# Neutrons and Fusion

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## Introduction

The use of fusion reactions as a source of energy is a concept currently mentioned in popular media with great regularity and with a general vagueness that indicates how little the general public is aware of how the concept might be implemented. Those within the technical community are likely to have a view of fusion reactors based primarily on the confinement problems which have dominated the field since its beginning. Solutions to the problem of confining the fusing nuclei at the required temperatures vary greatly in size, appearance, and physical basis. However, the fuel cycle is almost always based on the D-T reaction in devices proposed for near term construction. This results simply from the lower confinement requirements and leads to many consequences that are common to a wide range of these devices.

The D-T reaction results in a direct energy release of 17.6 MeV with 14.1 MeV appearing as kinetic energy of the product neutron. This neutron will undergo further reactions which generally yield a net addition to the energy production such that around 20 MeV results per D-T reaction. This can be contrasted with a fission reaction which produces approximately 200 MeV, including about 2.5 neutrons with an average energy per neutron of 2 MeV. Thus, for the same power, there are 4 times as many neutrons produced in a fusion as in a fission reactor. In addition, they carry seven times the energy per neutron. Thus the neutron flux in a fusion reactor is very intense and the spectrum very hard.

This gives rise to a variety of nuclear effects which are in many respects as diverse and intricate as those found in a fission reactor. However, the important behavior is quite different; for there is no eigenvalue problem for neutron multiplication. Further, no single problem dominates the subject like the neutron multiplication problem of fission reactors. Instead, a number of different, but more or less equally important, responses of the system to the neutron flux occur.

The energetic 14 MeV neutrons from the $D(T,n)\alpha$ reaction produce a highly anisotropic angular flux, at the first material wall, which requires a high order transport approximation for its accurate determination. Much new data in an energy range not previously of great importance is required for this as well as for the system responses. These responses strongly affect the economics of the systems.

Blanket and Shield Functions and Responses

As noted above the various fusion reactor concepts vary in many respects, but all form an intense neutron source in a region generally transparent to the neutrons. This results in an intense high energy flux which must be utilized and attenuated. The first zone surrounding the fusion zone is referred to as the blanket and is followed by a zone called the shield. The functions performed by the blanket are to breed tritium, convert the kinetic energy of the 14 MeV source neutrons into heat, transfer the heat to the external thermal cycle, and provide a vacuum chamber for the fusion zone. A schematic of a representative blanket and shield for a magnetic confinement reactor is given in Figure 1.

The requirement of tritium breeding arises since its instability precludes it from occurring naturally in significant quantities. The only effective reactions for this purpose are the neutron reactions in $Li^6$ and $Li^7$. The possibility of producing as much or more tritium that D-T fusion reactions consume is based on capturing most fusion neutrons in $Li^6$ and loosing very few fusion neutrons to parasitic capture, the production of tritium during inelastic scattering from $Li^7$, and the multiplication of fusion neutrons by (n,2n) reactions in some materials. The response function required here is simply the sum of the tritium production cross sections of $Li^6$ and $Li^7$ weighted by their respective number densities. The actual response can be influenced directly by the lithium density through changes in the lithium bearing materials and the fractional content of structure and other constituents of the breeding zone and by intentionally changing the isotopic composition of the lithium. Indirectly, the response is influenced by wall, structure and other composition influences on the spectral and spatial flux dependence. The feasibility of fusion power is clearly dependent on the possibility of tritium production exceeding its consumption; however, inventory considerations indicate that the ratio of production to consumption (i.e., the breeding ratio) need only slightly exceed unity.

In Figure 1, a first wall is shown which must withstand the most extreme environment in the system since it is exposed to intense radiation of all kinds and must operate at the highest temperatures possible for the sake of system thermal efficiency. A set of performance indices determined by nuclear properties are required for radiation damage analysis. This is most severe in the first wall. While ideally, one would relate the radiation fluxes to the specific material property effects, the phenomena involved are too complex to allow such a direct approach. Instead, one can only determine transmutation and initial displacement rates in the material. Composition changes, due to hydrogen and helium production, can cause deleterious property changes which limit the time during which acceptable material performance can be assured. The transmutation products may influence materials properties, but they may also be radioactive and thus create a new set of problems. For these reasons, cross sections for the various reactions form a set of response functions of great importance. A slightly different case is the displacement of atoms from their positions in the crystal lattice of the material. The damage due to displacements is complex since many displacements are offset by recombination of the vacant lattice sites with displaced atoms. The degree of recovery and the interaction of vacant sites and displaced atoms with one another and with other lattice imperfections depends on temperature and imperfection densities and is a major study area. The above quantities serve as input to these studies. However, even the initial displacement rate is a complex topic which depends on lattice properties as well as nuclear cross sections. Thus, a desirable response function, the displacement cross section, which gives the displacement rate when multiplied by the flux and integrated, must be based on a model of the displacement process and the various nuclear cross sections. This response function is important enough that it is determined by processing cross sections weighted by primary knock on recoil energies and a model predicting the number of displaced atoms per unit energy of the primary nucleus.

Most of the energy produced is carried by the neutrons. To determine the spatial distribution and the exact total amount of energy produced, neutron energy deposition cross sections known as kerma factors must be available. The energy deposition depends on the reaction Q values as well as the cross sections. Closely related to the kerma factors, the gamma production cross sections complete the energy balance for the reactions and provide the source for gamma transport calculations. Thus, while gamma production is not directly a response function of interest, it is related to energy deposition both through reaction energy conservation and through the eventual energy deposition by the gamma photons.

The shielding effectiveness is measured by energy attenuation. This is not a reaction rate and is not even a volumetric effect. While it is related to all reactions taking place, its determination by subtracting incident energy absorbed from the incident energy would be an awkward procedure. The energy weighted current can be used to determine the attenuation achieved, but the high energy total cross section is the data which most readily indicates the approximate attenuation rate. In any case, the energy leakage represents an important response of the blanket and shield since it measures the energy load to the magnets and thus to the cryogenic refrigerators.

The system responses discussed to this point are required in the technical analysis of reactor performance. Energy production is included above, where the emphasis is on the determination of the energy deposited. However, from an economic point of view, a comparative study of alternative materials and their relative energy production may strongly influence design decisions. Thus, while energy production is not a separate response function, this discussion is introduced to emphasize that a different set of calculations may be important when optimizing the performance than in simply analyzing a particular system.

Materials and Reactions of Interest

The nature of the problem of nuclear analysis of fusion systems is basically like many radiation shielding problems, but with a greater need to know the detailed reaction rates in the zones close to the source than is usual. The blanket clearly contributes to the shielding as it must extract most of the energy release. The high energy neutron capture cross sections are small and likely endoergic in any case; thus, it is necessary to slow the source neutrons down to an energy where they can mostly be absorbed in $Li^6$ to produce tritium. Fortunately, this reaction is highly exoergic and produces an additional 4.8 MeV for the reactor. The moderation of the energy of the source neutrons is carried out most effectively by inelastic collisions with materials of medium to heavy mass rather than through elastic collisions with light nuclei as in fission reactors. The reason is that at the source energy here, the elastic cross sections have fallen and anisotropic scattering occurs. On the other hand, inelastic events readily occur at these energies and structural materials are generally good for neutron moderation.

The first zone behind the initial wall will contain lithium in some form, a coolant, and structural materials. This may be followed by a reflector region which returns as many neutrons as possible to the lithium bearing zone. Beyond the reflector there may be a coolant zone and then the shield which simply attenuates the neutron and gamma fluxes as rapidly as possible.

