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A LARGE-VOLUME INTENSE NEUTRON SOURCE FOR CTR MATERIALS STUDIES

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ABSTRACT

The measurement of bulk radiation effects for the CTR program will require the irradiation of many hundreds of samples by energetic neutrons to fluences in excess of 10^{21}n/cm^2. The environment of the samples must be well controlled, particularly as regards to temperature and stress. There must be easy access for instrumentation and remote handling, and provision for pulsed operation may be required. A facility based on a 30-40 MeV 100 mA deuteron linac and a liquid lithium jet target appears to offer the best combination of intensity, experimental volume, energy spectrum and experimental access. The linear accelerator would be of the Alvarez type designed for high transmission efficiency and reliability and to take advantage of existing high power rf technology. The injector would be based on the Oak Ridge work with high current D.C. ion sources. Existing liquid metal technology appears adequate for the target design.

INTRODUCTION

CTR materials studies are severely hampered by the lack of suitable intense sources of energetic neutrons. The investigation of bulk radiation effects in first wall materials sets particularly severe requirements on the performance of an intense neutron source.

The ideal source would of course be a fully instrumented operating fusion reactor. As this cannot yet be built some alternative is needed to fill the medium term needs of the program. The most important characteristics of a neutron source in this context are the intensity, the experimental volume and the energy spectrum, all of which must meet certain minimum requirements if the facility is to be useful for studies of bulk radiation effects. In our view the source concept which can best provide these minimum requirements would be based on a 30 - 40 MeV 100 mA deuteron linac and a liquid Li target system, similar to that discussed by the Brookhaven group [1].

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WHAT DO WE NEED TO INVESTIGATE?

Before discussing the details of such a facility it is instructive to look at the goals of the bulk radiation effects program and the type of investigations required to meet those goals.

The primary purpose of the program is to develop materials for the structural components of a fusion reactor, particularly the first wall, which can tolerate the intense neutron flux from the plasma. For a D-T device operating at $1 MW/m^2$ wall loading with a Li blanket the neutron flux would be $\sim 2.8 \times 10^{14}$ $n/cm^2 sec$: for neutrons with energies $E_n > 0.1$ MeV (the approximate energy threshold for atomic displacement). About 30% of the neutrons would have an energy of 14 MeV. The resultant displacement damage is known to cause changes in mechanical properties such as ductility, creep, fatigue, etc. Furthermore, the high energy component will result in the rapid build-up of transmutation products, particularly He, which will certainly aggravate the damage.

Table I lists some of the important mechanical property changes which must be investigated as a function of various experimental parameters for an alloy development program. With this list in mind, we can now look at the characteristics of a neutron source which is needed for such a program.

1. Intensity

The intensity of the source must, at the very least, be sufficient to induce these property changes in the materials of interest in a reasonable period of time. This is clearly the most basic requirement. In Table II we have listed the magnitude of some radiation effects in reactor structural materials and the fluence or flux at which they occur. If we define a reasonable length of time to be $\lesssim 1$ year then the minimum flux needed is $\gtrsim 10^{14} n/cm^2/sec$: To provide some insurance against totally unexpected phenomena which might occur at high fluences it would be very desirable to have some limited capability at flux levels of 10^{15} $n/cm^2/sec$: or higher.

2. Experimental Volume

The factors which must be considered here are the size of the samples, the number of the samples and the space required to produce the desired environment for the samples. Swelling studies may be made reliably by transmission electron microscopy using standard 3 mm diameter TEM disc specimens. However, tensile studies require samples $\gtrsim$ 1-2 cm long while other measurements require pressurized tubes with similar linear dimensions. The neutron flux must therefore remain reasonably constant ($\gtrsim$ 30%) over distances of this order.

To get some feel for the number of samples to be irradiated it is again instructive to compare with the LMFBR alloy development program. Table III shows the ranges of interest in some of the appropriate experimental parameters for LMFBR and CTR irradiations. Particularly as regards the range of materials to be investigated the CTR program is likely to need more sample irradiations than the LMFBR program.

In July 1975 the LMFBR alloy development program had over 29,000 specimens undergoing neutron irradiation, 22,000 of which were TEM discs, the remainder being mostly made up of rods, sheet tensile specimens and tubes. The present EBR-II Row 7 and Row 8 experiments for potential CTR structural materials involve nearly 500 samples in the form of either sheet tensile specimens or tubes. These figures demonstrate that the neutron source facility must provide sufficient space for the irradiation of hundreds of specimens, even if the main purpose is limited to correlating the data from fission spectrum and fusion spectrum irradiations. A volume $\approx$ 1 litre in the high flux (> 10^{14} n/cm^2/sec) region would appear to be required.

