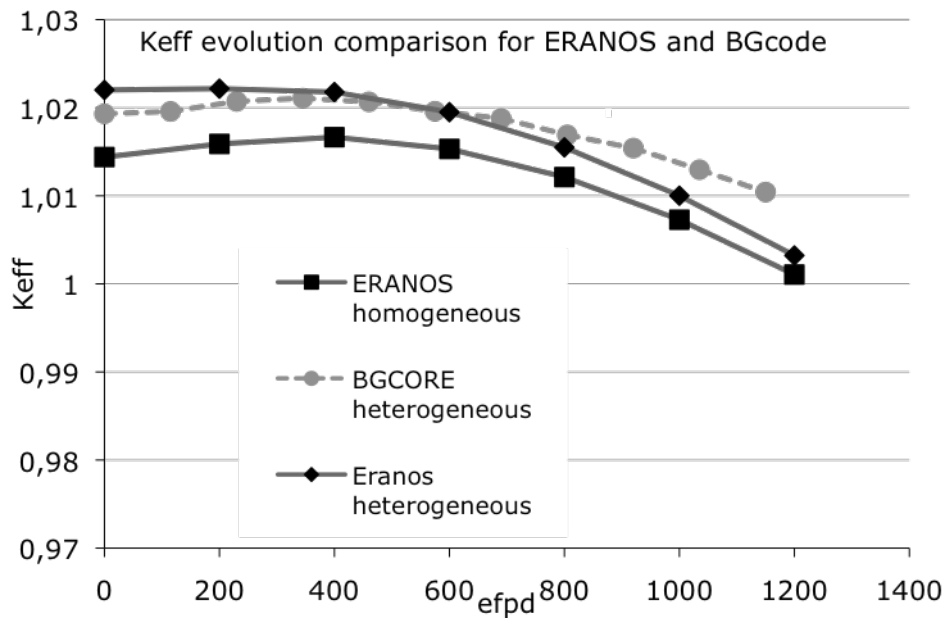
Fig 3.: Comparison of the k_{eff} evolution for the ERANOS code and for the BGcore code by equivalent full power days (efpd)
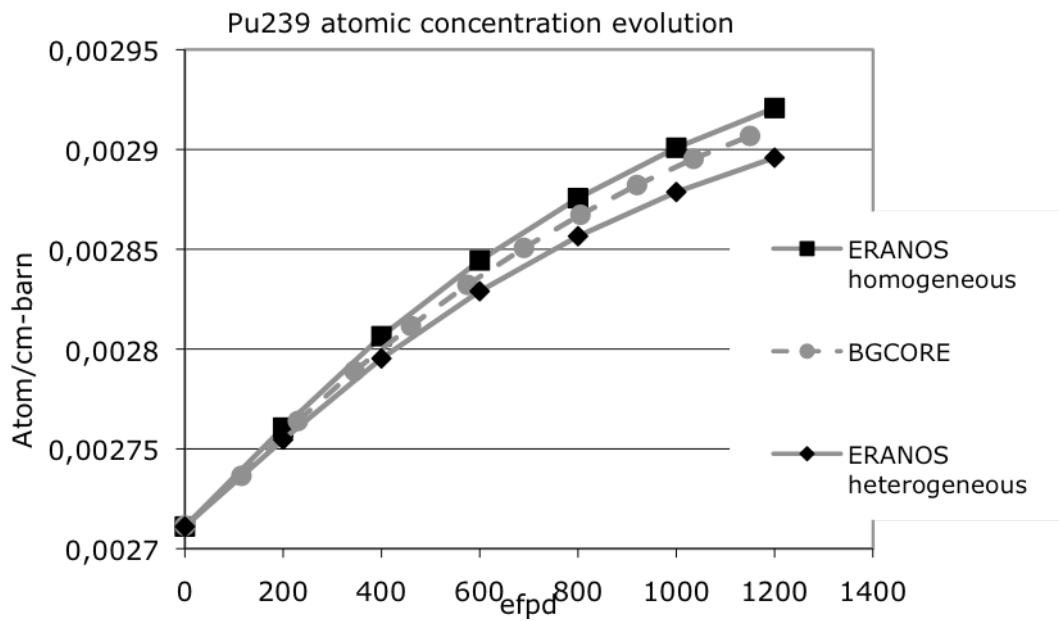
