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CHARACTERIZATION FOR FUSION FIRST-WALL DAMAGE STUDIES OF USING TAILORED D-T NEUTRON FIELDS*

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INTRODUCTION

Changes in the physical properties of materials due to neutron irradiations are an important factor in the design [illegible] reactor. The neutron field present at the first-wall [illegible] ically confined fusion device consists of both the [illegible] neutron flux coming from the plasma burn and the [illegible] lower energy (< 14-MeV) neutrons returning from the [illegible] blanket surrounding the plasma. This same neutron [illegible] outgoing 14-MeV neutron flux with a lower [illegible] can be generated by surrounding a physically small but [illegible] source of neutrons with a spherical blanket [illegible] lithium, enriched uranium, and beryllium. By [illegible] of these shells, the spectral distribution [illegible] closely the neutron spectra anticipated in fusion [illegible] full-scale experimental fusion reactors will [illegible] several decades to contribute to relevant [illegible] than accelerator based sources of neutrons [illegible] ion beam impinging upon a small deuterium [illegible] this important design data in a timely [illegible] modest budget.

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*Work performed under the auspices of the US Department [illegible] under a cooperative program with the [illegible]

The D-T intense neutron source, INS, is proposed as a "quasi" point source in order to achieve high enough neutron fluxes to be useful for accelerated irradiation studies. As a consequence, the $1/r^2$ fall-off of the primary 14-MeV flux along with the relatively uniform distribution of back-scattered lower energy neutrons provide a limited high-flux irradiation volume. For example, a source strength of 3×10^{15} neutrons per second emanating isotropically from a 1-cm diameter spherical source will provide only about 100 cm^3 of volume within the tailoring blanket which can be used for the purpose of radiation damage evaluations (~ 10 dpa/year). Such a small available volume will require miniaturized experiments and sophisticated diagnostics to operate within the confining space of the tailoring blanket.

As the tailored spectra will simulate accurately the first-wall [illegible] fusion reactors, many experiments can be performed to correlate experimental results from radiation damage results obtained from other neutron spectra (fission reactors, [illegible] 14-MeV [illegible], and stripping neutrons from D-Li or D-Be reactions, [illegible] experiments, and from [illegible] studies. [illegible] these experiments can become "benchmark" [illegible] studies [illegible] can be developed in great detail [illegible] neutron dosimetry and neutron [illegible] calibration, correlation, and reference ex[illegible] experiment that can be [illegible] stainless [illegible] correlation.

[illegible]

[illegible] INS [illegible] irradiation [illegible] irradiation [illegible] the addition of the converter [illegible] experiment [illegible] With a [illegible] source [illegible] blanket, the irradiation volume for [illegible].

[illegible] standard blanket and its relationship to the INS [illegible] in Fig. 2. The blanket is formed by concentric [illegible], enriched uranium, and beryllium. In the irradiation [illegible], the total neutron flux consists of a radial outward [illegible] 14-MeV neutrons falling off as r^{-2} and a nearly uniform [illegible] scattered neutrons with a peak flux near $10^{-[illegible]}$ MeV. [illegible] of the standard blanket are given in Refs. 1 and 3.

