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## **Modeling And Simulating A Breeder Hybrid Soliton Reactor**

**Jacques Maillard**

Institut National de Physique Nucléaire et de Physique des Particules (CNRS)  
3 rue Michel Ange

FR, 75794, Paris Cedex 16, France

Institut du Développement et des Ressources en Informatique Scientifique (CNRS) Campus  
Universitaire d'Orsay, rue John Von Neumann, Bât. 506

FR, 91403, Orsay Cedex, France

jacquesmaillard@wanadoo.fr

**N. Catsaros<sup>1</sup>, B. Gaveau<sup>2</sup>, M.-T. Jaekel<sup>3</sup>, A. Jejcic<sup>2</sup>, G. Maurel<sup>2</sup>, P.Savva<sup>1</sup>, J. Silva<sup>2</sup>, M. Varvayanni<sup>1</sup>, T. Xenofontos<sup>1</sup>**

<sup>1</sup>Institute of Nuclear Technology - Radiation Protection, NCSR "Demokritos"  
27, Neapoleos Str., GR, 15341, Aghia Paraskevi, Greece

<sup>2</sup>Université Pierre et Marie Curie, Campus Jussieu  
FR, 75252, Paris Cedex 05, France

<sup>3</sup>Laboratoire de Physique Théorique de l'Ecole Normale Supérieure (CNRS)  
24 rue Lhomond, FR, 75231, Paris Cedex 05, France

nicos@ipta.demokritos.gr, bernardgaveau@orange.fr, jaekel@lpt.ens.fr, ajejcic@yahoo.fr,  
gerard.maurel@sat.aphp.fr, savvapan@ipta.demokritos.gr, jorge.silva@upmc.fr,  
melina@ipta.demokritos.gr, thalia.xenofontos@ipta.demokritos.gr

### **ABSTRACT**

Understanding and controlling early damage initiation and evolution are amongst the most important issues in nuclear power plants. Intergranular cracking has been known to occur in both austenitic steels and nickel based alloys. Modelling efforts are under way to understand this phenomenon on the grain-level scale where the influence of the microstructure plays an important role. Here, the initiation and evolution of intergranular cracking can be modelled using the advanced finite element approaches with explicit account of the grains, their crystal- lographic orientation and explicit inclusion of grain boundaries. The cohesive-zone approach, with damage initiation and evolution, can be used for grain boundaries. However, the stability of such an approach can be problematic, especially in cases where there are a number of inter- granular cracks. These cracks can form complex networks which can have a negative impact on the stability of the analysis. This work addresses some of the issues related to the stability. The influence of the finite element individual model parameters like convergence controls and numerical viscosity on the model convergence is looked at. The effects are demonstrated on a simple geometry containing 3 grains. It is shown that the numerical viscosity has the highest beneficial influence on the convergence. However values of numerical viscosity of more than 10 % of the time step should be avoided.

## 1 SIMULATION

Analysis of a BHSR system must include investigation of its performance variation with varying reactor parameters, such as core radius, fuel/moderator ratio, fuel enrichment, beam intensity, source velocity, beam proton energy, nature of the fissile and fertile material. As a first approach, the present study focuses on the first four 4 parameters, considering two types of fresh fuel, i.e. U238 mixed with Pu and Th232 mixed with U233.

### 1.1 U238 / Pu239 fuel

A BHSR cycle fueled with fresh mixture of U238 and Pu239 has been simulated. Due to the short decay time of Np239, direct formation of Pu239 is considered. Pu240, Pu241 and Pu242 created by neutron capture are taken into account.

#### 1.1.1 Breeding capability variation with beam intensity

As reported in [1], an increase of beam intensity induces a decrease of core reactivity and therefore a decrease of the reactor efficiency. Here, the evolution of the reactor breeding capabilities is examined by computing the excessive mass of fissile material at the end of cycle (EOC). The corresponding number of fissions per incident proton is also calculated. Three different fuel enrichments in Pu239 have been considered, i.e. 1.7%, 1.8% and 1.9%. In all the above simulations the considered core vessel radius is 100 cm and the half distance between the centers of two fuel rods,  $\delta$ , is 1.52 cm. As shown in Table 1, depending on fuel enrichment, different types of breeding behaviour have been identified:

1. For lower fuel enrichment, the mass of fissile material increases with increasing beam intensity: occurrence of breeding behavior.
2. For higher fuel enrichments no breeding behavior is achieved for beam intensities below 13 mA.

