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FUSION TECHNOLOGY INSTITUTE

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NEW CONCEPTS FOR CONTROLLED FUSION REACTOR BLANKET DESIGN

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Abstract

Several new concepts for fusion reactor blanket design are presented based on the idea of shifting, or tailoring, the neutron spectrum incident on the first structural wall. The spectral shifter is a non-structural element which can be made of graphite, silicon carbide, or three dimensionally woven carbon fibers (and containing other materials as appropriate) placed between the neutron source and the first structural wall. The softened neutron spectrum incident on the structural components leads to lower gas production and atom diaplacement rates than in more standard fusion blanket designs. In turn, this results in longer anticipated lifetimes for the structural materials and can significantly reduce radioactivity and afterheat levels. In addition, the neutron spectrum in the first structural wall can be made to approach the flux shape in fast breeder reactors. Such spectral softening means that existing radiation facilities may be more profitably used to provide relevant materials radiation damage data for the structural materials in these fusion blanket designs. This general class of blanket concepts are referred to as Internal Spectral Shifter and Energy Converter, or ISSEC concepts. Specific design concepts have been presented which fall into three main categories: ISSEC/EB concepts based on utilizing existing designs which breed tritium behind the first structural wall: ISSEC/IB concepts based on breeding tritium inside the first vacuum wall; and ISSEC/Bu concepts based on using boron, carbon and, perhaps, beryllium to obtain an energy multiplier and converter design that does not attempt to breed tritium or utilize lithium. The detailed analyses presented here relates specifically to the nuclear performance of ISSEC systems and to a discussion of materials radiation damage problems in the structural material. There are a number of questions regarding these concepts which require further research and these are discussed.

I. Introduction

Several recent studies on technological problems of fusion reactors have concluded that the energy extraction component, or fusion blanket, will not retain its structural integrity for the complete expected plant life.[1,2,3] Rather, the vacuum chamber or first wall will have to be periodically removed and replaced due to radiation induced embrittlement and swelling. In particular, for 316 stainless steel, it has been concluded[4] that the first wall life in a deuterium-tritium fueled fusion system is nominally two years for a 14.1 MeV neutron wall loading of 1 MW/m^2. Any first wall subject to such an incident neutron flux will show high atom displacement rates and high gas production rates simultaneously.[5] In addition, recent studies of specific systems[6-8] as well as a comparative study[9] of several proposed blanket designs all have shown induced radioactivity levels on the order of 10^6 Ci/MW(th) and afterheat levels of about one percent of the thermal operating power at shutdown. These results pose difficult problems regarding reactor maintenance, materials availability, relatively long term solid radioactive waste disposal, and general environmental impact questions.

In essence, the cause of these problems is the highly energetic, 14.1 MeV neutrons resulting from the D-T fusion reaction. Specific structural materials have been proposed to minimize certain of these problems but no one material minimizes them all. Indeed, most problems still remain. For example, SAP[10] (sintered aluminum product) and vanadium[11] have been proposed as structural materials for fusion systems to alleviate the problem of long lived radioactive waste. These materials nevertheless are still subject to high atom displacement and helium production rates and can have other disadvantages due to temperature and stress limitations or to coolant-structure compatibility problems. Silicon carbide and carbon have also been proposed[12] as structural materials in fusion blankets both to minimize induced radioactivity and to minimize plasma impurity problems. However, there are major problems associated with the design, fabrication, and operation of large components made from such nonductile materials.[12]

In this paper, several new concepts for fusion reactor blanket design are presented based on the idea of shifting, or tailoring, the neutron spectrum incident on the first structural wall.[13] The spectral shifter is a non-structural element which can be made of graphite or silicon carbide, as described above, or it can be made of three dimensionally woven carbon fiber.[14] It would be placed between the neutron source and the first structural wall and may contain other materials as appropriate. The softened neutron spectrum incident on the structural components leads to lower gas production and atom displacement rates than in more standard fusion blanket designs. In turn, this results in longer anticipated lifetimes for the structural materials and can significantly reduce radioactivity and afterheat levels. In addition, the neutron spectrum in the first structural wall can be made to approach the flux shape in fast breeder reactors. Such spectral softening means that existing radiation facilities may be more profitably used to provide relevant materials radiation damage data for the structural materials in these fusion blanket designs. For ease of reference, we shall refer to this general class of blanket concepts as Internal Spectral Shifter and Energy Converter, or ISSEC, concepts.

A detailed analysis of the nuclear performance of ISSEC systems will be presented here along with a discussion of materials radiation damage problems insofar as they pertain to the structural material. As conceived, the spectral shifter component will not be actively cooled but will radiate the heat deposited in it to the first structural wall. The shifter may, however, be attached to the structural wall via heat pipes to attain effective thermal contact. A detailed analysis of both the radiation damage and the heat transfer in such systems will be discussed in future publications.[(15),(16)]

An additional potential benefit of the ISSEC concepts in tokamak or stellarator fusion systems is that wall originated impurities will be low Z. This can have an important impact on plasma performance, as discussed previously,[(12),(17)] but no feasible method for achieving the desired result has been available. Recently, however, we discussed[(18)] the use of flexible, two dimensionally woven carbon cloths attached to the first vacuum wall to protect the plasma from high Z impurities and protect the first wall from erosion by charged particles and neutral atom bombardment. A discussion of the impact on plasma behavior is contained in that paper.[(18)] These same benefits would accrue with the use of the ISSEC concepts. Note, however, that we do not limit the ISSEC concepts to a particular confinement approach. Indeed, this approach may be quite applicable to several fusion systems, including laser fusion, because of the good high temperature and thermal shock properties of the carbon, particularly in the form of the 3-D weave.

In section II, a detailed description of four basic ISSEC concepts is presented along with details describing the calculational procedures and nuclear data employed. This is followed in section III with the basic results and a discussion of the neutronics analysis. We also present several reaction rates of importance for materials analysis and discuss the implications of the results. Finally, section IV contains a summary and a discussion of remaining questions.

II. Description of ISSEC Concepts

a. Review of Three Dimensional Carbon and Graphite Weaves

One method for constructing a spectral shaper is to use three dimensionally woven carbon or graphite fibers. Since the main properties of bulk graphite and silicon carbide have been reviewed recently,[12] we briefly review here the main properties of these fibrous materials.

Fibrous carbon and graphite[19] is prepared by the controlled thermal conversion of organic fibers to residual carbonaceous material. The carbon fibers are produced by pyrolysis at relatively low temperatures (less than 1000°C) while graphite elements receive an additional step in which the temperature is raised to 2000°C or more. Typically, the carbon or graphite filaments are 6 to 10 μm in diameter and can be wound into bundles consisting of 700 to 1000 continuous filaments per bundle. These bundles, or tows, can be used as is, or can be twisted to form a twisted thread. In this way, yarns of any basic diameter can be formed.

With such carbon yarns, most of the basic textile techniques can be applied to produce both two and three dimensionally woven carbon materials.[20] The two dimensional weave will form a cloth while the three dimensional weaves can be used to form material of any desired thickness. A scanning electron micrograph of such a weave is shown in fig. 1. In this paper, we refer particularly to the use of the three dimensional weave in thicknesses up to 50 cm.

An advantage of carbon and graphite in fibrous form is its flexibility and strength.[19] Both the structure and the small diameter of the individual filaments contribute to the pliant quality of these materials, in contrast to the characteristic brittleness of more standard forms of graphite.[21] Fig. 2 shows schematic diagrams of two different three dimensional weaving patterns. The effective density of such woven systems is typically about 50% of the actual density of the fibers themselves. Further details on these materials are summarized elsewhere,[19,20,22] as are properties such as strength and stiffness, thermal conductivity, vapor pressure, and so on. In general, the type of yarn and weave geometry can be varied over a relatively wide range. In addition, fibrous materials other than graphite may be woven into the forms to further change the properties. Within limits, the material can be tailored to fit a wide range of requirements.

b. ISSEC Blanket Designs

The concept of a neutron spectral shifter can be utilized in at least three specific ways and three separate classes of blanket designs have been considered to illustrate this. In particular, one can utilize the ISSEC concepts either with existing blanket designs or with systems designed to take particular advantage of specific properties of the ISSEC concepts themselves. We consider each of these in turn.

Table 1 summarizes the design of four blanket systems in which the first structural wall and the blanket behind it are cooled with liquid lithium. System 1A is used as a reference for this type of system and is modeled after previous blanket designs[1,23,24] which utilizes liquid lithium as the coolant, moderator, and tritium breeding material. Systems 1B and 1C will be used to study the effect of placing different thicknesses of three dimensionally woven carbon elements in front of the first structural wall. Clearly, the neutron moderating properties of carbon suggests the use of lithium enriched in ^{6}Li to maximize the potential breeding ratio. Nevertheless, as we will show, such systems will not breed although conversion ratios can be close to one. However, the radiation damage and induced radioactivity in the first structural wall is greatly reduced. Case 1D has been included to show how tritium breeding can be produced with the ISSEC concept and a lithium cooled external blanket. (By external blanket, we shall mean the region of the blanket outside the first wall.) The internal blanket referred to in tables 1 through 4 is the blanket region between the plasma and the first structural wall. We have used a density factor of 1.0 in the internal blanket and a graphite density of 1.6 gm/cm^3. However, from a neutronics standpoint, these models are equivalent to three dimensional weaves of twice the thickness at a density factor of 0.5. We note again that these internal zones are not structural components and are not necessarily actively cooled. However, they may be supported from the first structural wall in such a way as to make effective thermal contact.(16) We have used vanadium as the structural material in all model blanket designs discussed here although the basic features could be illustrated with almost any other structural material and alloy.

Table 2 summarizes three blanket designs used to illustrate the use of ISSEC concepts with external blankets that use solid breeding materials, such as LiAl or $LiAlO_2$, and high pressure helium cooling. Examples of such systems include the SAP designs of Powell et al.,(10) the Incoloy design of Sato et al.,(25) and the 316 stainless steel design, UWMAK-II, of the Wisconsin group.(26) Case 2B and 2C are used to study the dependence of the breeding ratio on the amount of beryllium (in the form of Be_2C) in the internal spectral shifter. The 2 cm first structural wall has a density factor of 0.5 to account for direct cooling in that zone.

