Annex 2
REACTOR AND BEAM DESIGN CONSIDERATIONS

BNCT facility at the RA-6 reactor

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Abstract. The RA-6 is an open pool MTR type reactor with 500 Kw nominal power, using fuel elements enriched to 90 %. It was designed and constructed fully in Argentina and is owned and operated by the C.N.E.A. at the Bariloche Atomic Center. In this work the analysis of the different alternatives, depending on the main features of a research reactor (type, power, shielding, etc.) , are showed to design a BNCT facility. After that, the different steps followed to produce the epithermal beam at the RA-6 are presented:

- Because only small modifications were required, the first stage was the arrangement of a thermal beam to test and validate our calculation methods and to gain expertise in the different experimental techniques to design and characterise the epithermal facility.
- A basic design of the epithermal device was performed, analysing different and relative sizes of the materials conforming the neutron filter to optimise the neutron spectrum and the absolute value of the epithermal flux at the beam port. This design was used also to make preliminary studies regarding the nuclear safety and solve potential licensing problems.
- A complete design of the internal filter was presented to the Regulatory Authority and after some feedback the filter was constructed and mounted. During this stage a very simple (without any geometry complexity) external port was used to test the free beam facility and to get a complete on phantom dosimetry .
- Using the previous results the new beam port was designed, built and mounted by November 1998, the final characterisation of the facility is being currently performed.

Preliminary results of this job for the free beam are:
$\phi_{\text{epithermal}} = 1.1\text{ E9 n / cm}^2\text{ seg}$ ($0.5\text{ eV} < E < 10\text{ KeV}$)
$D_{\text{fast}} / n_{\text{epi}} = 7.5\text{ cGy cm}^2 / n_{\text{epi}}$
$D\gamma / n_{\text{epi}} = 3.0\text{ cGy cm}^2 / n_{\text{epi}}5.$
The next goal will be to optimise the irradiation room to adequate the facility to irradiate patients.

Introduction

The RA-6 reactor located at Bariloche Atomic Center, is a pool type one with 500 kW of nominal power and U 90 % enriched fuel owned and operated by C.N.E.A.. It is mainly devoted to research, development and teaching activities. It has five neutron irradiation beam channels and a thermal column (removed).

Due to its small power and a suitable operation schedule (usually one single experience each time) the alternative selected for getting an epithermal irradiation facility was to approach, as close as possible, to the reactor core by removing the external thermal column; instead of using one of the irradiation tubes. In order to fulfil this criteria no shutter system was considered in the design. The reactor shutdown is used as the shutter.

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The epithermal beam facility was then designed [1] and built replacing the old thermal column (internal and external). Figure 1 shows a plant view of the complete facility including the material composition of the neutron filter, the port and the external shield.

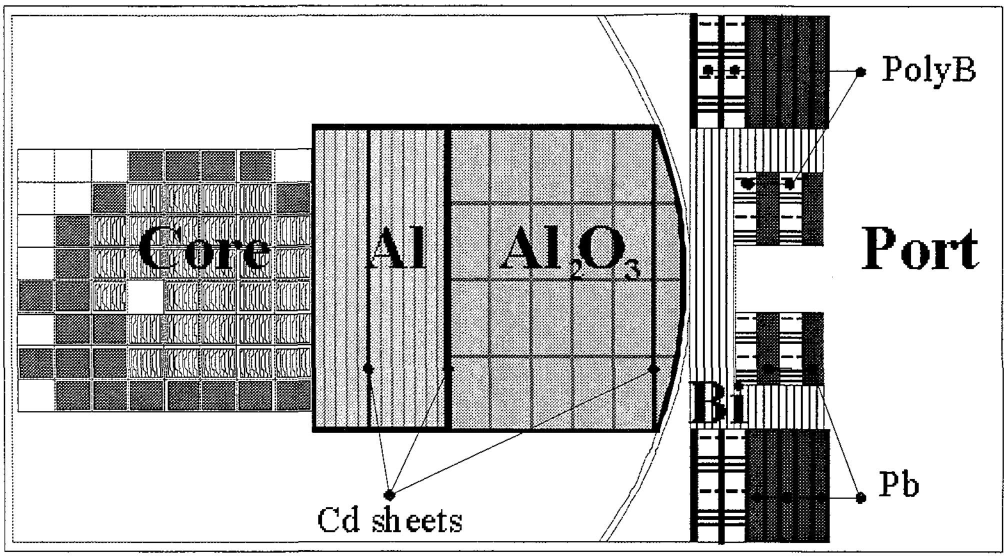

FIG. 1. Plant view of the epithermal facility.y

1. FREE BEAM MEASUREMENTS AND SPECTRUM ADJUSTMENT

1.1. Monte Carlo simulation

The main features of the calculation process were:

