CLAS Note 93-023

# Considerations for the Design of the CLAS Tagger Beam Dump

Hall Crannell
Physics Department
The Catholic University of America
Washington, DC 20064

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## INTRODUCTION

The Hall-B Tagger Beam Dump is designed to contain the unused electrons, and the secondary particles created by these stopping electrons, resulting from operation of the Hall B tagger. The beam dump is located in a beam-dump tunnel under the Hall-B floor. The shielding around the dump must accomplish two purposes; it must prevent the ground water located outside the dump tunnel from becoming excessively radioactive, and it must shield the CEBAF Large Aperture Spectrometer (CLAS) system from secondary radiation.

In both of these considerations it is the neutrons produced in the dump that are the most penetrating and therefore are the most difficult to shield. Ground water activation comes principally from fast neutron spallation reactions. In addition, many lower energy neutrons are produced from photonuclear reactions leading to the giant resonance. The major source of background for the CLAS comes from neutrons which exit through the beam transport pipe that carries the beam to the dump.

The design considerations for the beam dump must take into account the beam power to be dissipated. In the normal thin-radiator mode of operation this power will be low, typically a few hundred watts. However, plans have been put forward for producing polarized photons, either by off-axis tagging (Sober[1]) or by laser back-scattering (Norum[2]). These polarized photon sources would require a considerably more intense electron beam. The design criteria have therefore used a maximum power level of 10 kW. This power level is believed to be near the maximum that can be handled with an inexpensive gas cooling system for the dump.

In the sections that follow the preliminary design of the dump is described. The production of high energy neutrons and their effect on the ground water activation is discussed. The effect of giant resonance neutrons coming through the shielding is shown to be negligible. A design for minimizing the number of neutrons that enter Hall B through the beam transport tunnel is developed. Finally, some parameters for a gas cooling system are described.

## GENERAL DESIGN CONSIDERATIONS

The beam-dump tunnel is a cylindrical corrugated iron pipe 3.05 m in diameter and approximately 12 m long sloping down below the floor of Hall B at an angle of 30°. At its maximum depth the center of the beam tunnel is 6.1 m below the floor. The beam-dump tunnel is surrounded by bedrock, concrete, and construction back fill. The exact proportions and locations of these materials are uncertain. Since most of Hall B is located below the water table, ground water certainly exists in the environment outside the beam dump tunnel.

Based on the considerations detailed in the following paragraphs a relatively simple dump enclosed mostly in iron shielding is proposed. A 30-cm diameter evacuated pipe transports the beam down the center of the beam-dump tunnel from the floor to the front of the dump. The diameter of the transport pipe is consistent with the size considerations for the dump developed by Sober.[3] The dump itself consists of a 30-cm diameter cylinder. The first 50 cm of the dump is composed of sheets of graphite (carbon), and the final 30 cm of the dump is composed of sheets of tungsten. The actual dump volume is surrounded on the sides and the down stream end with iron that fills the dump tunnel. The beam transport pipe up stream of the dump is surrounded by concrete or gravel. Pipes 7.5 cm in diameter are threaded through the shielding to provide for flowing gas cooling for the dump.

## HIGH ENERGY NEUTRONS

### Ground Water Contamination

Fast neutrons, those with energy greater than 30 MeV, exiting the beam-dump tunnel cause spallation reactions in the water, soil, and rock surrounding the dump tunnel. The major radioactive species of concern outside the dump are tritium and $^{22}$Na. To meet environmental safety standards these species must be less than 90 pCi/ml and 0.4 pCi/ml in water, respectively. Because the $^{22}$Na is created in the soil and rock, it tends to bind in the rock. For design considerations it is generally accepted that only 15% of the $^{22}$Na will leach into saturated water.

The neutron spallation cross section for neutrons with energy greater than 30 MeV in rock are $7.7 \times 10^{-4}$ cm$^2$/g for tritium and $2.2 \times 10^{-4}$ cm$^2$/g for $^{22}$Na. The production of these isotopes by neutrons with energy less that 30 MeV is considered negligible.

The characteristics of water flow under the experimental halls is relatively unknown. We have therefore used the extreme assumption that the activity is allowed to accumulate in place until it reaches a maximum, and then flows to the surface undiluted.