It is noted that in all cases the reactivity (and therefore the reactor efficiency) decreases with increasing beam intensity.

Table 1: Evolution of the reactor performance with increasing beam intensity for different fuel enrichments.

	Fuel enrichment (%)					
	1.7		1.8		1.9	
Beam intensity (mA)	Excessive fissile material mass at EOC (kg)	Number of fissions	Excessive fissile material mass at EOC (kg)	Number of fissions	Excessive fissile material mass at EOC (kg)	Number of fissions
1	-25.075	944922	-30.00	1019560	-37.270	1164358
5	-22.933	513471	-32.00	535239	-44.056	568460
9	-0.129	405449	-13.00	424278	-34.690	445973
11	5.340	378526	-9.00	393733	-29.000	416297
13	19.52	355718	-0.44	367733	-17.855	383495

#### 1.1.2 Breeding capability variation with core vessel radius

Keeping a fuel enrichment of 1.7% and fuel/moderator volume ratio equal to 2, we consider two different core vessel radii, i.e. 100 cm and 106 cm for the simulation of BHSR. The obtained results concerning breeding capability are presented in Table 2. It can be seen

that with increasing beam intensity the breeding capability regularly increases. The point at which a closed cycle is obtained, i.e. produced fissile material becomes equal to the consumed one, is defined as “point zero”. Simulations have been performed for a given enrichment (1.7%), the same moderation ratio (fuel volume / moderator volume) and two different core vessel radii (100 and 106 cm). From Table 2, for vessel radius 100 cm, point zero corresponds to about 9 mA beam intensity and 405000 fissions, whereas for vessel radius 106 cm, point zero corresponds to about 10 mA beam intensity and 400000 fissions.

Table 2: Evolution of the reactor performance with increasing beam intensity for different core vessel radii.

	Vessel radius (cm)			
	100		106	
Beam intensity (mA)	Excessive fissile material mass at EOC ( kg)	Number of fissions	Excessive fissile material mass at EOC ( kg)	Number of fissions
1	-25.025	944922	-26.169	1036123
5	-22.900	513471	-23.135	552811
9	-0.129	405449	-5.260	443561
11	5.340	378526	3.653	405097
13	19.500	355718	15.609	385962
15	No data	No data	21.323	366935

In Table 3, various core vessel radii have been combined to various fuel enrichments and beam intensities in order to investigate an optimum combination leading to a “point zero” operation with acceptable reactor performance. It is observed that for the tested beam intensities, “Point zero” (i.e. breeding regime) is initially obtained for core radii above 96 cm and fuel enrichment below 1.8%. Therefore, a minimum radius is necessary in order to get breeding. Increasing the radius allows one to choose an optimum configuration for breeding and energy performance. As reactor efficiency decreases while breeding decreases with the intensity of the beam, the compromise between efficiency and total energy of the reactor may lead to a core radius allowing simultaneously “point zero” regime, minimum beam intensity and sufficient reactor efficiency.

Table 3: Evolution of the reactor performance with varying core vessel radius (m=max).

Core vessel radius (cm)	Enrichment (%)	Intensity (mA)	Number of fissions	Excessive fissile material mass at EOC ( kg)	Total fission product mass at EOC (kg)
84	2.1 no point zero	9 (m)	373879 (m)	-130.00 (m)	602 (m)
84	2.0 no point zero	9 (m)	367369 (m)	-35.00 (m)	594 (m)
90	2.1 no point zero	9 (m)	431688 (m)	-77.00 (m)	700 (m)
90	2.0 no point zero	11 (m)	405589 (m)	-39.00 (m)	657 (m)
90	1.9 no point zero	9 (m)	389131 (m)	-25.76 (m)	632 (m)
96	1.9 no point zero	11 (m)	393575 (m)	-27.90 (m)	781.9 (m)
96	1.8	12	370000	-2.00	790
100	1.9 no point zero	13 (m)	383495 (m)	-17.80 (m)	893 (m)
100	1.8	13	367999	-0.44	855
100	1.7	10	390000	2.60	710
106	1.75	12	404000	-0.50	840
106	1.7	10	420000	-0.80	777

### 1.1.3 Breeding capability variation with $\delta$ and moderation ratio

Changing the distance between fuel rods induces modification of the ratio between fuel volume and moderation volume. Keeping core vessel radius and fuel enrichment stable (at 106 cm and 1.7% respectively) two simulations are performed with different distance between fuel rods, one equal to 3 cm and one equal to 2.8 cm.

