Nuclear Data Requirements For Fusion Reactor Shielding*

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Abstract

The nuclear data requirements for experimental, demonstration and commercial fusion reactors are reviewed. Particular emphasis is given to the shield as well as major reactor components of concern to the nuclear performance. The nuclear data requirements are defined as a result of analyzing four key areas. These are the most likely candidate materials, energy range, types of needed nuclear data, and the required accuracy in the data. Deducing the latter from the target goals for the accuracy in prediction is also discussed. A specific proposal of measurements is recommended. Priorities for acquisition of data are also assigned.

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1. Introduction

The function of the shielding system in any nuclear reactor is: 1) to protect reactor components from intolerable levels of (a) radiation damage, (b) nuclear heating, and (c) induced activation that may result in maintainability and disposal problems; and 2) to protect workers as well as the general public from intolerable radiation exposure at all times during operation, shutdown, scheduled maintenance, and unscheduled failures.

Shielding calculations require methods and data to predict the nuclear performance parameters of interest. An extensive base of methods and data exists in the highly-developed fission field. However, the specific nature of fusion reactor systems and the high neutron energy range of interest make it necessary to pursue a research and development program to extend and improve the methods and nuclear data. The purpose of this paper is to detail the nuclear data requirements for experimental, demonstration, and the first generation of commercial fusion power reactors.

The scope of the paper is limited to fusion reactors operated with the D-T cycle. However, since roughly half the energy of the neutrons in the D-D cycle is carried away with 14 MeV neutrons, almost all general results and conclusions are also applicable for reactors operated on the D-D cycle with modest modifications. Both magnetic and inertial-confinement reactors are discussed, but most of the details are focused on the former with particular emphasis on tokamak-type reactors.

For convenience of the reader, the discussion of the nuclear data requirements in Sec. 3 is preceeded by a brief description of the fusion reactor shield components in Sec. 2. In addition, a rather comprehensive list of references is given at the end of the paper to cover publications related to fusion reactor shield. References 1-25 cover the general problems of the technological requirements for fusion power development. Some of these are conceptual designs for fusion power plants and include detailed discussions of the shielding problems. References 26-45 address the problems of the bulk shield. References 51-58 focus on the radiation streaming problems in fusion reactors.

It is useful to conclude this introductory section by underlying both the importance and difficulty of shielding fusion reactors. This may best be accomplished by comparing the problems of fusion reactor shielding in reference to those of the more familiar systems of fission reactors. The following items explain the key points of comparison:

(1) The blanket and bulk shield in fusion reactors are penetrated by many more large-size holes than are fission reactors. Fusion reactor penetrations are directly exposed to the energetic source neutrons and the functional requirements of some of them exclude making any significant bends in the penetration ducts.

(2) The 14 MeV neutrons produced in the D-T cycle are much more capable of deep penetration than are the fission neutrons whose average energy is ~2 MeV. Furthermore, the high energy neutrons induce a variety of nuclear reactions, with many radioactive residual nuclei, that are inaccessible to lower energy neutrons.

(3) The recoverable energy per fission reaction is ~9-10 times larger than that of a fusion reaction. Therefore, for the same power, a fusion reactor has ~4-5 times more neutrons than in a fission reactor.

(4) The interrelations between the shield and the components of the reactor are much more complicated in fusion compared to fission reactors. In addition, there are many major components of fusion reactors that are very sensitive to radiation and require extensive measures of radiation protection.

(5) Most fusion reactor concepts call for major scheduled maintenance tasks that require more time and manpower than in any of the fission reactors. This fact together with those in 1-4 make the problems of radiation exposure and maintainability in fusion reactors extremely important.

Nothing in the above points suggests that fusion reactor shielding problems cannot be solved at a reasonable cost. They do suggest, however, that the problems are difficult and prudent economically viable solutions need to be worked out early in the fusion reactor development. Obviously, the availability of a good base of methods and nuclear data is crucial to acccomplishing this goal.

2. Fusion Reactor Shield Components

Fusion reactors can be classified into two types according to the plasma confinement scheme: a) magnetic-confinement reactors (MCR), and b) inertial confinement reactors (ICR). Many of the shielding problems in MCR's and ICR's are similar, but there are several key differences. This section provides an overview of the shield components and their functions in the two types.

The shield system in fusion reactors consists generally of the following components: 1) blanket, 2) primary bulk shield, 3) penetration shield, 4) component shield, and 5) biological shield. Figures 1 and 2 demonstrate the physical relationship among these components and other reactor subsystems in the two leading magnetic-confinement schemes of tokamaks and mirrors. Figure 3 displays this relationship for a laser driven reactor, a leading contender among inertial confinement schemes.

The primary function of the blanket is to convert the kinetic energy of fusion neutrons and secondary gamma-rays into heat. It provides, of course, a significant amount of radiation attenuation. The neutron source strength in the fusion core is 0.625×10^{19} P/E_f neutrons/sec where P is the reactor thermal power in MW and E_f is the recoverable energy per fusion reaction in MeV. In the absence of energy multiplication by fissionable materials, E_f in reactors operated on the DT cycle is ~20 MeV. Thus, the neutron source strength is $\sim 3 \times 10^{20}$ neutrons/sec for every 1000 MW of thermal power. Tokamaks and mirrors are operated at quasi-steady state, and steady-state while ICR's are operated with repetitive short pulses. The above source strength is a time-average. In ICR's and MCR's the blanket must contain lithium in one form or another to regenerate tritium. The magnitude of radiation attenuation provided by the blanket in both types of reactors is roughly the same as the blanket must extract ~95-99% of the energy of the neutrons and secondary gammas.

The primary bulk shield[26-45] circumscribes the blanket. The basic function of the bulk shield is to protect reactor components exterior to the blanket from intolerable levels of nuclear heating, radiation damage and activation. The largest difference in shielding ICR's and MCR's comes from the markedly different boundary conditions for the primary shields in the two-types of reactors.

In magnetic-confinement reactors the primary magnetic field for plasma confinement is normally provided by superconducting magnets. Removal of heat from superconducting magnets at ~4°K is a powerconsuming process; about 300 watt of electric power is required to remove one watt of heat deposited in the magnets. Furthermore, heat generated in the magnets create distortions and stresses in the magnet particularly if the heat is generated non-uniformly. The components of a superconducting magnet are overly sensitive to radiation and the irradiation effects in these components strongly affect the design, operation, stability and safety of the magnets. Therefore, considerations of protecting the main superconducting (S.C.) magnets dominate the design criteria for the primary bulk shield in magnetic-confinement fusion reactors.

The trade-offs in the design of the bulk shield and the main magnets strongly impact the performance and economics of magnetic confinement reactors. Keeping the thickness of the bulk shield small results in unacceptably large power losses to run the S.C. magnet refrigerators as well as intolerable levels of radiation damage. Increasing the thickness of the primary bulk shield require displacing the magnets further from the plasma. This results in a reduction in the strength of the magnetic field in the plasma region and the reactor power in addition to an increase in the size of the magnets and the reactor. These considerations are discussed in Ref. 31.

