THE ARGONNE ACWL, A POTENTIAL ACCELERATOR-BASED NEUTRON SOURCE FOR BNCT.

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The CWDD (Continuous Wave Deuterium Demonstrator) accelerator was designed to accelerate 80 mA cw of D^- to 7.5 MeV. Most of the hardware for the first 2 MeV was installed at Argonne and major subsystems had been commissioned when program funding from the Ballistic Missile Defense Organization ended in October 1993. Renamed the Argonne Continuous Wave Linac (ACWL), we are proposing to complete it to accelerate either deuterons to 2 MeV or protons to 3-3.5 MeV. Equipped with a beryllium or other light-element target, it would make a potent source of neutrons (on the order of 10^{13} n/s) for BNCT and/or neutron radiography. Project status and proposals for turning ACWL into a neutron source are reviewed, including the results of a computational study that was carried out to design a target/moderator to produce an epithermal neutron beam for BNCT.

1. Introduction

The CWDD research and development program was set up to pursue four main objectives: cw operation, deuterium (D^-) beams, operation at cryogenic temperatures, and high beam brightness. The CWDD accelerator included a 200 keV dc D^- injector, and two cw structures: a 2 MeV radiofrequency quadrupole (RFQ) and a 7.54 MeV ramped-gradient drift-tube linear accelerator (RGDTL). Grumman Aerospace Corporation, the prime contractor, had overall system responsibility. Culham Laboratory UK was a major subcontractor for the injector, beam lines, diagnostics and controls and Los Alamos National Laboratory assisted with design, prototyping and cold-model testing. Site, services, and cryogenics were being provided by Argonne National Laboratory, and Argonne was to have responsibility for ongoing programs upon demonstration of compliance with contract specifications. CWDD was turned over to Argonne "as is"in October 1993.

The facility is being maintained in its nearly-completed state while we consider modifications to prepare it for new applications. To mark these changes and to avoid confusion with the previously published CWDD specifications and purpose, we have given the facility a new name, the Argonne Continuous Wave Linac (ACWL). One of the applications we are considering for ACWL is boron neutron capture therapy (BNCT). BNCT requires a beam of neutrons which penetrates a tumor-containing brain deep enough to create an intense thermal neutron field at the tumor site without excessive damages to the skin and other healthy tissues of the patient. A thermal beam is unsatisfactory in this respect and efforts have been made to develop epithermal beams using reactor, accelerator and isotope neutron sources.[1] As built, the ACWL RFQ will accelerate a cw beam of up to 80 mA of deuterons to 2 MeV. However, we are also considering modifications to the vanes of the RFQ to accelerate protons and could arrange for any desired proton energy and current up to about 3.5 MeV and 100 mA respectively. We have used the MCNP transport code[2] to look at several possible projectile-target and moderator combinations to produce an epithermal neutron beam with ACWL[3]. Although neutron yields are higher and neutrons can be produced at lower projectile energies with deuterons than with protons, neutrons produced by deuteron beams have significantly higher energies, making it difficult or impractical to obtain the high-purity, high-intensity epithermal beams required for BNCT. Our studies indicate that a proton beam with an energy hundreds of keV to a few MeV above threshold, impacting a beryllium or a lithium-compound target, can be moderated to produce a suitable beam for BNCT. We have also calculated the epithermal beam that could be produced using protons a few tens of keV above threshold. Although the neutron yield (per incident proton) is much lower, some compensation is provided by the more compact geometry of the beam tailor (because little or no moderation is required) and the beam may be more desirable because the fast-neutron component is essentially zero.

2. ACWL Status and Proposed Modifications for Protons

A schematic layout of the CWDD facility is shown in fig. 1. With the exception of the RGDTL, all items and subsystems shown have been installed and most have been commissioned or are awaiting final hookup to cooling or power.

The CWDD injector comprises a volume ion source, triode accelerator, high-power electron traps and low-energy beam transport (LEBT) with a single focusing solenoid[4]. The source has delivered more than 20 mA of D^- current to a beam stop in the LEBT line, and is expected to be capable of more than 80 mA when modifications for D^+ are completed.

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The RFQ is a four-meter long rf cavity, made by assembling four one-meter long segments[5]. RF power dissipation at design fields at room temperature is 544 kW. The RFQ has been installed, aligned with the injector and exit beamline, and connected to the rf drive lines. The previously-installed cryo-refrigeration lines have been removed and connectors for water cooling are being installed.