The areas immediately outside the dump tunnel that potentially receive the maximum neutron dose from the dump are those directly forward, corresponding to 0° neutron production, and those at right angles to the dump, corresponding the 90° neutron production. At 0° the neutron production cross section is a maximum, and the path through the forward shielding is a minimum. The thickness of the forward shielding can be adjusted, however, to reduce the neutron flux to almost any desired level.

Because of the limited size of the beam dump tunnel, the lateral thickness of shielding is limited. In addition the distance from the dump to the dump-tunnel wall is fixed and is a minimum in the direction at right angles to the beam. For neutrons produced at angles either greater than or less than 90° the shielding path length is greater and the resultant neutron flux outside the dump tunnel less. Calculations of the ground water activation have therefore been made only for the straight through and 90° lateral positions. At other production angles the shielding is thicker and the resultant activation less.

**High Energy Neutron Production**

The energetic neutrons come principally from the $\gamma p \rightarrow \pi^+ n$ reaction, where the $\gamma$'s are produced in the electromagnetic cascade shower in the dump. The $\gamma p \rightarrow \pi^+ n$ cross section grows approximately as $A^{2/3}$, but the competing process that removes high energy $\gamma$'s from the shower is proportional the pair production cross section, which in turn is proportional to $Z^2$. Thus the production of high energy neutrons is minimized by making the dump from a high Z material. For this reason, and to minimize the size of the region in which most of the energy from the electrons is deposited, the main dump volume has been designed using a small cylindrical volume of tungsten approximately 30 cm in diameter by 30 cm in length.

Calculations performed with the GEANT code indicate a depth of 20 radiation lengths of tungsten is sufficient to contain more than 97% of the energy associated with a 6 GeV electromagnetic cascade shower. Thus a total thickness of 7 cm of tungsten will suffice. The

30 cm of depth can consist of a number of plates of tungsten separated by about 3 times their thickness allowing space for the flow of cooling gas between the plates.

The angular distribution of neutrons coming from an iron dump has been extensively studied at SLAC,[4] and the analytic parameterizations developed for that work have been used here. The data from the SLAC study are for a 15 GeV beam of electrons. The maximum energy considered for the tagger dump is 6 GeV. Since the neutrons come from interactions in an electromagnetic cascade shower, the angular distribution of neutrons will be a slowly varying function of electron energy, the SLAC data being possibly somewhat more forward peaked than the neutrons from the tagger dump.

The data from the SLAC measurements has been parameterized in three integrated energy bands. For neutron energy $E_n$ greater than 25 Mev

$$\frac{1}{E_0}\left(\frac{dN}{d\Omega}\right)_{E_n>25} = \frac{3.13\times10^{-3}}{1-0.75\cos(\theta)}\ \mathit{neutrons/sr\cdot GeV\cdot electron}, \qquad (1)$$

where $E_o$ is the incident electron energy in GeV, and $\theta$ is the neutron production angle. For $E_n$ greater than 100 MeV the corresponding expression is

$$\frac{1}{E_0}\left(\frac{dN}{d\Omega}\right)_{E_n<100} = \frac{1.5\times10^{-4}}{(1-0.72\cos(\theta))^2}\ \mathit{neutrons/sr\cdot GeV\cdot electron}, \qquad (2)$$

while for $E_n$ greater than 150 MeV the expression is

$$\frac{1}{E_0}\left(\frac{dN}{d\Omega}\right)_{E_n>150} = \frac{5\times10^{-5}}{(1-0.43\cos(\theta))^6}\ \mathit{neutrons/sr\cdot GeV\cdot electron}. \qquad (3)$$

Equations 1 through 3 give the angular distribution of neutron production, and clearly imply a strong dependence on neutron energy, at least in the energy range below 100 MeV. In order to obtain an analytical expression that characterizes the energy dependence of these expressions, the data have been fit with a neutron production cross section that decreases with neutron energy from 25 to 100 MeV and is constant for neutron energies higher than 100 MeV. Several analytic formulations for the 25 to 100 MeV region were tried. The only formulation that gave a satisfactory smooth fit was an exponential decreasing function. With these assumptions it is possible to characterize the energy dependence of the neutron production cross section by

$$\frac{1}{E_0}\frac{dN}{dE_n} = K_E\, e^{-\lambda_E E_n}, \qquad (4)$$

where $K_E$ is a constant. It is then possible to fit Eqs. 1 - 3 to arrive at the following values for $\lambda_E$:
For $\theta = 0°$, $\lambda_E = 0.0561$ MeV$^{-1}$, and for $\theta = 90°$, $\lambda_E = 0.0601$ MeV$^{-1}$.

