

PREMISES FOR USE OF FUSION SYSTEMS FOR ACTINIDE WASTE INCINERATION

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Abstract

The main premise of the present study is a change in the attitude of the fusion community regarding the fission power – from perceiving it as an ally of fusion not a competitor. Seeing this, first some basic problems of the nuclear power have been sketched and then the question of spent fuel transmutations and its properties in view of energy content. In search for solutions subcritical Fusion-Driven Incinerator systems (FDI) have been considered. The advantage of subcritical systems lies in their remoteness from superprompt criticality. Next the problems of nuclear fusion have been addressed and the ways of solution with use of fission energy contained in actinides of spent nuclear fuel have been proposed. The main positive of that option of fusion power, /thanks to energy release from fissions/, is the prospect of a radical reduction of necessary plasma energy gain Q to levels achievable in much smaller i.e. much more economic devices. No less important advantages of the FDI system are: reduced load of the First Wall (FW) with 14 MeV neutrons and well homogeneous heating distribution. One should not forget that just the radiation damage is one of the main sources of difficulties in fusion technology. Then it has been suggested that one of the most viable incineration concepts is a symbiotic nuclear energy system, consisting of an incinerator of transuranics (Pu, Np and Am) and of a number of co-operating Light Water Reactors (LWRs). Summarising, the concept of actinides incineration in fusion-driven subcritical systems significantly heightens safety of nuclear power systems as a whole. In conclusion, the option of fusion presented herewith as a means to solve the problems inherent to fission based nuclear energy may facilitate the development and then launching of the fusion power.

Keywords: radiation damage, actinides incineration, subcritical systems, fusion-driven incinerator.

1. Introduction

1.1 Global Energy Problems

The famed forecasting of the end of cheap organic fuels (oil and gas) seems finally to come true. Since at present nearly one third of the world population lives outside of electrified areas within the next quarter of century the number of electricity consumers will double. Calmed by often spectacular energy savings in modern electronics (per device) one neglects its avalanche expansion in numbers (e.g. of the mobile phones and PCs). Besides, many households in the world are only going to be equipped with microwave ovens, air conditioners, (de)humidifiers, etc. Having all the above in mind, one should anticipate a global permanent increase in the electricity consumption. Such demand must not be met with organic fuels that threaten with unforeseeable consequences of further heightening of CO₂ concentration in the atmosphere (Kyoto Protocol). The opinion that a deployment of renewables to meet this demand is very desirable does not give rise to any doubts. Unfortunately, the present quite important share (about 1/5) of hydroenergy in the world electricity production cannot be significantly increased. In turn, the possibilities of other renewables /solar, wind/, because of physical /low power density/ and practical /low disposability/ limitations are by far insufficient. Therefore, the only option the contribution of which is simultaneously meaningful and has a potential to increase fast is nuclear energy.

1.2 Problems of Nuclear Power

Unfortunately, the existing i.e. fission based nuclear power provokes considerable social objections originating from subjective perception of potential risk associated with. These are:

- 1) Contingency of uncontrolled supercriticality in extreme accidents;
- 2) Highly radioactive, long-lived nuclear waste.

Ad 1) An intuitive factor of safety is the remoteness of the system state from the super prompt criticality. This distance of a critical system is determined by the Nature's bounty - the delayed neutrons, quantitatively, by their effective fraction β_{eff} specific for each composition of nuclides and neutron spectrum in the system. A safety margin larger than β_{eff} is thinkable, but can occur solely in subcritical systems that can operate in a steady state provided an external neutron source is continuously compensating the neutron deficit in each generation.

Ad 2) High radiotoxicity of nuclear spent fuel is the cause why finding a way of its definitive neutralisation has become a necessary condition of social acceptance of nuclear power. Meanwhile the problem is aggravating since at current level of world deployment of nuclear energy (ca. 370 GW_{el} installed civilian capacity) the yearly global yield of spent fuel exceeds 10 000 metric tonnes, whereas the global inventory of civilian spent nuclear fuel (including the reprocessed fraction) amounts to over 200 000 t [1] that contain nearly 4 000 tonnes of fissile nuclides. The NEA 2001 estimate of world depleted uranium stocks (not counting the weakly burned-up uranium from dedicated reactors supplying weapons-grade Pu) amounts to ca. $1.2 \cdot 10^6$ t.

The global problem of waste has not been resolved until now in an indisputable way. Spent nuclear fuel at present is stored either at the plant or in interim engineered installations. But as a final solution of the problem, up to now a disposal in geological formations is assumed. Since such option does not signify a physical destruction of fissile materials a permanent safeguarding of the disposal, in order to prevent its use (secret or open) as a plutonium mine, must be foreseen. /The Pu extraction becomes easier with time from the waste gradually less radioactive/. In view of the required properties of the repository that should guarantee the retention of the waste during millions of years, sufficient for decay of its longest-lived radioisotopes, this concept is not inexpensive. The danger posed by such amount of high level waste containing thousands of tonnes of fissile nuclides has been widely recognised pretty long ago. Yet the geological disposal physically should be considered as safe (cf. the Oklo phenomenon). Instead, one must not neglect the enormous energy content of actinides, ($200 \text{ MeV/atom} \approx 2500 \text{ MW}_{\text{t}}\text{yr/ton}$) equal to a striking number $8 \cdot 10^{20} \text{ J}$ in the world yearly spent fuel i.e. about twice the total world's annual energy consumption. Moreover, the energy contained in the global /civilian only/ inventory amounting to $2 \cdot 10^{22} \text{ J}$ is equal to the consumption of energy /at present rate/ in all forms by the whole humankind during 50 years. To bury such enormous amount of energy would be really deplorable. One should consider a duty of present generations to assure for the future ones the use of that precious energy source rather than only to protect them from the potential hazard linked to it. Thus, any *irreversible* disposal of actinides proves deeply unjustified, while rational is to work out a technology of safe utilisation of this waste.

