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TITLE: THE POSSIBLE USE OF A SPALLATION NEUTRON SOURCE FOR NEUTRON CAPTURE THERAPY WITH EPITHERMAL NEUTRONS

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The possible use of a spallation neutron source for neutron capture therapy with epithermal neutrons

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Abstract

Spallation is induced in a heavy material by 72 MeV protons. The hereby produced neutrons with essentially an evaporation spectrum with a peak energy of less than 2 MeV are moderated in two steps, first in iron, and then in carbon. Results from neutron fluence measurements in a perspex phantom placed close to the moderator are presented. Monte Carlo calculations of neutron fluence in a water phantom are also presented under some chosen configurations of spallation source and moderator. The calculations and measuremants show a good agreement and also show that useful thermal neutron fluences are attainable in the depth of the brain, at proton currents of less than 0.5 mA.

Introduction

The eventual aim of the present joint Swedish-Swiss project is to construct an accelerator-based intermediate energy neutron source that would permit irradiation of neoplasms in the central nervous system by an intermediate energy neutron fluence rate of at least 10^9 n cm^{-2} s^{-1}. The accelerator should be of a moderate size to permit accomodation in a hospital environment. Therefore the rather low proton energy of 72 MeV was chosen

The clinical interests beyond this collaboration are primarily focused on the treatment of vascular malformations in the central nervous system. In a longer perspective, the treatment of malignant brain tumours is given priority over other malignancies considered, such as melanomas and colorectal carcinomas.

The work on the project has so far been devoted to studies of different moderator materials and configurations useful for combination with neutron production by 72 MeV protons stopped in heavy materials.(Ref.1) The aim is to optimize the performance of a neutron source for NCT. The required characteristics are firstly that the bulk of the neutrons should have an energy between 1 and 100 keV, and secondly that the useful intensity of thermal neutrons should be at least 10^{12} n cm^{-2} h^{-1}.

Experimental results

The iron and graphite moderator option was studied experimentally at the 72 MeV injector I cyclotron at PSI August 29 to September 2, 1988. The neutrons were produced by stopping the 72 MeV protons in a tungsten block. The moderator consisted of an iron block, approximately 50 cm by 60 cm by 60 cm. On one side it was covered with 13 cm of graphite. (See Fig. 1)

The neutron field in two plastic phantoms (20 cm by 20 cm by 20 cm) was probed with different foil detectors: gold activation with and without Cd-shielding to measure the thermal neutron flux, and by plastic proton recoil track detectors (neutrak 144, Landauer Inc, see reference 2) to measure neutrons with energies above 144 keV.

The results from the gold activation foils are presented in table I and compared with Monte Carlo calculated values. It is seen that there is a fair agreement. The values are normalised to an integrated proton current to the target of 1 mC, which corresponds to the experimental conditions.

Table I

Results from gold foil measurements:

Phantom I, 34 cm iron

depth in phantom (cm)	thermal neutron flux (10^{10} cm^{-2}/mC)	
	MCNP	gold foil activation
0	3.36	-
2	16.6	12.4
5	17.2	13.1
10	6.8	5.13

Phantom II, 25 cm iron + 13 cm carbon (graphite)

depth in phantom (cm)	thermal neutron flux (10^{10} cm^{-2}/mC)	
	MCNP	gold foil activation
0	10.1	-
2	15	13.2
5	9.6	8.8
10	2.3	3.2

The results from the proton recoil track detector measurements are given in table II together with calculated values. As in table I the values are normalised to an integrated proton current of 1 mC. An upper limit for a meaningful readout of these detectors is 5.7 10^5 tracks cm^{-2}, so that some detectors received an overdose. The calculated neutron flux values were converted to detector track density using values for detector sensitivity as a function of neutron energy given in ref. 2. It is seen that the agreement is within a factor of two. The deviation can be due to uncertainties in the calculation of the neutron spectrum, uncertainties in the detector sensitivity values, and to a directional dependence of the detectors.