Since inertial confinement fusion reactors do not require magnets the design considerations for the primary shield are very similar to those in fission reactors. Space restrictions remain as important shield design considerations, but they are much more relaxed compared to those in magnetic-confinement reactors.

Present conceptual designs for fusion reactors call for many largesize holes to penetrate the blanket and bulk shield. The most troublesome of all these penetrations are those for supplementary plasma (or pellet) heating and vacuum pumping in MCR's and ICR's in addition to impurity control penetrations in MCR's. Shielding these penetrations represents a new challenge that no other nuclear system had to cope with before. The challenge can best be understood by recalling some of the characteristics of these penetrations: 1) large size, the cross section area varies from ~0.4 to 3 m^2, 2) these penetrations have openings in the first wall directly visible to the source neutrons generated in the fusion core; they pass through the blanket and bulk shield and extend to the reactor exterior leading to large size expensive equipment, and 3) the functional requirements of some of these penetrations do not permit significant bends in the penetration ducts.

The presence of penetrations makes it impossible for the bulk shield alone to satisfy the functional requirements of the primary shield. Penetration shields are, therefore, required as a necessary part of the primary shield and reactor design. A penetration shield is a mixture of attenuating materials that completely surrounds the penetration as it emerges from the bulk shield and extends to the penetration functional equipment (e.g., injector for neutral beams, pump for vacuum pumping, laser building for laser beams, etc.). Radiation streaming and penetration shielding is discussed in Refs. 51-58.

Two types of component shields are required. The first is to attenuate the radiation that streams through the component. Examples are the shields around the beam injector chamber and the vacuum pumps (see Fig. 1). The second type is the shield provided locally to protect a component that is overly sensitive to radiation such as some of the instrumentation equipment.

The primary shield which consists of the bulk, penetration and component shield provides for protection of components during reactor operation. Its biological shielding function is limited only to reducing the induced activation to appropriate levels as required by maintenance tasks during shutdown. The biological dose outside the reactor during operation is several million rems/hr. Therefore, a biological shield is necessary. Since the reactor building is required to be ~2-3 m of concrete to satisfy the structural containment function, the walls of the reactor building are presently conceived to serve the dual purpose of providing the necessary containment as well as biological shielding. It appears unlikely that practical designs to permit any type of personnel access into the reactor building during operation can be developed. On the other hand, fusion reactors require periodic major component replacement and maintenance tasks and the need for some personnel access into the reactor building after shutdown is unavoidable even with remote maintenance planned for. These considerations are discussed in Ref. 92.

3. Nuclear Data Needs

Commercialization of fusion power requires an aggressive research and development program in a large number of technical areas.[1-25] In the nuclear design area, we are very fortunate to have the extensive methods and data information base that has been developed over the past thirty years in the fission and weapons programs. Up to the present, the nuclear analysis of fusion reactors has relied almost entirely on this information base. It must be realized, however, that a nuclear design of an actual fusion reactor requires[77] some research and development (R&D). These R&D requirements can be characterized as low risk extensions and improvements to the state-of-the-art. However, they are also indespensible as they serve critical needs related to the reactor performance as well as economic, environmental and safety considerations. Much of these needs will have to be satisfied before building the next generation of experimental power reactors planned for the midto late 1980's.

The nuclear aspects of a fusion reactor can be classified into methods and data. The state-of-the-art and required developments in calculational methods were reviewed in Refs. 74, 75 and 92. In this section, the attention is focused on nuclear data needs; the subject of this meeting. Although our main concern is shielding, the data requirements for general fusion neutronics are covered as well.

As a first step, one needs to define the materials of concern. Table 1 gives a summary of materials being considered for the blanket and shield excluding hybrid applications. Table 1 shows the actual form of material to be used, but Table 2 shows the elemental materials of potential use in the blanket, shield and other fusion reactor components. The reason the list is long is that at this stage there is a diversity of design concepts and a number of reactor types for which the appropriate selection of materials vary widely. There is presently no committment to a specific reactor design with a definite material selection. This represents one of the serious difficulties in establishing the priorities in a nuclear data measurements program. Nuclear data is, of course, required for all these materials as a part of the input to the comparative technical evaluations necessary to select design concepts and materials. However, most of the requirements for this purpose can generally be satisfied by presently available data with a modest effort of data evaluation.[78] The major concern is the nuclear data measurements. Because of cost and limitations on available experimental facilities these measurements must be kept to a minimum. An important consideration, however, is the long time that these measurements consume. In order to ensure timely availability of important data needs, one is forced to make judgements now about the material selection. To satisfy this purpose, we have indicated a qualitative judgement in Table 2 on the probability of using each material in 1) the next generation of experimental power reactors, and 2) the demonstration and commerical power plants. These are careful judgements, but as our knowledge deepens and expands some of them may change.

The second area of concern in identifying the nuclear data needs is the energy range of interest. In fusion design application, this energy range extends from thermal energies to at least the average energy of the D-T neutrons, i.e. 14 MeV. It should also be noticed that there is a considerable width in the spectrum of the source neutrons emitted from DT plasmas significantly heated or driven by injecting energetic deutrons. Therefore, the high energy limit for nuclear data should extend to ~16 MeV. There are other fusion-related applications, such as materials irradiation facilities with D-Li neutron source, that require extending the data base to ~30 MeV, but these are not covered here as our concern is focused in this paper on reactor design applications. The fact that the energy range of the greatest importance in fusion extends to 16 MeV while there has been only a nominal interest above 5 MeV in fission suggests that most of the new nuclear data measurements needed for fusion is in the energy range 5-16 MeV.

The third area of concern is the type of nuclear data required in fusion design applications. Table 3 shows these data types. The nuclear designer needs to calculate: 1) Tritium breeding in the blanket and tritium production that may contaminate other regions, 2) nuclear heating, 3) radiation damage indicators (atomic displacement, gas production and transmutations), 4) induced activation and related parameters such as the decay heat and biological dose, and 5) neutron and gamma-ray shielding attenuation characteristics. To evaluate these quantities one needs a variety of nuclear data that can be broadly classified into three areas: a) neutronics, b) γ-ray production, and c) gamma-ray interactions. The nuetronics data consist of cross sections for individual neutron reactions and secondary neutron energy and angular distributions. The reactions of importance are most affected by the energy range of interest which extends to ~16 MeV. For example, high energy neutrons are capable of inducing a variety of important reactions that are inaccessible to lower energy neutrons. Therefore, in fusion design one needs cross sections for reactions such as (n,α), $(n,n'\alpha)$, (n,p) and $(n,n'p)$ for which there is presently no or little information for several important materials.[79-81] It should be emphasized that while lumped cross sections such as the total helium production cross section may be suitable for radiation damage calculations, induced activation requires cross sections for individual reactions. Furthermore, accurate calculation of induced activation requires the nuclear data for each individual isotope. It has also been shown[79,80] that although nuclear heating calculations can be made directly from lumped data for a mixture of isotopes, the correct averaging of data, e.g., energy dependent Q-values, implicitly assumes that the isotopic data is known.

