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NEUTRON SOURCES FOR THE MEDICAL USE

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Contributed Paper to the IAEA Consultants' Meeting on
Neutron Source Properties, Debrecen, Hungary, 17-21 March 1980

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Abstract:

Recently encouraging results of the neutron radiation therapy have been obtained in clinical trials. In addition to the therapy, the neutrons are applied to the diagnosis besides the production of radioisotopes, that is, in-vivo activation analysis and neutron radiograph.

In the medicine, high energy neutrons are effectively used. The necessary conditions, especially neutron source reactions, angular distributions, etc., and the neutron dosimetry including neutron kerma factors are discussed.

Finaly the requirements for neutron sources, their related problems and nuclear data are enumerated.

§ 1. Present status on medical use of the neutrons

a. In this paper both of the radiation therapy and the diagnosis by using the neutron sources, mainly accelerators, are surveyed. In the neutron radiation therapy, though a lot of studies have been performed since invention of the accelerators, the encouraging results were obtained in clinical trials at Hammersmith only in the last 10 years. However, it was already suggested by Gray et al.[1] in 1953 that in the treatment of tumors the neutrons were more effective than the X-rays.

On the other hand, it is a rather recent topic that the neutrons have been applied to the diagnosis in addition to production of radio isotopes. Being compared with the X-rays, the neutrons can detect the difference of the nuclear properties even if the atomic number Z is very close or even the same. Furthermore, the density effect is smaller for the neutron diagnosis than for X-rays. This is because the attenuation of the X-rays in the body is proportional to Z^5 in low energy, Z in medium energy and Z^2 in high energy, and the attenuation of the fast neutrons is roughly proportional to $Z^{2/3}$ if individual differences of the nuclear properties are smoothed out. In-vivo neutron activation analysis [2,3] provides a mean of estimating changes in total or a large fraction of skeletal calcium during life with an accuracy of a few percent. In some cases,[3] 12 pieces of Pu-Be neutron sources (60 curies in total) were used to irradiate the trunk in 20 min. Another application is neutron radiograph.[4] At present it is only beginning to be recognized as a valuable tool. Perhaps the most interesting medical application of it is in bone surgery. X-ray techniques have failed to reveal the extent of tumors into the surrounding bone. The neutron radiography, on the other hand, can not only show the invasion of the tumor into the surrounding narrow vascular spaces, but also allow to discriminate between tumor masses in the bone and destruction of bone without tumour invasion per se. Until now it has not been performed in human medicine. The main obstacles are the large radiation doses necessary and the low penetrability of tissue to thermal neutrons. The latter problem has been proposed to circumvent with antiscattering grids between the sample and detector, and also by the use of fast neutrons.

The former problem may be overcome by development of the more sensitive fast neutron detectors than the present ones. Some of these now considered are transfer-detection materials activated by (n,γ), (n, p), (n, 2n) and (n, n') reactions, viewing of a scintillation phosphor excited by knock-on protons, direct production of track-etch images and crossing of two multiwire proportional counters.

For the production of radioactive isotopes, thermal neutrons in nuclear reactors have been mainly used, but charged particles from accelerators are more used to produce short-lived neutron-defficient isotopes (β^+ emitters) for the medical use.

b. Features of the neutron radiation therapy are high RBE, simpleness and low cost to produce the radiation, and handling techniques to be enough proven, though high dose part is not localized compared with γ or heavy charged particle therapy. Therefore clinical trial of the neutrons has been stepped forward after those of X-rays and electrons, and going ahead of those of protons, π^- and heavy ions.

World-wide joint project of the clinical trials of the neutrons among several centers in Japan, the U.S.A., Great Britain and also Continental Europe have been proceeding. The research programs were the first detailed RBE intercomparisons between clinically used neutron therapy facilities. The biological intercomparisons were preceded by detailed dosimetry intercomparisons. Table 1[16] is a list of all of the facilities that have been intercompared to date.

c. The main features and qualifications of a neutron beam and its source that determine their suitability for therapy are as the followings according to the Cross' paper[7] at the Harwell Conference.

(1) low attenuation in the body
(2) yield $\geq 10^{12}$ n/sec.sr.
(3) low cost
(4) low skin dose
(5) low OER

(6) small target spot
(7) suitable angular distribution
(8) low scattering

Accelerators and their related problems including the source neutrons are discussed in the following sections. Because of low attenuation and low scattering in the body, primary neutron energies E_n should be higher than 10 to 20 MeV as seen in Figs. 1A[8] and 1B[43]. Since only the affected part should be desirable to be irradiated, the neutron beam should be well-collimated and the scattered neutrons should be mainly limited to forward direction. As seen in Fig.2[9], the scattered neutrons inside the body are more in the forward direction with increasing neutron energy ($\gtrsim$10 MeV), though scattering by a hydrogen nucleus is hindered to go backward in the laboratory system.

The minimum dose rate at the patient should be larger than 10 rad/min[10]. It takes 5 to 10 min for irradiation of the body, and these may be the longest tolerable time for a patient. It requires source yield $\gtrsim 10^{12}$ n/sec.sr. By the way, intermittent irradiation of the neutrons, total dose of which is, for example, 5000 rad/5 weeks, and boosted irradiation with photons, e.g. photons of 3000 rad/3 weeks and neutrons of 2000 rad/2 weeks, are tried in Phase III neutron therapy for carcinoma in U.S.A.[11].

It is reported[12][44] for skin dose that in the first few mm below the surface of the body the dose will be lower built up to equilibrium with incident neutrons. The depth increases with the increasing neutron energy as seen in Fig.3[44], and at 50 MeV it is about 3 mm.

Energy dependences of RBE* and OER** are shown in Fig. 4[13]. RBE values are almost the same in a region of 10 to 60 MeV and

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* RBE: Relative Biological Effectiveness expressed as the effect of a given dose of the radiation divided by the dose of a standard radiation required to produce the same biological effect. The normal standard which has been adopted is 220 keV X-rays, although ^{60}Co gamma-rays may be used in some circumstances.

**OER: Oxygen Enhancement Ratio Expressed as the ratio of radiation dose required to produce a given biological effect in a defined

hypoxic condition divided by dose required to produce the same effect in oxic conditions.

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equal to 2 - 3. Below 10 MeV it increases to 3 - 6 at 1 MeV. OER values are also constant and equal to 1.7 - 2 in a region of 10 - 60 MeV. Below 10 MeV it slightly decreases. In the case of X-rays OER ranged 2.5 to 3.0. It is reported[14] that for all neutron energies RBE increases with decreasing dose, and at very low doses RBE appears to reach about the same value independently of the neutron energy used ($\sim$4)[13].

d. Interaction modes of the neutrons with the bodily tissue

Effects of the neutrons in the bodily tissue are classified as follows.

(1) Effects of atoms (mainly hydrogen atoms) recoiled by the neutrons.
(2) Effects of products of low-energy nuclear reactions induced by the neutrons, which are mainly $^{12}C(n, n')$, (n,α) and $(n, n'3\alpha)$, $^{14}N(n, n'p)$ and (n,α), and $^{16}O(n, p)$, (n,α) and $(n, n'\alpha)$.
(3) Effects of nuclear-spallation products induced by the high-energy neutrons[15].

In the energy range concerned here, effects (1) and (2) are predominant. Contribution of those effects is estimated by using tissue kerma factor (see §3-6). Effect (3) is different from the others.
In Fig. 5[16] number of the spallation neutrons are shown as a function of the neutron energy. In Table 2[17] RBE values are shown for the various neutron energies including 400 and 600 MeV.

§ 2. Neutron Source for the Medical and Related Biomedical Uses

a. Desirable source conditions for the neutron radiation therapy

As desirable criteria, the followings are enumerated.

(1) neutron energy
(2) neutron source yield

(3) suitable angular distribution of the neutrons emitted from the source
(4) neutron energy spectrum
(5) low background including filtering of the low-energy neutron tail
(6) small target spot and neutron collimation
(7) simple target
(8) simple and low cost accelerator with easy maintenance

Though neutron energy is desirable to be lower from the viewpoint of RBE, it should be higher than 10 MeV considering penetration depth of the neutrons in the body, angular distribution of the scattered neutrons and others. Neutron yield is necessarily more than 10^{12} n/sec.sr. This value corresponds to 10 rad/min at the position of a patient (about one meter from the neutron target and irradiation area of about 10 cm x 10 cm) as mentioned in §1.