In some cases, there is a concern over obtaining adequate tritium breeding. This leads to the introduction of a material called a neutron multiplier because of its relatively large (n,2n) cross section in the part of the blanket near the source. Another consideration of importance for a fusion reactor is the activation of the reactor constituents. The first wall is not expected to last the life of the plant, thus maintenance and replacement will occur in the presence of the radiation by the activated materials.

Materials that have been suggested for the first wall and the structure include steels, alloys of the refractory metals, nickel based alloys, Aluminum, and Zirconium. Each has its merits from the thermal, mechanical, and fabricability points of view. From a neutron physics standpoint, steel, Niobium, and Molybdenum are good neutron moderators, have helpful (n,2n) cross sections, but they activate to long lived products to a significant degree. On the other hand, Aluminum and Vanadium have very low activation cross sections. From the standpoint of radiation damage, there are large uncertainties in all of the materials. This is due primarily to lack of materials studies in the expected radiation environment. To reduce these uncertainties there is a need for nuclear data on helium and hydrogen production as well as data for determining displacements, since the calculated production of these impurities and defects can be correlated with actual material properties.

The coolants that have been favored in most studies have been liquid lithium and helium. Liquid lithium has been given considerable attention since it is a good coolant, lithium must be present in any case, and the technology for handling liquid metal coolants could be borrowed from the fast reactor development programs. Helium is well-known as a coolant and is innocous from the nuclear standpoint. The reasons for avoiding water as a coolant are the risk of lithium-water reactions in an accident and the difficulty of removing tritium produced in the blanket from the water if leakage or diffusion result in contamination.

If a coolant other than lithium is chosen, then lithium must be introduced in a form suitable for both tritium production and removal. Lithium bearing solid compounds have been proposed for this purpose, with $LiAl_2O_3$ a prominent example. Tritium production is not expected to be a problem at the present time. However, it was considered very carefully since it is essential to sustained energy production from this fuel cycle. The possibility of using a neutron multiplier has been developed. For this purpose berylium has a very large (n,2n) cross section and is clearly the best choice. The expense and availability of berylium have resulted in the evaluation of other materials and several metals have been considered for this function including lead as well as most of the structural materials since they are present in all cases.

Another idea for increasing tritium production is to introduce a reflector behind the lithium bearing zone in analogy to the use of reflectors in fission reactors. The material should have a large scattering cross section, low scattering anisotropy, and a low neutron capture cross section. Carbon meets these criteria well and is often the choice for the reflector. However, it has been observed that if tritium breeding is more than adequate, the use of a reflector may still be desirable as the $Li^6(n,\alpha)t$ reaction is a good energy producer. The reflector material may then be chosen to minimize energy losses in the nonelastic reactions which are often endoergic. For example, there is less energy loss to the system in using a steel reflector compared to a carbon reflector.[1] The inelastic scattering in iron produces a very hard gamma which is eventually absorbed, while the $C(n,3\alpha)$ reaction results in a binding energy loss that is then not available to the reactor.

For an efficient use of the energy, on the order of 99% should be recovered at reasonably high temperature in the blanket. The remainder must be removed by the shield to protect magnets and equipment. The biological shield will be the walls of the containment structure and is treated separately. The region referred to as the shield is constrained by magnet and other equipment costs to be relatively thin and total costs may dictate the use of expensive shield materials if radiation intensity gradients can be enhanced. The most penetrating radiation is the 14 MeV neutron flux. For this reason a heavy material with a large inelastic cross section should be present. Ideally this should produce only soft gammas and not activate to a significant degree. Lead, for example meets this criteria well, but will not support itself. Iron is suitable and in the form of stainless steel is a good relatively inexpensive non-magnetic structural material. Unfortunately, iron produces the previously mentioned very hard gamma which requires a significant amount of high Z material for its attenuation. The heavy materials will only slow neutrons down efficiently at the higher neutron energies and are very inefficient below about 1 MeV. A good material to include for this energy range and for capture of the neutrons is $B_4C$. The boron and carbon will aid in moderation especially at the lower energies, and the boron capture is an $(n,\alpha)$ reaction preventing $(n,\gamma)$ capture in other materials which might produce a hard $\gamma$. Many materials have been proposed for the shield and the best choices for different situations are still not settled. The attenuation to be achieved is determined by a number of criteria. The criteria which is limiting varies with the design. Examples of these criteria are the acceptable thermal load to the magnet cryogenic system, radiation damage to the cryogenic thermal insulation or the conductor stabilizing material.

In addition to the above effects, activation of the blanket and shield constituents will result in radiation problems for maintenance operations and for wall replacement.

Cross Sections and Spectra

The neutron spectra at different locations is clearly dependent on the particular system; however, the general trend is not overly sensitive to the particular design since all have the same source, a medium mass structure and lithium. Shield materials also have enough common features to allow a typical spectrum to characterize the behavior. The system shown schematically in Figure 2 has been used to generate the representative spectra of Figure 3. This displays conveniently normalized spectra for the first structural wall, the middle of the lithium zone, the reflector, and in the lithium behind the reflector. The 14 MeV peak is characteristic of the source and is suppressed as the position gets further from the source. The dip extending from a few MeV to the 14 MeV peak results from the source neutrons being scattered below this region by inelastic collisions, with only the elastic collisions moderating the neutrons into this region. In the first zones, a fairly flat region extends to around 10 KeV in which resonances are prevalent but the average cross section remains roughly constant. There is a dip at a few hundred keV which is due to the Li elastic scattering resonance peak. At still lower energy, the flux falls off rapidly to its thermal level except in the reflector with its low thermal capture. The trend is for a softer spectrum further from the source as would be expected.

To illustrate the energy regions of importance, three responses are used here. These are the atomic displacement, the helium production, and the tritium production rates. The time independent neutron transport equation can be written in operator form as

$$L \psi = S$$

where L is the transport operator, $\psi$ the angular neutron flux, and S the neutron source distribution. The equation involving the adjoint operator

$$L^+ \psi^* = S^*$$

with solution $\psi^*$ called the adjoint flux can easily be shown to relate to the original problem through the relation

$$\int S^*(\underline{r},E,\underline{\Omega})\psi(\underline{r},E,\underline{\Omega})\,drdEd\Omega = \int S(\underline{r},E,\underline{\Omega})\psi^*(\underline{r},E,\underline{\Omega})\,drdEd\Omega$$

This leads to the interpretation of $\psi^*$ as an importance function for a source neutron to contribute to response $S^*$ which may be chosen to be a macroscopic cross section resulting in one of the responses of interest. Adjoint sources equal to the displacement, helium production, and tritium production cross sections are employed to obtain importance spectra. The displacement cross section is obtained as follows. The recoil spectra of atoms from each type of collision is determined and a solid state model employed to give the number of atoms displaced from their lattice positions by the primary knock on. The original cross section is multiplied by the number of displacements and on summing over all collision types, the displacement cross section is obtained. This response cross section is illustrated for several structural metals on Figure 4. [2] It is large at high energies as the number of displacements due to the energetic primary more than offsets any cross section differences. After decreasing with energy, it again increases at low energy where the primary energy is supplied by recoil during reactions and the increase is due to the increase is the reaction cross sections. The helium production cross sections emphasize the high energy region even more as they are usually threshold reactions. It should be noted that the appropriate cross section here is the sum over all cross sections where helium is a product, i.e., $(n,\alpha)$, $(n,n'\alpha)$ $2(n,2\alpha)$, etc. These are shown for the main constituents of stainless steel and for vanadium in Figure 5. The tritium production cross sections are not shown but consist of a very large cross section at low energies in $Li^6$ and an inelastic scattering event at high energy in $Li^7$.

