Proton Source Efficiency for different Inert Matrix Fuels in Accelerator Driven Systems

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Abstract *– In order to study the beam power amplification of an accelerator driven system (ADS), a new parameter, the proton source efficiency (ψ^*) was introduced in a previous study. ψ^* represents the average importance of the external proton source, relative to the average importance of the eigenmode production, and is closely related to the neutron source efficiency (φ^*), which is frequently used in the ADS field. The main advantage with using ψ^* instead of φ^* for ADS is that the way of defining the external source is unique and that it is proportional to the core power divided by the proton beam power, independently of the neutron source distribution.*

It has been shown that the source efficiency can vary considerably for different reactor core systems. Studying ψ^* for different system parameters is therefore of interest when designing an ADS. In this paper, numerical simulations have been performed with the Monte Carlo code MCNPX in order to study ψ^* as a function of spallation target radius for different inert matrix fuels. It was found that, in order to maximize ψ^*, and thereby minimizing the proton current needs, a target radius as small as possible should be chosen. A ZrN or an YN matrix, mixed with the plutonium and americium mixed nitride fuel, appears to be a slightly better choice than a HfN matrix, considering only the proton source efficiency. It was also found that a power flattened double-zone core, compared to a single-zone core, decreases ψ^* by about 5% for the ZrN matrix and by about 10% for the HfN matrix.

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I. INTRODUCTION

Accelerator Driven Systems (ADS) [1, 2, 3, 4] are being investigated as a possible mean for reducing the long-term radiotoxicity of spent reactor fuel. These systems allow for a much higher concentration of minor actinides than what is acceptable in critical reactors.

Optimizing the output/input power, without exceeding the limits determined by safety constraints and other target-core characteristics play an important role in the overall design of an ADS and on the economy of its operation. The neutron source efficiency parameter φ* is commonly used to study this quantity, since it is related to the number of fissions produced in the core by an average external source neutron. However, calculating φ* for an accelerator driven system involves some complications, since the actual source particles are protons, and not neutrons. With the motivation of simplifying the concept of source efficiency, we have introduced in a previous paper [5] a new parameter ψ*, which refers to the number of fissions produced in the core by each source ***proton***. The advantages with using ψ* instead of φ* is that there is no ambiguity in how to define the external source, and that it is proportional to the beam power amplification, without the need of a weighting factor.

In order to guarantee the stability of uranium free fuels at high temperatures, the use of inert matrices is foreseen. Different safety parameters of several possible inert matrix fuels have been studied [6]. In the present paper, three inert matrices (ZrN, YN and HfN), mixed with a plutonium and americium mixed nitride fuel have been investigated in terms of ψ*. In Section II, the neutron source efficiency is first defined and discussed and then the proton source efficiency parameter is introduced. Section III describes the lead-bismuth cooled ADS modelled in this study. In Section IV.A, ψ* is studied as a function of target radius for the different matrices, while in Section IV.B, ψ* has been compared for a single-zone core and a power flattened double-zone core.

II. SOURCE EFFICIENCY φ*

II.A. *Definition of the Neutron Source Efficiency*

The neutron flux distribution ϕ_s in a sub-critical core is the solution to the inhomogeneous steady-state neutron transport equation

$$\boldsymbol{A}\phi_s = \boldsymbol{F}\phi_s + S_n \qquad (1)$$

where **F** is the fission production operator, **A** is the net neutron loss operator and S_n is the external neutron source.

The neutron source efficiency [7, 8], usually denoted φ*, represents the efficiency of the external source neutrons and can be expressed according to the following equation [9]:

$$\varphi^* = \left(\frac{1}{k_{eff}} - 1\right)\cdot\frac{<\boldsymbol{F}\phi_s>}{<S_n>} \qquad (2)$$

which is valid in the range $0 < k_{eff} < 1$. $<\mathbf{F}\phi_s>$ is the total production of neutrons by fission and $<S_n>$ is the total production of neutrons by the external source. Eq. (2) shows that, for given values of k_{eff} and $<S_n>$, the larger φ* the larger the fission power produced in the system.

II.B. *Introduction of the Proton Source Efficiency*

A new parameter, called "proton source efficiency" and denoted ψ*, which represents the product of φ* and the number of source neutrons generated per source proton (S_n/S_p), has been introduced [5]. We have the following relation between the ***proton*** source efficiency ψ* and the ***neutron*** source efficiency φ*:

$$\psi^* = \varphi^*\cdot\frac{<S_n>}{<S_p>} \qquad (3)$$

This parameter could also, in analogy with φ*, be expressed in terms of k_{eff} and the total number of neutrons produced by fission in the core, for each source ***proton***. Inserting Eq. (2) in Eq. (3) it is expressed in the same way as φ*, only with the replacement of S_n by S_p,

$$\psi^* = \left(\frac{1}{k_{eff}} - 1\right)\cdot\frac{<\boldsymbol{F}\phi_s>}{<S_p>} \qquad (4)$$

$<\mathbf{F}\phi_s>/<S_p>$ is the total production of neutrons by fission over the total number of source protons.