Fig 4.: Comparison of Pu239 atomic concentration evolution for the ERANOS code and for the BGcore code
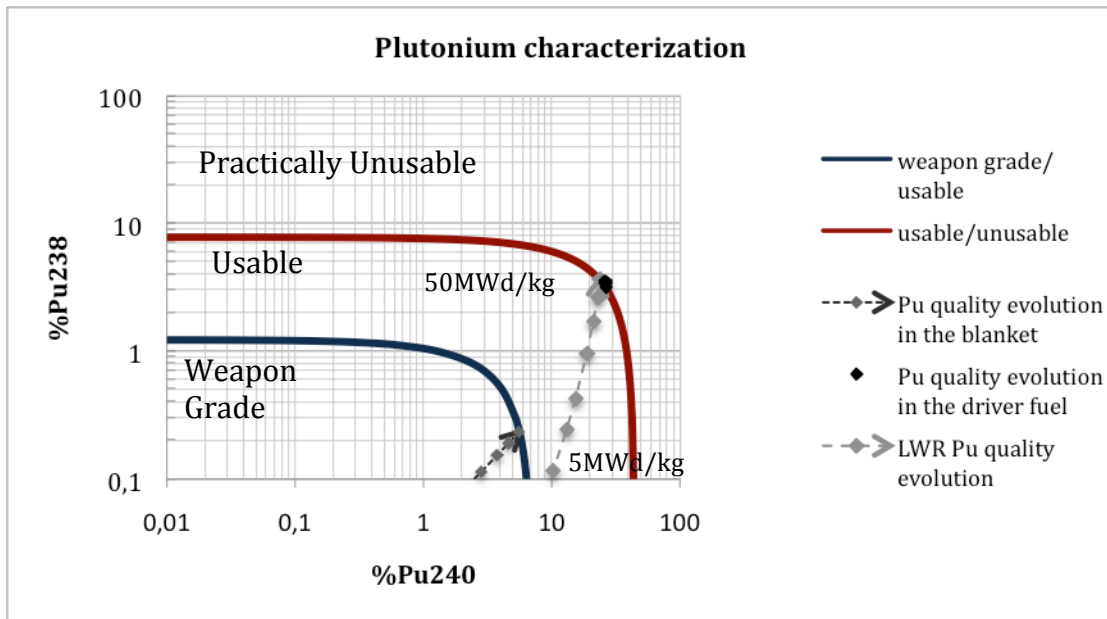
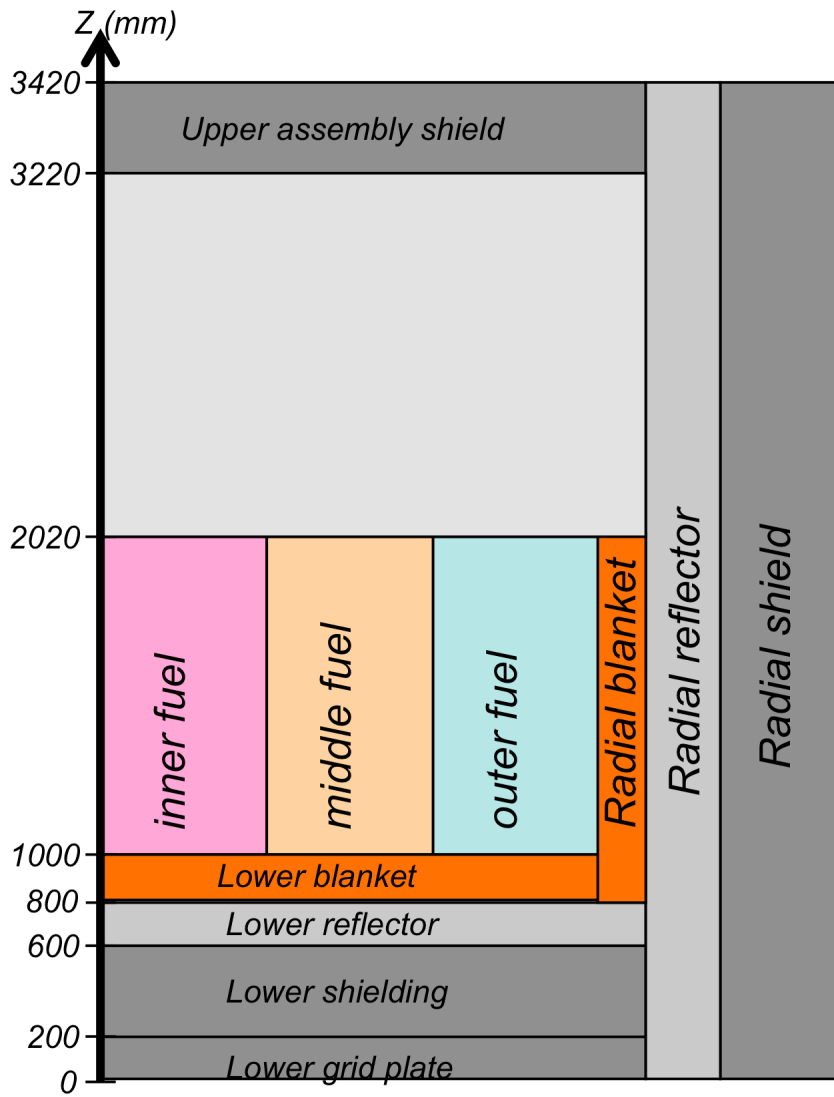Fig 5.: Plutonium quality evolution in the blanket