We summarize in Table 3 ISSEC blanket designs which illustrate the potential for both neutron spectral shifting and tritium breeding internal to the first structural wall. Such an approach has an advantage in that all tritium will be handled by a single gas control system already provided to handle gases in the vacuum chamber. This would remove tritium from contact with the primary coolant system and thus eliminate the main potential path for tritium release from proposed fusion power reactors.(1)

Finally, systems 4A to 4D summarized in table 4 illustrate fusion burner blanket concepts designed for energy conversion without tritium breeding. Such systems may be used with D-T fueled reactors if minimizing tritium inventory and associated environmental hazards is an overiding consideration. Relatively near term experimental power reactors are prime candidates for such blanket designs. Of course, such blankets could also be used for fusion reactors based on other fuel cycles, such as D-D, which do not require fuel breeding. In these cases, the external blanket is designed as a helium cooled system which utilizes graphite and boron carbide in a form used in high temperature gas cooled (HTGR) reactor systems.(27) The presence of boron in a system affects the neutron spectrum and is radioactivity induced by thermal neutron reactions. The beryllium carbide and carbon zone in design 4D multiplies the incident neutrons and tends to maximize energy production in such ISSEC burners.

In various cases, carbon and other materials are included in the internal blanket systems. This may be achieved in several ways. One can form particles of the appropriate materials, such as Be_2C or $LiAlO_2$, coated with pyrolytic carbon layers as is done with nuclear fuels.(28) These particles could then be embedded in graphite or three-dimensional carbon weaves to achieve the desired material composition. If the pellets contain lithium, the tritium would be allowed to diffuse into the plasma vacuum chamber. It may also be feasible to coat fibers of the desired material with carbon.(29) These details will be addressed in two future publications.(15),(16)

In summary, systems 1B-1D and 2B-2C will be used to illustrate ISSEC concepts in conjunction with existing fusion reactor blanket designs. Systems 3B-3C demonstrate ISSEC concepts with internal breeding and systems 4B-4D illustrate ISSEC burner concepts. Models 1A, 2A, 3A, and 4A are reference systems with which the performance of the other systems will be compared.

c. Calculational Methods

The nuclear performance of the fusion blanket designs outlined in Tables 1 to 4 have been studied by solving the discrete ordinates[30] form of the transport equation for the neutron and gamma fluxes using the ANISN program[31] in the S_4-P_3 approximation and using slab geometry. As noted by Dudziak,[32] S_4-P_3 calculations are adequate to predict integral parameters, such as tritium breeding and gas production rates, to within approximately 2% of a high order calculation like S_{16}-P_5. An albedo of 0.3 in all groups has been used at the back of all blankets and no shield has been included. The neutron and gamma multigroup cross sections were processed using the programs SUPERTOG[33] and MUG[34] from nuclear data compiled in ENDF/B3.[35] The photon production cross sections were processed from ENDF/B3 with the program, LAPHANGAS,[36] except for ^{6}Li, ^{7}Li, and C, for which the photon cross sections are from reference (37). All calculations were performed using 46 neutron groups and 43 gamma groups in a group structure discussed in detail previously.[1,38]

III. Nuclear Performance of ISSEC Systems

a. ISSEC with External Breeding (ISSEC/EB)

The fundamental impact of the ISSEC concepts can be demonstrated most readily by first analysing the nuclear performance of somewhat more standard fusion reactor blanket designs modified to include a neutron spectral shaper placed between the plasma and the first structural wall. The systems outlined in table 1 are examples in which the external breeding blanket is cooled with liquid lithium and the structural material is vanadium. The neutron spectrum in this first structural wall (zone 3 in table 1) is shown in fig. 3 for the reference case, for model 1B with a 12.5 cm carbon spectral shaper, and for model 1C with a 25 cm carbon spectral shaper. The impact of the internal blanket zone is clear. For both cases 1B and 1C, the 14 MeV flux is reduced by more than an order of magnitude compared to the reference, model 1A, while the thermal flux has increased significantly. This shift in the neutron spectrum reduces displacement damage rates, gas production rates, and long term radioactivity in the vanadium first structural wall. These reductions are shown in fig. 4 and summarized in table 5. A 12.5 cm carbon shaper leads to about a factor of 7 reduction in the H and He production rates and about a factor of 3.5 reduction in the displacement damage rates in the first wall (zone 3). A 25 cm carbon shaper produces about a factor of 15 reduction in H and He production rates while the dpa rate in the vanadium is reduced by an order of magnitude. Since the first wall lifetime tends to vary inversely with these response rates, (particularly the dpa and helium production rates) one can expect extended structural wall lifetimes as compared with previous approaches. Note that if the spectral shaper is made of three dimensional woven carbon fibers, these neutronics results still apply. For a density factor of 0.5, model 1B corresponds to a 25 cm spectral shaper while model 1C would be a 50 cm internal blanket.

Of course, the softening of the neutron spectrum by the carbon leads to a reduction in the breeding ratio, even though the lithium is enriched to 90% ^{6}Li. As suggested earlier, this may be remedied by including beryllium as a neutron multiplier in the spectral shaper. For example, the use of beryllium carbide pellets coated with pyrolytic carbon and embedded in the 3-D carbon weave is one possible approach. Model 1D has been analysed to illustrate such a blanket design. The spectral shaper zone is assumed to be composed of 50% Be_2C and 50% C, at one half of actual density to model carbon coated pellets embedded in a weave system. As indicated in table 5 and on fig. 4, the breeding ratio is above 1 in this case, and the energy per fusion is also substantially increased. Both these quantities can be increased even further by increasing the thickness of the lithium breeding zone in the external blanket. For example, in model 1A, an increase in zone 4 from 30cm to 50cm increases the breeding ratio from 1.29 to about 1.45.

It is interesting to compare the nuclear performance of cases 1B and 1D since they both include a 12.5 cm internal blanket using a density factor of 1.0. As seen in table 5, both the He production rate and the dpa rate are lower when Be_2C is used together with carbon. The reason is that the Be_2C slows down neutrons more effectively than pure C particularly via the (n,2n) reaction, so that the flux above 1 MeV in the first wall is lower in model 1D than in model 1B. This is a general result and is found to hold in all cases discussed in this paper.

The inclusion of a spectral shaper in these ISSEC/EB systems can also be viewed as making the neutron spectrum more similar to that in fission reactors, particularly fast breeder systems. This is illustrated in fig. 5 where the percentage of dpa's produced by neutrons of energy $E_n > E$ is plotted versus E for various thicknesses of carbon internal blankets and for EBR-II. Clearly, as the thickness of the spectral shaper is increased, the ISSEC system curves approach that for EBR-II. For example, 60 percent of the displacement damage in an unprotected vanadium first wall is produced by 14 MeV neutrons. By contrasts, 5 cm of carbon in front of this wall drops this number to 40% and a 30 cm carbon internal blanket reduces the displacement damage by 14 MeV neutrons to 10% of the total. This is particularly relevant for microstructural defects which are sensitive to the size of the displacement spike caused by 14 MeV neutrons. The net result is that damage information obtained from such fast reactor facilities becomes more meaningful for fusion systems with carbon spectral shapers.

An important characteristic of all fusion reactors will be the amount of induced radioactivity and afterheat that is generated. This is typically very small in carbon[(12)] but quite substantial in metallic structural materials.[(6-9)] We have summarized in table 6 the radioactivity in the vanadium first wall of all the models examined in this paper. The radioactivity is tabulated by considering only the main contributing isotopes (namely, $^{48}Sc(t_{1/2}= 1.82d)$, $^{51}Ti(t_{1/2}= 5.76m)$, and $^{52}V(t_{1/2}= 3.75m)$) at shutdown and at one week after shutdown. For models 1B, 1C, and 1D, there is a substantial reduction in the ^{48}Sc and ^{51}Ti activity compared to case 1A and this leads to reduction by a factor of 10 or more in the long term radioactivity (greater than 1 week). The reason is that both the 48 Sc and ^{51}Ti activities are both produced by high energy neutrons, which are moderated by a spectral shaper. On the other hand, the ^{52}V activity, which is induced by an (n,γ) reaction, is increased sharply in cases 1B, 1C, and 1D because of the increase in the number of slow neutrons. These specific results illustrate the general affects that can be expected regardless of the structural material.

Another important characteristic of the concepts analysed here is the space dependent heating rate in the spectral shaping zones. A detailed heat transfer analysis of these ISSEC systems will be given in another paper,[16] and we show in fig. 6 the heating rates in the spectral shaper of models 1B, 1C, and 1D. The key temperature that will ultimately determine the maximum thickness of any particular ISSEC internal blanket is the temperature at which the vapor pressure of carbon becomes comparable with the background pressure in the plasma chamber. For a typical pressure of 10^{-5} torr, this temperature is approximately 2000°C for carbon.[39] There are, however, a number of design alternatives which can affect the allowable maximum thichness,[16] such as the use of heat pipes to make effective thermal contact between the internal blanket and the first structural wall.

Helium cooled external blankets form an important complementary class of blanket designs to the liquid lithium cooled systems we have just discussed. Several such designs have been studied previously and are based on using high pressure gas cooling, typically helium, together with solid breeding compounds.[10],[26],[27] Model 2A outlined in table 2 is an example of such a system[27] and it includes pure Be for neutron multiplication and lithium aluminate ($LiAlO_2$) as the solid breeding compound.[40] This model will be used as a reference.

The use of carbon internal blankets between the plasma and the first wall will produce effects quite similar to those just discussed for the ISSEC/EB systems with liquid lithium cooling. Therefore, we report here only calculations made to determine the amount of Be_2C required to achieve breeding. The spectral shaper thickness has been taken as 12.5 cm since this system produces about an order of magnitude improvement in gas production rates and long term radioactivity, about a factor of 5 reduction in dpa rates, and appears to be reasonable from the point of view of temperature limitations.[(41),(16)] Actual results are indicated in table 7 which summarizes the nuclear performance of designs 2A, 2B, 2C. In fig. 7, the breeding ratio is shown as a function of the fraction of Be_2C in the spectral shaper. It appears that about 85% of the shaper must be Be_2C to obtain a breeding ratio greater than one with such an external blanket design. This is in contrast with the results for model 1D where 50% Be_2C is adequate to achieve breeding. Of course, the reason is the relatively low Li atom density in the breeding zones when $LiAlO_2$ is the breeding material. Other materials, such as LiAl or Li_2O, while having different, non-nuclear, restrictions,[(10),(42)] would yield higher Li atom densities and thus somewhat higher breeding ratios.

The effect of the spectral shaper on the radioactivity in the vanadium of the series 2 models is shown in table 6. The results are quite similar to those found for models 1A-1D and the explanation of the results is the same.

b. <u>ISSEC with Internal Breeding (ISSEC/IB)</u>

A logical extension of the ideas in section III.a. are blanket systems in which both neutron spectral shifting and tritium breeding are carried out in a region between the plasma and the first structural wall. Two examples of such conceptual systems are models 3B and 3C in table 3. Model 3A will be taken as the reference system for comparative purposes.