Neutron Spectrum

The two principal mechanisms by which neutrons induce radiation damage in metals are atomic displacement and nuclear transmutation. The neutron source spectrum must produce both these effects in roughly the correct ratio in order to provide useful data on CTR radiation effects. Calculations have been made [2,3] of the displacement and transmutation rates to be expected for various neutron energy spectra, but their accuracy is intrinsically limited at high neutron energies by the paucity of neutron cross-section data. For a spectrum with a high energy tail, such as that from a d-Li source, the calculations are particularly suspect because there are often no data at all above 15 MeV or so. In these cases quite sophisticated theoretical calculations may be needed to compensate for the lack of experimental data. Recently at ORNL an experiment was performed [4] to correlate the displacement damage induced in pure Cu and Nb samples by fission neutrons from the Bulk Shielding Reactor and by neutrons from the ORNL d-Be source [5]. The spectrum from the source is very similar to that produced by 40 MeV deuterons on a thick Li target. Irradiations were done at ambient temperatures. The fluences obtained were 1.0 x 10^{18} n/cm^2 for the fission source and 1.7 x 10^{17} n/cm^2 for the d-Be source. The surviving damage, in the form of dislocation loops, was estimated using diffuse x-ray scattering and electron microscopy to measure the distribution of the dislocation loops. Preliminary data for the measurements on Cu are shown in Figure 1. By integrating these data the total number of surviving defects can be estimated to give the ratio of the damage effectiveness of a d-Be neutron compared to that of a fission neutron. This ratio was also calculated using the method described by M. T. Robinson [2] and the appropriate energy spectra. The calculations for the d-Be spectra involved cross-section information for neutron energies up to 40 MeV, which was generated by C. Y. Fu using the Hauser-Feshbach code TNG [6]. Table IV shows the theoretical and experimental ratios which are in very satisfactory agreement. On the basis of this same calculation we would estimate the damage effectiveness of a d-Be neutron to be twice that of a CTR spectrum neutron (E_n > 0.1 MeV).

Helium and hydrogen production rates are often difficult to estimate from available cross-section data because of the possibility of significant contributions from multiple particle final states, e.g. (n,nα) or (n,pα) reactions. In the case of He it is possible to measure the effect directly. In a recent experiment Holt and Hosmer [7] using the RTNS measured the He content of Cu foils irradiated to a fluence $\approx$ 7 x 10^{16} n/cm^2 and derived

a cross-section of 58 mb for the production of He by 14 MeV neutrons. The existing (n,α) cross-section data are scattered between about 26 mb and 55 mb [8]. Using the ORNL d-Be source we plan to make similar irradiations on various materials to measure the effective α production cross-section for the d-Be spectrum. By comparing these results with calculated cross-sections the accuracy of the calculated hydrogen production cross sections can then be estimated.

From the evaluation of various source spectra given by Goland and Parkin [3] the ratio of He production to displacement damage for a 19 MeV d-Li source is quite similar to that expected from a fusion spectrum for materials such as Al, Cu and Nb. As the neutron energy increases, the He production cross-section increases faster than the damage effectiveness, so that for a 40 MeV d-Li source spectrum we calculate the ratio to be a factor $\sim$ 2 too high. This still represents a great improvement over reactor spectra for which the ratio is too low by a factor $\sim$ 100, and appears to be a price worth paying to achieve higher intensity and a larger experimental volume.

CHARACTERISTICS OF A 40 MeV d-Li SOURCE

There are a number of neutron sources now operating using thick Be targets bombarded by deuterons, such as those at U. C. Davis, NRL Washington, Texas A & M and ORNL. The ORNL source which is based on the 40 MeV deuteron beam from the ORIC, has been used for some CTR related irradiations. In connection with this work measurements have been made of the neutron yields for both Be and Li targets. Figure 2 shows ToF measurements of the neutron energy spectrum at 0° from a thick Be target, while Figures 3 and 4 show similar data for a natural Li target taken at 0°, 10° and 20°. The main characteristics are a broad energy peak centered at about 17 MeV which is produced mainly in the forward direction in a cone with half angle $\sim$ 10°. The spectra for Li and Be are very similar. From these data one can estimate the neutron flux contours to be expected down-stream of the target.

One can satisfy the intensity and volume requirements discussed above by using a 100 mA 40 MeV deuteron beam on a thick ($\sim$ 2.5 cm) Li target. Of the various geometries which are possible, we have chosen to investigate a circular beam spot on the Li target. The intensity profile was assumed to be gaussian with a f.w.h.m. of 2 cms. Figure 5 shows the flux contours calculated for this system. The intensities shown are for neutrons whose energy E_n > 3 MeV. In terms of displacement damage one average d-Li neutron is worth about two average fusion spectrum neutrons (E_n > 0.1 MeV), so that the largest contour shown corresponds to a flux of CTR spectrum neutrons (E_n > 0.1 MeV) of about 10^{14} n/cm^2/sec: The experimental volumes contained within the three contour lines are 80 cm^3, 420 cm^3 and 1170 cm^3 respectively. In Figure 6 we have shown a possible arrangement of experiments within this experimental volume. Liquid Li loops are provided in which tensile specimens and pressurized tubes are immersed. Accelerated testing can be done at flux levels somewhat higher than would be expected at a reactor first wall, and real time testing in the lower flux regions. The tensile specimens and tubes shown are of the sizes currently being used at

Evaporation losses of Li from the free surface of the jet appear to be easily managed. At the temperatures and flow rates envisaged the loop can be constructed from stainless steel without any significant erosion problems. The tritium production can be handled by secondary containment of the loop coupled with occasional (once or twice a year) extraction of the tritium using a hot Nb foil for example. The thermal time constants of the system are such that any loss of beam power can be easily compensated by auxiliary heaters and louvers on the air-cooled heat exchanger.

CONCLUSION

In summary, we feel that the minimum neutron source characteristics required for the CTR bulk radiation effects program are:

An intensity > 10^{14} n/cm^2/sec fusion spectrum equivalent;
An experimental volume $\sim$ 1 litre at this intensity;
A neutron spectrum which approximates the He production/displacement energy ratio of a CTR spectrum; and
Technical feasibility.