- Coupled neutron-gamma calculation with MCNP4B [2] and cross sections based on ENDFB6 data library.
- Point detector tallies at the beam centre and at several positions near the external shielding (for neutrons and photons).
- A detailed neutron and photon source in the core was obtained through a KCODE calculation.
- Neutron spectrum in 29 energy groups was calculated at the beam centre (2 thermal / 15 epithermal / 12 fast).
- Photon doses were calculated by using the ICRP-21 flux-to-dose rate conversion factors. The calculated photon doses rate at the beam centre agree within 20 % with the measured ones.

1.2. Neutron and gamma characterization

Multiple activation detectors (Diluted, 0.1 mm, bare and Cd covered foils of Mn, Au, Cu, In and pure, 0.127 mm, Cd covered foils of Sc, Ag, In), with different energy response, were irradiated at the beam center, and the induced activities were measured by gamma spectroscopy for neutron energy characterisation. The gamma dose rate was measured at the beam centre, with TLD's 700 and paired ionisation chambers.

1.3. Spectrum adjustment

Figure 2 shows the calculated and adjusted neutron flux at the beam centre. Measured activities and calculated spectrum were adjusted with the NMF-90 package [3]. Some of the results and remarks were:

- The IRDF-90/NMG-G was upgraded, including self-shielded data for pure epithermal reactions.
- Group input uncertainties were evaluated conservatively, regarding their statistical errors, and the group to group correlation were assumed exponential on a lethargy exponential scale. Reaction rate uncertainties were lower than 10 % and actual correlation were considered and evaluated.

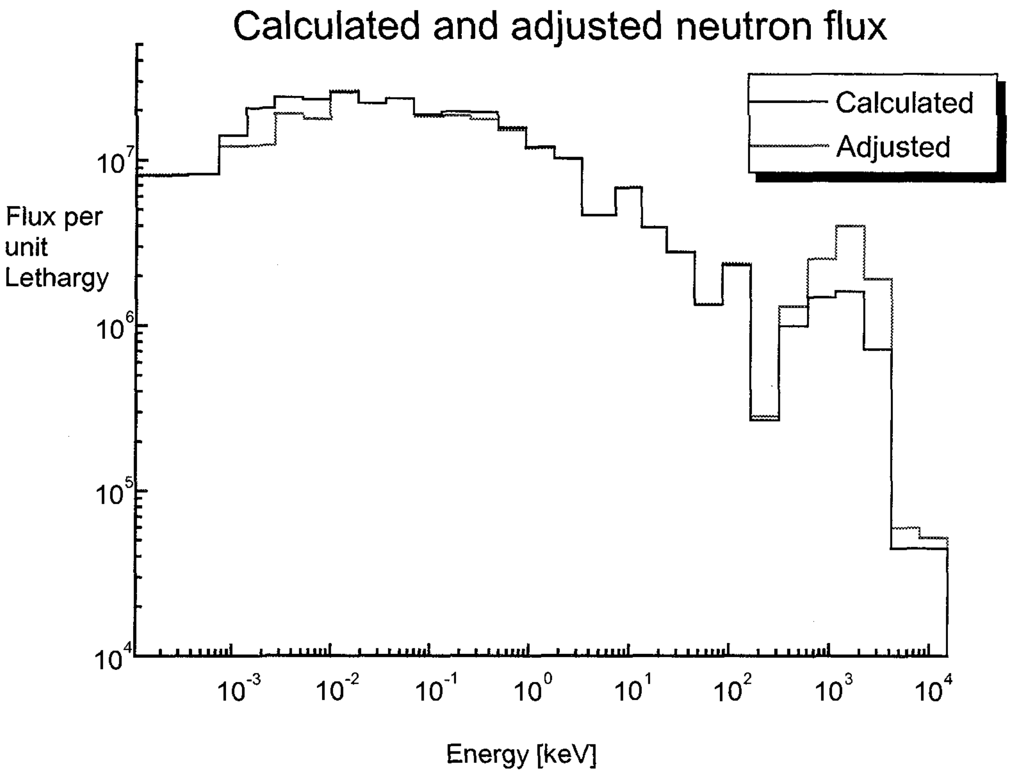

FIG. 2 Calculated and adjusted neutron flux.