Since shielding plays a major role in fusion design, the data requirements for shielding must be emphasized. These requirements are generally different from those for the blanket. In shielding, the main interest is neutron and gamma attenuation, deep penetration and streaming. This requires emphasizing the 1) accuracy of basic cross sections such as total and elastic and inelastic scattering, 2) gamma-ray production and interaction, 3) energy and angular distribution of secondary neutrons and gammas; scattering anisotropy is generally crucial to streaming and deep penetration problems, and 4) good resolution of cross section minima.

Gamma-ray production data is very crucial to nuclear heating and radiation shielding application. The status of nuclear data in this area is particularly serious despite significant recent improvements reflected in the latest ENDF/B version.[82] For example, there is presently no reliable gamma production data for important materials such as ^{11}B and tungsten. The data measurements and evaluation for gamma production can actually be simplified by recognizing that only two types of information are required: a) the total gamma production cross section as a function of the incident neutron energy, and b) the energy distribution of emitted gammas as a function of the incident neutron energy. The angular distribution of emitted gammas is also required, but at a lower priority since the nature of the volumetric source distribution tends to largely compensate the modest anisotropies in emission. Measuring or identifying gamma production by reaction and isotope is of secondary importance except in special cases.

Nuclear data for gamma-ray interaction is generally the best known of all types of data. Only modest revisions are required in this area.

The fourth area of concern in defining the nuclear data needs is the required accuracy in the data. This is a difficult area and is a part of the more general question of the required accuracy in predicting the nuclear performance characteristics. The errors in nuclear calculations come from a variety of errors and approximations such as those in data measurements, data representation in evaluated files such as those of ENDF/B, data processing, multigroup energy representation, geometric representation of the system, transport calculations and response function evaluation. Therefore, a knowledge of the target accuracy in the estimated nuclear parameters is necessary but not sufficient to define the accuracy goal for the basic nuclear data.

The desirable accuracy in predicting the nuclear performance characteristics can be determined from an elaborate cost-benefit analysis. The cost is principally that of the research and development, the man and computer-time for performing the calculations and verification experiments. The benefits are the economic gains realized by reducing the degree of conservatism usually necessary to assure satisfactory operation and safety of the power plant. For example, overpredicting radiation attenuation in the shield has very serious consequences of impairing operation of many fusion reactor components, increasing the number of unscheduled failures, reducing plant availability and increasing the potential of radiation exposure. The seriousness of the situation is compounded by the fact that there is normally no space for shield improvement after the reactor has been built. Therefore, shielding calculations are always required to be conservative. The larger the uncertainties in prediction the higher the safety margin and the degree of conservatism have to be. A high degree of conservatism in shield design can be an unacceptable burden on the reactor economics.

It is very doubtful that a reliable cost-benefit analysis of the type referred to above can be performed for fusion reactors for many years, and perhaps decades, to come. Quantifying the costs and benefits is extremely difficult in practice. It appears, therefore, that the fusion community has to be content with only evaluating the penalties resulting from uncertainties in prediction or the benefits that can be derived from improving the accurancy of prediction. This is still a difficult task, but some effort in this area is definitely required as a part of fusion reactor research and development program. For our purpose here let us qualitatively discuss an elementary example. Figure 4 shows[31] the cost of energy in a tokamak reactor as a function of the blanket/shield thickness, Δ^i_{BS}, on the inner side of the torus with stainless steel and boron carbide as the constituents of the blanket/shield. The results are shown for several sizes of the major radius. At present, the tokamak design effort is focused on small size reactors of major radius R = 6 m or less for better economics. From Fig. 4 one notices the great sensitivity of the cost of energy to the value of Δ^i_{BS} at $R \leq 6$ m. The optimum value of Δ^i_{BS} is ~1 m. Using smaller values of Δ^i_{BS} will result in a sharp increase in the cost of energy due to the large increase in the power required to run the superconducting magnet refrigerators and the large increase in the magnet cost necessary to accomodate higher radiation levels. At these small values of Δ^i_{BS} there are risks associated with the reliability of the operation and safety of the magnets. Therefore, it appears now that the design value for Δ^i_{BS} must be greater than the optimum value of 1 m. Figure 4 indicates the penalty in the cost of energy resulting from using larger Δ^i_{BS}.

One should carefully note here that the penalty as shown in Fig. 4 is due to the increase in Δ^i_{BS} with the shield actually performing as calculated. The penalty from increasing Δ^i_{BS} and the shield providing less attenuation than calculated is much larger than that in Fig. 4. To provide a more realistic indication of this penalty we have plotted in Fig. 5 the cost of power as a function of the additional non-shield increase, δ, in Δ^i_{BS}. This is roughly the effect of the actual thickness of the blanket/shield built as $\Delta^i_{BS} + \delta$ while its attenuation is only that predicted by the present calculation for a thickness Δ^i_{BS}. The results in Fig. 5 suggest that for small-size tokamaks the penalty of the increased cost of power can be as high as 1% (for a 1000 MWe this is ~20 million dollars) for every loss of attenuation equivalent to that provided by only 1 cm (in this example, 1 cm is 1% of Δ^i_{BS}) of shielding. This is a very large penalty and serves to demonstrate that very good accuracies will be required for most of the shielding calculations in fusion reactors.

In Table 4, we attempt to define some target accuracies in predicting the important nuclear parameters in the blanket, shield and other reactor components where radiation is of concern. As in many instances in this section, these must be viewed as careful judgements some of which may change as our experience and knowledge of fusion reactors deepen and expand. A few notes on the accuracies defined in Table 4 are in order. Generally, very good accuracies are required in the blanket where primary energy conversion, tritium production and severe radiation damage occur. The target accuracies for calculating the nuclear responses in the shield can be much less than those in the blanket. However, the need for relatively high accuracies in predicting the nuclear responses in the superconducting magnets in MCR's requires that the characteristics of the radiation emerging from the bulk shield (and penetration shields) be known to an appropriately good accuracy. Only a factor of 2-3 has been set as the target accuracy for the biological dose in the reactor floor (outside the bulk shield) and outside the reactor building. Better accuracies are, of course, desirable, but they are not practically achievable because of the large number of decades of radiation attenuation involved.

The most difficult question is to define the accuracy goals for each type of basic nuclear data measurement for each material. These goals must, of course, be consistent with the target accuracies for predicting the nuclear design parameters discussed above and shown in Table 4. But two key questions arise. One is how much of the tolerance in design calculation accuracy can be permitted for nuclear data. The second is how much inaccuracy in estimating a nuclear performance parameter results from an error in a particular part of nuclear data in a specific energy range for a given material.

Sensitivity analysis[83] is generally resorted to for defining the nuclear data accuracy needs. The general purpose of the sensitivity analysis is to determine the sensitivity of calculated parameters for a nuclear system to the information used. Thus, sensitivity analysis can be utilized to examine the effects of uncertainties in nuclear data as well as variations in materials and geometry on the calculated parameters of interest. In the past few years, there has been a very significant progress in developing theoretical formalisms and computer codes for sensitivity analysis.[84,85] The lastest of these developments is the channel theory[86] which makes it possible to determine the "channels" in space and energy that contribute most to the radiation field in a particular location. A number[87-90] of sensitivity studies for fusion applications have also been recently performed.