The only design concept which satisfies these conditions at present is a 100 mA 30-40 MeV deuteron linac used in conjunction with a liquid Li jet target.

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*Research sponsored by Union Carbide Corporation under contract with ERDA.

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TABLE I

Properties and Parameters Required for
CTR Bulk Radiation Effects Studies

Properties		Parameters
Ductility Uniform and total elongation		Temperature
		Fluence
Stresses Yield and Fracture		Flux
Creep Rate Time to rupture Strain at rupture	as a function of	Composition Microstructure
		Stress
Fatigue Rate of cycling Stress per cycle Strain at failure Cycles to failure		Chemical Environment
Swelling		

TABLE II

Irradiation Parameters for Measurable Property Changes in Reactor Structural Materials

Property	Fluence (fusion neutrons)	Flux (fusion neutrons)	Example
Swelling	$\approx 10^{22}$		1% ΔV/V in 316-SA
Tensile Ductility	$\approx 5 \times 10^{21}$		50% decrease in elongation in 304-SA
Irradiation Creep		$> 10^{14}$	easily observed in 316-SA+20% C.W.
Fatigue	5×10^{21}		decrease in cycles to failure by 30 or in ε_f of ≈ 2
Creep Fatigue	$\approx 5 \times 10^{21}$		decrease in ε_f by ≈ 2 and cycles to failure by ≈ 50

TABLE III

Comparison of Irradiation Requirements

	LMFBR	CTR
Temperature	375 - 700°C Relatively Constant	250 - 1200°C Cyclic Variations
Stress Effects	Constant or Slowly Varying	Constant, Pulsed
Materials (Including variations in composition and microstructure)	Iron and Nickel Base Alloys	Iron and Nickel Base Alloys Niobium Alloys Vanadium Alloys Insulators Curtain Materials Weldments

TABLE IV

Damage Effectiveness of Be(d,n)* Neutrons as Compared With Fission Neutrons

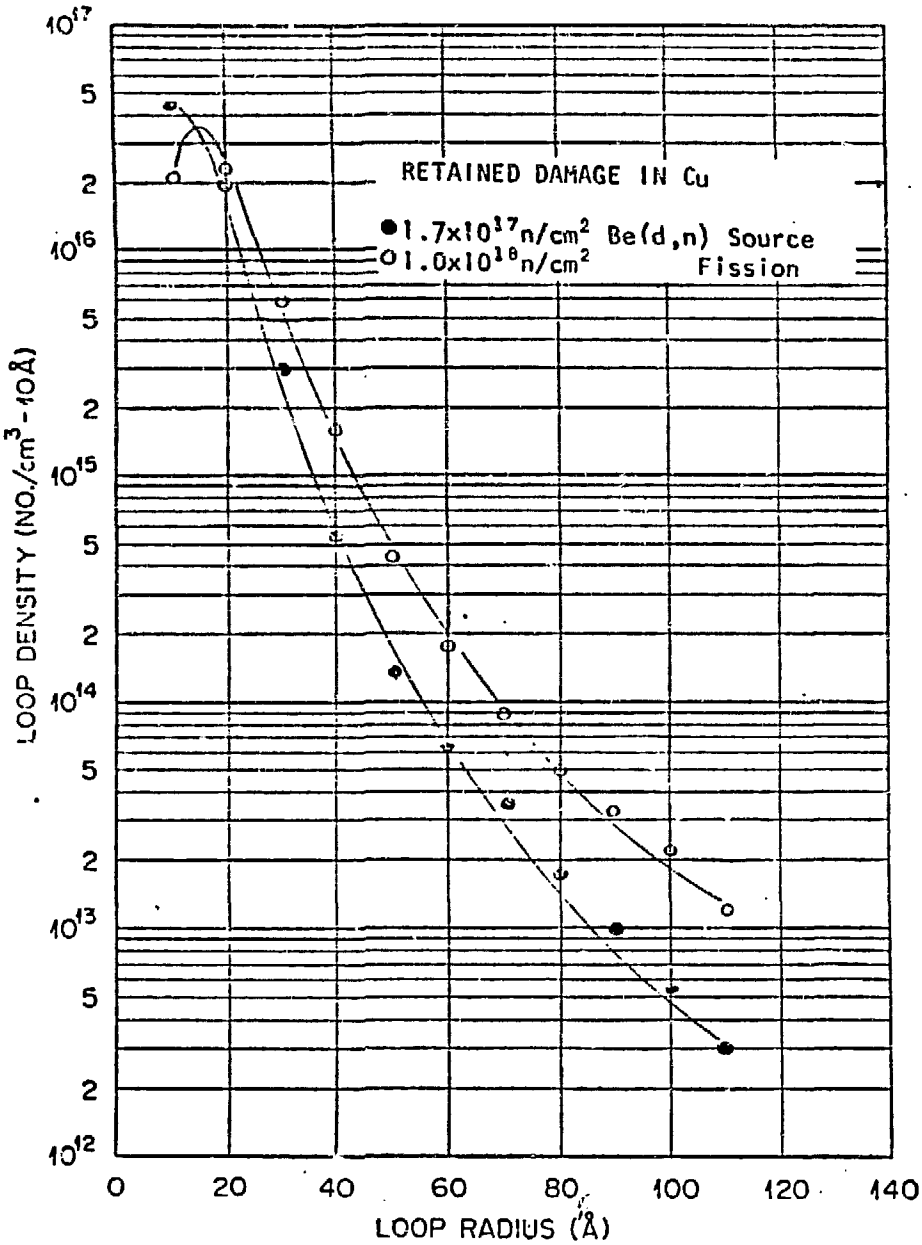
Material	Experiment Retained Damage Be(d,n)/Fission	Theory Damage Energy Be(d,n)/Fission
Cu	3.9	3.84
Nb	3.5	2.90

