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2.4 Accelerator Conceptual Design and Needs of Nuclear Data for Boron Neutron Capture Therapy

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An optimization study has been made on an accelerator-based facility for the boron neutron capture therapy. The energy of the incident proton and the arrangement of the moderator assemblies are optimized. The beam current and the accelerating voltage are determined so that the accelerator power becomes minimum. The proposed facility is equipped with a 2.5 MeV proton accelerator of 10-25 mA, a lithium target, and a heavy water moderator contained in an aluminum tank. Each of these equipments is feasible, if proper R&D works have been done. Our new design requires the beam power of less than a hundred kW for the accelerator, although that of our previous design was 1 MW. The reduction of the beam power makes the cooling system for the target much simpler. The essential issues for realization of this concept are long-life lithium targets under high heat flux and high current proton accelerators with average currents of more than 10 mA

It is necessary for the reasonable design of a small-sized and low cost facility to get good accuracy nuclear reaction data. Especially, the latest Li/Be(p,n) neutron yield data in a range of threshold energy - few MeV are required for exact evaluation of neutron energy spectrum used therapy. And damage data by low energy proton beam are also important to evaluate integrity of target material

1. Introduction

We have been studying nuclear reactor concepts suitable for the boron neutron capture therapy at a hospital since July, 1988. One concept was proposed at the 3rd Asian Symposium on Research Reactors in 1991 [1] and an advanced concept was proposed at the 5th Symposium on Advanced Nuclear Energy Research in 1993 [2]. Since construction of a nuclear reactor at a hospital is considered to have difficulty in obtaining public acceptance, we have proposed a deuteron accelerator of 1 MW beam power as an alternative neutron source. The accelerator is based on the concept of ESNIT [3] design which uses the Li (d, n) reaction by a 20mA-50MeV accelerator. A numerical study of optimizing the moderator assemblies was presented in the 1st International Workshop on Accelerator-Based Neutron Sources for Boron Neutron Capture Therapy, Jackson, in 1994 [4]. But an accelerator with 1 MW beam power is too massive and also too expensive for a hospital use. We have challenged to reduce the accelerator beam power thoroughly using the Li (p, n) reaction instead of the Li (d, n) reaction. We have been working to reduce the beam power of the accelerator required for medical treatment. In this paper the measures to reduce the beam power are described with several numerical results.

2. Optimization of Facility

2.1 Design objectives

We have studied to reduce the beam power of the accelerator based on the following design objectives: The time interval for clinical treatment will be less than 1-2 hours. The therapeutic neutron fluence (time integrated flux) at the irradiation field should be more than 6 x 10^{12} n/cm^2 for the epi-thermal neutron(1eV-1keV). The contaminant at the irradiation field should be less than 2Gy for the fast neutron (> 1keV) dose and less than 1Gy for the gamma-ray dose.

2.2 Procedure

It is necessary to slow the neutrons produced by the nuclear reaction of the charged particle with the target down to the epi-thermal neutron energy, which is the most suitable for the treatment. It is also required to decrease the number of high-energy neutrons, which are harmful for the treatment, and to increase the number of epi-thermal neutrons sufficiently for the treatment. At the irradiation field of a patient, the ratio of the fast neutron dose to the epi-thermal neutron fluence must be less than 2Gy/ (6 x 10^{12}n/cm^2) = 3.3 x 10^{-13}Gy・cm^2, in order to make the amount of the fast neutron dose less than 2Gy, and to make the amount of the epi-thermal neutron fluence more than 6 x 10^{12} n/cm^2.

A neutron source of unit strength is fixed on the target, then the neutron flux distribution in the moderator has been calculated by the neutron transport analysis method with the acceleration energy and the composition of the moderator material as parameters. The distribution of the ratio of the fast neutron dose to the epi-thermal neutron fluence has been derived from these analyses, and the minimum thickness of the moderator, which satisfies the above condition, is determined. The required neutron source strength at the target has been estimated so as to make the epi-thermal neutron fluence in the irradiation field exceed 6 x 10^{12} n/cm^2.

For each incident energy the beam current, which produces a sufficient neutron source strength, has been evaluated from the neutron yield data, and the one, which makes the accelerator beam power minimum has been selected.