Next, it should be reminded that a definitive way of getting rid of radiotoxic actinides is solely fissioning, since other nuclear reactions with exchange of only several nucleons leave the nucleus to remain an actinide one. Simultaneously, the increasing amount of world spent nuclear fuel indicates that it will remain a problem for many decades – not excluding, till the end of century. As regards fission products, since their transmutations bring no energy bonus this option is not considered here. In addition, it may be hoped that indispensable social acceptance of nuclear energy can be facilitated by the possibility of definitive destruction of nuclear waste, thus adding an important social value to this concept. The development of a subcritical Fusion-Driven Incinerator (FDI) is a major step in this direction.

1.3 Problems of Nuclear Fusion

The worldwide antinuclear phobia has not left untouched also the field of nuclear fusion. On the part of the fusion community one used to generally observe the avoidance of mentioning any relationship of fusion to fission, as if in hope that decision makers and the general public usually allergic about, will not associate fusion with nuclear. Yet, the specialists, though aware of the important differences between these two forms of *nuclear* energy cannot perceive fusion as free of radioactive waste [2]. Thus, one can be sceptical about the rationale of opposing fusion energy to the fission one, in belief to make the public or investors to like the former. We believe that other arguments, based on concepts of environmentally benign fusion-fission symbiosis are better. The change in the attitude of the fusion community towards the fission power – from perceiving the latter as an ally of fusion instead of a competitor - is the main premise of the present study.

The proposal is the use of a fusion reactor as the device for safe incineration of the waste produced by fission based nuclear energy [3], since the persistence of fission based nuclear energy (LWRs) within the foreseeable future – is assured. Thus, the LWR costs (the fuel cycle back-end ones including) seem to determine the future electricity prices. This factor together with high investment costs of the fusion reactor put in doubt whether its mere energy production, even at reduced radioactive waste level, proves sufficient for making it economically competitive. But its additional use and thus income from secure /as free of criticality dangers/ incineration /i.e. fissioning/ of actinides in the fusion-driven device can resolve this question. It is true that at present the fusion technology is not yet ready. Nevertheless, since as mentioned above, the problem of actinide waste seems prolonged enough, the fusion technology - in conditions relaxed due to fission component (see below) – will be then ready. Thus, in this way, an attractive picture of fusion appears – as a means to solve the problems inherent to fission based nuclear energy.

Another important question that must be addressed here is the proliferation. Yet it seems that a closed fuel cycles do not provide more proliferation problems as the well-known MOX fuel cycle. The decades long experience of many thousand tons of reprocessed spent fuel in the UK and France indicates that a reliable Pu accountancy, safeguarding and diversion prevention are possible.

2. Fusion-driven Incinerator (FDI)

As one may expect, a fusion reactor could be the external neutron source for such subcritical system (e.g. [4]). A satisfactory power level of externally driven subcritical system requires high number of source neutrons and a sufficient value of neutron multiplication factor k_{eff} . In FDI both demands are not that easy to be satisfied, since certain minimum plasma Q and k_{eff} are needed at the same time. The difficulties in attaining plasma Q high enough are evident, whereas the upper limit to the k_{eff} can be set by assuring the system to remain subcritical in spite of any conceivable rearrangements. Even at normal operation step-wise changes in this value are inevitable, following e.g. a necessary fuel shuffling or simply a system reloading, thus safe values of k_{eff} are rather low.

Therefore, a specific objective appears: maintenance of the energy gain of the system at lowest but

sufficient k_{eff} . Fortunately, there is an effect apparently increasing the k_{eff} [5] by the factor k_s , named k -source. The k_s represents the number of neutrons additional to those born in the k_{eff} -based fundamental mode, mostly in the first cycles of the multiplication chain (Fig.1). The – 14 MeV generated fast fission and (n,2n) neutrons – additionally relax our demand for higher, less safe k_{eff} at unaffected number of fissions in the system.

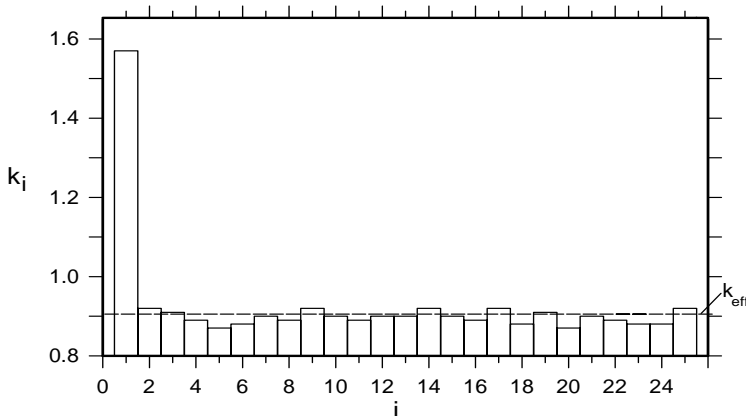


Fig.1. Illustration of neutron multiplication in successive neutron generations vs. generation number i .