A reasonable value (1.3) for χ^2 /N resulted from the adjustment.
— Large (~ 2) adjustment factors resulted in few groups of the fast energy region.
— Sensitivity analysis was performed but integrated flux values remained between their estimated errors.

1.4. Free Beam Parameters

The free beam parameters evaluated from the adjusted spectrum and group calculated KERMA factors are showed in the Table I:

Table I. Free Beam Parameters

Epithermal flux (0.5 ev — 10	$(0.32 \pm 9\ \%)\ 10^9$ n/ cm^2 seg
Fast neutron dose (> 10 kev)/ n_{epi}	$(11.3 \pm 16\ \%)\ 10^{-13}$ Gy/ n cm^2
photon dose / n_{epi}	$(7.5 \pm 13\ \%)\ 10^{-13}$ Gy/ n cm^2
thermal flux (< 0.5 ev) / n_{epi}	$0.07 \pm 22\ \%$

2. IN PHANTOM MEASUREMENTS

To make these measurements we used a 17.3 cm diameter and 20.5 cm long cylindrical water phantom. The gamma dose and the fast neutron dose rates inside the phantom were evaluated using the paired ionisation chambers method [4]. The thermal neutron flux was measured using bare and Cd covered gold foils. The N^{14} and B^{10} dose rates were calculated through the measured thermal neutron flux (0–0.45 eV) and the corresponding KERMA factor. Boron concentrations of 30 ppm in tumour and 8.6 ppm (1–3.5 tumour to healthy tissue ratio) in healthy tissue and Nitrogen concentration of 1.8% (in brain) were used. Figure 3 shows the absorbed dose in the center axis of the phantom.

