ON POTENTIAL OF THERMO-NUCLEAR FUSION AS A CANDIDATE FOR EXTERNAL NEUTRON SOURCE IN HYBRID SYSTEMS (APPLIED TO THE "WISE" CONCEPT)

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Abstract - The WISE (Waste-free, Intrinsically Safe, and Efficient) concept, based on the sequent application first natural U and then Th liquid fuel (molten salt, liquid metals, etc.), seems to be particularly attractive for Nuclear Power (NP) both for transmutation of wastes and for long-term energy production. However, the use of natural thorium fuel as well as of "once-through fuel cycle" make neutronics of WISE-core particularly weak and it requires a significant external neutron source to support sub-critical cores. Traditionally, spallation reactions have been considered as a potential source in Accelerator Driven Systems (ADS), although an important fraction of elaborated power must be spent to feed the corresponding powerful accelerators. Fusion types of the external neutron source, if they are relatively small and economically viable, can allow to get more advantages of WISE concept. The general analysis, given in this paper, shows that a fusion source is a real alternative to a spallation type of neutron source for multiple hybrid applications.

Keywords: hybrid systems, thermo-nuclear fusion

1. INTRODUCTION

Fission-fusion hybrid systems have been intensively studied a long time ago with orientation on different goals: utilization and multiplication of fusion energy, breeding of fission materials for conventional fission reactors, enhanced breeding of tritium, etc. In these concepts, fusion was called to play the leading role in energy production while fission played the subsidiary role.

The high cost of fusion energy, as well as its cumbersome designs do not allow to use them in practice: its practical economics still remains very questionable. Meanwhile, some innovative fission-spallation hybrid concepts like the Energy Amplifier of Prof. C. Rubbia (1995), or the "mobile" fuelled WISE (Slessarev et al., 2001), etc. have the extraordinary potential to satisfy current requirements of nuclear energy production for long term if reasonable neutron sources are found. WISE (Waste-free, Intrinsically Safe, and Efficient) concept, based on the sequential application of first natural U and then Th fuel (in the form of molten salt, liquid metals, etc.), seems to be particularly suited for NP for several reasons: there is no longer the necessity of fuel enrichment and of irradiated fuel massive reprocessing, a considerable reduction of long-lived toxic wastes, significant protection against weapons material proliferation, enormous fuel reserves, etc. However, the use of "poor" natural Th fuel as well as of the “once-through” fuel cycle make neutronics of WISE-core particularly weak and it requires a considerable external neutron source to support sub-critical cores.

Traditionally, spallation reactions have been considered as such a potential neutron source in Accelerator Driven Systems (ADS), although an important fraction of elaborated power has to be spent to feed the corresponding powerful accelerators. This causes both economic and technologic problems.

Spallation by protons is evidently not the single means to support this innovative fuel cycle: for example, unsatisfactory elevated cost of energy production of a small size current fusion design will not penalize excessively the neutron production regarding, for example, WISE advantages. Appearance of WISE stimulates to revise the attitude to such “non-economical” fusion design which would play now a subsidiary but important role as the external neutron source. Hence, *realization of WISE with all their advantages can compensate the economic penalty for their utilization*.

2. FUSION REACTIONS

There are several schemes of fusion reactions (Harms and Heindler, 1982) to be applied:

- “pure D-D” fusion (two channels) presents altogether (after summing all channels):

$$4\mathrm{D} \to {}^{3}\mathrm{He} + \mathrm{T} + n + p$$

with the total energy output: 7.3 MeV (the neutron production is equal to 1 neutron with energy 2.4 MeV);

- “SCAT-D” multi-channels:

$$5\,\mathrm{D} \to {}^{3}\mathrm{He} + 2n + \alpha + p$$

with the total energy output: 24.9 MeV (the neutron production is equal to 2 neutrons with energies 2.4 MeV and 14.1MeV);

- “D-T” reaction:

$$\mathrm{D} + \mathrm{T} \to n + \alpha$$

with the total energy output: 17.6 MeV (the neutron production is equal 1 neutron with energy 14.1 MeV);

and some other less attractive reactions.

