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NUCLEAR CROSS-SECTION REQUIREMENTS FOR FUSION REACTORS

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By

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ABSTRACT

1. The paper considers nuclear cross-section requirements for the plasma and the surrounding blanket.

2. Both toroidal and open-ended (e.g. mirror) confinement systems are considered. From the permissible plasma pressure it appears that the former are limited to temperatures up to 100 keV (energy equivalent), whilst for open-ended machines the temperature limit appears to be as high as 1 MeV.

Taking into account:-

(i) The various forms of energy loss from the plasma;

(ii) Economic considerations related to magnetic field winding costs;

a relationship is derived for selecting possible thermonuclear reactions. In general it excludes reactions with $Z > 10$, and all reaction with cross-sections less than a millibarn at energies less than 10 MeV. The number of 'interesting' reactions remaining is surprisingly large, and a table of data on reactions for Z up to 3 is given. A literature search has revealed the cross-section data to be poor for many of these reactions.

3. Since the neutronic design of fusion reactors is still at a very early stage, a model blanket design is used to illustrate the importance of nuclear cross-sections in various blanket problems. The blanket is designed around a fusion system using the D-T reaction which emits 14·1 MeV neutrons. The accuracy of the nuclear cross-sections and their effect on the neutron spectra, tritium breeding, heat generation, radiation damage and radioactivity, are commented on.

The main fields in which there is a shortage of data are:-

(a) non-elastic cross-sections in the range 1 MeV to 14 MeV (e.g. (n,2n) in Niobium and Molybdenum);

(b) secondary neutron spectra from elastic, inelastic and (n,2n) scattering;

(c) gamma-ray spectra from non-elastic events (mainly inelastic scattering and radiative capture).

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NUCLEAR CROSS-SECTION REQUIREMENTS IN FUSION REACTOR DESIGN

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1. INTRODUCTION

The controlled release of nuclear fusion energy under thermonuclear conditions has been a gleam in the eye of nuclear physicists since the early years of this century. However, large scale research programmes on practical means of achieving controlled thermonuclear reactions are a post-war phenomenon, with the major effort dating only from the late 1950s, and progress has been very uneven, with smooth advances punctuated by disappointments and setbacks. Even today it is possible to regard controlled fusion research as something directed towards a distant goal with a quite uncertain outcome. However, opinion has recently swung towards the view that the prototype fusion reactor will be constructed during this century, and some very preliminary attempts have been made to produce self-consistent and technically plausible fusion reactor designs. Accounts of this work can be found in the proceedings of the International Conference on Fusion Reactors, held at Culham in September 1969.

The reactor designs which have been produced so far fall into about six groups, each based upon a different thermonuclear plasma confinement concept. It is likely that during the next few years each of the countries involved in this research will have to make some hard technological decisions and concentrate its efforts on one (or at most a very few) system concepts. It is in this context that accurate nuclear cross-sections may come to play a crucially important role. In spite of the various features which distinguish these rival concepts, there are a number of features which are common to all the current fusion reactor systems. These features are schematically represented in Fig.1 (due to Carruthers et al 1967). There is an inner core of confined plasma, at a temperature in the range 10 keV-1 MeV. The nuclear fuels present in the plasma are still open to debate, with the various isotopes of hydrogen, helium and lithium (at least) as possible contenders, although a 50:50 deuterium-tritium mixture has hitherto been preferred. In almost every case however, at least one of the reactions occurring in the plasma releases neutrons. Consequently a feature of every reactor which has been considered seriously so far is a "neutron blanket" surrounding the plasma, in which the neutrons are captured, normally after some neutron multiplication, and their energy recovered as heat. In addition, if the plasma contains isotopes not readily available in nature (e.g. T, ^{3}He), these have to be bred in the blanket (e.g. by (n,t) reactions). The precise spectrum and flux of neutrons entering the blanket depend on the design: however for orientation, a typical D-T reactor with an "economic" overall heat flux out of the plasma of $1{\cdot}3$ KW/cm^2 has an incident current of $7\ 10^{14}$ neutrons cm^{-2} sec^{-1} of 14 MeV neutrons. Because of back-scattering in the lithium coolant channels the <u>flux</u> in the first wall is $2{\cdot}8 \times 10^{15}$ neutrons cm^{-2}s^{-1}. This is comparable with the flux in the Dounreay Fast Reactor (D.F.R.), and in Fig.3 we give spectra taken from the fusion reactor First wall, from the D.F.R. core (flux of $2{\cdot}5 \times 10^{15}$ n cm^{-2} s^{-1}) and the D.F.R. inner breeder region (flux $1{\cdot}5 \times 10^{15}$ n cm^{-2} s^{-1}). The histograms represent absolute flux values over the appropriate energy interval. In spite of the comparability of the fluxes, the point to emphasise is that the 14 MeV peak in the fusion spectrum means that non-elastic processes are much more significant than in a fission reactor - even for fast fission designs. Finally, surrounding the neutron blanket are the windings used to produce the magnetic field which confines the plasma. In most designs, for economic reasons, these windings are superconducting, and there is therefore a upper limit to the incident neutron flux and the nuclear heating in them.

The structure which has just been described, which we might call the "nuclear boiler", is integrated into a power station in the manner indicated in the functional diagram shown in Fig.2 (due to Carruthers et al), in which a system using the basic reaction cycle, T(d,n)^{4}He in the plasma + ^{6}Li(n,t)^{4}He, ^{7}Li(n,nt')^{4}He in the blanket has been assumed. Although this is by no means the only possible cycle, it has been investigated in more detail than any other, because of a number of attractive features. The deuterium-tritium fusion reaction has the advantage of having the largest known fusion cross-section

(5 barns), reaching its maximum at an energy (107 keV) which is four times lower than any other fusion resonance. Deuterium exists as 0·0153% of the hydrogen in sea-water, so the supply is effectively limitless. Tritium is radioactive and not naturally found and must therefore be bred in the neutron blanket. Lithium, the other fuel material, is likewise abundant (to about the same degree as uranium), and the two lithium reactions are the only ones which appear to offer real hope of tritium regeneration.

Of the features which distinguish the various fusion reactor concepts, only three require discussion: (i) the temperature of operation, (ii) the location of the windings used to produce the confining magnetic field and (iii) the means used to heat the plasma.

(i) The temperature of operation

This is crucial because if it is less than about 100 keV then only the D-T reaction can be considered, all others having a cross-section at least two orders of magnitude smaller. However, by 400 keV a number of alternative reactions are becoming of interest, and by 1 MeV a wide range of possibilities needs to be considered. In reactor concepts based on confinement in a toroidal magnetic field, it appears at present that plasma physics restrictions on the permissible plasma pressure effectively exclude operation at temperatures exceeding 100 keV; in "open-ended" machines, such as the mirror machine or the Astron however, the plasma is typically created by injecting high energy particles into the confinement system, and although temperatures as high as 1 MeV raise formidable technological problems, it is difficult to exclude them at the present stage, and the current design trend is towards higher temperature operation. A further feature to be considered in these machines is the comparatively long time (say of order 1 second) which it takes for a high energy charged reaction product to come into thermal equilibrium with the plasma. It is therefore necessary to take into account the possibility of nuclear reactions in the multi-MeV range during this "slowing down" period.

(ii) Location of the magnet windings

There is one reactor concept - the theta-pinch - in which the plasma is created in a series of fast pulses of the magnetic field. In such a system the windings have to be inside the blanket in order to allow a sufficiently rapid rise time for the magnetic field, and they have to have simultaneously a sufficiently low electrical resistivity and acceptable neutronic properties. One material system which has been investigated (Bell et al 1969) in this context is a copper-zirconium coil backed by molybdenum hoops. The difficulties raised by this approach are formidable, and are not considered in this paper.

(iii) Plasma heating

This has cross-section implications only if the apparatus used to heat the plasms is situated inside the blanket. One possibility which is being considered for toroidal systems is a radio-frequency heating system, requiring electrically insulated coils inside the blanket. The neutronic properties of both the conducting and insulating components of this system have still to be investigated.

2. THERMONUCLEAR CROSS-SECTIONS

In standard reference works on controlled fusion research, the reactions normally mentioned are $T(d,n)^4He$, $D(d,n)^3He$, $D(d,p)T$ and $^3He(d,p)^4He$. However, as has been noted, recent developments in at least two potential fusion reactor concepts - the mirror machine and the Astron - have been in the direction of substantially higher working temperatures, with particle injection at energies measured in hundreds of keV or even MeV, and a number of plasma physicists (notably McNally and Post) have pointed out advantages in considering reactions other than these four. The question therefore arises whether there exist criteria by which one can determine in advance whether a given reaction is of potential interest in fusion research. The answer appears to be that there are, and that they arise because (i) it must be possible to sustain the plasma temperature in spite of various energy loss processes and (ii) the reactor must generate power in an economically competitive manner. These considerations restrict the number of "interesting" reactions as follows.

(i) The principal causes of energy loss from a confined thermonuclear plasma are particle loss, heat conduction, synchrotron radiation and bremsstrahlung radiation. Each of the first three can in principle be reduced indefinitely, though it is no easy matter to reduce all three at once. The bremsstrahlung loss is essentially irreducible since a laboratory plasma is virtually transparent to it, and it cannot be reflected back into the plasma, so its energy can only be recovered by passing it through a thermal cycle with (at most) 50% efficiency. Thus it is essential that P_{th}, the net thermonuclear power released (including the energy resulting from neutron induced reactions in the blanket) should be of the same order as the bremsstrahlung power radiated P_b. Now

$$P_{th} = 4\ 10^{-14}\ n^2\ \overline{\sigma v}\ Q_t \text{ watts/cm}^3$$

and

$$P_b = 1{\cdot}7\ 10^{-29}\ n^2\ \zeta\ \overline{Z^2}\ \sqrt{T_e} \text{ watts/cm}^3$$

where n is the plasma density (in particles/cm³), $\overline{\sigma v}$ the mean reaction rate parameter in cm³/sec., Q_t the net energy yield per fusion reaction in MeV (including that of consequential neutron or disintegration reactions), $\overline{Z^2}$ the mean square ionic charge (in atomic units), T_e the electron temperature in MeV and ζ a relativistic correction factor (of order unity unless $T_e \gtrsim 5$ MeV), so at the very least we must have

$$\overline{\sigma v} \gtrsim 4{\cdot}2\ 10^{-16}\ \zeta\ \overline{Z^2}\ \sqrt{T_e}\ /Q_t \qquad \ldots (1)$$

(ii) The economic criterion arises from a combination of an upper limit on the permissible plasma pressure, taken below as about 2000 atmospheres, and a lower limit on the permissible thermonuclear power density, shown to be about 1 watt/cm³. The plasma pressure limit results from the fact that above a certain field strength, the cost of providing the magnetic field which confines the plasma rises very rapidly. At moderate field strengths (e.g. ~ 100 KGauss) the cost scales roughly as B^2 and as the surface area of the plasma: at sufficiently high field strengths however, as one approaches the absolute limit set by the strength of the materials used to withstand the magnetic forces, the cost rises more rapidly than this. Since the thermonuclear power output scales as the square of the plasma pressure (which must of course be less than the magnetic pressure $B^2/8\pi$), the reactor designer has a clear incentive to increase the plasma pressure until the steeply rising magnet cost ensures that there is no further decrease in the magnet cost per unit of power output. At the present time, this limit is encountered around 150KGauss: however it is to some extent a function of the state of magnet technology, and for present purposes we have taken it as 220KGauss (2000 atmospheres) to allow for plausible developments in this technology.

The power density limit is due to the fact that there is an upper limit to the plasma radius (again largely dictated by magnet costs) and a lower limit to the power flux through the plasma surface, due to the need to keep the capital cost of the magnet per unit of power output at an acceptable level. The maximum practicable plasma radius is of order 10 meters, since (as Rose has shown) for magnets of larger radius the cost of the structural material used to withstand the hoof stresses in the windings becomes dominant. The minimum power flux through the first wall turns out (magnet costs being what they are) to be essentially equal to the maximum flux permitted by thermal stress and/or radiation damage considerations - about 1 KWatt/cm². Thus the minimum power density is of order 1 watt/cm³.

Combining these two limits, a reaction is "interesting" if

$$\overline{\sigma v} \gtrsim 1{\cdot}6\ 10^{-17}\ (T_e+T_i)^2/Q_t \qquad \ldots (2)$$

where T_e and T_i are the electron and ion temperatures in MeV. Only a limited significance should be attached to the numerical factor in (2), which varies inversely as the square of the maximum pressure which is regarded as economically and technologically feasible.

The quantity T_e appearing in the criteria (1) and (2) above should strictly be determined by means of an energy balance calculation, in which the energy transferred from the ions to the electrons is equated to the energy radiated by the electrons as bremsstrahlung and synchrotron radiation plus the energy which they carry off when they eventually escape from the plasma confinement system. This balance depends on the ion energy distribution and hence on the cross-sections for the thermonuclear reactions which heat the ions, and this dependence is rather sensitive: in the calculations of Petravic et al, for example, a change amounting to only a factor of two in the fusion cross-section taken essentially reversed the verdict of Fowler and Rankin on the feasibility of a mirror reactor based on the $T(d,n)^4He$ reaction. Fortunately, however, it is not necessary for present purposes to perform such a calculation, since it is possible to state with sufficient precision the temperature T_e which it must yield if the fusion reaction concerned is to be of interest. This is because the synchrotron radiation rises rapidly with T_e, becoming dominant for $T_e \gtrsim 100$ keV (see for example Mills (1969)), whereas the cooling of the ions by the electrons increases as $(T_i-T_e)/T_e^{3/2}$ and (for $T_i \gtrsim 1$ MeV) becomes unacceptable if $T_e \ll 100$ keV. Thus reactions which require ion temperatures $T_i \gtrsim 1$ MeV are of interest only if it is possible to run the reactor in such a way that the electron temperature is close to 100 keV.