Some neutron source reactions, e.g. D-T reaction, have uniform angular distribution of the emitted neutrons, but the others, e.g. stripping and knock-on reactions, have sharp forward peak.
The latter distribution is more convenient for the neutron shielding, but in the case of too sharp peak, if size of a tumor is large, flattening filter is necessary to get uniform irradiation of the tumor.
Semiangle of 8° or a little less is typical therapy beam collimation[12].

The energy spectra are categorized into three types: monoenergy, Gaussian distribution and mixed spectrum.
The D-T reaction has monoenergetic spectrum. The energy spread depends upon target thickness, and tritium-titanium target is usually thick enough.
The neutrons from the stripping reactions have Gaussian distribution, but three-body break-up reaction (low energy continuum)and ground-state reaction (high energy tail) are mixed to the stripping. The knock-on reactions have more complicated spectra, which are nearly of flat shape with a strong low energy component.

Smaller target spot is better, but too small spot brings about target deterioration due to large heat dissipation density.
Low background is essential for handling of the apparatus and also the medical treatment. Most of the background are low energy part of the neutron spectrum, X-rays and room background.

Since low energy neutrons (see b 3-3) are sometimes harmful for the therapy, they should be filtered with nylon (e.g. 6 cm thick) and others[18]. With the collimator made by Benelex (densly compressed wood, Masonite Co.) of 80 cm long, background neutrons of about 2 % of the collimated neutrons were observed[14]. In the case of too short distance between the target and patient, care should be taken to β rays from the target.

In order to decrease the irradiation of the bodily normal tissue, rotatable isocentric irradiation is important for the medical treatment of the tumor which is deep in the body. For this purpose the accelerator is desirable to be small. As modern accelerators a cyclotron, especially isocronous one, is most popular and convenient. Recently a superconducting cyclotron[20][21] is considered to be convenient for the neutron therapy. Since it is of small size and light weight, it will be useful especially for higher energy.

The D-T neutron generators are generally small, handy and movable, which are of electrostatic or transformer type. Most difficult is target problem (see b). Proton linacs are also used[22]. At Fermi Lab., a part of 200-MeV injector linac for high-energy synchrotron is used for the neutron therapy (see Table 1). In the linac, the machine background will be made smaller, since beam spill is supressed to be smaller (in a recent example, one part in 10^4 - 10^5 may be possible), and, furthermore, high gradient machine is under development (for PIGMI[23], 5-8 MV/m).
As the accelerator cannot be movable, a beam bending magnet is used and a patient is moved to be rotatable.

b. Source reactions and targets

(1) (γ, n) reactions: as an intense neutron source for nuclear data measurements this reaction has been adopted by using and electron linac with Time-of-Flight method (Table 3). Since X-ray background is large, it is unsuitable for the neutron therapy.

(2) low-energy nuclear reaction: the D-T reaction is used for the neutron therapy. Since a reasonance for neutron production is at E_d=100 keV and its peak cross section value is 5 barns, the low-energy D-T neutron generator is now commercial one for the therapy[24].

However, the neutron yield of 10^{13}n/sec which correspond to the dose rate of 10 rad/min at patient position is technically marginal to produce. With water-cooled rotating T-titanium target, life of the target is about 10 hours. If diameter of the target is increased with increasing rotation speed and the target is slowly oscillated in addition to the high speed rotation, the yield of 10^{13}n/sec and half life of 100 hours are attained (Table 4). This is because beam current can be increased due to efficient cooling of the target, temperature of which can be kept under 200°C, and target deterioration is tolerable for longer time due to increased target area. However, as seen in Table 4, target technology to deal with a lot of tritium will be very much hazardous. At Sandia Laboratory[25], a 200 kV 200 mA deuterium ion accelerator has been constructed to evaluate high-temperature hydrides of materials such as scandium and erbium for use as targets in the D-T neutron generator. The goal of this program is to develop a target capable of producing 10^{13}n/sec for the use in cancer therapy. The target is water-cooled and non-rotating one. Its substrate is made of copper. The surface temperature should be kept below 450°C. Mixed beams of tritium and deuterium ions will be accelerated. Up to now, D-D neutron output rate of 6×10^{10}n/sec for 180 kV 160 mA on scandium target, which scales to about 1×10^{13} D-T neutrons/sec for 200 kV 180 mA, 50 % D and 50 % T beam on scandium, and target life time of 15 h on a 10 μm thick film, which scales to about 75 h for 50 μm thick film, were attained. This will be able to be done in a sealed system, a feature that is very desirable in a hospital. Sealed tubes for neutron source have been manufactured commercially in the UK, the Netherlands, West Germany and the U.S.A. Their problem has been insufficient neutron source strength ($< 10^{12}$n/sec) and/or short life. However, the sealed neutron tubes are showing rapid improvement. They have been installed or will soon be installed in several hospitals.

(3) Stripping and knock-on reactions: D-p, D- and T-d, Be-p, -d and -^{3}He, and Li-p and -d reactions have possibilities to be used. Here, D-p, D- and T-d reactions are not considered because of target problems[7].

Since $E_p=2E_d$ and $E_{^3He}=2.7\ E_d$ with the same isochronous cyclotron of fixed energy, neutron yield, angular distribution and energy spectrum of each reaction should be compared at the beam energy for respective ion.

(3-1) Neutron yield: Fig. 6[7] shows the variation of neutron dose/μA with proton and deuteron energies at 125 cm in front of thick targets of Be and Li. Neutron yield of Li-d not shown in the figure is similar with that of Be-d (see Table 5). Fig. 7[26] shows neutron yields ($E_n>4$ MeV) from thick targets of B, C and Cu bombarded by deuterons. Yield of Be-^{3}He is by a factor of 1/2·5 — 1/3·5 smaller than that of Be-d[7].

(3-2) Angular distribution: Angular distributions of all reactions have forward peaks, which are more remarkable at higher energies, especially higher than 20 MeV, and those of Be-d and Li-d are more pronounced than those of Be-p and Li-p. See Fig. 8A[27], Fig. 8B[12] and Fig. 9[27].

(3-3) Energy spectrum: Each of energy spectra is divided into high and low energy parts. The boundaries are 4 and 10 MeV for deuterons and protons, respectively. For Be-d and Li-d, the high energy parts are of Gaussian shape and for Be-p and Li-p they are rather flat. See Fig. 10[27], Fig. 11[27], Fig. 12[27], Fig. 13[27], Fig. 14A[7], Fig 14B[12] and Fig.15[7]. Energy spectrum of Be-^{3}He is rather similar to that of Be-d as seen in Fig. 16[46].

In the high energy part ($E_n>4$ MeV) of the angular distribution of Be-d, 50 MeV 10μA of a deuteron beam is necessary for 100 rad/min to irradiate an area of 10 cm x 10 cm at 1 m 0° from the Be target. In order to convert the neutron flux to the absorbed dose rate, the data reported in ICRP-Publication 21 and the quality factor of 10 are used. Dose rate of the neutrons by 23 MeV 10μA of deuteron and proton beams for an area of 10 cm x 10 cm at 1 m 0° are calculated in Table 5. As seen in the table, contributions of low energy parts are large for the proton reactions, and the dose rate of Li-p is especially small.

Heat dissipation of the Be target for 50-MeV deuterons is 500 watt for 100 rad/min of the neutrons. Since melting point of Be is 1556°K, water cooling is enough for the target. The penetration depth is about

8 mm. In the case of Li target, melting point of which is 454°K, it may be necessary to circulate liquid lithium to avoid the vaporization, and the penetration depth is about 2.5 cm. Water circulation of Li_2CO_2, melting point of which is 1008°K, also will be enough for cooling of the target.

(4) Spallation and fission: Neutron production mechanisms are very much complicated in these reactions. Average neutron energy is low and X-ray contamination is large for the neutrons, though neutron yield is very large. Therefore the use of fission neutrons is mainly for the thermal neutrons from nuclear reactors. High-energy neutrons from spallation are often used for the biomedical experiments.

3. Neutron dosimetry

a. Neutron detectors

(1) Scintillation counters: Scintillation counters have been used for measurements of the neutron source intensity and its energy spectrum. They are plastic or organic scintillators with Time-of-Flight method, if necessary to suppress the γ-ray random background, with γ-ray discrimination. Over 10 MeV, however, neutron total cross sections of carbon are larger than those of hydrogen, and, over 20 MeV, neutron inelastic cross sections of carbon become larger as seen in Fig. 1A[8]. So calculation of the detector efficiency[8] is very much complicated.