For neutron energies above 100 MeV the production cross section is assumed to be independent of energy.

**High Energy Neutron Absorption**

For 10 kW of electron beam power in the dump the neutron production rates given by Eqs. 1 - 3 exceed reasonable safety limits. Thus the dump must be surrounded with shielding that prevents most of the neutrons from escaping the beam tunnel. For very energetic neutrons the mean free path is given by[5]

$$\lambda_n = 35\,A^{1/3}\ (g/cm^2)\,. \qquad (5)$$

This expression leads to the following Table 1.

Table 1. High Energy Neutron Attenuation Lengths

| Material | A | $\lambda_n$ (g/cm$^2$) | $\rho$ (g/cm$^3$ | $\lambda_n/\rho$ (cm) |
|---|---|---|---|---|
| carbon | 12 | 80 | 2.2 | 36.5 |
| concrete | 28 | 106 | 2.3 | 46.1 |
| iron | 56 | 134 | 7.8 | 17.2 |
| tungsten | 183 | 199 | 19.3 | 10.3 |
| lead | 208 | 207 | 11.3 | 18.3 |
| uranium | 238 | 217 | 19.0 | 11.4 |

Within the confined volume of the dump tunnel it is desirable to have a neutron absorber with a small attenuation length. Among reasonable cost materials iron appears to be the most suitable, and therefore has been used in all the considerations that follow.

Not all the neutrons produced in the dump are at the high energies appropriate to Table 1. Neutrons with energies in the range from 25 to 100 MeV have a larger interaction cross section and are therefore more easily absorbed. For this work the attenuation lengths for the neutrons in this lower 25 to 100 MeV energy range has been parameterized by using the inelastic cross section data presented in Fig. 28 of Jenkins[4] for copper and scaled to give the correct values for iron at 400 MeV as reported by Whitney.[6] From these data the neutron attenuation length can be approximated by the following expressions:

For 25 Mev $< E_n <$ 100 MeV $\qquad \lambda_n(E_n)[cm] = 7.7 + 0.093\, E_n[MeV]\,,$ **(6)**

For 100 $< E_n <$ 150 MeV $\qquad \lambda_n[cm] = 17\,,$ **(7)**

while for 150 MeV $< E_n <$ 6 GeV, $\qquad \lambda_n[cm] = 19.2\,.$ **(8)**

**Neutron Flux Estimates**

In estimating the neutron flux escaping the beam dump tunnel it has been assumed that there is 152 cm (5 ft) of iron between the end of the tungsten dump and the tunnel. It has also been assumed that there is 137 cm (4.5 ft) of iron surrounding the dump on the sides. In order to calculate the neutron flux in the energy interval $25 < E_n < 100$ MeV, where both the production cross section and the absorption in the shielding are functions of the energy, it is necessary to evaluate the appropriate integrals. The effective attenuation $\epsilon_n$ produced by the shielding is given by

$$\epsilon_{E_n<100} = \frac{\int_{25}^{100} e^{-\lambda_E \cdot E_n} \cdot e^{-t/\lambda_n(E_n)}\, dE_n}{\int_{25}^{100} e^{-\lambda_E \cdot E_n}\, dE_n}, \qquad (9)$$

where t is the thickness of the neutron shield.

For neutron energies above 100 MeV the calculation of neutron flux is much simpler since the production cross section is assumed to be constant and the neutron mean free path is also assumed to be constant over each of the respective energy intervals $100 < E_n < 150$ MeV and $E_n > 150$ MeV. In this case the attenuation is given by

$$\epsilon_{E_n>100} = e^{-t/\lambda_n}. \qquad (10)$$

Equations 1 - 3 give the neutron production rates for an iron dump. For a tungsten dump, such as proposed here, the SLAC results, Table 1 of reference 4, shows the neutron production rate is dependent on the A of the material. These data, which give the neutron yield relative to copper, $Y_{Cu}$, can be fit with the empirical formula

$$Y_{Cu} = 15.7 \cdot A^{-0.646}. \qquad (11)$$

Equation 11 predicts that energetic neutron production from tungsten is a factor of 2 lower than from iron.