The sensitivity analysis is of considerable value in many problem areas. Unfortunately, at this stage of fusion reactor development, it cannot be used as the primary tool for defining the nuclear data needs. A principal difficulty with the sensitivity studies is that the information they yield are highly system, geometry, response, material and reaction specific. For example, radiation streaming in complex geometry changes substantially from one design to another and the relative importance of particular pieces of nuclear data can be widely different. At present, there is a diversity of reactor types, design concepts and materials being considered for fusion reactors. Furthermore, sensitivity studies require part of the input information to be the uncertainties in the cross sections and the correlations between the various cross section errors. These are available only for very few materials. Some of the cross sections needed for fusion application have never been measured and a sensitivity analysis for these cross sections is obviously meaningless. It is desirable, however, to provide realistic estimates of the carefully evaluated data in the data files for future use in sensitivity studies.

Table 5 shows the recommended nuclear data measurements needed for fusion reactors. These are not limited to the shield requirements, but they cover also the blanket and reactor components where the radiation field is of concern. The needs indicated in Table 5 are for measurements and do not include data for which evaluation or theoretical estimates can suffice. The priorities of the data needs are assigned as follows: (1) urgent, (2) high priority, (3) needed, and (4) low priority. These priorities were assigned based on careful judgements[91] of (a) the probability that the isotope or element will be used in fusion reactors particularly in the next generation of experimental machines; (b) the significance of the reaction to neutron transport, energy deposition, radiation damage, tritium production and induced activation; (c) accuracy of currently available data; and (d) the variety of considerations that have been discussed in this section.

4. Summary

Valuable extensive experience and a broad base of methods and data is available to the fusion reactor shield designer from the highly developed field of fission. However, fusion reactor shielding presents new, interesting and sometimes challenging problems above and beyond those familiar in fission reactors. Furthermore, the specific nature of fusion reactor systems and the high neutron energy range of interest in the D-T cycle make it necessary to pursue a nuclear research and development program.

No technical systematic method exists for rigorously quantifying the specific nuclear data requirements. Nor is it likely that such a method would become available in the near future for reasons discussed in the paper. Therefore, only a framework of nuclear data requirements can be developed at present with heavy reliance on the experienced judgement of researchers in the field to fill in the specific details. Flexibility is necessary to modify these judgements as our knowledge and experience deepen and expand. Close interaction among experimentalists, evaluators and reactor designers is crucial to any prudent data acquisition program.

An attempt was made to define the specific nuclear data requirements, as we see them today, for fusion reactors with particular emphasis on those for the shielding. Six key areas were analyzed: (1) materials, (2) energy range, (3) specific types of nuclear data, (4) accuracy of data, (5) priority, and (6) time scale needed for acquisition of data. The presence of a diversity of design concepts and the lack of a committment to any material at present poses the most serious obstacle to defining the nuclear data needs. Assigning a probability of using potential materials was resorted to as shown in Table 2. For near-term experimental reactors, it appears that the use of the following materials is very likely: iron-based alloys (Fe, Cr, Ni, Mn) in the shield and blanket and magnet structure, boron-carbide (B, C) and lead in the shield, copper in the magnets, aluminum in a variety of components, and H, C and O in insulators. Tungsten is an exception in that the decision on using it will depend on verifying its apparent benefits by new differential and integral experiments. Lithium is probably the only material whose use in commercial reactors is almost certain.

Most of the new measurements needed are in the energy range of 5-16 MeV. This high energy range of interest dictates the need for knowledge of data for virtually all the variety of reactions that are energetically possible up to ~16

MeV; albeit a wide variation in accuracy requirements. The need for data by isotope and reaction has been shown. In shielding, the main interest is neutron and gamma attenuation, deep penetration and streaming. This requires emphasizing the (a) accuracy of basic cross sections such as total, elastic and inelastic scattering, (b) gamma-ray production and interaction, (c) accuracy of neutron emission spectra and angular distributions; scattering anisotropy is generally crucial to streaming and deep penetration problems, and (d) good resolution of cross section minima.

Specifying the needed accuracy in data was shown to be extremely difficult at this stage of fusion reactor development. An attempt was made to define target accuracies for predicting the various responses in several reactor components. These are shown in Table 4.

Table 5 shows the nuclear data measurements needs for fusion reactors as derived in this work. It should, be clear that some of the items in this table will very likely require revisions as a result of future work. The table, however, should serve as a useful guide for developing a nuclear data measurement program to serve the needs of fusion reactors; particularly the near-term experimental power reactors.

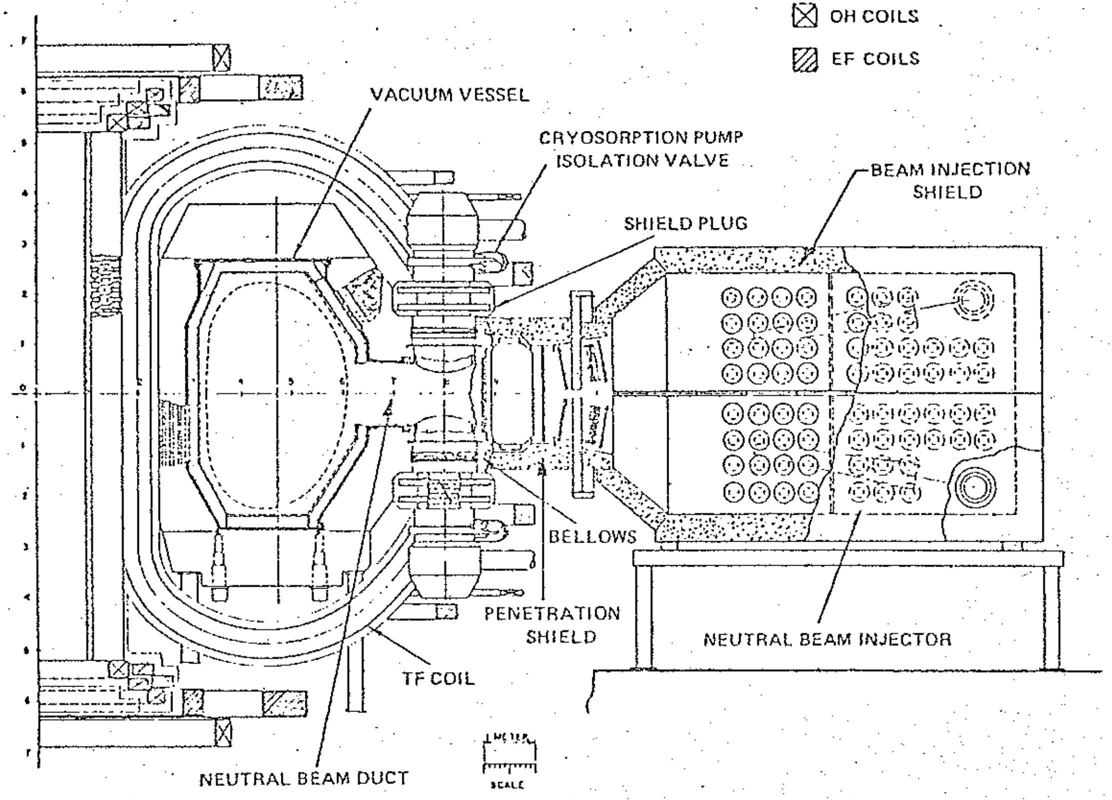

Fig. 1 Vertical cross section of a tokamak reactor design.

