SEPTEMBER 1972

MATT-922

NEUTRON-PLASMA INTERACTION
IN FUSION REACTORS-EVALUATION
OF POSSIBILITIES
AND IMPLICATIONS

RECEIVED BY TIC. NOV 16 1972

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Neutron-Plasma Interaction in Fusion Reactors-Evaluation of Possibilities and Implications

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ABSTRACT

The possibilities for direct neutron - plasma interaction to have practical effects on the performance of fusion reactors are investigated. The implications such interactions, if occurred, will have on the plasma energy balance, particle balance, and fusion probability are studied. The dependence of neutron-plasma interaction probabilities on fusion reactor blanket composition, plasma composition, temperature, density, and radius is also investigated.

It is found that by incorporating Li^6 or He^3 in the plasma, one can increase significantly the neutron energy deposition as well as bring about tritium production in the plasma. The probability that the tritons thus produced will undergo a D-T reaction in the process of their slowing down is calculated. It is found that for the neutron-plasma interaction to have

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a practical contribution to fusion reactors, the allowable plasma pressure times radius will have to be increased by at least 10^4 relative to their presently conceived values.

A new scheme for fission-fusion reactor symbiosis is evaluated. The scheme consists of non-self-sustained (subcritical) fission and fusion reactors that become critical via the neutron-plasma direct interaction. It is concluded that unless present values of plasma pressure times radius are increased by at least 10^2 , the direct coupling between the fission and fusion reactors will be too weak to have any advantages.

1. INTRODUCTION

A significant part of the fusion energy generated in the fusion reactors conceived for the first generation is carried away from the plasma by the neutrons produced in the fusion reaction of the 17.6 MeV liberated in the D-T reaction, for example, the neutron carries 14.1 MeV. The neutron kinetic energy is converted into thermal energy in the blanket regions surrounding the plasma. The first phase in this conversion process involves the transfer of the neutron energy to kinetic energy of ions (and photons) as a result of a variety of neutron interactions. These neutron interactions in the blanket are also utilized for the generation of additional energy as well as for the production of tritium through neutron interactions with the lithium isotopes. The thermal energy generated in the blanket is converted to electrical energy (with efficiencies of the order of 40%). Some fraction of this electrical energy may be required for plasma ignition, heating, and fueling. The tritium produced in the blanket has to be recovered, reprocessed, and fed back into the plasma as fresh fuel.

Direct interaction of the fusion neutrons with the plasma ions could, if taken place, increase the fraction of the fusion energy available for heating the plasma. Moreover, if the plasma contains He^3 or if one deliberately adds Li^6 to the plasma the neutron-plasma interactions may result in the production of high energy tritons in the plasma. These reactions, if taken place, lead to in-plasma tritium production and energy (reaction Q value) deposition. Moreover, the tritons will be born in the

plasma with high initial energies and can undergo fusion in the process of their slowing down in the plasma.

In this work we consider the concept of a D-T fusion reactor the plasma of which contains He^3 or Li^6 . The questions we are concerned about include the following: 1) How do the neutron-plasma interaction probabilities depend on the fusion reactor design. 2) What implications neutron-plasma interactions, if they occur, may have on the plasma energy balance, particle balance, and fusion probability and, 3) Is it possible to couple, by neutron interactions, a subcritical (not self-sustaining) fusion reactor and a subcritical fission reactor to form a critical hybrid system. How do the safety and other properties of the hybrid system, if realized, compare with those of a fission reactor.

2. EFFECT OF BLANKET DESIGN AND PLASMA CONDITIONS ON NEUTRON-PLASMA INTERACTION

Conceptual designs of fusion reactors, either of open-ended or of closed configurations, have plasma densities between 10^{14} ions/cm³ and 10^{15} ion/cm³. Typical plasma radii proposed for these reactors are about 2 meters. The mean free path (mfp) for a collision of a 14.1 MeV neutron in homogeneous plasma of a density of 10^{14} cm⁻³ is of the order of 10^{10} cm. Hence the probability that a fusion-born neutron will interact with this plasma, before leaving it for the first time, is negligibly small. The overall neutron-plasma interaction probability is larger than the first flight interaction probability. This is so because neutrons leaving the plasma have a chance to return to it after undergoing

one, or several collisions in the blanket. In general, the larger the probability for neutron interaction with the plasma nuclei, and the smaller the neutron absorption probability of the blanket, the larger will be the overall neutron-plasma interaction probability. This later probability can also be increased by increasing the plasma density and size, and, for certain plasmas, also by decreasing the plasma ions temperature.

Figure 1 shows the Kerma Factors¹ (KF) for neutron interactions with several plasma, moderating, and structural isotopes. The KF is the average kinetic energy released per atom and per unit neutron fluence (flux-time) as a result of all kinds of neutron interactions. The KF of hydrogen gives an upper limit to the KF of deuterium and tritium. The KF of He^3 is similar to the KF of Li^6 ; it is lower by only about 10% of the Li^6 KF. (Except in the energy range around the 250 keV Li^6 resonance, where it is even lower.) Based on the KF data, the following observations are made:

- 1) In the energy range above 1 MeV, the KF of Li^6 , hydrogen, and moderating materials (Be,C) are comparable.
- 2) The Li^6 and He^3 KF are larger than KF of other isotopes considered over all the energy range below 1 MeV.
- 3) The ratio between the Li^6 and other KF increases with decreasing neutron energy. This ratio gets to 3 - 4 order of magnitude for 1 keV neutrons.
- 4) The KF of the structural materials (Fe,Nb) are the lowest of all KF considered.