For a given beam intensity, decreasing of the moderation ratio decreases the core reactivity and the energetic efficiency of the reactor, but increases the breeding balance. Therefore optimization of the reactor (search of "point zero" or search of optimal energetic efficiency or compromise between global power, electric efficiency and breeding balance), needs to take into account the moderation ratio. In Tables 4,5 relevant results are shown.

Table 4: Evolution of the reactor performance with varying distance between fuel rods.

Beam intensity (mA)	Distance between fuel rods (cm)					
	3.0			2.8		
	Number of fissions	Excessive fissile material at EOC (kg)	Created fission products (kg)	Number of fissions	Excessive fissile material at EOC (kg)	Created fission products (kg)
1	1097868	-30.44	213	869917	0.6	174
5	569939	-30.47	543	525518	61	498
9	452135	-11.05	742	428387	114	709
11	417858	-5.90	839	404048	137	804
13	394022	4.60	916	379219	152	879

### 1.2 Th232 / U233 fuel

The Th232 – U233 cycle has been investigated in a BHSR, considering also Pa233 beta-decay with a half life of 29 days. All U-isotopes have been taken into account. The optimization parameters and the simulation constraints were the following:

- Core radius as small as possible
- Mass of fissile matter as low as possible
- Reactor efficiency as high as possible
- Electric power as high as possible
- Breeding coefficient near zero (closed cycle achievement).

Table 5: Evolution of the reactor performance with beam intensity. Core radius 188 cm and distance between fuel rods 2.6 cm.

Fuel Enrichment (%)	0.58		0.65	
	Number of fissions	Excessive fissile material at EOC (kg)	Number of fissions	Excessive fissile material at EOC (kg)
0	616164	0.000	1237226	0.0
2	516048	-0.331	852699	-46.6
4	467181	0.897	700447	-73.0
6	428600	2.427	615455	-92.6
8	401506	3.544	555661	-106.0
10	378622	7.066	510937	-118.0
12	363809	6.230	479774	-134.0
14	347922	7.772	453524	-144.8
16	335588	7.062	424154	-143.0
18	320475	11.480	405694	-149.5
20	No data	No data	386461	-153.0

### 1.2.1 Variation with intensity of the beam

Core reactivity and consequently reactor efficiency always decrease with beam intensity.

Concerning the variation of breeding capability with beam intensity, three types of behavior exist:

- constantly increasing breeding balance
- a decrease of the breeding balance, followed by a period of increase
- constantly decreasing balance.

For a given core configuration the first case corresponds to a low enrichment, the second case to higher enrichment (0.58%), and the last case to an even higher enrichment (0.65%). The increasing neutron capture by fertile material induces decrease of reactivity. The optimization of the reactor corresponds to a breeding balance equal to zero. This necessitates a compromise between reactivity and breeding.

### 1.2.2 Variation with the enrichment

As can be seen in Table 6, for a low initial enrichment, the reactivity is low and the breeding balance is large. For a large initial enrichment, the opposite effect is observed. In the case of intermediate enrichment (0.58%) and low intensity of the beam low breeder balance and high reactivity is obtained while for higher intensity of the beam large breeder balance and low reactivity is obtained.

Table 6: Evolution of the reactor performance with fuel enrichment.

Enrichment (%)	Excessive fissile material mass at EOC ( kg)	Number of fissions
0.55	11.400	428888
0.56	7.934	456995
0.57	3.489	488674
0.58	-0.331	516048
0.59	-4.978	556335
0.60	-11.447	601036
0.61	-17.366	639460
0.62	-23.134	682636
0.63	-30.249	732832
0.64	-37.484	785307
0.65	-46.664	852699

The optimal behavior of the reactor is obtained when the quantity of fissile material is the same at the EOC and at the BOC. The optimum choice of the initial enrichment allows one to reach an optimal core reactivity and therefore to optimize the required beam intensity.

Table 6 shows the variation of the reactor performance with enrichment, for a given configuration (beam intensity 2 mA, 188 cm core radius, 2,6 cm of distance between fuel rods). An effective working point is reached for about 0.58% enrichment in U233.

