A Review of Neutronic Design Criteria

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A REVIEW OF NEUTRONIC
DESIGN CRITERIA

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Abstract

The neutronic design criteria for fusion reactors are reviewed. We found that some values for criteria are poorly fixed. For example, the tritium breeding ratio has often been set unrealistically high with no provisions for adjusting values. We also found that although energy production is the primary reason for a reactor's existence, little effort has been made to maximize it by blanket energy multiplication. Lastly, we suggest that further optimization studies could result in thinner shields.

Introduction

In a fusion reactor, the naturally occurring neutron and photon flux give results for a variety of responses that strongly affect the design of the reactor. As advances in physics and technology bring us closer to commercialization, we felt that a review of the neutronic design criteria was necessary to insure that essential or desirable characteristics had not been overlooked. It is not our intent here to look at data or material deficiencies, but to review the nuclear design criteria with respect to their effect on reactor design.

We begin with a short history of fusion reactor development from the standpoint of nuclear design. Next we define the basic functions of a blanket and shield. Then we discuss the design criteria related to these functions and their effect on reactor design.

Historical Perspective

Neutronic design criteria have been a necessary consideration beginning with the first conceptual fusion reactor. In 1951 Spitzer[1] recognized the need to breed tritium in the blanket. In 1958 Bell[2] et al. discussed various neutronic problems associated with blanket design and in 1961 Rose and Clark[3] generated a list of blanket and shield requirements that remain rather complete today. In the sixties neutronic studies were mainly parameter studies. In the seventies conceptual design studies began and the bulk of the neutronic work was associated with these designs.

This short history is not intended to be all inclusive of the neutronic work done in the last thirty years, but simply to reflect our impression of the trends in neutronic calculations. The literature survey was made in order to examine changes in the neutronic design criteria with the passage of time. Surprisingly, there has been little change, and this fact prompted us to examine them in more detail on the possibility that little change has been made because little additional thought had been given to them since their inception.

Blanket Functions

The basic functions of the blanket and shield are:

- To maintain vacuum integrity and aid structural stability
- Tritium production
- Thermal energy production
- Magnet, equipment and biological protection.

The neutronic design criteria are usually set prior to beginning a design, as goals to be reached to insure a viable design. The criteria are met by obtaining certain results in terms of the nuclear response functions. In the next few sections we shall review the design criteria with respect to their effect on the blanket functions.

Radiation Damage

The neutronic design criterion which impacts on the structural integrity of the blanket is:

- The blanket should be resistant to radiation damage.

Stress, temperature, and radiation damage, such as embrittlement and swelling, have direct deleterious effects on the mechanical properties of the blanket structural material. This affects the blanket's ability to remain structurally sound and free of breaks or cracks which could lead to loss of vacuum or coolant. It may become necessary then, because of radiation damage, to periodically replace blanket components, such as a first wall. The components' lifetime, if it is shorter than plant life, will have serious effects on the economics of the system.

Radiation damage in a blanket may be inferred from the neutron fluence and neutronic response functions; dpa, helium and hydrogen production, and transmutations. Thus, for a particular blanket design, the radiation damage expected may be determined and used in connection with other parameters to estimate the life expectancy of blanket components. Subsequent calculations can then be made to discover the economic ramifications of various components' life expectancy. There will be trade-offs in many areas between longer component life and economic advantage.

Thus, the neutronic design criterion that the blanket be radiation resistant is a statement concerned with the components' lifetime. Ideally, then, the component life should be maximized to the point of maximum economic advantage. In our literature review, we found that this point has been adequately considered.

Tritium

The second blanket function, that of producing tritium, has been considered from the earliest phases of fusion reactor development. In the past, the neutronic design criterion associated with this function has been:

- The tritium breeding ratio should be greater than or equal to one.

This requirement arises from the fact that in a large D-T energy economy, the quantities of tritium necessary to sustain a reactor could not economically be obtained.

Lithium in one chemical form or other has been the tritium breeding material. The nuclear response functions of importance then are the ^{6}Li(n,α)T and ^{7}Li$(n,n\alpha)$T reactions and the $(n,2n)$ and $(n,3n)$ reactions for neutron multiplication. Because of these reactions it is rather easy to design a blanket with a tritium breeding ratio greater than one. Tritium breeding ratios of 1.1 are typical design goals, although blankets with much higher values, for example UWMAK-I[4] with 1.49, are found in the literature. The fact that tritium breeding ratios have been set considerably higher than 1 is a result of valid concerns over data and calculational deficiencies, design errors, blanket penetrations and also perhaps expectations of a market for tritium.

However, considering that tritium breeding ratios of not much larger than one result in rather short doubling times, and that it is unlikely that new plants would purchase more than a few months supply, then it could be postulated that there would be no appreciable market for tritium, even in a growing fusion economy. Any extra tritium produced would become a burden, an environmental hazard, rather than an asset. In addition, tritium production, as discussed in the next section, is at the expense of power production.