(2) Threshold detectors: It is simple and convenient to measure the neutron source intensity and its spectrum with combination of several kinds of known threshold detectors[24].

(3) Tissue equivalent ionization chambers: The absorbed dose is measured by using the ionization cavities surrounded by suitable solid[30], e.g. polyethylene.

(4) Albedo neutron dosimeters: Albedo dosimeters are increasingly being used as neutron detectors in routin personnel monitering. Today, various types of albedo dosimeters are in use, which may contain one or more pairs of $^6LiF/^7LiF$ thermoluminescent detectors (TLD), providing separate indication of incident and backscattered neutrons[31].

One practical disadvantage of albedo dosimetry has been found in the marked energy dependence of the neutron dose reading. Compared to a single dosimeter, albedo dosimeters containing several LiF pairs are able to distinguish between incident field neutrons and neutrons back-scattered by the body.

b. Tissue kerma factor

Interactions between the incident neutrons and the bodily tissue are very complicated and change with the neutron energy. The quantity "tissue kerma factor" is convenient for calculating dose distributions throughout the body.

In a region of $E_n < 20$ MeV, there are several reports of the kerma factors. Tanaka et al.[32] calculated energy-dependent kerma factors for 26 nuclides by neutrons. Each component arising from the nuclear reactions is also shown separately. In a region of $E_n > 30$ MeV, data are meager. Fig. 17[7] shows the calculations for H, C, N and O between 20 and 70 MeV by Alsimiller et al.[33] At 20 MeV, 70 %, 20 % and 10 % of tissue kerma are due to H, O and C, respectively, but, at 70 MeV, only 50 % comes from H. In a region of 10 - 30 MeV (also higher than 30 MeV), the emissions of α from C and O, and p from N are dominant[44]. Concerning Ca in a region of 4 - 16 MeV, contribution of (n, p) is dominant[32].

c. Background neutrons and internal neutron sources

Background neutrons from medical pion facilities are enormous. Neutrons are produced at the same target as the π^- production. By using an electron beam of 810 MeV[34], n/π^- is calculated to be 3×10^2 for a carbon target of 5 cm long with a radiator of one radiation length, π^- momentum being 130 MeV/C, its width $\pm$ 2 % at 90^o. By using a proton beam of 730 MeV, n/π^- is to be 9×10^2 for a carbon target of 5 cm, the other conditions being the same.

Another source of the neutrons is due to the star by π^-, which produces various heavy ions, γ-rays and neutrons. In the target of oxygen, on an average, 2.9 neutrons are produced and total energy carried off by them is 61 MeV[36]. Their dose distribution in the tissue is calculated in Fig. 18[37].

These neutrons have the similar medical effects as those from spontaneous fission of ^{252}Cf (3.76 n/fission, $\bar{E}_n$ = 2.15 MeV[42]).

§4. Concluding remarks

a. The followings are essentially important for the radiation cancer therapy[38]

(1) Deliver high dose to the tumor, and
(2) Deliver as near as possible no dose to critical normal tissue.

In order to make effectively bringing in operation, the following items are important.

(1) Utilize to advantage the physical properties of various radiation beams and internal sources,
(2) Utilize to advantage the biological properties (RBE, OER, etc.) of various beams, and
(3) Increase radiosensitivity of tumor compares to normal tissue, and decrease radiosensitivity of normal tissue.

From the practical viewpoint of the medical uses of neutrons, the followings are necessary[39].

(1) The beam always be available to meet clinical requirements.
(2) The output must give treatment time not exceeding four minites or so,
(3) Depth dose and isodose shape must be at least as good as those of ^{60}Co,
(4) The neutron machine must be within a hospital,
(5) The set-up of neutron treatments must be compromised, and
(6) The beam should not be fixed in one position.

In addition to these[40],

(7) Low background,
(8) Good collimation,
(9) More intensity, and
(10) Taking off the low energy tail of the neutron spectrum.

b. Neutron source requirements

(1) Effective filtering of low energy tail of the neutrons, and
(2) Development of intensive and sealed D-T neutron generator.

c. Nuclear data requirements

From Request list of UKNDC Biomedical Subcommittee[41],

(1) γ-ray production cross section for in-vivo activation analysis by fast neutrons: ^{12}C, ^{14}N, ^{16}O, ^{31}P, ^{40}Ca (10 % accuracy), especially in 8-15 MeV range,
(2) More kerma analysis: number of emitted particles and their spectra (10 % accuracy), especially, in 5-50 MeV range, and
(3) Stopping power for application to the dosimetry of neutron radiation: 0.01 - 10 MeV for protons,
0.01 - 8 MeV for α - particles, and
0.01 - 2 MeV for C, N and O ($\pm$ 3% accuracy)

From the paper by Cross[7],

(4) Transport calculation for collimation and shielding of fast neutrons: O, C, Fe, and
(5) Measurements of exact excitation functions of threshold detectors.

Finally, according to the conclusion of a European Neutron Dosimetry Intercomparison Project (ENDIP)[45], the variations in the results from the mean obtained by the participants in ENDIP for neutron and total kerma or absorbed dose are in the order of 7 to 8 percent.
These variations seem to be in accordance with the relatively large systematic uncertainties quoted, which are attributed to inadequote knowledge of basic physical parameters.

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TABLE 1. Clinical Neutron Facilities Intercompared.

	Facility	Location	Production Process	Energy of Accelerated Particle (MeV)	Mean Neutron Energy (MeV)
USA	Fermilab*	Batavia Illinois	$p^+ \rightarrow Be$	66	25
	TAMVEC**	College Station, Texas	$d^+ \rightarrow Be$	50	19.3
	NRL/MANTA**	Washington, D.C.	$d^+ \rightarrow Be$	35	14.3
	NASA/GLANTA	Cleveland, Ohio	$d^+ \rightarrow Be$	25	10
	Univ. Wash.	Seattle, Wash.	$d^+ \rightarrow Be$	22	8
	Univ. of Chicago	Chicago, Ill.	$d^+ \rightarrow d$	8	6
U.K.	MRC, Hammersmith**	London	$d^+ \rightarrow Be$	16	7
	MRC, Edinburgh	Edinburgh	$d^+ \rightarrow Be$	15	6
Nether-lands	Antoni van Leuwenhoek Hospital***	Amsterdam	$d^+ \rightarrow T$	--	14
Japan	NIRS+	Chiba	$d^+ \rightarrow Be$	30	12
	IMS++	Tokyo	$d^+ \rightarrow Be$	15	6

* proton linac 30 rad/min
** cyclotron
*** d-T generator and two small cyclotron
\+ cyclotron 45 rad/min 70 MeV protons also accelerated
++ cyclotron 20 rad/min

T A B L E 2

RBE values for the various neutron energies[17]

Neutron energies	RBE at 50%[b]	RBE at 30%[b]	RBE[a]
Fission (0.4 MeV)	7.6	7.7	7.7
1 MeV	13.2	15.5	14.1
5 MeV	(3.8)	3.9	3.9
15 MeV	(2.3)	2.2	2.3
400 MeV	(1.7)	1.9	2.1
600 MeV	(2.4)	2.2	2.3

( ) Extrapolated values

a) RBE calculated after subtraction of the radioresistant fraction of the tests

b) RBE for two different levels of effects

T A B L E 3

Electron Linac for Intense Neutron Sources

Facility	Harwell	Oak Ridge	Geel
Energy	130 MeV	140 MeV	108 MeV (long pulse) 130 MeV(short pulse)
Averge current	1.5 mA(long pulse) 0.06 mA(short pulse)	0.3 mA	0.11 mA
Averge beam power	140 kW	50 kW(short pulse) 35 kW(long pulse)	13.5 kW 3.9 kW
Peak Current	1 A 5 A	15 A	0.22 A 12 A
Pulse width	5 μsec 5 nsec	24 - 1000 nsec 16 - 24 nsec	2 μsec 3 nsec
Repitition	300 H_z 2 KH_z	700 H_z 1 KH_z	250 H_z 900 H_z
Duty cycle	0.15%	0.07%	0.05%
Frequency	L band	L band	S band
Peak power	-	96 MW	-
Max. mean Neutron output	11×10^{13} n/s 22×10^{15} n/s	8×10^{13} n/s	-
Reference	Information for prospective users, Harwell (1978)	ORELA Performance ORNL/TM-5112(1976)	A. Bensussan & J.M. Salome, Nucl. Instr.Meth.155(1978) 11