### 1.2.3 Variation with geometry of the reactor

Two crucial parameters define the geometry, for a given radius of the fuel rods:

- the radius of the reactor core
- the moderation ratio.

### 1.2.3.1 Variation with the reactor radius

For the same initial reactivity (intensity of the beam equal to 0), a larger radius allows to start with a lower enrichment and therefore a better breeding balance.

For given enrichment (0.55% of U233), beam intensity (2mA) and geometry (distance between fuel rods of 2.6 cm) the variation of the breeding balance and the reactivity (number of fissions) as a function of the radius of the reactor core is presented in Table 7.

Table 7: Evolution of the reactor performance with core radius.

Core radius (cm)	Excessive fissile material mass at EOC ( kg)	Number of fissions
126	10.329	325448
128	9.890	336152
130	10.267	338038
132	10.584	342877
134	10.515	349133
136	10.070	354155
138	10.700	362158
140	10.600	364518
142	10.640	365413
144	10.950	369191
146	10.700	374936
148	10.800	380480
150	10.900	375619
152	11.500	383020
154	10.900	384854
156	11.450	392086
158	11.200	393108
160	10.900	396253
162	10.700	397943
164	10.700	410301
166	11.300	409352
168	10.980	413065
170	11.400	408177
172	10.900	411953
174	10.900	416302
176	11.500	424720
178	10.400	429941
180	11.600	424651
182	11.780	420784
184	11.100	429965
186	11.100	436215
188	11.400	428888

The breeding balance does not change with core radius, but the reactivity increases. Nevertheless, the total mass of fissile material increases with core radius (from 2.635 tons to 6.087 tons).

### 1.2.3.2 Variation of the moderation ratio

The variation of the moderation ratio has a more complex effect. If in the case of the constant radius the distance between fuel rods is decreased (and therefore the moderation ratio increases), the total mass of fissile material increases which increases the reactivity, and decreases the breeding balance. In order to avoid this bias, the number of fuel rods is kept constant so only the distance between rods is changed. This leads to a smaller core radius.

For a given accelerator beam intensity, decreasing of the enrichment induces a decrease of reactivity (related to the number of fissions). Meanwhile, the total inventory of fissile material increases. A particular level of enrichment may be determined for which a closed fuel cycle is achieved. The corresponding reactivity value increases with the fuel volume over moderator volume ratio.

Table 8: Evolution of the reactor performance with varying distance between fuel rods.

Enrichment (%)	Excessive fissile material at EOC ( kg)	Number of fissions	Excessive fissile material at EOC ( kg)	Number of fissions	Excessive fissile material at EOC ( kg)	Number of fissions	Excessive fissile material at EOC ( kg)	Number of fissions
0.68							-40.400	549528
0.67							-32.300	535448
0.66							-22.400	498146
0.65							-14.628	465225
0.64							-6.531	445225
0.63							-0.955	422082
0.62							0.403	408341
0.61							11.765	381865
0.60					-17.454	524913	17.619	368717
0.59					-9.419	499171		
0.58					0.807	467181		
0.57					6.662	449582		
0.56					13.505	422867		
0.55			-27.801	592084	20.540	387786		
0.54			-17.007	568115				
0.53			-7.722	536876				
0.52			2.309	497104				
0.51			12.355	465872				
0.50	-41.000	665779	19.410	444567				
0.49	-29.000	629935						
0.48	-16.000	592972						
0.47	-4.000	552643						
0.46	5.021	525333						
0.45	14.891	488524						

The reactor performance has been investigated for varying fuel enrichment and for four different values of the fuel/moderator volume ratio. In the case of constant total number of fuel rods (67) and accelerator beam intensity (4 mA), four different core configurations have

been analyzed, with the distances between fuel rods 2.23 cm, 2.43 cm, 2.63 cm and 2.83 cm respectively. The obtained results are summarized in Table 8.

## CONCLUSIONS

Preliminary investigations with the ANET code indicate that a HSR may operate in a breeding regime with both U238/Pu239 and Th232/U233 fuels. The accelerator beam intensity as well as the core dimension, the moderator ratio and the fuel enrichment are crucial parameters. A study of their variations shows that values exist where HSR can operate in a closed fuel cycle while preserving an efficient energy output.

## REFERENCES

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