It remains an open question whether one could design a fusion reactor in which the temperature ratio T_i/T_e was as high as this argument requires ($\gtrsim 10$). The calculations of Petravic et al mentioned above showed that a ratio of the order of 5 is possible, and this figure might be increased in a system in which the fusion reactions released a larger fraction of their energy as charged particle energy. Reliable calculations on this point will be made possible by more accurate cross-section data. However, on the assumption that electron temperatures of order 100 keV are feasible, we can set $T_e = 0{\cdot}1$ in (1), obtaining

$$\overline{\sigma v} \gtrsim 1{\cdot}4\ 10^{-16}\ \overline{Z^2}\ /Q_t$$

a condition which is seen to be more stringent than (2) except at very high ion temperatures. We can rewrite (1) as

$$\sigma \gtrsim 100\ \overline{Z^2}\ (m/T_i)^{1/2}/Q_t \text{ mbarns} \qquad \ldots (3)$$

where m is the reduced mass for the reaction in atomic units and $1 \lesssim T_i \lesssim 10$ MeV, and in this form it provides a useful rule-of-thumb for selecting reactions of interest. It excludes most if not all thermonuclear reactions in which Z is greater than about 10 and all reactions in which σ is less than one millibarn at energies less than 10 MeV. The number of reactions which remain is however surprisingly large.

We present here some preliminary results, relating to charged species with $Z \leqslant 3$, of an extensive literature search for information on the cross-sections of thermonuclear reactions satisfying the criterion (3) in the range 0–10 MeV. The reactions which meet this requirement are listed in table 1, together with their Q values, the known or suspected reaction channels, the maximum value of σ(for $\varepsilon < 10$ MeV) and the energy at which it occurs. The symbol > in this table indicates that the maximum lies at a higher energy than the maximum at which data are available, and ~ indicates an order of magnitude figure in cases where there is substantial disagreement in the literature. In Figs.4–13 we show compilations of the cross-section measurements for each of these reactions. The energy scale is logarithmic running from 10 keV to 10 MeV in each case; the cross-section scale is linear, and marked in millibarns. The name given is that of the first author of the publication from which it was derived. For the most part these are uncritical compilations, with no data adjustments apart from those sanctioned by the authors concerned, though un-normalised yield curves have been normalised to the work of other authors. In a few cases the cross-sections have been renormalised in the light of subsequent and more accurate determinations of absolute cross-sections, or to ensure a standard definition of the cross-section (e.g. in the reaction $^6Li(d,\alpha)^4He$, which disintegrates one lithium nucleus and produces two alpha particles). When only differential cross-sections at a single angle were available, total cross-sections were derived by assuming isotropic angular distributions.

Table 1

Reaction	Q value (MeV)	σ_{max}(mb)	ε_{max}(MeV)	Sources
D(p,np)P	-2.2	>400	>5.5	Henkel
D(d,n)^{3}He	3.27	105	1.9	Blair, Brolley
D(d,p)T	4.03	90	2.0	Blair, Brolley
T(p,n)^{3}He	-0.76	500	3.0	Taschek, Willard
T(d,np)T	-2.2	>700	>6.0	Henkel, Smith
T(d,2n)^{3}He	-3.0	?>1200	>6.5	
T(d,n)^{4}He	17.6	5000	0.108	Arnold, Balabanov, Conner
T(d,n)^{4}He*				Poppe
T(t,n)^{5}He(n)^{4}He		>100	>1.8	
T(t,2n)^{4}He	11.4			Agnew, Allen, Govorov, Leland
T(t,n)^{5}He*(n)^{4}He		?>1200	>2.4	
^{3}He(d,np)^{3}He	-2.2	>70	>1.0	Henkel
^{3}He(d,p)^{4}He	18.4	700	0.4	Bonner, Kunz, Yarnell
^{3}He(t,d)^{4}He	14.3			
^{3}He(t,p)^{5}He(n)^{4}He	11.3+1.0	~50	~1.0	Almquist Barry Kuhn Youn
^{3}He(t,np)^{4}He	12.1			
^{3}He(t,n)^{5}Li(p)^{4}He	10.3+1.8			
^{3}He(^{3}He,p)^{5}Li(p)^{4}He	11.0+1.8	>30	>0.8	Good
^{3}He(^{3}He,2p)^{4}He	12.8			
^{4}He(d,np)^{4}He	-2.2	>240	>6	Henkel
^{6}Li(p,^{3}He)^{4}He	4.02	~200	1.8	Bashkin, Jeronymo Marion
^{6}Li(d,n)^{3}He+^{4}He	1.72	~>600	>5.0	Baggett Slattery Whaling
^{6}Li(d,n)^{7}Be(e_k)^{7}Li 43 day	3.34			
^{6}Li(d,p)^{7}Li	5.02	100	1.2	Nickell, Whaling
^{6}Li(d,p')^{7}Li*(γ)^{7}Li	4.54+0.45			
^{6}Li(d,t)^{5}Li(p)^{4}He	0.9+1.6	>300	>4.0	Macklin
^{6}Li(d,α)^{4}He	22.4	30	3.7	Jeronymo, Mani, Meyer, Whaling
^{6}Li(t,d)^{7}Li	0.995			
^{6}Li(t,d')^{7}Li*(γ)^{7}Li	0.509+0.45	>320	>2.1	Pepper, Serov, Valter
^{6}Li(t,p)^{8}Li(e_-)2α	0.800			
^{6}Li(t,n)^{8}Be* or 2^{4}He	16.0			
^{6}Li(^{3}He,p)^{8}Be(α)^{4}He	16.8	30	~5	Schiffer
^{6}Li(^{3}He,p)^{8}Be*($\alpha\gamma$)^{4}He	13.9+2.9	>60	>5	Schiffer
^{7}Li(p,n)^{7}Be	-1.63	>800	>7	Blaser, Taschek
^{7}Li(p,α)^{4}He	17.5	65	3	Heydenburg, Jeronymo, Mani, Taschek
^{7}Li(d,n)^{8}Be(α)^{4}He	15.0	>1000	>5	Baggett, Bennett, Slattery
^{7}Li(d,p)^{8}Li(e_-)^{8}Be(α)^{4}He	-0.26+16.0	?160	3	Bennett, Bashkin, Baggett
^{7}Li(d,t)^{6}Li	-0.995	>150	>4	Macklin
^{7}Li(t,2nα)^{4}He	8.88			
^{7}Li(t,n)^{9}Be	10.52			
^{7}Li(t,2n)^{8}Be(α)^{4}He	8.83	>1300	>2.1	Crews, Serov, Valter
^{7}Li(t,2nα)^{4}He	8.85			
^{7}Li(t,nα)^{5}He(n)^{4}He	8.08+1.0			
^{7}Li(t,α)^{6}He, ^{6}He*	9.83	>40	>1.8	Holmgren
^{7}Li(^{3}He,n)^{9}B(p)^{8}Be(α)^{4}He	9.3+0.3			
^{7}Li(^{3}He,np)^{8}Be(α)^{4}He	9.5+0.1	>600	>1.4	Allen, Moak, Serov
^{7}Li(^{3}He,p)^{9}Be	11.2			
^{7}Li(^{3}He,d)^{8}Be(α)^{4}He	11.7+0.1			

Note: The Q values have been taken from the source quoted when given. Missing values were supplied from Maples et al. UCRL 16964. Discrepancies of up to 0.3 MeV can be detected.

This rather crude procedure was made necessary by the paucity of the data available for many of these reactions. A more detailed account of this data, together with a full bibliography, will be published shortly as a separate report (Dancy & Watson CLM-BIB 9): the papers cited here cover only the most directly relevant publications.

It will be seen from Figs.4–13 that the state of knowledge of the "interesting" charged particle reaction cross-sections is by no means uniformly satisfactory. The data on the D-D and D-T reactions sets a standard which is hardly approached by any other reaction. For several reactions - notably the ^{3}He–^{3}He, $^{4}He(d,np)^{4}He$, $^{6}Li(d,t)$, $^{6}Li(^{3}He)$, $^{7}Li(p,n)$, $^{7}Li(d,t)$, $^{7}Li(^{3}He)$ reactions, we have only found one absolute measurement of the cross-section in the relevant energy range, and for several more reactions no measurement extends up the energy scale as far as the first cross-section maximum. When a number of overlapping measurements exist, the disagreement often lies outside the stated experimental error (when it <u>is</u> stated). These disagreements are particularly marked in the T-T ^{3}He-T, ^{6}Li-P, $^{6}Li(d,n\alpha)$, $^{6}Li(t,n)$, $^{7}Li(d,p)$ reactions. The branching ratios are in many cases unknown, or known only at one energy.

It is difficult at this stage to give a clear list of priorities for the cross-section requirements in this area. The $^{6}Li(p,^{3}He)^{4}He$ and $^{6}Li(^{3}He,p)^{8}Be$ reactions are of particular interest in that they are apparently the only one leading to exclusively charged particle reaction products, raising the tempting possibility of a fusion reactor without a neutron blanket. The ^{3}He-D, ^{7}Li-D, ^{7}Li-T and ^{7}Li-^{3}He reactions have attractively high cross-sections. (The problem of breeding ^{3}He has been discussed by for example Post (1969) and is not obviously insuperable). The accuracy required is not enormously high; $\pm$ 10% for the principal reaction channel in each case would probably suffice, and would certainly be a substantial improvement on the existing situation. As regards elements with Z > 3: it is our intention to extend the survey to higher Z numbers, but without any great expectation of return, since with increasing Z the difficulty of maintaining the necessary ratio of ion to electron temperatures becomes much more severe, as does the net particle loss rate from the confinement system. However, a reaction with a large resonance cross-section below about 1 MeV might be of interest.

Finally, it should be remarked that we have considered only fusion and stripping reactions: however inelastic scattering cross-sections and elastic scattering cross-sections which are substantially different from the Rutherford limit are also relevant to the energy exchange between species in the plasma, and hence to the effective overall reaction rate.

3. NEUTRON BLANKET CALCULATIONS

(i) Introduction

In this section the cross-section data required for the design of the neutron blanket surrounding a fusion plasma are considered. Since the design of fusion reactors is still at a very early stage, it is not possible to predict with any degree of confidence what materials will be used in the construction of a viable reactor, although there are certain general requirements which a blanket must satisfy (see Impink (1965) Chapter II). We shall therefore restrict attention here to one particular class of blankets for which detailed neutronic calculations have been performed, which is illustrative of the cross-section requirements that arise. It is assumed that the plasma reaction is the D-T reaction, producing 14 MeV neutrons, and that the functions of the blanket are to regenerate the tritium by means of the reaction scheme described in the introduction, to extract the neutron energy as heat, and to provide a stable engineering structure.

(ii) Blanket Model

To illustrate the importance of neutron cross-sections in various blanket problems, and to put the discussion on a quantitative basis, a model has been chosen which includes structure, reflector and (for illustrative purposes) two different coolants. This is shown in Fig.14, Test Case 7. The radius of the first wall, the containment wall, is 1·5 m. It is of cellular construction, fabricated of either niobium or molybdenum. It is cooled by a fused salt LiF(66%) + BeF_2(34%), normally written as Li_2BeF_4 and known as 'Flibe'. This region is then followed by a coolant plus structure region, which for the purposes of this paper consists of Flibe and Lithium with some structural material. There is then a thickness of graphite to slow down and reflect the neutrons. This is followed by a further lithium coolant channel. Surrounding this structure are the magnetic field windings and shield.

The list of materials above is not exhaustive but is considered at the present stage to represent a reasonable balance between strength, cost, and desireable neutronic properties. The first wall operates at $600^{\circ}C$, considered too high for stainless steel but suitable for the refractories niobium and molybdenum. Lithium in many respects is preferred to Flibe, but losses are incurred in pumping it across magnetic lines of force, and its hold up of tritium is high. Flibe is probably better from the safety view point but is poorer for tritium breeding.

This blanket model, Fig.14, Test Case 7, has been analysed neutronically (Blow et al 1969) and some of the reaction rates, based on one incident 14 MeV neutron are given in tabular form in the same Figure.

An accurate knowledge of the cross-sections of the materials composing the blanket is vital for estimating breeding (tritium production, neutron multiplication, parastic capture); heat generation (particle reactions, recoil nuclei, γ-ray production); radiation damage (displacement damage, helium production, transmutation); and radioactivity (for maintenance, etc.).

The importance of the calculated neutron spectra for the blanket must not be overlooked. All the above features are influenced by the accuracy of these calculated spectra. The spectra are particularly important in areas where the physical limit is being approached. Such regions are those close to the first wall where heat fluxes are extremely high and radioactive damage severe. Similar limitations, but of a much smaller magnitude, could apply to the superconducting coils in which heat deposition and radiation damage must be limited. It is thus important that the neutron cross-sections, particularly of the bulk material, must be know accurately enough to enable the reactor spectra to be adequately calculated.