2.3 Planning an accelerator concept for BNCT facility

The acceleration energy is limited up to 20MeV to make the accelerator compact. Because of the easiness of making the ion source and the high efficiency of the neutron production in low energy proton has been selected as an acceleration particle and lithium as a target material. From our neutron irradiation system design experience of the nuclear reactor for BNCT aluminum is chosen as moderator material for the removal of the fast neutron. To increase the epi-thermal neutron flux heavy water is used. The ratio of the mixture of aluminum and heavy water is changed as a parameter of the analysis.

Analytical models are as follows: a 2-dimensional cylindrical model described in Fig.1 is used by the 2-dimensional discrete ordinates neutron and gamma ray coupled transport code, DORT [5]. The number of energy groups for neutron is 21 and the number of gamma-ray energy groups is 9. The nuclear group constants have been processed from the JENDL-3 (SSTDL-100/40) nuclear cross section library [6].

We have studied sixteen cases of combination of the moderator composition and the incident proton energy. The moderator is composed of homogeneous mixture of heavy water and aluminum. The contents of heavy water are 100,70,40 and10 percent. The incident proton energies are 2.5, 5, 10 and 20 MeV.

3. Specifications of Accelerator Facility

The fast neutron dose and the epi-thermal neutron fluence distributions in the assemblies are described in Fig.2 and Fig.3 where the incident proton energies are 2.5MeV and 10MeV,respectively. From these analytical results, the minimum moderator thickness have been derived and are shown in Table 1. The required beam current (mA) and the beam power (kW) vs. the incident proton energy are shown in Fig.4.

Through the analyses the following results have been derived: the lower the acceleration energy, the less beam power is required but more beam current is required. The beam power required for the treatment in an hour is 63 kW. (^{7}Li (p, n) ^{7}Be: 25 mA in 2.5MeV)

For the high current proton accelerator of the BNCT facility the specifications of the accelerator equipments are determined and described in Table 2. Because more than several milliampere currents and a few to several million electron volt acceleration voltages are challenges, our basic design of the accelerator is based on the JAERI's R&D work. [7]. Each of these equipments is feasible, if proper R&D works have been done.

4. Target and Moderator Assenbly

A light water coolant should remove the heat of the proton beam power dissipated in the thin lithium target. To improve the heat removal capability, corrugated panels are attached onto the opposite surface of the aluminum base metal on which lithium is deposited by evaporation. The numerical result in Fig. 5 shows that the peak heat flux of the incident proton beam should be reduced to less than 160 W/cm^2 since the melting of the target should be avoided. A cylindrical tank filled with heavy water, which has a 30cm diameter and a 25cm height is used as a moderator of the neutron energy. The concept of the cooling structure in the target assembly is shown in Fig. 6.

5. Requirements on Nuclear Data

First, we require the latest energy and angular distribution data of neutron and γ production by the reaction in a range of threshold energy to a few MeV Another engineers and we make a design of an accelerator facility for BNCT use the same nuclear data as shown in Fig. 7 and Fig. 8 [8]. For example, existence and height of Li(p,n)resonant reaction at about 2.3MeV is needed to evaluate efficiency of neutron production. The precise cross section curve of Li/Be(p,n) reaction near the threshold energy is so sensitive to decide incident proton energy in order to obtain lower energy neutron. γ Production data is needed to shielding calculations of a target and an accelerator. Because this data was published in 1975, we think more precise data can be measured with new methodology and new instruments. It is necessary for the reasonable design of a small-sized and low cost facility to get good accuracy nuclear reaction data.

Next, we have no damage data by low energy and high intensity proton beam. He atoms are accumulated inside of a target surface by irradiation of proton beam. It is also important to evaluate integrity of target materials.

6. Conclusion

Based on these concepts, a typical arrangement of the facility is proposed in Fig. 9. A high current proton accelerator of 10 mA, Li (p, n) type target with a high heat flux condition, and an aluminum tank moderator assembly containing heavy water (D_2O). Development of a high current accelerator, which has more than the several mA capacity is the essential issue for the facility. It is also necessary to continue the effort to reduce the beam power requirement.

