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BY

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Fusion Neutron Sources Induced by Neutron Interactions*

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ABSTRACT

The potential of neutron-nucleus interactions to provide sources of 14 MeV neutrons for radiation damage experiments is investigated. Two types of neutron interactions are considered: absorption reactions in LiD converters, and elastic scattering collisions in DTO converters. Several combinations of neutron source-converter systems are evaluated. The driving neutron sources include localized sources and fission reactors.

It is estimated that the strength of the 14 MeV sources attainable in fission reactors can be as high as 10^{12} and 10^{13} n/sec/MW with LiD and DTO converters, respectively. The neutron fluxes provided by these systems can be, however, of the order of 10^{11} n/cm²sec only. These fluxes are too low for high-fluence radiation damage studies.

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INTRODUCTION

Laboratory sources of 14 MeV neutrons are required to support the development of technologies and accumulation of knowhow important for the development of fusion reactors. Of particular importance are radiation damage effects on materials, including surface damage and radiolysis of coolant materials. Radiation damage studies carried out in fission reactors do not include the effects of the high energy (up to 14 MeV) neutrons. Existing sources of 14 MeV neutrons do not have the intensities to provide the neutron fluences required for radiation damage studies. In these sources the D-T reactions (that provide the 14 MeV neutrons) are brought about by accelerating or heating the reactants using electrostatic or electromagnetic forces.

In this work we evaluate the potential of using nuclear energy, in the form of neutron-nucleus interactions, to bring about the D-T reactions. The driving neutron sources considered are fission reactors as well as radioactive and accelerator neutron sources.

The purpose of the evaluation is to explore possible schemes for the conversion of low energy (including fission) neutrons to 14 MeV neutrons and to provide estimates for the magnitude of the 14 MeV neutron fluxes thus expected. It does not include detailed (neutron transport) calculations or design studies.

NEUTRON CONVERSION PROCESSES

The conversion of neutrons to 14 MeV neutrons can be brought about by the following chain of events: the neutrons interact with the nuclei to produce high energy D and/or T ions. These energetic ions can fuse during their slowing-down process to produce the 14 MeV neutrons. Once the high energy ions are obtained, the rest of the processes that lead to the production of

the 14 MeV neutrons are similar to the ones taking place in the targets of the conventional 14 MeV neutron generators.

Production of High Energy Ions

Neutrons can impart a significant fraction of their kinetic energy to hydrogenous nuclei as a result of collisions. This fraction may be as high as $8/9$ or $3/4$ respectively, for a collision with D or T. For elastic collisions that are isotropic (in the center of mass system) the average fraction of its initial energy the neutron impart to the D and T nuclei is, respectively, $4/9$ and $3/8$.

During its slowing down, a neutron can transfer, by successive collisions, all its energy to D and T nuclei. Table I gives the average energies an average fission neutron will impart to deuterons if slowed down by collisions with deuterons only. Table I gives also the source of energetic tritons produced when the fission neutron slows down by collisions with tritons only. The data of Table I was calculated based on the following simplifying assumptions:

1. The fission neutron initial energy is 2 MeV.
2. The neutron loses its energy as a result of elastic collisions with D (or T) only.
3. The elastic collisions are isotropic. As a result of a collision, a nucleon gains $(1 - \alpha)/2$ of the kinetic energy of the colliding neutron ($\alpha = (A-1/A+1)^2$ where A is the atomic mass number of the nuclei).

A different mechanism for the production of energetic tritons is provided by the exothermic neutron absorption reaction $\text{Li}^6(n,\alpha)\text{T}$. The Q value for this reaction is 4.78 MeV. The kinetic energy of the triton thus produced will be 2.7 MeV, for an absorption of a low energy neutron. The triton initial energy

will be higher when a high energy neutron is absorbed. This neutron reaction does not only provide the energy for the fusion reaction, but also converts Li^6 to the much more expensive T.

Other reactions leading to the production of tritons: $\text{He}^3(\text{n},\text{p})\text{T}$ and $\text{Li}^7(\text{n},\text{n}'\alpha)\text{T}$ are of less practical interest; the first reaction, due to the scarcity of He^3 as well as the lower Q value of the reaction (0.76 MeV). The second reaction, due to its high threshold (2.47 MeV).