Table II

Results from track detector measurements:

Phantom I, 34 cm iron

depth in phantom (cm)	track density (10^5 cm^{-2}/mC)	
	MCNP	neutrak 144
2	80	>5.7
5	20	>5.7
10	3.5	1.6
15	1.1	0.59

Phantom II, 25 cm iron + 13 cm carbon (graphite)

depth in phantom (cm)	track density (10^5 cm^{-2}/mC)	
	MCNP	neutrak 144
2	13	>5.7
5	4.0	2.0
10	0.7	1.1
15		0.39

In table III the results from a measurement of neutrons of energy above 10 MeV is shown. It was made with a NE 213 liquid scintillator with pulse shape discrimination of gamma pulses. The detector was placed at a distance of 200 cm from the iron moderator, perpendicularly to the beam direction, on the side with no carbon. The results are given per coulomb of integrated proton current to the target.

Also shown are Monte Carlo calculated values at different distances from the moderator. The agreement at 200 cm is nearly within a factor af two, which is reasonable considering the possible sources of error: uncertainties in the setting of the detector threshold, uncertainties in the source spectrum, and uncertainties in the calculation of the detector efficiency. The calculated flux of neutrons above 10 MeV at the surface of the moderator corresponds to a dose of 8 Gy/C at a depth of 5 cm in a plastic phantom. Compared to the calculated dose under the experimental conditions from all epithermal and fast neutrons which is 210 Gy/C, it is a small correction. Although the fast neutrons are less effectively stopped by adding more moderating material, this result indicates that even in a more realistic design the dominating background neutron dose will be given by neutrons below 10 MeV.

Table III

Results from liquid scintillator measurements
of neutrons with energy above 10 MeV:

distance from iron moderator (cm)	neutron flux (cm-2/C)	
	calculated	NE 213
0	$1.25\ 10^{11}$	-
200	$4.4\ 10^{9}$	$1.6\ 10^{9}$

Results of Monte Carlo calculations

For the Monte Carlo calculations presented here the well known code MCNP (ref 2) was used. The neutron source was an evaporation source, i.e. the neutron spectrum is given by

$$\Delta N/\Delta E = C\ E\ \exp(-E/E_0),$$

where $E_0 = 1.29$ MeV.
This was shown to be a valid approximation for neutron energies below 10 MeV by comparision with calculations of the source neutron spectrum made with the code HETC (cf ref 3), from which the neutron yield was also computed.Neutrons of energies above 10 MeV were not taken into account because of limitations in the cross section libraries of MCNP. However, as discussed above neutrons above 10 MeV are not expected to give a major contribution to the background dose.

The neutron transport calculations were made for spherical iron moderators of three diameters: 50 cm, 100 cm and 150 cm.They were covered with 15 cm of graphite. Both the iron and the carbon contained 1 percent boron-10 to suppress the thermal neutron flux at the phantom surface. The arrangement of the moderators and the phantoms is shown in Fig 2. The spherical head phantoms were filled with water containing 1.84% nitrogen, see table IV. The results are given in fig 3 to 5.

It is seen that useful intensities of thermal neutrons can be obtained in the depth of the phantom at proton currents of less than 0.5 mA and that the fast neutron contribution is small if the iron moderator is thick enough. It is also clear that the useful depth is increasing with moderator thickness. However, the background dose is underestimated, as the gamma dose component is not included.This component will be calculated as a part of the continued project. The RBE-values used were 1.6 for fast neutrons and nitrogen capture, and 2.3 for boron-10 capture.These values are chosen to facilitate comparisions with results of others, and might not prove to be the best to use.

Table IV

Composition of head phantom.
Density: 1 g /cm3
Composition: H_2O with 1.84 percent N.
Fractional composition by weight:

H	0.109
O	0.872
N	0.0184

Conclusion

It is shown that a spallation neutron source is a realistic option when the construction of an accelerator based neutron source of a reasonable size and cost is to be considered. The next step of this work will be the construction of a full scale prototype source where radiobiological as well as radiophysical studies can be made. Special attention must be payed to the cooling and maintenance of the target, where several kilowatts of heat will be produced.