The rf amplifier systems comprise two 1 MW cw klystron amplifiers (for the RFQ and future drift tube linac respectively) and a 25 kW tetrode amplifier (for the matching-section cavity after the RFQ). All are installed; the tetrode has operated to full power and the RFQ klystron amplifier operated cw to >550 kW (limited by the rf load). Most of the control and diagnostics systems are completed and major parts, such as the injector/LEBT controls and diagnostics, the PASS (personal access safety system), fire and radiation protection systems etc., have been in service now for over two years. The water cooling systems are completed and in service, except for connections between the pump station and the RFQ.

Calculations with the RFQUIK and PARMTEQ codes show that by changing the vane profile, the RFQ could be modified to accelerate over 100 mA of protons to at least 3 MeV and somewhat lower currents to 3.5 MeV. We are proposing to initially commission the RFQ with deuterons to obtain engineering data for the present configuration. Depending on program constraints and the results of cost estimates, we will then either remove the present RFQ and modify it, or replace it with an entirely new structure. Preliminary estimates indicate replacement may be a factor of two more expensive, but will lessen the down time for the facility by as much as one year.

3. BNCT Neutron Beam Design

For BNCT applications, epithermal neutrons from 4 eV to 40 keV are desired according to a dosimetric study[6]. They could be obtained by moderating a neutron source of higher energies or by bombarding a target with charged particles at an energy just 40 keV above the reaction threshold. The former method has the advantage of starting with a much higher neutron yield. However, it requires significant moderation (which limits the final achievable epithermal flux intensity) and the neutron beam output is always contaminated by a fast neutron component (E_n>40 keV). Neutrons from the latter method need minimal moderation and contain no fast contamination above 40 keV, but the neutron yield and thus the epithermal flux output may be very low. Most accelerator BNCT neutron beams to date have been designed based on the former approach and we will mainly exploit this option with ACWL.

For choosing a target, we note that certain light nuclei are known to produce a great deal of neutrons under the bombardment of charged particles[7]. However, only a few of them can be fabricated in a high density form and generate high, thick-target neutron yields and we limited our studies primarily to tritium, lithium-7, beryllium-9 and carbon-12. For 2 MeV deuterium bombardment of these targets, the corresponding maximum neutron energies are approximately 16 MeV, 17 MeV, 6.6 MeV and 1.7 MeV; lower energies are preferable, so beryllium and carbon were selected for further evaluation. For proton bombardment, carbon is ruled out by its low yield and the high-yield lithium and beryllium targets were evaluated. Scandium, among other medium-weight target materials, was added to the comparison study since it was known to have a high near-threshold neutron yield for producing monoenergetic neutrons for neutron instrumentation calibration[8].

Fig. 2 presents the moderation study of the spectra of the d-Be, d-C, p-Li and p-Be neutrons. In this study, a unidirectional beam of 6 cm diameter and a circular slab of D_2O moderator with 50-cm radius were used. The thickness of the slab was changed to examine the variation in the moderated spectra of the source neutrons. The neutron spectra over a circular area of 12-cm radius on the down-stream surface of the slab were recorded. The flux intensity of the neutrons in the energy interval 4 eV-40 keV was calculated and plotted in solid circles for various D_2O thicknesses. The percentage of the neutrons with E_n>40 keV compared with the total neutrons for E_n > 4 eV was calculated and referred to as the fast neutron contamination and is plotted in open circles. The thermal-neutron flux for E_n < 4 eV was not shown as it can be filtered out fairly easily with lithium-6, boron-10 or other thermal absorbers. The goal of moderation is to increase the flux intensity in 4 eV-40 keV while reducing the fast neutron contamination to a small percentage. The data in Fig. 2 (a)-(d) enables one to determine the epithermal flux level and fast neutron contamination for a given D_2O thickness.

Fig. 2(a) shows the epithermal flux and percentage of fast neutrons for 2.6 MeV deuterons on a beryllium target. (An E_d=2.6 MeV spectrum was used[9] because spectral data for 2 MeV was not available but would be expected to have a similar shape to the 2.6 MeV spectrum.) The main characteristic of the spectrum is that about 70% of the neutrons have energies below 2 MeV while the remaining 30% neutrons are spread out in energy from 2 MeV up to 6.6 MeV to form a long tail. As the scattering cross section decreases with neutron energies, the 70% neutrons below 2 MeV are moderated faster than the 30% above 2 MeV. As a result, the fast neutron contamination percentage stops decreasing after reaching the 40% level as shown by the circles. Even when the D_2O thickness increases to 100 cm, where the epithermal flux becomes as low as $3x10^{-8}$ n/cm^2/source neutron, the fast neutron component remains at 40%. This shows that the tail in the d-Be spectrum has a disabling effect and that it may not be possible to obtain a BNCT beam with low contamination from a d-Be combination.