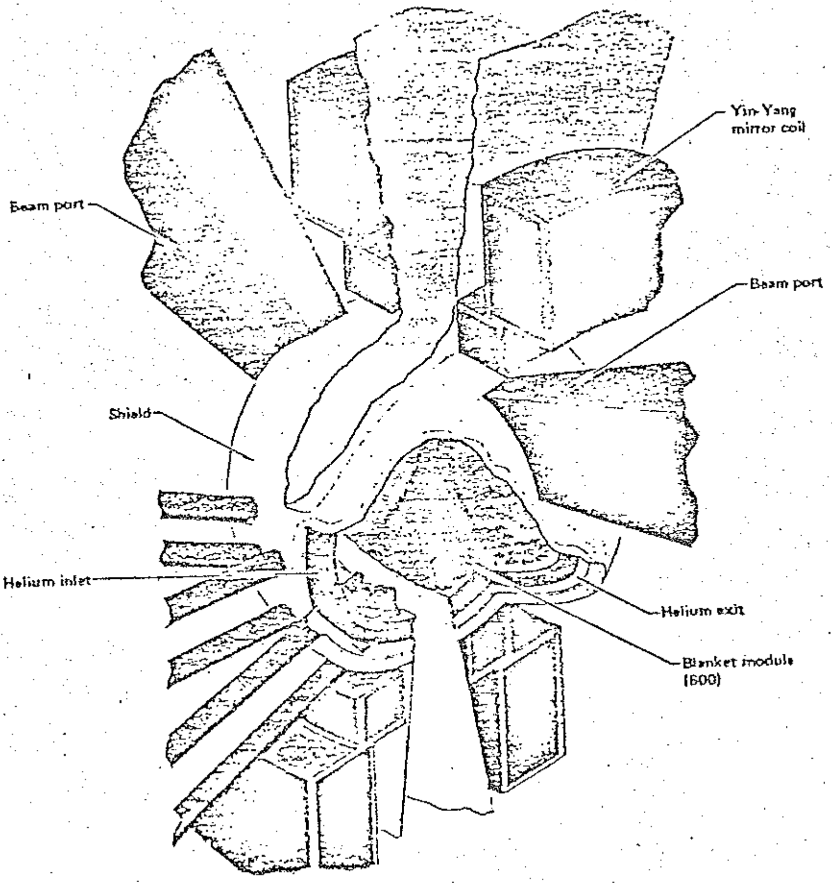

Fig. 2 Cutaway view of the blanket and bulk shield in a mirror reactor design.

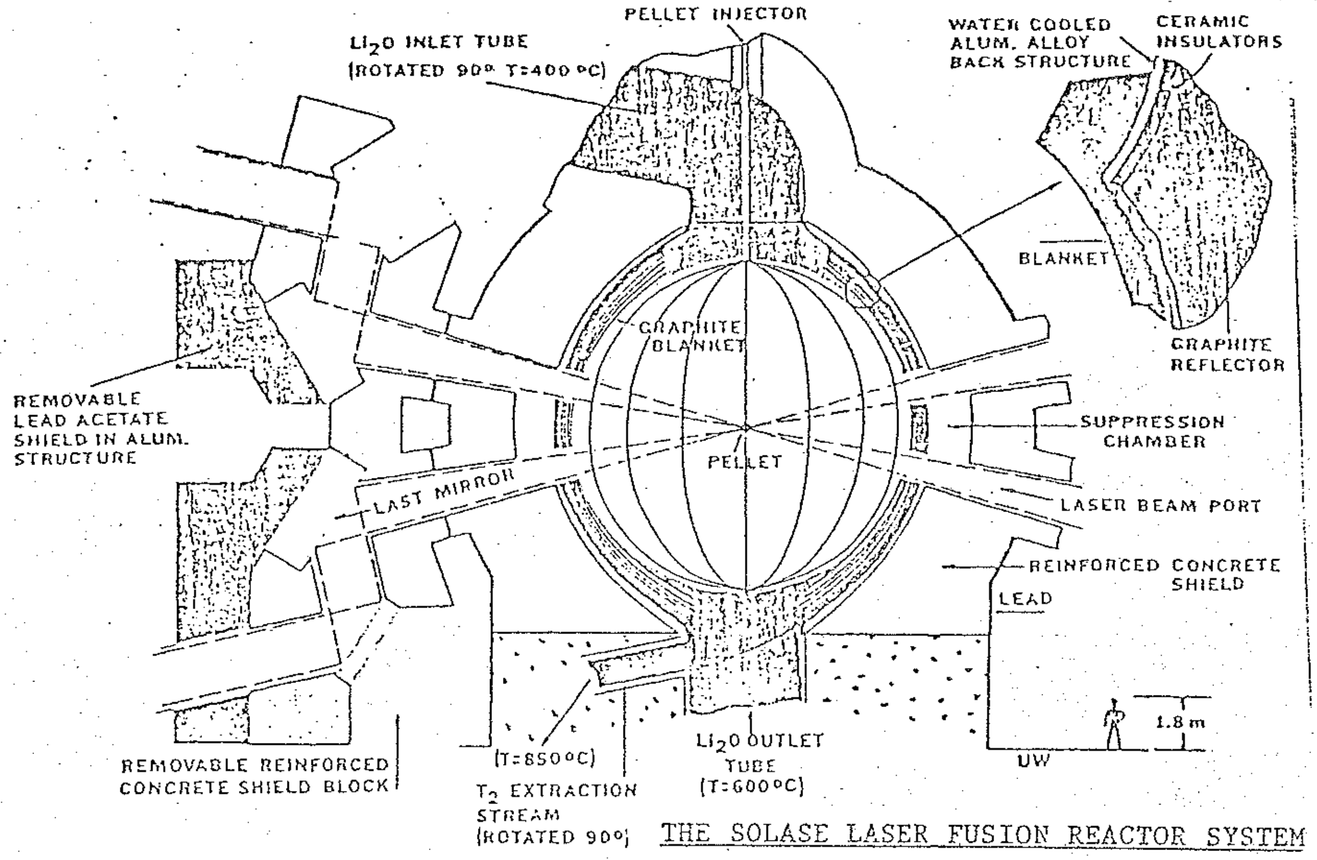

Fig. 3 A schematic of the Univ. of Wisconsin design,[10] SOLASE, for a laser fusion reactor.

