A1－2

A Consideration about Neutron Irradiation Systems for Boron Neutron Capture Therapy using Accelerators and Research Reactors

Tooru Kobayashi, Yoshinori Sakurai and Kenichi Tanaka

Res. Reactor Insti., Kyoto Univ.

INTRODUCTION

The principle of boron neutron capture therapy (BNCT) was suggested by Locher in 1936. In 1951, the first BNCT clinical irradiation using thermal neutrons was tried at Brookhaven National Laboratory (BNL) in the USA. Until the 1961, 63 treatments were carried out at BNL and Massachusetts Institute of Technology (MIT). Unfortunately, the treatment results were not so good because of the problems of the ^{10}B compounds and the quality of the thermal neutron beams. In Japan, the fundamental study was started in 1959. The first clinical trial was performed at Hitachi Training Reactor (HTR) in 1968 and the better result was obtained. As of June 1999, 230 patients, 207 for brain tumors and 23 for melanomas, were treated mainly by thermal neutron irradiation in Japan. In 1994, the BNCT treatment in the USA was restarted with epi-thermal neutrons. The first BNCT trial in Europe was carried out using epi-thermal neutron beam at the Petten High Flux Reactor (HFR) in the Netherlands in 1997 and at the Finnish Research Reactor (FiR 1) in Finland in 1999. In the near future, the effectiveness and the limit of these reactor-based neutron sources for BNCT will be clarified.

Total irradiation dose in radiation therapy is decided mainly from (i) the minimum curable dose for the tumor part and (ii) the maximum acceptable dose for the normal part. In BNCT, the doses of ^{1}H(n,n)^{1}H reaction for epi-thermal and fast neutrons and ^{14}N(n,p)^{14}C reaction mainly for thermal neutrons are estimated as the unavoidable background doses for normal tissue. In the Kyoto University Research Reactor Institute (KURRI), we suppose that the physical absorbed dose from the ^{10}B(n, α)^{7}Li and ^{14}N(n,p)^{14}C reactions should be exceeded 15Gy at the deepest tumor part, and not exceeded 10Gy at any normal tissue for an effective BNCT. The thermal neutron fluence of 6.5×10^{12} n/cm^2 and 30 ppm ^{10}B concentration are needed for the dose of 15Gy.

For the neutron irradiation techniques, following characteristics are important in the current BNCT: (1) For tumors seated near the surface, low energy neutrons such as thermal and cold neutrons are effective. (2) For deep-seated tumors, high energy neutrons such as epi-thermal neutrons (0.5 eV-10 keV) are effective. In addition, (3) to increase the thermal neutron fluence at the deeper part, forward directional components of the incident neutron beam and larger field size are effective for all neutrons such as thermal, hyper-thermal and epi-thermal neutrons.

REACTOR-BASED NEUTRON IRRADIATION FACILITY FOR BNCT

Table 1 shows a list of the reactor-based neutron irradiation facilities for BNCT on active service. The neutron irradiations with several energy spectra, from thermal to epi-thermal neutrons, are applicable at Japanese facilities. In the while, the facilities is only for epi-thermal neutron irradiation in the other countries, because the under-surgery BNCT is not available. The ^{235}U fission reactions generate neutrons, whose energy is 2 MeV in average and a few 10 MeV in maximum. Thermal or epi-thermal neutrons are obtained by "proper" moderation and filtration using D_2O, Al, AlF_3, Al_2O_3, S, Ar and so on.

Figure 2 shows the outline of the KUR Heavy Water Neutron Irradiation Facility (HWNIF), which was remodeled at March 1996 mainly for the advance on BNCT. The epi-thermal neutron moderator, which consists of aluminum and D_2O (80%/20%), is added to the inside of the heavy water tank to adjust the neutron energy spectrum to enhance the epi-thermal neutron component. Using the D_2O spectrum shifters and the thermal neutron filters of cadmium and boral, the several neutron energy spectra from almost pure thermal neutrons to epi-thermal

Table 1. Reactor-based BNCT facilities on active service in the world (as of October 1998).

Country	Nuclear reactor	Power (MW)	Thermal neutron flux (10^9 n/cm^2/s)	Epi-thermal neutron flux (10^9 n/cm^2/s)	Fast neutron dose /epi-thermal neutron flux (10^{-11} cGycm^2/n)	Gamma-ray dose /epi-thermal neutron flux (10^{-11} cGycm^2/n)
Japan	KUR-M	5				
	(thermal)		0.9	0.009	0.05^{*1}	1.7^{*1}
	(mix)		1.8	0.37	1.6^{*1}	1.9^{*1}
	(epi-thermal)		-----	0.37	7.9	9.4
USA	BMRR	3	-----	0.84	4.8	2.0
	MITR-II	5	-----	0.22	12.5	14.0
Netherlands	HFR-Petten	45	-----	0.33	8.6	10.3

*1 For the thermal and the mix irradiation modes of the KUR-M, dose/thermal neutron flux.

neutrons are obtained. After the remodeling, fourteen BNCT irradiations, four for the thermal neutron irradiation and ten for the mix irradiation of thermal and epi-thermal neutrons, were already performed as of June 1999. Near future, epi-thermal neutron irradiation will be started. The Japan Atomic Energy Research Reactor 4 (JRR-4) was also remodeled at June 1998 according to the similar design concept as the KUR facility.