The advantages of such ISSEC/IB designs is that the reduction in radiation damage indicators will still occur but, in addition, the lithium bearing zone will filter thermal neutrons before they reach the first wall. Another feature of this concept is that it can allow all tritium in the system to be handled by a single gas control system already provided for the vacuum chamber. As indicated earlier, this would remove tritium from contact with the primary coolant and thereby eliminate the main flow path for potential tritium release.[1] A difficulty with such designs is that there will be high heat deposition rates in the internal blanket, particularly in the breeding zones. This will limit the practical thickness of such systems but a detailed heat transfer analysis is required to establish a maximum thichness accurately. We will present space dependent heating rates to illustrate the nature of the problems.

Since the tritium breeding and most of the heat deposition occur on the vacuum side of the first structural wall, the external blanket can be flexibly designed with various coolant-material combinations. For illustrative purposes, we have considered a helium cooled, solid graphite system as the external blanket, much like the structures employed in high temperature gas cooled (HTGR) reactors.[27],[12]

The solid breeder material in the ISSEC/IB designs is illustrated by the use of $LiAlO_2$. The basic properties of this material and its potential use in fusion reactors has recently been discussed.[40] Lithium aluminate (using Li enriched to 90% ^6Li) has good high temperature properties but at the temperatures expected in the internal blanket (~2000°C), its vapor pressure is quite high. It would therefore be coated with a material having acceptably low vapor pressure as well as reasonable permeation properties for tritium. Pyrolytic carbon is acceptable for this role at temperatures in the 1500-2000°C range. For this reason, and because such composites could be in the form of pellets embedded in graphite or a 3-D carbon weave, as described earlier, the composition of zone 2 in models 3B and 3C is taken as a 50-50 mixture of $LiAlO_2$ and carbon.

The nuclear performance of models 3A, 3B, and 3C is summarized in table 8. Again, the hydrogen and helium production rates in the vanadium first wall have been decreased by an order of magnitude and the dpa rate has decreased by a factor of five. From an interpolation of the breeding ratio between models 3B and 3C, it appears that the ratio of Be_2C to total Be_2C plus C content in the first 20cm of the internal blanket must be approximately 0.65 to achieve a breeding ratio of 1.0. Note, however, that this is very much dependent on both the thickness of zones 1 and 2 in models 3B and 3C and the lithium bearing compound. As stated earlier, compounds with higher Li atom density, such as Li_2O, would yield higher breeding ratios for the same thickness of the tritium breeding zone.

The induced radioactivity in the vanadium is given in table 6 and one can see that the presence of the breeding zone has significantly reduced the ^{52}V activity at shutdown compared with either cases 1B to 1D or 2B and 2C. The reason is that the ^{6}Li removes the thermal component of the neutron flux incident on the vanadium wall, as shown in fig. 8. The neutron intensity in the vanadium wall of model 3B is lowered significantly at both high and low energy compared to reference designs 1A, 2A, or 3A. Therefore, an ISSEC/IB model decreases radiation damage and radioactivity problems resulting from both high energy neutrons (greater than 1 MeV) and from thermal neutrons.

The nuclear heating in an ISSEC/IB design is higher than in cases where only neutron spectral tailoring is desired because of the energy release caused by neutrons captured in ^{6}Li. This is seen clearly in fig. 9 where the nuclear heating rate is shown as a function of distance into the internal blanket. The heating rate peaks sharply at the multiplier-breeder interface (at 20 cm) due to thermal neutron capture in ^{6}Li.

c. <u>ISSEC Burner Concepts ISSEC/Bu)</u>

We have discussed earlier the reasons non-breeding blanket designs for fusion systems are of interest. Systems 4B, 4C, and 4D listed in table 4 illustrate these concepts while model 4A will be used as a reference. A comparison of designs 4B and 4C will illustrate the effect of a thermal neutron filter in front of the vanadium wall (zone 3). Model 4D is a system designed to yield higher energy production via neutron multiplication in beryllium followed by capture in boron. The external blanket in all these models is a helium cooled, boron carbide and carbon system which serves as a neutron absorber and shield.

The neutron spectrum in the vanadium first wall (zone 3) for designs 4A, 4B, and 4C is shown in fig. 10. The spectrum for model 4D is similar to that for model 4C. It is clear that the 1 cm boron carbide zone has a significant effect on the thermal component and will lead to a reduction in radioactivity caused by thermal neutron captures when models 4C and 4D are compared with model 4B. This is tabulated in table 6. The nuclear performance of these ISSEC/Bu designs is summarized in table 9. Of the nominal 12.5 cm internal blanket systems, model 4D is clearly superior in that it maximizes the energy per fusion while leading to substantial reductions in first wall radioactivity, gas production rates, and dpa rates. Such a concept allows one to "burn" boron to enhance energy production without having to handle large amounts of tritium.

d. Radiation Effects in the Carbon Spectral Shaper

A key feature of the ISSEC concept is that it transfers the radiation damage problems from critical structural components to nonstructural members of the reactor. However, the neutrons slowing down in the internal blanket do considerable damage via both elastic and nonelastic collisions in the carbon, beryllium and lithium containing materials. We will consider only the major component of the ISSEC concept here, namely, a graphite internal spectral shaper.

Figure 11 shows the displacement rate and helium production rate as a function of distance in a carbon internal blanket normalized to a 1 MW/m^2 neutron wall loading. The displacement damage, calculated from dpa cross sections of Morgan,[43] varies from 9.8 dpa per year at the surface facing the plasma to 1.7 dpa per year at the other end. Even more dramatic than the factor of 6 drop in dpa values is the factor of 21 drop in helium production rate from 2785 appm per year at the inside to 131 appm per year at the outside. This larger drop in helium production is due to the fact that the cross section for alpha production, such as the (n,n')3α reaction, has a high energy threshold. By contrast, neutrons of only a few keV can cause displacements in carbon.

The effects of this irradiation can be correlated to fission neutron damage by the factor 1.0×10^{-21} dpa per fission spectrum neutron. Hence, the maximum displacement in carbon is equivalent to approximately 10^{22} fission spectrum neutrons per cm^2 per year. A recent analysis by Gray and Morgan[44] shows that in reactor grade graphites (which may be quite different from the carbon fibers used here) irradiated at temperatures between 1200 and 1400°C, radiation damage may induce length changes (shrinkage) of 2-6% in one year and perhaps some expansion (a few percent) after 2 years of full power operation. No data are available for temperatures above 1400°C or at high fluences, nor is there any information about how such graphite (or carbon) structures with what might behave with such high helium contents. Clearly, more work in this area is needed to assess correctly the nature of such high-temperature, high-fluence damage. At this time we might speculate that the lifetime of such a spectral shaper will be in the neighborhood of approximately 2 years but the recombination of defects at 2000°C might extend this to longer values.

IV. Summary and Discussion

In this paper, several new concepts for fusion reactor blanket designs have been presented based on the idea of shifting, or tailoring, the neutron spectrum incident on the first structural wall. The spectral shifter or internal blanket is a nonstructural element which could be made of bulk graphite, silicon carbide, or 3 dimensional woven carbon fibers. Specific design concepts have been presented which fall into three main categories: ISSEC/EB concepts based on utilizing existing designs which breed tritium behind the first structural wall; ISSEC/IB concepts based on breeding tritium inside the first vacuum wall; and ISSEC/Bu concepts based on using boron, carbon and perhaps beryllium to obtain an energy multiplier and convertor design that does not attempt to breed tritium or utilize lithium. These latter concepts may be particularly attractive for near term experimental fusion power systems and, in the long term, on fusion power reactors operating on alternate fuel cycles that do not require tritium breeding.

We have evaluated the nuclear performance of these systems and have found that substantial reductions in gas production rates, displacement damage rates, and induced radioactivity in the structural materials can be achieved. This opens the possibility for longer structural component lifetimes and can lead to a reduction in the amount of solid radioactive waste which must be handled. The shifted neutron spectrum in the first wall of an ISSEC design has been shown to yield dpa spectra as a function of neutron energy which approach the results found in fast breeder reactors. This can add to the relevance for fusion reactors of radiation damage data for structural materials obtained from fission reactors.

The use of low Z materials facing the plasma can have substantial beneficial effects, as has been discussed previously,[(12),(17),(18)] and these benefits will likewise accrue from the use of ISSEC concepts. An analysis of the compatibility of elements made from woven carbon or graphite fibers with the vacuum environment of the plasma chamber has also been considered elsewhere.[(18)]

There are many remaining questions regarding these ISSEC systems which require further research. We have indicated that the displacement damage rates and helium production rates in a graphite spectral shaper will be quite high and we have discussed some limited experimental experience.[(44)] Clearly much more research is required to better understand radiation damage to carbon fibers at high temperatures and high fluences in the presence of high helium content. Heat transfer is also very important for these concepts and work in this area has already begun.[(16),(41)] For the internal breeder concepts, the problems of tritium diffusion from the breeding compound and, if pyrolytic carbon coated pellets are used, the diffusion of tritium through high temperature carbon, are most important. Surface effects on the carbon, such as sputtering and blistering, are also relevant and data in this area are becoming available.[(45)] The potential for greatly reduced radioactivity, afterheat, and radiation damage, increased structural material lifetime, and increased flexibility in the choice of structural materials and coolants in system design appear to invite further study of these concepts.

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Figure Captions

Fig. 1 Scanning electron micrographs of graphite fabric at a number of magnifications.

Fig. 2 Schematic diagram of three dimensional weaving patterns.

Fig. 3 Integrated group flux in the first structural wall (zone 3) of a lithium cooled external blanket.

Fig. 4 Variation of important reactor parameters as a function of thickness-density factor product of the carbon internal blanket.

Fig. 5 Percentage of displacements per atom produced by neutrons of energy greater than energy, E, as a function of E, for various thicknesses of a carbon internal blanket.

Fig. 6 Heating rate as a function of distance in several spectral shapers.

Fig. 7 Breeding ratio as a function of the amount of beryllium carbide in the spectral shaper for model 2 blanket designs.

Fig. 8 Integrated group flux in the first structural wall (zone 3) for ISSEC/IB concepts.

Fig. 9 Heating rate as a function of thickness in the internal blanket of model 3B.

Fig.10 Integrated group flux in the first structural wall (zone 3) for ISSEC/Bu concepts.

Fig.11 The dpa rate and He production rate as a function of distance into a graphite internal blanket. The zero thickness point represents the carbon position facing the plasma. For a 3-D weave with a density factor of 0.5, the above results hold when the abscissa distances are doubled.