(iii) Tritium Breeding Reactions

Looking at the table in Fig.14, Test Case 7, the value for total tritium production, T, is 1·17. The criterion of accuracy chosen is that we would like to know T to ± 1%. On this basis the required accuracy for any reaction rate is judged by its magnitude relative to 1·17.

a. $^6Li(n,t)^4He$: $T_6 = 0.91$. Obviously this important reaction should be known as accurately as possible - to about 1%. Recent measurements at Harwell (Silk, 1969) show that $\sigma_{thermal} = 953 \pm 5$ barns. The accuracy is ½%. Silk intends also to measure around the resonance peak at 250 keV ($\sigma \sim 2$ barns). He hopes to get 5% accuracy in this range which is as good as can be done at present.

b. $^7Li(n,n't)^4He$: $T_7 = 0{\cdot}26$. We would like to know this other important cross-section to at least 10% (preferably 5%) instead of the present ~ 25%. From Pendlebury (1964) the cross-section accuracy is ~ 15% at 14 MeV, and ~ 25% at 8 MeV (see Fig.15). However, several of the published values lie well away from the preferred curve. Experimental results up to 1962 are included by Pendelbury. There appear to be no further measurements since ~ 1963. The American ENDF/B file (Honeck, 1967) values are based on the U.K. compilation (Pendlebury, 1964b). For a description of the format of the U.K. data file see Parker, 1963.

Fig.15 shows the tritium production cross-sections in natural lithium (composed of 7.42% ^6Li and 92·58% ^7Li) in the high energy region. At lower energies the cross-section gradually assumes a V^{-1} dependence and reaches a value of 71 barns at thermal energy. This low energy contribution arises from the ^6Li isotope; pure ^6Li has a cross-section of 953 barns at 0·025 eV. We assume natural lithium will be used since no great advantage accrues from isotopic enrichment in ^6Li (typically, a 5% increase in breeding for a 50% ^6Li content, see Impink, 1965).

c. $^9Be(n,t)^7Li$: The contribution from this reaction is negligible.

(iv) Neutron Multiplication Reactions

From the table in Fig.C the total (n,2n) reaction rate is 0·17, so we would like to know the (n,2n) contribution to ~ 7% accuracy.

TABLE II

Multiplication Reactions in Blanket Model

REACTION	CONTRIBUTION	REQUIRED ACCURACY
Nb(n,2n)	0·03	~ 30%
Mo(n,2n)	~ 0·07	~ 20%
Be(n,2n)	0·09	~ 15%
F(n,2n)	0·02	~ 50%
^{6}Li(n,2n)D	0·003	ignore
^{7}Li(n,2n)^{4}He	0·01	~ 100%
^{7}Li(n,2n)^{6}Li	0·01	~ 100%

On the three most important reactions we make the following comments:-

a. Nb(n,2n): The activation value (which is the one in the ENDF/B American file and the U.K. nuclear data file) for σ at 14 MeV is ~ 450 mb. Allen and Drake (1967) state that the current value may be up to 3 times as great. This is based on theoretical work done by H.G. Carter (1966). The activation value (Bramlitt and Fink, 1962; Basu et al, 1966) is derived from intensity measurements on the 10·1 day half-life of what is now established as the first excited state of ^{92}Nb with a spin of 2. The ground state of ^{92}Nb has a spin of 7. If this state has a long half-life then virtually no activity will be measured as a result of its decay. The question to ask is: how many decays from the ^{93}Nb(n,2n) ^{92}Nb reaction proceed to the first excited state, how many go to the ground state?

An estimate has been made using the Troubetzkoy formalism (Troubetzkoy, 1961) which gives a ratio of 1 to 1·5 for decays going to the first excited state and ground. This indicates that we should multiply the activation value (450 mb) by 2.5, giving ~ 1100mb, which closely agrees with Carter's estimate of 1136 mb.

Carter also points to the possibility of a significant (n,np) cross-section at 14 MeV (with a value ~ 350 mb).

b. Mo(n,2n): This cross-section has simply never been measured (up to 1966). Values in the ENDF/B and U.K. files are based on theoretical calculations by S. Pearlstein (1964). The value deduced at 14 MeV is 1·28 barns.

c. Be(n,2n): The accuracy at 14 MeV is about 10%. The preferred measurement of McTaggart and Goodfellow (1963) is 450 ± 40 mb. Data over the rest of the range (threshold is at ~ 2·5 MeV) are not very good (see BNL 325, Suppl.2, Vol.1, Goldberg et al., 1966). The preferred curve is probably accurate to within 25% away from the 14 MeV point.

(v) Parasitic Neutron Capture

From Fig. 14, Test Case 7, the total contribution to absorption is 0·26, so we would like to attain 5% accuracy here.

TABLE III

Significant Absorption Reactions

REACTION	CONTRIBUTION	REQUIRED ACCURACY
Nb(nγ)	0·112	15%
Mo(nγ)	~ 0·11	15%
F(n,abs)	0·124	10%
Be(nα)	0·010	100%

Besides the four reactions given in Table III, reaction rates were calculated for ^{6}Li(np), ^{7}Li(nd), Nb(np), Nb(nα), ^{6}Li(nγ), ^{7}Li(nγ), Be(nγ), and C(nα). None of these contributed significantly in the present sense.

On the three important reactions we make the following comments:-

a. Nb(nγ): Data in the region thermal to 10 keV should be accurate to within a few per cent. From 100 keV to 1 MeV the accuracy is ~ 25%. Above 1 MeV there are no measurements available but in any case the cross-section is dropping to a negligibly small value. These observations are made from graphs given in BNL 325, Suppl.2, Vol.IIB, 1966.

b. Mo(nγ): The state of the data is very similar to that of niobium.

c. F(n,abs): Contributions from (nt), (nd), (nα), (np) and (nγ) processes have all been lumped together in a total absorption cross-section by R.S. Buckingham et al (1960).

The data for (nα), the largest contributor, are very poor over the range 3·0 MeV to 9·0 MeV, with variations of up to 100%. (BNL 325, Suppl.2, Vol.1, 1964). The (nα) and (np) reactions have been re-measured recently (Prasad and Sarkar, 1966; Pasquarelli 1967; Mitra and Ghose, 1966). The measurements were taken only at around 14 MeV, and there is still a failure of overlap between the different experimental values.

The F^{19} (nγ) reaction has a value of only 10 mb at thermal energies (Glickstein and Winter, 1963).

(vi) Heating

Gamma-ray absorption cross-sections are derived from the well-known processes of Compton scattering, photoelectric effect, and pair production. There appears to be no problem with accuracy here. Details of heating effects thus revolve around having adequate knowledge of gamma-ray source intensity and spectral description, recoil effects, and charged particle emission. For the medium-heavy nuclides, niobium and molybdenum, these three effects are now considered in inverse order of importance.

a. Charged Particle Emission: The cross-sections for the only two reactions producing charged particles in Nb, (np and nα), are 30 mb and 10 mb respectively at 14 MeV. The accuracy is ~ 20%. Contributions to heating from these two processes are therefore insignificant. The (nα) cross-section is, however, very important in radiation damage work (see 3.(vii).b).

b. Recoil Effects: Steiner (1969) has calculated that ~ 8% of heating in the first wall of a reactor is caused by primary recoil processes. The important reactions are elastic scattering and inelastic scattering (quite well-known) and (n,2n) events (poorly known). The cross-sections from 0 to 14 MeV are shown in Fig.16.

The calculation of recoil is made using simple hard-sphere dynamics. The accuracy of the calculation depends on the adequacy of the secondary angular distribution. For elastic scattering only one measurement of anisotropy has been made (Western et al., 1966) at 14 MeV. For inelastic scattering isotropy in the centre of mass (c.m.) system is assumed. We would like to see a measurement of any anisotropy in inelastic scattering at 14 MeV.

The form of energy distribution of the two emitted neutrons in (n,2n) is a total unknown. The (n,2n) reaction contributes significantly to recoil, and therefore damage processes (see 3.(vii)), in a fusion spectrum.

c. Gamma-Ray Source Intensity and Spectral Description: Steiner (1969) calculates that ~ 92% of the heating in the first wall is caused by gamma absorption. Around 30% of the total energy released in the blanket is emitted as gamma-radiation. An adequate intensity and spectral description is therefore necessary.

The only two important processes are inelastic scattering and (nγ). For the first wall region neutron spectrum, the reaction rate for inelastic scattering is some eight times that for (nγ).

Following Groshev's early work (1959) a literature survey has not revealed a useful measurement of the gamma-ray spectrum from radiative capture, over the entire energy range. There is likewise a dearth of data for gamma-rays from inelastic scattering at, say, 14 MeV. Any γ-ray spectra produced from inelastic scattering have been mainly used for establishing excitation functions and energy values for excited states (see e.g., Degtyarev, 1970; Beghian et al., 1967). Such measurements have therefore been made in the energy region 1 to 2·5 MeV, whereas we would like to see γ-ray spectra from inelastic scattering in the 5 to 14 MeV regime.

(vii) Radiation Damage

(a) Displacement: Displacement damage is closely related to the magnitude of the recoil energy of struck nuclei. Recoil effects have been discussed in 3.(vi).b.

A comparison of the spectrum in the first wall of a fusion reactor (Blow et al, 1969) with that in the core centre of the Dounreay Fast Reactor (Birss and Bishop, 1966) is made in Fig.3. The flux values are nearly the same at $2{\cdot}8 \times 10^{15}$ n cm^{-2} sec^{-1}, and $2{\cdot}5 \times 10^{15}$ n cm^{-2} sec^{-1}, respectively. Despite the much greater energy available in the fusion spectrum the displacement rate is only twice that in the D.F.R. spectrum. The main reasons for this are: (a) forward peaking in elastic scattering at high energies; and (b) greater proportional loss of energy by excitation, rather than displacement of other atoms, by struck nuclei of high initial energy.

Displacement rates of niobium atoms in the first wall are high. A figure of 165 displacements per atom per year is calculated (Blow, 1970a). Fig.17 shows damage energy spectra from elastic, inelastic, and (n,2n) scattering in a fusion reactor first wall.

(b) Void and Bubble Formation: Helium tends to be trapped in a metal like niobium, even at $600^{\circ}C$, whereas hydrogen will diffuse out (Martin, 1969). It is essential to have an accurate value of the rate of helium formation for two reasons:

(a) helium nuclei may agglomerate to form mobile bubbles; and

(b) they may act as nuclei for void formation.

The creation and growth of bubbles and voids will cause swelling in the structural material and ultimate mechanical failure (Martin, 1969).

There have been several experimental measurements of the (nα) cross-section in niobium (BNL 325, Suppl.2, Vol.IIB). There is a discrepancy of some 20% at 14 MeV. The accepted value is 10 mb.

(viii) Radioactivity and Transmutation

A recent calculation (Blow 1970b) has shown that the activity of a segment of first wall, 300 cm in diameter, 0·5 cm thick and 100 cm in length, will be ~ 17 megacuries at the end of a 20 year irradiation period.

Nearly 80% of this activity is caused by excitation of the first excited state of ^{93}Nb in inelastic scattering. This state, of energy 30 keV, has a half-life of 13·7 years. It decays by internal transfer to the ground state. It is estimated, using a simple theoretical model of Troubetzkoy's (1961), that 23% of the decays following inelastic scattering at 14 MeV will land in the first excited state. It is highly desireable to have an experimental determination confirming or modifying this value.

Transmutation in the wall from niobium to zirconium depends cirtically on the magnitude of the (n,2n) cross-section. Using the recommended value of 450 mb, 7·5% of the niobium is converted to zirconium after 20 years. Using a higher value of 1,000 mb (see sec.(iv)a) the answer is 15%. This is a formidable transmutation rate which may have significant effect on structural integrity.

TABLE IV

Nuclear Reactions having inadequate data for Neutronics, Heating, Damage and Activity Calculations

REACTION	SPHERE OF INTEREST	PRESENT STATE OF DATA ACCURACY
1. $Li^7(n,n't)$	Tritium Breeding	~ 25% Accurate
2. Nb(n,2n) 3. Mo(n,2n)	(i) Recoil Heating (ii) Damage (iii) Transmutation	Nb Very uncertain Mo not measured
4. F(n,abs)	(i) Neutron Absorption (ii) Gamma-Ray Heating	Several Reactions contributing. Poor experimental agreement
5. Gamma-Ray spectra from (nY) and inelastic scattering in Nb	(i) Gamma-Ray Heating	No complete spectral measurement
6. Nb(nα)	(i) Damage	~ 20% Accurate
7. Excitation of first state in Nb^{93}	(i) Radioactivity	Not measured

CONCLUSIONS

(i) Charged particle cross-sections

A rather large number of thermonuclear reactions are potentially of interest to the fusion reactor designer, although for good reasons attention has hitherto been focussed on the $T(d,n)^4He$ reaction. The basic requirement for a reaction to be of interest is that it should have a cross-section in excess of about 10 millibarns at an energy not exceeding a few MeV, that the nuclei involved should have a low charge (with Z certainly less than 10 and probably less than 4) and that the reaction Q value should be positive and reasonably large (several MeV). The reactions involving species with $Z < 4$ which satisfy these requirements are listed in Table 1, together with their peak cross-section and Q value, and compilations of the existing cross-section data in Figs.4-13. The data for the $D(d,n)^3He$, $D(d,p)T$ and $T(d,n)^4He$ reactions are seen to be in very reasonable (better than 90%) agreement. For all the other reactions, particularly those involving the isotopes of lithium, substantial discrepancies are observed. In many cases absolute normalizations of yield curves are absent, angular distributions unknown, branching ratios uncertain or known only at one energy, and in several cases the cross-section is still increasing at the highest energy at which a measurement is avilable. There is considerable scope for further work in this area.