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TABLE 1. Minimum Thickness of the Moderator

Composition	**(in unit: cm)**			
(contents of D_2O)	**Acceleration Energy (MeV)**			
	2.5	5.0	10	20
100%	21	28	44	**
70%	24	33	49	**
40%	31	42	59	143
10%	49	66	83	110

** not analyzed

TABLE 2. Specifications of Accelerator for BNCT

Ion Source	
Particle	proton
Extraction Energy	several tens - 100 keV
Beam Current	120 mA (peak)
Duty	10-100%
R F Q	
Extraction Energy	a few MeV
Beam Current	20 mA (average)
Duty	10 100%
Transmission Rate	around 90%
R F Power Source	
Peak Power	around 850kW
Duty	10 100%

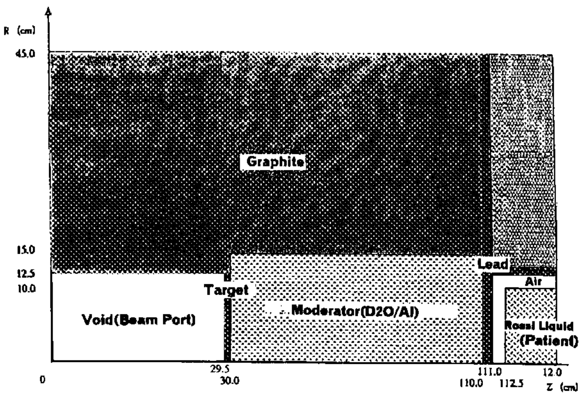

FIGURE 1. Analytical Model of Neutron Moderator Assembly

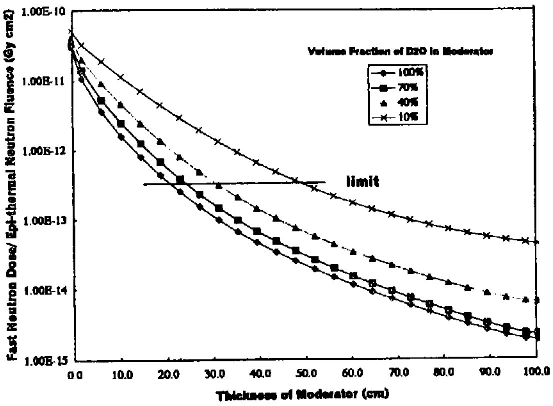

FIGURE 2. Fast Neutron Dose/Epi-thermal Neutron Fluence (Ep = 2.5 MeV)

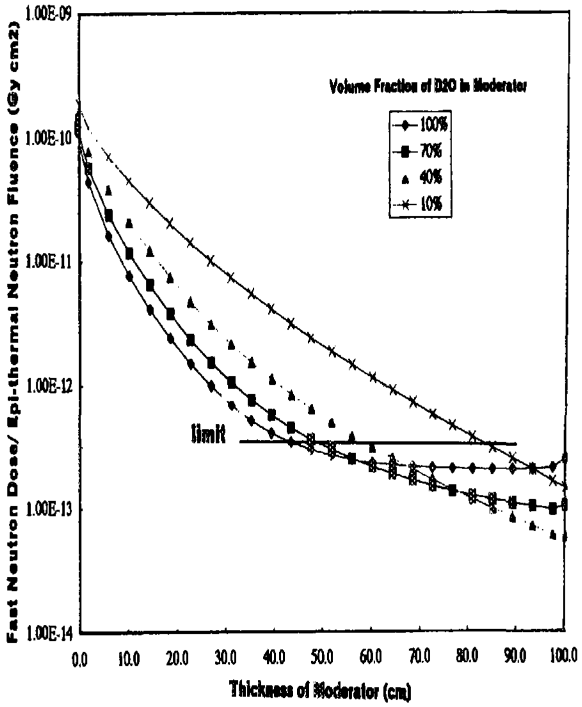

FIGURE 3. Fast Neutron Dose/Epi-thermal Neutron Fluence (Ep = 10 MeV)