Table 1

<u>FUSION REACTOR BLANKET DESIGNS USED TO STUDY THE INTERNAL SPECTRAL SHIFTER AND ENERGY CONVERTER (ISSEC) CONCEPTS</u>

ISSEC Concepts with Lithium Cooled External Blankets

(W(cm) = Zone Thickness; Comp = Zone Composition by Volume; D.F. = Zone Density Factor)

Model	Internal Blanket						First Structural Wall			External Blanket								
	Zone 1			Zone 2			Zone 3			Zone 4			Zone 5			Zone 6		
Number	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.
1A	-	Void	-	-	Void	-	1	V	1.0	30	95%Li (nat) + 5% V	1.0	15	V	0.8	5	95%Li (nat) + 5% V	1.0
1B	-	Void	-	12.5	C	1.0	"	"	"	"	95% Li (90% ^{6}Li) + 5% V	"	"	"	"	"	95% Li (90% ^{6}Li) + 5% V	"
1C	-	Void	-	25	C	1.0	"	"	"	"	"	"	"	"	"	"	"	"
1D	-	Void	-	25	50% C + 50% Be_2C	0.5	"	"	"	"	"	"	"	"	"	"	"	"

Table 2

FUSION REACTOR BLANKET DESIGNS USED TO STUDY THE INTERNAL SPECTRAL SHIFTER AND ENERGY CONVERTER (ISSEC) CONCEPTS

ISSEC Concepts with He Cooled, Solid Breeder, External Blankets

(W(cm) = Zone Thickness; Comp = Zone Composition by Volume; D.F. = Zone Density Factor)

Model Number	Internal Blanket				First Structural Wall			External Blanket														
	Zone 1	Zone 2			Zone 3			Zone 4			Zone 5			Zone 6			Zone 7			Zone 8		
		W	Comp.	D.F.	W	Comp	D.F.	W	Comp	D.F.	W	Comp	D.F.	W	Comp	D.F.	W	Comp	D.F.	W	Comp	D.F.
2A	Void	-	Void	-	2	V	0.5	3	90%$LiAlO_2$ ($90\%^6Li$) + 10% V	0.5	18	90% Be + 10% V	0.5	10	90%$LiAlO_2$ ($90\%^6Li$) + 10% V	0.5	38	90% C + 10% V	0.8	8	V	0.9
2B	Void	25	Be_2C	0.5	"	"	"	13	"	"	35	90% C + 10% V	0.8	4	V	0.9	Void			Void		
2C	Void	25	50% C + 50% Be_2C	0.5	"	"	"	"	"	"	"	"	"	"	"	"	Void			Void		

Table 3

FUSION REACTOR BLANKET DESIGNS USED TO STUDY THE INTERNAL SPECTRAL SHIFTER AND ENERGY CONVERTER (ISSEC) CONCEPTS

ISSEC/I.B. Concepts with Internal Breeding

(W(cm) = Zone Thickness; Comp = Zone Composition by Volume; D.F. = Zone Density Factor)

Model Number	Internal Blanket						First Structural Wall			External Blanket		
	Zone 1			Zone 2			Zone 3			Zone 4		
	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.
3A	-	Void	-	-	Void	-	2	V	0.5	50	C	0.8
3B	20	Be_2C	0.5	10	50% $LiAlO_2$ (90% ^6Li) + 50% C	0.5	"	"	"	"	"	"
3C	20	50% C + 50% Be_2C	0.5	10	50% $LiAlO_2$ (90% ^6Li) + 50% C	0.5	"	"	"	"	"	"

Table 4

FUSION REACTOR BLANKET DESIGNS USED TO STUDY THE INTERNAL SPECTRAL SHIFTER AND ENERGY CONVERTER (ISSEC) CONCEPTS

ISSEC/Burner Concepts

(W(cm) = Zone Thickness; Comp = Zone Composition by Volume; D.F. = Zone Density Factor)

Model Number	Internal Blanket						First Structural Wall			External Blanket		
	Zone 1			Zone 2			Zone 3			Zone 4		
	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.	W(cm)	Comp	D.F.
4A	-	Void	-	-	Void	-	2	V	0.5	60	30% B_4C (92% ^{10}B) + 70% C	0.8
4B	-	Void	-	12.5	C	1.0	"	"	"	"	"	"
4C	11.5	C	1.0	1	50% B_4C 92% ^{10}B) + 50% C	1.0	"	"	"	"	"	"
4D	11.5	50% Be_2C + 50% C	1.0	1	50% B_4C (92% ^{10}B) + 50% C	1.0	"	"	"	"	"	"

Table 5

Comparison of Important Reaction Rates in Reference Systems and in Designs Using ISSEC Concepts

Model Number	Model Class	Breeding Ratio	Energy Per Fusion (MeV)	He Prod. Rate in First Wall (zone 3) appm/yr*	H Prod. Rate in First Wall (zone 3) appm/yr*	DPA Rate in First Wall (zone 3) dpa/yr*
1A	Reference Li Cooled Blanket	1.29	17.85	72.1	134.4	14.7
1B	ISSEC + Li Cooled External Blanket	0.75	17.33	10.6	26.1	3.92
1C	ISSEC + Li Cooled External Blanket	0.536	17.03	2.71	7.9	1.59
1D	ISSEC + Li Cooled External Blanket	1.05	20.0	7.77	20.8	3.49

* Normalized to 14.1 MeV neutron wall loading of 1 MW/m^2.

TABLE 6

Comparison of Radioactivity in the First Structural Wall (Zone 3) at Shutdown and One Week After Shutdown of Reference Systems and ISSEC Design Concepts

(After 10 years of Operation; In Units of Ci/cm^3 per 1 MW/m^2 of 14.1 MeV neutrons)

Model Number	Model Class	Activity from ^{48}Sc ($t_{1/2}$= 1.82d)		Activity from ^{51}Ti ($t_{1/2}$= 5.76m)		Activity from ^{52}V ($t_{1/2}$= 3.75m)		Total Radioactivity	
		t=0	1 WK	t=0	1 WK	t=0	1 WK	t=0	1 WK
1A	Reference-Li Cooled	4.34	0.302	8.1	-----	30.5	-----	32.8	0.302
1B	ISSEC/EB	0.67	0.0466	1.57	-----	28.3	-----	30.5	0.0466
1C	ISSEC/EB	0.16	0.011	0.47	-----	110	-----	110.6	0.011
1D	ISSEC/EB	0.47	0.033	1.25	-----	128	-----	129.4	0.033
2A	Reference-He Cooled Solid Breeder	4.56	0.317	8.33	-----	18.3	-----	31.2	0.317
2B	ISSEC/EB	0.24	0.0167	0.71	-----	316	-----	317.5	0.0167
2C	ISSEC/EB	0.34	0.0237	0.96	-----	169	-----	170	0.0237
3A	Reference	4.3	0.3	7.97	-----	341.2	-----	353.5	0.30
3B	ISSEC/IB	0.28	0.0195	0.82	-----	50.3	-----	51.4	0.0195
3C	ISSEC/IB	0.34	0.024	0.97	-----	49.2	-----	50.5	0.024
4A	Reference-Burner	4.32	0.30	7.97	-----	1.0	-----	13.3	0.30
4B	ISSEC/Ab	0.64	0.0445	1.61	-----	30.5	-----	32.8	0.045
4C	ISSEC/Ab	0.61	0.0424	1.55	-----	12.7	-----	14.8	0.0424
4D	ISSEC/Ab	0.46	0.032	1.26	-----	2.07	-----	4.79	0.032

Table 7

Comparison of Important Reaction Rates in Reference Systems and in Designs Using ISSEC Concepts

Model Number	Model Class	Breeding Ratio	Energy Per Fusion (MeV)	He. Prod. Rate in First Wall (zone 3) appm/yr*	H Prod. Rate in First Wall (zone 3) appm/yr*	DPA Rate in First Wall (zone 3) dpa/yr*
2A	Reference He Cooled Blanket with Solid Breeder	1.35	21.9	75.8	138.4	15.2
2B	ISSEC + He Cooled External Blanket	1.06	22.3	4.2	12.4	2.9
2C	ISSEC + He Cooled External Blanket	0.87	20.0	6.0	17.0	3.5

* Normalized to 14.1 MeV neutron wall loading of 1 MW/m^2.

Table 8

Comparison of Important Reaction Rates in Reference Systems and in Designs Using ISSEC Concepts

Model Number	Model Class	Breeding Ratio	Energy Per Fusion (MeV)	He Prod. Rate in First Wall (zone 3) appm/yr*	H Prod. Rate in First Wall (zone 3) appm/yr*	DPA Rate in First Wall (zone 3) dpa/yr*
3A	Reference Burner: He Cooled Blanket Without Boron	-----	15.3	71.6	132.4	14.2
3B	ISSEC/I.B.**	1.21	18.3	4.58	13.6	2.93
3C	ISSEC/I.B.**	0.9	18.4	5.69	16.1	3.26

* Normalized to 14.1 MeV neutron wall loading of 1 MW/m^2.

** An ISSEC/I.B. (ISSEC/Internal Breeder) system designed for tritium breeding inside the first structural wall (zone 3 in Table 1).

Table 9

Comparison of Important Reaction Rates in Reference Systems and in Designs Using ISSEC Concepts

Model Number	Model Class	Breeding Ratio	Energy Per Fusion (MeV)	He Prod. Rate in First Wall (zone 3) appm/yr*	H Prod. Rate in First Wall (zone 3) appm/yr*	DPA Rate in First Wall (zone 3) dpa/yr*
4A	Reference Burner: He Cooled Blanket Containing Boron	-----	15.3	71.8	132.5	12.9
4B	ISSEC/Bu**	-----	15.7	10.7	26.8	4.08
4C	ISSEC/Bu**	-----	15.6	10.1	25.7	3.75
4D	ISSEC/Bu**	-----	18.3	7.67	20.9	3.48

* Normalized to 14.1 MeV neutron wall loading of 1 MW/m^2.