The KF of Li^6 for thermal neutrons is larger than those of hydrogen isotopes, moderators, and structural materials by seven orders of magnitude and more.

The properties of a material on the balance of the neutrons interacting with it can be characterized by the net non-absorption probability (NNAP). The NNAP is defined as the average number of neutrons one finds after a collision of the original neutron with the material under consideration. Numerically it is evaluated from the expression,

$$\text{NNAP} = [\sigma_t - \sigma_a + \nu\sigma_f + \sigma_{n,2n} + 2\sigma_{n,3n}]/\sigma_t, \quad (1)$$

and is a function of the incident neutron energy.

Figure 2 shows the NNAP calculated for selected isotopes from the data of the CASDAR library.² U-238 is seen to have the largest (positive) contribution to the neutron balance for an interaction with a 14 MeV neutron. Following the U-238 are, in order of decreasing contribution, Pb, Be, Li^6 , Li^7 , Fe, and C. In the energy range below 1 MeV, the NNAP in most of the isotopes considered is about unity. Excluded are the U-238 and in particular Li^6 , having smaller NNAP. Based on the data of Fig. 2 it is expected that the total path length traversed by neutrons in the plasma, per original 14.1 MeV neutron, will be the largest with a Be blanket, and the smallest with a Li^6 containing blankets.

Three tritium producing reactions are considered:

and

The cross sections for these reactions are shown in Fig. 3. The He^3 cross section is somewhat larger than the Li^6 cross section (except in the resonance region), but the resulting triton energy is somewhat lower. The energy of the triton emerging from the first (exothermic) reaction is between 0.19 MeV and 3.71 MeV, corresponding to the neutron energy range from 0 (thermal) to 14.1 MeV. Similarly, the energies of the triton resulting from the Li^6 (exothermic) reaction is 2.7 MeV - 10.8 MeV. Li^7 has the highest probability for tritium production by interaction of a 14.1 MeV neutron, but the reaction (endothermic) has a threshold at about 2.5 MeV.

The data presented in Figs. 1 - 3 indicate that the probabilities for neutron energy deposition and tritium production in the plasma may vary several orders of magnitude, depending on the plasma conditions and blanket design. To find the overall probabilities one has to solve the complete neutron transport problem for the specific systems considered. Neutron interaction probabilities, mainly the energy deposition and tritium production, were estimated for several idealized plasma-blanket combinations based on the numerical solution of the Boltzmann equation for neutron transport. Details of the numerical scheme and data used are summarized in Appendix A. The idealized fusion reactors are represented by a central plasma region, two meters in radius, surrounded by a blanket region having an inner radius of 3 meters

and a thickness of one meter. The blanket is uniform and consists of a single isotope, unless otherwise stated. Fusion neutrons of 14.1 MeV are assumed to originate uniformly from the plasma region. Three types of plasma composition are considered: hydrogenous plasma, plasma containing He^3 , and plasma containing Li isotopes. The neutron-plasma interaction probabilities are studied as a function of five independent variables: blanket composition and geometry, plasma composition, plasma temperatures, plasma density (or pressure), and plasma size.

All cross sections employed for the numerical calculations were for room (sub-eV) temperatures. The results of calculations with these cross sections were corrected to take account of the plasma ion temperature.

For low density plasma ($n_i \lesssim 10^{15} \text{ cm}^{-3}$) in which the neutron interaction is negligible, the neutron plasma interaction can be characterized by two parameters: the blanket "Albedo" and the average Kerma factor. The "Albedo" is defined here as the total number of neutrons entering the region surrounded by the blanket per one 14.1 MeV neutron leaving the plasma. It is a function of the blanket only when the plasmas are of low density. The average KF is a function of both the blanket, through its effect on the neutron spectrum, and of the plasma constituents via its energy dependent KF.

Table I summarizes the Albedo of different materials in the blanket and the average KF for several plasma constituents surrounded by the various blankets. The proton represents the other hydrogenous isotopes (D and T). The total neutron energy

deposition in the plasma is proportional to the product of the Albedo times the average KF. This product, to be designated the Figure of Merit, is also given in Table I. Based on the data of Table I, the following observations are made:

1) The blanket composition has a pronounced effect on the Albedo. A Be blanket has the largest Albedo due to the high neutron multiplication ($n, 2n$), low neutron absorption probability, and relatively high neutron interaction probability of the Be. Li^6 has a very low Albedo, about 1/50 that of Be, due to its high absorption probability. U-238 Albedo is only about 1/4 that of Pb despite its high neutron multiplications. This is due to the large absorption probability of U-238 relative to Pb.

2) The average KF vary strongly with the plasma constituent and the blanket material. Li^6 and He^3 have, in general, larger average KF than H and Li^7 , as expected from the data of Fig. 1. The Li^6 KF is particularly large for the moderating blankets (Be and C) due to its high probability to capture low energy neutrons ($\sigma \propto 1/v$).

3) Be - Li^6 combination has the largest Figure of Merit - almost four orders of magnitude larger than the Figure of Merit of a fusion reactor consisting of hydrogenous plasma and Li-Nb blanket. The Figure of Merit for hydrogenous plasmas is almost independent of the blanket composition. The Li^7 Figure of Merit is very similar to that of H.