References

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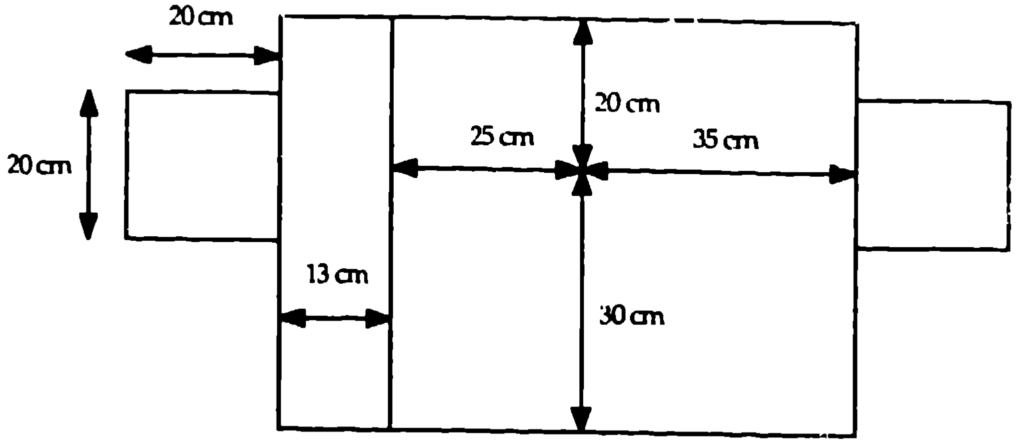
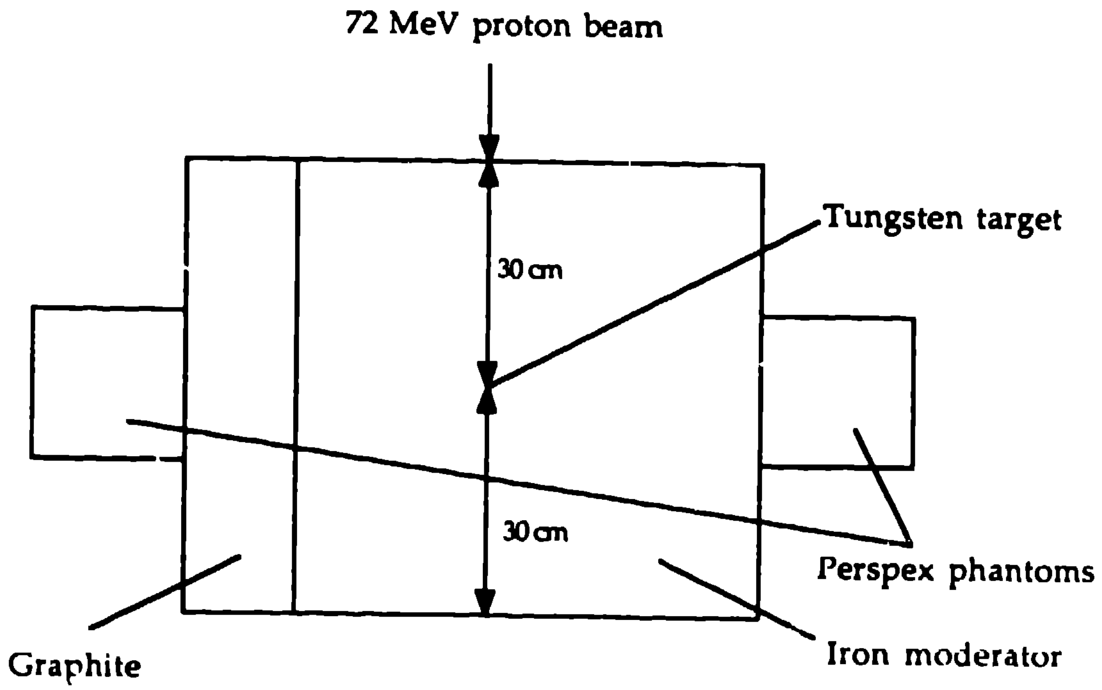
2. E.V.Benton et al, Health Physics, 40(1981)801-809

3. J. F. Briesmeister, (ed.), MCNP- a general Monte Carlo code for neutron and photon transport, Los Alamos National Laboratory, Los Alamos, 1986.



Front view



Top view

Fig 1. The moderator and phantom arrangement used for the experiments at PSI 1988.