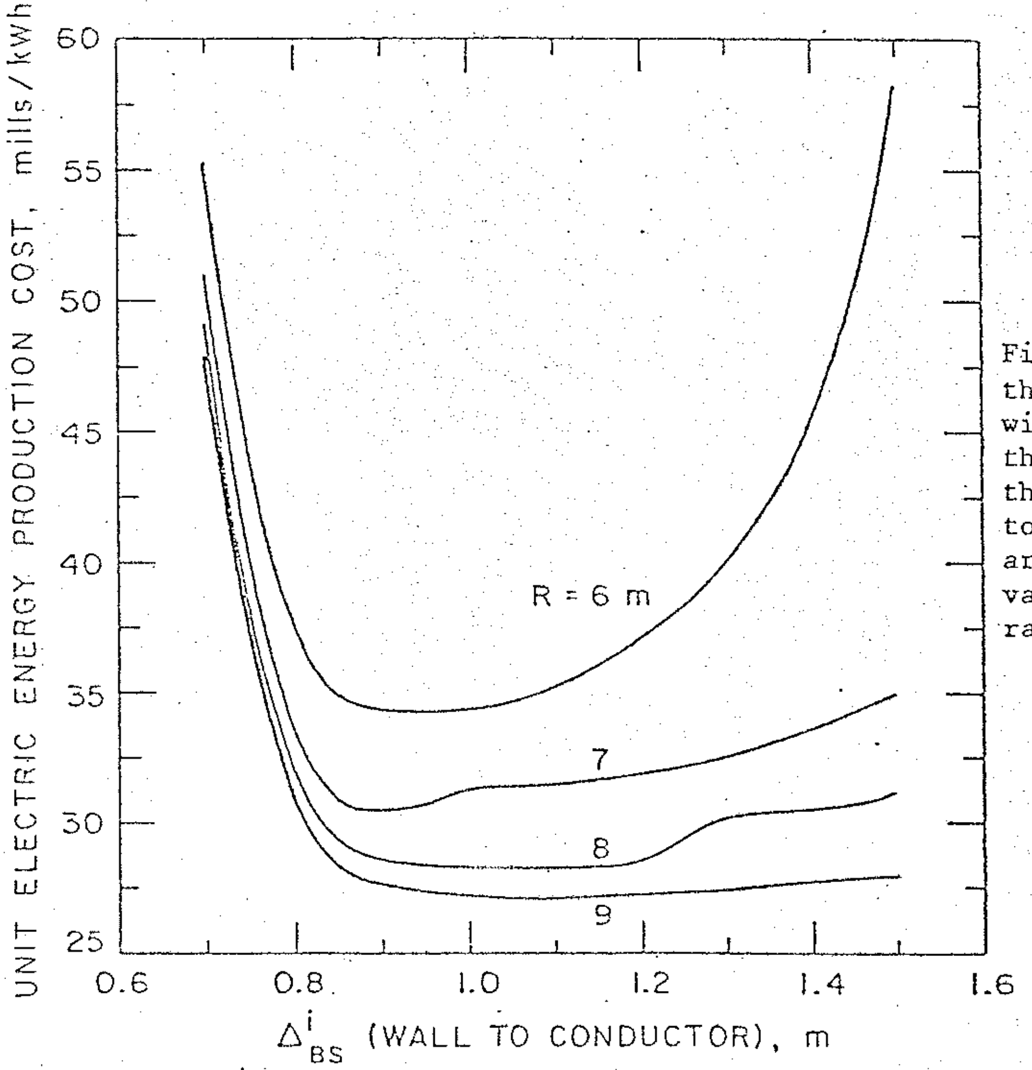

Fig. 4 Variation of the cost of energy with the thickness of the blanket/shield on the inner side of tokamaks. Results are shown for four values of the major radius.

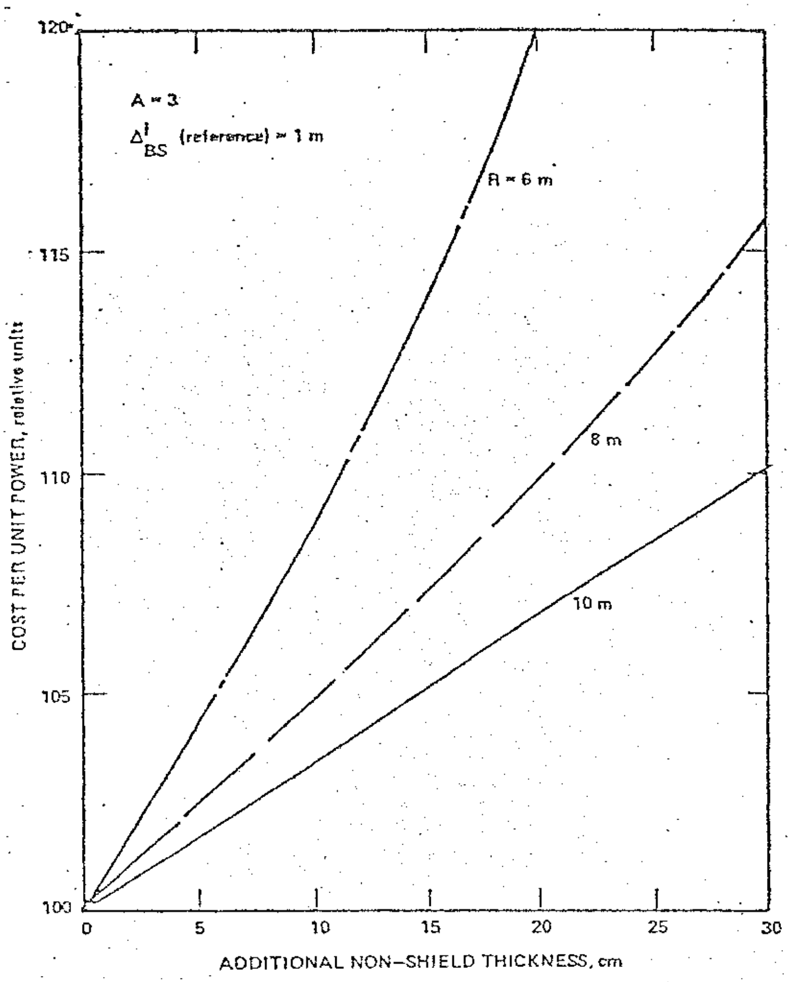

Fig. 5 Sensitivity of the cost of power in tokamak reactors to any non-attenuating increment in the blanket/shield thickness on the inner side of the torus.

Table 1

Summary of Material Proposed for Blanket and Shield.

Application	Material
Tritium Breeding	Liquid Lithium Molten salts (Li_2BeF_4) Aluminum Compounds ($LiAl$, $Li_2Al_2O_4$) Ceramic Compounds (Li_2O, Li_2C_2) Lithium-Lead eutectic
Structural Material	Iron-Based Alloys Nickel-Based Alloys Refractory-Based Alloys (V, Nb, Mo) Titanium Aluminum-Based Alloys
Coolant	Liquid Lithium Molten salts Helium, Water
Neutron Multiplication	Beryllium, Lead
Reflector	Graphite, Stainless steel
Shield	Stainless steel, Tungsten Lead, Lead Mortar, Lead Acetate Boron Carbide (B_4C) Borated Water Iron Mortar, Concrete LiH, LiD

Table 2

Elementary Materials of Potential Use in Fusion Reactors

A qualitative judgement on the probability of using the material is shown
(H = high, M = average, L = Low)