The plasma ion temperature influences the neutron-plasma interaction rates through its effect on the relative velocity between the neutrons and the plasma nuclei. The ion temperature

may thus strongly effect reactions, the cross section of which has pronounced energy dependence (below the plasma ion temperature). This is so provided the neutron flux has a significant component below the plasma ion average energy. This is found to be the case for a Li^6 or He^3 plasmas in the moderating, non-absorbing, blankets - Be and C. Tables II and III summarize the energy deposition and tritium production, respectively, in a Li^6 plasma at 10^{14} cm^{-3} in a variety of blankets for selected ion temperatures. A Be blanket with a Li^6 plasma is seen to provide for the highest energy deposition and tritium production. At the keV temperature range, however, the neutron plasma interaction probability is not very sensitive to the blanket and plasma compositions.

An increase in the plasma density (and/or volume) will cause an increase in the neutron-plasma interaction probabilities. At low enough plasma density the relation between reaction rates and plasma density is expected to be linear. Figure 4 shows the variation of the neutron energy deposition in Li^6 and H as a function of its density in a Be blanket. The dependence of tritium production in Li^6 on its density is shown in Fig. 5. Results are given for the Li^6 and H nuclei at two different temperatures: sub-eV (room temperature) and 5 keV. The results of Figs. 4 and 5 refer to plasma (gas) occupying a central region, 3 m in radius.

Figures 4 and 5 indicate the following:

- 1) The linear relationship between the energy deposition and tritium production in Li^6 holds up to Li^6 densities of about 10^{17} cm^{-3} .

2) The energy deposition in H increases linearly with plasma density, at least up to densities of 10^{20} cm^{-3} .

3) The effect of plasma temperature on Li^6 energy deposition and tritium production decreases as the Li^6 density increases.

4) As the temperature and density increase, the difference between the H and Li^6 energy deposition decreases.

At this stage it can already be concluded that in the range of plasma temperatures, densities, and sizes conceived today, neutron-plasma interactions cannot have any significant effect on the fusion-reactor characteristics, even with Li^6 or He^3 in the plasma. But this does not necessarily imply that neutron-plasma interactions cannot have a significant role in other concepts of fusion reactors. A reduction in the plasma temperature, for example, can bring about a significant increase in the neutron-plasma interaction by virtue of two phenomena. The increase in the average interaction cross section ($\sigma \propto 1/\sqrt{T_i}$), and the consequent possible increase in the plasma density ($n \propto 1/T_i$) for the same constraint of pressure. And even though the plasma reactivity decreases with decreasing temperatures, the energetic tritons, if produced by neutron interaction in the plasma, can contribute to the fusion probability.

Before turning to the evaluation of other concepts of fusion reactors, including the fission-fusion symbiosis, the question of fusion probability, while slowing down, of energetic tritons is considered.

3. FUSION PROBABILITY OF SLOWING DOWN IONS

The interactions of neutrons in the plasma can bring about an enhancement of the fusion probability beyond their direct effect on the energy and the tritium balance in the plasma. This is due to the nature of the neutron-plasma interaction in which the neutrons impart kinetic energy that may be as large as several MeV to single ions. The possible contribution of a high energy triton or deuteron to the fusion probability during the process of their slowing down was calculated parametrically with the variables being:

- 1) The ion initial energy.
- 2) Plasma ions average temperature.
- 3) Plasma electrons average temperature.
- 4) Plasma composition.

The calculations of the fusion probability (FP) were performed numerically for ions slowing down both in fully ionized plasmas (the computer program FUPSLOP) and in non-ionized matter (program FUPSLOG). Details of the numerical calculations and the data employed are summarized in Appendix B.

Figure 6 shows the FP of a triton slowing down in a deuterium plasma as a function of its initial energy, E_0 , and the plasma electron temperature, T_e . The plasma ion temperature, T_i , is assumed to be the same as T_e , and the slowing down (due to both the plasma electrons and ions) is followed down to an energy $E_\ell = (3/2) T_e$. The cross section for the D-T reaction was not averaged over the velocity distribution of the plasma ions, and

thus the results give a lower bound to the FP. Values of FP calculated by FUPSLOP agree well with the results of Dawson, Furth, and Tenney.³

The effects of electron temperature and plasma composition on the fusion probability of a slowing down triton are shown in Fig. 7. Also shown in Figs. 6 and 7 is the FP of a triton slowing down in a deuterium gas (non-ionized). Based on the data of Figs. 6 and 7 and on results from other calculations, it is observed that:

- 1) The FP increases considerably with the increase of T_e . For $T_e \leq 20$ keV, the fusion probability $FP \propto T_e^x$, with $x \approx 1.2$. With the neglect of the effect of the plasma ions on the slowing down, and with the neglect of the T_e dependence on $\ln \Lambda$, the expected value of x is 1.5.
- 2) With T_e kept constant, variation of T_i has only a little effect on FP.
- 3) The FP increases, in general, with the increase of E_0 . Above $E_0 \approx 2$ MeV, the increase of FP with E_0 is, however, very small. As a consequence, the probability that a 10 MeV triton, for example, will undergo fusion while slowing down in a $T_e = 10$ keV D plasma is 5.5% as compared to a total FP of about 47% due to 10 tritons starting each with $E_0 = 1$ MeV.
- 4) The FP in a D-Li⁶ plasma containing 50% Li⁶ ions is about 1/4 of the FP in a D only plasma, both at the same T_e . The FP in a D-T (1:1) plasma is 1/2 of its value in a D only plasma. In general, for a given T_e , the FP of a slowing down triton will be approximately proportional to n_D/n_e where n_D and n_e are, respectively, the density of the deuterons and electrons in the plasma.