3. PARTICULARITY OF FUSION REACTIONS

Let us consider the potential of thermo-nuclear fusion to supply a sub-critical hybrid core with sufficient amounts of neutrons. Neutron production is also accompanied dy energy production. To assess effectiveness of this neutron production by fusion, the special parameter will be used: ϵ_{Fus} is energy released per fusion neutron produced in a fusion reaction. One has to take into account the neutron importance φ^*_{Fus} (which reflects the difference between released neutrons and the "averaged" neutron worth in a fusion blanket) as well as the "parasitic" neutron captures in a wall, which separates the fusion reaction domain and the blanket.

Neutron balances of considered schemes have the following specific features:

- **"Pure D-D" reactions**

produce *one* fast neutron per fusion of about "fission energy". After transportation through the "first wall" which separates fusion and fission domains, a fraction of such neutrons (about 20% (Chmelev, 2000)) is lost. For the corresponding correction, one can use a_w as the coefficient showing the neutron loss in the walls: it is the ratio of all fusion neutrons to all neutrons entering in the blanket. Once in the hybrid core, their importance φ^*_{Fus} does not exceed 1.2. Hence: $\epsilon_{\mathrm{Fus}} = 7.3$ MeV/neutron,

- **"SCAT-D" reactions**

produce *one* hard neutron (14.1 MeV) with assessed importance $\varphi^*_{\mathrm{Fus}} = 1.8$ (Chmelev, 2000) and *second neutron* similar to those realized in D-D reactions. On average, for both neutrons, $\varphi^*_{\mathrm{Fus}} = 1.5$; $\epsilon_{\mathrm{Fus}} = 12.45$ MeV/neutron.

- **"D-T" reaction (T breeding is required as one of fuel components)**

produces one hard neutron (14.1 MeV) with expected importance $\varphi^* = 1.8$ (i.e. the number of all incoming neutrons can be multiplied by this factor for the account of (n,2n); (n,3n), etc. reactions (Chmelev, 2000). The neutron balance can be considered in two ways:

a) where approximately one neutron is consumed for tritium (T) breeding: T is produced by (n,γ) exothermic (4.8 MeV) reaction on ^{6}Li. However, breeding requires one *thermal* neutron with importance close to unity ($\varphi^*_b = 1$), thus, one can evaluate the neutron "efficient" importance as $\varphi^*_{\mathrm{Fus}} = \varphi^* - \varphi^*_b = 0.8$. Hence, $\epsilon_{\mathrm{Fus}} = (17.6 + 4.8) = 22.4$ MeV/neutron. With respect to neutron economy, this reaction seems not to be too attractive;

b) where ^{7}Li is used (Harms and Heindler, 1982) for T-breeding; no neutron consumption in this case is foreseen for breeding: $^7\mathrm{Li} + n_f \rightarrow n' + \alpha + \mathrm{T}$, where n_f and n' are a fast and the thermalized neutrons respectively. In fact, if the importance of fast and thermalized neutrons are similar (in thorium spectrum, the neutron potential of the main fissile isotope ^{233}U is weakly sensitive to neutron spectra), then it is not required to spend neutrons for thorium breeding. Besides, the neutron importance is close to 1: $\varphi^{*}_{\mathrm{Fus}} = 1$. In this case, the breeding reaction is endothermic, so $\epsilon_{\mathrm{Fus}} = 17.6 - 2.5 = 15.1$ MeV/neutron .

4. NEUTRON ANALYSIS. FUSION NEUTRON SOURCE

Installations, using all mentioned above fusion reactions, produce in practice less energy than they consume, although are approaching gradually to the "break-even-point" due to enormous international strengths of scientists. In this paper we to demonstrate that even with such a "negative" energy balance, these schemes can already be rather effective to replace, for example, proton sources in hybrids when external sources have to be very powerful, particularly for natural Th fueled WISE (Slessarev et al., 2001).

Each fusion design consumes electrical energy for its needs and produces "output" energy in the form of kinetic energy of charged and neutral particles. Let us define m as the ratio of the total consumed energy (E_{spent}) to the total output electric energy. The m-value plays a role of "power effectiveness" of a fusion installation. Denoting E_{Fus} as the total output energy of fusion reaction and η_e as the efficiency of its transformation to the electric energy in a fusion blanket, then:

$$m = \frac{E_{spent}}{\eta_e E_{\mathrm{Fus}}}$$

where $m = 1$ corresponds to the "break-even-point" and $m > 1$ corresponds to the "negative" energy balance of a fusion installation. Referring to one produced neutron, one can evaluate m by the following way:

$$m = \frac{\epsilon_{spent}}{\epsilon_{\mathrm{Fus}} \eta_e} .$$

Note, that at $m \geq 1$, *it makes no practical sense to use "pure" fusion for energy production, however, it could have the significant sense as a supplementary neutron source for a hybrid system, if such a system opens an attractive perspective for NP.*