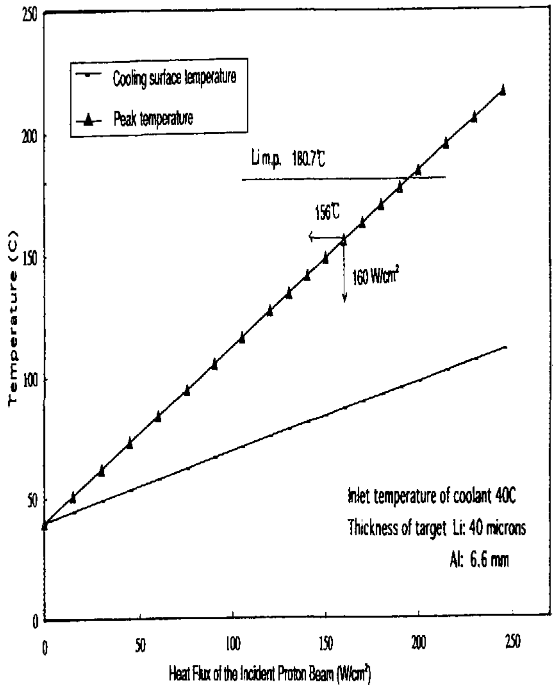

FIGURE 5. Relation between Temperature of Target and Incident Heat Flux Density

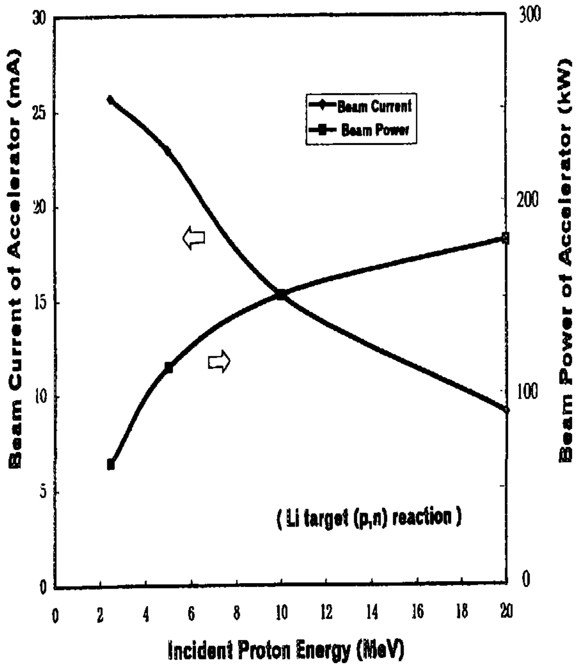

FIGURE 4. Incident Proton Energy vs. Beam Strength of Accelerator (Irradiation Time 1 Hour)