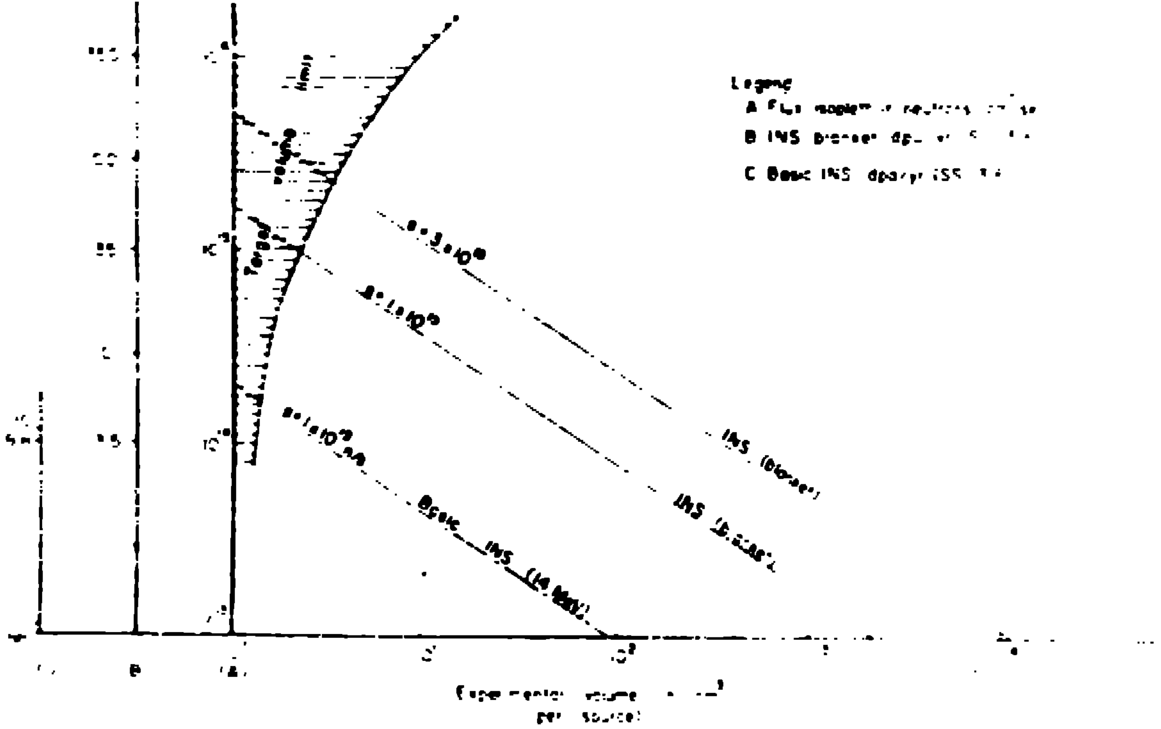

Fig. 1. Flux-volume relationship for the INS [illegible].

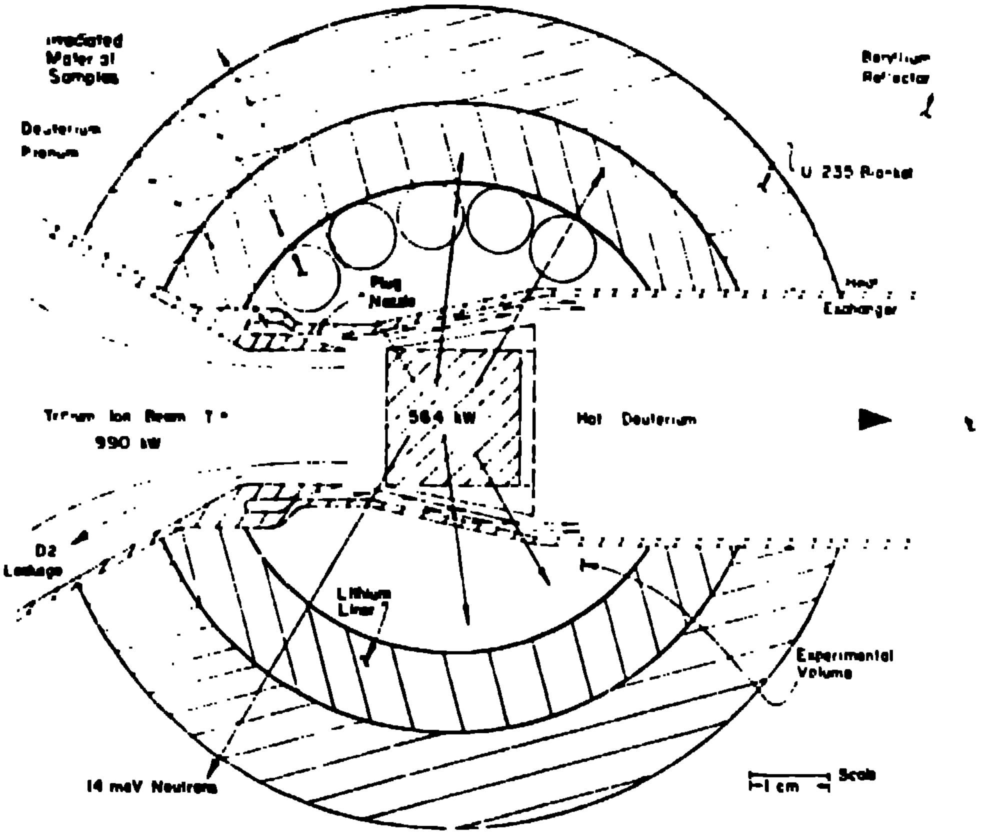
Irradiated Material Samples
Deuterium Plenum
Beryllium Reflector
U 235 Blanket
Heat Exchanger
Plug Nozzle
Tritium Ion Beam T+
990 kW
564 kW
Hot Deuterium
D2 Leakage
Lithium Liner
Experimental Volume
14 meV Neutrons
Scale
1 cm