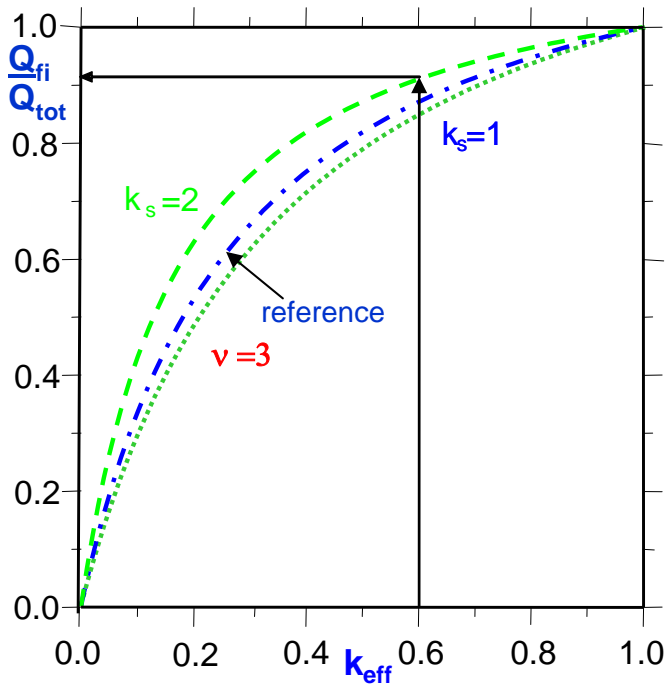


Fig.2. Fission fraction of energy released in the FDI system vs. k_{eff} .

(Reference values: energy - fusion $Q_{fu} = 17.6$ MeV, - fission $Q_{fi} = 200$ MeV, self-consumed power fraction $c_{ps} = 0.25$, conversion efficiency of self-consumed power $c_p = 0.16$, $k_s = 1.5$, $\nu = 2.5$.)

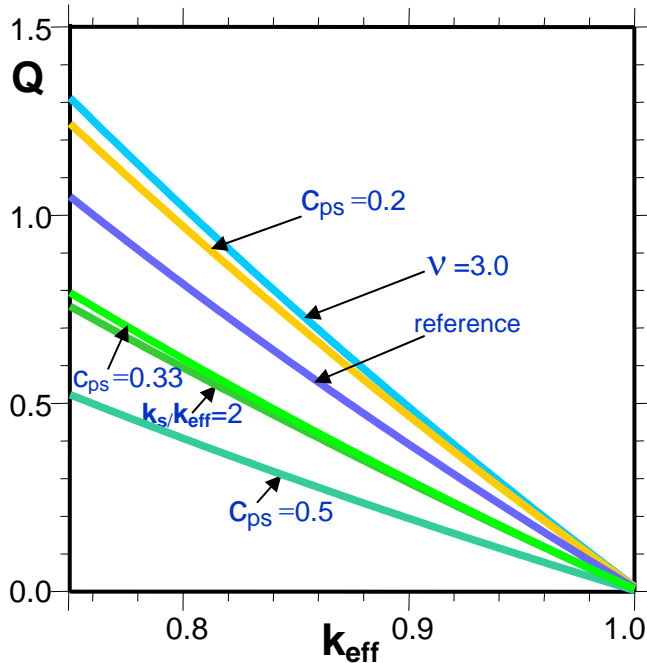


Fig.3. Plasma Q reduction in FDI systems for given fixed power vs. k_{eff} .

The energy gain achieved in this way can be sufficient for a significant reduction in the plasma Q . However, since an accumulation of fissile material directly at the FW may easily lead to an excessive energy release in there, thus achievable values of k_s are limited by the admissible power density and its peaking in designing of the system. In turn, the presence of fissile material deeper in the blanket increases the volume of nuclear heating, thus allowing for achieving the sufficient power of the whole system at reduced area of the first wall.

It is interesting what values of k_{eff} are needed that to achieve the desired energy gains. The contribution of fission to the total energy released in an FDI system is shown in the Fig.2. [6].

It can be seen that a significant contribution to the FDI energy balance occurs already at the k_{eff} above 0.6-0.7. The several curves in the picture correspond to different values of most significant parameters of the system.

The Fig.3 [6] demonstrates that at unaffected power of the FDI system, a radical drop in the value of Q , down to a level 0.3 is feasible. /E.g. for so low k_{eff} as equal to 0.85 plasma $Q = ca. 0.5$ seems sufficient/. This should draw attention to such devices as e.g. tandem mirror or spherical tokamak in order to check whether the above values are achievable at much smaller sizes and expenses than needed for a regular tokamak.