(ii) Neutron cross-sections

Table IV summarises the conclusions from the sections of this report on neutron reactions for which the present state of data accuracy is insufficient. Reaction 5 in this table refers specifically to niobium, the currently preferred structural material, but a similar lack of data exists for both molybdenum and iron (stainless steel) which are other possible structural materials.

Three general comments can be made:-

(a) It is in the region 1-14 MeV that neutron cross-section data are relatively poor. This region is more important for fusion systems based on the D-T cycle, than for fission systems.

(b) the materials selected for the neutron blanket should not be regarded as unique, so that for any new structural material, say iron, the comments under (a) would apply.

(c) secondary γ-ray production appears to be very important in fusion systems and has been inadequately investigated.

(iii) Data library services

It appears that none of the existing nuclear data libraries compile or evaluate data on charged particle cross-sections or on γ-ray production in neutron interactions. It would be valuable if the data centres at Obninsk, Vienna, Saclay and Brookhaven were to consider extending their services in these directions. As regards charged particle interactions, the data required include total cross-sections, differential cross-sections, angular distributions, reaction product energy distributions, branching ratios and excited state energy levels for fusion, stripping, elastic and inelastic scattering processes. On the neutron side, the requirement is for neutron cross-sections for γ-ray production which could be integrated with neutron spectra in order to describe γ-ray source spectra emitted in non-elastic neutron interactions.

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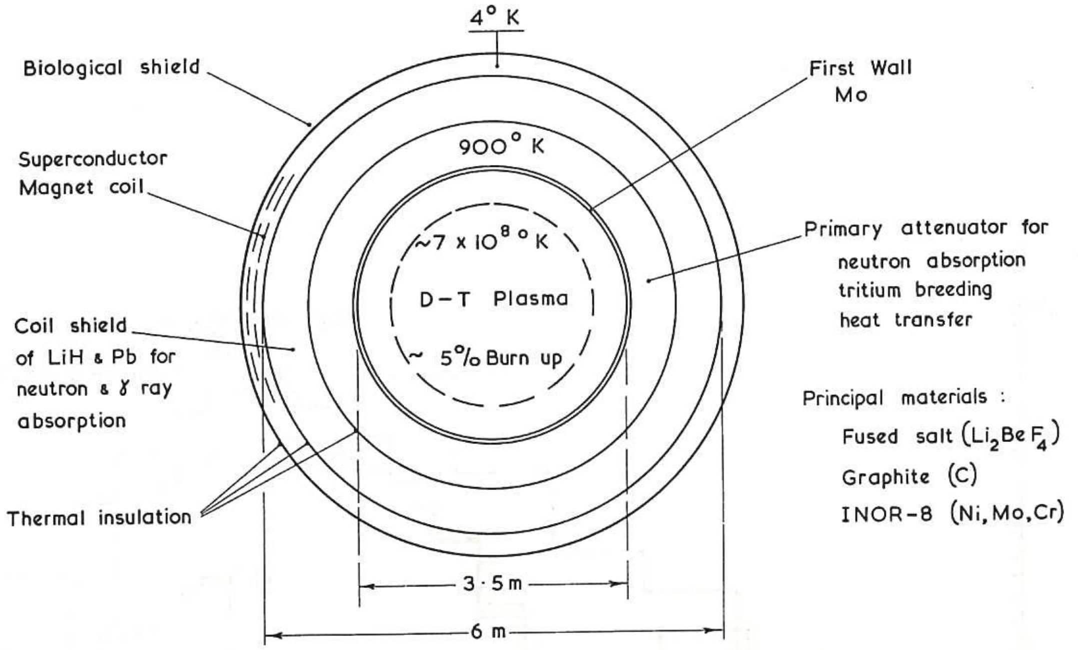


Fig.1 Conceptual design cross-section of D-T Reactor - blanket after Homeyer (1965).

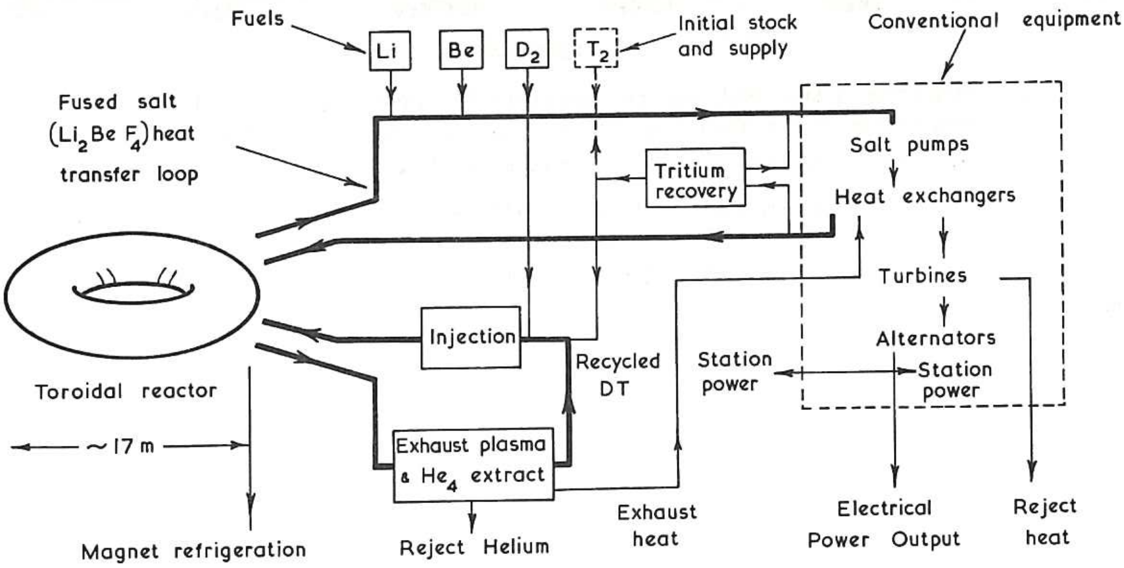


Fig.2 Functional diagram of D-T fusion reactor generating station.

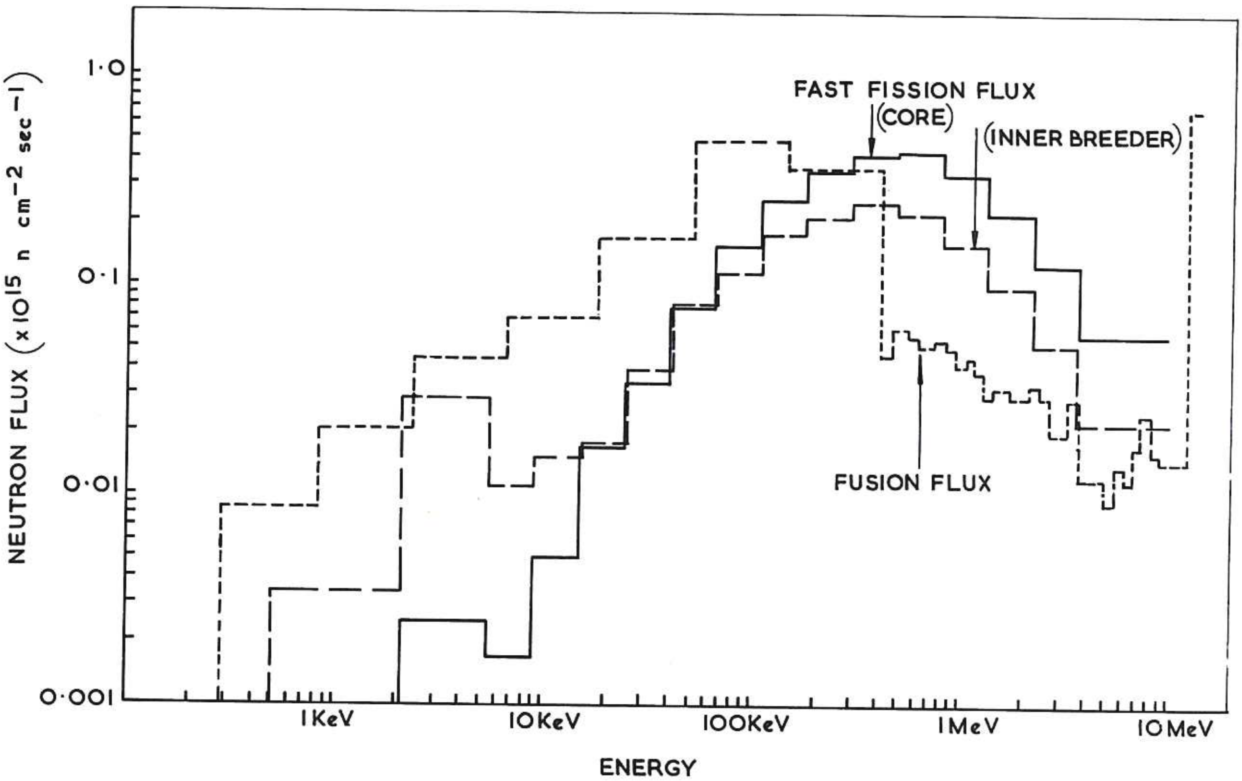


Fig. 3 Neutron Flux Values in various Energy Groups in (a) Dounreay Fast Reactor Core; (b) D.F.R. Inner Breeder; (c) Fusion Reactor Model First Wall.

Total Flux in (a) = $2{\cdot}5 \times 10^{15}$ n $cm^{-2}sec^{-1}$
(b) = $1{\cdot}5 \times 10^{15}$ "
(c) = $2{\cdot}77 \times 10^{15}$ "

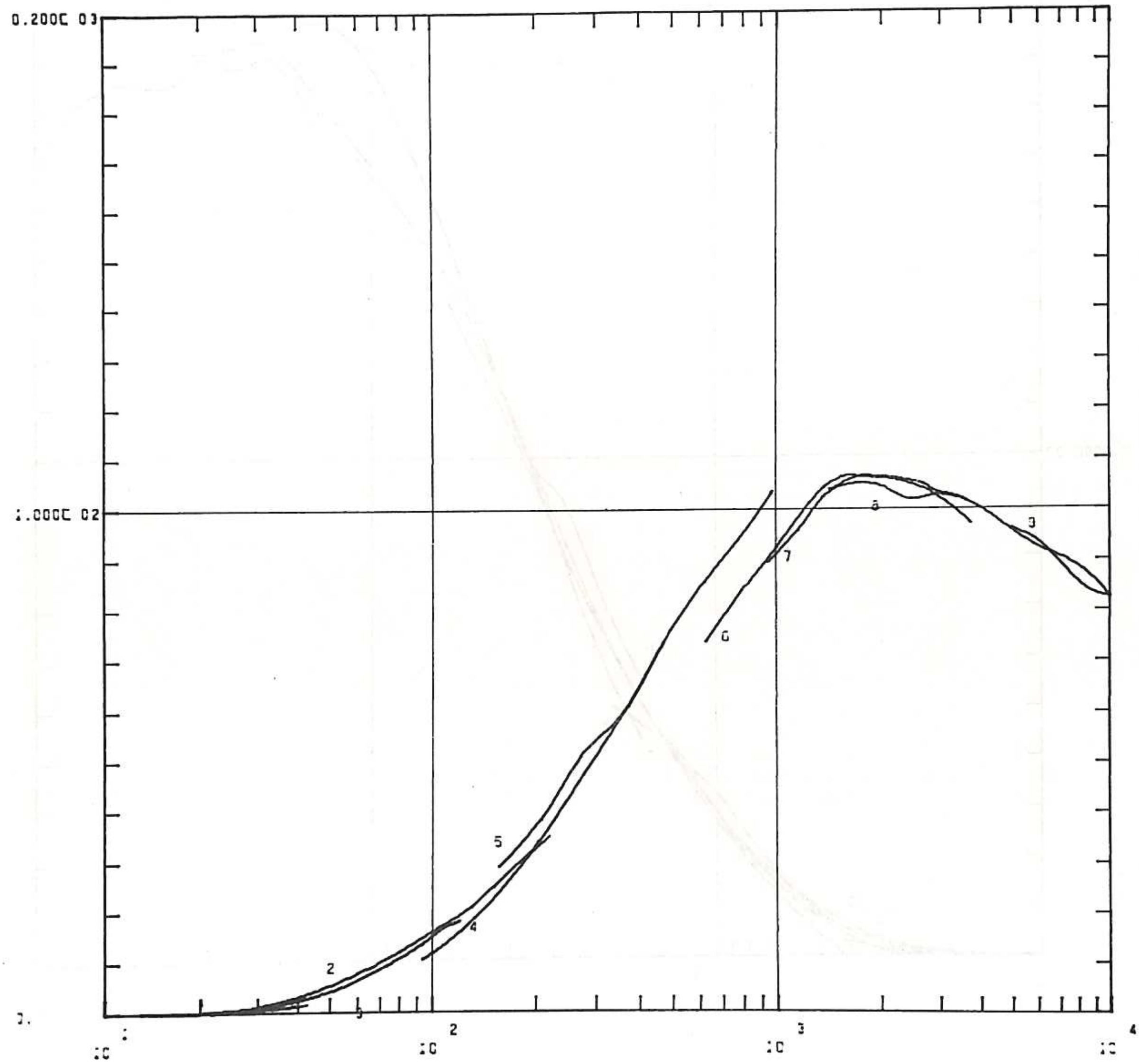


Fig.4 D(d,n)^{3}He Arnold[3] Blair[7] Brolley[8] Davidenko[2] Eliot[1] Ganeev[4] Hunter[6] Preston[5] Thornton[9]