TABLE 4

High intensity D-T neutron sources

	PTNS-I	PTNS-II	INS
location	Lowrence Livermore Lab.	Lowrence Livermore Lab.	Los Alamos Scientific Lab.
evergy of accelerator	400 kv	400 kv	270 kv
beam current (spot size, ion)	20 mA (1.6 cmø, D ion)	150 mA (1 cmø, D ion)	1.1 A (1 cmø, T ion)
power dissipation at the target	8 KW	60 KW	300 KW
target radius	22 cmø	50 cmø	supersonic D_2 gasjet
rotating speed	1100 rpm	5000 rpm	D_2: 280 kg/h circulation(loss- 2%)
loading of tritium	500 curies/ target piece	2600 curies/ target piece	5.7×10^4cc/day (loss - 20%)
neutron yield	$5 - 6 \times 10^{12}$n/sec	4×10^{13}n/sec	0.9×10^{15}n/sec
target life	100 h(80%)	100 h(80%)	
operation started	1973	one of two sets 1978	(planned)
reference	R. Booth, Nucl. Instr. Meth. 120(1974) 353	R. Booth et al., Nucl. Instr.Meth 145 (1977) 25	D.D. armstrong et. al., Nucl. Inst. Meth 145 (1977) 127

TABLE 5

Dose rate of the neutrons by 23 MeV, 10 μA of deuteron and proton beams for an area of 10 cm x 10 cm at 1 m, 0°, from targets

	$\bar{E}_n$	dose rate	$\bar{E}_n$	dose rate
energy range	$E_n > 4.3$ MeV		$E_n > 0.3$ MeV	$0.3 \text{ MeV} < E_n < 4.3$ MeV
Be - d	10 MeV	16 rad/min	7.5 MeV	6.7 rad/min
Li - d	10	16	8	3.3
Be - p	11	2.0	5	3.3
Li - p	7.5	1.4	5.5	1.3

$\bar{E}_n$: mean neutron energy

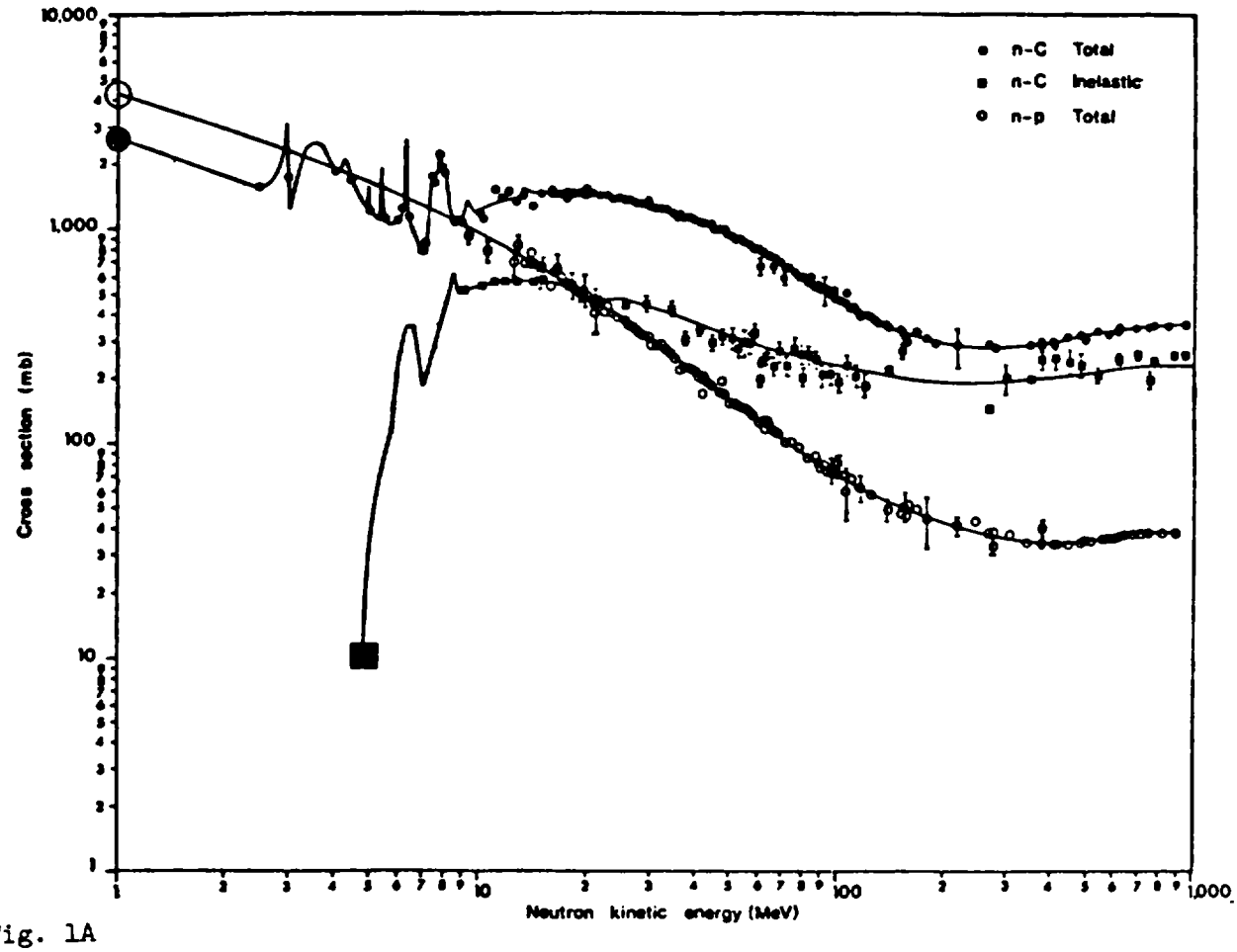


Fig. 1A

n–C total, n–C inelastic and n–p total cross sections data. The full lines show the cross sections used in the Monte Carlo program.

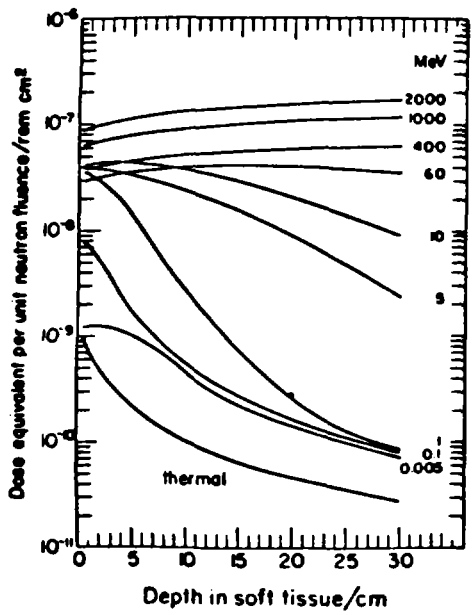


Fig. 1B Dose equivalent as a function of depth in a 30 cm thick slab of tissue irradiated normally, on one face, by a broad beam of monoenergetic neutrons. (From ICRP Publication 21, ICRP, 1973.)