Fig. 2. INS Spectrum Tailoring Converter (Blanket).

The neutron spectrum at several radial positions in the sample irradiation region of the standard blanket have been compared to a Tokamak first-wall spectrum.[1] There are only minor differences between the differential neutron spectra for INS with the standard blanket and the spectrum calculated for a fusion first wall. A more instructive comparison of the INS spectra, including the bare source and the standard blanket source ($r = 2.45$ cm), with a fusion first wall and other relevant neutron spectra is given in Fig. 3. In comparing the first-wall recoil spectra for iron (Fe), we found the INS blanket and the UWMAK-I essentially the same and characteristically different from the spectra of the fission, pure 14-MeV, and D-Li ([illegible]-MeV D^+) sources.

DAMAGE RESPONSE TO NEUTRON ENVIRONMENT

We need to examine, both theoretically and experimentally, the agreements and disagreements between the differential neutron and recoil spectra expected at irradiation test facilities and those spectra expected in a fusion reactor. These comparisons translate into a better understanding of characteristic displacement cross sections, average recoil energies and helium- and hydrogen-production cross sections. Recoil energy determines the nature of the displacement cascade and plays an important role in determining the nature of the damage state, as shown theoretically[4] and experimentally.[5-7]

The role of gas production has received a considerable amount of attention in the materials community because it is considerably higher in fusion reactors than in fission reactors. This difference is usually expressed by calculations of the ratio between the displacement cross section and the gas-production (usually helium) cross section; therefore, we employ these two intrinsic properties of the neutron spectrum.

A possible critical problem in mechanical design of a fusion reactor is the swelling due to irradiations. Most theories include as parameters displacement rates, flux-times-displacement cross sections and gas generation rates, flux-times-gas production cross sections, but usually not the effects of recoil energy. Relevant parameters for the neutron spectra considered are listed in Table I. The special converter referred to in Table I is similar to the standard blanket but has no lithium liner and the uranium shell comes nearly up to the neutron source wall. Although this is not a very practical configuration, it represents the peak flux conditions achievable with a blanket.