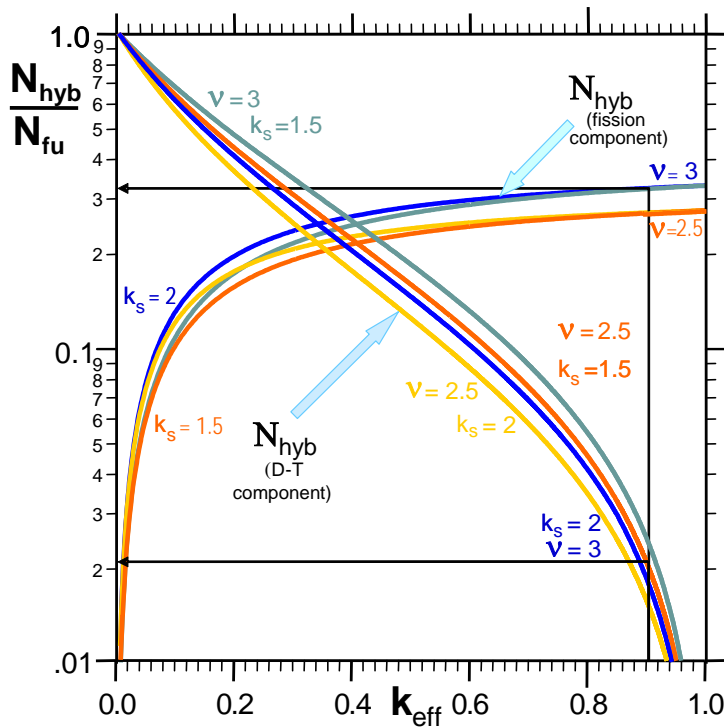


Fig.4. Neutron yield reduction in FDI systems for given fixed power vs. k_{eff} .

Thus the requirements regarding plasma Q can be significantly softened. Instead, in the Fig. 4 one can see that at $k_{eff} \approx 0.90$ in place of fusion neutrons about 3 times less fission neutrons appear. In addition, one should not lose sight that these neutrons are much more uniformly distributed (over large volume) than fusion neutrons all emitted from the plasma.

Therefore thanks to fissions both the alpha's and 14 MeV neutron yield can be reduced by factor of several tens, eg. ca. 50.

2.1. Material Problems

Another key problem of fusion is the radiation damage. Its main sources are: charged particle flux from plasma to - first of all - the divertor and neutrons inducing displacement of atoms (DPA), gas production and transmutations also in the FW. The attenuation of all the radiation (charged particles, neutrons and photons) from plasma follows the reduction in the fusion component in the system. Though instead of D-T neutrons the fission neutrons appear, yet in much lesser number (Fig.4). Besides it should be emphasized that the destructive potential of the latter is much lower (Fig.5 and 6). Exemplary pertinent cross-sections compared with fusion and fission neutron spectra illustrate probabilities of gas production, activation and DPA (Fig.5-7).

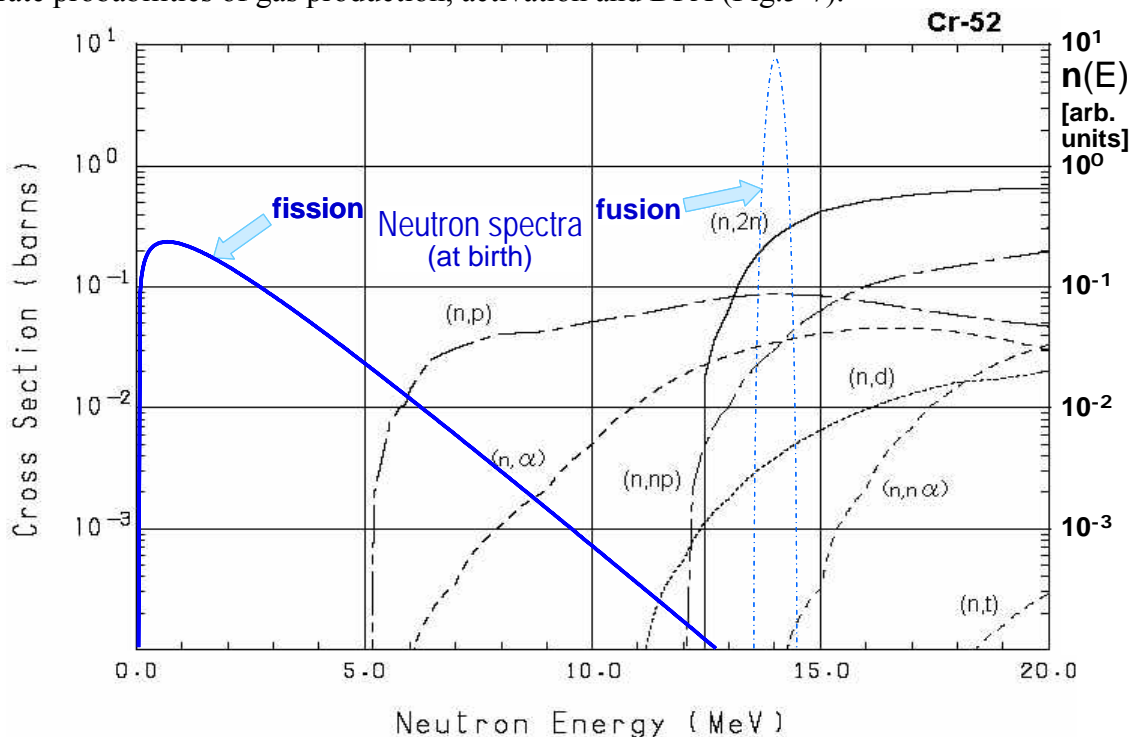


Fig. 5. Example of gas production reaction cross-sections and neutron spectra [7].

The Fig. 5. shows that the thresholds of gas production reactions – as expected – are pretty high, mostly confined within the range from a few to ~12 MeV. More data can be seen in Fig. 6 below.