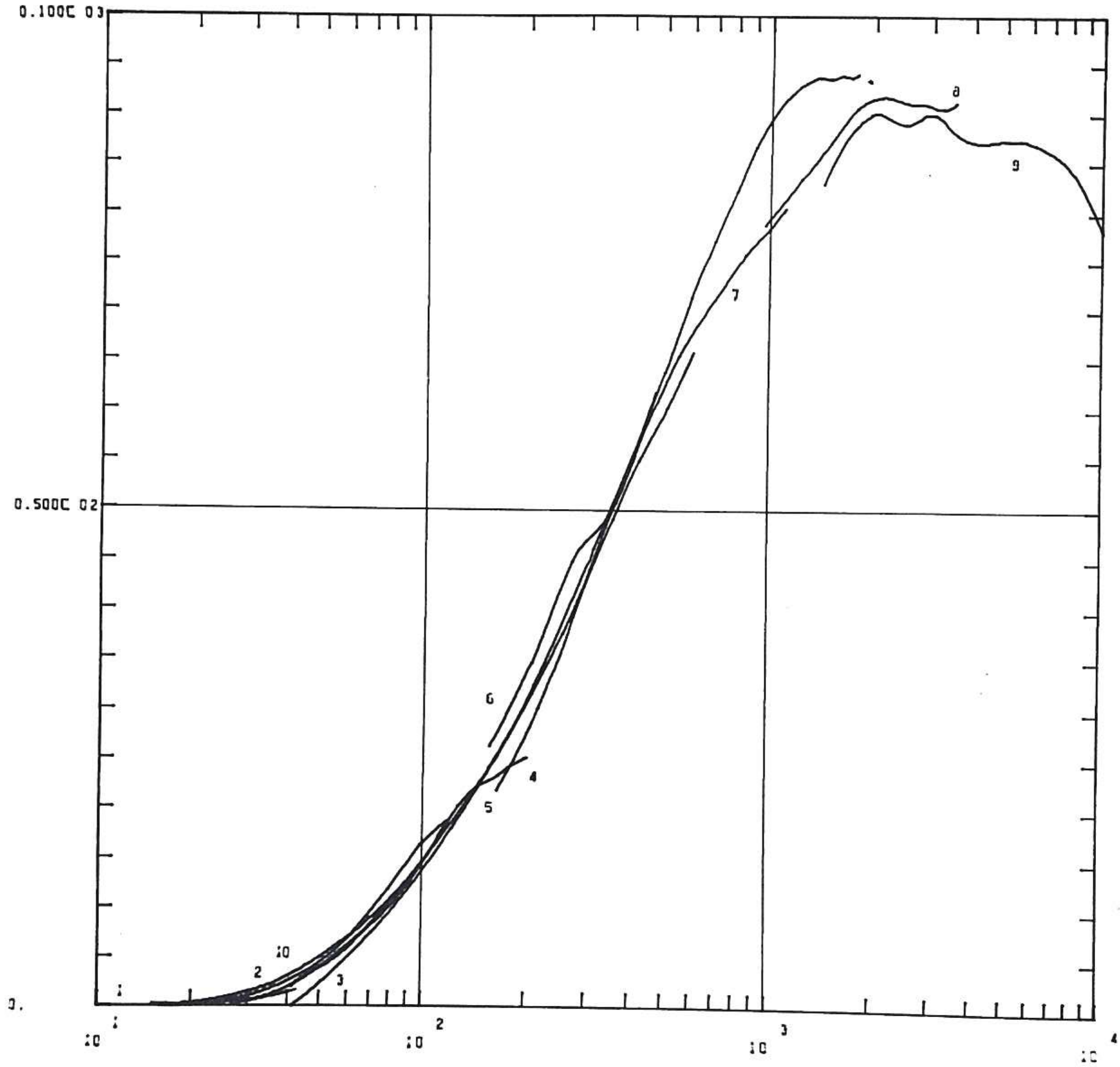
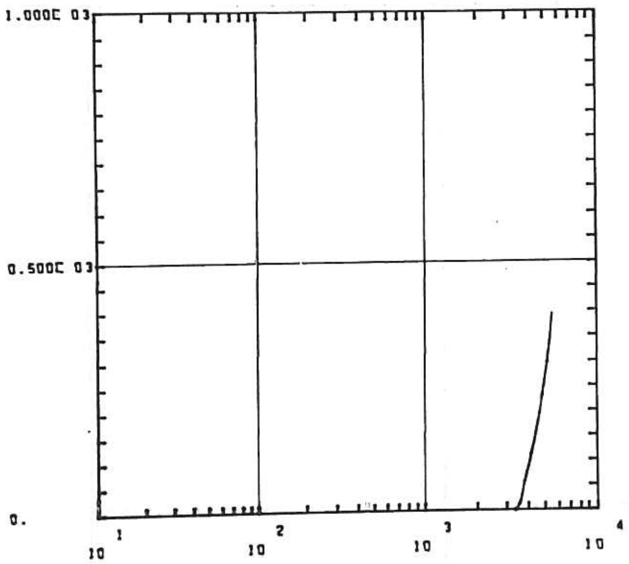
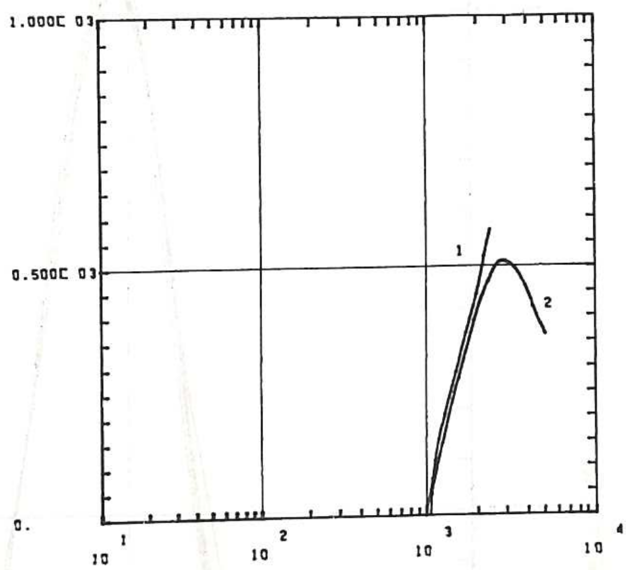


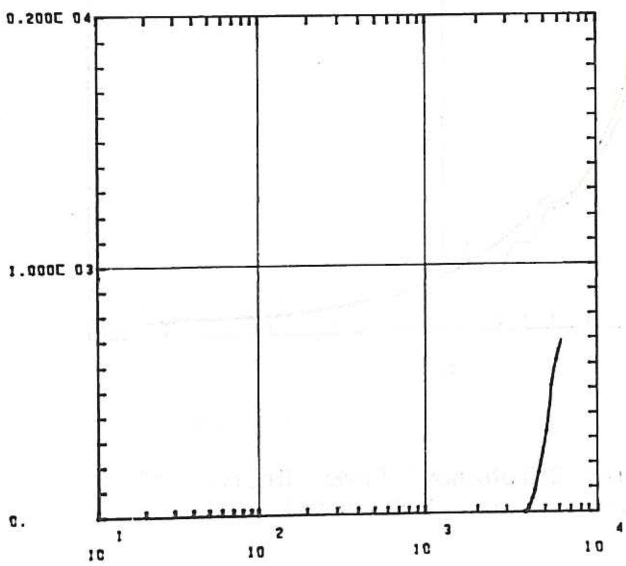
Fig.5 D(d,p)T Arnold[1] Balabanov[4] Blair[8] Brolley[9] Cook[10] Eliot[2] Ganeev[7] Preston[6] Volkov[5] Wenzel[3]



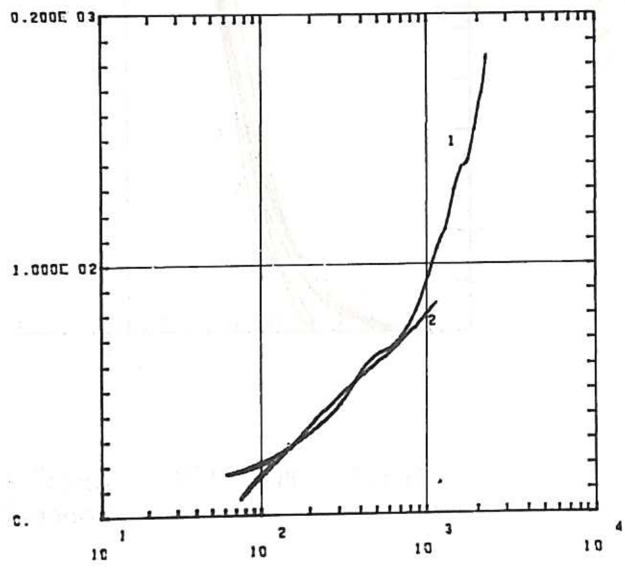
D(d,np)P Henkel



T(p,n)^{3}He Jarvis[1] Willard[2]



T(d,np)T Henkel



T(t,2n)^{4}He Agnew[1] Govorov[2]

Fig.6

Vicigraph plan

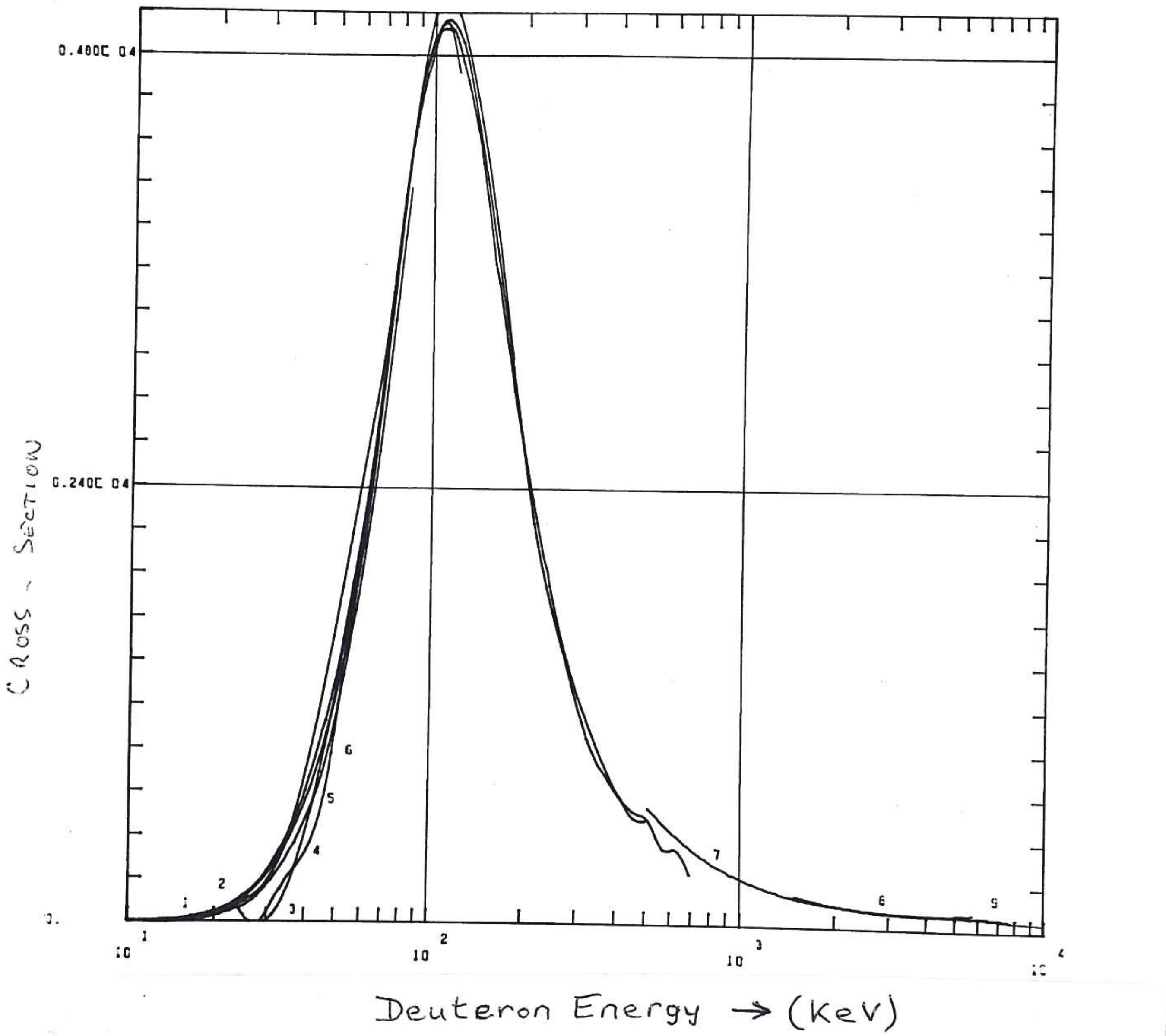


Fig.7 T(d,n)^{4}He Argo[6] Arnold[1] Balabanov[4] Bame[7] Bretscher[5] Conner[3] Cook[2] Galonsky[8] Stewart[9]