Fig. 2 (b) presents the results for the d-C neutron spectrum. The spectrum used was approximated by applying momentum and energy conservation to the reaction. With 45 cm of D_2O, the beam contamination reached a 10% level with an epithermal flux level of $8x10^{-6}$ n/cm^2/source neutron. Fig. 2 (c) and (d) are respectively for p-Li and p-Be neutrons. The neutron spectra are similar for both reactions and the variations in flux and fast contamination are also similar as shown in (c) and (d). Since the thick-target yield of p-Li at 2.5 MeV is about the same as that of p-Be at 3.5 MeV, the comparison of the epithermal fluxes would indicate their relative merits. Fig. 2 (c) indicates that one obtains from p-Li a 10% purity at 30 cm D_2O with a flux of $5x10^{-5}$ n/cm^2/source neutron. Fig. 2 (d) shows that one reaches 10% at 35 cm D_2O with a flux of $2.5x10^{-5}$ n/cm^2/source neutron, half that of p-Li. As faster neutrons also correspond to larger doses, the 10% of p-Be neutrons are more harmful than the 10% p-Li neutrons which are slower. The comparison puts p-Li at an advantage over p-Be. However, the thermo-mechanical properties of a beryllium target compared with those of lithium may offset the above difference to some extent. If one assumes that you must use a lithium compound such as Li_2O, then the yield per incident proton is reduced by about a factor of two from that with lithium metal, and the yield advantage of lithium disappears.

Figure 3 shows a comparison of different projectile-target combinations when the yield factor and spectral moderation factor are combined. The fast neutron contamination factor for each case is indicated in the figure. Because the fast neutron contamination with d-Be is so great, the choices would appear to be between p-Be and protons on lithium or a lithium compound.

4. Conclusions

MCNP calculations show that a useable neutron beam for BNCT can be produced with a proton accelerator able to deliver 10-50 mA of 2.5-4 MeV protons onto a lithium or beryllium-rich target. Pure lithium would be best from a neutronics point of view, but the engineering difficulties associated with a lithium metal target at these currents may make beryllium or a lithium compound (e.g. Li_2O) a better choice. The particular energy and current will depend on the choice of target material and the desired treatment time (higher energy if beryllium, higher current to reduce treatment time) but in any event should be within operational range of the ACWL facility once the RFQ has been modified to accelerate protons. The ACWL facility could provide a versatile and cost-effective testbed for the development of accelerator-based BNCT therapy.