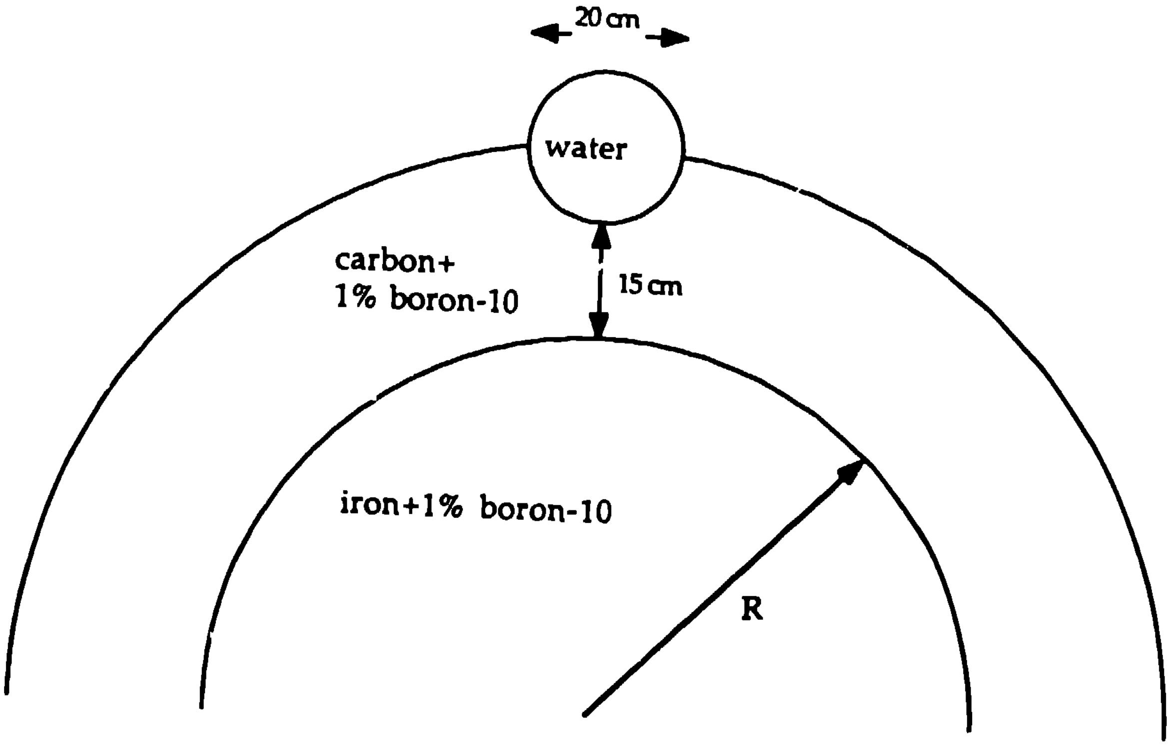


Fig 2. Moderator and head phantom arrangement used in the Monte Carlo calculations. R = 25, 50, or 75 cm.