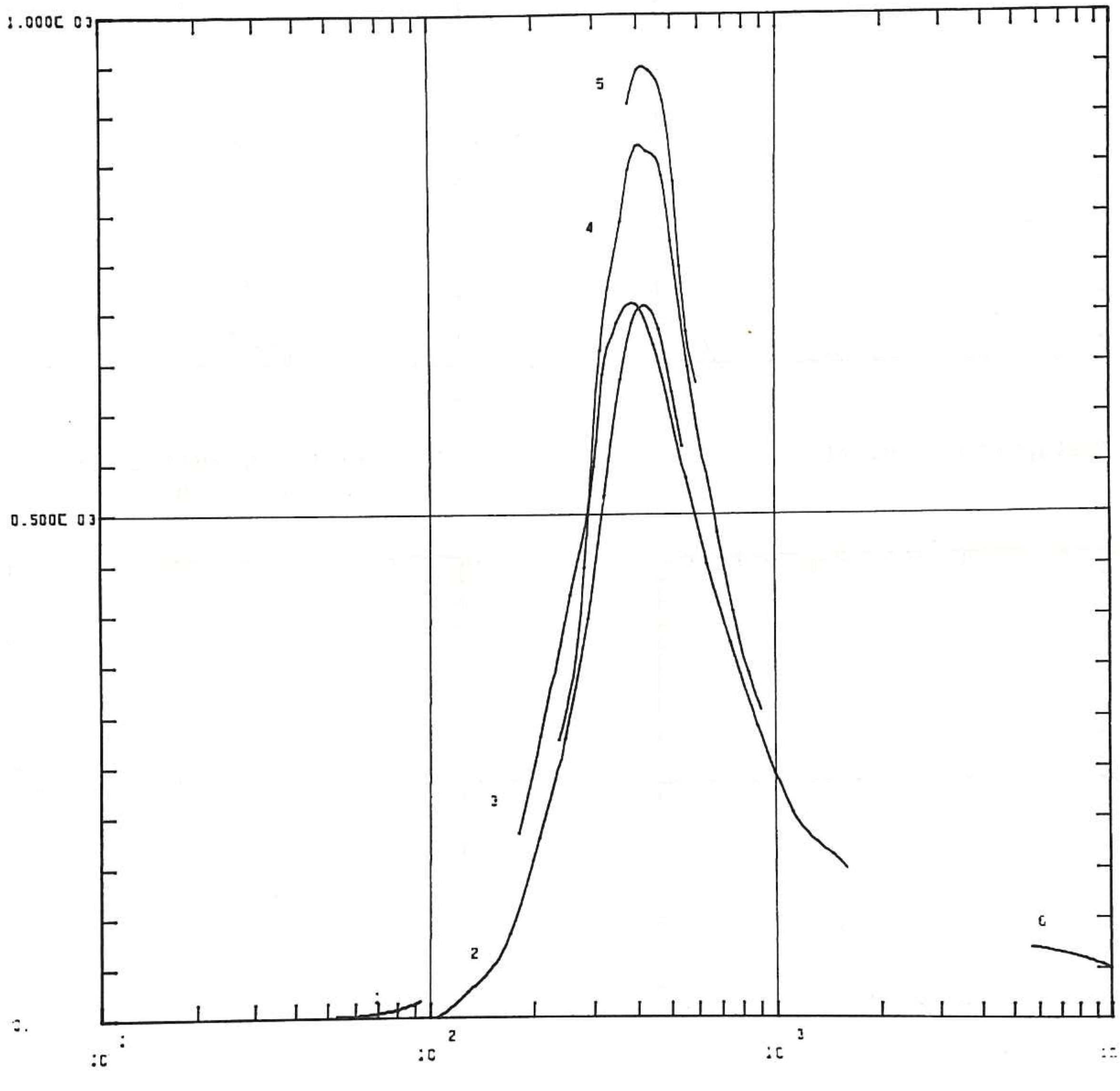
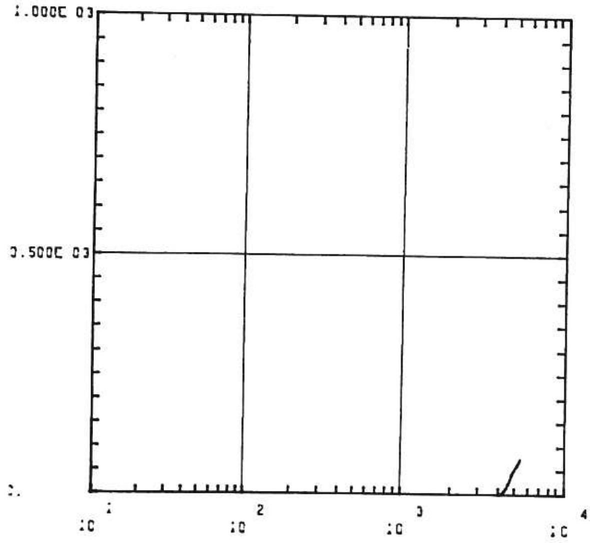
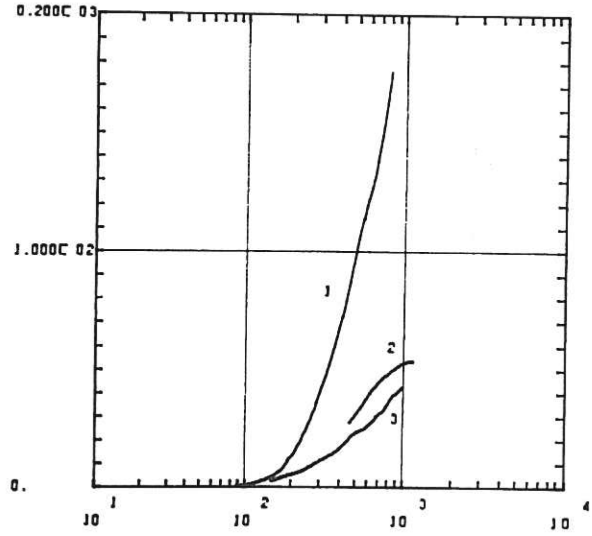


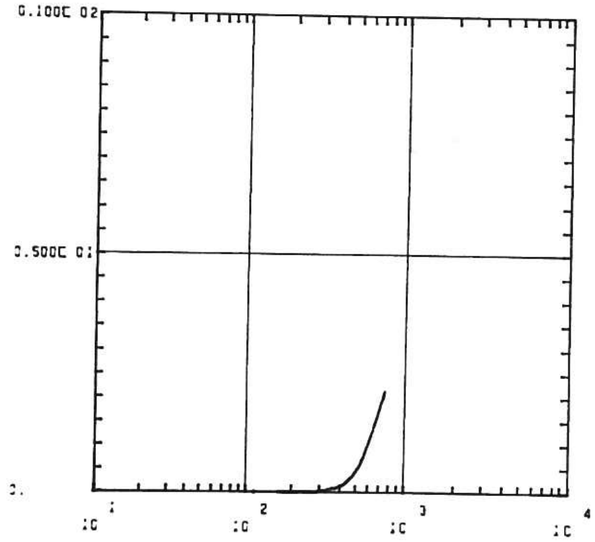
Fig.8 $^{3}He(d,p)^{4}He$ Arnold[1] Bonner[3] Frier[5] Kunz[2] Stewart[6] Yarnell[4]



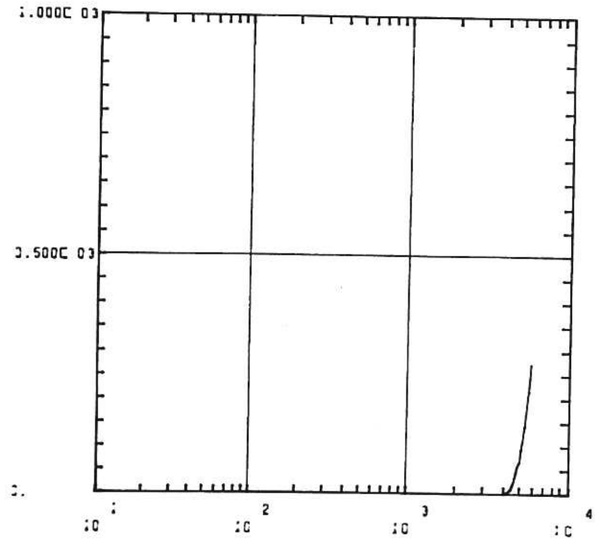
$^3He(d,np)^3He$ Henkel



$^3He(t,np)^4He$ and $^3He(t,d)^4He$
Kuhn[3] Moak[1] Youn[2]



$^3He(^3He,2p)^4He$ Good



$^4He(d,np)^4He$ Henkel

Fig.9 Helium reactions

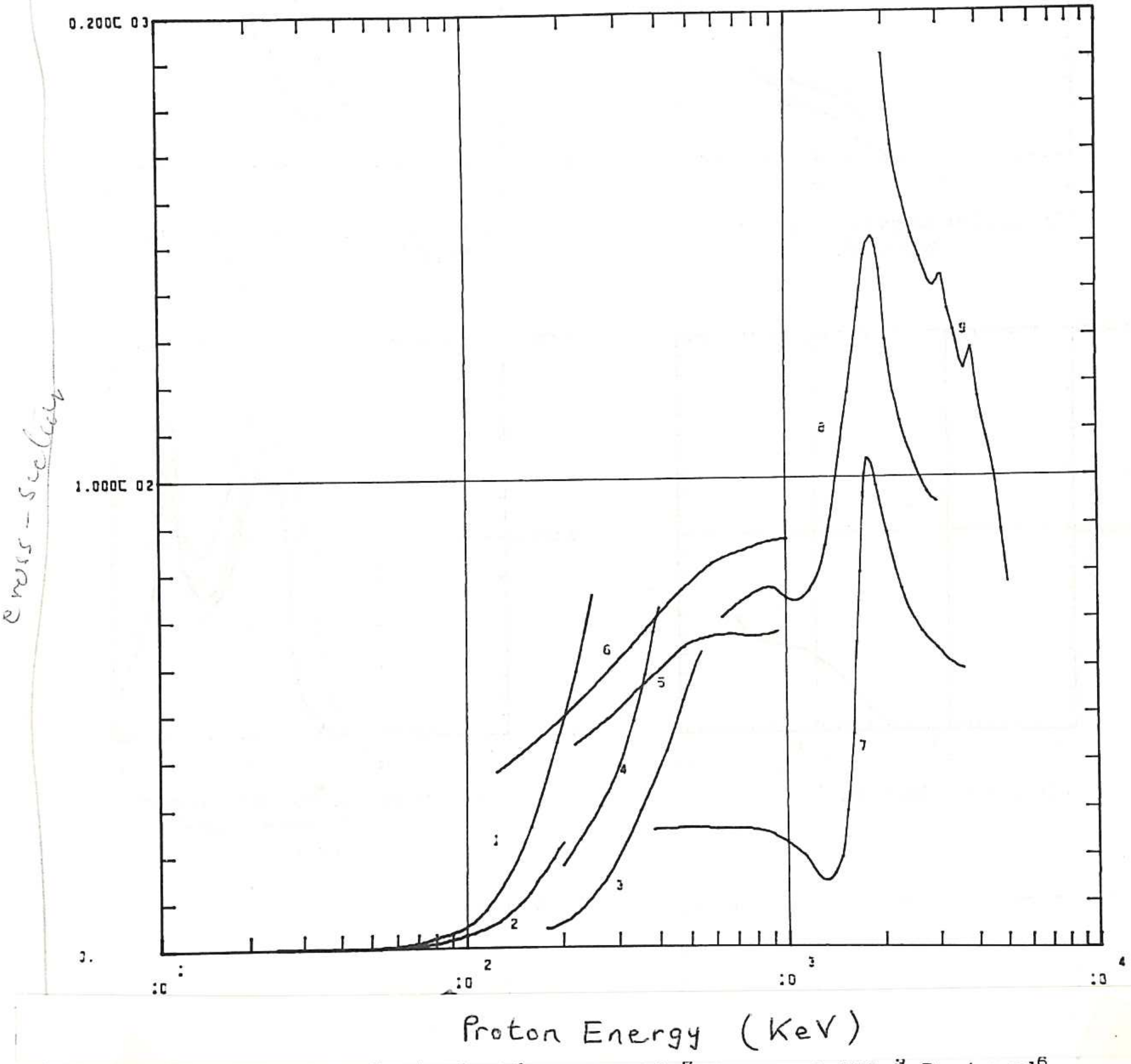
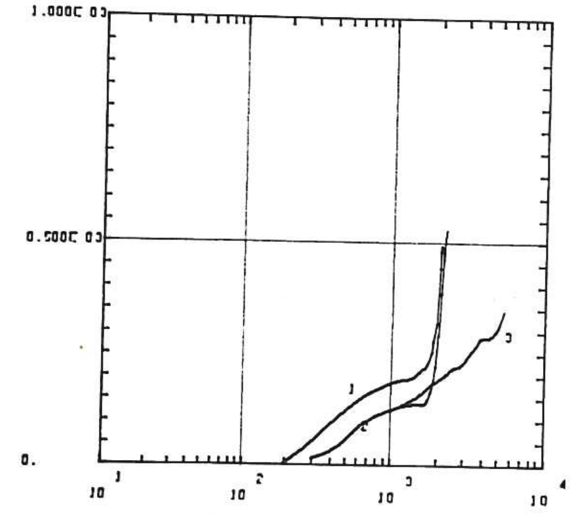
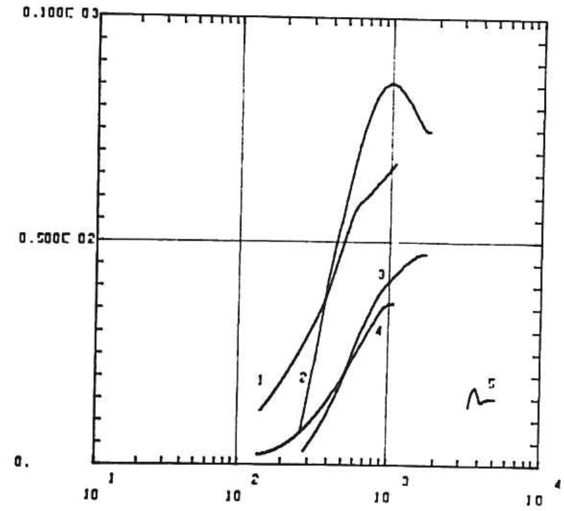