ACCELERATOR-BASED NEUTRON IRRADIATION FACILITY FOR BNCT

Accelerator-based neutron irradiation facility for BNCT has been studied mainly in the USA and EU since the beginning of 1980's. The Ohio State University (OSU), MIT, Idaho National Engineering and Environment Laboratory (INEEL), University of California, and University of

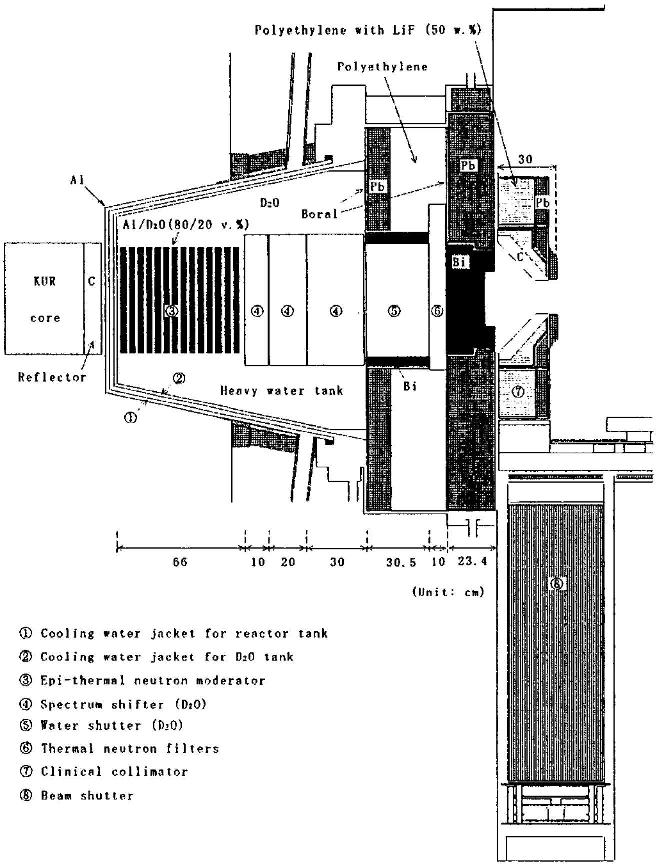

Figure 2. The KUR Heavy Water Neutron Irradiation Facility.

Table 2. Recommended reactions and particles for accelerator-based BNCT facilities.

Nuclear reaction	Q-value (MeV)	Threshold energy (MeV)	Accelerated particle	Accelerated energy (MeV)
^{7}Li(p,n)^{7}Be	-1.64	1.88	proton	~2.5
^{9}Be(p,n)^{9}B	-1.85	2.06	proton	~4
^{2}D(x,n)^{1}H x: bremsstrahlung from W target	-2.23	2.23	electron	~6

Birmingham are taking the initiative at present.

The design concept for the accelerator-based facility is fundamentally the same as that for the reactor-based facility. The "key" for the design of the accelerator-based facility is the selection of the target reaction, and accelerated particle energy. Table 2 shows the target part investigated for the BNCT. The ^{7}Li(p,n)^{7}Be reaction of 2.5 MeV proton is recommended from the energy and yield of the generated neutrons. The energy is approximately 800 keV in maximum and 500 keV in average. The moderators and filters can be downsized comparing with the fission neutrons. Recently, the utilization of the "near-threshold reaction" for ^{7}Li(p,n)^{7}Be is proposed. For 1.9 MeV proton energy, though the neutron yield decreases about 1/100 times as 2.5 MeV proton energy, but the maximum neutron energy is almost 90keV. So, the further downsizing or omission of the moderator are possible, then the decrease in the neutron yield is expected to be somewhat made up.

Figure 2 shows the comparison of neutron energy spectra between reactor-based and accelerator-based facilities. The epi-thermal neutron irradiation mode of the KUR-HWNIF is shown as a reactor-based facility. For the accelerator-based facility, 2.5 MeV proton, ^{7}Li(p,n)^{7}Be reaction, BeO neutron moderator, and 6 MeV electron with W target, ^{2}D($x_{\mathrm{bremsstrahlung}}$,n)^{1}H reaction, D_2O neutron moderator, are shown. In Fig. 2, the fast neutron component over MeV is little attendant for the accelerator-based ones. So, the accelerator-based facility takes advantage in the reduction of the background dose, mainly the ^{1}H(n,n)^{1}H dose.