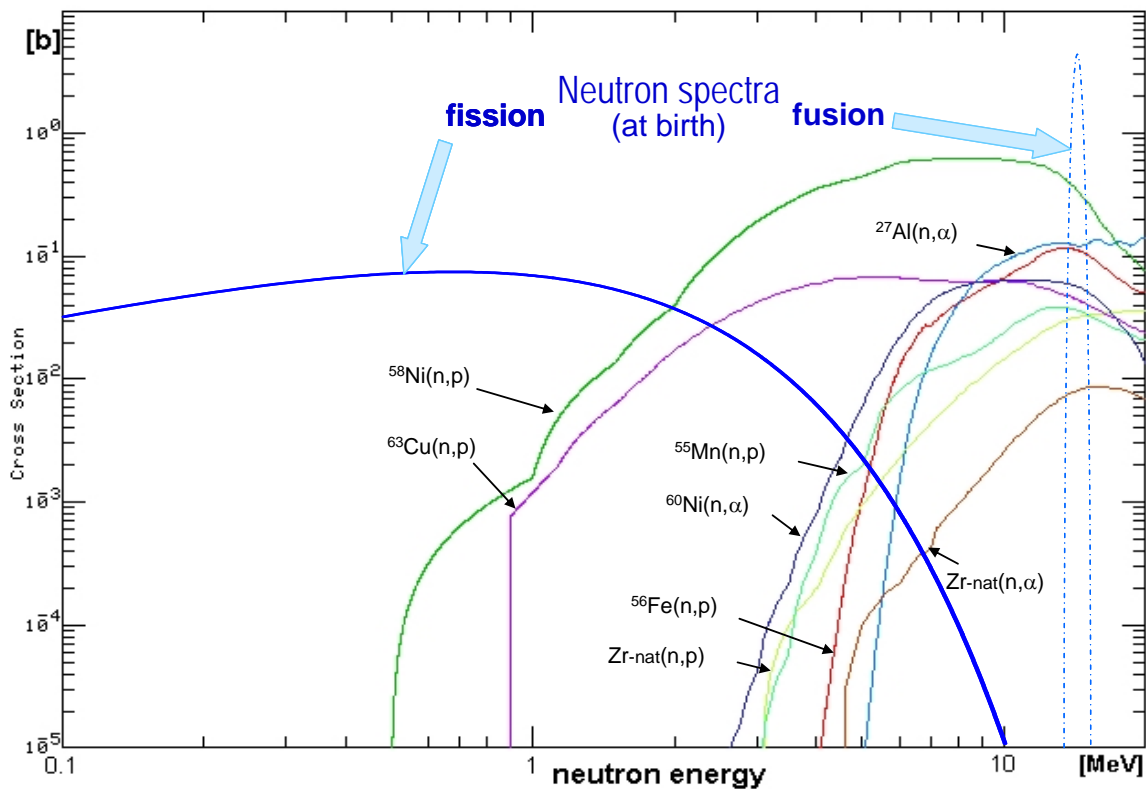


Fig. 6. Cross-sections for gas production in selected construction materials [8].

From the picture in Fig. 6. results that the gas production by the fission neutrons (energy ca.1 MeV) is rather exceptional – limited to H and particular isotopes (e.g. ^{58}Ni).

As regards the DPA, one should look at the efficiency of fission neutrons and of 14 MeV ones in displacing the atoms of main metallic components of construction materials of Fig.7.

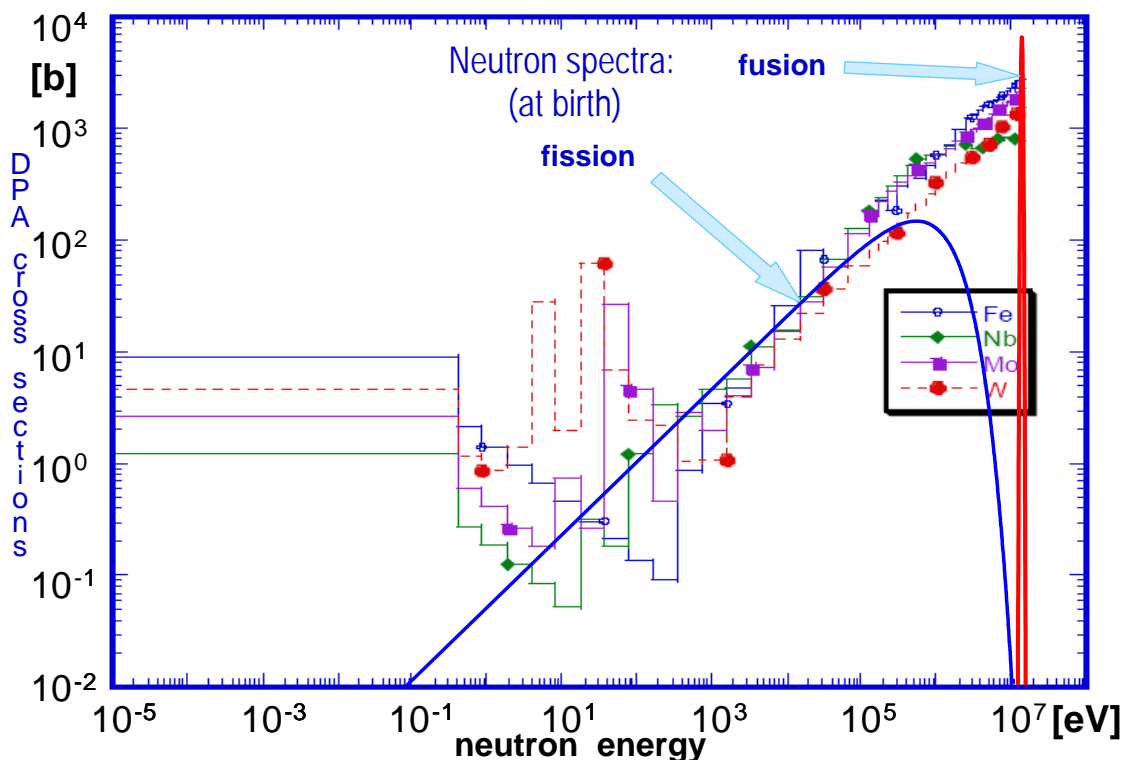


Fig. 7. DPA cross-sections of several elements of construction materials /Youssef, [9]/.