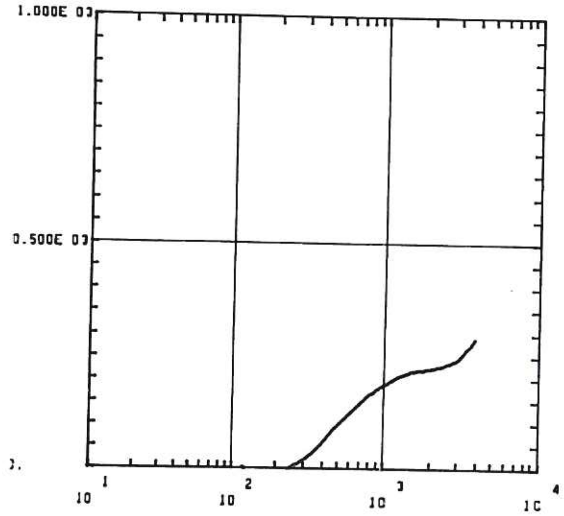
Fig. 10 $^{6}Li(p,{}^{3}He){}^{4}He$ Bashkin[7] Beaumevieille[3] Bertrand[6] Bowersox[4] Burcham[5] Gemeinhardt[2] Jeronymo[9] Marion[8] Sawoyer[1]



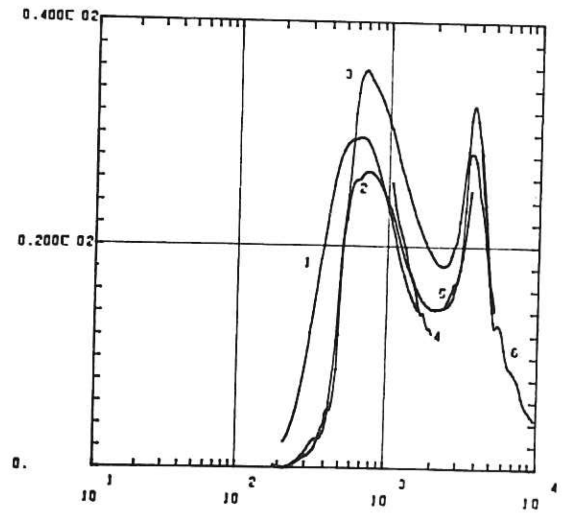
$^{6}Li(d,n\alpha)^{3}He$ Baggett[1] Slattery[3]
Whaling[2]



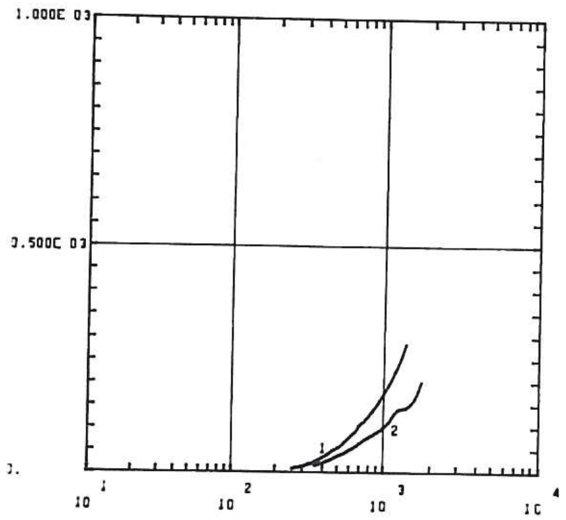
$^{6}Li(d,p)^{7}Li$ Bertrand[1] Whaling[3]
$^{6}Li(d,p')^{7}Li^{*}$ Bertrand[2] Meyer[5]
Whaling[4]



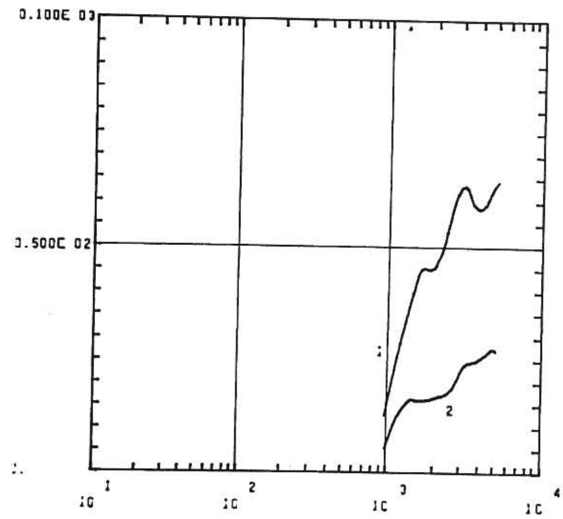
$^{6}Li(d,t)^{5}Li$ Macklin



$^{6}Li(d,\alpha)^{4}He$ Bruno[4] Heydenburg[3]
Jeronymo[2] Mani[6]
Whaling[1]



$^{6}Li(t,n)^{8}Be$ Serov[1] Valter[2]



$^{6}Li(^{3}He,p')^{8}Be^{*}$ Schiffer[1]
$^{6}Li(^{3}He,p)^{8}Be$ Schiffer[2]

Fig.11 ^{6}Li reactions

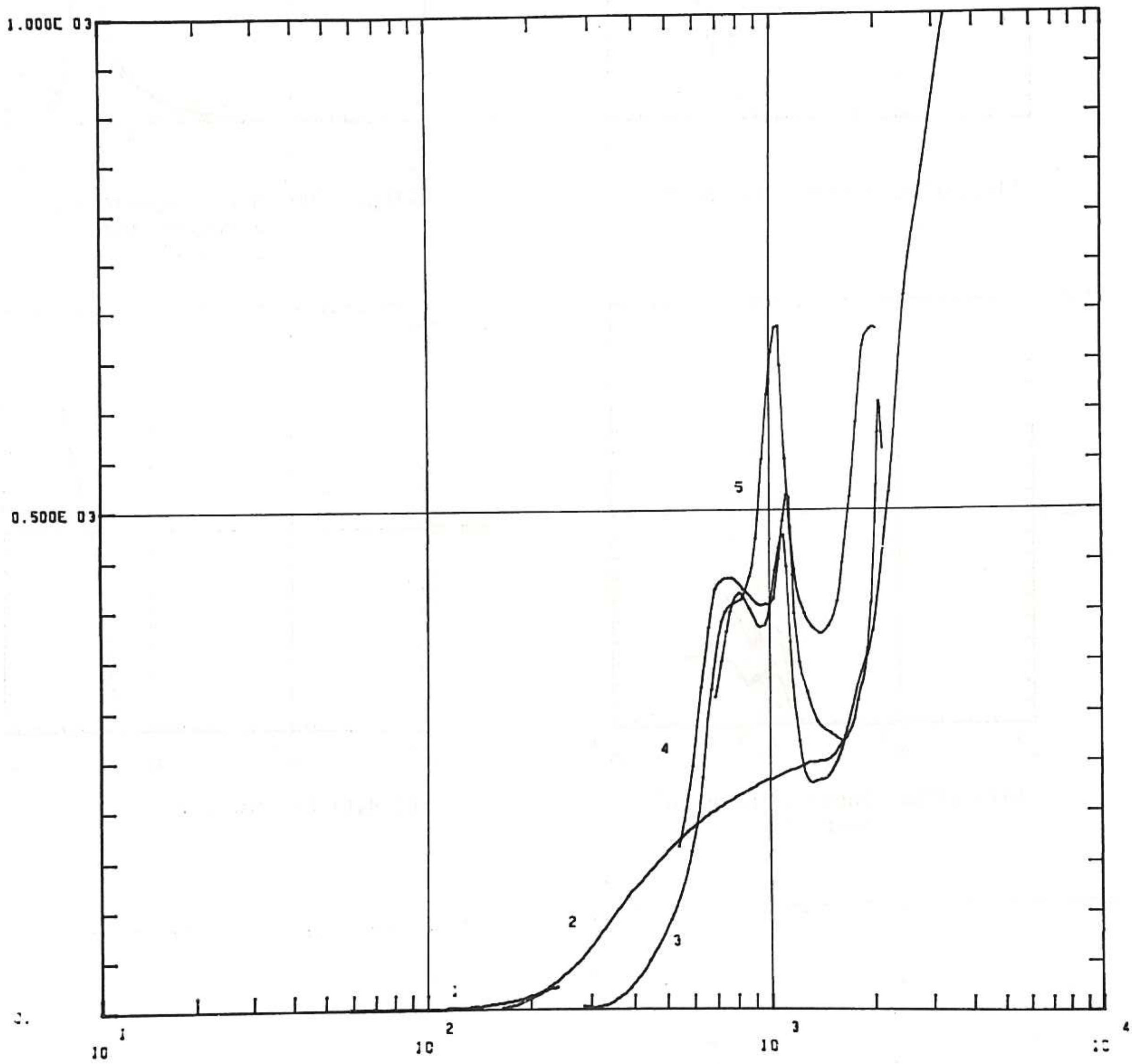
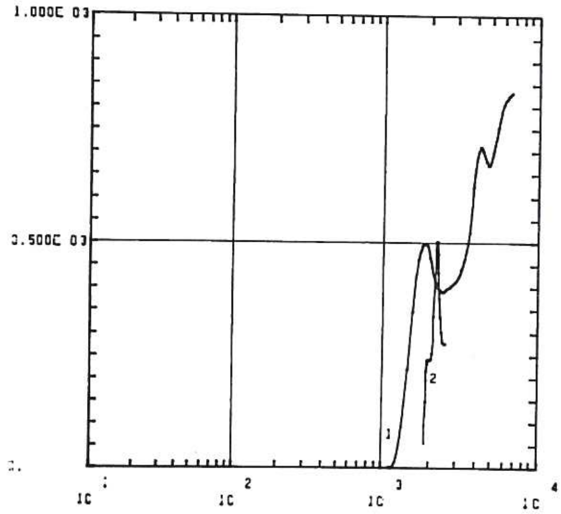
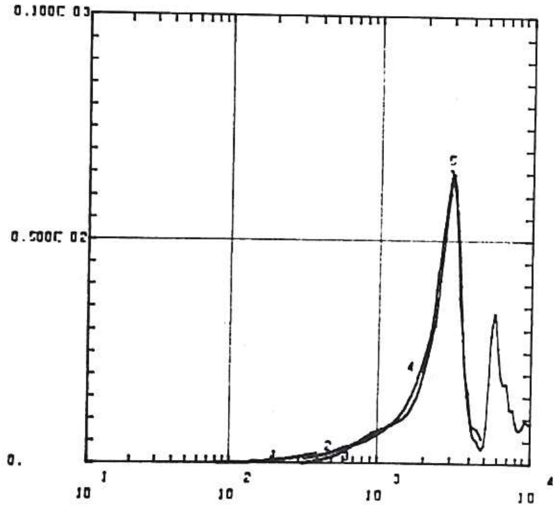


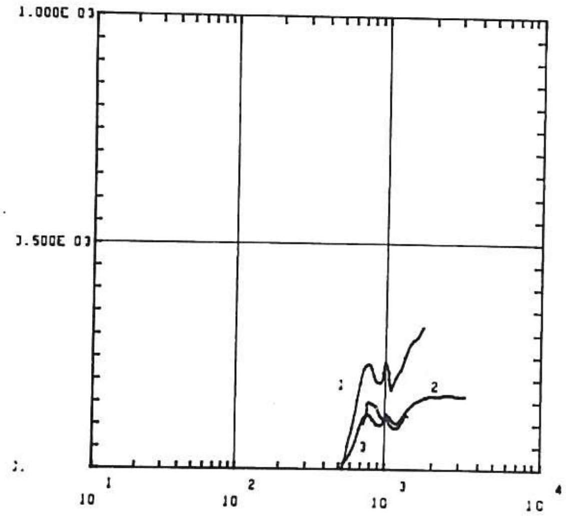
Fig. 12 $^{7}Li(d,n)^{8}Be$ Baggett[2] Bennett[4] Sawyer[1] Slattery[5] Whaling[3]