Now, accelerator-based neutron irradiation facility for BNCT does not exist in the world. For realization of accelerator-based BNCT facility using the ^{7}Li(p,n)^{7}Be reaction, the necessary

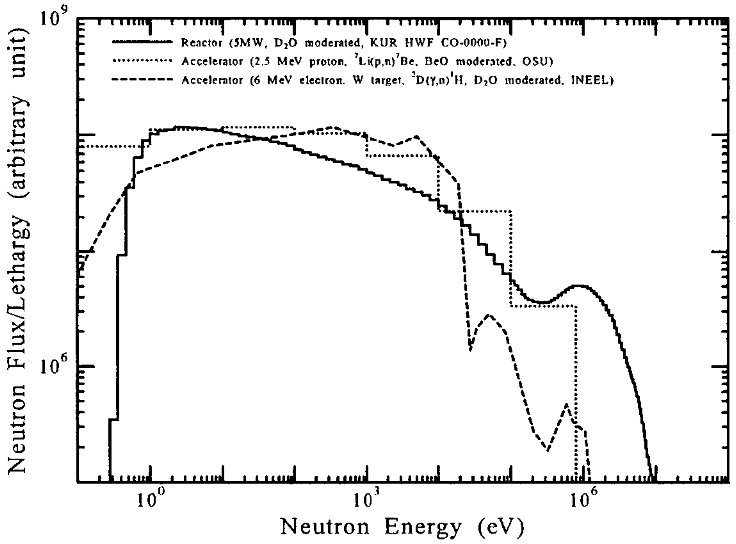

Figure 2. Neutron energy spectra between reactor-based and accelerator-based facility.

current of the accelerated proton is approximately 10 mA. The problem about heat removal from the Li metal target which is low melting point (179℃) and low heat conductivity (45 W/m/℃), should be resolved.

CONCLUSION

On the comparison about the characteristics as neutron sources, accelerator is better than reactor, in the viewpoints of safety, economy, locatability with a hospital in town, the simplicity of start and stop in the operation and so on. From the viewpoint of improvement and control of depth dose distribution, we have arrived at the following conclusions:

(1) Utilization of only thermal neutrons: Reactor is advantageous due to generating more neutrons with wider irradiation field. Also, for the hyper-thermal neutron irradiation, it is advantageous because more thermal neutrons are necessary to generate irradiation field of hyper-thermal neutrons,

(2) *Utilization of only epi-thermal neutrons:* Neutrons both from reactor and accelerator will be useful if the contamination of fast neutrons is reduced to tolerance level. Accelerator with the ^{7}Li(p,n)^{7}Be reaction is more advantageous on the assumption of enough beam intensity, because the contamination of fast neutrons can be made small compared with reactor in principle,

(3) Utilization of both thermal and epi-thermal neutrons: From the same reason of the above-mentioned (2), accelerator is more advantageous. But, reactor is sufficiently useful because the contamination of fast neutrons is relatively less comparing with the utilization of only epi-thermal neutrons, and

(4) Utilization for forward-directional beam, high intensity beam and wide irradiation field: Reactor is advantageous.

We understand that both the reactor-based and accelerator-based neutron irradiation field for BNCT are complementarily needed. The period of the reactor-based facility will continue for a while. We are convinced that the period of the accelerator-based facility will come according as the technical innovation in the accelerator system.

REFERENCES

1. Proceedings of the First International Workshop on Accelerator-based Neutron Sources for Neutron Capture Therapy: *Eds.* Nigg, D.W., *et al.*, INEL CONF-940976, 1994.
2. Proceedings of the First International Symposium on Neutron Capture Therapy: *Eds.* Fairchild, R.G., *et al.*, BNL 51730, 1983.
3. Proceedings of the Second International Symposium on Neutron Capture Therapy: Neutron Capture Therapy, *Ed.* Hatanaka, H., Niigata: Nishimura, 1986.
4. Proceedings of the Third International Symposium on Neutron Capture Therapy: *Eds.* Gabel, D., *et al.*, Strahlentherapie und Onkologie 165, 1989.
5. Proceedings of the Forth International Symposium on Neutron Capture Therapy: Progress in Neutron Capture Therapy for Cancer, *Eds.* Allen, B.J. *et al.*, New York: Plenum Press, 1992.
6. Proceedings of the Fifth International Symposium on Neutron Capture Therapy: Advances in Neutron Capture Therapy, *Eds.* Soloway, A.H. *et al.*, New York: Plenum Press, 1993.
7. Proceedings of the Sixth International Symposium on Neutron Capture Therapy: Cancer Neutron Capture Therapy, *Ed.* Mishima, Y., New York: Plenum Press, 1996.
8. Proceedings of the Seventh International Symposium on Neutron Capture Therapy: Advances in Neutron Capture Therapy, *Eds.* Larsson, B., *et al.*, Amsterdam: Elsevier, 1997.