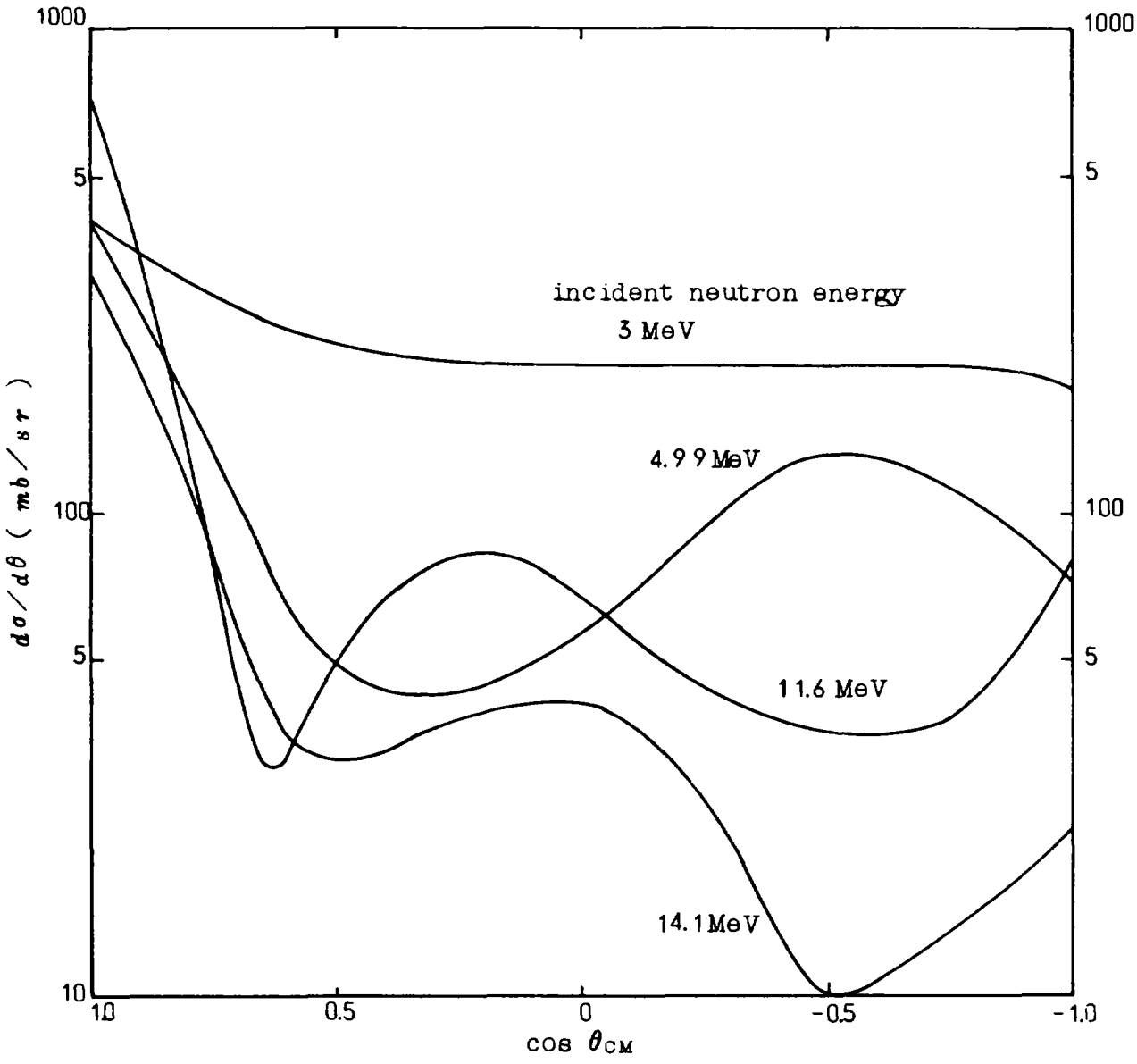


Fig. 2 Angular Distribution of Neutrons Elastically Scattered by Oxygen[9]

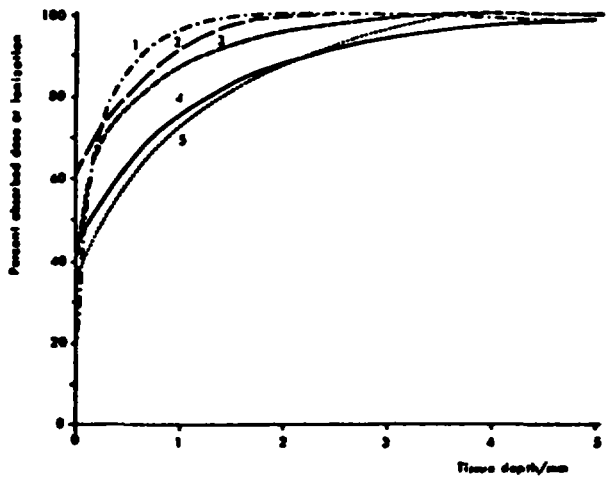


Fig. 3 Charged particle build-up for ^{60}Co gamma radiation (curve 5) (Johns and Cunningham, 1974) and neutron beams of various energies. Curve 1: neutrons with a mean energy of 8 MeV produced by 16.7 MeV deuterons bombarding Be (Bewley, 1971), curve 2: 14 MeV neutrons (Greene and Thomas, 1968), curve 3: neutrons from 30 MeV deuterons bombarding thick Be, and curve 4: neutrons from 50 MeV deuterons bombarding thick Be (Curves 3 and 4 from Smith *et al.*, 1974). [Used with permission of the authors (0) Charles C Thomas Publishing Co., (1) Pergamon Press., (2) The British Journal of Radiology, and (3 and 4) Radiology.]

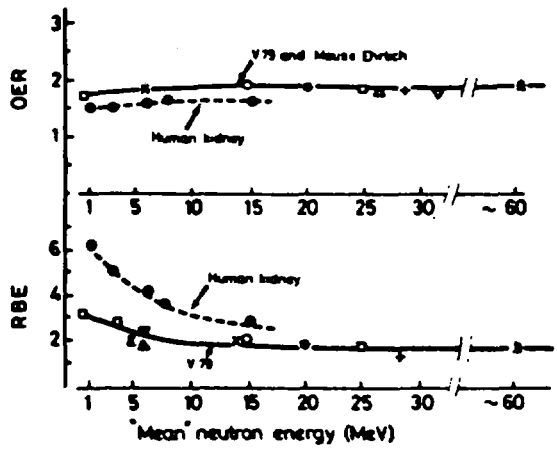


Fig. 4 OER and RBE vs. neutron energy for cells in vitro.

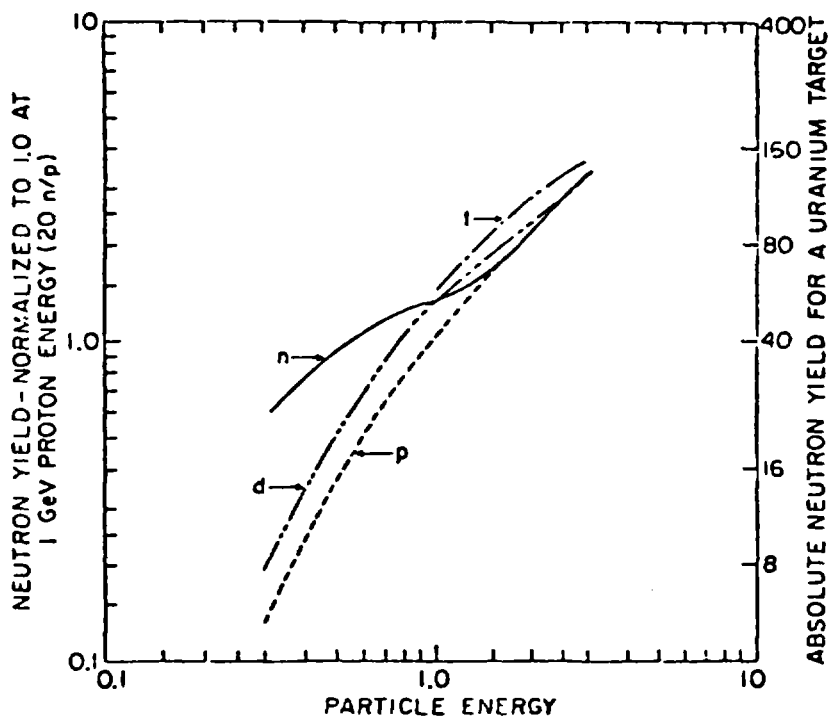


Fig. 5 Neutron yield vs. energy for proton, triton, deuteron, and neutron particles.

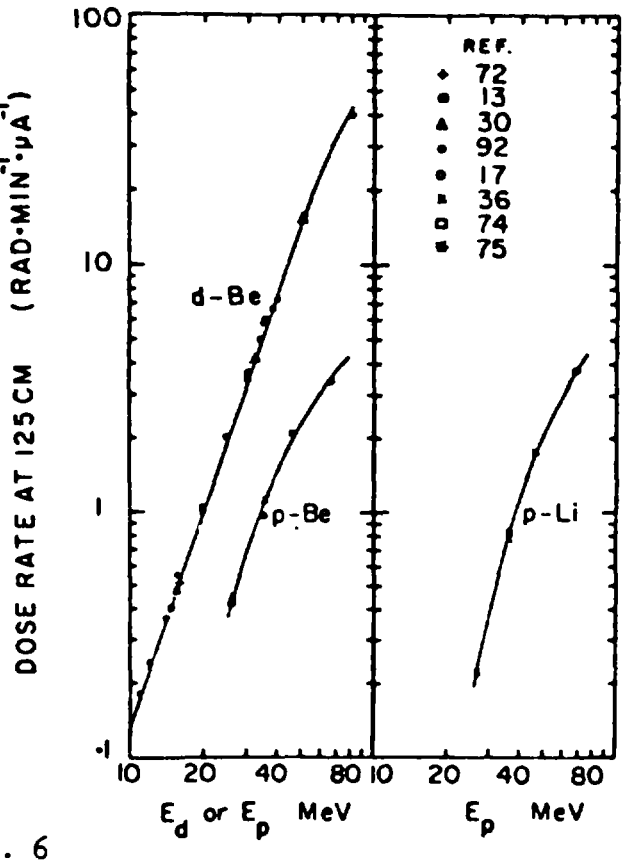


Fig. 6

Variation of dose rate/μA with bombarding energy, for d-Be, p-Li and p-Be sources. Dose rates are measured at 0^{o}, 125 cm from thick targets.