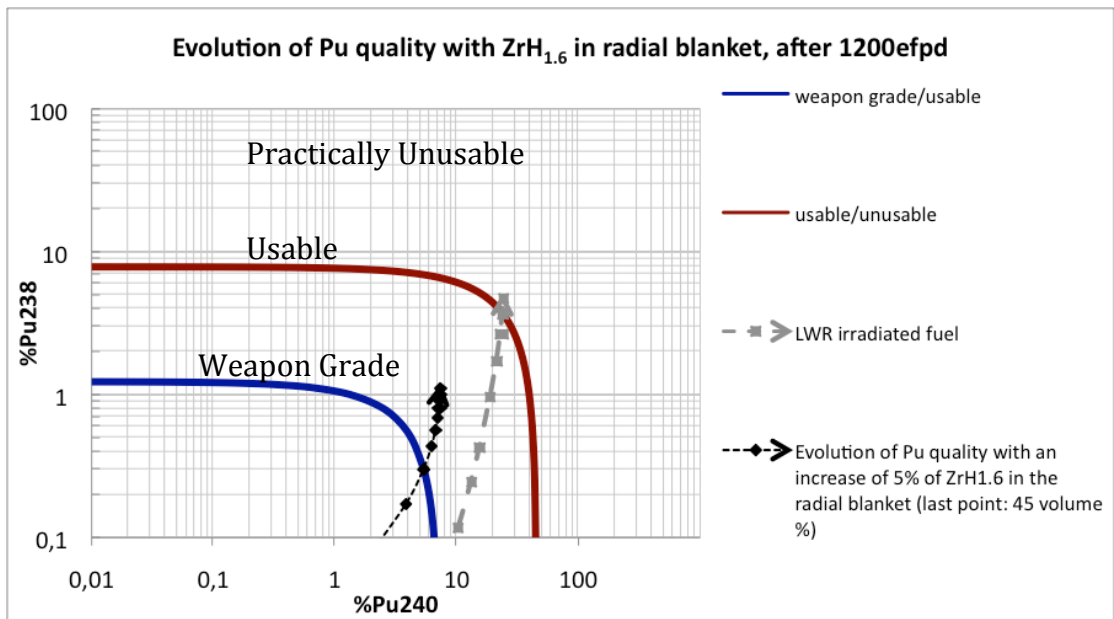Fig 6.: Axial layout of the core with axial and radial blankets

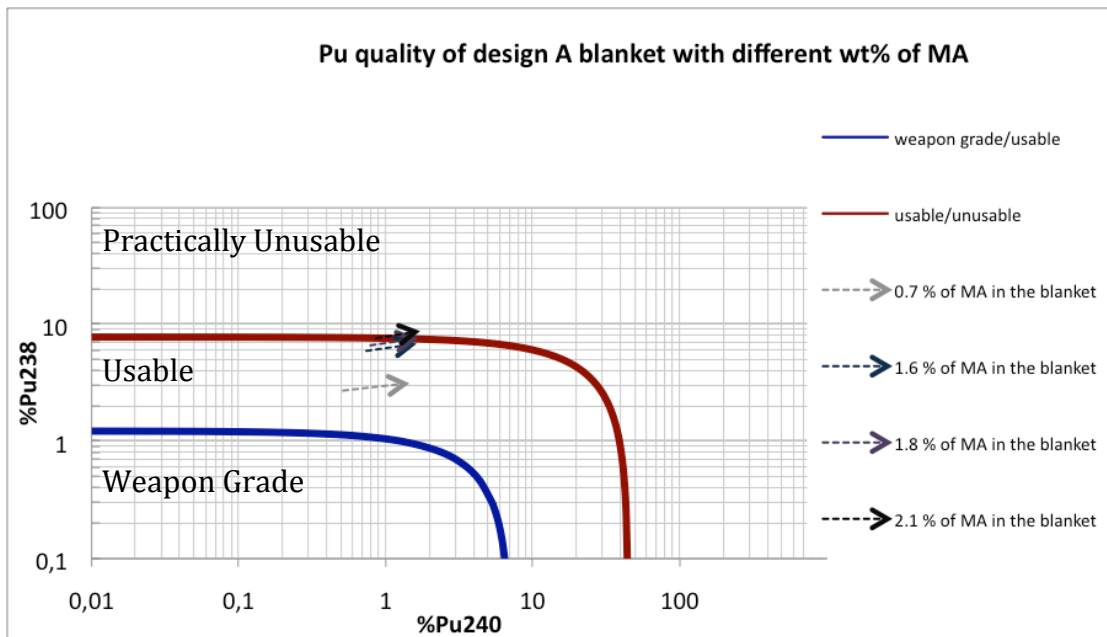Fig 7.: Evolution of Pu quality after 1000efpd irradiation