The Fig.7 indicates that the destructive displacing of the atoms by 14 MeV neutrons is also much more intensive than that of fission ones. Summarising, one may foresee that in the most sensitive zones of the FDI (divertor, FW) the gas production component of the radiation damage can be reduced by the same factor as the D-T neutron yield (i.e. for k_{eff} equal to ca. 0.85 by several tens times), whereas the reduction of DPA (non-threshold reaction) seems to be lesser.

Tab. 1. Comparison of MCNP evaluated radiation damage effects in the first wall (pure Fusion Reactor vs. FDI of the same power)

Effect Option	E – energy per src.n [MeV]	tot. H prod. [nuclei/ (src.n.*cm ³ *E)]	tot. He prod. [nuclei/ (src.n.*cm ³ *E)]	dpa [events/ (src.n.*E)]
Fusion Reactor	22.4	2.69E-07	5.08E-08	6.21E-07
FDI	1100	5.94E-09	1.06E-10	4.05E-08
FDI/FR ratio	49.1	0.0225	0.0208	0.0652

In view of all the above the size of FDI can be radically reduced as compared with the pure fusion reactor - usually a Tokamak (Fig.8) [2].

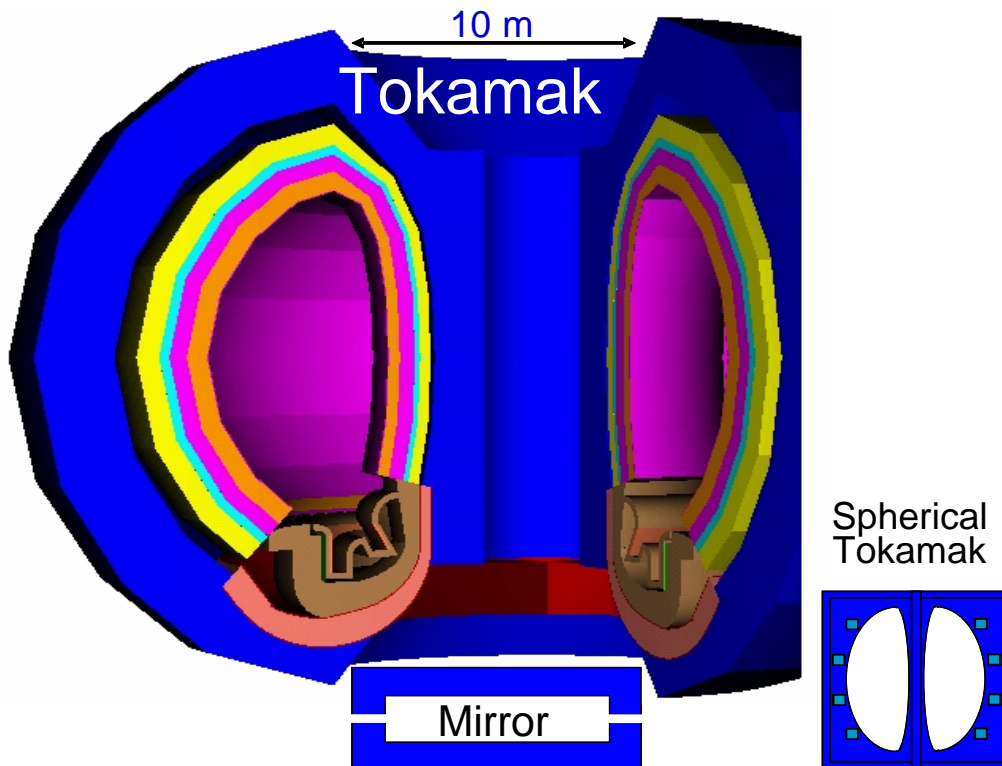


Fig. 8. Size of fusion reactors: a Tokamak vs. a Mirror and a Spherical Tokamak device

A Mirror based FDI can be incomparably smaller than a Pure Fusion system. On the other hand it should be emphasised here that the concept of a Mirror system (selected for calculations presented here) is not at all a definitive choice. It has been taken rather for demonstration of the long time underestimated potential of fusion technology for incineration of actinides.

2.2 Transmutations

The main advantage of fusion over fission – safety must not be undermined by a threat of supercriticality in case of a worst accident to be considered for a FDI – reactor meltdown (Fig. 9) [10]. Thus, the MCNP [11] calculation model of the FDI in question has been completed with the configuration of the molten core.