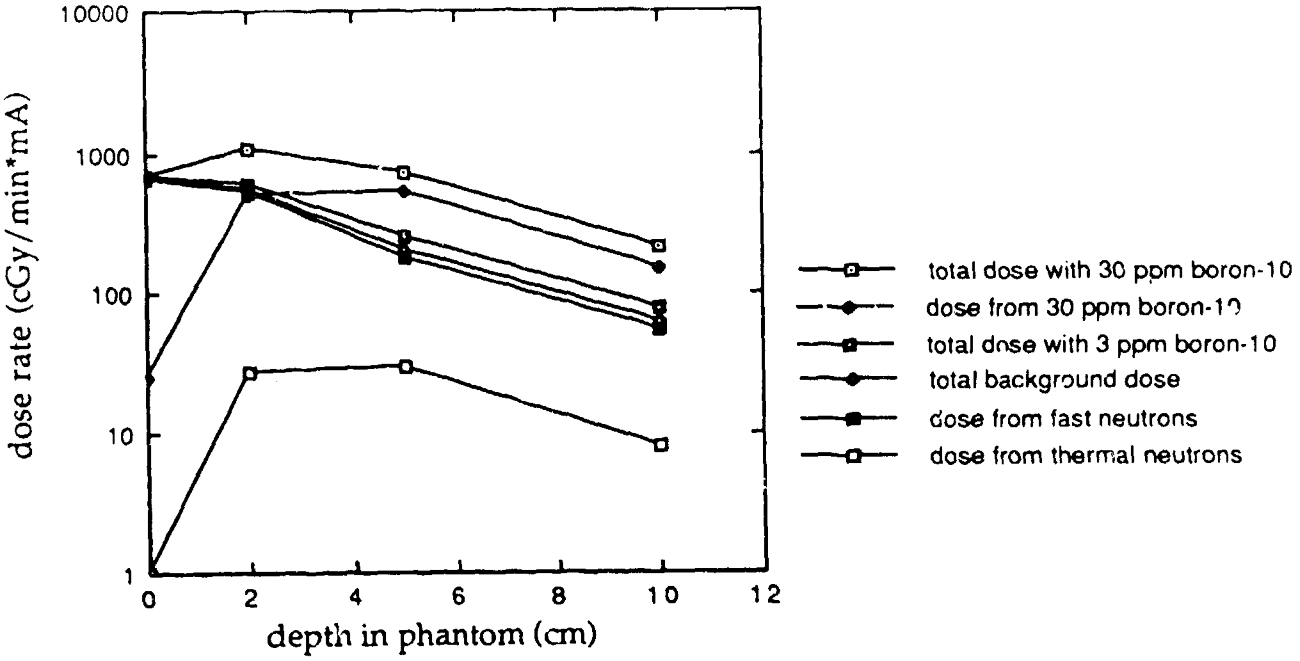


Fig 3a. Monte Carlo calculated depth dose curves in a head phantom, close to a 50 cm diameter iron moderator with 15 cm graphite.

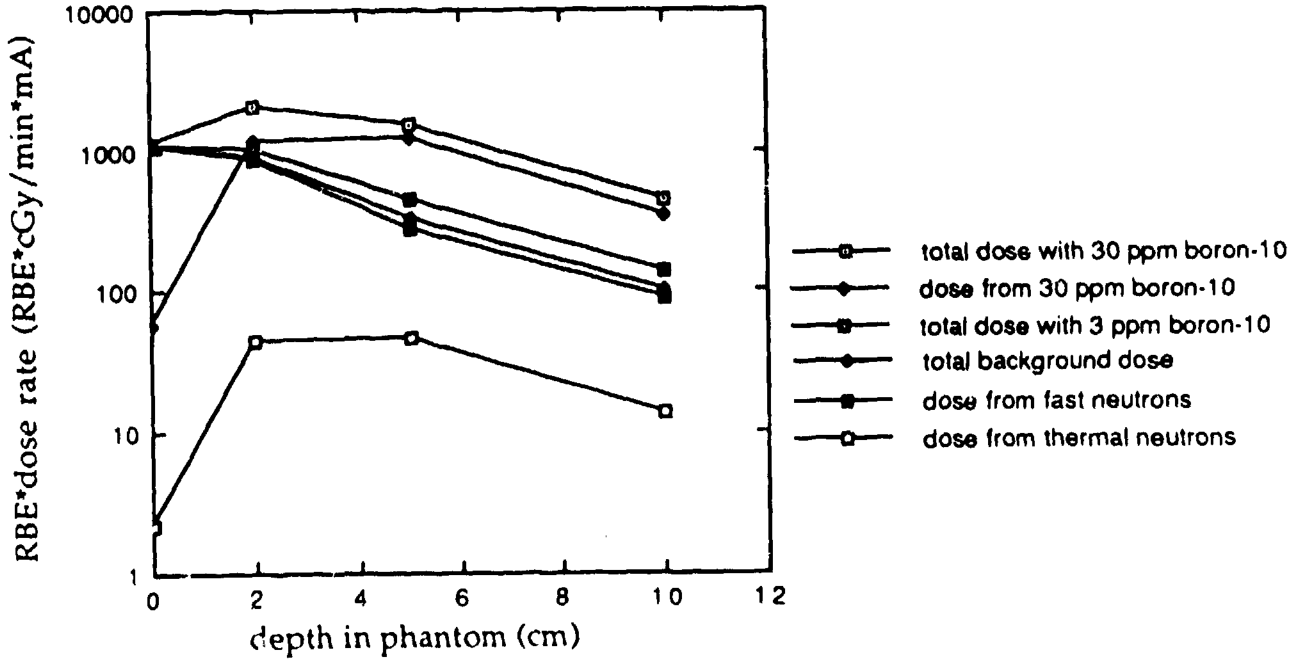


Fig 3b. RBE times depth dose, (RBE=2.3 for boron capture, and 1.6 for other neutron reactions). Moderator as in 3a.