Fusion Probability of Slowing Down Ions

The probability for a D-T reaction during the slowing down of an energetic T (or D) in a D (or T) containing media was calculated numerically using the computer code FUPSLOG.¹ The calculations make use of the stopping cross-sections from the compilation of Whaling² and on the analytic fits of Kuo-Petravic, Petravic and Watson³ for the D-T fusion reaction.

Figure 1 shows the Fusion Probability (FP) of a triton slowing down in D, DT, and LiD media as a function of the initial triton energy. The FP of energetic D slowing down in a DT medium is similar to the FP of a T slowing down in the same medium. It is seen that the probability that a triton produced in the $\text{Li}^6(\text{n},\alpha)\text{T}$ reaction will cause fusion while slowing down in a LiD medium is 2×10^{-4} . The probability that a fission neutron will bring about a D-T reaction as a result of its slowing down in a DT medium is the sum of the FP for the energetic deuterons and tritons thus produced. Using the deuterons and tritons source distribution of Table I the total probability for a D-T reaction is found to be approximately 3×10^{-4} . One can also conceive an ideal converter composed of DT with a small concentration of Li^6 . In such a converter both the neutron kinetic energy and the Q value of the

$\text{Li}^6(n,\alpha)\text{T}$ reaction can be utilized to produce 14 MeV neutrons. The total FP for this idealized converter is about 5×10^{-4} . For a DTO converter a FP of the order of 10^{-4} is estimated.

NEUTRON SOURCE-CONVERTER SYSTEMS

Several combinations of neutron source and converter assemblies are posed and analyzed. They are also evaluated as potential sources of 14 MeV neutrons required for experimental studies of radiation effects. The neutron source requirements for the CTR developmental program assumed for this evaluation are summarized in Table II.

A Point Source Surrounded by a Converter

Consider a small localized neutron source surrounded by a spherical shell containing LiD. The localized source can be a radioactive source, such as a Cf^{252} spontaneous fission neutron source, the neutron-producing target of an accelerator or even a beam of neutrons. The converter does not have, in reality, to be spherical or even to completely surround the neutron source. The lithium in the converter can be natural Li or enriched with Li^6 . For the converter to slow down and absorb a substantial fraction of the source neutrons, its thickness has to be several mean free paths for neutron scattering and absorption. Assuming its outer radius to be at least 10 cm, the outer surface area of the converter will be of the order of 10^5 cm^2 . With the conversion efficiency of 10^{-4} , one will need a source strength of at least 10^{13} n/sec for providing 14 MeV neutron surface currents of 10^4 n/cm²sec. Radioactive neutron sources can not, practically, provide this intensity. Linear electron accelerators, such as the Oak Ridge ORELA, can provide (fission-like spectrum) sources of 10^{14} n/sec. In the Los Alamos Meson Physics Facility, LAMPF, neutron source intensities of 10^{16} are conceived. It should be recalled

however, that commercially available 14 MeV neutron generators can provide intensities of 10^{10} n/sec. These neutron generators are relatively inexpensive.

LiD Converter in Fission Reactors

By inserting LiD into the core (or its vicinity) of a fission reactor one can convert excess fission neutrons to 14 MeV ones. The converter can be inserted into irradiation channels in the reactor. It can also be substituted for control rods or burnable poison.

The system selected for evaluation is the Oak Ridge High Flux Isotope Reactor,⁴ HFIR, into the central gap of which a LiD converter is inserted. It is assumed that the excess of the fission born neutrons available for absorption in the converter is 10% of the fission neutrons produced. When the HFIR operates at its 100 MW nominal power the absorption rate of reactor neutrons in the converter is calculated to be 7.5×10^{17} n/sec. With a conversion efficiency of 2×10^{-4} , an upper bound for the 14 MeV neutron source of 1.5×10^{14} sec⁻¹ is obtained. The surface area of the converter required for the absorption of 10% of the neutrons in the HFIR we estimate to be of the order of 10^3 cm². Consequently, the maximum currents of 14 MeV neutrons anticipated in this system is of the order of 10^{11} n/cm²sec. Similar currents of 14 MeV neutrons are estimated for fast reactors if an appropriate converter replaces a control assembly.

Reactor-Converter systems of this category can provide ample 14 MeV neutron fluxes for the study of radiolysis effects. They can also be utilized for radiation damage studies to low fluences--of the order of 10^{18} n/cm², but they are at least 4 orders of magnitude too low in intensity for the high-fluence radiation effect experiments.