** An ISSEC - Burner System designed for energy conversion without tritium breeding.

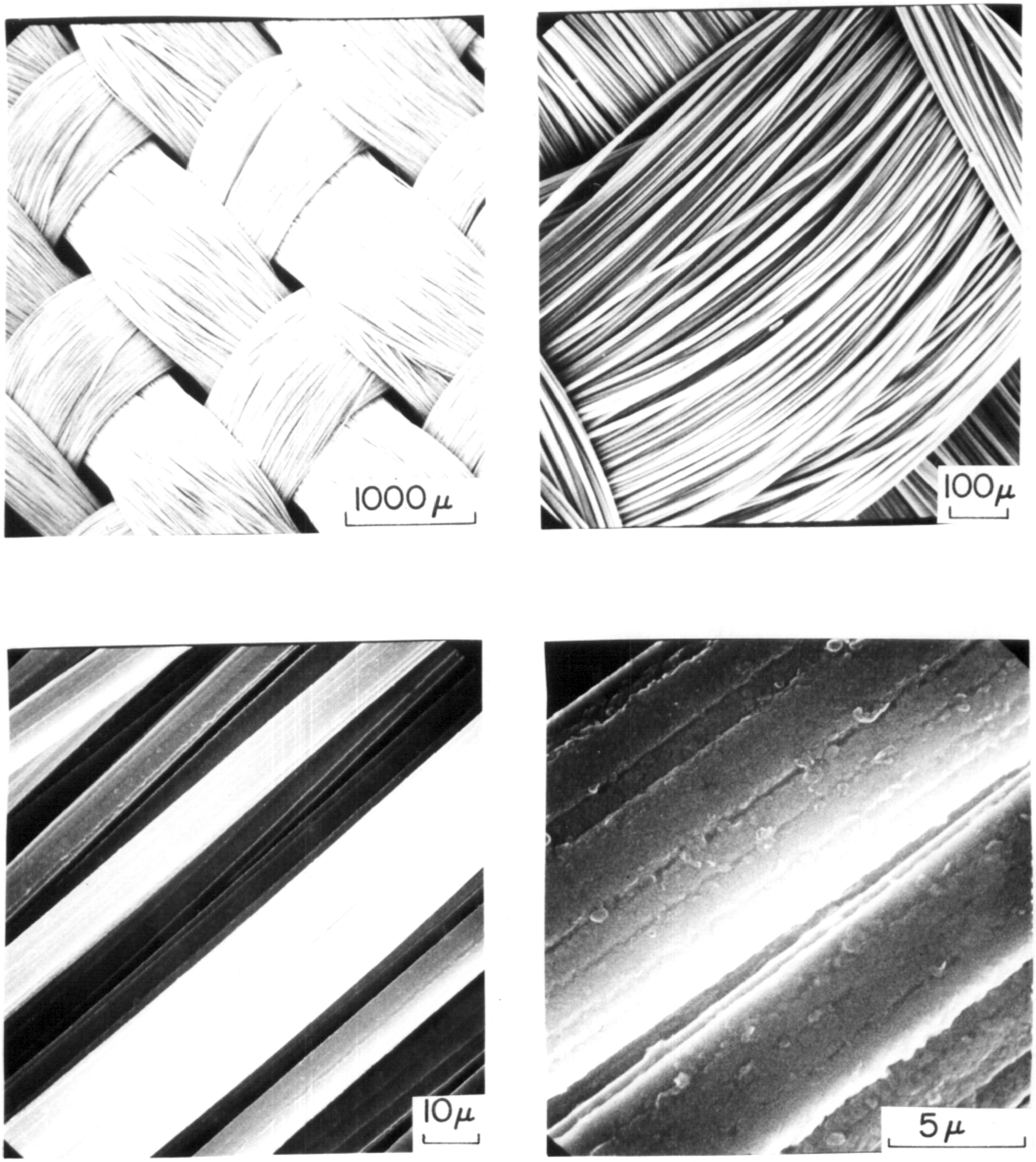
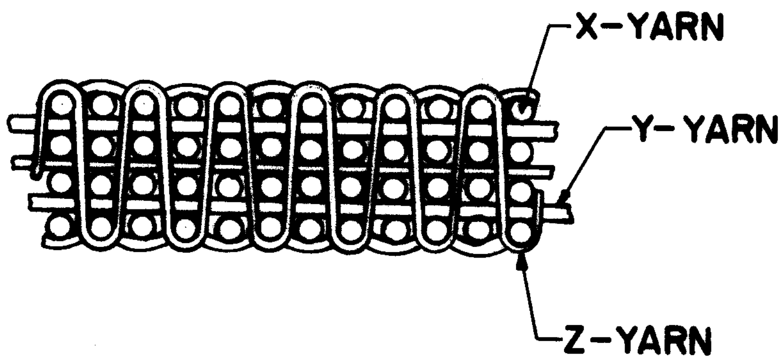
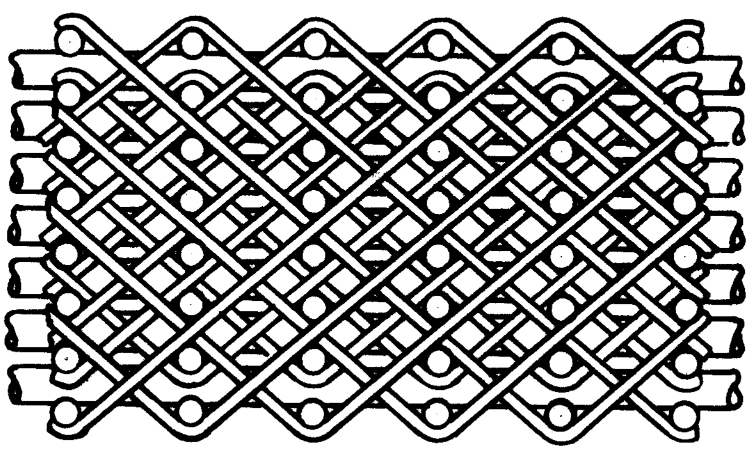


Figure 2. Photographs of Graphite Fabric at a Number of Magnifications



ORTHOGONAL WEAVE



ANGLE INTERLOCK WEAVE

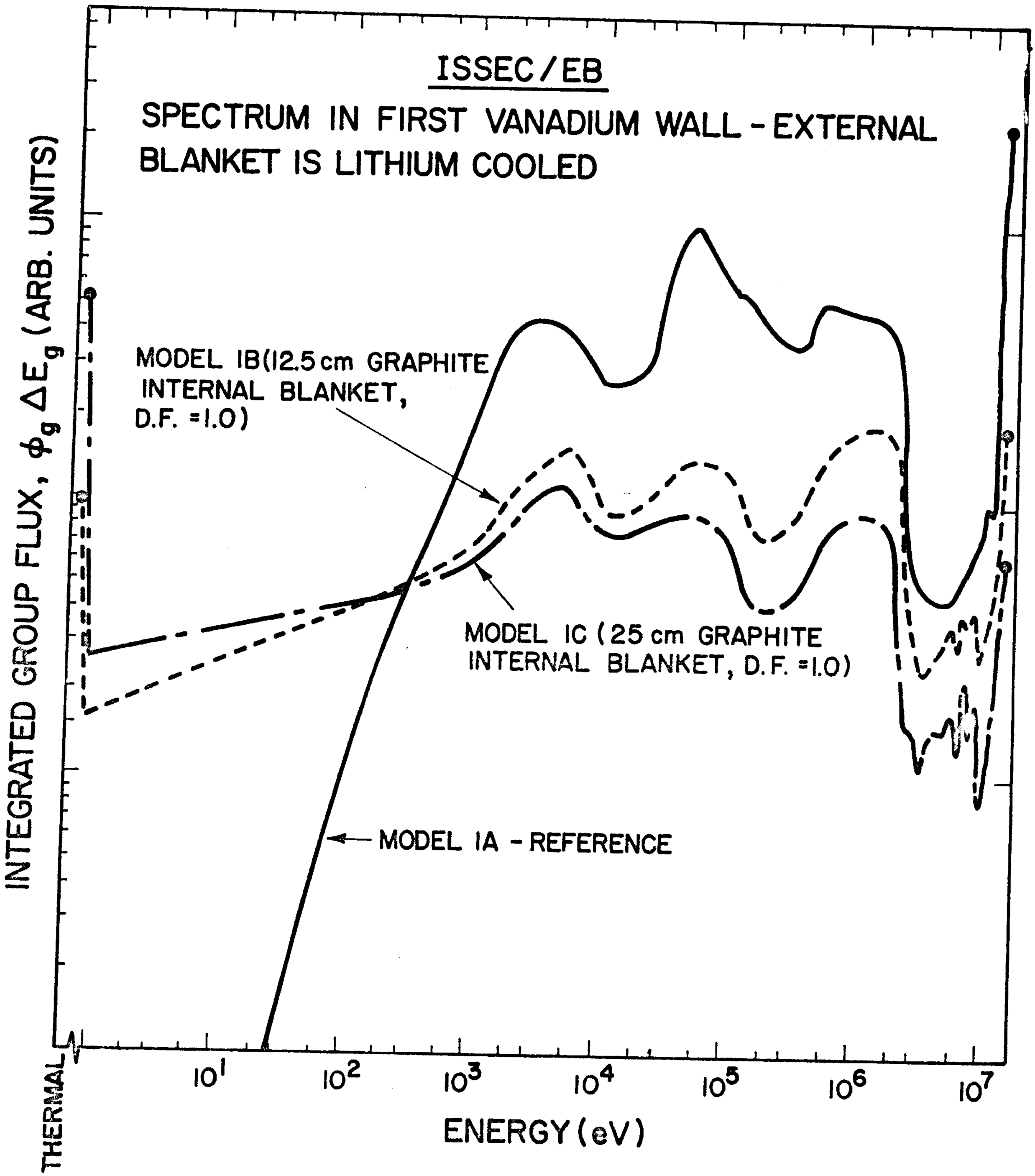
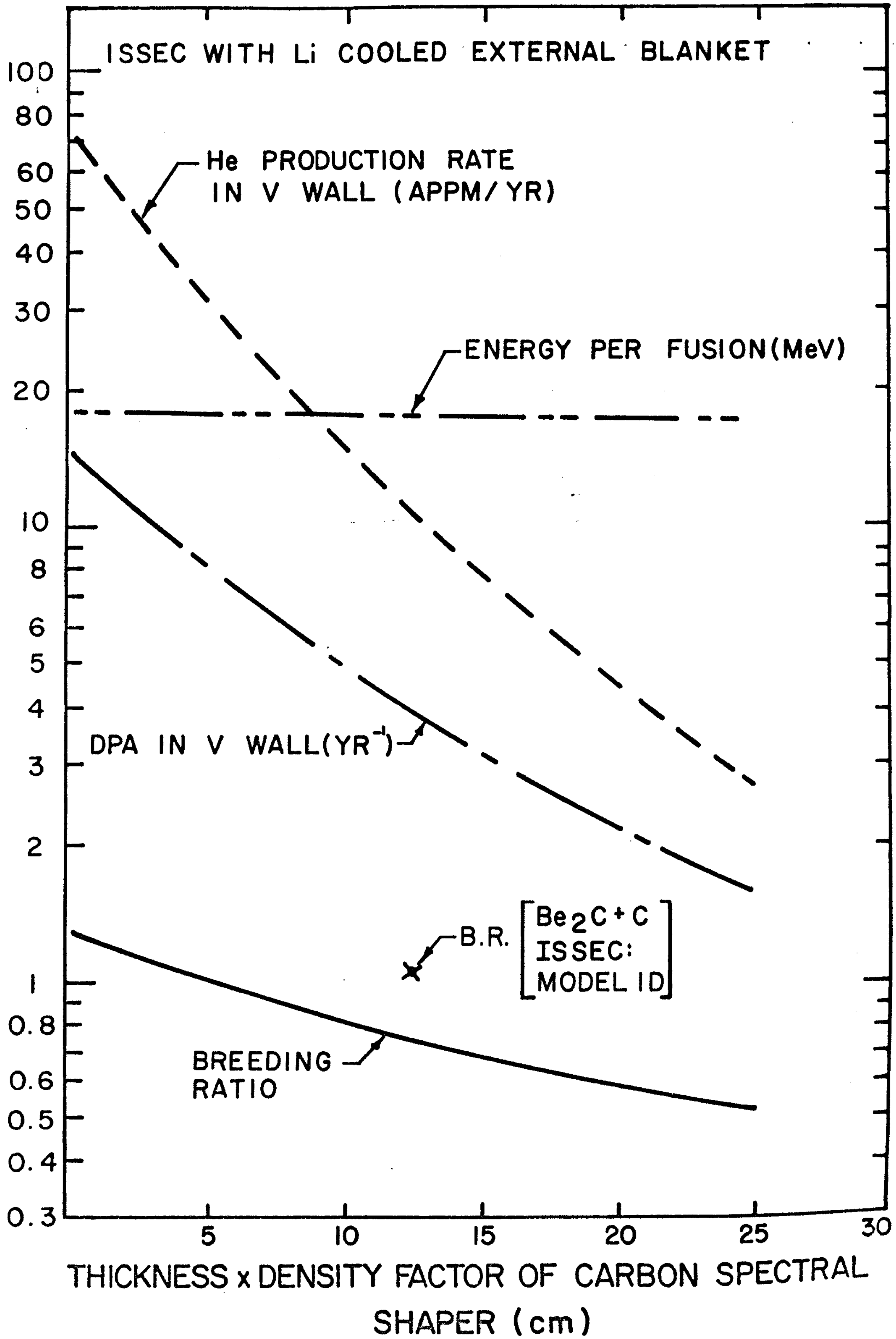