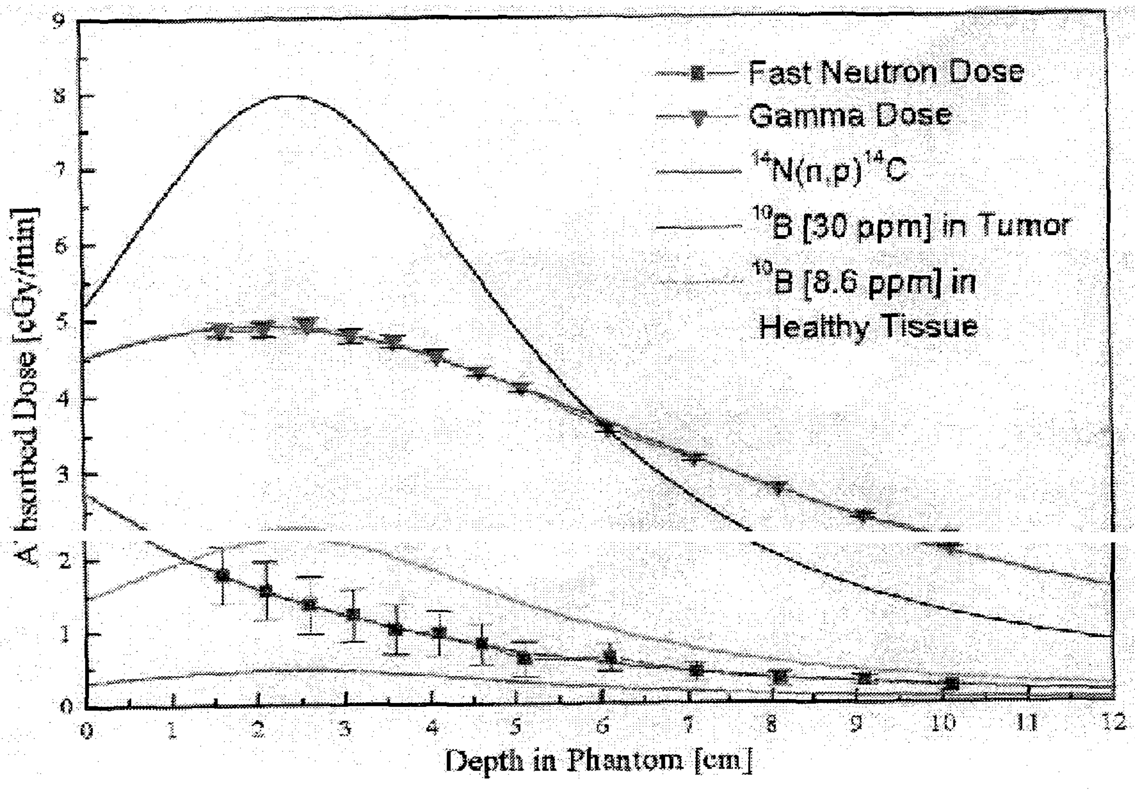

FIG 3. Absorbed dose in phantom.

The estimated uncertainties for gamma and fast neutron dose at 3 cm depth in phantom are showed in Table II:

Table II. Uncertainties For Photon And Fast Neutron Dose In Phantom

Source	Uncertainty in photon dose (%)	Uncertainty in fast neutron dose (%)
Electrometer	1	1.5
Calibration of Graphite chamber	1	3.5
Calibration of TE chamber	0.1	4.5
Relative sensitivity of Graphite	2.5	6
Relative sensitivity of TE chamber	0.1	5
Thermal response of Graphite	1.5	5
Thermal response of TE chamber	0.2	22
Positioning of chambers	1.3	2.6
Reactor power	1	1
Displacement correction factor	0.5	0.5
Thermal flux	0.5	4
Total uncertainty	**4**	**24**

The most relevant contribution to the fast neutron dose uncertainty is due to the uncertainty in the thermal response of the tissue equivalent chamber. The uncertainty in this parameter is assumed to be about 50%; around a mean value between reported values for the same kind of chamber, [4] and our own roughly estimated one: 9.0E-20 C/min/ncm^{2}s. For the Graphite chamber a reported value [4] for an identical chamber was used: 1.45E-20 C/min/n/cm^{2}s.

Considering as RBE factors for gamma dose, fast neutron dose, N^{14} dose and B^{10} dose 1, 3.2,3.2 and 3.8 [5] respectively, and 1.3 for B^{10} in healthy tissue; the beam quality factors are: AD = 6.8 cm; AR = 2.8 and ADDR = 16.25 cGy/min. Figure 4 shows the RBE dose in the center axis of the phantom.