in a blanket, with moderator added

Fig 8.: Plutonium quality evolution after 1200efpds, for a blanket without moderator materials (called design A), using various percentages of MA doping.
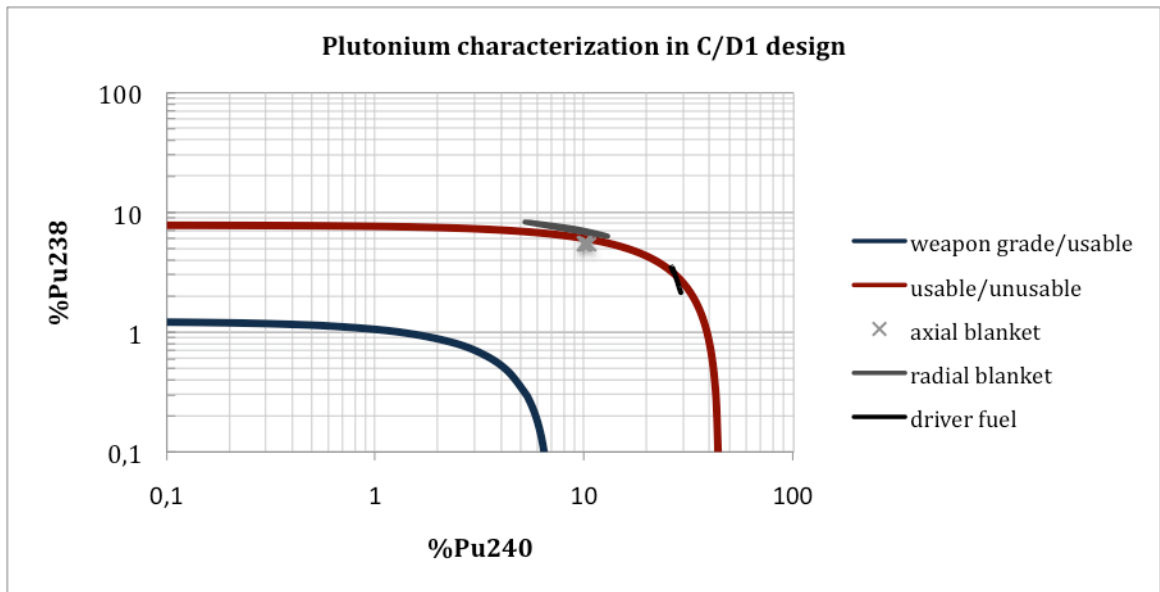