Importance spectra are clearly both system and response specific, but give good insight into the energy region's that dominate a given response. Figure 6 shows importance spectra at the same points for which the flux spectra are given for displacement production in the first wall. As would be expected, the high energy range dominates but there is no 14 MeV peak. At the first wall, the top curve, the spectrum follows approximately the cross section itself. However, the remaining spectra become negligible at low energy because they stand little chance of further interaction in the first wall. Figure 7 is a similar plot of the importance spectra for helium production in the first wall. Again the largest spectrum is in the first wall corresponding to point 1 of Figure 2. These spectra emphasize the high energy neutrons in the extreme. Figure 8 shows the importance spectra for total tritium production. The first wall and main breeding zone spectra are almost superposed on top of one another since the first wall neutrons at most energies end up in the breeding zone. At the very lowest energies there is a difference and the first wall spectra is the lowest of the four. The initial drop for the first few MeV below 14 MeV occurs as the energy passes through the $Li^7$ breeding reaction. The reflector spectrum shows all energies to be of essentially equal importance as most neutrons of any energy in the reflector will end up contributing $Li^6$ reactions in one of the lithium zones. The low importance, except at the lowest energies, of neutrons in the second lithium zone results from the thinness of the zone so most neutrons will simply leak into the shield.

There is a well developed formalism for determining the effect of data uncertainties on uncertainties in design responses. The information is summarized by a sensitivity coefficient or function. If an uncertainty in cross section for reaction Y, $\delta\sigma_y$ results in an uncertainty $\delta R_x$ in response $R_x$, this coefficient is defined as

$$\frac{\delta R_x}{R_x} / \frac{\delta \Sigma_y}{\Sigma_y} .$$

If this is not integrated over energy, a sensitivity profile results which can be determined in terms of $\delta L_y$ the perturbation of the transport operator, $\psi_x^*$, and $\psi$. This is very specialized information as it is system, response, material, and reaction specific and thus will only be representative for a narrow range of designs. Three examples have been carried out to illustrate the sensitivity concept. The first example considers the tritium breeding of the system of Figure 2, and its sensitivity per unit energy to the stainless steel cross sections in the first wall and in the middle of the breeding zone.

The results are shown in the lower and upper curves respectively for these points. The sensitivity is greater for changes involving the center of the breeding zone as is appropriate for this response. The profile may be either positive or negative depending on whether the source or loss terms of the transport operator containing the cross sections in question dominate. Actually the absolute values are plotted for convenience. In this particular case the upper curve corresponds to positive values to the mark at a few KeV and to negative values above this. Lower values are positive as scattering from the larger flux at higher energy dominates, the losses due to collisions at these low energies. Above the mark the effect is negative as the total cross section is larger than the scattering cross section at higher energy while the spectra are closer to the same value. A large amount of detailed interpretation is possible. For example, the initial drop occurs both due to the source peak and the threshold nature of the breeding reaction in $Li^7$.

Similar insights are gained from Figures 10 and 11 for the displacements per atom and helium production respectively. Both show the extreme importance of the high energy data compared to the low energy data. The effects illustrated are for the entire contribution of the material in question. One could also do this by individual reaction for even more detailed analysis of the influence of data on design quantities.

## Current Status

The interest in this field is indicated by the large division of the American Nuclear Society devoted to controlled thermonuclear research with several sessions at a recent national meeting devoted to the nuclear analysis aspects of fusion power. This interest is widely dispersed geographically and indicates that many nations are starting to look beyond the confinement problem to the reactors. The general technology problems have been the subject of several conferences and have recently been reviewed.[3]

The neutron aspects of fusion divide naturally into the calculational methods and the nuclear data. Both areas have borrowed heavily from the fission reactor development of the past thirty years. The calculational approaches have thus far been completely taken from earlier work. It appears that special methods and computer programs for fusion will require only modest extensions of those already available. Nuclear data needs extend very significantly the data base needed for fission. The energy range of importance now extends to at least 14 MeV whereas in fission there is only a nominal interest above about 5 MeV. In this higher energy range the number of reactions of consequence increases dramatically. A response function involving these reactions is the energy deposition cross sections or kerma factors which played a very minor role in fusion but are quite important in fusion where the neutrons carry most of the energy. Some of the materials of prime interest are also new. The data needs have been reviewed recently [4] in greater detail.

While the data needs have not always been met, and much data is of rather uncertain quality, the data community has generally been very responsive. Some very good data has been available from the weapons programs and the data files and evaluation procedures developed for fission and other applications have been extended to allow the handling of the needs of fusion. [5] Computerized implementations of nuclear models have been used to fill in some of the needed data. [6] At this point, data is available for fusion power studies and we are just starting the assessment of its adequacy.

Several studies [7,8] have looked at tritium breeding and the lithium cross section data. While the final assessment must await large scale tests; it seems that adequate breeding is possible with existing data uncertainties. The materials degradation by the radiation is very uncertain, but this stems from materials behavior more than from data uncertainty. While materials performance may be a limiting factor in fusion systems, additional nuclear data will have only a small impact on the problem. A possible exception here are the total helium production cross sections which are often not well-known. There are current experimental programs to reduce this problem.

The real importance of better nuclear data on neutron interactions for fusion will be felt in the details of reactor economics. Since competitive power systems will not be reached in the present century, there is no great urgency in carrying out detailed improvements in much of the data. This allows time for a careful appraisal of the results from experimental reactors. Those cross sections of prime importance can be studied using the formalisms developed to date to establish quantitative information on required accuracy. [9,10]

The discussion to this point has not mentioned the fusion-fission hybrid reactor concept in which the fusion neutron source drives a blanket consisting at least in part of fertile and fissile materials. Such a system can amplify the energy production from fusion alone and breed fissile fuel for use in other reactors. A variety of optimizations are possible in such systems. Much of the neutron data needed is well-known from the intensive studies for fission reactors. The higher energies have again not been explored intensively. The interactions of greatest importance in this energy range are the fission, (n,2n), and (n,3n) cross sections. The energy distribution of the secondary neutrons from these reactions will be important to the systems performance. [11]

The neutron data of greatest near term interest is that required for the first large experiments to produce intense fusion neutron sources or simulations of such sources. In order to characterize spectra precisely, dosimetry must be well-developed in the energy range above a few MeV. Since D-Li and other neutron producing reactions are proposed for use in intense neutron sources, spectra extending well above 14 MeV must be characterized to aid in evaluating the appropriateness of each source in simulating effects in a fusion reactor. [12]

Activation data is also of importance in the near term due to its consequences for shielding and maintenance. [13]

## Conclusions

Neutron interactions are of great interest for fusion development programs. They will influence many reactor design and operational decisions, and affect plant economics. The crucial tritium breeding reactions possess cross sections that currently seem adequate to assure the fuel supply. The cross section data will play an important role in materials research both as a basis for correlating damage data to the radiation and in characterizing the radiation environment in which studies are carried out. Other data effects are primarily economic and not as urgently needed. A continuing assessment program is necessary to quantify priorities and necessary accuracies.