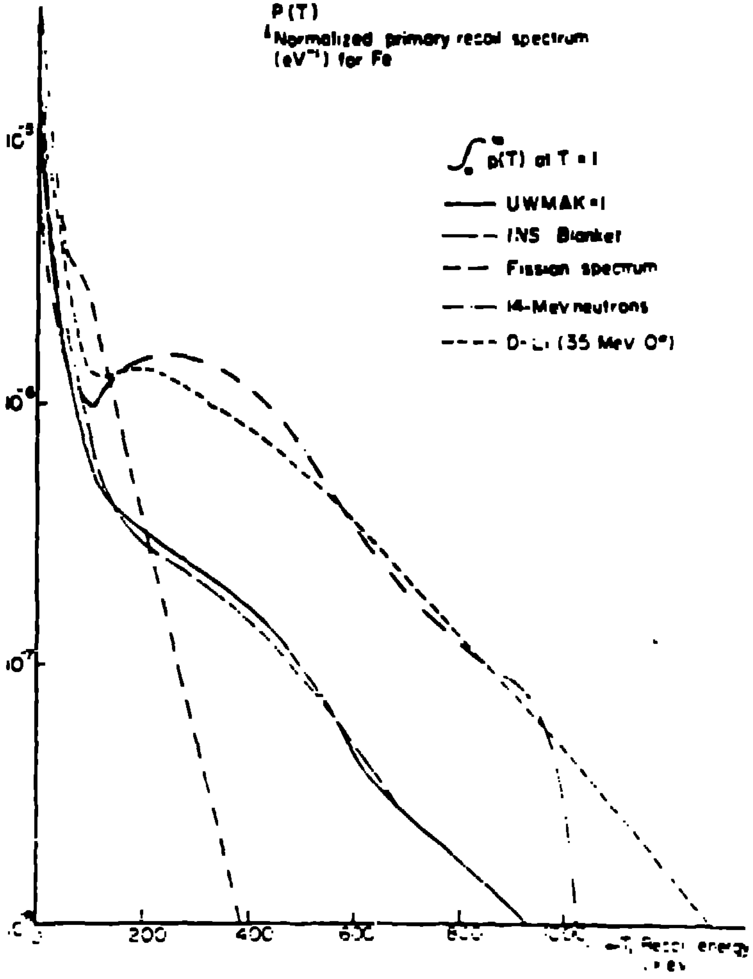

Fig. 3. Normalized primary recoil spectra for various sources.

TABLE I

COMPARISON OF NEUTRON SOURCES

Description of Source	Total Flux (n/cm^2/s)	Cross-sections for SS-316: Displacement Production (b)	Helium Production (mb)	Hydrogen Production (mb)	Production of: Displacement dpa/s	Helium appm/s	Hydrogen appm/s	Displacement over Helium Production dpa/appm	Displacement over Helium and Hydrogen Production dpa/appm
UWMAK-I first wall	4.7×10^{14}	1006	13.7	51.2	4.7×10^{-7}	6.4×10^{-12}	2.4×10^{-11}	7.3×10^{4}	1.6×10^{4}
INS-3A, Distance from Source 2.1 cm: Standard Converter	2.4×10^{14}	1071	13.7	51.2	2.6×10^{-7}	3.3×10^{-12}	1.2×10^{-11}	7.8×10^{4}	1.7×10^{4}
INS-3A, 0.85 cm: Special Converter	1.3×10^{15}	1071	13.7	51.2	1.4×10^{-6}	1.8×10^{-11}	6.6×10^{-11}	7.8×10^{4}	1.7×10^{4}
INS-3A, 0.85 cm: Standard Converter	5.6×10^{14}	2120	38	136	1.2×10^{-6}	2.1×10^{-11}	7.6×10^{-11}	5.7×10^{4}	1.2×10^{4}
INS-3A, 0.85 cm: 14 MeV	1.9×10^{14}	2270	53	189	1.1×10^{-6}	2.1×10^{-11}	7.6×10^{-11}	5.2×10^{4}	1.2×10^{4}
D-Li (35 MeV-0°)	1.0×10^{15}	2700	52	206	4.7×10^{-6}	5.2×10^{-11}	2.1×10^{-10}	9.2×10^{4}	1.1×10^{4}
HFIR	3.3×10^{15}	268	--	2.7	8.2×10^{-7}	7.0×10^{-11}* (experimental)	8.9×10^{-12}	1.2×10^{4}	1.1×10^{4}
EBR-II (row 2)	2.7×10^{15}	437	0.15	2.6	1.2×10^{-6}	4.1×10^{-13}	7.0×10^{-12}	2.9×10^{6}	1.6×10^{5}