The neutron flux $\mathscr{F}$ at the edge of the dump tunnel is given by

$$\mathscr{F} = E_0 \cdot k \cdot \Delta\Omega \cdot \epsilon, \qquad (12)$$

where $k$ is the production rate, $\Delta\Omega$ is the cross section presented by 1 cm$^2$ at the dump tunnel surface, and $\epsilon$ is the attenuation coefficient. Tables 2 and 3 give the neutron flux for the 0° and 90° directions, respectively.

Table 2. Neutron flux escaping the beam tunnel in the forward direction for 10 kW of beam power.

| $E_n$ range (MeV) | $k$ (n/sr/e/GeV) | $\Delta\Omega^{(a)}$ (sr) | $\epsilon^{(b)}$ | $\mathcal{F}$ (n/cm$^2$/s) |
|---|---|---|---|---|
| 25-100 | 0.0054 | $3.6\times10^{-5}$ | $5.1\times10^{-6}$ | 59 |
| 100-150 | $1.7\times10^{-4}$ | $3.6\times10^{-5}$ | $1.3\times10^{-4}$ | 47 |
| 150-6000 | $7.3\times10^{-5}$ | $3.6\times10^{-5}$ | $3.3\times10^{-4}$ | 77 |

(a) based on an average neutron created 168 cm from the end of the dump tunnel.
(b) based on 152 cm of iron absorber.

Table 3. Neutron flux escaping the beam tunnel in the perpendicular direction for 10 kW of beam power.

| $E_n$ range (MeV) | k (n/sr/e/GeV | $\Delta\Omega^{(a)}$ (sr) | Attenuation (b) | n flux (n/cm$^2$/s) |
|---|---|---|---|---|
| 25-100 | $1.5\times10^{-3}$ | $4.3\times10^{-5}$ | $1.5\times10^{-5}$ | 60 |
| 100-150 | $5.0\times10^{-5}$ | $4.3\times10^{-5}$ | $3.2\times10^{-4}$ | 42 |
| 150-6000 | $2.5\times10^{-5}$ | $4.3\times10^{-5}$ | $7.4\times10^{-4}$ | 48 |

(a) based on an average neutron created 1.5 m from the side of the dump tunnel.
(b) based on 137 cm of iron absorber.

The results presented in Tables 2 and 3 neglect absorption of neutrons in the dump material. This effect has been be crudely estimated to be about 25% for forward going neutrons and a factor of 3 reduction in the lateral neutron flux.

**Ground Water Activation**

Based on the results presented in Tables 2 and 3 it is clear that the escaping neutron flux is approximately the same ($\approx 200$ /cm$^2$/s for 10 kW of beam power), both forward and laterally. In order to determine the maximum buildup of radioactive species in the soil it has been assumed that the beam dump is used in the high-power (10 kW) mode 2000 hours per year, and the buildup is allowed to take place for several life times. (The half life of $^{22}$Na is 2.6 yr and of tritium 12.3 yr.) In this limit the specific activity eventually becomes equal to the production rate. Because of the much lower limit on specific activity and because the shorter life-time, and thus the build-up time, for $^{22}$Na, calculations have been done only for this nucleus.

For an assumed density of the material outside the dump tunnel of 2 g/cm$^3$, a production cross section for $^{22}$Na of $2.4 \times 10^{-4}$ cm$^2$/g, a neutron flux of 200/cm$^2$/s, and 2000 H of 10 kW production per year the eventual activity of $^{22}$Na is 0.5 pCi/cm$^3$. With a sticking fraction leading to a 15% leach rate, the build up of activity is always comfortably (a factor of 5) under the limit in the worse case.

The core of the beam dump sits almost directly below the CLAS. As is shown above, a flux of high energy neutrons, which can be as large as 150/cm$^2$/s, escapes the dump tunnel headed in the direction of CLAS. Fortunately more than 240 cm of soil and concrete cover the dump tunnel above the actual dump. This material provides an additional 500 g/cm$^2$ of shielding and leads to an additional attenuation of the neutrons in excess of $5 \times 10^3$. Thus high energy neutrons coming directly from the dump should not be a factor for the operation of CLAS.