5) The FP in an atomic (molecular) medium is larger than the FP in a plasma (of the same composition), the temperature of which is $T_e \leq 0.2$ keV.

Two conclusions of importance to the fusion reactor concepts investigated can be drawn based on the results presented:

1) Substantial values of FP ($> 10\%$) can be obtained for electron temperatures $T_e > 20$ keV. This is so regardless of the ion temperature.

2) The temperature range of $1 \text{ eV} \lesssim T_e \lesssim 100 \text{ eV}$ is of no interest for our consideration since

(a) No fusion takes place in the plasma at these (ion) temperatures and

(b) the FP of energetic triton (or D, He^3) in the non-ionized medium is larger.

4. NEUTRON-PLASMA INTERACTION IN FUSION REACTORS

The overall contribution of neutron-plasma interactions to the fusion probability under a variety of conditions and constraints is considered as a function of four independent variables:

Plasma composition

Plasma electron temperature, T_e

Plasma ion temperature, T_i

and

Plasma radius.

Based on these independent variables and the constraint on the maximum plasma pressure, p (or magnetic field intensity, B), the following characteristics of the fusion reactors are evaluated:

- 1) Plasma total ion density, n_i

$$n_i \propto p / \sum_l X^l (T_i^l + Z^l T_e^l) \quad , \quad (5)$$

where X^l is the fraction of ion specie, l , of the total ion density.

- 2) Total reactor D-T fusion power:

$$P \propto R^3 n_i^2 X_T X_D \langle \sigma v \rangle (T_i) \quad . \quad (6)$$

- 3) The energy flux of virgin 14.1 MeV neutrons through the inner surface of the blanket:

$$Q \propto P/R^2 \quad . \quad (7)$$

- 4) The Bremsstrahlung energy loss:

$$\text{Brem} \propto R^3 T_e^{1/2} n_i^2 \sum_l X^l (Z^l)^2 \sum_k X^k Z^k \quad . \quad (8)$$

These characteristics are evaluated relative to a reference reactor having a D-T plasma of total ion density $n_i^0 = 2 \times 10^{14} \text{ cm}^{-3}$. The plasma ion and electron average temperature is 20 keV, and its radius is 2 m.

Characteristics of neutron-plasma interaction are estimated for the plasma conditions defined above based on the results presented in Secs. 2 and 3. The results for the interaction probabilities refer to the B_e blanket concept.

Table IV lists the values of the independent variables for 10 of the cases considered. Table V summarizes the various characteristics evaluated for the 10 cases described in Table IV under the constraint of the same maximum pressure ($p/p^0 = 1.0$). The energy flux ("wall loading") ratio is equal to the power ratio ($Q/Q^0 = P/P^0$). The energy deposition in H is substituted

for the energy deposition in D and T, thus giving an upperbound (~ 10% for D and 30% for T). The energy deposition and tritium production in He^3 have been substituted by the corresponding values for Li^6 . In evaluating the FP values, the initial energy assumed for the tritons was 2 - 3 MeV. Based on the results in Table V, the following observations can be made:

- 1) The probability that the direct interaction of the neutrons with the plasma will lead to a fusion event is very small. The number of source neutrons required to bring about one fusion directly, is for all plasma cases considered in Table V, of the order of 10^8 .

- 2) The highest probability for fusion induced by a neutron-plasma interaction is obtained for a low temperature, high density non-ionized gas, case number 10. This probability is larger, by about four orders of magnitude, than of previous cases. The density assumed for case 10 corresponds to a gas at 3000°K and 100 atm (or $30,000^\circ\text{K}$ and 1000 atm). Going to even lower temperatures could increase the density further—as high as to the solid density at room temperature. This increase in density is not expected, however, to increase the fusion probability significantly.

- 3) As the temperature of the plasma decreases, the probability for neutron-induced fusion increases, but not significantly.

- 4) Lowering of the plasma ion and/or electron temperature brings about a pronounced decrease in the fusion power and an increase in the bremsstrahlung power radiation.

5) Replacement of some of the hydrogenous plasma by Li^6 or He^3 increases the total energy deposited by the neutrons in the plasma, but not substantially, as long as the plasma temperature is in the keV range. The ratio of bremsstrahlung power radiation to fusion power produced increases, on the other hand, significantly for the ratio of non-hydrogenous plasmas considered.

It is possible, in principle, to increase the contribution of neutron-plasma interaction for the plasma conditions described for cases 1 - 9 (Table IV) by increasing either the allowable pressure (B) and/or the plasma radius. The neutron-induced FP will increase, for cases 1 - 9, approximately linear with both the plasma pressure and radius. Hence, even two orders of magnitude increase in pressure times radius leaves the neutron-induced FP too low to be of practical significance.

Several of the concepts for fusion reactors involve plasma densities much higher than the $2 \times 10^{14} \text{ cm}^{-3}$ of the reference reactor considered for the above analysis. In these very high plasma density concepts, however, the plasma radius is very small. The radius associated with a 10^{19} cm^{-3} plasma is of the order of 1 cm. The neutron-induced FP in such a reactor being at a temperature of 20 keV is estimated to be of the order of 10^{-4} . Under the fictitious temperatures, $T_i \approx 1 \text{ eV}$, $T_e \approx 50 \text{ keV}$, this FP becomes of the order of 10^{-3} .