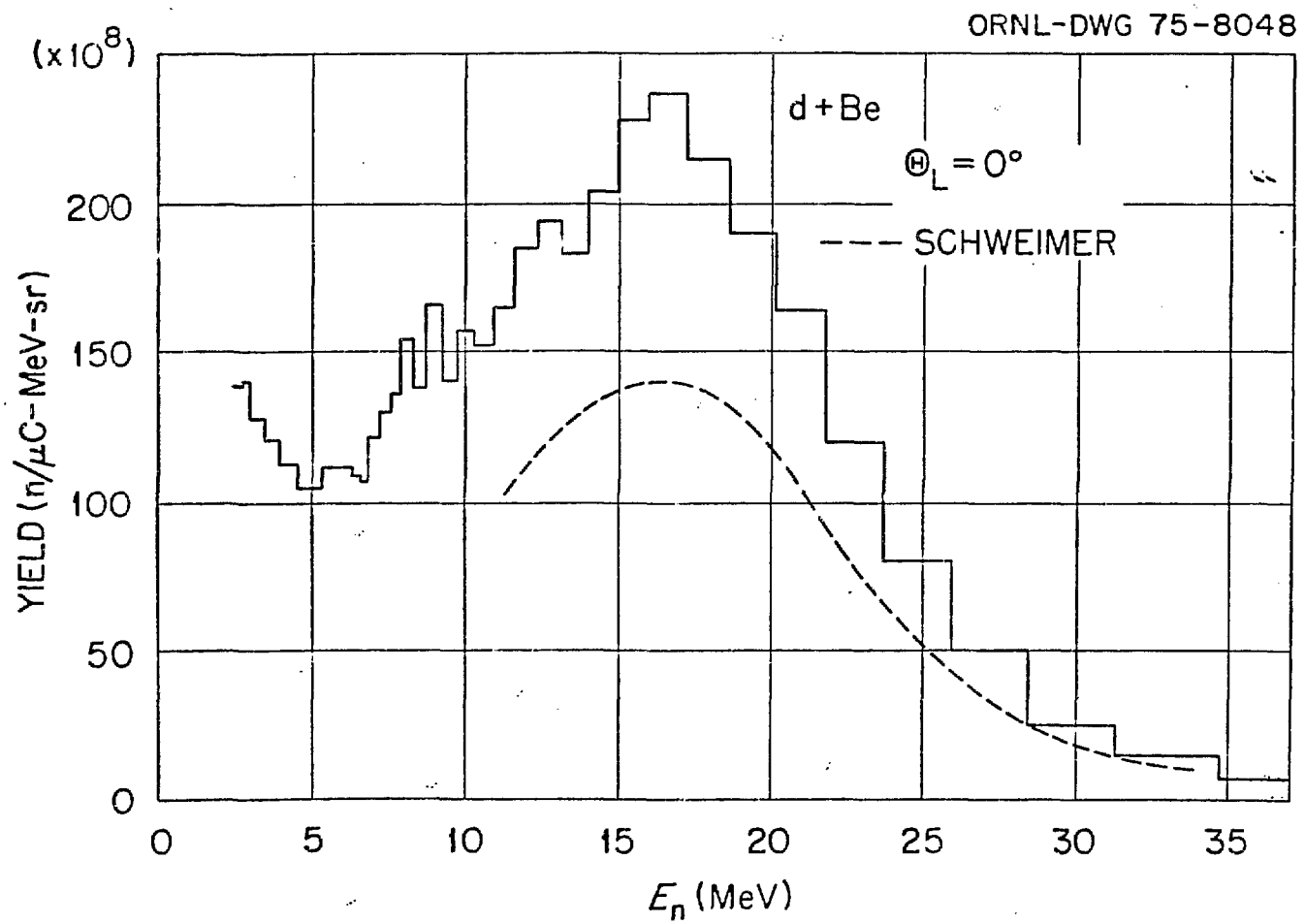
* Deuteron Energy = 40 MeV

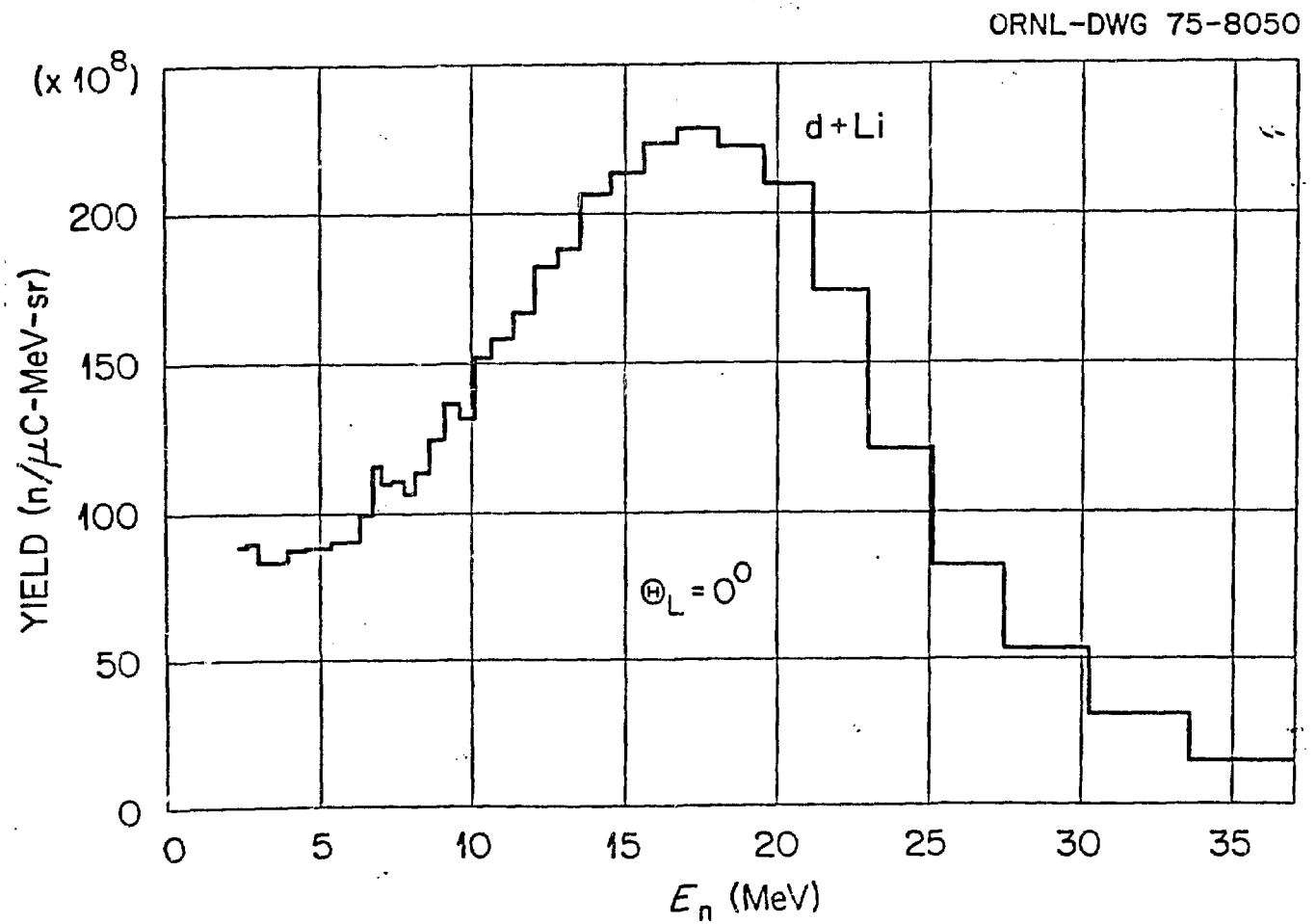