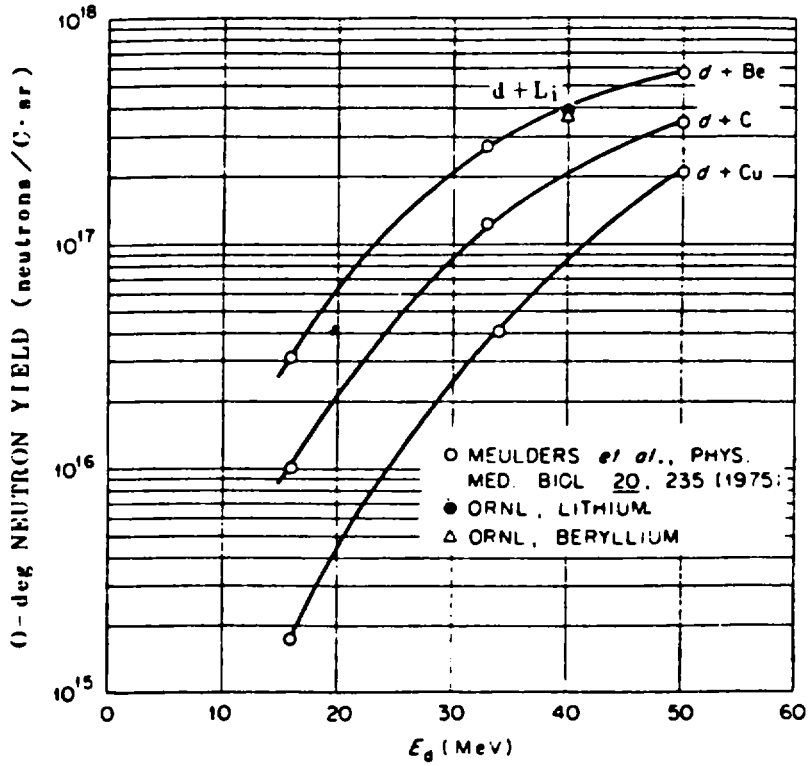


Fig. 7

Neutron yields (E_n > 4 MeV) from thick targets bombarded by deuterons. (Note: the lines drawn through the data points are only to guide the eye.)

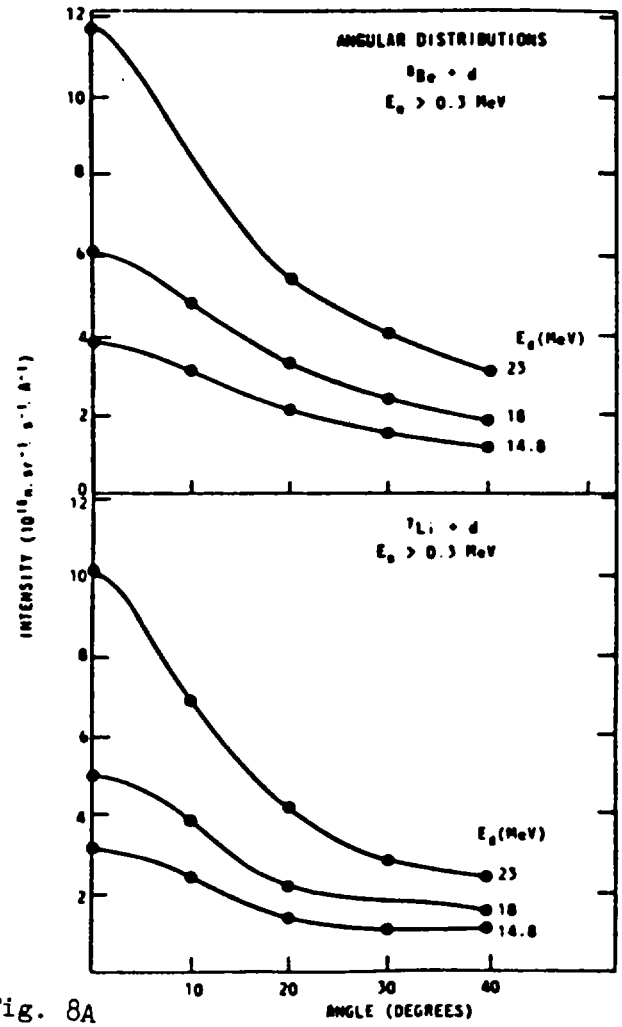


Fig. 8A Angular distribution of the neutron intensity from the $^{9}Be+d$ and the $^{7}Li+d$ reactions.

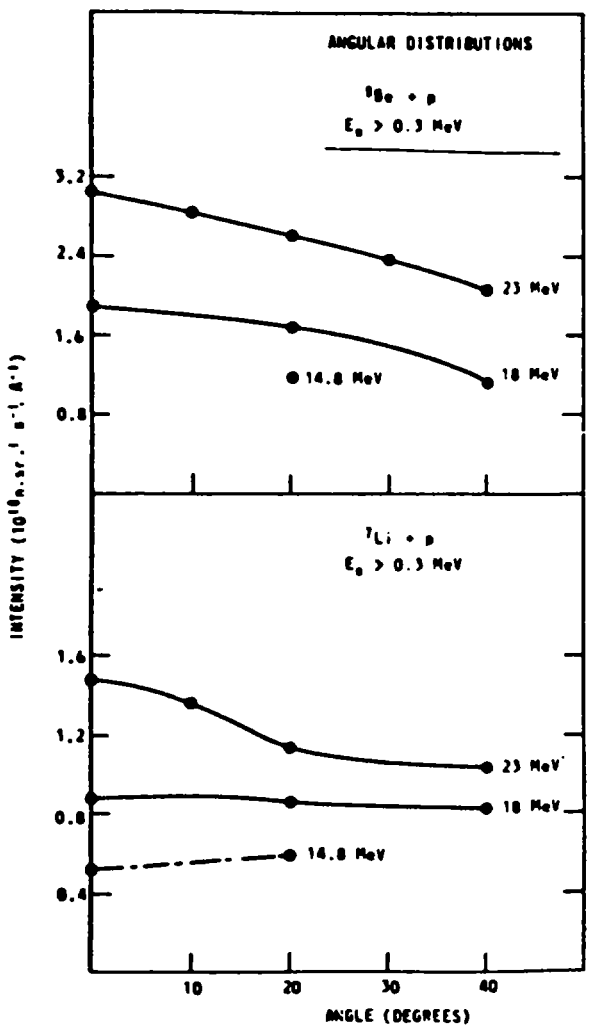


Fig. 9 Angular distributions of the neutron intensity from the $^{9}Be+p$ and the $^{7}Li+p$ reactions.