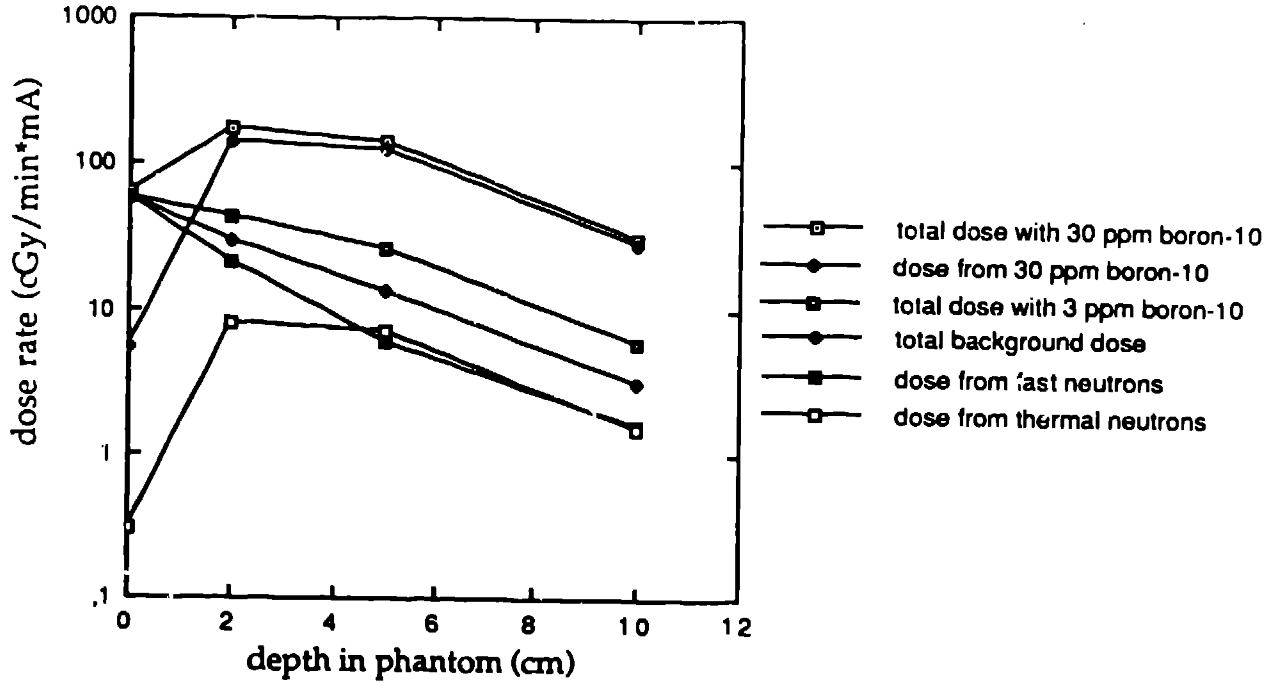


Fig 4a. Monte Carlo calculated depth dose curves in a head phantom, close to a 100 cm diameter iron moderator with 15 cm graphite.