TABLE V

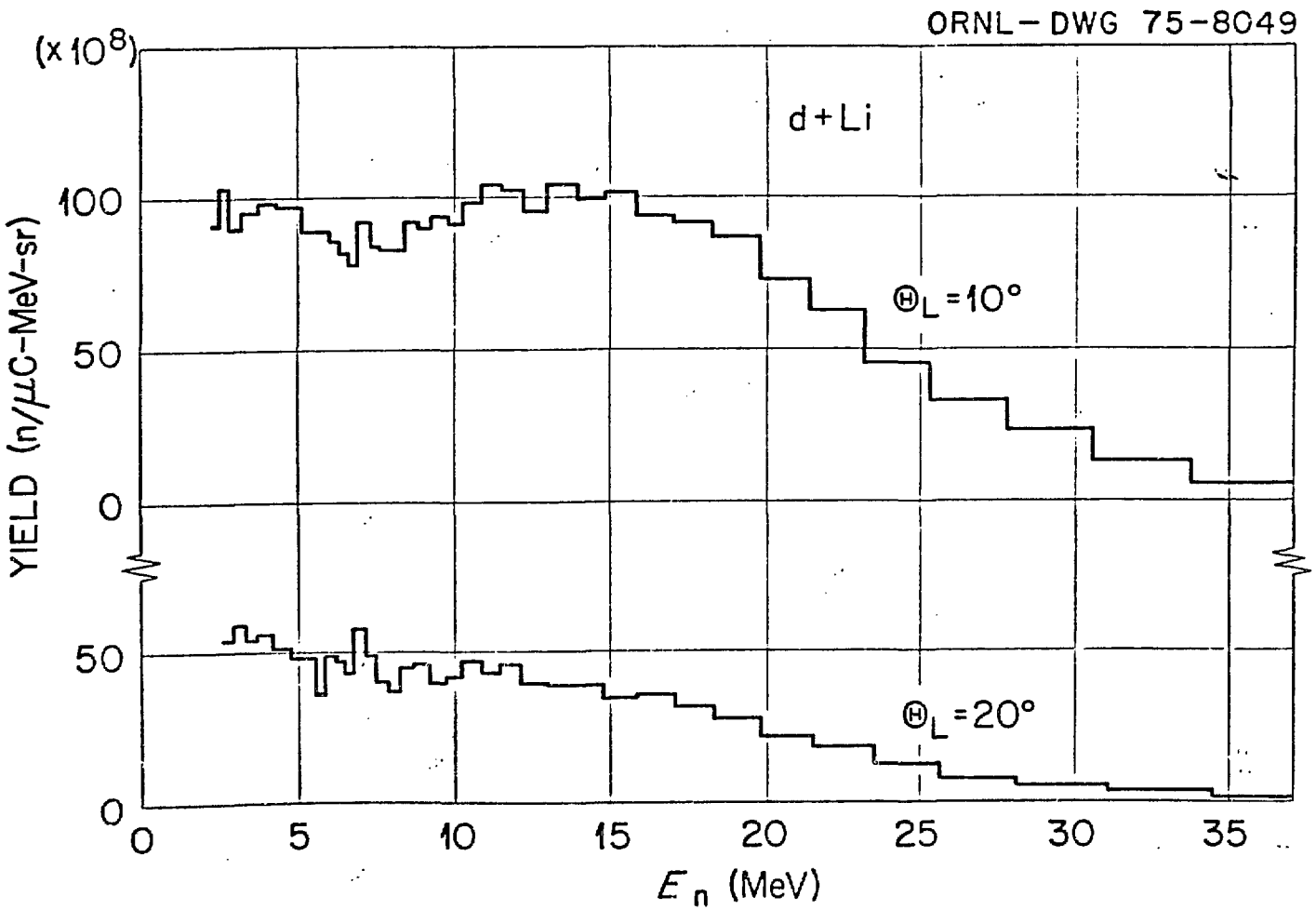
Miscellaneous Engineering Data for Lithium Circuit