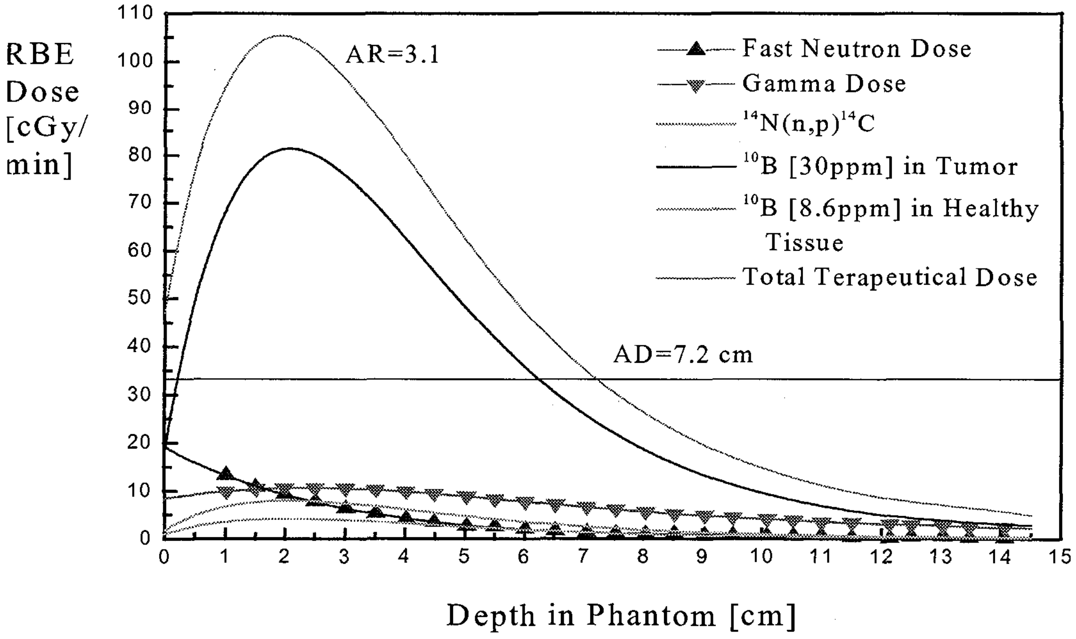

FIG 4. RBE dose in phantom.

3. BEAM OPTIMIZATION AND CHARACTERIZATION

During November 1998 the cylindrical port was replaced by a new one as showed in Figure 5; and characterised following a similar procedure than with the previous beam.

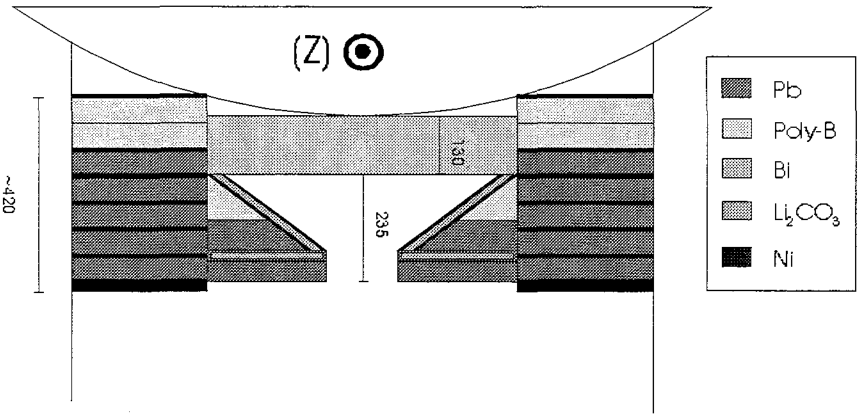

FIG 5. Conical port.

Free beam parameters preliminary evaluated with gold foils and paired ionisation chambers are given in Table III.

Related absorbed and RBE doses in phantom, measured as indicated in the previous section are showed in Figures 6 and 7.

Table III. Free Beam Parameters For The Conical Port

Epithermal flux (0.5 ev — 10	$1.1 * 10^9$ n/ cm^2 seg
Fast neutron dose (> 10 kev)/ n$_{epi}$	$7.5 * 10^{-13}$ Gy/ n cm^2
photon dose / n$_{epi}$	$3.0 * 10^{-13}$ Gy/ n cm^2
thermal flux (< 0.5 ev) / n$_{epi}$	0.03