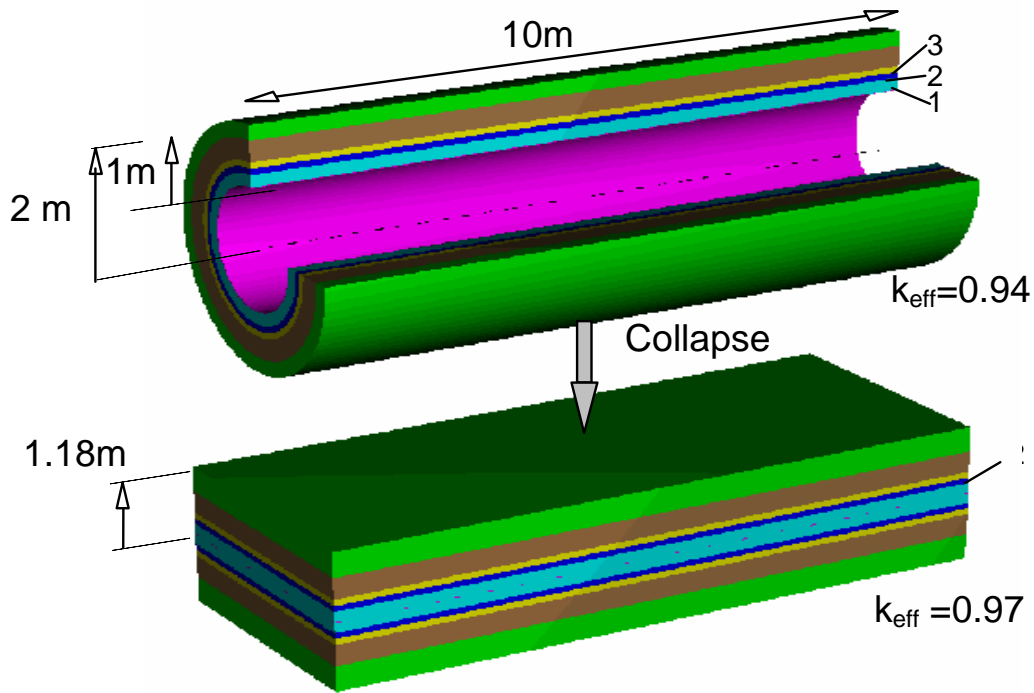


Fig.9. Model of the FDI Mirror system in operation and after meltdown

The assembly after collapse remains subcritical ($k_{\text{eff}} = 0.97$)

Both the processes - fissile incineration and breeding are not uniform in space and time, running at different rates within the system volume in the course of the transmutation cycle. The local incineration rates (thus nuclear heating too) can vary very significantly that draws behind the necessity of adequate compensation by adjustment of the respective fissile concentrations. The achieved this way quite effective power flattening (Fig. 10) /normalised to the same maximum power density/ illustrates the superiority of the heating distribution in the FDI as compared with a pure fusion reactor.

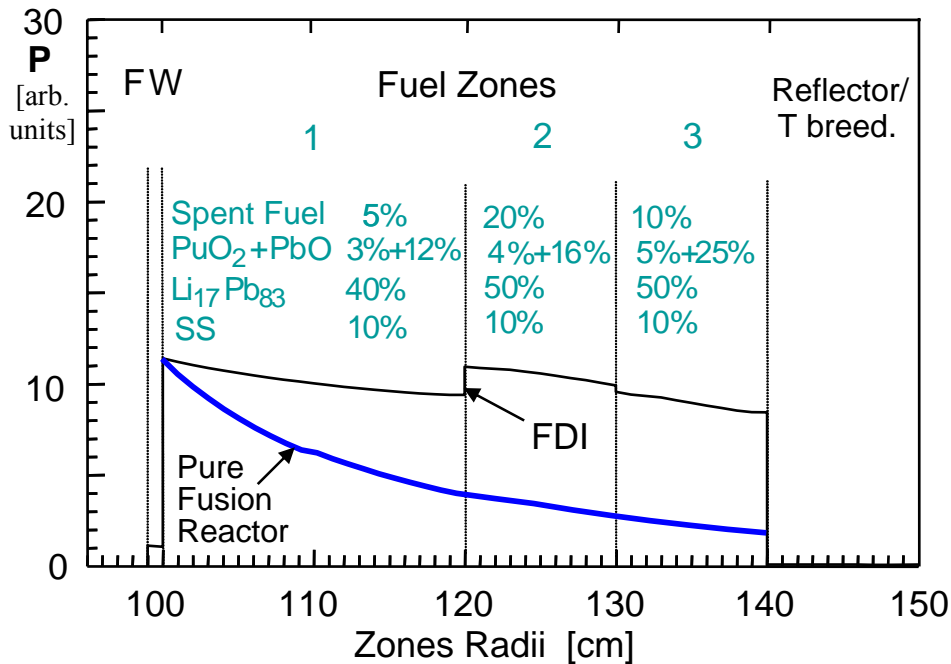


Fig. 10. Heating distribution in a Mirror FDI system compared to the one without actinides.
 Materials composition [at./Å³], SF: ²³⁸U 2.3-2, ²³⁵U 2.2-4, ²³⁹Pu 1.71-4, ²³⁷Np 1.5-5, O 4.7-2, F.P 8.8-4,
 PuO_2 : ²³⁸Pu 3.7-4, ²³⁹Pu 1.36-2, ²⁴⁰Pu 5.15-3, ²⁴¹Pu 3.05-3, ²⁴²Pu 1.34-3, ²³⁹Np 9.-4, O 4.88-2,
 $\text{Li}_{17}\text{Pb}_{83}$: ⁶Li 3.64-4, ⁷Li 4.53-3, Pb 2.39-2, PbO : Pb 2.48-2, O 2.48-2,
 SS: Cr 1.255-3 Ni 9.849-3, Mo 1.5757-2, Fe 5.7272-2.