Thus, we propose a modification to the design criterion that the tritium breeding ratio be greater or equal to 1. We propose that:

- The tritium breeding ratio should be _exactly_ one.

In connection with this proposal, we suggest that equipment be added to the plant for on line changes to the tritium production. Neutron absorbing rods or changes in ^{6}Li enrichment come to mind as possible methods. The possibility of changing the production rate would provide means to cover data and design deficiencies. It is also felt that the extra energy produced in going from (for example) a tritium breeding ratio of 1.1 to 1 would more than pay for the extra equipment required. This, of course, would require an economic analysis for verification.

Energy Production

The third blanket and shield function is that it serves as a thermal energy source. The neutronic design criterion associated with this function is:

- The blanket must convert the kinetic energy of the fusion neutron into heat.

This design criterion is dictated by the fact that energy production is the goal of fusion power. The related nuclear response functions would be the gamma and particle production and scattering reactions. These responses may be used to develop KERMA factors which in turn are used to calculate energy deposition, both from neutron and gamma fluxes.

Since energy is the final product, considerable economic advantage may be obtained through energy multiplication in the blanket, which is possible because many of the nuclear responses are exothermic. The relationship between the total dollar value of the power produced and the blanket energy multiplication is linear as noted in Figure 1. The economic advantage of even small changes in multiplication is immediately obvious. This suggests an addendum to the criterion under discussion, namely

- The blanket energy multiplication should be as high as possible.

There are, of course, constraints. Hybrids have high energy multiplication; however, they may be unacceptable because of political concerns. However, even within certain constraints, there are material choices to be made which enhance energy production. In addition lowering the tritium breeding ratio to 1, as discussed in the last section, also increases energy production. A neutron absorbed in ^{6}Li releases ~ 4.8 MeV, yet if it is absorbed in the structure about 7 MeV is released. The net results are not trivial. In the WITAMIR-I[5] conceptual design, a change in the tritium breeding ratio from 1.1 to 1 would result in approximately 287 million dollars of additional income at constant dollars over a 30 year life.

Flux Attenuation

The fourth function, that the blanket and shield provide magnet, equipment and biological protection, may be expressed in terms of a neutronic design criterion as:

- The blanket and shield must attenuate the flux to a point where radiation damage and energy deposition in the magnets and equipment and the environmental hazards are within design limits.

The magnets are large and costly. Thus, maintaining their integrity is of primary importance in design of a fusion reactor. Radiation damage increases the stabilizer resistance and after reaching a design limit, the reactor would be shut down to anneal the magnets. The amount of damage may be inferred from the number of displacements per atom, a neutronic response readily obtained from neutronic calculations. Should annealing be required too often, there would be a serious negative impact on the economics of the system.

The radiation leakage from the outboard wall could also result in the failure of the magnets' thermal and electrical insulation, should the dose exceed certain limits. The refrigeration load may be affected if the energy deposition is too high.

Radiation leakage results in air and equipment activation. This impacts on building access, maintenance abilities, and biological shield thickness. Such factors affect not only the environmental and safety, but have direct effect on the cost.

Increasing shield thickness reduces the radiation leakage, but also increases cost.[6] Optimization studies have been made in the past[7,8] both on shield composition and thickness. As a continuation of these studies, we feel that further optimization of shield thickness might be possible by spectral tailoring through careful material selection, as was suggested in previous work.[9] Such studies could have considerable economic impact on a design.

Conclusion

In our paper we have reviewed the neutronic design criteria for fusion reactor blankets. We found that more attention should be given to maximizing energy multiplication and minimizing shield thickness. We also feel that the design criterion for tritium breeding ratios has been set unrealistically high in the past. We suggest setting the criterion and designing to a value of 1, with provisions for adjusting the value if necessary.

Acknowledgement

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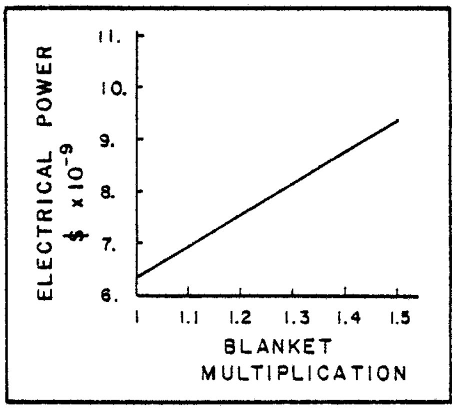

Figure 1 Value of Power Generated Over a Thirty Year Life. Power is Valued at 3¢ a Kilowatt-Hour. Basis is a 2500 MW_t (1000 MW_e) Blanket With a Plant Capacity Factor of 80%.