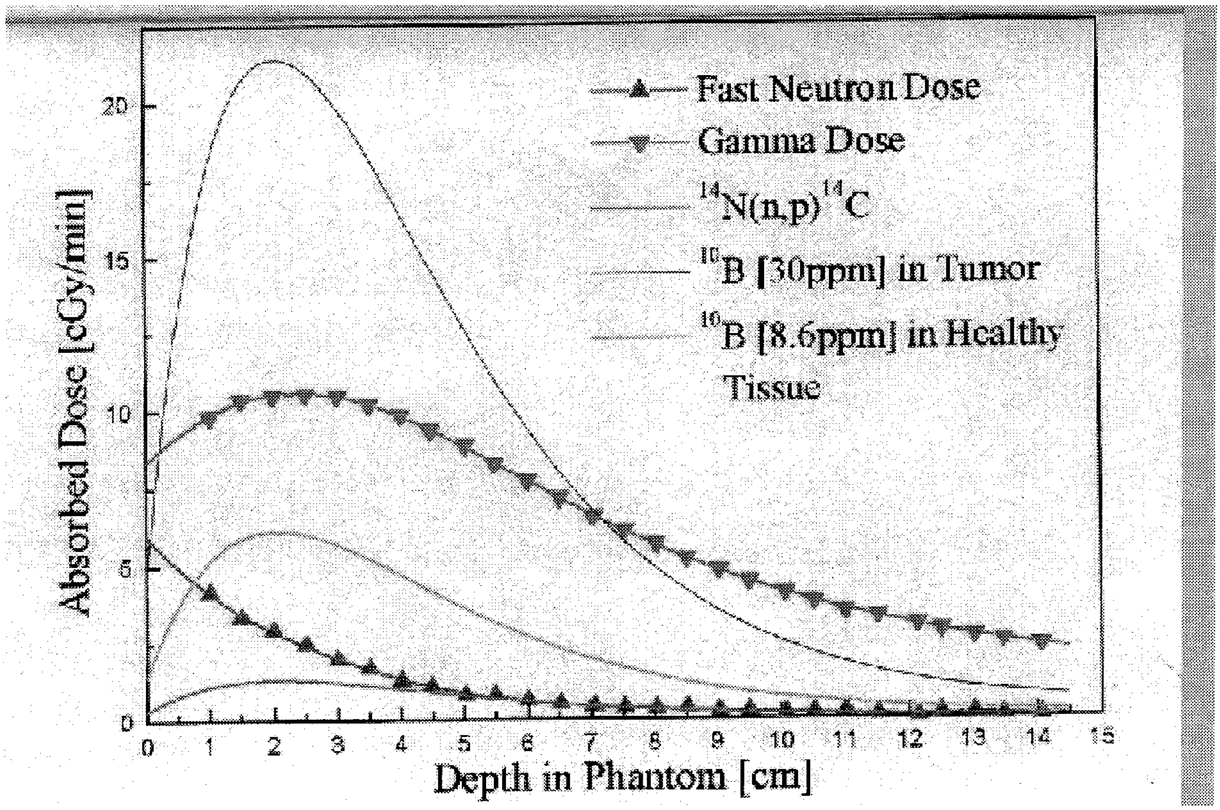

FIG 6. Absorbed dose in phantom for the conical port.

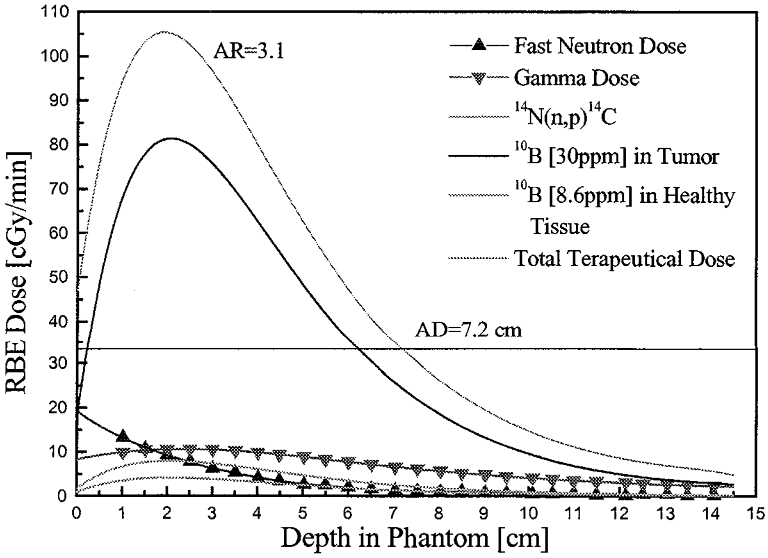

FIG. 7. RBE dose in phantom for the conical port.

The beam quality factors for the optimized beam are: AD=7.2 cm; AR=3.1 and ADDR = 33.3 cGy/min. With this new configuration, a significant increase in the ADDR has been reached, together with a small improvement in AD and AR.

Due to the associated increase in the thermal flux within the phantom, fast neutron dosimetry is, in this new configuration, strongly affected by the thermal response of the TE ionisation chamber. Figure 8 shows relative change in gamma and neutron dose rate due to relative change in thermal response of the TE chamber (K_T) and the Graphite chamber (K_C); considered as independent parameters, for a thermal flux of 1.0E9 n/cm^{2}s.