	Demo and Commercial			Experimental Reactors			
Material	Blanket	Shield	Others	Blanket	Shield	Others	Comments
Hydrogen	M	H	H		H	H	plasma, H_2O, in organic insulators
Helium	M	M	H		M	H	coolant, also in S.C. magnets
Lithium	H	M		L			tritium breeding, neutron absorption
Beryllium	M						neutron and energy multiplication
Boron		H		M	H		probably in B_4C form
Carbon	L	H			H	H	B_4C, reflector, wall coating, in insulators
Nitrogen			M		M		reactor building atmosphere, insulators
Oxygen		H			H		H_2O, reactor building atmosphere
Flourine	L						in molten salts
Sodium			M				secondary coolant
Aluminum	L	L	H	L	L	H	S.C. magnet stabilizer and structure
Silicon	M	M	M				SiC, Stainless steel
Argon			M			M	reactor building atmosphere
Titanium	M	L		L			structural material
Vanadium	M	L		L			structural material
Chromium	H	H	H	H	H	H	in steel and super alloys
Manganese	H	H	H	H	H	H	in " " " "
Iron	H	H	H	H	H	H	in " " " "
Nickel	H	H	H	H	H	H	in " " " "
Copper			H			H	normal and superconducting magnets
Niobium	M		H				structural material, also in superconductor
Molybdenum	L	L					
Tin			M			L	in Nb_3Sn superconductor
Tantalum		L			L		
Tungsten		H			H		in space-restricted shield region
Lead	M	H			H		in lithium-lead compounds and lead shield
Bismuth		L					

Table 3

Types of Nuclear Data Required in Fusion Nuclear Design

Application	Tritium Breeding	Nuclear Heating	Radiation Damage Indicators	Induced Activation	Radiation Shielding
<u>Data Type</u>					
Total	X	X	X		X
Elastic	X	X	X		X
Inelastic	X	X	X		X
Neutron Emission	X	X	X		X
$(\sigma_{em}, d\sigma/d\Omega, P(E')$					
(n,2n), (n,3n)	X	X		X	X
(n,α), (n; n'2)		X	X	X	
(n,p), (n; n'p)		X	X	X	
(n,d), (n; n'd)		X	X	X	
(n,t), (n; n't)	X	X	X	X	
(n, γ), (n; n'γ), (n; xγ)		X		X	X
Gamma Production		X			X
$\{\sigma^P, d\sigma/d\Omega, P(E_n \to E_\gamma)\}$					

Table 4

Some Required Accuracies[a] in Fusion Reactor Shielding

Location/Response	Desired Accuracy
First Wall/Blanket	
Nuclear Heating	total 2%, spatial distribution 10%
Tritium Producing	breeding ratio 5%, local 10%
Atomic Displacements	10%
Helium Production	10%
Transmutations	20%
Induced Activation	50%
Bulk Shield	
Nuclear Heating	gross 20%, local 30%
dpa and He and H production	factor of 2
Activation	factor of 2
Tritium Production	factor of 3
Main (Superconducting) Magnets	
Nuclear Heating	gross 10%, local 20%
dpa	gross 10%, local 20%
H, He production	gross 40%, local 80%
Activation	factor of 2
Penetration Duct Walls	
Nuclear Heating	local 20%
dpa and He and H production	local 50%
Penetration Functional Equipment (e.g. vacuum pumps, neutral beam injectors)	
Nuclear Heating	gross 30%, local 50%
dpa and He and H production	50%
Activation	factor of 2
Tritium production	factor of 2
Reactor Floor (outside the shield and inside the containment building)	
Biological Dose during operation	factor of 3
Biological Dose after shutdown	factor of 2
Coolant Manifolds and Heat Exchangers	
Biological Dose after shutdown	factor of 2
Containment Building	
Nuclear Heating	factor of 2
dpa and He and H production	local factor of 4
External Biological Dose (outside containment building)	factor of 3

a – These accuracies are approximate and they may change as our knowledge and experience deepen and expand. Some of these accuracies (e.g. that for the nuclear heating in the blanket) may be relaxed for near-term experimental machines.

Table 5

Nuclear Data Measurements Needs for Fusion Reactors

Reaction	Type of Measurement	Incident Energy (MeV)	Accuracy Goal (%)	Priority*	Comments
^{6}Li elastic scattering	$\sigma_{n,n}$, $d\sigma/d\Omega$	2-16	10	2	Reaction is important for good interpretation of other reactions.
^{6}Li inelastic scattering	$\sigma_{n,n'}$, $d\sigma/d\Omega$	2-16	10-20	2	
^{6}Li(n,α)t	$\sigma_{n,\alpha}$	0.3-16	5	2	
^{6}Li(n,2n′)	$\sigma_{n,2n'}$, $F\left(E_{n'}\right)^{+}$	6-16	10-20	2	Source of helium and hydrogen production.
^{6}Li(n,n′p), ^{6}Li(n,n′α)	$\sigma_{n,n'p}$, $\sigma_{n,n'\alpha}$	5-16	30	4	Cross sections may be small but need to be examined.
^{6}Li(n,n′d)	$\sigma_{n,n'd}$, $P\left(E_{n'}\right)$	3-16	10-20	2	
^{6}Li neutron emission	$\sigma^{\dagger}_{n,em.}$	3-16	5	2	
^{7}Li(n;n′t)	$\sigma_{n,n't}$, $P\left(E_{n'}\right)$	3-16	5	1	
^{7}Li elastic	$\sigma_{n,n}$	2-16	10	2	Elastic scattering is essential to interpreting important reactions such as (n;n′,t).
^{7}Li inelastic scattering	$\sigma_{n,n'}$	2-16	10-20	2	
^{7}Li neutron emission	$\sigma^{\dagger}_{n,em.}$	2-16	5	1	
Boron eleastic scattering	$\sigma_{n,n}$	6-16	5-15	2	Isotopic values needed; reaction affects the interpretation of other reactions.
B neutron emission	$\sigma_{n,em.}$	6-16	10	1	
^{10}B(n,t)	$\sigma_{n,t}$	1.2-16	20%	1	
^{11}B(n,t)	$\sigma_{n,t}$	12-16			
^{10}B(n,p)	$\sigma_{n,p}$	0.01-16	20	2	
^{10}B(n,2n)	$\sigma_{n,2n}$, $P\left(E_{n'}\right)$	9-16	20	2	$^{10}B(n,2n)^{9}B \rightarrow 2\alpha + P$
^{10}B(n;n′p)	$\sigma_{n;n'p}$, $P\left(E_{n'}\right)$	7-16	30	2	
^{11}B(n,α)	$\sigma_{n,\alpha}$	7-16	30	2	The decay product is 2α.
^{11}B(n,2n)	σ_{n2n}, $P\left(E_{n'}\right)$	12-16	30	2	
Boron gamma production	$\sigma_{n,x\gamma}$, $P\left(E_{\gamma}\right)$	10^{-6}-16	20	1	
C(n,xα)	$\sigma_{n,x\alpha}$	6.5-16	10	2	
C(n,α)	$\sigma_{\alpha_0}, \sigma_{\alpha_1}, \ldots$	6.5-16	20	3	Energy distribution of the charged particles is useful.
C(n;n′3α)	$\sigma_{n;n'3\alpha}$, $P\left(E'_{n}\right)$	8-16	10	1	Total helium production, heating and neutron transport in carbon is very sensitive to this reaction.
C neutron emission	$\sigma_{n,em.}$	6-15	10	1	
Fe neutron emission	$\sigma_{n,em.}$	8-16	10	1	
^{54}Fe, ^{56}Fe(n,α)	$\sigma_{n,\alpha}$	10^{-6}-16	20	2	Energy distributions of emitted alphas are very useful.
	$\sigma_{\alpha_0}, \sigma_{\alpha_1}, \sigma_{\alpha_2}, \ldots$		40	3	
^{54}Fe(n;n′,p)	$\sigma_{n,n'p}$, $P\left(E_{n'}\right)$	~9.5-16	20	2	
Cr neutron emission	$\sigma_{n,em.}$	8-16	10	1	
Cr(n,xα)	$\sigma_{n,x\alpha}$	Threshold-16	20	2	
Cr(n,xp)	$\sigma_{n,xp}$	Threshold-16	20	2	
^{52}Cr(n,p) ^{53}Cr(n,p) ^{54}Cr(n,p) ^{50}Cr(n,p)	$\sigma_{n,p}$, $\sigma_{np_0}, \sigma_{np_1}, \ldots$	Threshold-16	30	2 2 4 4	
^{52}Cr(n,2n)	$\sigma_{n,2n}$, $P\left(E_{n'}\right)$	~12-16	20	2	
^{52}Cr(n,d)	$\sigma_{n,d}, \sigma_{nd_0}, \sigma_{nd_1}, \ldots$	~9-16	30	3	
^{58}Ni inelastic scattering	$\sigma_{n,n'}$	4-16	10-20	2	
(level and continuum)	Angular and energy distributions	6-16	20-30		