III. SYSTEM MODELING

A homogenized model of a uranium free nitride fuelled and lead-bismuth cooled ADS was used. Simulations have been performed for two different fuel compositions (curium free), with the ratio of plutonium to americium set to 80/20 and 40/60. For all matrix-fuel combinations, the fraction of inert matrix was adjusted in order to obtain a k_{eff} of about 0.95. The volume fractions of the different matrix fuels are displayed in Table I. We note that the plutonium based fuels enable a much larger fraction of inert matrix than the americium based ones.

TABLE I

Volume Fraction of Inert Matrix in order to obtain k_{eff} = 0.95.

Matrix	Volume fraction	
	Pu/Am = 80/20	Pu/Am = 40/60
ZrN	82.9%	63.4%
YN	83.4%	63.5%
HfN	67.0%	49.5%

The height of the active core of the reference model, depicted in Fig. 1, is 100 cm and the outer radius is 70 cm. The inner radius is 20 cm, which is also the boundary of the lead-bismuth target. The accelerator tube has a radius of 15 cm and the axial position of the proton beam impact is 25 cm below the top of the core. The radius of the radially uniform 1000 MeV proton beam is 7.5 cm. Above and below the active zone of the core, plena for accommodation of gas release are included, having lengths of 100 and 50 cm, respectively. The radial reflector is assumed to consist of 90 % steel and 10 % lead-bismuth.

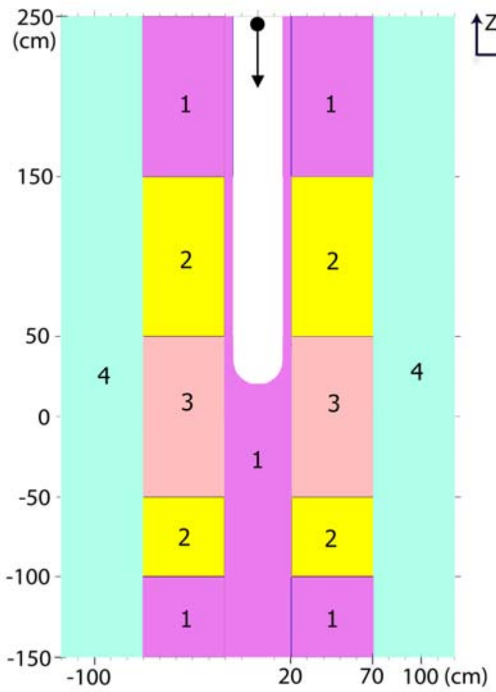

Fig. 1. RZ-view of the homogenised reference model. The 1000 MeV protons are guided through the accelerator tube and impinge on the Pb-Bi target. The different regions in the model are pure Pb-Bi (1), the plena (2), the active core (3) and the reflector (4).

The relative fractions of matrix fuel, cladding and coolant material used in the homogenized model correspond to a pin radius of 2.5 mm and P/D = 1.72. The spallation target and the core coolant consist of lead-bismuth eutectic and the fuel pin cladding of 10% chromium and 90% iron.

The Monte Carlo code MCNPX [10] (Version 2.3.0), in coupled neutron and proton mode, was used for all simulations, relying on the evaluated nuclear data library ENDF/B-VI.8. The Intranuclear Cascade model used by MCNPX was the Bertini package [11].

IV. THE PROTON SOURCE EFFICIENCY FOR DIFFERENT INERT MATRIX FUELS

The proton source efficiency ψ* has been studied for different inert matrix fuels. The starting point for each parameter study is the reference model, described in the previous section.

IV.A. *ψ* as function of Target Radius for different Inert Matrix Fuels*

In this section, ψ* has been computed as a function of target radius for the three different inert matrix fuels. Each time the target radius was changed, k_{eff} was kept constant at 0.95 by adjusting the outer radius of the core. We see in Fig. 2, where the results for the plutonium based fuel have been plotted, that ψ* decreases considerably when the target radius increases [5]. There are mainly two reasons for this behaviour. One of them is the softening of the radial neutron leakage spectrum from the target, when the target is enlarged. The probability to induce fission for the neutrons entering the active core strongly decreases with decreasing energy, especially when the core is loaded with even-neutron number actinides, such as Am-241 and Am-243. The other reason for the decrease in ψ* is that the axial target neutron leakage increases with increasing target radius. The major part of the axial leakage is in the backward direction, through the accelerator tube.