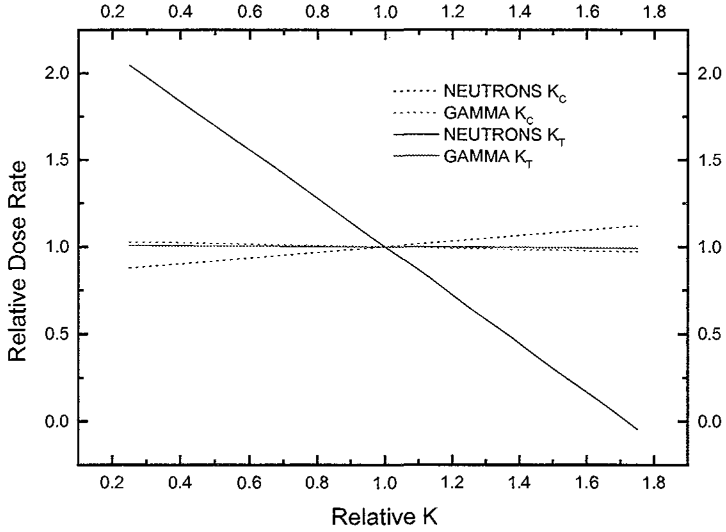

FIG. 8. Relative dose rate vs. relative change in the thermal neutron sensitivity for both chambers at a thermal flux of 1.0 E9 n/cm^{2}s, using as reference values of K_{TE}=9E-20 C/min/n/cm^{2}s and K_C=1.5E-20 C/min/n/cm^{2}s.

K_C has nearly negligible influence on both dose rates; but neutrons dose rate changes approximately 75% due to a 50% change in K_{TE}. This parameter should then be determined in a more precisely way.

In order to achieve the possibility of lateral irradiation, assuming a distance of 10 cm between the beam port and patient's head, the beam quality was also evaluated by in phantom measurement at 10 cm of the beam exit surface. Results are showed in Figure 9.

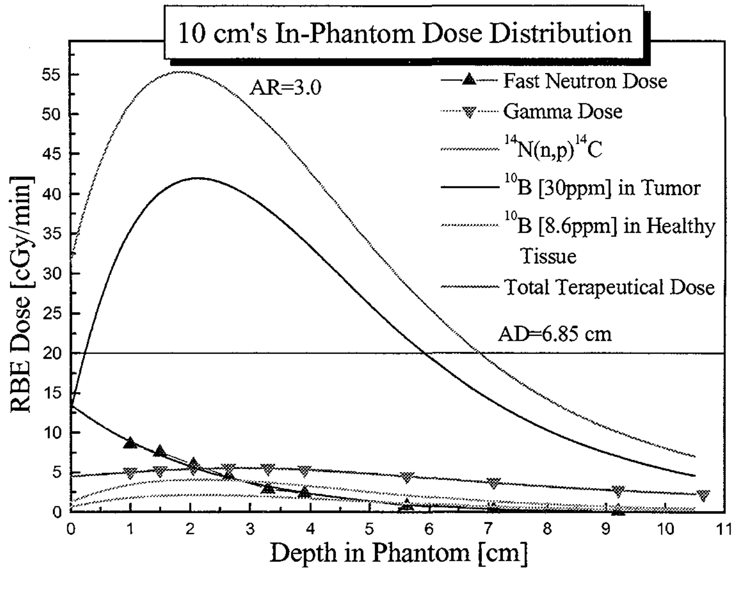

FIG. 9. In phantom RBE doses at 10 cm from beam exit surface.

The most relevant modification observed in the beam quality parameters, at 10 cm from the beam port surface is the reduction in the ADDR from 33.3 cGy/min to 20.5 cGy/min. Another alternative which is being studied is a non symmetric port as is showed in Figure 10.