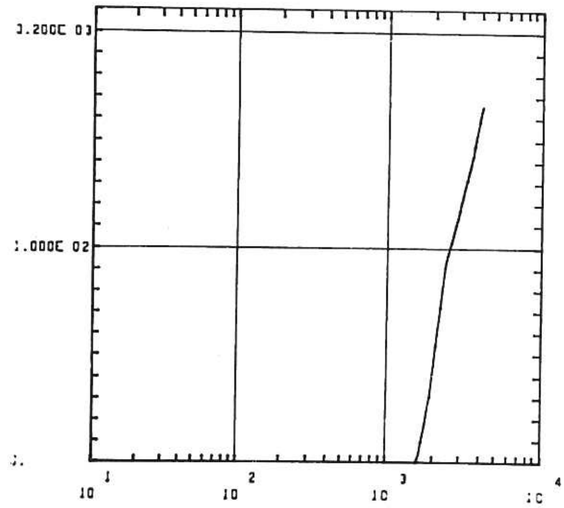
$^{7}Li(p.n)^{7}Be$ Blaser[1] Taschek[2]



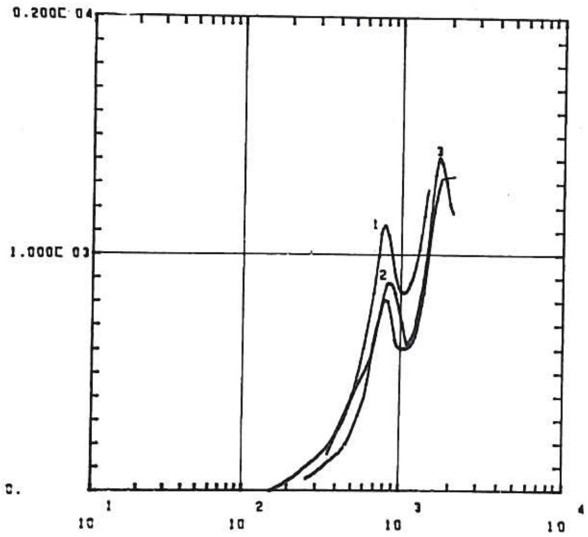
$^{7}Li(p,\alpha)^{4}He$ Herb[1] Heydenburg[2] Jeronymo[4] Mani[5] Sweeney[3]



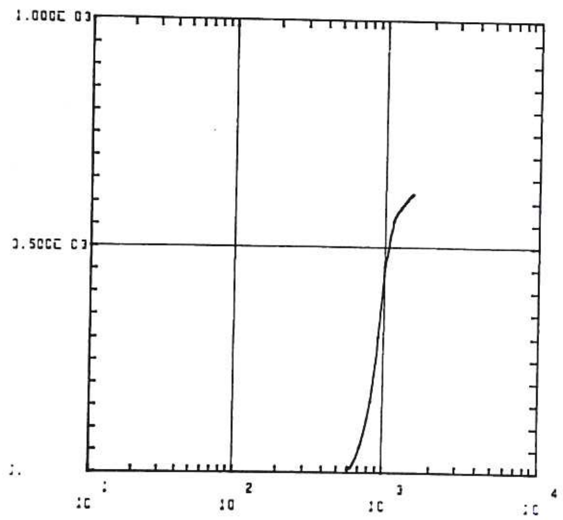
$^{7}Li(d,p)^{8}Li$ Baggett[1] Bashkin[2] Bennett[3]



$^{7}Li(d,t)^{6}Li$ Macklin



$^{7}Li(t,2n)^{4}He+^{4}He$ Crews[3] Serov[1] Valter[2]



$^{7}Li(^{3}He,p)^{9}Be$ etc. Serov.

Fig.13 ^{7}Li reactions

TEST CASE	REGIONS 5,7, 9,12	REGIONS 6,8, 10	(n,2n)	T_6	T_7	T	ABS	LOST
6	98% Li 2% Nb	98%Li 2% Nb	0·131 ± 0·001	0·894 ± 0·015	0·398 ± 0·006	1·292 ± 0·021	0·207 ± 0·006	0·027 no reflection
7	98% Li 2% Nb	FLIBE	0·169 ± 0·003	0·908 ± 0·019	0·257 ± 0·006	1·165 ± 0·025	0·256 ± 0·005	0·005
8	FLIBE	FLIBE	0·187 ± 0·003	0·896 ± 0·013	0·131 ± 0·002	1·027 ± 0·015	0·290 ± 0·005	0·001

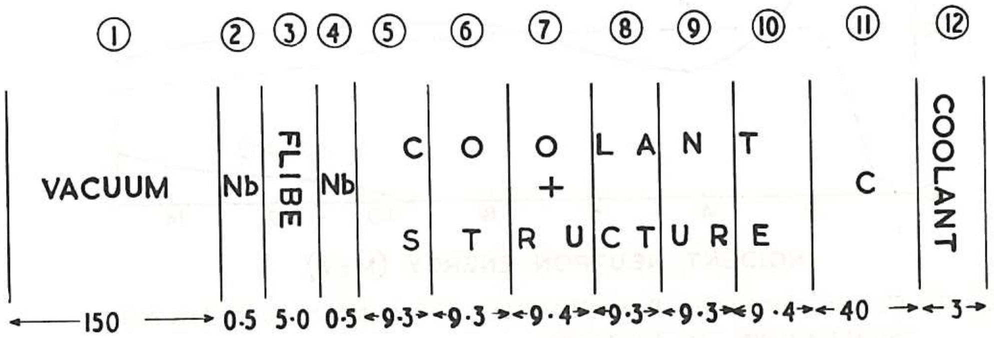


Fig. 14 Typical Blanket Design and Reaction Rates

Key: FLIBE ≡ Li_2BeF_4

T_6 ≡ Reaction Rate from $Li^6(n,t)$

T_7 ≡ Reaction Rate from $Li^7(n,tn')$

T ≡ $T_6 + T_7$.

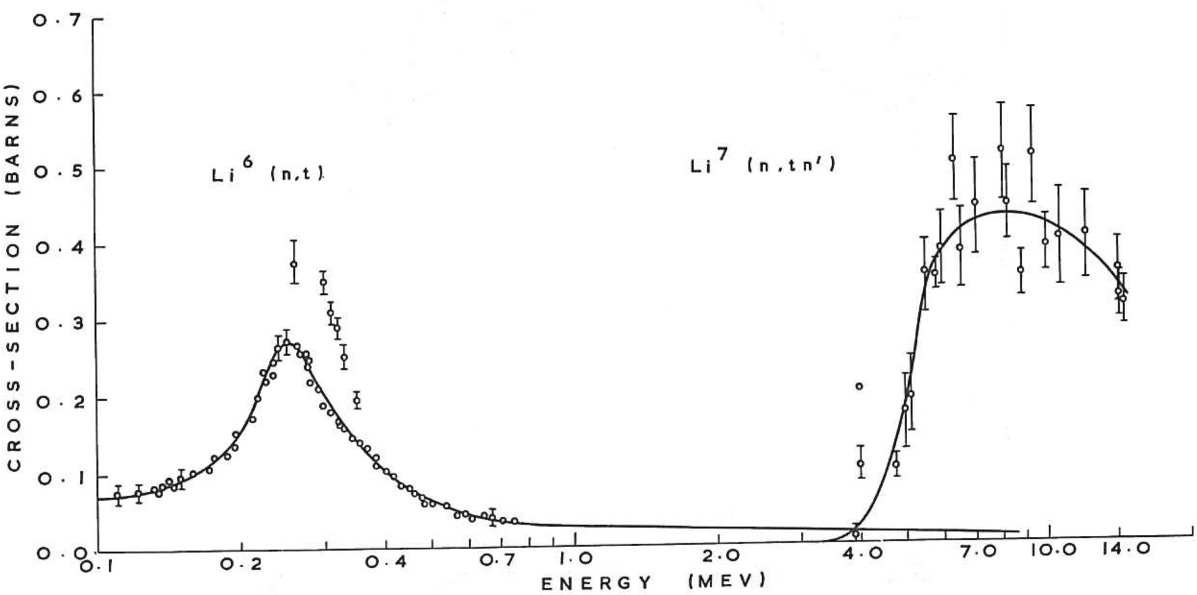


Fig. 15 Tritium Breeding Cross-sections for Lithium Isotopes in the High Energy Region. The circles represent Experimental Points from several sources.

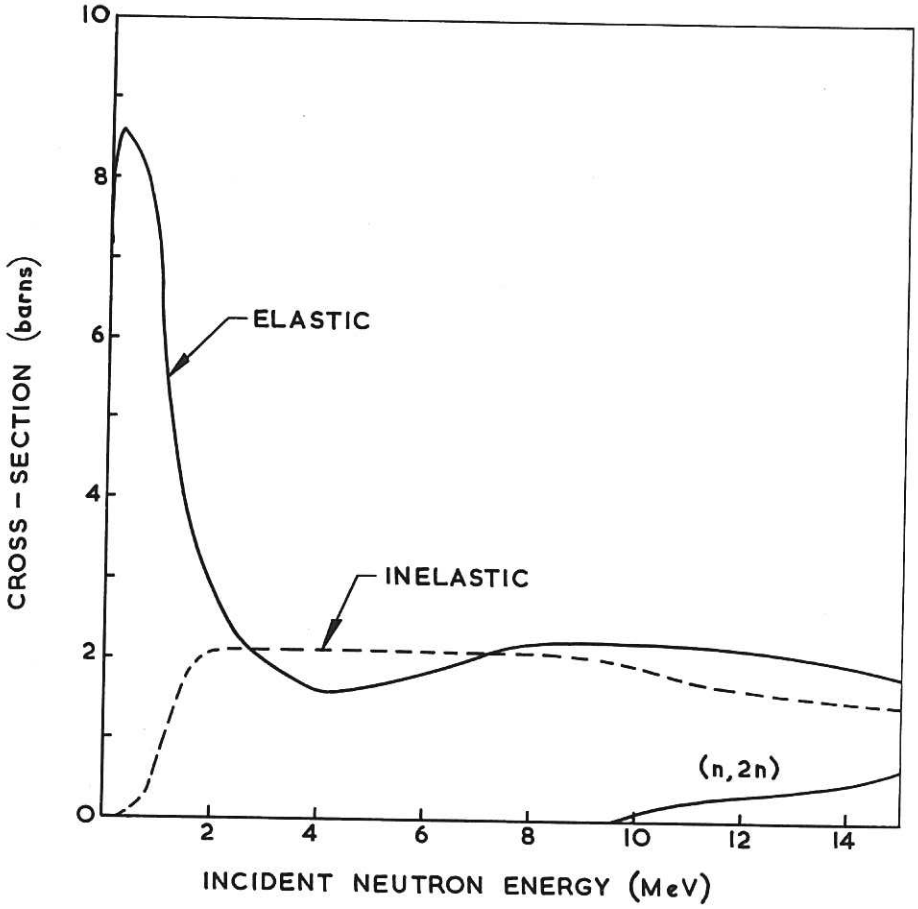


Fig.16 Cross-sections for Elastic, Inelastic, and (n,2n) Scattering in Niobium.

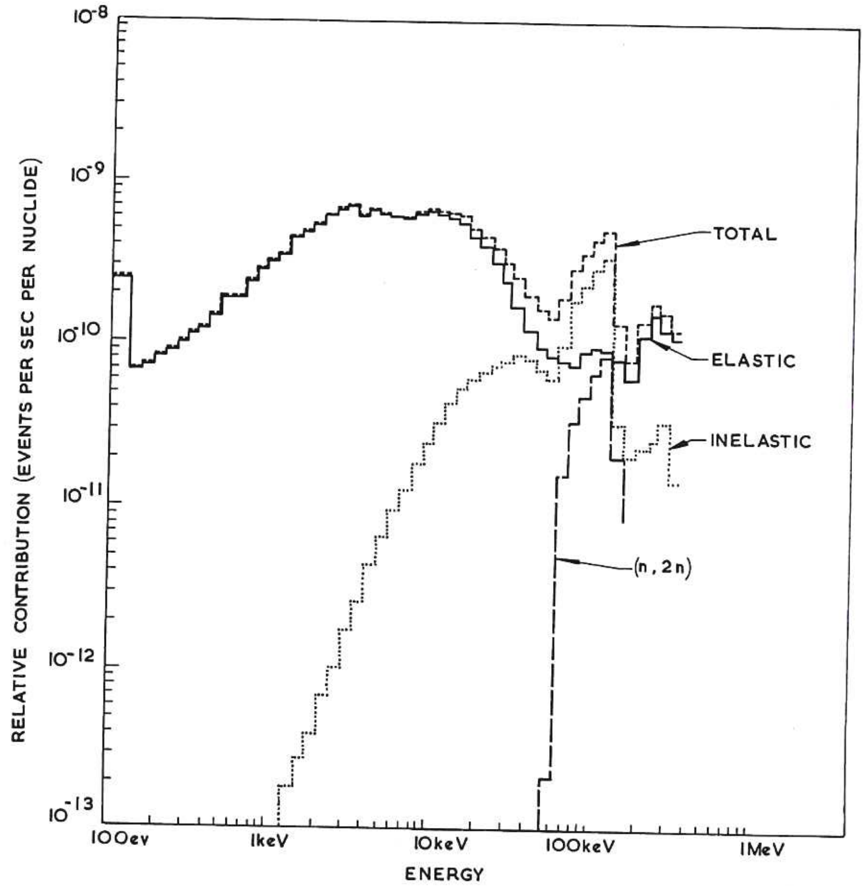


Fig.17 A Histogram of the Three Contributing Damage Energy Spectra, and their sum, in the Neutron Flux in the First Wall of a Model Fusion Reactor.