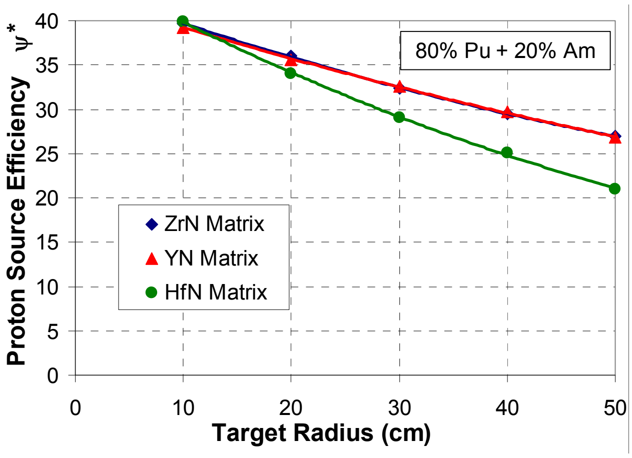

Fig. 2. ψ* versus target radius for different plutonium based matrix fuels (80% Pu + 20% Am).

Comparing the different matrix fuels, it is also shown that, for the ZrN and the YN matrices, ψ* has similar dependence on the target radius. This is expected, since Zr and Y have similar neutron cross-sections and similar mass numbers. However, for the HfN matrix fuel, ψ* decreases faster with increasing target radius. The reason for this is that Hf has higher absorption and scattering cross-sections for low-energy neutrons (below a few keV), and therefore it is more sensitive to the softening of the neutron energy spectrum. This effect increases with increasing target radius, as the energy spectrum of the neutrons leaking out from the target is softer for larger target radii. For instance, for the 10 cm target radius, the ψ* values for the different matrices are very similar, since only a very small fraction of the target leakage neutrons have energy of the order of a few keV or lower. On the other hand, for the 50 cm radius, ψ* is lower by about 23% for the HfN matrix than for the ZrN and YN matrices, due to the much softer target neutron leakage spectrum.

For the americium based fuel (Fig. 3), there are mainly two different effects arising, compared to the plutonium based fuel. Firstly, the decrease in ψ* with increasing target radius is faster, due to lower fission probability (mainly for neutrons below ~ 1 MeV) for the americium isotopes than for the plutonium isotopes [5]. Secondly, the difference between the HfN matrix fuel and the two other fuels is smaller (~ 13% for the 50 cm target radius). The explanation for this is that the fractions of matrix are lower and consequently a switch of matrix has a smaller impact on ψ*.

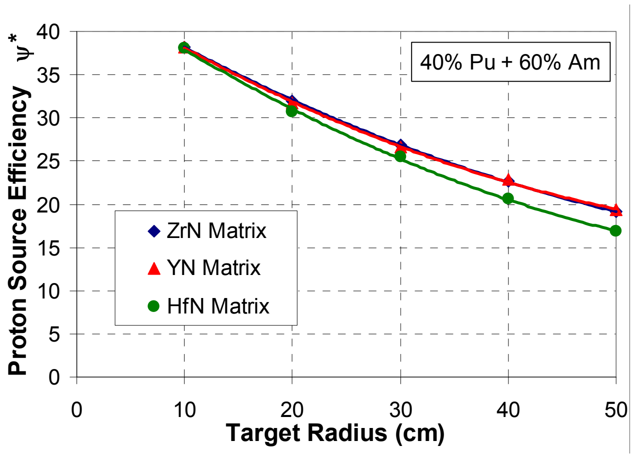

Fig. 3. ψ* versus target radius for different americium based matrix fuels (40% Pu + 60% Am).

We conclude that, in order to optimize the proton source efficiency and the output/input power, a HfN matrix fuel is slightly less favorable than a ZrN or a YN matrix fuel, in particular for large target radii. However, a HfN matrix is desirable for other reasons, e.g. its high melting point and the hard spectrum it induces, which leads to less production of curium. Therefore, HfN might still be a good choice of inert matrix, despite the loss in proton source efficiency, in particular if an americium based fuel with relatively small target radius is used.

IV.B. *ψ* for a single-zone core compared to a power flattened double-zone core.*

The proton source efficiency ψ* has been studied for the reference model (single-zone core), compared to a model where the core has been divided into two zones with different matrix fractions, with the purpose of lowering the power peaking. The single-zone and the double-zone power densities, calculated for the plutonium based ZrN matrix fuel, are depicted in Fig. 4. For the double-zone core, the matrix fractions have been adjusted in order to obtain the same maximum power density for the two zones.