Fission Reactors with Converting Moderators

Most of the kinetic energy of the fission neutrons, slowing down in thermal reactors to sub-eV energies, is given to the moderator. If the moderator contains D and T, the fission neutron kinetic energy can be imparted to these nuclei, that can then undergo fusion. A converting moderator can be conceived that will fulfill the functions of a conventional moderator with similar (or even improved) efficiencies. At the same time this converting moderator will utilize a major fraction of the fission neutron kinetic energy (about 5% of the fission energy) for the acceleration of D and T ions.

Consider, for example, the Savannah River High Flux Demonstration (SRHFD) reactor⁴ in a region of which the D_2O moderator is replaced by a DTO one. The fission power density in the SRHFD is of the order of 100 KW/l. The source of fission neutrons slowing down in the moderator is therefore of the order of 10^{13} n/cm³sec. The source of 14 MeV neutrons produced in the converting moderator will be, at most, 10^9 n/cm³sec. The flux of 14 MeV neutrons will be of the order of 10^{10} n/cm²sec. For the above estimates we assumed that the fusion probability, per fission neutron, is of the order of 10^{-4} and that the 14 MeV neutron mean free path for collision in the core is approximately 10 cm.

The highest power densities achievable in high flux reactors (non pulsed), is⁴ one order of magnitude larger than in the SRHFD. The upper limit for the 14 MeV neutron fluxes achievable in a converting moderator system is, thus of the order of 10^{11} n/cm²sec. But the very high density reactors, such as the HFBR,⁴ are not very well suited for the incorporation of a converting moderator. The distance between their fuel plates is very small, and the moderator is also the coolant.

SUMMARY

By incorporating converters in fission reactors it is possible to obtain 14 MeV neutron sources of high total intensity: of the order of 10^{12} n/sec and 10^{13} n/sec per 1 MW of reactor power, in absorbing converters (LiD) and converting moderators (DTO) respectively. These sources of 14 MeV neutrons, however, are distributed over large volumes. The 14 MeV neutron fluxes and currents they can provide are, at most, of the order of 10^{11} n/cm²sec. These flux levels are 4 orders of magnitude too low for carrying radiation damage studies to high fluences. They can, however, be utilized for the study of radiation damage effects requiring low fluences, including radiolysis of materials and, possibly, superconducting systems.

The source of 14 MeV neutrons provided by the converters will not be monoenergetic. It will include lower energy neutrons of the driving neutron source as well as from the interaction of the 14 MeV neutrons with the converter. The spectrum of neutrons available for the experiments can be optimized by the design of the converter assembly. Detailed neutron transport calculations are needed in order to find the magnitude and spectrum of the neutron fluxes that can be provided by a specific design.

The converting moderators considered here are very expensive. This due to the high cost of tritium and large quantities (at least kilograms) of this isotope needed.

Table I. Initial Kinetic Energy Imparted by
a Fission Neutron to Deuterons and Tritons During
its Slowing Down

Collision Number	Initial Kinetic Energy (KeV)	
	Deuterons	Tritons
1	890	750
2	494	469
3	274	293
4	152	183
5	85	114
6	47	72
7	26	45
8	14.5	28
9	8.1	18
10	4.5	11
11	2.5	7
12	1.4	4.3
13	0.8	2.7
14		1.7
15		1.0

Table II. Neutron Source Requirements^a

Purpose	Energy Range	Neutron Flux or Current (n/cm ² sec) ^b	Neutron Fluence (n/cm ²)	Source Geometry ^c
Superconducting systems	eV - 14 MeV	10 ⁴ - 10 ⁸ C	10 ¹⁷	P, B
Radiolysis	KeV - 14 MeV	10 ⁹ - 10 ¹⁰ F	10 ¹⁸	B, R
Surface Physics	KeV - 14 MeV	>10 ¹² C	10 ¹⁸ - 10 ²¹	P, B
Material Radiation Damage	KeV - 14 MeV	>10 ¹⁵ F	10 ²⁰ - 10 ²⁴	P, B, R

a. Based on evaluation of P. J. Persiani, ORNL.

b. C stands for current and F for flux.

c. P stands for Point source, B--Beam flux, R--Irradiation inside the reactor (fission) core is possible

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Fig. 1. Fusion probability of energetic triton while slowing down in D, DT, and LiD media.

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