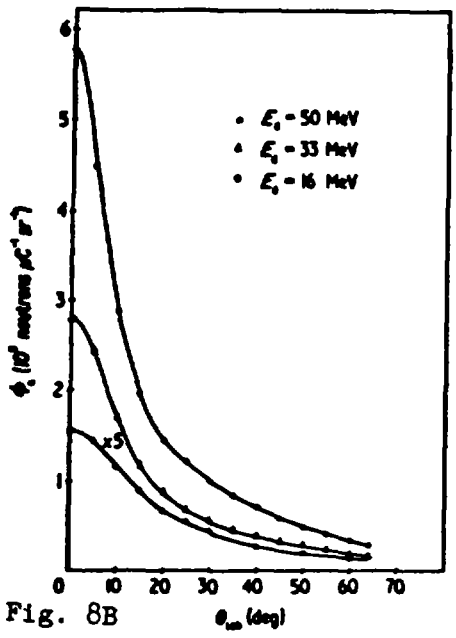


Fig. 8B

Angular distribution of the neutrons from the ^{9}Be(d, n) reaction at E_d = 16, 33 and 50 MeV

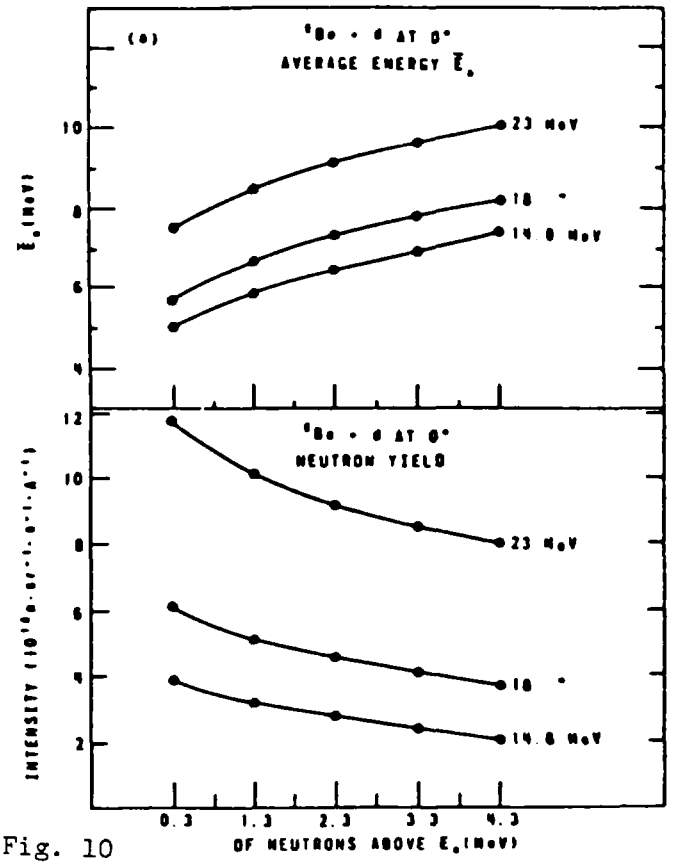


Fig. 10

Zero degree neutron intensity and the average neutron energy as a function of neutron energy cut-off, from the ^{9}Be+d reactions.

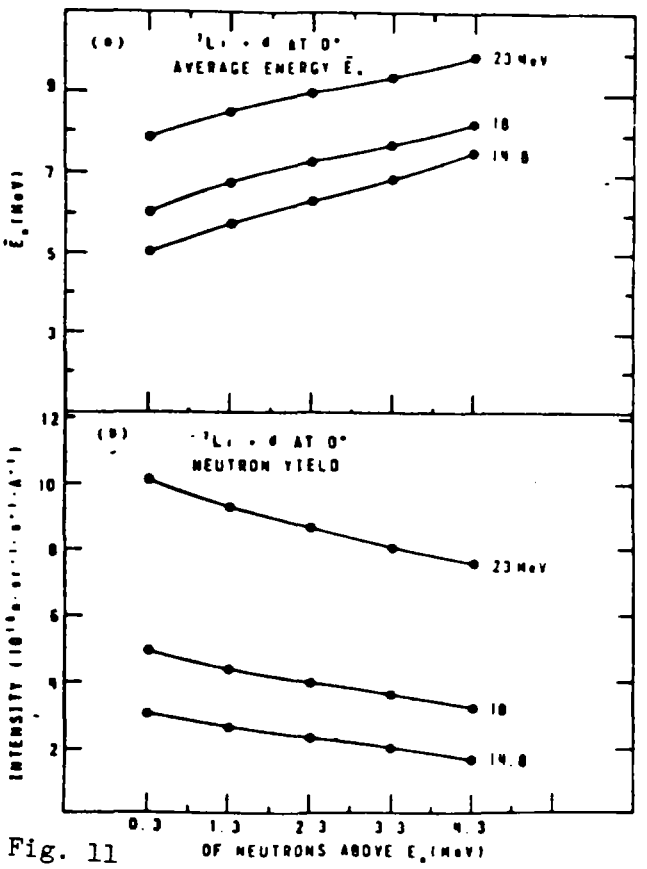


Fig. 11

Zero degree neutron intensity and the average neutron energy from the ^{7}Li+d reactions.

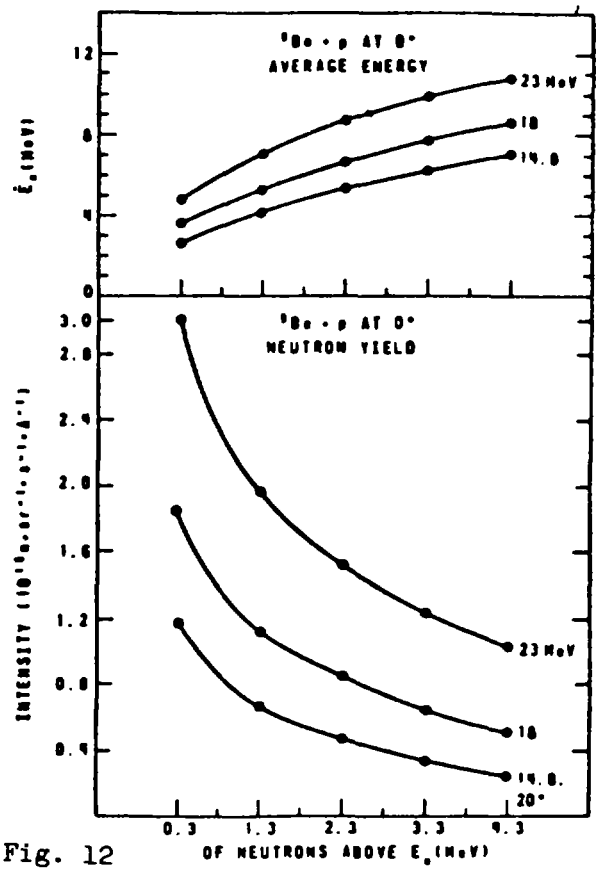


Fig. 12 Zero degree neutron intensity and the average neutron energy from the $^{9}Be+p$ reactions.

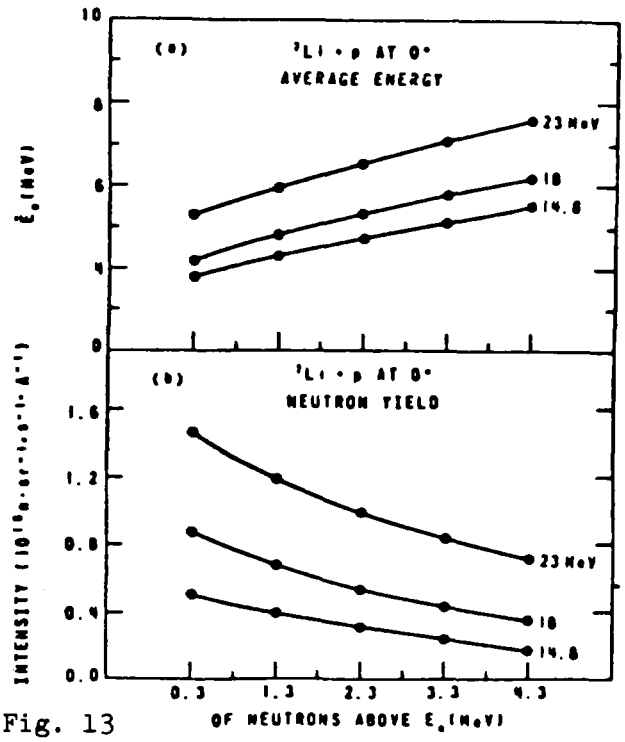
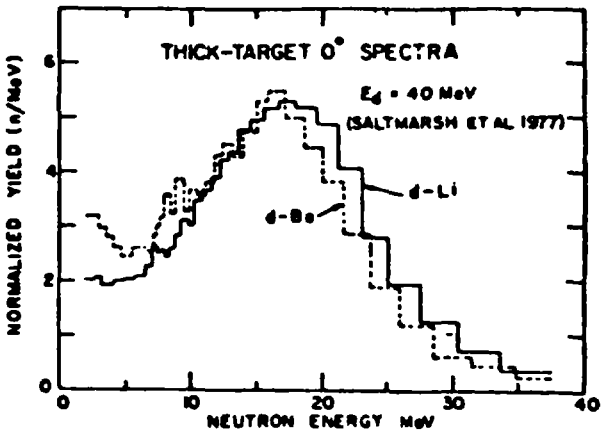


Fig. 13 Zero degree neutron intensity and the average neutron energy from the $^{7}Li+p$ reactions.