The lateral iron shielding must extend past the dump in the direction of the entering electrons in order to provide adequate shielding against neutrons produce at angles greater than 90°. It has been assumed, however, that the bulk of the dump tunnel will be filled with concrete, or other stony material in the form of gravel or sand. Thus many neutrons headed in the backward direction will pass through some iron and then through the stony material. While the neutron absorption lengths in concrete are almost 3 times as long as for iron, the oblique angle of the neutrons produced at large angles means they have a long path in the stony material, and this material becomes an effective shield. For both cost and weight reasons it is desirable to minimize the extent of the iron shielding.

A simple calculation has been performed that requires for all neutron production angles the net effective attenuation must be at least as great as for neutrons traversing the iron shield laterally. The criterion can be met if the iron portion of the shield is extended 91 cm (2.5 ft) in the upstream direction beyond the start of the tungsten portion of the dump.

## LOW-ENERGY GIANT-RESONANCE NEUTRONS

An additional source of background for the CLAS comes from lower energy neutrons produced by giant resonance photoneutron reactions in the target. Unfortunately the yield from giant resonance reactions rises with increasing Z of the dump in a form given by[7]

$$Y_{GR} = 0.0149 \cdot E_o \cdot Z^{0.73} \; neutrons/Gev \cdot electron \,. \tag{13}$$

Thus to reduce the giant resonance neutrons a dump composed of low Z material is desired. Clearly this requirement is incompatible with the need to reduce the production of high energy neutrons from the dump. The giant resonance neutrons are produced with lower energies, typically in the range from 2 to 15 MeV. While they are produced copiously, the adsorption length in iron is short, of the order of 5 cm, and thus they are easily absorbed in the dump and its shielding and provide no direct line-of-sight threat to the CLAS.

## NEUTRON EXITING THE BEAM PIPE

While neutrons cannot penetrate the shielding in sufficient numbers to pose a problem for the CLAS, they can pass unimpeded back through the beam transport pipe and exit into Hall B. There they are scattered until captured, producing a gamma-ray induced background from $(n,\gamma)$ reactions.

Equations 1-3 and 13 can be used to estimate the total neutron production in the dump and the number of neutrons that can exit the beam transport tunnel. If the opening of the beam pipe in to Hall B has an area of 400 $cm^2$ and is located 8 m from the dump, then the neutron fluxes for each energy range of interest are given in Table 4.

Table 4. Neutron Production in the Tagger Dump for 10 kW of power

| Neutron Energy | Production ($n\ sr^{-1}\ s^{-1}$) | Fraction absorbed in Dump | Exiting Neutrons ($s^{-1}$) |
|---|---|---|---|
| Giant Resonance | $1.6 \times 10^{12}$ | 0.5 | $5.0 \times 10^{8}$ |
| 25-100 MeV | $5.4 \times 10^{10}$ | 0.25 | $2.5 \times 10^{7}$ |
| 100-150 MeV | $1.6 \times 10^{9}$ | 0.25 | $7.5 \times 10^{5}$ |
| >150 MeV | $1.8 \times 10^{8}$ | 0.25 | $8.4 \times 10^{4}$ |

The results of the calculations presented in Table 4 show that most of the neutrons entering Hall B from the tagger beam dump are from giant resonance reactions and to a lesser extent, from the lower energy range of higher energy production, called henceforth, intermediate energy neutrons.

The giant resonance neutron flux from the tungsten portion of the dump can be reduced by placing a low Z absorber between the dump and the beam transport pipe. The removal cross section for these low energy neutrons can be characterized by

$$\sigma_r = 0.21 \cdot A^{-0.58}\ cm^2/g\ . \tag{14}$$

Equation 14 leads to the following Table 5.