5. FISSION-FUSION SYMBIOSIS

A variety of fission-fusion symbiosis concepts have been proposed in the past.^{4,5} Included among them is the concept of

driving a subcritical fission reactor by a fusion reactor that may, or may not, be self-sustained. In the non-self-sustained fusion reactor concepts the fission system provides, indirectly, the energy required to drive the fusion system.

Another symbiosis concept is considered here: the symbiosis of fusion and fission reactor, each non-self-sustained by itself, but having an inherent coupling, to form a self-sustaining system. Thus, consider the fusion reactors dealt upon in Sec. 4 in which fissile isotopes have been added to the blanket to make it a high neutron (and energy) multiplier, but still subcritical. When the multiplication of the fission reactor will reach some threshold value, the fusion reactor will provide a constant source of fusion neutrons, thus making the system critical (self-sustaining). The aspects of such a symbiosis concept considered are the contribution of the fusion reactor to the total power produced and to the control and safety of the fission reactor.

Referring to data of Tables IV and V it is found that the minimum multiplication required from the subcritical fission reactor for this concept to work is about 2270. For such a multiplication, the reactor should have a negative reactivity of the order of 7 cents and 20 cents, respectively, for a U-235 or Pu-239 fuel. The safety aspects involved in the operation of a fission reactor so close to critical are similar to the ones encountered in an all fission reactor.

The effect of the fusion neutrons on the control of the fission reactor can be estimated by considering these neutrons as another group of delayed neutrons. The fraction of this delayed neutron

group is, in all cases of Table V, only a small fraction of the actual delayed neutron fraction. Since the mean time for the emission of the fusion neutrons is not expected to be considerably longer than that of the fission induced delayed neutrons, the contribution of the fusion-fission symbiosis to the system control is negligible.

Another possible concept for fission-fusion symbiosis is a reactor in which the fissile and fusile fuels are mixed together.⁵ This may be achieved, for example, in a gas-core reactor⁶ in which direct contact is conceivable between the various fuel isotopes, all of which being at a gaseous state (can be partially ionized). In such a reactor the contribution of the fusion reactions is expected to be bigger than in the fissile blanket concept for two reasons:

- 1) The probability for neutron-plasma interaction is larger, and
- 2) The fission products will transfer a part of their kinetic energy to the D and T nuclei present thus augmenting the fusion probability per fission event.

6. SUMMARY

The incorporation of Li^6 or He^3 in the plasma will result in the increase of the in-plasma neutron energy deposition as compared with hydrogenous plasma, as well as to tritium production in the plasma. The tritons produced in the exothermic neutron absorption reactions have high initial energies: over 2.7 MeV and 0.2 MeV from the Li^6 and He^3 reactions respectively. These high energy

tritons will slow down and heat the plasma, but in the process of their slowing down they can bring about a fusion reaction. This probability was calculated parametrically for tritons slowing down in both ionized and non-ionized D containing media. The probability for a direct D-T reaction from the slowing down of a 2 MeV triton in a D plasma, the electron temperature of which is 20 keV, is about 1%. The fusion probability varies as $T_e^{1.2}$ with the electron temperature, in the triton energy range $E_T > 1$ MeV. In this energy range it depends only weakly on the triton initial energy. Its dependence on the plasma composition is like n_D/n_e . The fusion probability in non-ionized (atomic or molecular) media is of the order of 10^{-4} to 10^{-3} . It is comparable to the fusion probability in ionized media of the same composition, the temperature of which is about 0.2 keV.

The total energy deposition and tritium production in the plasma was calculated for a variety of blanket-plasma compositions. The number of neutrons entering the plasma region per original fusion neutron, referred to as the Albedo, may vary by almost 2 orders of magnitude, depending on the blanket composition. Among the blanket materials considered (Li^6 , Li^7 , Be, C, Nb, Fe, Pb, and U^{238}) Li^6 has the lowest Albedo (0.5) and Be the highest Albedo (26). The largest neutron energy deposition in homogeneous plasmas is obtained for a Pb blanket. It depends, however, only weakly on the blanket composition, does not depend on plasma temperatures, and is very small: a fraction of an eV per fusion reaction in plasmas 2 m in radius and 10^{14} cm^{-3} in density.

In plasmas containing Li^6 or He^3 the neutron energy deposition can be significantly higher. It strongly depends on the blanket composition as well as on the plasma ion temperature. The largest energy deposition is calculated for a Be blanket. The neutron energy deposition in a Li^6 plasma in a Be blanket is larger than in an homogeneous plasma of the same density by over one order of magnitude when the ion temperature is of the order of 10 keV. As the ion temperature decreases, the energy deposition in the Li^6 increases (due to the energy dependence of the Li^6 absorption cross section). In the extreme case of room temperature, the energy deposition in Li^6 (He^3) is about 4 orders of magnitude larger than in D and T.