Energy in Deuteron beam	4 MW
Duration of Typical Test	4 months
Material of Construction	300 Series Stainless Steel
Pipe Size	5 in. Sch 10 IPS (6-in. Sch 10 at pump suction)
Lithium Flow Rate	615 gpm
Lithium Bulk Fluid Temperatures	
Normal Maximum	649°F
Normal Minimum	550°F
ΔT	99°F
Lithium velocity in 5-in. pipe	9 1/2 ft/sec
Reynolds Number in 5-in. pipe	392,000
ΔP per 100 ft of 5-in. pipe	1.2 psi
Lithium velocity at target area	49.2 ft/sec
Vacuum within deuteron beam enclosure	$\sim 10^{-7}$ torr
Lithium inventory being circulated	120 ft^3 3360 Lb
Tritium generation rate	$\approx$ 20 Ci/day
Evaporation rate of Li at target area	$\sim$ 0.02 lb/day

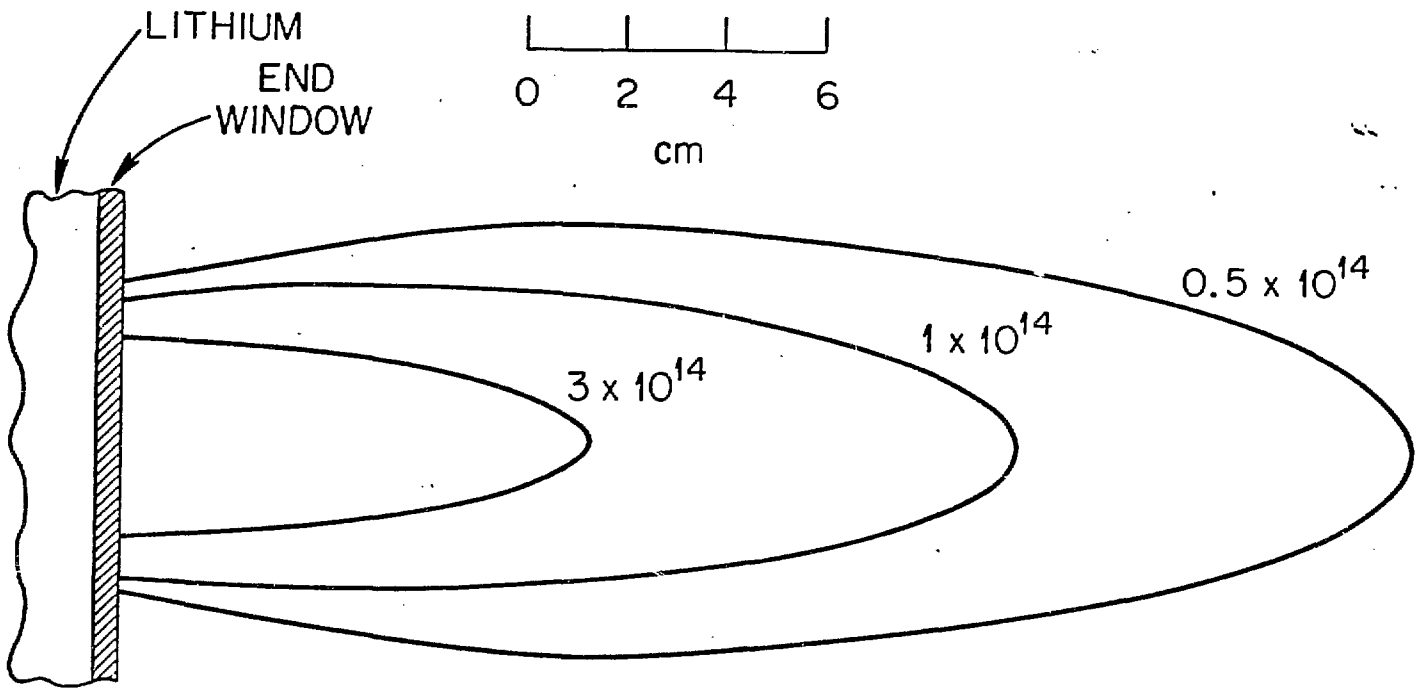

RETAINED DAMAGE IN Cu
●1.7x10¹⁷n/cm² Be(d,n) Source
○1.0x10¹⁸n/cm² Fission
LOOP DENSITY (NO./cm³-10Å)
LOOP RADIUS (Å)
10¹⁷
5
2
10¹⁶
5
2
10¹⁵
5
2
10¹⁴
5
2
10¹³
5
2
10¹²
0
20
40
60
80
100
120
140


ORNL-DWG 75-8048
(x10^8)
d + Be
Θ_L = 0°
SCHWEIMER
YIELD (n/μC-MeV-sr)
200
150
100
50
0
0
5
10
15
20
25
30
35
E_n (MeV)

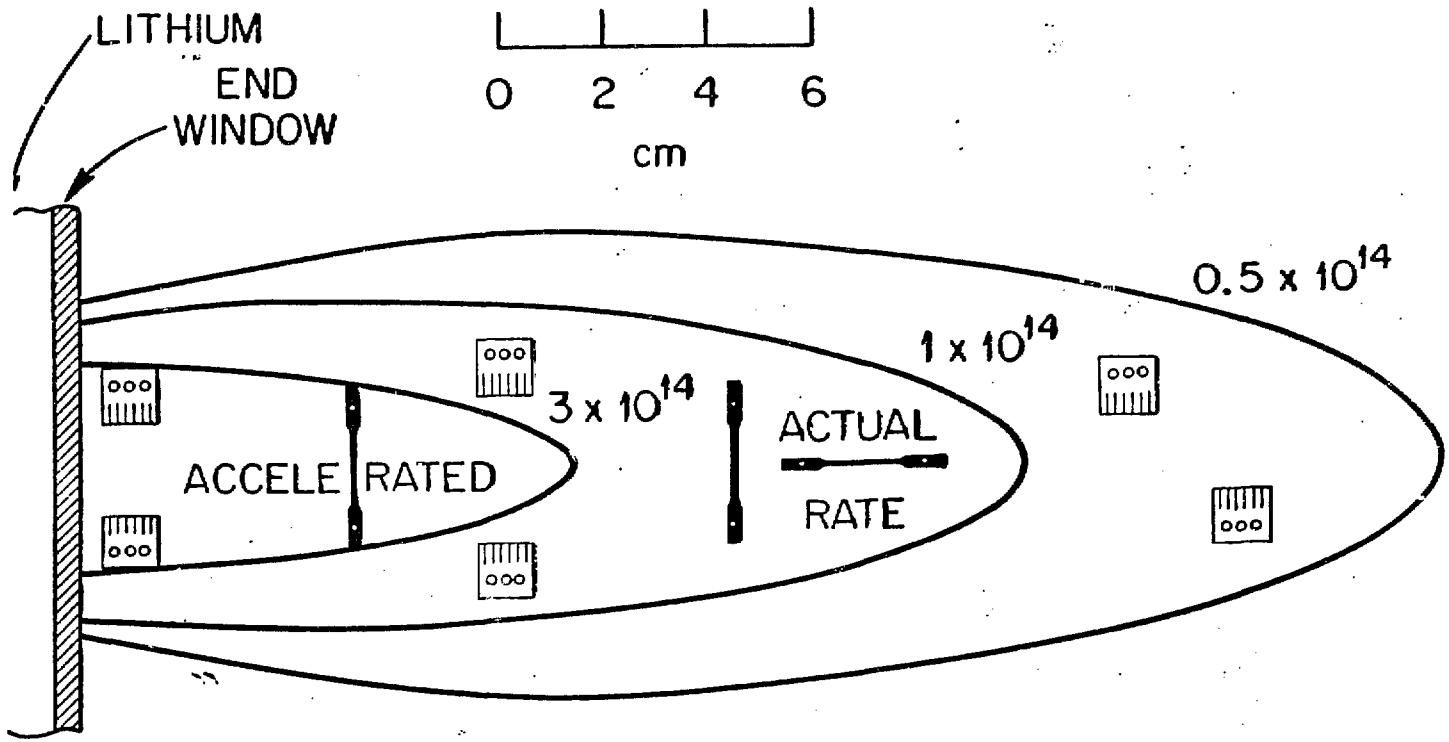

ORNL-DWG 75-8050
(x 10^8)
YIELD (n/μC-MeV-sr)
200
150
100
50
0
d+Li
Θ_L = 0°
0
5
10
15
20
25
30
35
E_n (MeV)


ORNL-DWG 75-8049
(x 10^8)
d+Li
100
50
0
50
0
YIELD (n/μC-MeV-sr)
Θ_L = 10°
Θ_L = 20°
0
5
10
15
20
25
30
35
E_n (MeV)