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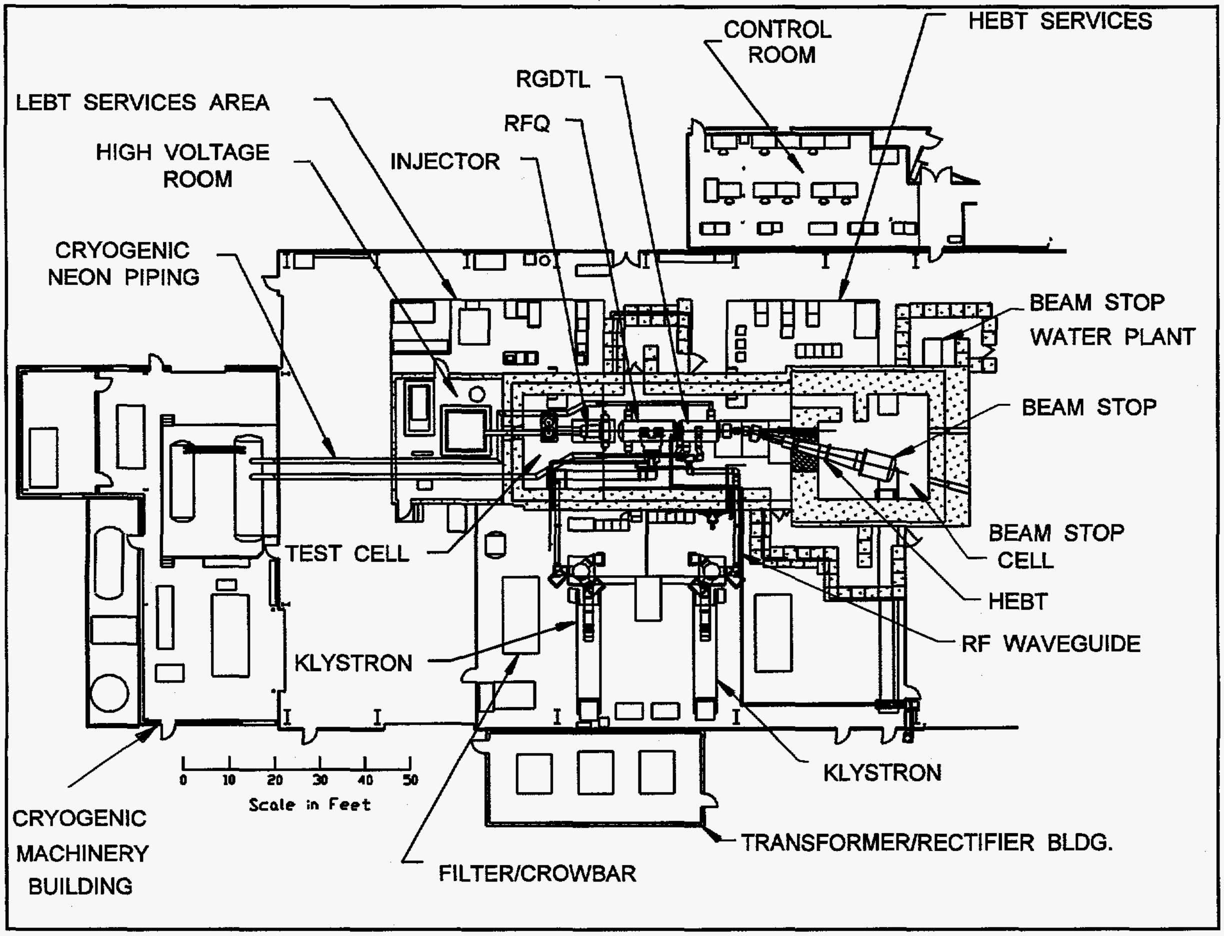
6. References

1. G. L. Brownell, J. E. Kirsch, and J. Kehayias, 2nd Int. Conf. on Neut. Capt. Ther., Tokyo, Japan (1985) 127.
2. J. F. Briesmeister (Ed.), Los Alamos National Lab, LA-7396-M, (1986).
3. X.-L. Zhou and G.E. McMichael, "Des. of Neut. Beams at the Argonne CW Linac (ACWL) for BNCT and Neut. Rad.", Proc. 1994 Workshop on Accel.-Based Neut. Sources for BNCT, Jackson, Wyoming, September 12-14, 1994, to be published.
4. J. Carwardine, G. Pile and T. Zinneman, Proc. 1993 Part. Accel. Conf., IEEE 93CH3279-7, (1993) 3210.
5. J. Rathke and L. Young, "Eng. Des. and Fab. of a CW Deuterium RFQ", Proc. 1994 Lin. Accel. Conf, Tsukuba, Japan, Aug. 21-26, 1994, to be published.
6. J. C. Yanch, X. L. Zhou, and G. L. Brownell, Rad. Res. 126, (1991) 1.
7. M. R. Hawkesworth, Atomic Energy Review 15 (2), (1977) 179.
8. D. W. O. Rogers, Nucl. Instrum. Meth. 142, (1977) 475.
9. J. W. Meadows, Nucl. Instrum. Meth. Phys. Res. A324, (1993) 239.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INJECTOR
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BEAM STOP
TEST CELL
BEAM STOP CELL
HEBT
RF WAVEGUIDE
KLYSTRON
KLYSTRON
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Scale in Feet
CRYOGENIC MACHINERY BUILDING
TRANSFORMER/RECTIFIER BLDG.
FILTER/CROWBAR

Fig. 1. CWDD Facility layout.