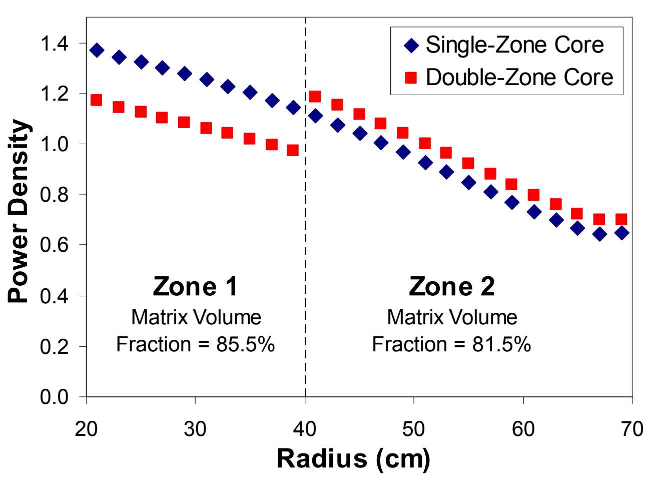

Fig. 4. Power density profiles for a single-zone core and a power flattened double-zone core, calculated for the plutonium based ZrN matrix fuel. Target radius = 20 cm.

The comparison of ψ* for the single-zone core and the double-zone core has been performed for the plutonium based and the americium based fuel, dispersed with either ZrN or HfN matrices. The calculations were performed for a target radius of 20 cm and the results are listed in Table II. We see that ψ* decreases for the power flattened double-zone core, by about 5-6% for the ZrN matrix fuels and about 10-11% for the HfN matrix fuels. If a double-zone core is assumed, the loss in ψ* by substituting the ZrN matrix by a HfN matrix is approximately 12% for the plutonium based fuel and 8% for the americium based one. Hence, a trade-off arises, where one has to consider whether the advantages with a power flattened core or the wish of using a HfN matrix fuel is worth the loss in proton source efficiency.

TABLE II

ψ^* calculated for a Single-zone Core (1Z) and a Double-zone Core (2Z). Target radius = 20 cm.

Fuel	Matrix	ψ^*		
		1Z	**2Z**	**Diff.**
Pu/Am = 80/20	ZrN	36.0	34.3	-4.8%
	HfN	34.0	30.3	-10.7%
Pu/Am = 40/60	ZrN	32.0	30.1	-5.9%
	HfN	30.7	27.6	-9.9%

There are mainly two effects arising when the content of matrix in zone 1 increases. Firstly, the absorption and slowing-down of the neutrons increases, in particular for low-energy neutrons. For the studied 20 cm radius target model, the energy spectrum of the neutrons entering into the fuel is softer than the average fission neutron spectrum in the core. Therefore, since the source efficiency (ψ^* or φ^*) relates the ratio between the source neutrons and the fission neutrons, the increase of the matrix fraction has a larger impact on the source neutrons than on the fission neutrons. Consequently, ψ^* decreases. As Hf has higher absorption cross-sections for low-energy neutrons than Zr, this effect on ψ^* is stronger for the HfN matrix, as is seen in Table II. It also increases with increasing target radius, since the energy of the neutrons that leak out from the target decreases with increasing target radius, while the average fission neutron energy is unchanged.

Secondly, increasing the matrix content in zone 1 suppresses the (n,xn)-multiplication in the inner parts of the active core, which will also tend to decrease ψ^*. This effect is strong for small radii when the target neutron leakage spectrum is hard, but decreases as the target radius increases.

V. CONCLUSIONS

Instead of using the neutron source efficiency parameter φ^*, in order to study the beam power amplification, a new parameter ψ^*, representing the efficiency of the source protons, has been introduced in a previous study. Maximizing the proton source efficiency minimizes the proton current needs and relaxes the constraints on the construction of the high-power accelerator. Studying ψ^* when optimising different system parameters therefore becomes an important factor in the overall design of an ADS.

It has been shown that the proton source efficiency decreases significantly with increasing target radius. Thus, in order to maximize ψ^* and the output/input power within the safety limits, a target radius as small as possible should be chosen.

Moreover, it was found that the HfN matrix fuel yields a lower ψ^* than the ZrN and the YN matrix fuels. However, for the americium based fuel and in particular for small target radii, the difference is relatively small. Due to other favourable properties of HfN, it is therefore still an interesting option of inert matrix material, despite the loss in proton source efficiency.

It was also found that ψ^* is lower for a power flattened double-zone core, compared to a single-zone core. The differences are about 5% for the ZrN matrix fuels, while about 10% for the HfN matrix fuels. Comparing the ZrN matrix with the HfN matrix, assuming a double-zone core, the difference in ψ^* is larger for the plutonium based fuel (~12%) than for the americium based fuel (~8%).

We conclude that, when designing an ADS, there is a trade-off arising between several different aspects. Various parameters, such as optimal target radius, power flattening and choice of inert matrix material together with other target-core characteristics and the various safety limitations, have to be weighted against the advantage of optimizing ψ^* and minimizing the proton current needs.

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