ISSEC/EB
SPECTRUM IN FIRST VANADIUM WALL - EXTERNAL BLANKET IS LITHIUM COOLED
MODEL IB(12.5 cm GRAPHITE INTERNAL BLANKET, D.F. =1.0)
MODEL IC (25 cm GRAPHITE INTERNAL BLANKET, D.F. =1.0)
MODEL IA - REFERENCE
INTEGRATED GROUP FLUX, $\phi_g \Delta E_g$ (ARB. UNITS)
THERMAL
10^1
10^2
10^3
10^4
10^5
10^6
10^7
ENERGY (eV)

Figure - 3


ISSEC WITH Li COOLED EXTERNAL BLANKET
He PRODUCTION RATE IN V WALL (APPM/YR)
ENERGY PER FUSION (MeV)
DPA IN V WALL (YR⁻¹)
B.R. [Be2C + C ISSEC: MODEL ID]
BREEDING RATIO
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1
0.8
0.6
0.5
0.4
0.3
5
10
15
20
25
30
THICKNESS x DENSITY FACTOR OF CARBON SPECTRAL SHAPER (cm)

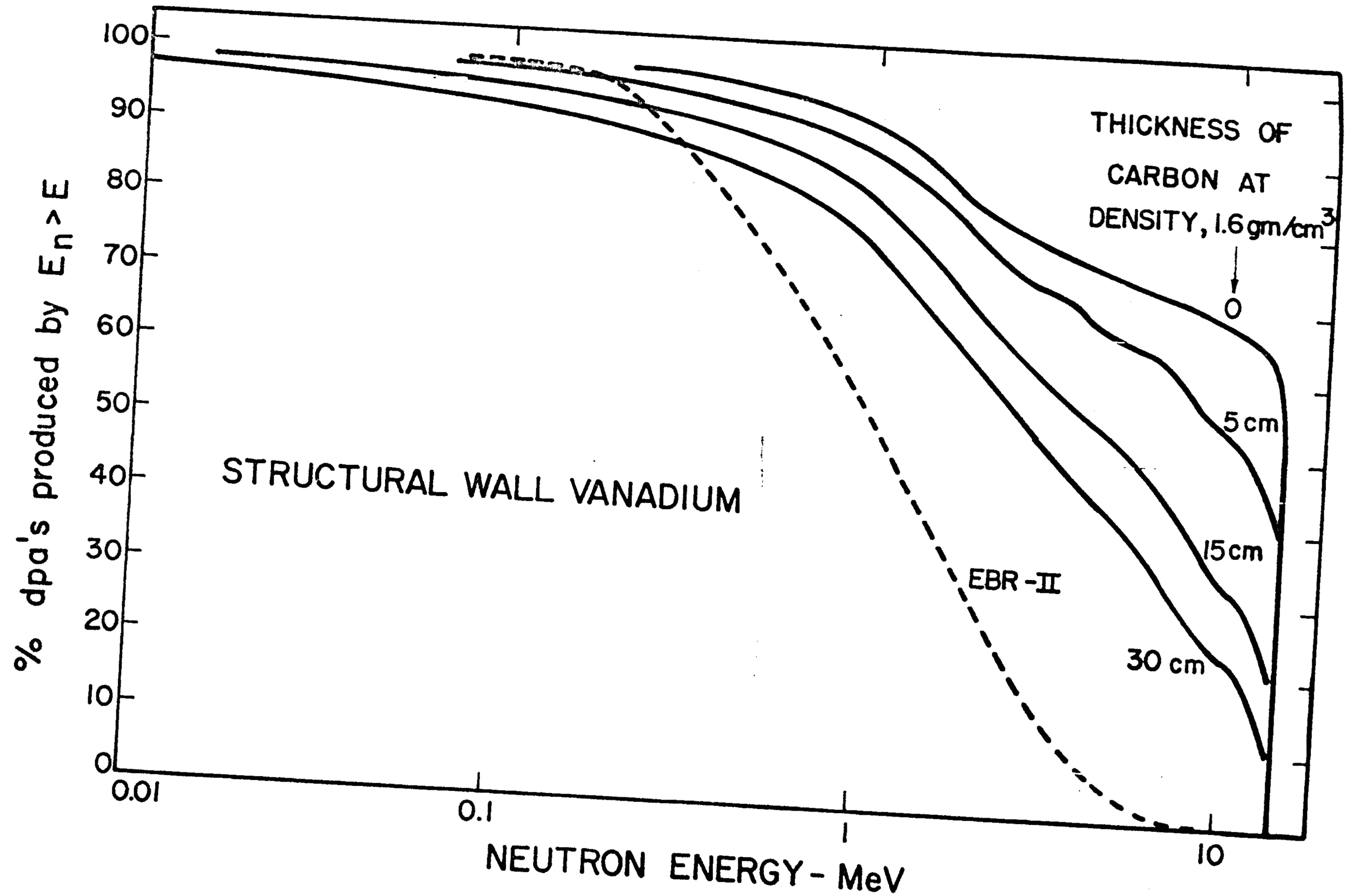

THICKNESS OF
CARBON AT
DENSITY, 1.6 gm/cm3
0
5 cm
15 cm
30 cm
EBR-II
STRUCTURAL WALL VANADIUM
% dpa's produced by En > E
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
NEUTRON ENERGY - MeV

Figure 5

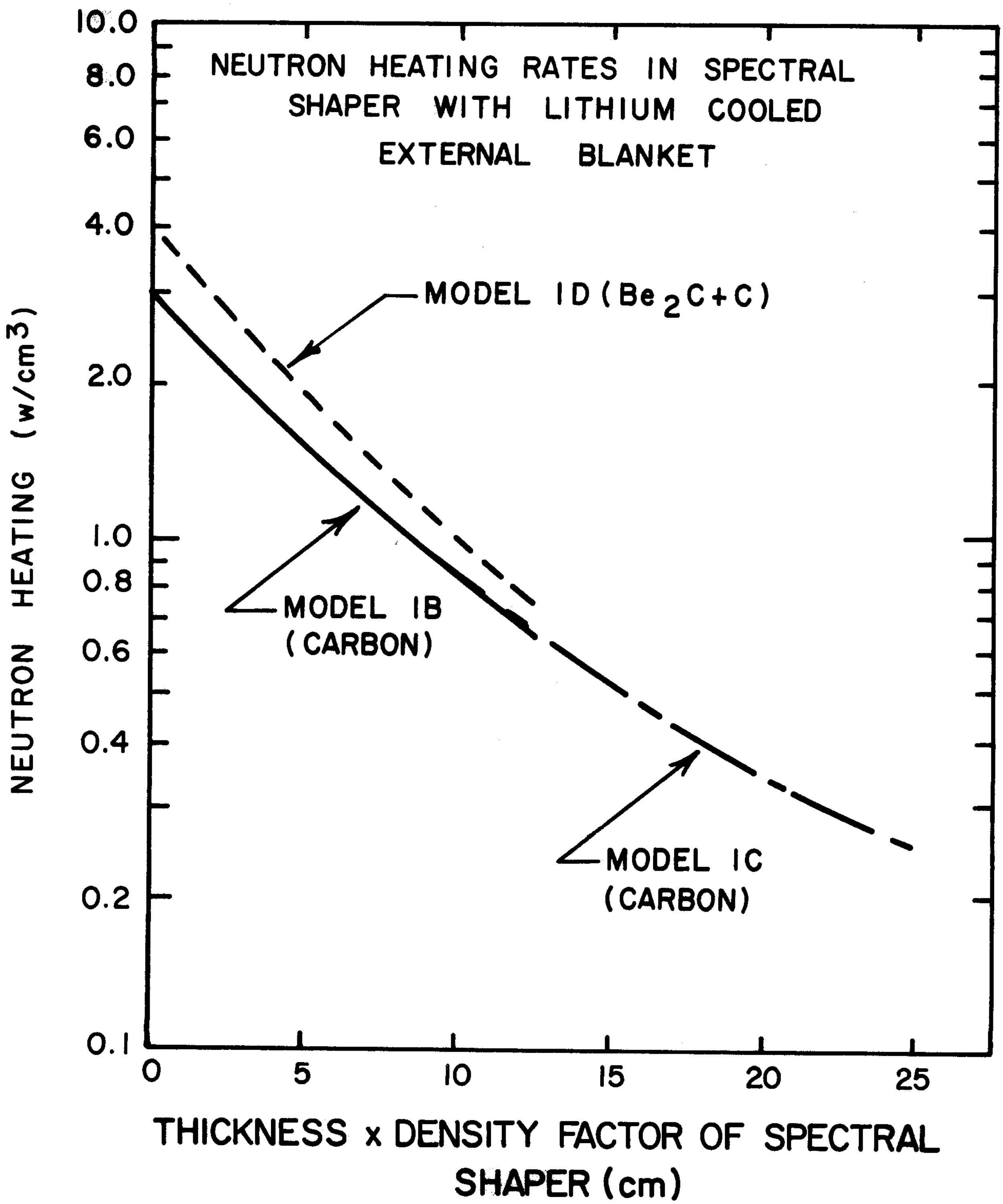

NEUTRON HEATING RATES IN SPECTRAL SHAPER WITH LITHIUM COOLED EXTERNAL BLANKET
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
NEUTRON HEATING (w/cm3)
MODEL ID (Be2C+C)
MODEL IB (CARBON)
MODEL IC (CARBON)
0
5
10
15
20
25
THICKNESS x DENSITY FACTOR OF SPECTRAL SHAPER (cm)