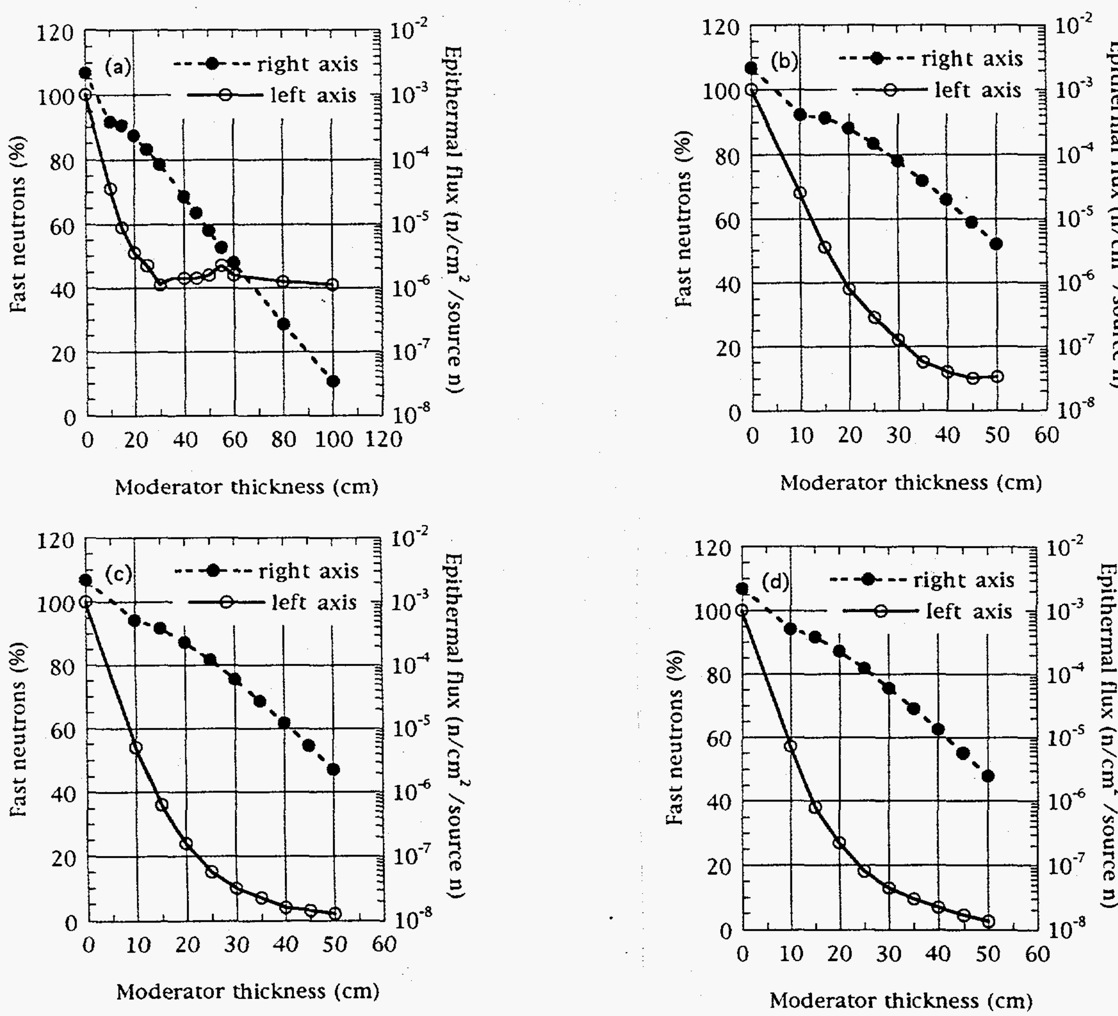

Fig. 2. Spectral properties of D_2O-moderated neutrons from (a) 2.6 MeV d on Be, (b) 2.0 MeV d on C, (c) 2.5 MeV p on Li and (d) 3.5 MeV p on Be. Left axis gives ratios in percentile of neutrons with E_n>40 keV to those with E_n> 4 eV. Right axis gives epithermal flux (E_n between 4 eV and 40 keV).

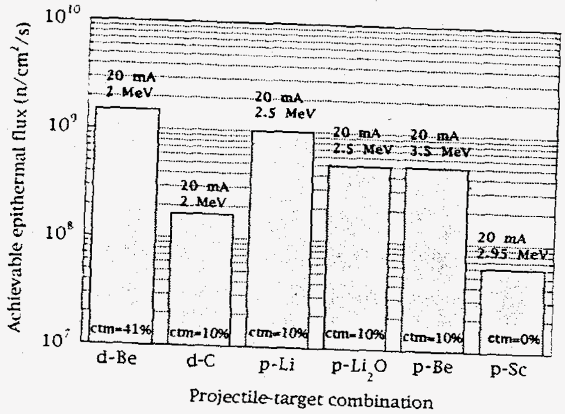

Fig. 3 Comparision of six projectile-target combinations showing achievable epithermal flux (energy between 4 eV to 40 keV). The percentages marked within the bars are the fast neutron contamination of the epithermal beams.