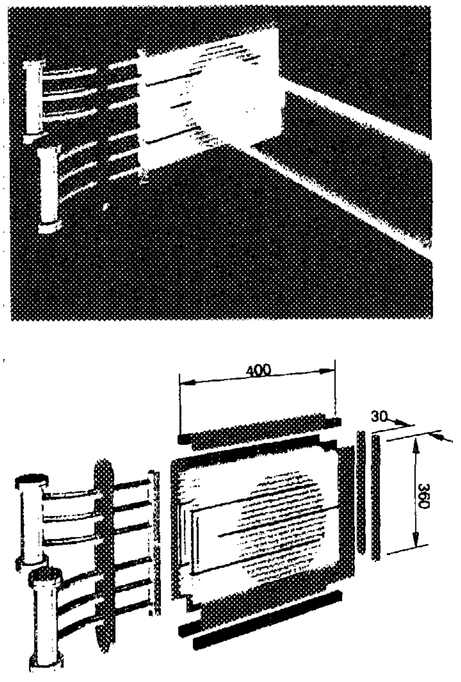

FIGURE 6. Concept of the Cooling Structure in Target Assembly

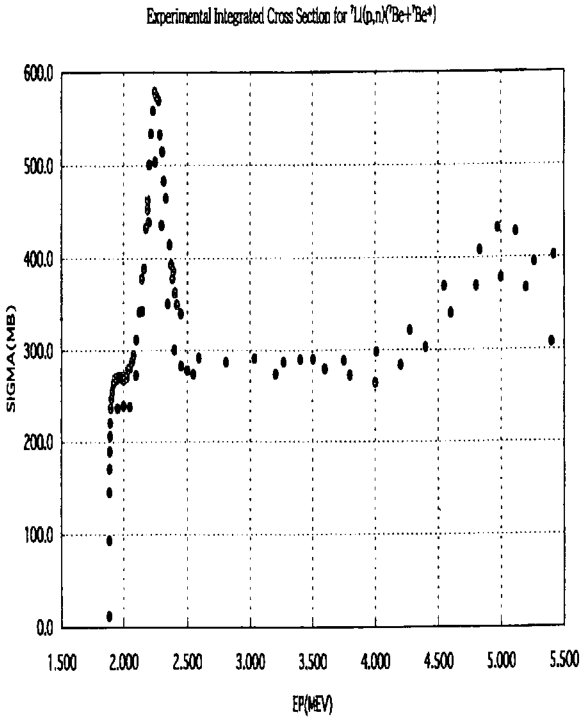

FIGURE 7. ^{7}Li(p,n) Reaction Cross Section

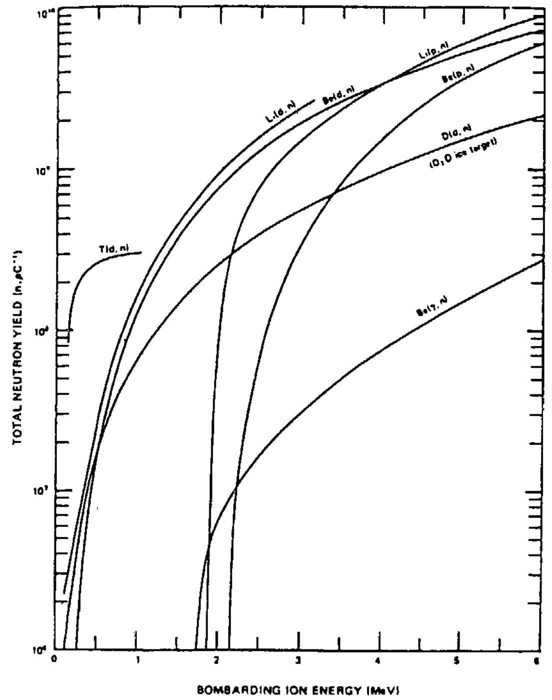

FIGURE 8. Total Neutron Yield Curve of Li/Be(p,n) and Li/Be(d,n) Reactions

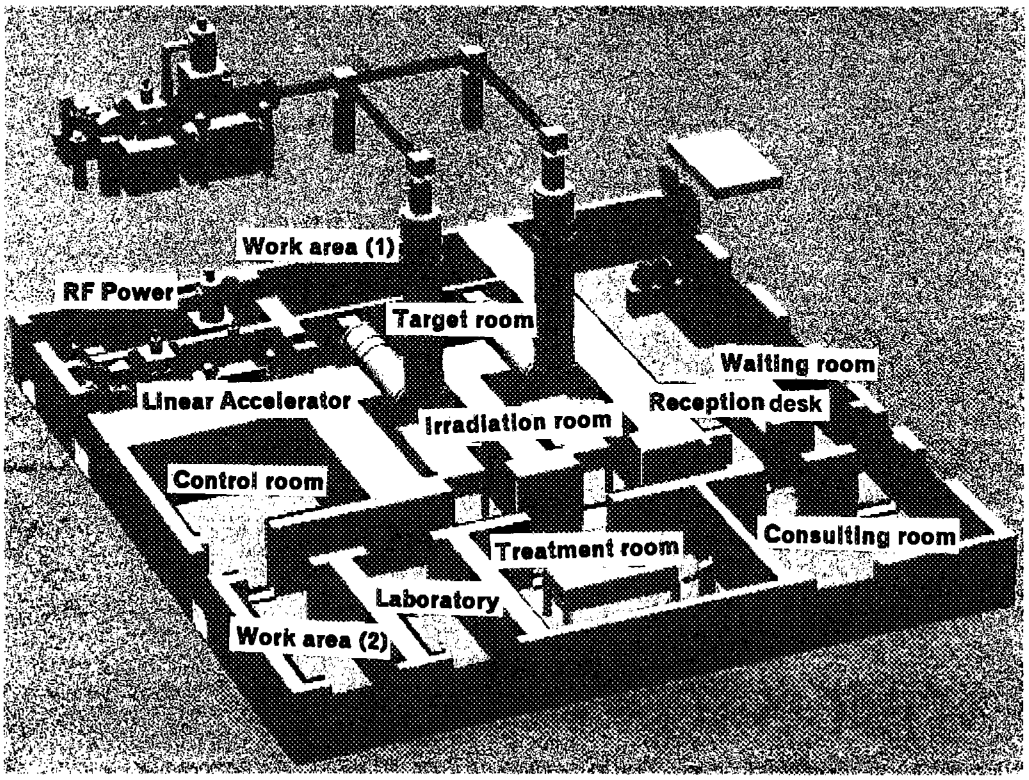

FIGURE 9. View of an Accelerator Based BNCT Facility