The neutron-plasma interaction in a reactor where the plasma has a radius of about 2 meters and a density of the order of 10^{14} cm^{-3} is found to be too small to be of practical importance, even under the most optimistic conditions. Thus, in a Be- Li^6 reactor the neutron energy deposition will be about 1 keV and the tritium production probability of the order of 10^{-4} even when the Li nuclei are at room temperature. The total neutron-plasma interaction probabilities increase with the plasma density. The dependence of the interaction probability on plasma density is found to be linear except for plasmas containing Li^6 (or He^3) of densities exceeding about 10^{17} cm^{-3} . Above these densities the increase in the Li^6 -neutron interaction probabilities become more moderate, as they approach saturation values.

Direct neutron-plasma interaction probability increases also with the increase of the plasma radius. The dependence of the interaction probability on the plasma radius is similar to its dependence on the plasma density.

The potential for augmenting direct neutron-plasma interaction by increasing plasma density and radius, and by decreasing plasma temperatures was investigated under the constraint of a constant plasma pressure. It is found that significant improvements in the neutron-plasma interaction probabilities are possible (6 orders of magnitude going from the keV to the sub-eV energy range). But at the same time, the other major reactor characteristics are strongly deteriorated. Thus, for example, the energy deposition in a D:T:Li⁶ (1:1:1) plasma at 1 keV is 0.15 keV relative to 1 eV energy deposition in a reference D:T (1:1) plasma at a temperature of 20 keV. At the 1 keV D:T:Li⁶ plasma, however, the fusion power density is 3 orders of magnitude lower, and the bremsstrahlung power loss is 2 orders of magnitude higher, as compared with the reference 20 keV homogeneous plasma. It is concluded that for the neutron plasma interaction rate to be of practical significance, at least a four order magnitude increase in plasma pressure times radius, relative to present fusion reactor conceptual designs, is necessary. In the extreme temperature range of sub-eV, energy deposition of 9.5 MeV and tritium production probability of 2.2 per original fusion neutron are obtainable. In this temperature range, however, no fusion reactions take place as a result of the thermal motion of the fusile nuclei.

The possibilities to combine a non-self-sustained fusion and fission reactors to form a self-sustained system was finally explored. It is found, however, that the neutron multiplication required from the fission reactor in this scheme of fusion-fission symbiosis is so high, that it offers no advantages relative to a conventional fission reactor. Moreover, the contribution of the fusion born neutrons to the neutron balance of the fission reactor is too small to have a significant effect on the control of the reactor.

ACKNOWLEDGMENTS

Mr. P. Bonanos and Dr. W. G. Price contributed to the establishment of the computer capability employed for the neutron transport calculations.

This work was supported in part by U. S. Atomic Energy Commission Contract AT(11-1)-3073; also use was made of computer facilities supported in part by National Science Foundation Grant NSF-GP579.

APPENDIX A. NEUTRONICS CALCULATIONAL METHOD

The numerical calculations of the neutronic characteristics of the fusion reactors were performed with the one-dimensional discrete-ordinate (S_n) code ANISN.⁷ Following is a summary of details about the calculational scheme:

1) The neutron energy range, 0 - 14 MeV, was divided into either 52 or 100 (for Pb and U-238) energy groups. The energy group structure and average group cross section data used were those of D. Steiner⁸ or DLC-2⁹ library, respectively.

2) The angular representation utilized was the $P_1 - S_4$ approximation.

3) The reactor was represented as an infinite cylinder. The blanket region extended from an inner radius of 3.00 m to an outer radius of 4.05 m. The blanket region was composed, in the majority of cases considered, of a single material having a uniform density. Several two-region blankets were also considered.

4) The boundary conditions used were a reflective B.C. at the reactor centerline and a vacuum B.C. at the outer boundary.

5) The spatial grid consisted of 5 cm intervals in the blanket region increasing gradually up to 50 cm in the plasma region.

6) The neutron source was assumed to consist of 14.1 MeV neutrons uniformly distributed in the central cylindrical region, 2.0 m in radius.

APPENDIX B. THE COMPUTER CODES FUPSLOP AND FUPSLOG

The computer code FUPSLOP was written to calculate the Fusion Probability of energetic ions while SLOWing down in a Plasma. The calculations are based on Sivukhin's formulation.¹⁰ Following is a summary of the equations solved by FUPSLOP. In its present form FUPSLOP is written to calculate the FP of a T ion in a D containing plasma, or of a D ion in a T containing plasma. The fusion probability, FP, of an energetic T ion starting with an initial energy E_0 and slowing down to energy E_L in a deuterium plasma is calculated from:

$$FP = \left(\frac{2}{m_o}\right)^{1/2} n_D \int_{E_L}^{E_0} dE \frac{\sqrt{E} \sigma(E)}{(dE/dt)(E)} \quad (B1)$$

where n_D is the density of the deuterium ions in the plasma, $\sigma(E)$ is the fusion cross section, and the index, o, refers to the slowing down ion. The energy loss rate is given¹⁰ by the expression:

$$\begin{aligned} \frac{dE}{dt}(E) = & \frac{4\pi e^4}{(2/m_o)^{1/2}} \frac{z_o^2}{(E)^{1/2}} \left\{ \sum_{\ell=1}^I z_\ell^2 \left(\frac{n_\ell}{m_\ell}\right) L_\ell \left[FI(X_\ell) - \left(1 + \frac{m_\ell}{m_o}\right) DFI(X_\ell) \right] \right. \\ & \left. + \frac{n_e}{m_e} L_e \left[FI(Y) - \left(1 + \frac{m_e}{m_o}\right) DFI(Y) \right] \right\} \end{aligned} \quad (B2)$$

with

$$m_e = \sum_{\ell} z_\ell n_\ell \quad (B3)$$

$$x_{\ell} \equiv \left(\frac{m_{\ell}}{m_0} \frac{E_0}{T_{\ell}} \right)^{1/2} \quad (B4)$$

$$y_{\ell} \equiv \left(\frac{m_e}{m_0} \frac{E_0}{T_e} \right)^{1/2} \quad (B5)$$

$$FI(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-\xi^2} d\xi \text{ is the error integral} \quad (B6)$$

$$DFI(x) = \frac{2}{\sqrt{\pi}} x e^{-x^2} \quad (B7)$$

ℓ designates the ion specie, and there are I species in the plasma. T_{ℓ} and T_e are, respectively, the plasma ion and electron average energy.