## Acknowledgements

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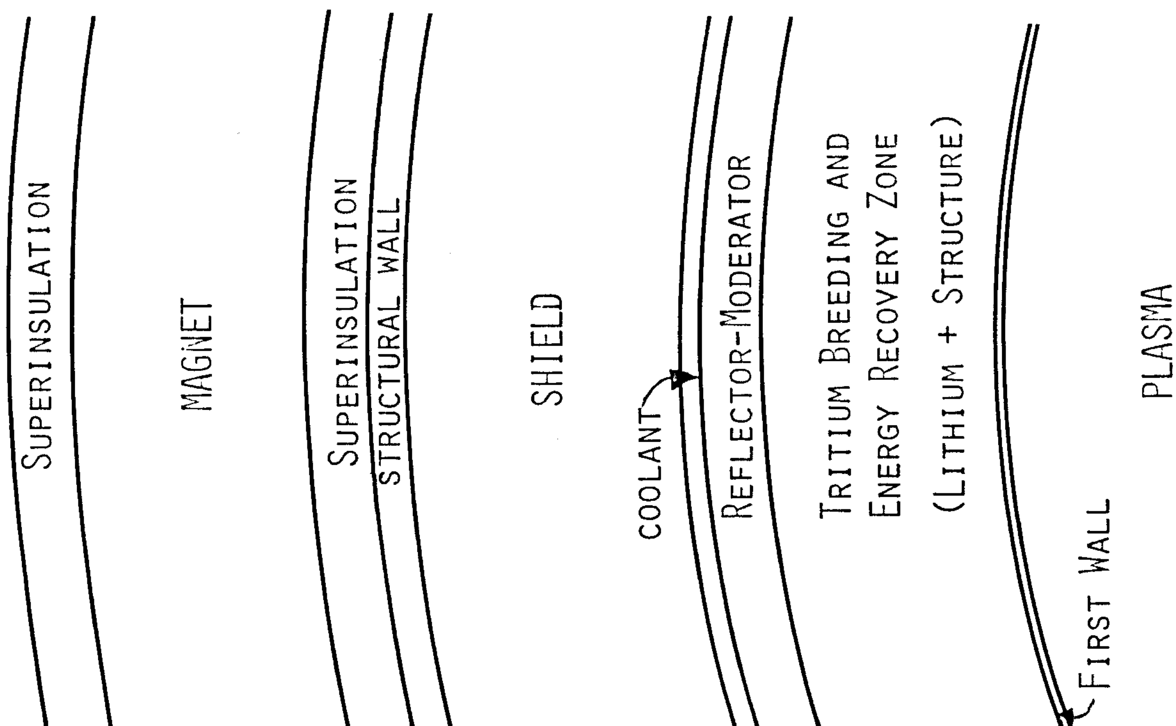
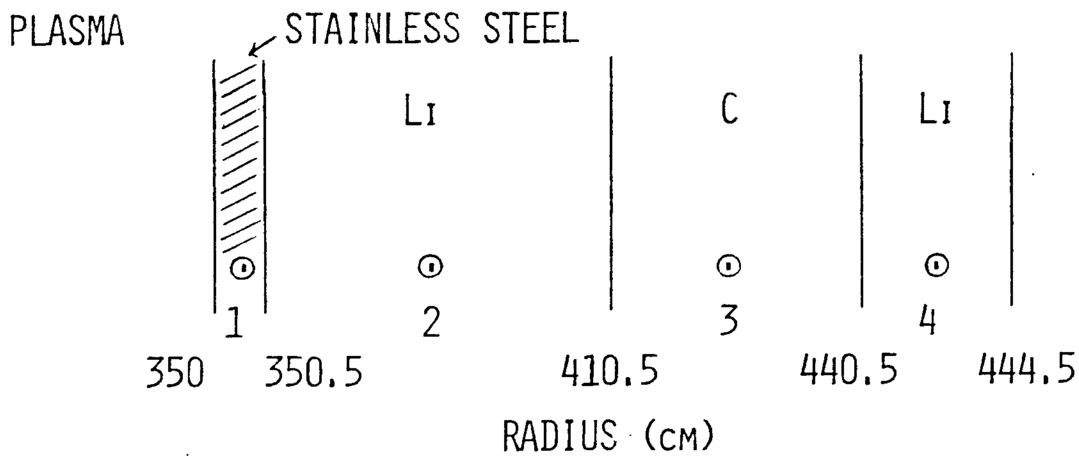