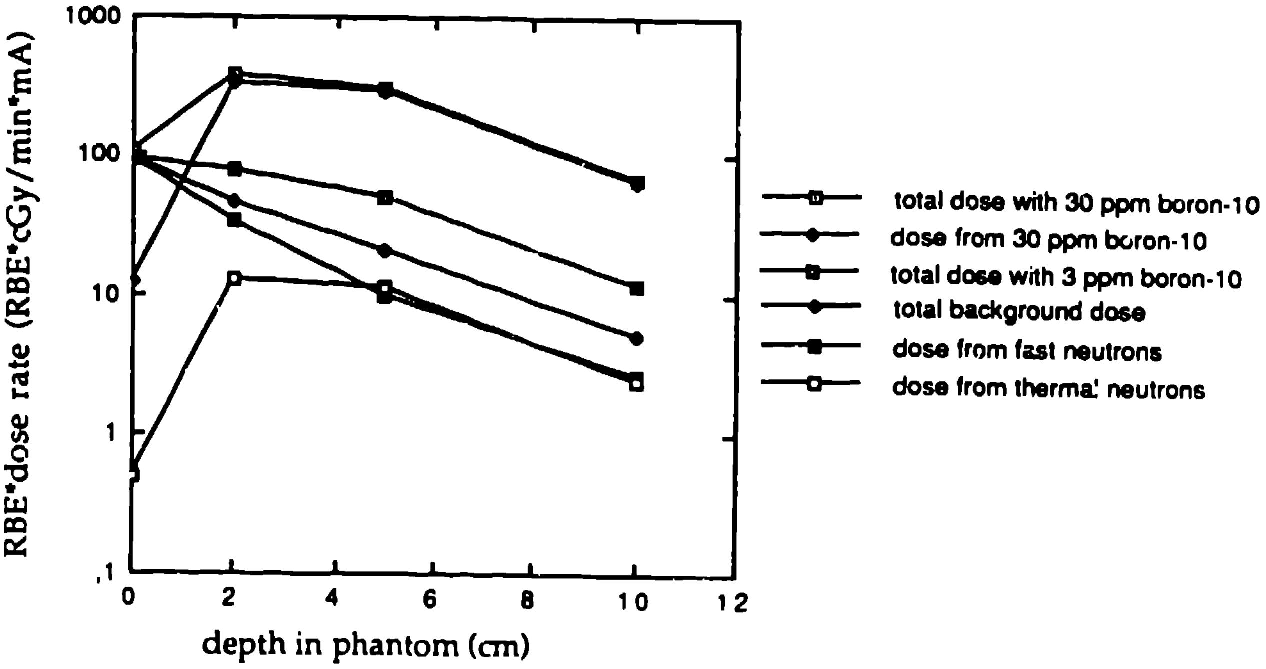


Fig 4b. RBE times depth dose, (RBE=2.3 for boron capture, and 1.6 for other neutron reactions). Moderator as in 4a.