The logarithmic integrals, L_{ℓ} and L_e are calculated as follows:

$$L_{\ell} = \ln \left(\frac{3}{(8\pi)^{1/2} e^3 z_{\ell} z_0 (z_p)^{1/2}} \right) + \frac{3}{2} \ln T_{\ell} - \frac{1}{2} \ln n_p \quad (B8)$$

$$L_e = \ln \left(\frac{3}{(8\pi)^{1/2} e^3} \right) + \frac{3}{2} \ln T_e - \frac{1}{2} \ln n_e \quad (B9)$$

with

$$z_p \equiv n_e/n_p \quad (B10)$$

and

$$n_p \equiv \sum_{\ell=1}^I n_{\ell} \quad (B11)$$

In Eqs. (B8) and (B9), T is in units of eV and n in cm^{-3} .

For the value of the fusion cross section for the D-T reaction, the expressions of Kuo-Petravic, Petravic and Watson¹¹ was used.

The same cross section was used when the energy of the slowing down ion approached the average energy of the plasma ions. Using

this cross section rather than cross section averaged over the (relative) velocity distribution results, usually, in underprediction of the total fusion probability.

The integration of Eq. (B1) is performed numerically by Simpson's rule. Lethargy, defined as:

$$u = \ln (E/E_L) \quad , \quad (B12)$$

is used as the variable of integration. The lethargy intervals employed for the numerical integration for most problems are of the order of 0.1.

The computer code FUPSLOG is a modified version of FUPSLOP designed to calculate the fusion probability of a T (or D) ion slowing down in an non-ionized D (or T) containing medium. The rate of the ion energy loss while slowing down in the neutral medium is calculated from the expression:

$$\frac{dE}{dt} = v \sum_{\ell} n_{\ell} \epsilon_{\ell} (E) \quad (B13)$$

where v is the velocity of the slowing down ion, n_{ℓ} is the atomic density and ϵ_{ℓ} is the stopping cross section of the atoms of isotope ℓ in the medium.

Values of the stopping cross sections were taken from the graphs of ϵ vis E included in the review article by Whaling.¹²

REFERENCES

- ¹J. J. Ritts, M. Solomito, and D. Steiner, Oak Ridge National Laboratory Report ORNL-TM-2564 (1970); also Radiation Shielding Information Center, ed., RSIC Library Collection DLC-10; Oak Ridge National Laboratory Report ORNL-TM-2558 (1969).
- ²D. Jenkins (private communication).
- ³J. M. Dawson, H. P. Furth, and F. H. Tenney, Phys. Rev. Lett. 26, 19 (1971).
- ⁴L. M. Lidsky, Nuclear Fusion Reactors Conference, Proceedings (British Nuclear Energy Society, London, 1969), CLM-MFR, pp. 41-53.
- ⁵H. Jung, Nucl. Fusion 9, 169 (1969).
- ⁶J. D. Clement and Y. R. Williams, Reactor Technology 3, 226 (1970).
- ⁷W. W. Engle, Jr., Oak Ridge Gaseous Diffusion Plant Report K-1693, Oak Ridge National Laboratory (1967).
- ⁸D. Steiner (private communication).
- ⁹Radiation Shielding Information Center Data Library Collection DLC-2, Oak Ridge National Laboratory (1971).
- ¹⁰D. V. Sivukhin, Reviews of Plasma Physics, ed., M. A. Leontovich (Consultants Bureau, New York, 1966), Vol. 4, pp. 93-240.
- ¹¹L. G. Kuo-Petravic, M. Petravic, and C. J. H. Watson, Nuclear Fusion Reactor Conference Proceedings (British Nuclear Energy Society, London, 1969), CLM-MFR, pp. 144-172.
- ¹²W. Whaling, Handbuch der Physik (Springer-Verlag, Berlin, 1958) Bd. XXXIV, pp. 193-217.

TABLE I. Integral Parameters for a Variety of Blanket and Plasma Constituents.

Plasma Constituent	Blanket Material							
	Li ⁶	Li ⁷	Be	C	Fe	Nb	Pb	U-238
Albedo	0.5	3.2	26.6	9.0	5.2	3.6	27.7	6.0
Average Kerma ₂ (10 ¹³ erg/atom/n/cm ²)								
H	6.5	2.5	0.6	0.9	2.3	2.9	1.0	2.5
Li ⁶	6.6	80	2.2 x 10 ³	2.1 x 10 ³	18.6	8.1	1.3 x 10 ²	8.7
Li ⁷	5.8	1.9	0.6	1.0	1.2	1.6	0.4	
He ³						2.1	1.4 x 10 ²	2.2
Figure of Merit (arbitrary units)								
H	3.2	8.0	16.0	8.1	12.0	10.4	23.7	15.0
Li ⁶	3.3	256	5.8 x 10 ⁴	1.9 x 10 ⁴	96.5	29.2	3.1 x 10 ³	52.2
Li ⁷	2.9	6.1	16.0	9.0	6.2	5.8	9.5	
He ³						7.6	3.3 x 10 ³	13.2

TABLE II. Effect of Plasma Temperature on Total Energy released in Li^6 Plasma (eV/n).
Plasma at 10^{14} cm^{-3} .