Another objective may be not only to keep the neutron multiplication factor k_{eff} below a certain value recognised as safe one but also maintain it steady that would keep the power of subcritical system constant at the optimum load of its fusion driver. Here, however, the calculations have been limited to transmutation balance at the beginning of life (BOL). The incineration of particular nuclides obtained with MCNP calculations of another Mirror FDI (fueled also with Am) system is given in Tab.2.

Tab.2 Incineration of transuranics in an FDI

Nuclide	Inventories (BOL) [t]	Net incineration rate [kg/500GW*yr] (BOL)	Fission rate [kg/500GW*yr] (BOL)
²³⁷ Np	0.21	8.49	1.56
²³⁸ Pu	0.29	1.83	5.6
²³⁹ Pu	4.28	149.3	121.2
²⁴⁰ Pu	2.36	5.28	17.7
²⁴¹ Pu	0.87	20.9	33.9
²⁴² Pu	0.87	4.8	4.8
²⁴¹ Am	0.596	23.0	3.54
^{242m} Am	0.004	-19.3	0.1
²⁴³ Am	0.53	14.0	2.4
Total	10.00	208.3	190.8

First it should be reminded that efficiency of the incineration is predominantly affected by the composition of the inventory. This composition, in turn, cannot be chosen arbitrarily, as being determined first of all by the composition of spent fuel to be incinerated. In addition, due to the technical reasons (e.g. intensity of spontaneous fissions) Cm was omitted in the initial inventory.

Looking at the differences between the net incineration rates and the fission rates one sees, for instance, that ²³⁷Np though effectively incinerated, since its fissioning fraction is only 20% mainly turns into ²³⁸Pu. To the contrary ²⁴⁰Pu is fissioned quite efficiently, in spite of its rather low net incineration, due to neutron captures in ²³⁹Pu regenerating ²⁴⁰Pu. In turn, fast incineration of ²⁴³Am signifies mostly production of ²⁴⁴Cm, as of ²⁴¹Am leads to ^{242m}Am. Yet, the incineration of Pu, and Np can be very efficient, as well as that of Am, the ^{242m}Am including, though it is abated only after its build-up occurs. nearly absent in the input is only The same remark is only partially valid for Cm since its cross-sections are much lesser than those of ^{242m}Am. In general, two primary objectives of transmutations can be considered:

- 1) Incineration of actinides and only if reasonable, of other radwaste;
- 2) In addition to current exoergic actinide destruction, a supply of fuel for future use.

A number of options of power systems with transmutation unit have been proposed, principally distinct by different assumptions of primary objectives. One can aim either at a more farsighted idea of a self-sustaining nuclear power system with closed fuel cycle or confine oneself to a development of technology of nuclear waste incineration (the global amount of which anyway will continue to grow during next half century). There are good grounds for doubts if a fully closed fuel cycle can ever be licensed in critical reactors (due to positive reactivity coefficients of MA). In other words the use of subcritical systems may prove indispensable. Thus, one of the most viable incineration concepts seems a symbiotic nuclear energy system, consisted of an incinerator of transuranics (Pu, Np and Am) and of a number of co-operating Light Water Reactors (LWRs) [12]. In the frame of such a symbiotic system two extreme variants can be noted:

- 1) Conservative - sole nuclear waste incineration (e.g. of the stored Pu and MA);
- 2) Optimistic - self-sustaining nuclear power system (more precisely, assuming a replenishment of incinerated actinides in the system with natural or depleted uranium or thorium) and restrained to use only self-generated fissile materials (except of initial inventory).

Between these extremes there are intermediate feasible options. On such a background appears the concept of fusion-driven systems for the neutralisation of nuclear waste with energy production.

3. Conclusions

The concept of Fusion-Driven Incinerator system provides a feasible way of radical reduction of necessary plasma Q of fusion reactors. Thanks to the fission component the 14 MeV neutrons yield can be reduced by factor of several tens, thus, also the radiation damage in the system principally in the first wall and in the divertor due to a general reduction of the fusion component (i.e. of all: charged particles, 14 MeV neutrons and photons in the system. The distribution of nuclear heating can be well flattened. Symbiotic character of the proposed nuclear energy system composed of a fusion-driven subcritical assembly and existing LWRs does not urge to a revolutionary turning point in development of nuclear energy by pretending to replace all the present power plants. The FDI applied for transmutations of actinide waste thus associated with energy production seem to be a most attractive emerging option of nuclear power. While incinerating the most toxic long-lived actinide waste this concept can efficiently shorten the duration of related hazard. The fissioning of materials that could not be licensed in critical systems (i.e. transplutonics) makes this operation safe in subcritical assemblies, thus promising to achieve a closed fuel cycle. Moreover, that radical abatement of actinides i.e. of the main source of heat in the long range facilitates and reduces costs and scale of the waste disposal in geological repositories. This application of fusion is deeply pro-environmental, even though the hazard caused by the FDIs alone is higher than by pure fusion reactors, since the overall environmental load of the fission waste + FDI is effectively reduced [10]. Thus, the Fusion-Driven Incinerator concept - smaller and cheaper deserves consideration - also as an intermediate step towards the Pure Fusion.

Summarising, on the basis of the presented discussion and evaluations, one can state that the concept of fusion-driven subcritical systems for transmutations should approach deployment of fusion energy, as being just a technology that reduces environmental impact of present nuclear energy thus having a positive social undertone.

Acknowledgement

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