^{60}Ni inelastic scattering	$\sigma_{n,n'}$	8–16	10–20	2	
(level and continuum)	Angular and energy distributions	6–16	20–30		
^{58}Ni(n;n',p) ^{60}Ni(n;n',p)	$\sigma_{n,n'p}$, $P(E_{n'})$	Threshold-16	20	1	Current uncertainity ~200%.
^{58}Ni(n,2n)	$\sigma_{n,2n}$, $P(E_{n'})$	Threshold-16	10	3	Data currently available but there are some discrepancies at high energies.
^{60}Ni(n,2n)	$\sigma_{n,2n}$, $P(E_{n'})$	Threshold-16	10	2	Currently, no data.
^{58}Ni(n,α) ^{60}Ni(n,α)	$\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1}, \ldots$	10^{-6}–16	10	1	
^{58}Ni(n;n'α) ^{60}Ni(n;n'α)	$\sigma_{n,n'\alpha}$ $P(E_{n'})$	7–16	20	4	
Nickel, neutron emission	$\sigma_{n,em.}$	Threshold-16	10–20	2	Angular distribution required where significantly anisotropic.
Cu neutron emission	$\sigma_{n,em.}$	2–16	10	1	
^{63}Cu(n,p)	$\sigma_{n,p}, \sigma_{np_0}, \sigma_{np_1}, \ldots$	1–16	20	1	
^{63}Cu(n,d), ^{65}Cu(n,d)	$\sigma_{n,d}, \sigma_{nd_0}, \sigma_{nd_1}, \ldots$	10–16	30	2	
^{63}Cu(n;n'p)	$\sigma_{n,n'p}$, $P(E_{n'})$	9–16	20	1	
Cu gamma production	$\sigma_{n,x\gamma}$, $P(E_{\gamma})$	10^{-6}–16	20	1	
V inelastic scattering	$\sigma_{n,n'}$, angular and energy distributions	7–16	10–20	3	
V neutron emission	$\sigma_{n,em.}$	7–16	10–20	2	Angular distribution is of interest.
V(n,p)	$\sigma_{np}, \sigma_{p_0}, \sigma_{p_1}, \ldots$	2–16	20	3	
V(n,α)	$\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1}, \ldots$	3–16	20	3	
V(n,2n)	σ_{n2n}, $P(E_{n'})$	12–16	10	2	
V(n;n'p) V(n;n'α)	σ_r, $P(E_{n'})$	8–16	20	4	
Ti elemental total cross section	Total cross section	1–20	2	2	
^{46}Ti inelastic scattering ^{48}Ti inelastic scattering	$\sigma_{n,n'}$	4–16	10	2	
^{47}Ti(n,p)	$\sigma_{np}, \sigma_{p_0}, \sigma_{p_1}, \ldots$	10–16	20	2	
^{47}Ti(n,α)	$\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1}, \ldots$	10^{-6}–16	20	2	
^{47}Ti(n,2n)	$\sigma_{n,2n}$, $P(E_{n'})$	9–16	20	3	
^{48}Ti(n,2n)	$\sigma_{n,2n}$, $P(E_{n'})$	12–16	20	2	
^{48}Ti(n,α)	$\sigma_{n\alpha}, \sigma_{\alpha_0}, \sigma_{\alpha_1}, \ldots$	Threshold-16	20	3	
Lead neutron emission	$\sigma_{n,em.}$	6–16	20	2	
Lead (n,n')	Discrete inelastic scattering	8–16	20	2	
^{55}Mn(n,2n)	$\sigma_{n,2n}$	12–16	20	2	
^{55}Mn(n,p)	$\sigma_{n,p}$	2–16	20	3	
^{55}Mn(n,α)	$\sigma_{n,\alpha}$	1–16	20	3	
^{55}Mn(n;n',p)	$\sigma_{n,n'p}$	6–16	30	3	
^{55}Mn(n;n',α)	$\sigma_{n,n'\alpha}$	8–16	30	3	
W inelastic scattering	$\sigma_{n,n'}$	1.5–4	10	4	
W elastic scattering	$\sigma_{n,n}$, $d\sigma/d\Omega$	2–6 8–16	10	4	
W neutron emission	$\sigma_{n,em.}$	4–16	20	3	
W gamma production	$\sigma_{n,x\gamma}$, $P(E_{\gamma})$	10^{-6}–16	20	1	
Al(n,2n)	$\sigma_{n,2n}$	13.5–18	20	2	Cross section to the isomers ^{26}Al (positron emitter) is major concern for induced activation.
Al(n,p)	$\sigma_{n,p}$	14–16	20	2	
Al neutron emission	$\sigma_{n,em.}$	5–16	20	2	

^{5}Be(n,2n)	$\sigma_{n,2n}$	1.8-16	10	3
^{9}Be neutron emission	$\sigma_{n,em.}$	1.8-16	10	3
^{40}Ar(n,2n)	$\sigma_{n,2n}$	Threshold- 15	20	2
O Neutron emission	$\sigma_{n,em}$	5-16	10	2

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[*] $P\left(E_{n}'\right)$ refers to the energy distribution of secondary neutrons.

[†] For all entries in the table, $\sigma_{n,em.}$ refers to the neutron emission spectra and angular distribution, $\sigma_{n,Nem}(\theta_{n'}, E_{n'})$ generally required at several angles with outgoing neutrons recorded down to a few hundred KeV.

a. Priorities are assigned as follows: (1) Urgent, (2) high priority, (3) needed, (4) low priority.

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