Table 5. Low Energy Neutron Attenuation Lengths

| Material | A | $\sigma$ ($cm^2/g$) | $\rho$ ($g/cm^3$) | $\lambda_r$ (cm) |
|---|---|---|---|---|
| lithium | 7 | 0.068 | 0.53 | 27.7 |
| beryllium | 9 | 0.059 | 1.84 | 9.4 |
| carbon | 12 | 0.050 | 2.2 | 9.1 |
| aluminum | 27 | 0.031 | 2.7 | 11.9 |
| tungsten | 184 | 0.010 | 19.3 | 5.2 |

Table 5 illustrates that a good choice for a low Z absorber is carbon. The giant resonance neutron flux coming from the tungsten portion of the dump for a beam power of 10 kW is attenuated according to

$$N_{GR-W} = 5.0\times10^{8} \cdot e^{-x/\lambda_r}, \tag{15}$$

where x is the thickness of the carbon absorber.

Giant resonance neutrons are also produced in the carbon. Fortunately, as predicted by Eq. 13, the giant resonance neutron production falls with decreasing atomic number. According to this equation photoneutron production in carbon is more than a factor of 6 less than that in tungsten.

The neutron yield is assumed to be proportional to the energy deposited in the dump. At the front of the dump the energy deposited grows exponentially with depth in the shower material. For a low Z material (water) the energy deposited in the shower as a function of depth has been measured[8] to be

$$\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{x=0} \cdot e^{\lambda_+ x}, \tag{16}$$

where $\lambda_+ = 0.0563$ cm$^{-1}$, and $\left(\frac{dE}{dx}\right)_{x=0} = 4.4$ MeV/cm.

The region of exponentially increasing energy deposition is of course, restricted to the depth well before shower maximum. In carbon this depth is several radiation lengths, and Eq. 16 is entirely appropriate for the thicknesses considered here.

Giant resonance neutrons produced at some depth x in the carbon portion of the dump are attenuated by absorption in the dump before they can exit in the backward direction. Thus the expression for the giant resonance neutrons produced in the carbon that escape the beam tunnel is

$$N_{GR-C} = 2.4 \times 10^{6} \cdot \left(1 - e^{-x/\lambda_c}\right), \tag{17}$$

where $\frac{1}{\lambda_c} = \frac{1}{\lambda_+} + \frac{1}{\lambda_n}$.

Some fraction of the energy is deposited in the carbon and therefore not in the tungsten portion of the dump. This is not an important effect. Monte Carlo simulations of the proposed dump performed using the code GEANT predict the energy deposition in the different portions of the dump. These calculations show that for showers initiated by electrons with an energy of 6 GeV only 21% of the total beam power is deposited in 50 cm of carbon. Thus the reduction of neutrons coming from the tungsten due to the reduced power level reaching the tungsten is ignored in the calculations that follow.

Higher energy neutrons are also produced by the carbon. The production of these higher energy neutrons from carbon has been estimated under the following assumptions: 1) the production is proportional to the energy deposited, given by the same expression used for estimating giant resonance production (Eq. 16), 2) the production has the same angular dependence as for iron (given by Eq. 1), 3) the production cross section is energy dependent and of the same general form as assumed for forward and lateral production, 4) the production cross section must be scaled to be appropriate for carbon, and 5) the absorption of neutrons in the carbon is energy dependent.

Using the predictions of Eq. 1 for neutron production at 180° and assuming a energy dependence of the cross section of the form given in Eq. 4, the exponential constant is $\lambda_E = 0.065\ \mathrm{MeV}^{-1}$.

Equation 11 predicts that the high energy neutron production in carbon is 5.8 times that in tungsten.

The energy dependence of the neutron attenuation in carbon has been estimated by using the data plotted in Fig. 1 of Jenkins[4] and scaled to give the correct value for $E_n = 400$ MeV given by

$$\lambda_n = 45 \cdot A^{0.3} [cm] . \qquad (18)$$

This leads to the expression for the neutron attenuation in carbon for energies in the range from 25 to 100 MeV of

$$\lambda_n(E_n)\,[cm] = 0.34\, E_n\,[MeV] + 4.5\,[cm]. \qquad (19)$$

Using these assumptions and expressions, the number of intermediate energy neutrons produced in the tungsten escaping the dump as a function of carbon thickness for 10 kW of deposited power can be estimated by evaluating the expression

$$N_{IE-W} = 8.3\times10^{6} \cdot \int_{25}^{100} e^{-\frac{E_n}{\lambda_E}} \cdot e^{-\frac{x}{\lambda_{n(E_n)}}} dE_n \quad neutrons/\text{sec}. \tag{20}$$