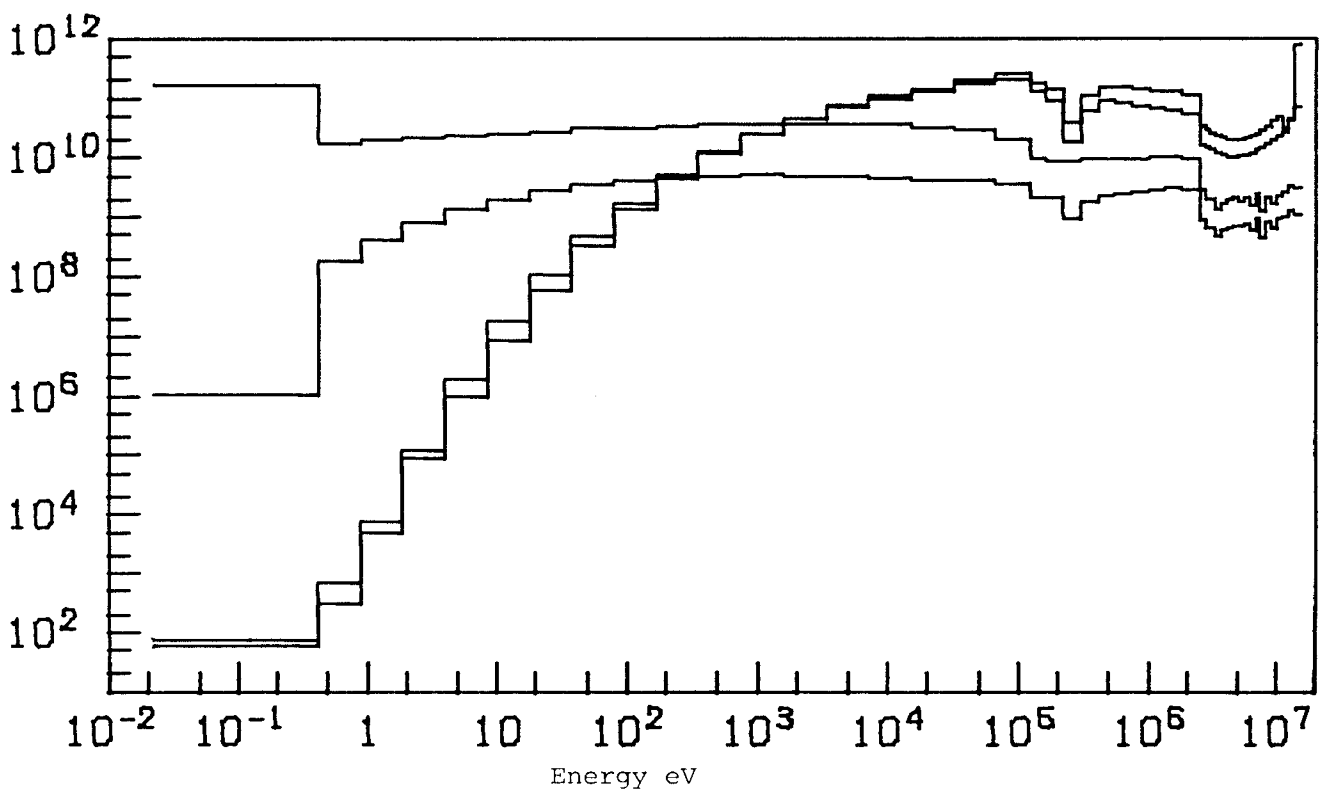

SCHEMATIC OF BLANKET AND SHIELD REGIONS

FIGURE 1

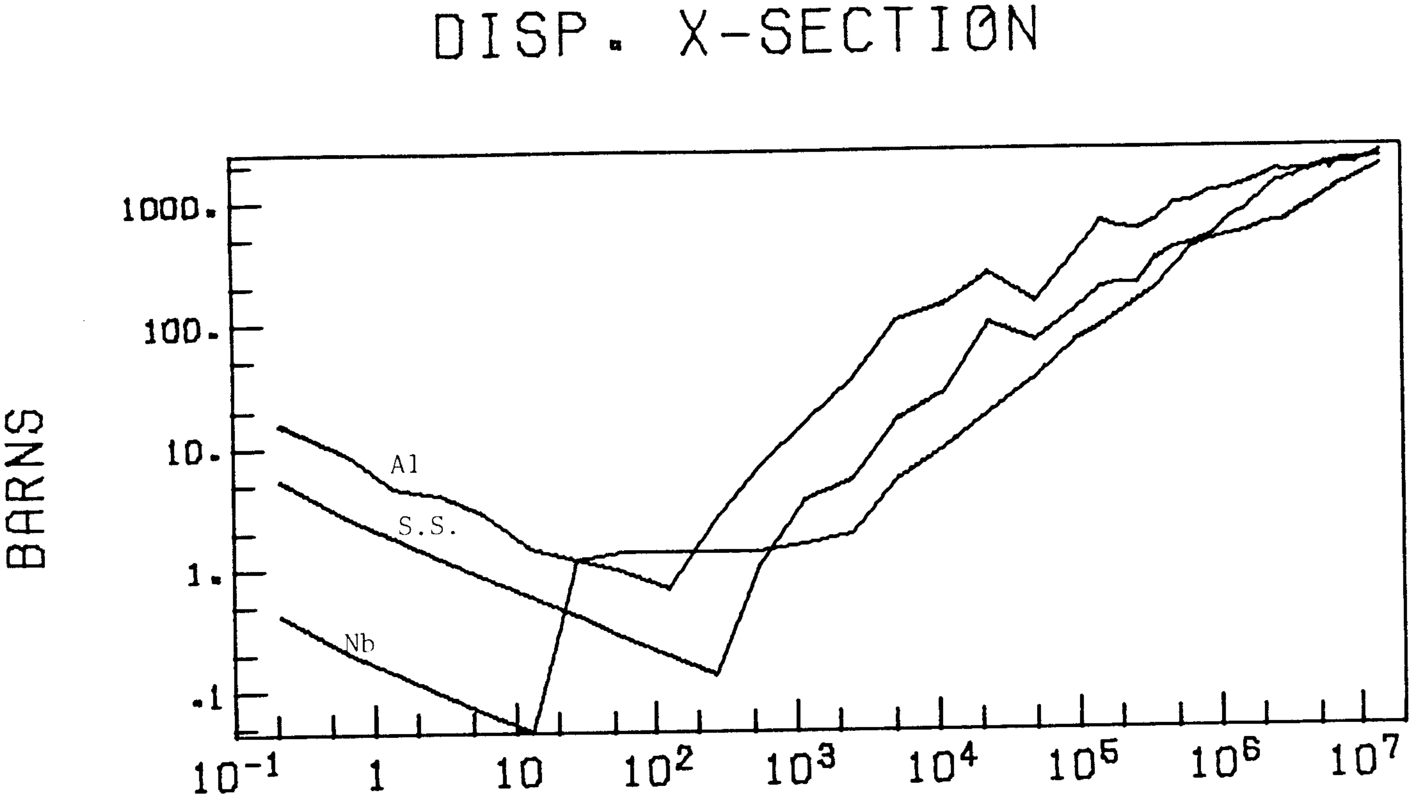



A CYLINDRICAL, 46 ENERGY GROUP, $S_4$, $P_3$ CALCULATIONAL MODEL IS EMPLOYED FOR THIS BLANKET SCHEMATIC.