Blanket Material	Plasma Temperature			
	0.025eV	1eV	0.1keV	5keV
Li^7	4.8	3.7	2.3	0.8
Be	9.5×10^2	2.5×10^2	38.3	6.5
C	3.3×10^2	85.2	13.1	2.3
Fe	1.7	1.7	1.4	0.8
Nb	0.5	0.5	0.5	0.5
Pb	50.5	37.9	14.7	4.8
U^{238}	0.9	0.9	0.9	0.9

TABLE III. Effect of Plasma Temperature on Tritium Production in Li^6 Plasma.
Plasma at 10^{14} cm^{-3} .

Blanket Material	Plasma Temperature			
	0.025eV	1eV	0.1keV	5keV
Li^7	1.0×10^{-6}	8.2×10^{-7}	3.7×10^{-7}	1.1×10^{-7}
Be	1.7×10^{-4}	5.8×10^{-5}	8.4×10^{-6}	1.4×10^{-6}
C	5.9×10^{-5}			
Fe	3.4×10^{-7}	3.4×10^{-7}	2.6×10^{-7}	1.5×10^{-7}
Nb	8.7×10^{-8}	8.7×10^{-8}	8.7×10^{-8}	8.7×10^{-8}
Pb	1.1×10^{-5}	8.6×10^{-6}	3.2×10^{-6}	9.9×10^{-7}
U^{238}	1.6×10^{-7}	1.6×10^{-7}	1.6×10^{-7}	1.6×10^{-7}

TABLE IV. Summary of Plasma Conditions for Fusion Reactors Studied.

Case No.	X_D	X_T	X_{Li}	X_{He}	T_i (keV)	T_e (keV)	Remarks
1	1/2	1/2			20	20	Reference
2	1/3	1/3	1/3		20	20	
3	1/3	1/3		1/3	20	20	
4	1/2	1/2			1	1	
5	1/3	1/3		1/3	1	1	
6	1/3	1/3		1/3	0.1	0.1	
7	1/2	1/2			1	20	
8	1/3	1/3		1/3	1	20	
9	1/3	1/3		1/3	$< 10^{-3}$	20	fictitious temperatures non-ionized
10	1/2		1/2		$< 10^{-3}$	$< 10^{-3}$	

TABLE V. Characteristics of Fusion Reactors.

Case No.	n_i (cm^{-3})	P/P^0	B_r/B_r^0	Energy Deposition (MeV)		Tritium Production (T)	F.P.	T x F.P.
				H	Li ⁶			
1	2×10^{16}	1.0	1.0	1×10^{-6}			5×10^{-2}	0
2	1.5×10^{14}	0.25	3.4	5×10^{-7}	1.8×10^{-6}	4×10^{-7}	2×10^{-2}	8×10^{-9}
3	1.7×10^{14}	0.33	2.0	5.7×10^{-7}	2×10^{-6}	4.6×10^{-7}	2.5×10^{-2}	1.2×10^{-8}
4	4×10^{15}	5.9×10^{-3}	89	2×10^{-5}			2.2×10^{-2}	0
5	3.4×10^{15}	1.9×10^{-3}	1.8×10^2	1.2×10^{-5}	1.5×10^{-4}	3.3×10^{-5}	1×10^{-3}	3.3×10^{-8}
6	3.4×10^{16}	4.7×10^{-17}	7.5×10^4	1.2×10^{-4}	4.3×10^{-3}	9.2×10^{-4}	7.5×10^{-5}	7×10^{-8}
7	4×10^{14}	5.9×10^{-5}	4	2×10^{-6}			5×10^{-2}	0
8	3.1×10^{14}	1.6×10^{-5}	6.4	1×10^{-6}	1.4×10^{-5}	3×10^{-6}	2×10^{-2}	6×10^{-8}
9	3.1×10^{14}	0	6.4	1×10^{-6}	1.0×10^{-3}	1.7×10^{-4}	2×10^{-2}	3.4×10^{-8}
10	2.7×10^{20}	0	0	1.35	9.5	2.2	2×10^{-4}	4.4×10^{-4}

724200

Fig. 1 Kinetic energy deposition of neutrons in a variety of isotopes.

724201

Fig. 2. Net non-absorption probability (NNAP) for a variety of isotopes.

724202

Fig. 3. Microscopic cross section for tritium production in Li^6 , Li^7 , and He^3 .

724206

Fig. 4. Effect of plasma density on energy deposition in Li^6 and H. Blanket is Be.

724205

Fig. 5. Effect of plasma density on Li^6 tritium production. Blanket is Be.

724204

Fig. 6. Fusion probability (FP) for energetic triton slowing down in a deuterium plasma, as a function of initial energy (E_0) and electron temperature (T_e).

724203

Fig. 7. Fusion probability (FP) of a 2.7 MeV triton slowing down in a D-Li and D-T plasma, as a function of electron temperature (T_e).

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