The number of intermediate energy neutrons coming from carbon is obtained from evaluating the double integral

$$N_{IE-C} = 1.1\times10^{5} \cdot \int_{0}^{x} \int_{25}^{100} e^{\frac{x'}{\lambda_+}} \cdot e^{-\frac{E_n}{\lambda_E}} \cdot e^{\frac{x'}{\lambda_n}} dE_n \, dx' \quad neutrons/\text{sec}. \tag{21}$$

Table 5 gives the result of evaluating these expressions for a range of carbon thicknesses. As can bee seen the neutrons coming from the tungsten dump are attenuated by increasing carbon thickness, while the number of neutrons coming from the carbon increases with increasing carbon thickness. The increase in neutrons from carbon is particularly significant for intermediate energies. The total neutron production is at a minimum with a carbon thickness of approximately 50 cm. At this high power the flux of neutron (in the range of $2\times10^{7}$) could limit the operation of the CLAS, unless additional shielding around the beam dump pipe in Hall B can be employed.

Table 6 Neutron flux exiting beam pipe from different sources as a function of carbon thickness for a 10 kW dump

| Carbon Thickness (cm) | GR from Tungsten ($\times 10^6$/sec) | GR from carbon ($\times 10^6$/sec) | 25-100 MeV from tungsten ($\times 10^6$/sec) | 25-100 MeV from carbon ($\times 10^6$/sec) | Total neutrons ($\times 10^6$/sec) |
|---|---|---|---|---|---|
| 0 | 500 | 0 | 25 | 0 | 525.0 |
| 10 | 167 | 0.9 | 14 | 3.3 | 185.2 |
| 20 | 55 | 1.5 | 8 | 6.6 | 71.1 |
| 30 | 18.5 | 1.8 | 4.6 | 9.9 | 34.8 |
| 40 | 6.2 | 2.0 | 2.7 | 13 | 23.9 |
| 50 | 0.2 | 2.1 | 1.6 | 17 | 20.9 |
| 60 | 0.1 | 2.1 | 1.0 | 21 | 24.2 |
| 70 | | 2.2 | 0.6 | 25 | 27.8 |
| 80 | | 2.2 | 0.4 | 29 | 31.6 |
| 90 | | 2.2 | 0.3 | 34 | 36.5 |
| 100 | | 2.2 | 0.2 | 40 | 42.4 |

ENERGY DEPOSITED IN THE DUMP

Using the design criteria developed above, the energy deposition in the dump has been investigated using the code GEANT. The design consist of five 10-cm thick absorbers of carbon followed by ten 7-mm thick absorbers of tungsten. Each absorber consists of a disk 30-cm in diameter, and the different absorbers are all separated by 2 cm to allow the passage of cooling gas between the absorbers. Figure 2 shows the percentage of the total energy deposited in each absorber for 4 different incident energies. The percentage of power deposited in each absorber is quite uneven. As expected the shower maximum, and thus the peak power, occurs deeper in the dump as the energy rises. The maximum power dissipated in any one absorber is 18% of the total. Even at 6 GeV the total energy absorbed by the dump is greater than 97.5% of the energy carried by the beam.

COOLING THE DUMP

Operating the dump at or near the 10 kW level will require some method of removing the heat deposited by the beam. A simple gas flow system, probably employing dry nitrogen, is envisioned. The specific heat of nitrogen is 0.25 cal/g or 1.04 J/g. The density of nitrogen gas at STP is 1.25 g/l. If the temperature rise of the nitrogen is limited to 50° C, a flow rate of 160 l/s (340 CFM) is required.

The cross sectional area of the pipe required to carry this flow can be addressed with the use of the Darcy formula[9]

$$\Delta P_l = 1.21 \times 10^4 \cdot f \cdot \frac{\mathfrak{F}^2 S_g^2}{d^5 \rho}, \tag{22}$$

where $\Delta P_l$ is the pressure drop per length of pipe in Pa/m,

$f$ = friction factor,

$\mathfrak{F}$ = gas flow rate in l/s,

$S_g$ = specific density of gas relative to air,

$d$ = diameter of pipe in cm, and

$\rho$ = = density of gas in g/cm$^3$.