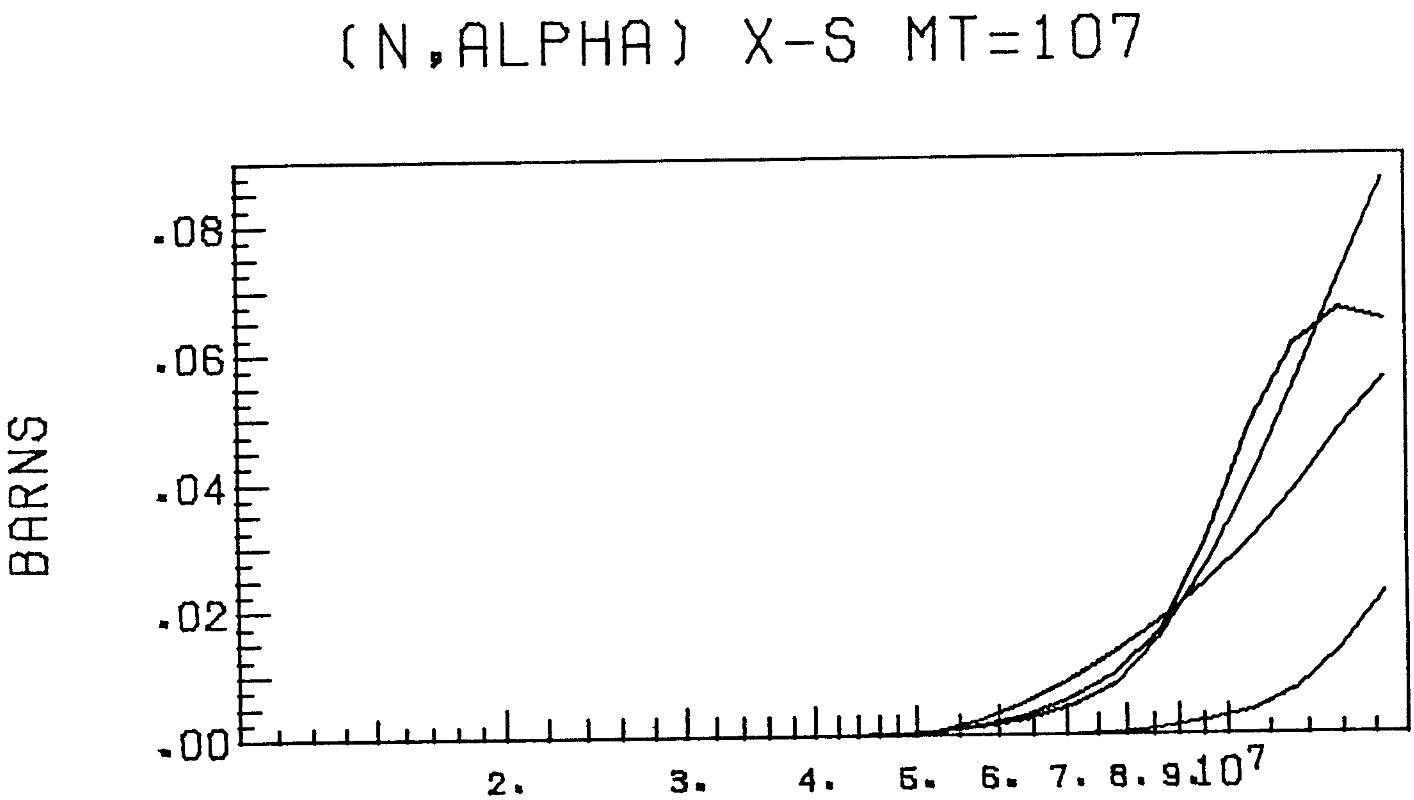
Figure 2



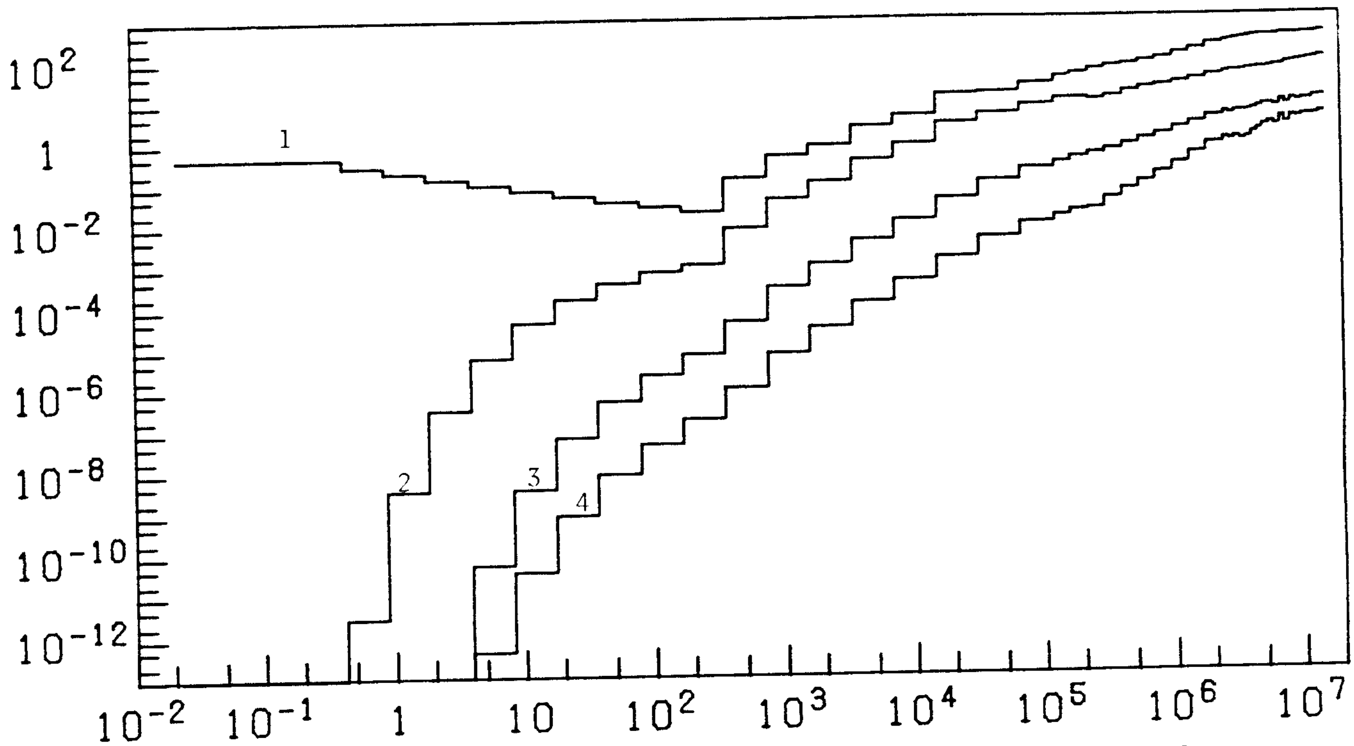

Flux spectra in arbitrary units versus energy. Numbers refer to points designated in Figure 2.
Figure 3




Displacement cross section in barns versus energy in eV for aluminum, stainless steel, and niobium.
Figure 4

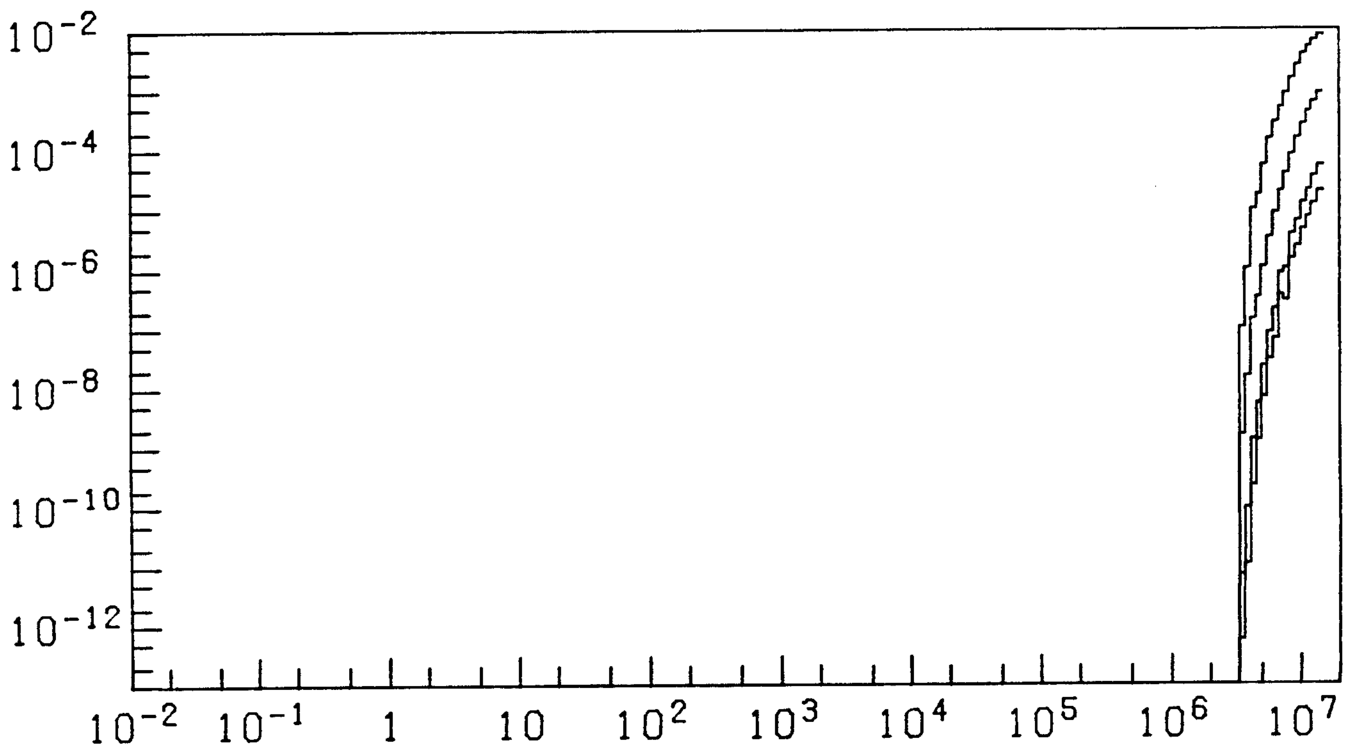



Helium production cross section in barns versus energy in eV for iron, chromium, nickel, and vanadium. Original data from ENDF/B4
Figure 5