The thermal energy which is produced in a sub-critical core (blanket) when this core has received one "fusion" neutron consists of the energy of fusion reactions plus the total energy released from fission reactions in the core with the given multiplication coefficient K_{eff} due to the multiplication of neutrons:

$$\epsilon_{\text{th}} = \epsilon_{\text{Fus}} + \frac{K_{\text{eff}}}{\left(1-K_{\text{eff}}\right)} \frac{\varphi^{*}_{\text{Fus}}}{\bar{\nu} a_{w}} \epsilon_{\text{Fis}}$$

where $\bar{\nu}$ is the average number of the secondary neutrons per fission; φ^{*} is the importance of fusion neutrons; ϵ_{Fis} is the fission energy; a_{w} is the ratio of all fusion neutrons to all neutrons entering in the blanket.

Taking into account the efficiency of transformation of core thermal energy to electrical energy, one gets $\epsilon_{e} = \epsilon_{\text{th}} \eta_{e}$.

Hence, the fraction of total electrical energy which has to be spent for the reproduction of one fusion neutron and to sustain the energy production can be assessed now as

$$f_{\text{Fus}} = \frac{\epsilon_{spent}}{\epsilon_{e}} = m \frac{1}{1 + \frac{\epsilon_{\text{Fis}}}{\epsilon_{\text{Fus}}} \frac{K_{\text{eff}}}{\left(1-K_{\text{eff}}\right)} \frac{\varphi^{*}_{\text{Fus}}}{a_{w} \bar{\nu}}}.$$

Estimations show that for “WISE”-core ($K_{\text{eff}} \approx 0.9$) one can neglect the first term in the denominator, so one get:

$$f_{\text{Fus}} \approx \frac{\left(K^{-1}_{\text{eff}} - 1\right)\bar{\nu}}{Y_{\text{Fus}} \epsilon_{\text{Fis}}} = \frac{1}{Y_{\text{Fus}}} \frac{1}{K_{A} \epsilon_{\text{Fis}}} \tag{1}$$

where the “effective” neutron yield Y_{Fus} in a blanket per consumed energy is defined as

$$Y_{\text{Fus}} = \frac{\varphi^{*}_{\text{Fus}}}{\epsilon_{\text{Fus}} m a_{w}}$$

and K_{A} is the coefficient of multiplication (amplification) of fission energy in the sub-critical blanket:

$$K_{A} = \frac{K_{\text{eff}}}{\left(1-K_{\text{eff}}\right)\bar{\nu}}.$$

This means that the power fraction consumed by the supplementary source is inversely proportional to the effective neutron yield of this source and to the coefficient of power amplification of the blanket.

5. NEUTRON ANALYSIS. SPALLATION NEUTRON SOURCE

Fusion is not a single nuclear reaction to produce supplementary neutrons for hybrids. Let us to inter-compare the energy consumption of the supplementary neutron sources due to fusion with well-known ADS systems where neutrons are produced by proton beam due to spallation reaction.

One can conduct similar assessment of energy, which required for production of neutrons via spallation.

As result, the total electrical energy which is produced by ADS core per one proton (neutron yield is expecting as Z neutrons after spallation) is evaluated as

$$\epsilon_e = \eta_a \left[\epsilon_{\mathrm{Sp}} + \frac{K_{\mathrm{eff}}}{\left(1-K_{\mathrm{eff}}\right)} \frac{Z\varphi_{\mathrm{Sp}}^{*}}{\bar{\nu}} \epsilon_{\mathrm{Fis}} \right],$$

where ϵ_{Sp} is energy released after spallation per one incident proton (for example, in the lead target, $\epsilon_{\mathrm{Sp}} \approx 0.5\epsilon_p$, ϵ_p is proton energy (Harms and Heindler, 1982)); $\varphi_{\mathrm{Sp}}^{*}$ is the importance of spallation neutrons.