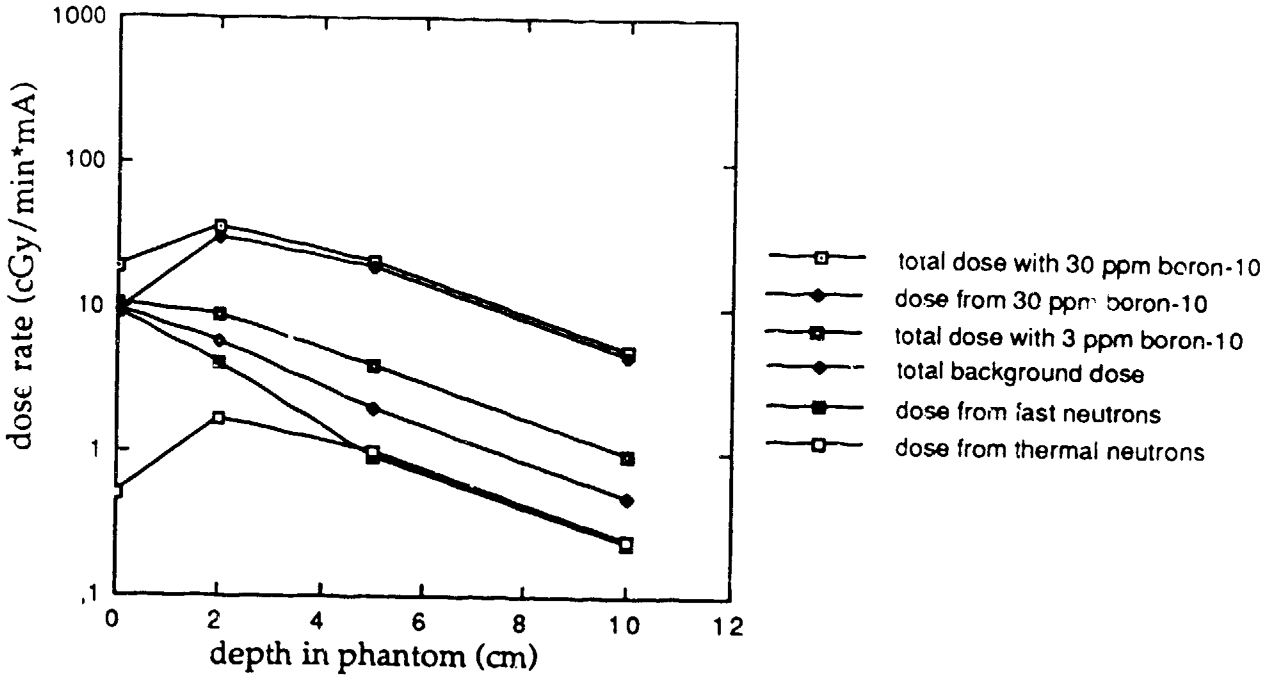


Fig 5a. Monte Carlo calculated depth dose curves in a head phantom, close to a 150 cm diameter iron moderator with 15 cm graphite.

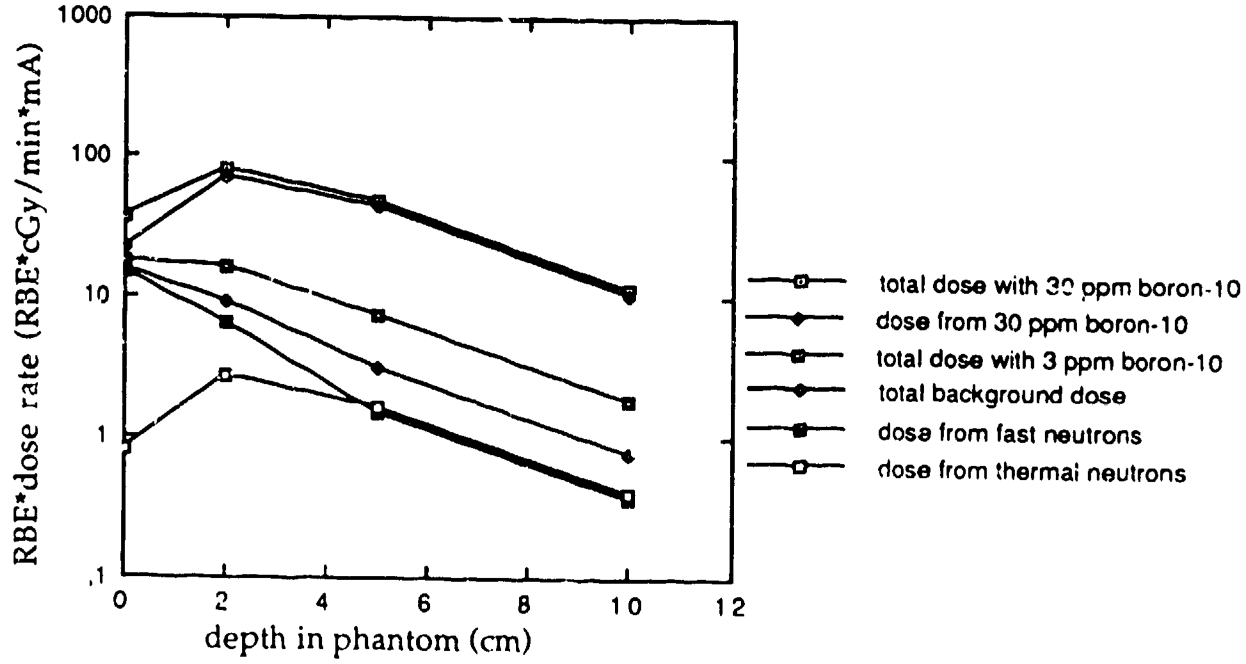


Fig 5b. RBE times depth dose, (RBE=2.3 for boron capture, and 1.6 for other neutron reactions). Moderator as in 5a.