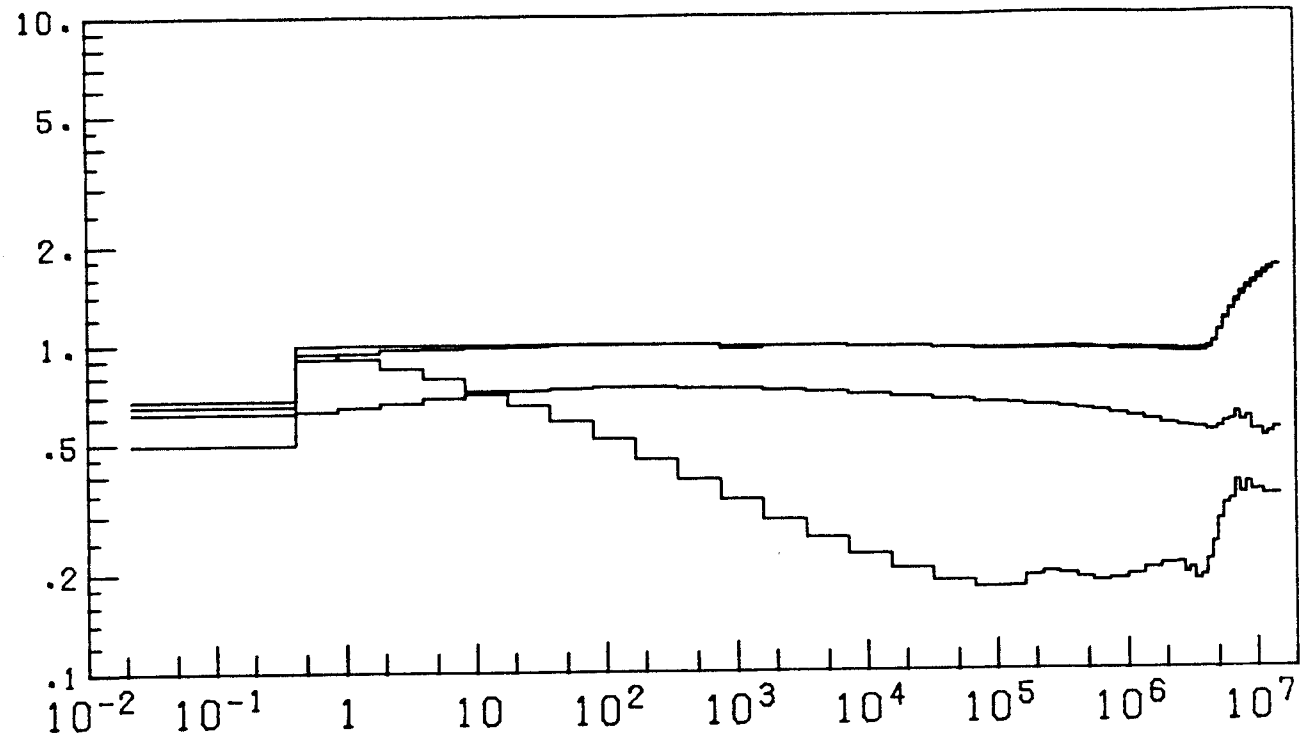



Importance Spectra for displacement production in the stainless steel first wall versus energy in eV at the numbered points of figure 2.
Figure 6

FIRST WALL HELIUM PRODUCTION IMPORTANCE SPECTRA

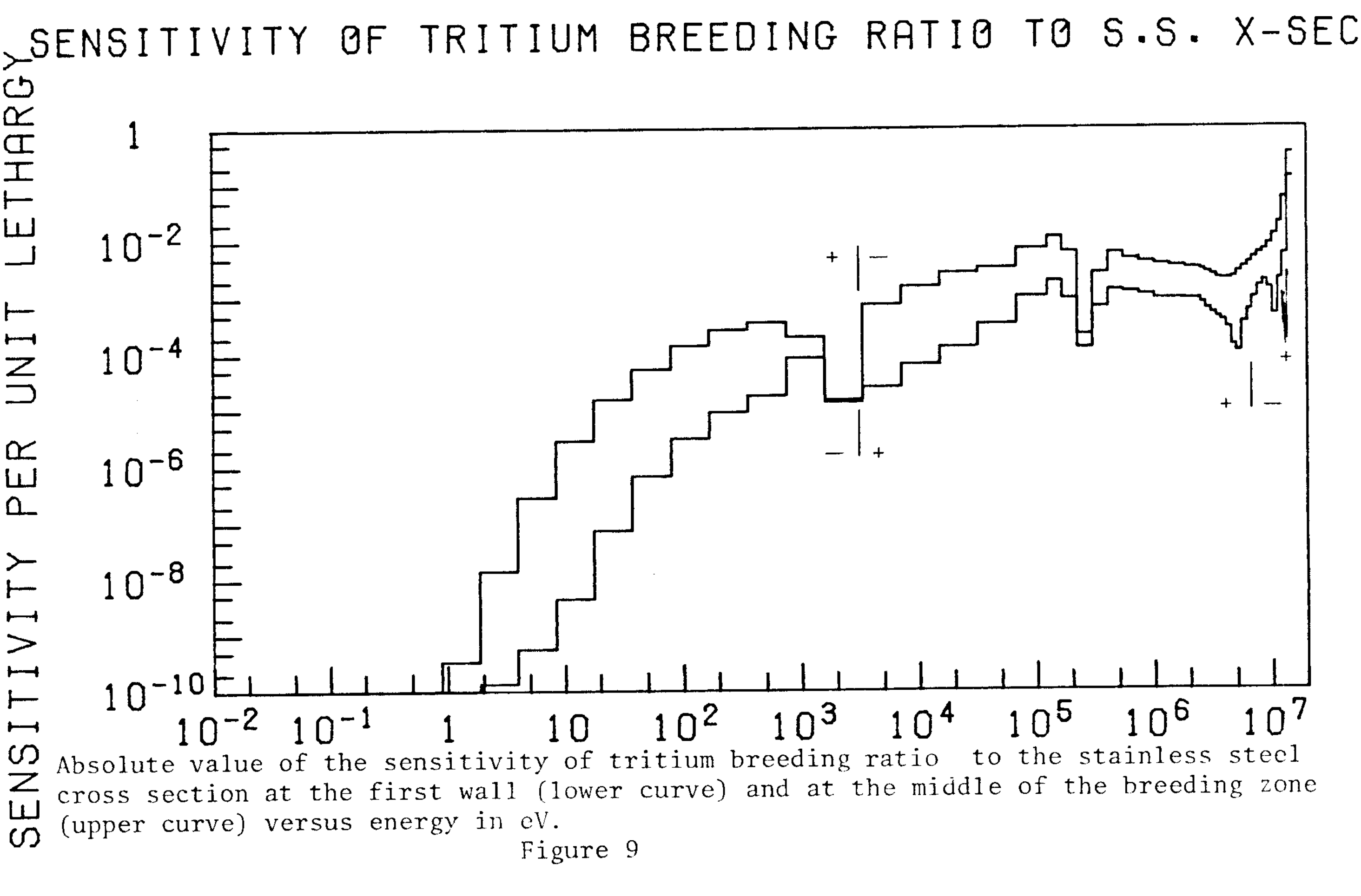



Importance spectra for helium production in the first wall as a function of energy in eV at the points for which flux spectra are given in Figure 2.
Figure 7