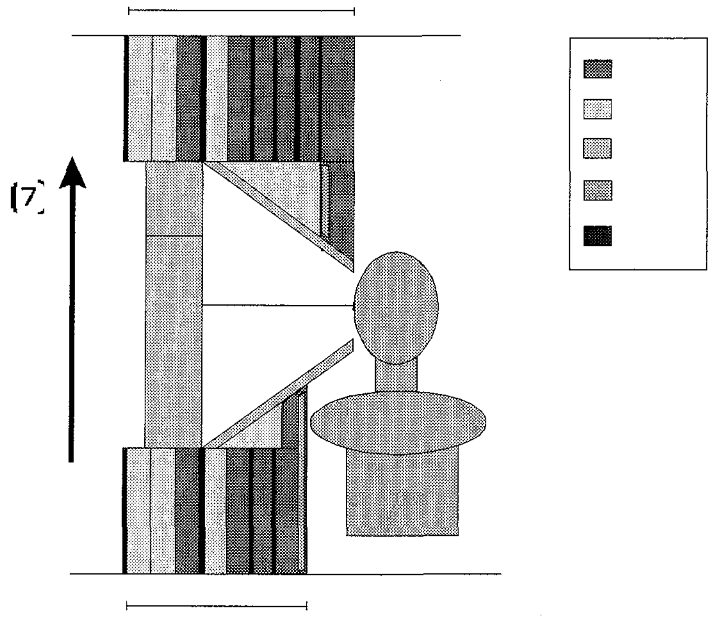

FIG. 10. Port's proposed design for lateral irradiation situation.

4. IRRADIATION ROOM

Irradiation room plant is showed in Figure 11.

An internal borated polyethylene shielding of 10 cm thickness was chosen, together with an external shielding of 50 cm thickness of concrete.

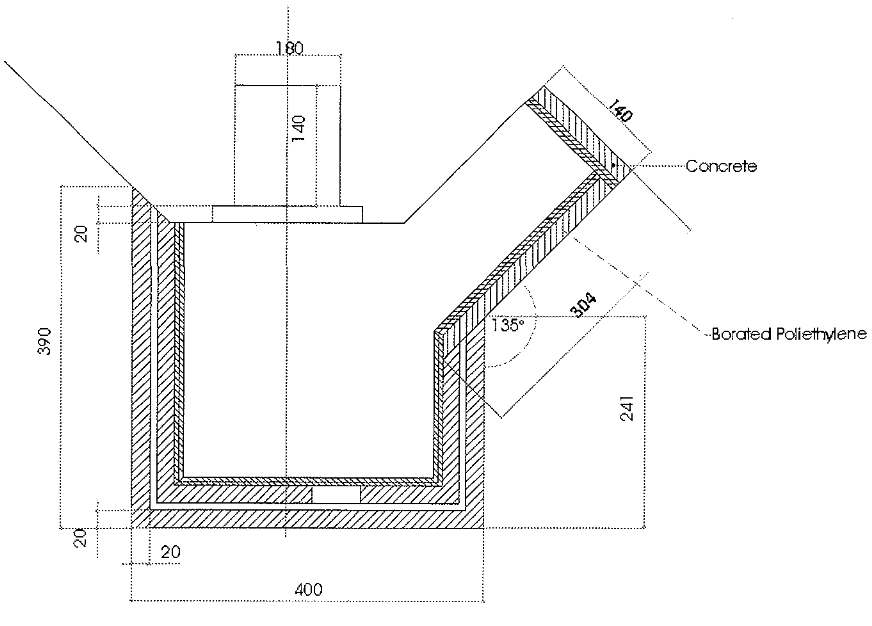

FIG. 11. Irradiation room.

REFERENCES

[1] BUSTOS, D., CALZETTA LARRIEU, O., BLAUMANN, H.,.. Epithermal beam in the RA-6 reactor. In: Larsson B, Crawford J, Weinreich R (eds) Advances in Neutron Capture Therapy. Volume 1, Medicine and Physics. Amsterdam: Elsevier Science, 1997; 420–423.

[2] BRIESMEISTER, J.F. (ed). MCNP-A General Monte Carlo N-Particle Transport Code, Version 4B

[3] LA-12625-M, UC705 and UC700, March 1997.

[4] KOCHEROV N.P.. Neutron Metrology File NMF-90. IAEA-NDS-171, January 1996.

[5] ROGUS, R., HARLING, O., YANCH, J., Mixed field dosimetry of epithermal neutron beams for boron neutron capture therapy at the MITR-II research reactor. Med. Phys. 21 (10), Oct. 94; 1611–1625.

[6] CAPALA J. et al. Radiation doses to brain under BNCT protocols at Brookhaven National Laboratory. In: Larsson B, Crawford J, Weinreich R (eds) Advances in Neutron Capture Therapy. Volume 1, Medicine and Physics. Amsterdam: Elsevier Science, 1997; 51–55.