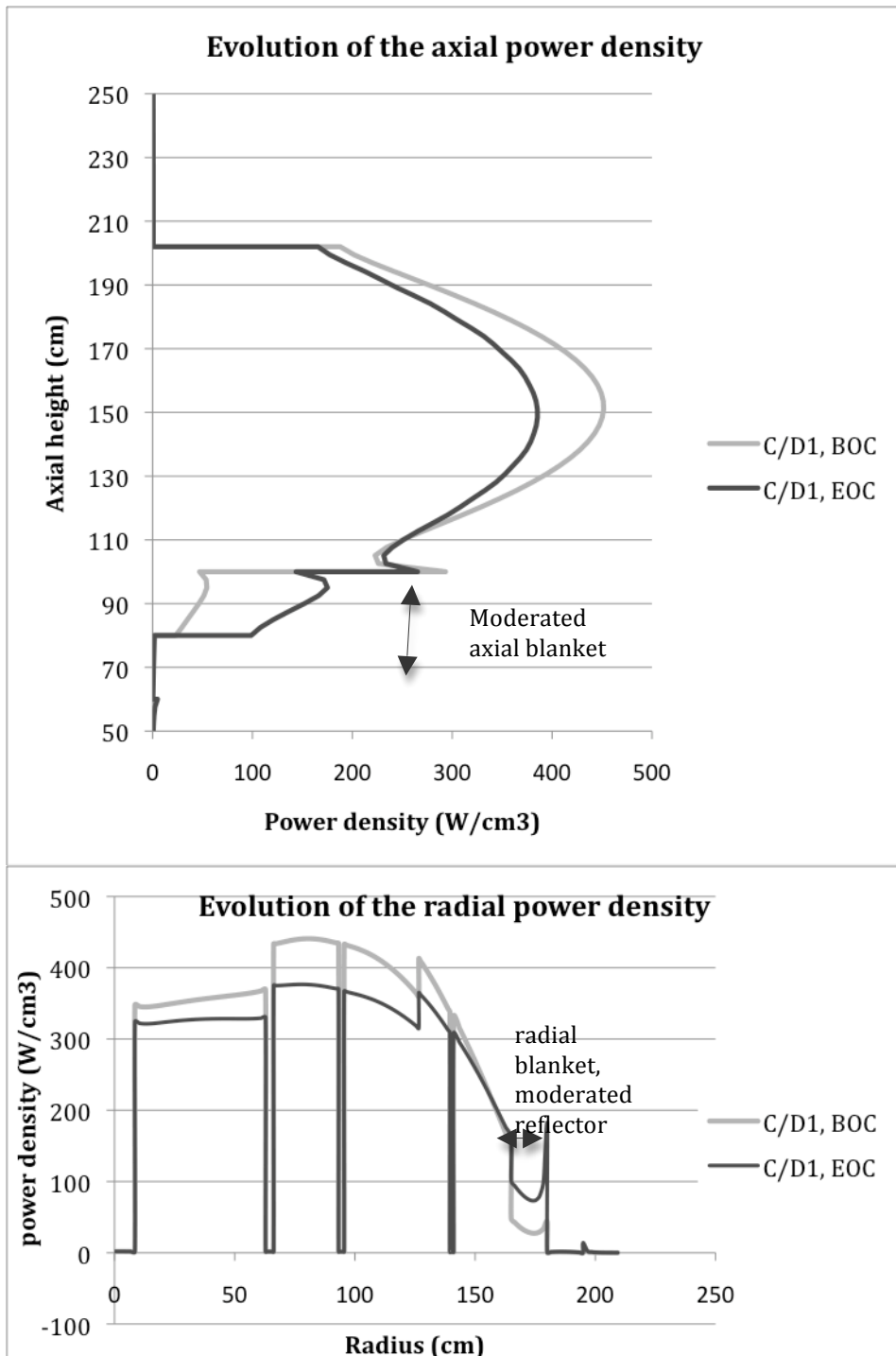Fig 9.: Plutonium quality evolution in each part of the C/D1 design, compared to LWR bred plutonium.

Fig 10.: Axial and Radial power density of design C/D1