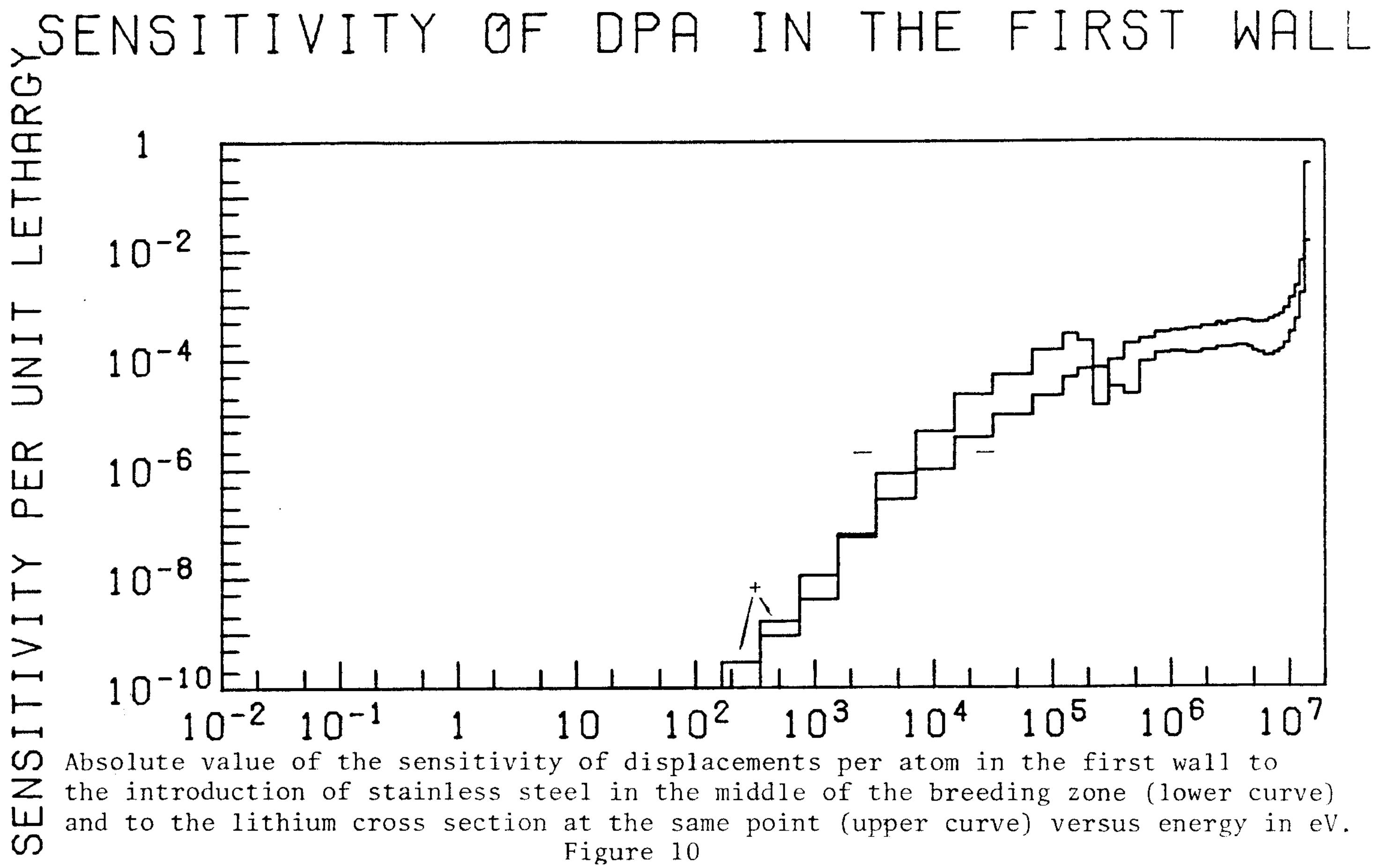

Importance spectra for total tritium production versus energy in eV for the numbered points of Figure 2.

Figure 8



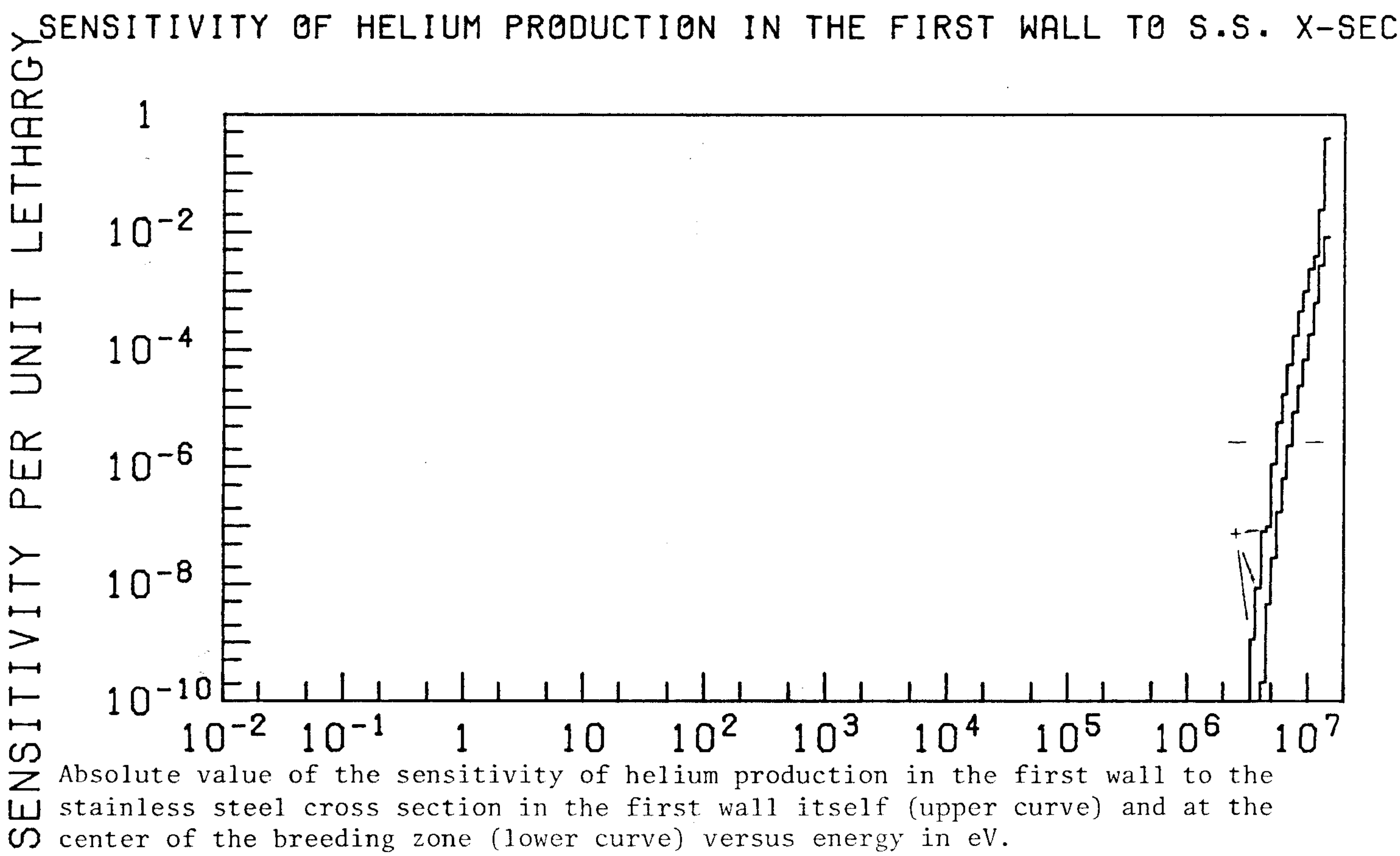

Absolute value of the sensitivity of tritium breeding ratio to the stainless steel cross section at the first wall (lower curve) and at the middle of the breeding zone (upper curve) versus energy in eV.

Figure 9




Absolute value of the sensitivity of displacements per atom in the first wall to the introduction of stainless steel in the middle of the breeding zone (lower curve) and to the lithium cross section at the same point (upper curve) versus energy in eV.

Figure 10




Absolute value of the sensitivity of helium production in the first wall to the stainless steel cross section in the first wall itself (upper curve) and at the center of the breeding zone (lower curve) versus energy in eV.

Figure 11

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