* Ref. 10

CORRELATIONS FROM BASIC SWELLING THEORIES

To illustrate the effects of the differences in neutron spectra from the INS and other neutron sources and fusion reactor spectra, we have applied the swelling theory of Bullough and Haynes[8] to hypothetical SS-316 irradiations. This theory predicts that the swelling can be dependent on the gas (helium) generation rate and calculations have been compared with results from the High Flux Isotope Reactor (HFIR) and the Experimental Breeder Reactor II (EBR-II).[3-9] The Bullough-Haynes paper has a complete discussion of these calculations. Using their calculated swelling data for SS-316, we have established a very simple correlation between swelling, S, gas production rate, K_g, and displacement rate, K. Up to an exposure of 100 dpa, swelling can be expressed as

$$S = \left(A \frac{K_g}{K}\right)^{C_2\left(K_g,T\right)} (Kt)^{C_1\left(K_g,T\right)} \quad . \qquad (1)$$

A function such as Eq. (1) can be used to predict swelling under various irradiation conditions where it is expected to apply. Because the Bullough-Haynes results were only given for one displacement rate (10^{-6} dpa/s), we must assume that by normalizing the neutron fluxes given for the sources in Table I that meaningful results, in a comparative sense can be obtained. Note that this procedure alters the gas production rate but preserves the ratio of gas production rate to displacement rate. The swelling vs dose calculated at 700°C in Fig. 4 is obtained using this procedure.

In Table II, the anticipated dose is given in displacements per atom required to reach 5 percent swelling; however, for this calculation we assumed that the Bullough-Haynes data directly apply to the calculated displacement rate for each source. Thus, the gas generation rates used are the real rates in each source.

SUMMARY

The approximation required to apply the Bullough-Haynes results to the present calculations is somewhat crude and may imply that the details of the results contain considerable error. However, when the results for each neutron source are viewed in a relative context, several valid and important observations can be made. The almost identical swelling results obtained for the INS with a standard blanket and the fusion first wall are most striking. This fact is not surprising when one recalls the close similarity of the neutron spectrum and recoil spectrum data from Fig. 3. A further comparison with a fusion reactor shows that even the spatial and energy