Figure 6

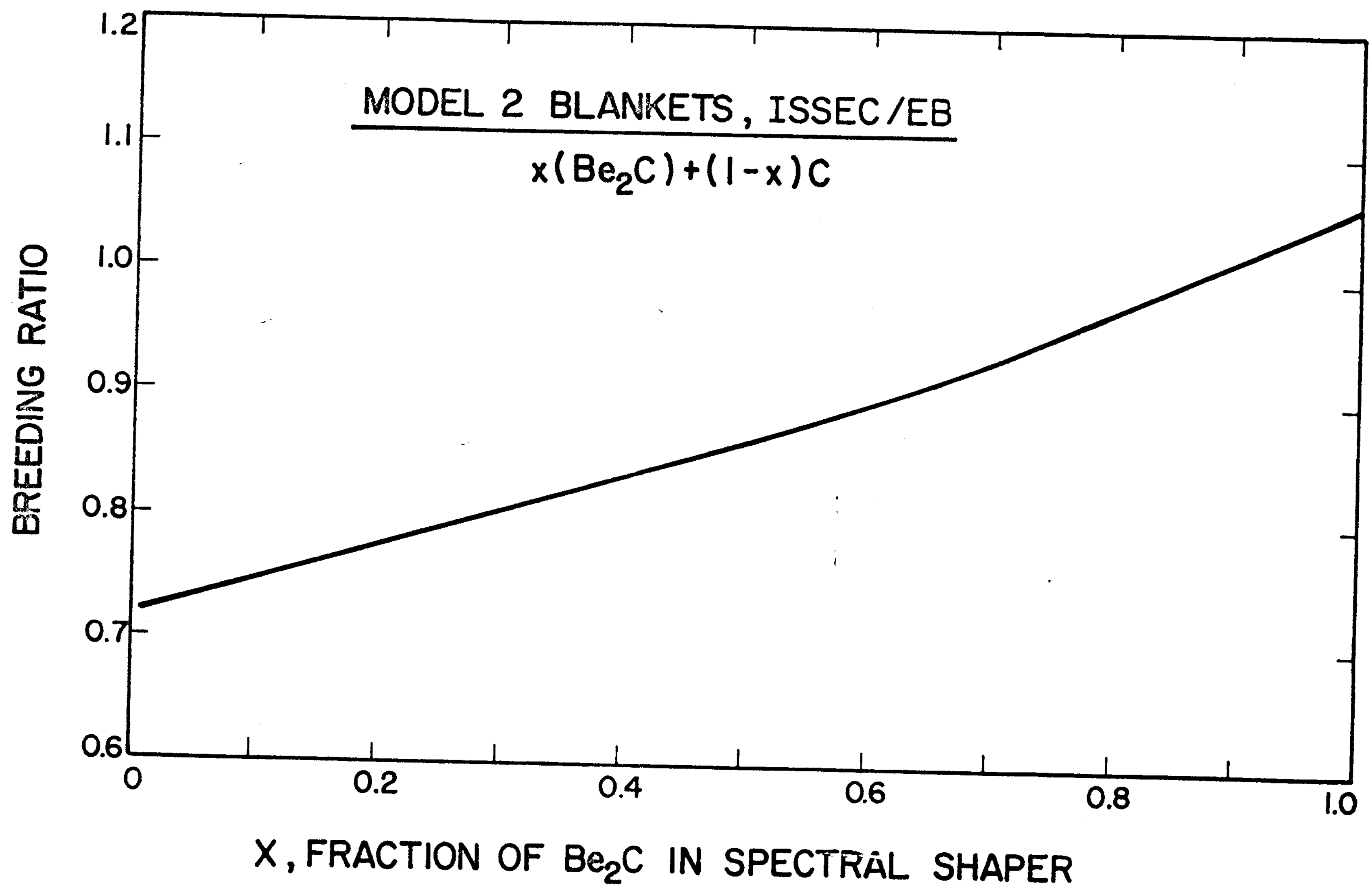

MODEL 2 BLANKETS, ISSEC/EB
x(Be2C)+(1-x)C
BREEDING RATIO
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0
0.2
0.4
0.6
0.8
1.0
X, FRACTION OF Be2C IN SPECTRAL SHAPER

Figure 7

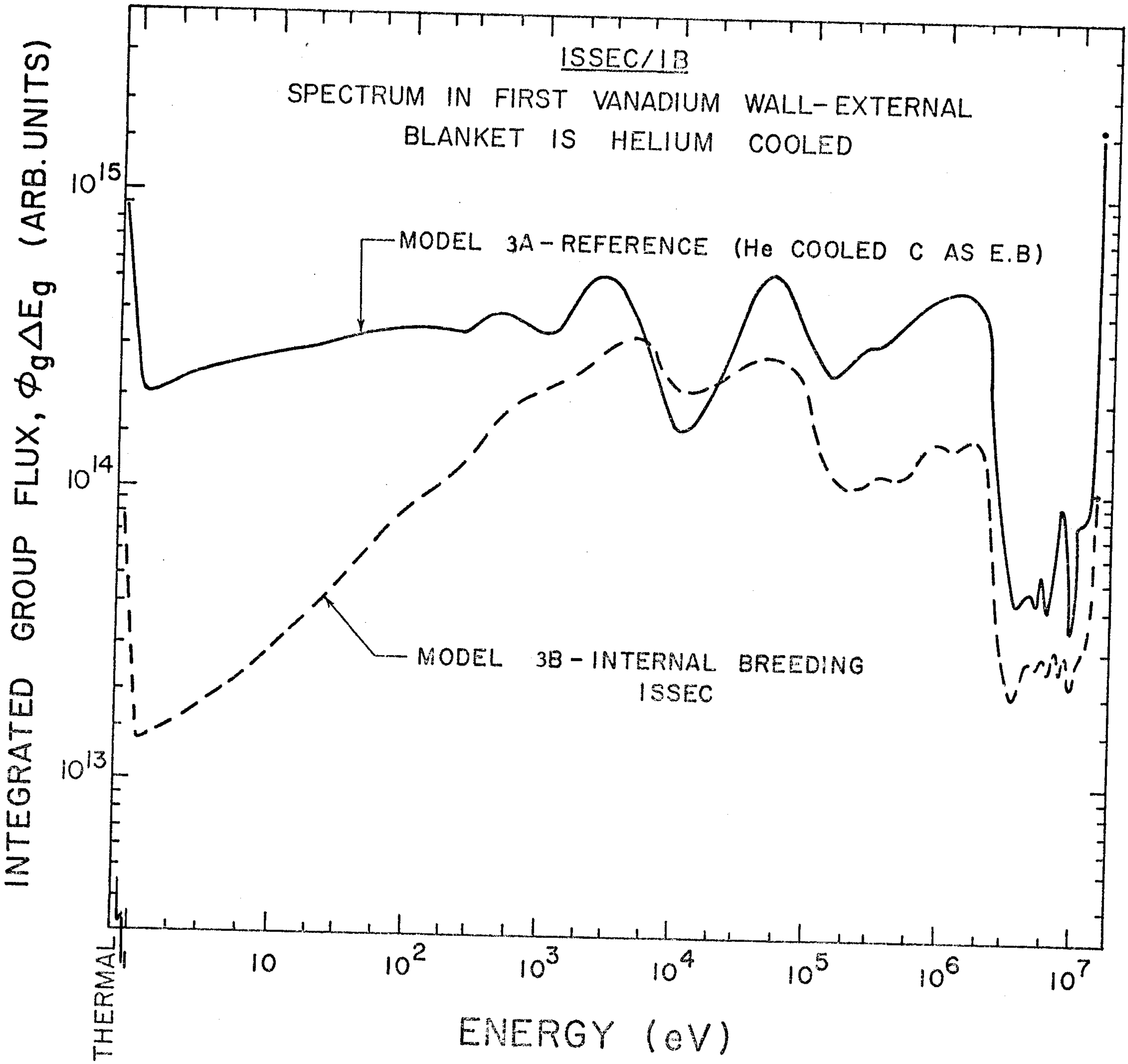

ISSEC/IB
SPECTRUM IN FIRST VANADIUM WALL-EXTERNAL
BLANKET IS HELIUM COOLED
MODEL 3A - REFERENCE (He COOLED C AS E.B)
MODEL 3B - INTERNAL BREEDING
ISSEC
INTEGRATED GROUP FLUX, $\phi_g \Delta E_g$ (ARB. UNITS)
10^{15}
10^{14}
10^{13}
THERMAL
10
10^2
10^3
10^4
10^5
10^6
10^7
ENERGY (eV)