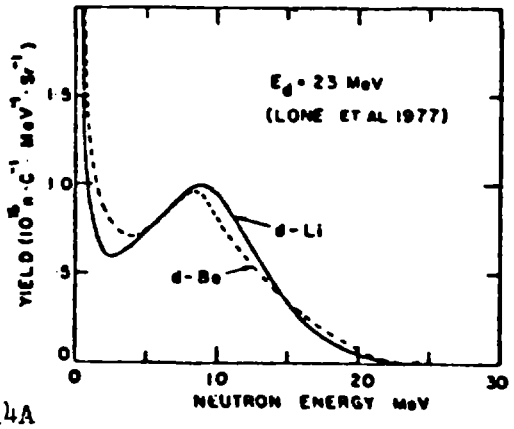
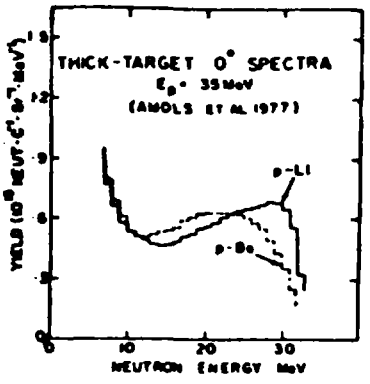


Fig. 14A
Comparison of 0° neutron spectra produced by deuterons on thick Li and Be targets.



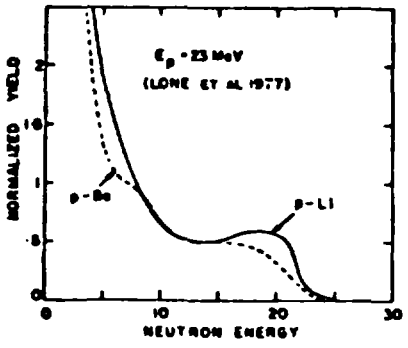


Fig. 15
Comparison of 0° neutron spectra produced by protons on thick Li and Be targets.

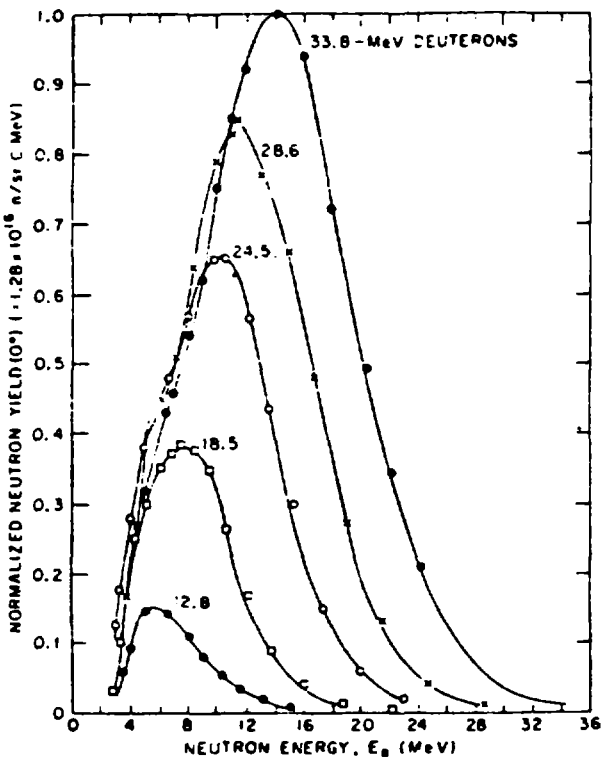


Fig. 14B
Neutron Yields from Deuterons
Incident on Thick Li Target

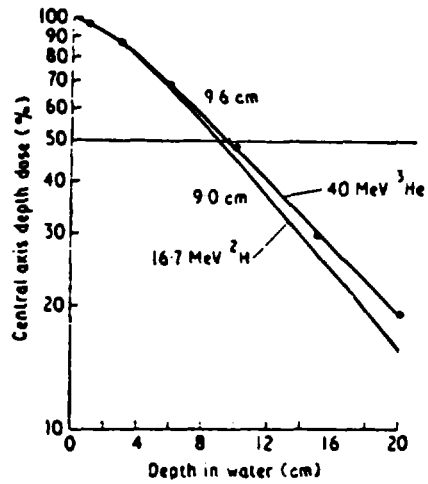


Fig. 16 Comparison of fast neutron central axis depth doses for neutrons produced by bombarding a 150 mg cm^{-2} beryllium target with 40 MeV ^{3}He or 16·7 MeV deuterons.

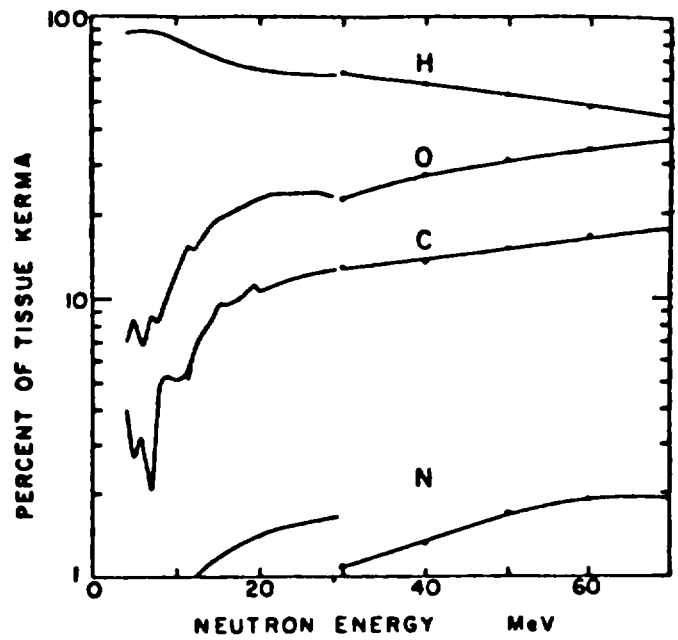


Fig. 17
Percent of tissue kerma for the 4 major elements in tissue. For energies below 30 MeV values are derived from Caswell et al, 1977; at higher energies from Alsmiller and Barish, 1976.

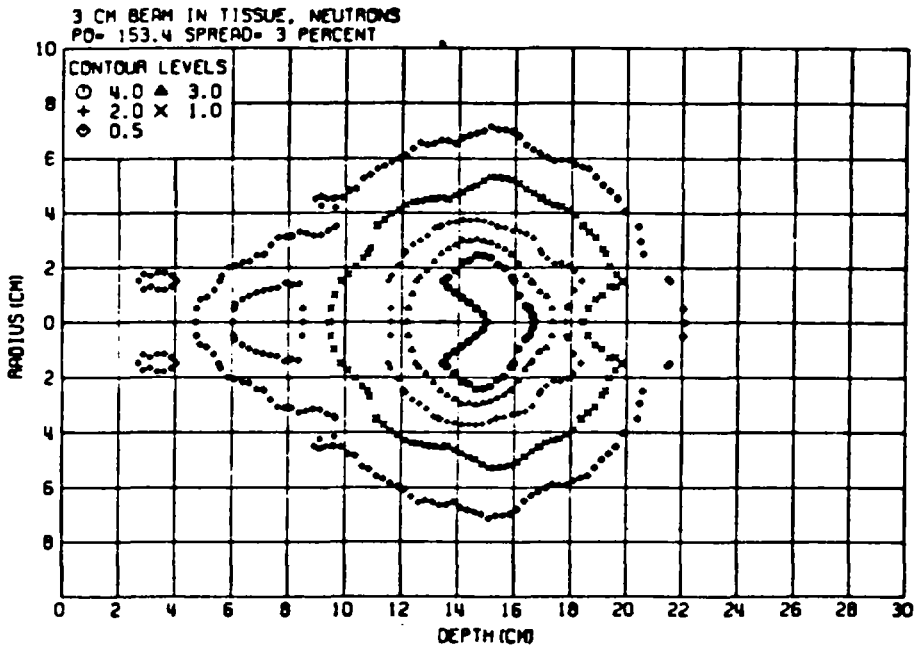


Fig. 18 Isodose contours from neutron interactions for the 3 cm beam with 3% spread. Contours are for 4, 3, 2, 1, and 0.5 Rad, compared with a peak total dose of 100 Rad. Waviness of low-dose contours is due to statistical fluctuations, as explained in text.