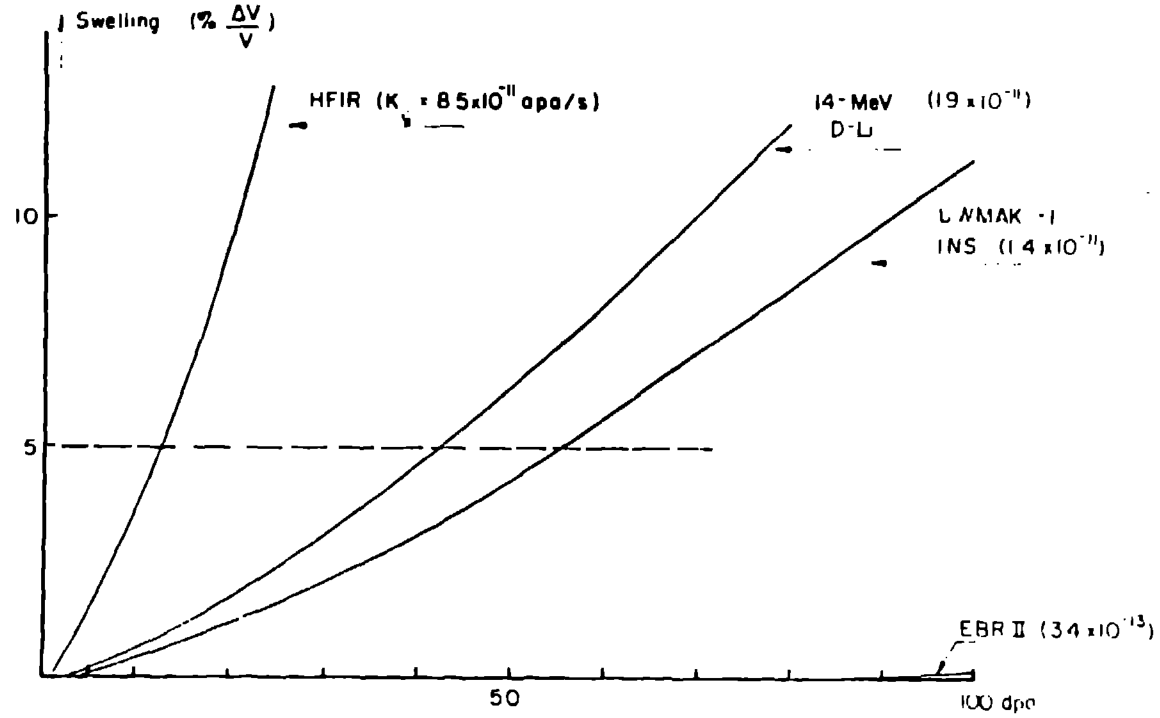

Fig. 4. Swelling for SS-316 at 700°C in various neutron sources.

TABLE II

SWELLING DATA FOR THE DIFFERENT NEUTRON SOURCES

	Description of Source	Total Flux $(n/cm^2/s)$	Production of Displacement (dpa/s)	Production of Helium (apa/s)	dpa necessary for 5% swelling at 500°C (dpa)	dpa necessary for 5% swelling 700°C (dpa)
	UWMAK-1 first wall	4.7×10^{14}	4.7×10^{-7}	6.4×10^{-12}	91	107
INS 3-A Distance from Source 2.1 cm	Standard Converter	2.4×10^{14}	2.6×10^{-7}	3.3×10^{-12}	94	~150
	Special Converter	1.3×10^{15}	1.4×10^{-6}	1.8×10^{-11}	80	47
0.95 cm	Standard Converter	5.6×10^{14}	1.2×10^{-6}	2.1×10^{-11}	78	42
	14 MeV	3.9×10^{14}	1.1×10^{-6}	2.1×10^{-11}	78	42
	D-Li (35 MeV 0°)	1.0×10^{15}	2.7×10^{-6}	5.2×10^{-11}	58	20
	HFIR	3.3×10^{15}	8.2×10^{-7}	7.0×10^{-11}	50	15
	EBR II	2.7×10^{15}	1.2×10^{-6}	4.1×10^{-13}	99	>300

distributions of the neutron flux are similar. In both the INS with blanket and at the first wall of a fusion reactor, there is a radial source flux component of 14-MeV neutrons and a more or less isotropic flux component of low energy (< 14-MeV) neutrons. One must therefore conclude that from the point-of-view of neutron radiation damage, the INS with a blanket, *unlike all the other types of neutron sources,* is not a simulation environment. It is, in fact, a small scale fusion device, and data obtained from INS irradiation experiments would represent fusion reactor results. Such data could then be used to develop correlative procedures for applying data obtained from other simulation sources to fusion reactor conditions.

Another point is the similarity of the D-Li neutron source and a 14-MeV neutron source and their relationship to the fusion first wall and INS blanket conditions. Although the relationships of D-Li, 14-MeV, and the fusion first wall have been described[10] and are now well recognized, the calculated swelling results describe these relationships in a physical context.

The variation of the calculated swelling curves indicate that all of the neutron sources included would provide useful information. Each source has a characteristic swelling curve that predicts a broad range of experimental results. If these or similar trends are found in experimental results from neutron irradiations, the inclusion of the fusion conditions available at the INS would play an important role in developing data correlation procedures. One of the data sets in the correlation scheme would be based on an irradiation environment essentially the same as in a fusion reactor first wall.

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