Figure 8

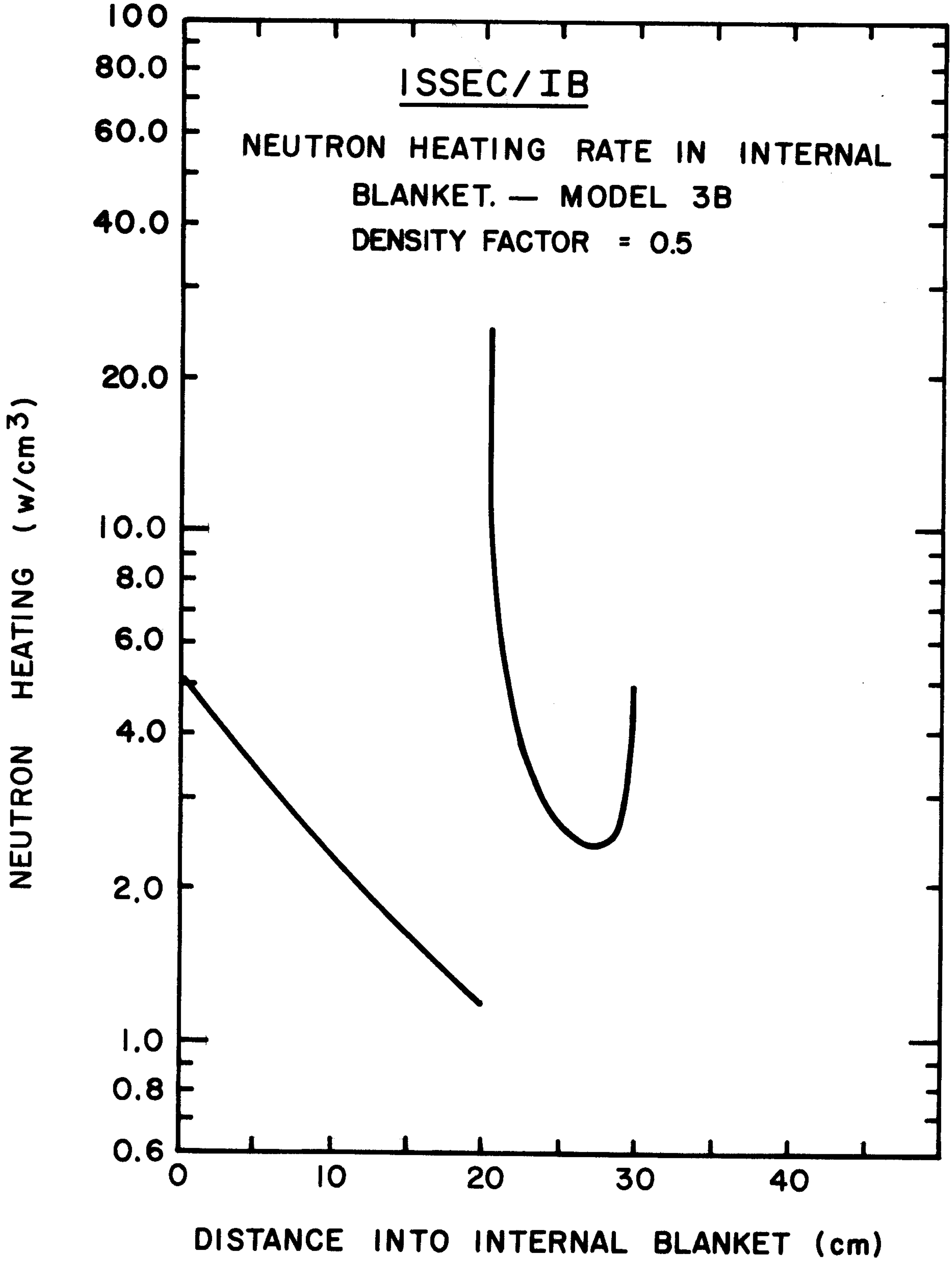

ISSEC/IB
NEUTRON HEATING RATE IN INTERNAL
BLANKET. — MODEL 3B
DENSITY FACTOR = 0.5
100
80.0
60.0
40.0
20.0
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
NEUTRON HEATING (w/cm3)
0
10
20
30
40
DISTANCE INTO INTERNAL BLANKET (cm)

Figure 9

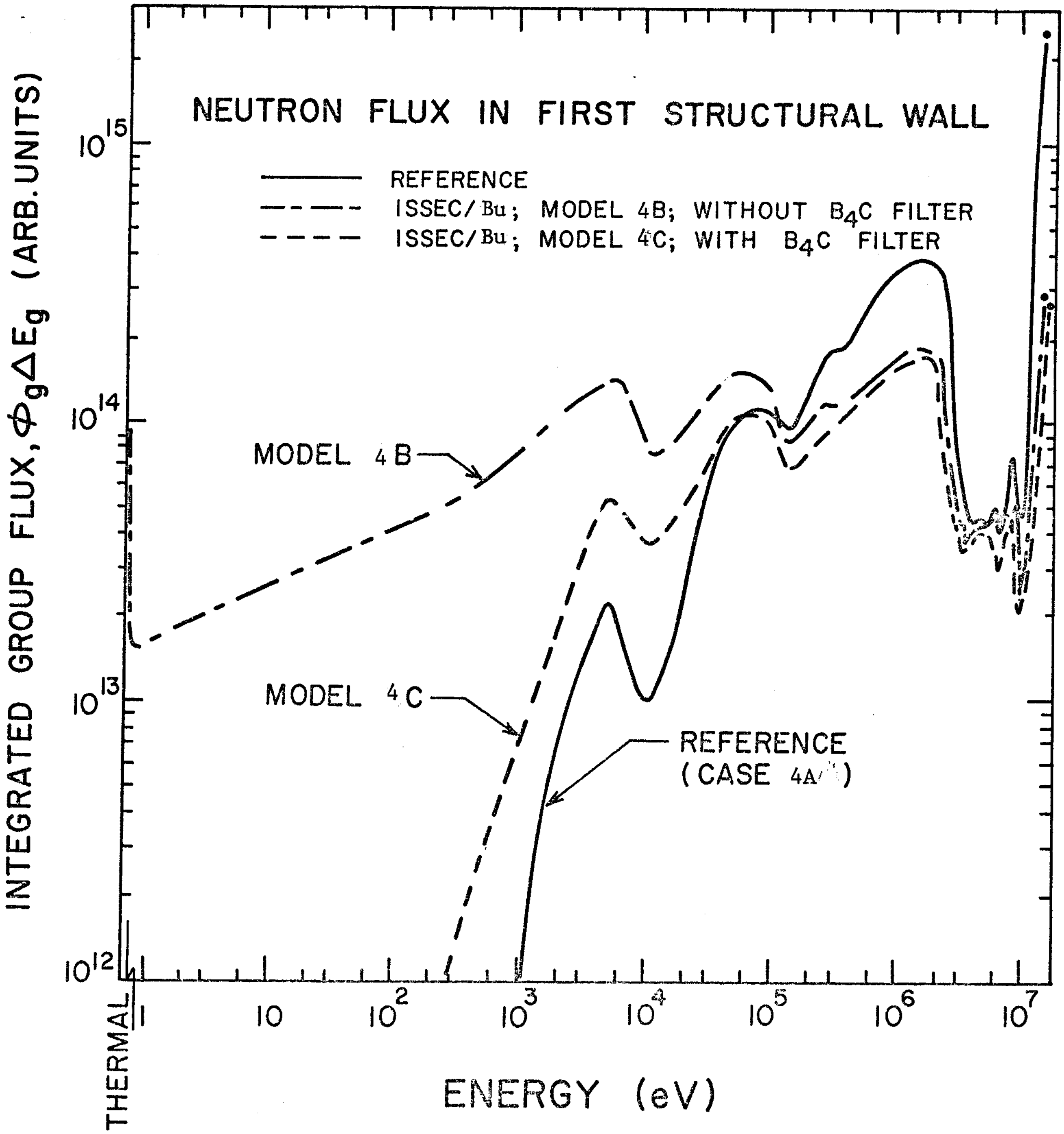

NEUTRON FLUX IN FIRST STRUCTURAL WALL
REFERENCE
ISSEC/Bu; MODEL 4B; WITHOUT B4C FILTER
ISSEC/Bu; MODEL 4C; WITH B4C FILTER
MODEL 4B
MODEL 4C
REFERENCE
(CASE 4A)
INTEGRATED GROUP FLUX, ΦgΔEg (ARB.UNITS)
10^15
10^14
10^13
10^12
THERMAL
1
10
10^2
10^3
10^4
10^5
10^6
10^7
ENERGY (eV)

Figure 10

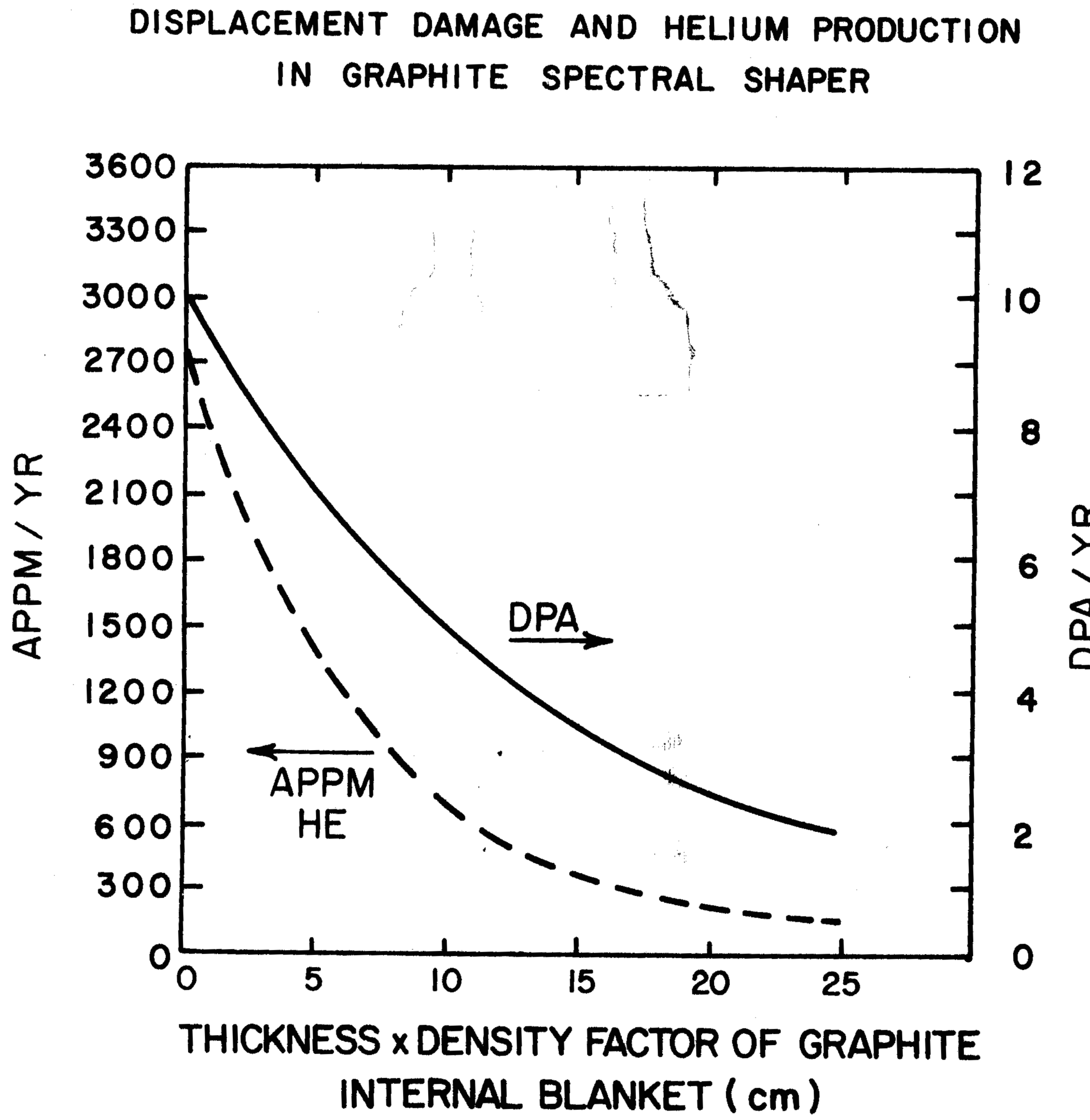

DISPLACEMENT DAMAGE AND HELIUM PRODUCTION
IN GRAPHITE SPECTRAL SHAPER
APPM / YR
DPA / YR
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
12
10
8
6
4
2
0
0
5
10
15
20
25
DPA
APPM
HE
THICKNESS x DENSITY FACTOR OF GRAPHITE
INTERNAL BLANKET (cm)

Figure 11