ORNL-DWG 75-8013

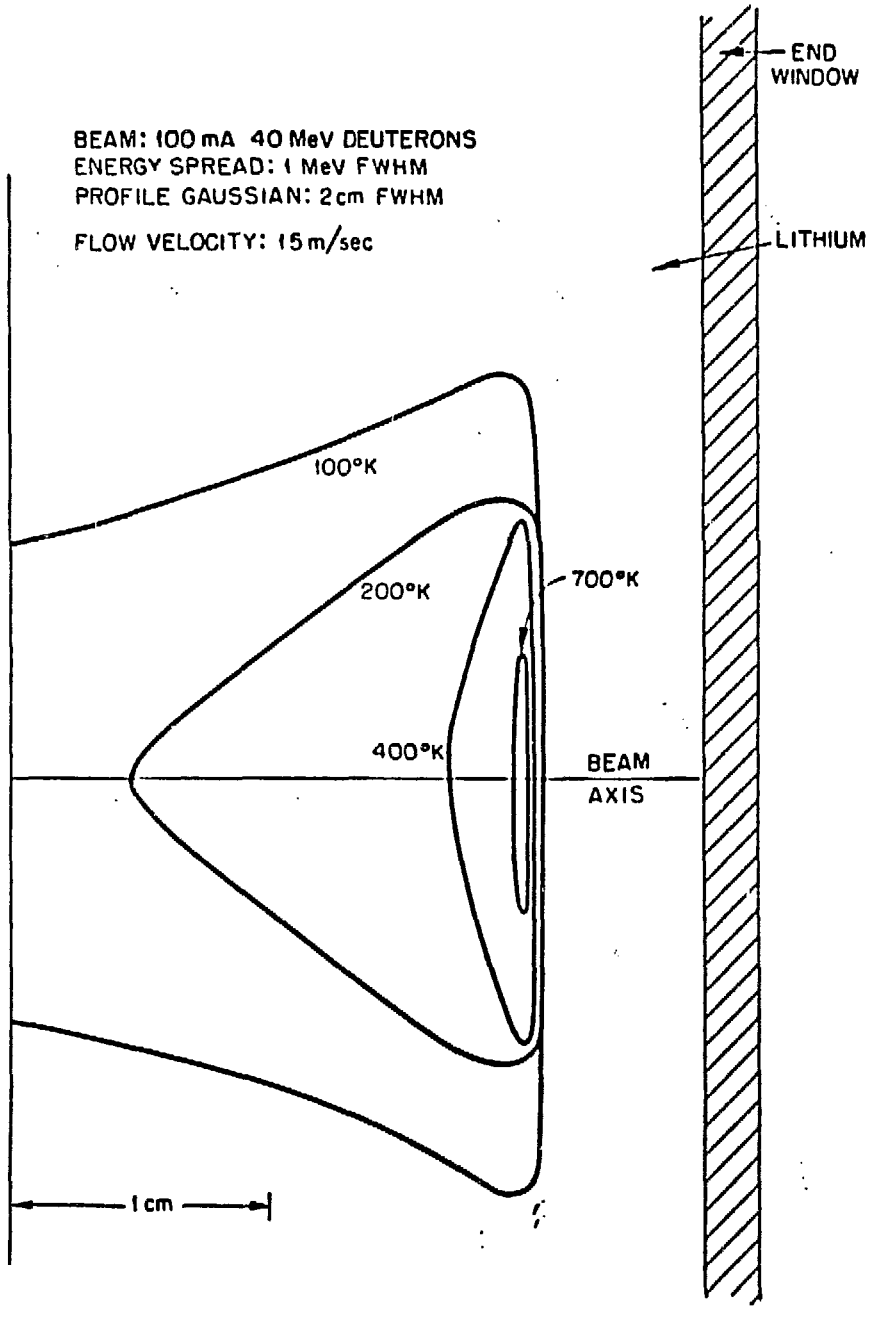


Neutron Flux Profiles in Units of neutrons/cm^2/sec
100 mA, 40 MeV d on Li



Neutron Flux Profiles in Units of neutrons/cm^2/sec
100 mA, 40 MeV *d* on Li

ORNL-DWG 75-8014



Temperature Rise in Lithium Jet.

FIGURE CAPTIONS

Figure 1 Preliminary data on the number density and size distribution of dislocation loops induced in pure Cu by neutron irradiation with two different source spectra. From J. B. Roberto and J. Narayan.

Figure 2 The 0° neutron yields from a thick Be target bombarded with 40 MeV deuterons. The histogram is recent ORNL data, while the dotted line represents earlier data of Schweimer [11]. (ORNL 75-8048).

Figure 3 Same as for Figure 2 except that the target was natural Li. (ORNL 75-8050).

Figure 4 Same as for Figure 3 but at angles of 10° and 20°. (ORNL 75-8049).

Figure 5 Neutron flux contours calculated for a 100 mA 40 MeV deuteron beam incident on a 2.5 cm Li target. The deuteron beam is incident from the left, and stops within the Li target. The units are $n/cm^2/sec$: for d-Li spectrum neutrons above $E_n \sim 3$ MeV. To convert to fusion neutron equivalent fluxes ($E_n > 0.1$ MeV) multiply by 2. (ORNL 75-8013).

Figure 6 Possible experimental layout in the high flux region of a d-Li source. The tensile specimens illustrated are of the size currently in use at ORNL. Both real time and accelerated irradiations can be accommodated. Possible configurations for small liquid Li loops containing sheet and tube specimens are indicated.

Figure 7 A cross section through the Li jet just after it has traversed the beam spot showing the spatial variation of the temperature rise induced by the beam. (ORNL 75-8014).