For production of one proton, one has to spend ϵ_{spent} energy, where $\epsilon_{spent} = \epsilon_p / \eta_a$ and η_a is the accelerator efficiency. Finally, the fraction of total electrical energy which has to be spent for production of one proton and to sustain energy production in ADS can be evaluated as

$$f_{\mathrm{Sp}} = \frac{\epsilon_{spent}}{\epsilon_e} = \frac{1}{\eta_e \eta_a} \frac{1}{\left[\frac{\epsilon_{\mathrm{Sp}}}{\epsilon_p} + \frac{\epsilon_{\mathrm{Fis}}}{\epsilon_p} \frac{K_{\mathrm{eff}}}{\left(1-K_{\mathrm{eff}}\right)} \frac{Z\varphi_{\mathrm{Sp}}^{*}}{\bar{\nu}} \right]}$$

and, after neglecting with the first term in the denominator, one get, similar to the case of the fusion source:

$$f_{\mathrm{Sp}} \approx \frac{\left(K_{\mathrm{eff}}^{-1} - 1\right)\bar{\nu}}{Y_{\mathrm{Sp}}\epsilon_{\mathrm{Fis}}} = \frac{1}{Y_{\mathrm{Sp}} K_A \epsilon_{\mathrm{Fis}}}, \qquad (2)$$

where the “effective” neutron yield Y_{Sp} of spallation per consumed energy is defined as

$$Y_{\mathrm{Sp}} = Z\varphi_{\mathrm{Sp}}^{*} \frac{\eta_e \eta_a}{\epsilon_p}.$$

6. INTER-COMPARISON: ADS VERSUS A FUSION-HYBRID

Table I shows the fractions of energy consumption to create a neutron source by spallation or by fusion.

It is evident that fusion produces many more neutrons per unit power than spallation. Estimations show that one can neglect source particle energy with respect to fission energy. So, one can obtain the simple formula for the inter-comparison of the fractions of spallation/fusion parts in a hybrid required to support energy production by fission:

$$\frac{f_{\text{Sp}}}{f_{\text{Fus}}} = \frac{Y_{\text{Fus}}}{Y_{\text{Sp}}} .$$

The inter-comparison of *Y*-values demonstrates that the effectiveness of fusion for neutron production (when $m \to 1$) is significantly higher when compared with spallation and it is reducing when the m increases (Table 1).

It is important to note that the consumed power of the fusion sources is surprisingly small in many cases. So, for D-D reactions, the proportion between power of fusion source and the core of WISE is expecting to be 1:100 if $m = 1$. Certainly, the fraction of the fusion part will grow if less effective fusion reactions or less beneficial economy of fusion sources ($m \geq 3$) are used.

Table I: Required supplementary energy consumptions (*f*, %) in sub-critical hybrids supplied with spallation or with fusion reactions. ($K_{\text{eff}} = 0.9$, $\eta_e = \eta_a = 0.45$, $\bar{\nu} = 2.5$).

Sources of supplementary neutrons in different Hybrids	**Effective neutron yields *Y* (MeV)$^{-1}$**	**f_{Fus}, %, (1)**		
FUSION (a_w= 1.2)	$m = 1$	$m = 1$	$m = 3$	m = 10
D-D (WISE-Fusion)	0.14	1.0	3.0	10
SCAT-D (WISE-Fusion)	0.10	1.4	4.2	14
D-T, breeding on Li-6 (WISE-Fusion)	0.030	4.1	8.2	41
D-T, breeding on Li-7 (WISE-Fusion)	0.055	2.5	7.5	25
SPALLATION				
Spallation by proton E_p = 1 GeV, lead target, Z = 20, φ^*_{Sp} = 1.3 (Slessarev et al., 2001)	0.0053	f_{Sp} = 26%, (2)		

7. CONCLUSION

The neutron abundance of fusion reactions (particularly D-D reactions) per consumed energy could make such sources more rich compared with the spallation source. For example, fusion sources are preferable (when compared with the spallation source) if their electric energy consumption does not exceed the total thermal energy production by factor of about $m \leq 10$.

The closer the "break-even-point" the more beneficial fusion sources become. Even for significant core sub-criticality hybrids (i.e. the WISE with Th-fuel), the required power (for the external neutron production) can be assessed as only 3% of the total blanket power if D-D sources with $m = 3$ used. The weakest potential is expected for DT (breeding on Li-6) reaction.

Fusion types of the external source, if they are relatively small and, hence, hybrids are not too much penalized economically, can allow getting the new advantages of hybrid concepts. Possibly, it could be consider as a real alternative to spallation type of neutron source (ADS) taking into account the technical feasibility of current fusion installations with $m > 1$.

5. REFERENCES

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