For a fully turbulent flow in steel pipe $f = 0.189\ N_R^{-0.187}$, where $N_R$(Reynolds number)

$= 156 \cdot \mathfrak{Z} \cdot \frac{S_g}{d\,\mu}$, and $\mu$ is the gas viscosity in centipoise. For nitrogen gas $S_g = 0.969$. The viscosity of nitrogen gas is a slowly varying function of temperature, ranging from 170 to 220 $\mu$poise for temperatures between 10 and 130°C. The term $\mu^{0.187}$ varies even less, ranging from 0.466 to 0.489 over this range of temperatures. For a temperature of 55°C, $\mu^{0.187} = 0.474$.

The friction factor $f$ for nitrogen is thus given by

$$f_{Ni} = 0.0351\left(\frac{d}{\mathfrak{Z}}\right)^{0.187} . \tag{23}$$

and the pressure drop per unit length for nitrogen gas operating at STP is given by

$$\Delta P_l = 319\frac{\mathfrak{Z}^{1.813}}{d^{4.813}} . \tag{24}$$

If we assume that the length of pipe needed is twice the length needed in the dump tunnel, or about a total of 30 m, that the pressure drop should be no more than 10 kPa, and that a flow rate of 190 l/s (400 CFM) is used, then a pipe diameter of 7.5 cm is sufficient. Table 5 illustrates the rapid dependence of pressure drop on pipe diameter.

Table 5. Pressure drop in 30 m of pipe for a flow rate of 190 l/s of nitrogen at standard pressure.

| diameter (cm) | ΔP (kPa) |
|---|---|
| 2.5 | 1600 |
| 5.0 | 56 |
| 7.5 | 8 |
| 10.0 | 2 |

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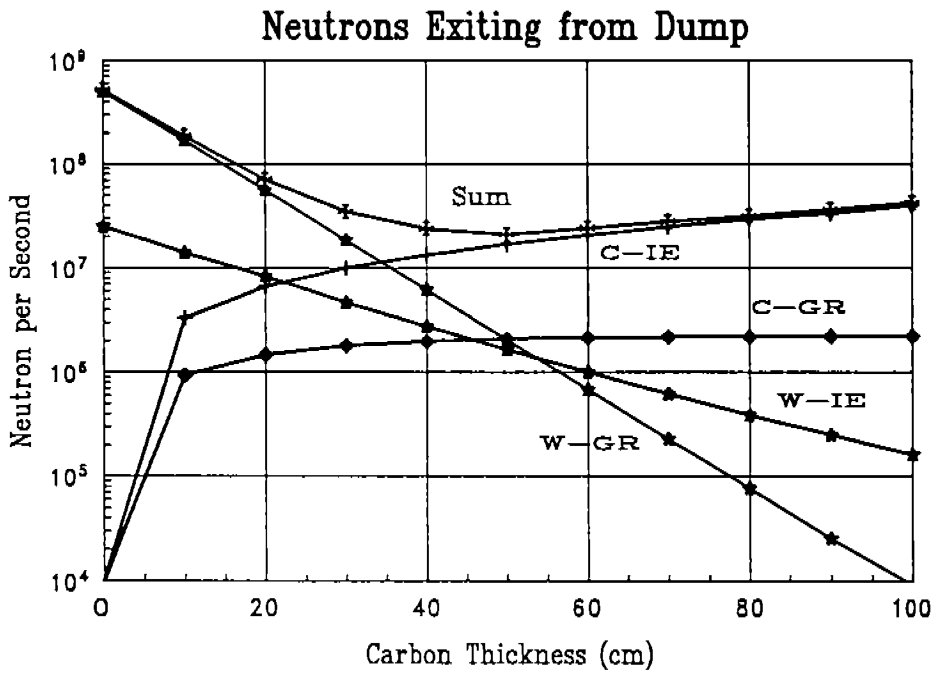


Figure 1. Neutrons exciting the tagger beam dump as a function of the thickness of the carbon absorber. The neutrons come either from the tungsten (W) or carbon (C), and are created either by the giant resonance reaction (GR) or intermediate energy pion production (IE).

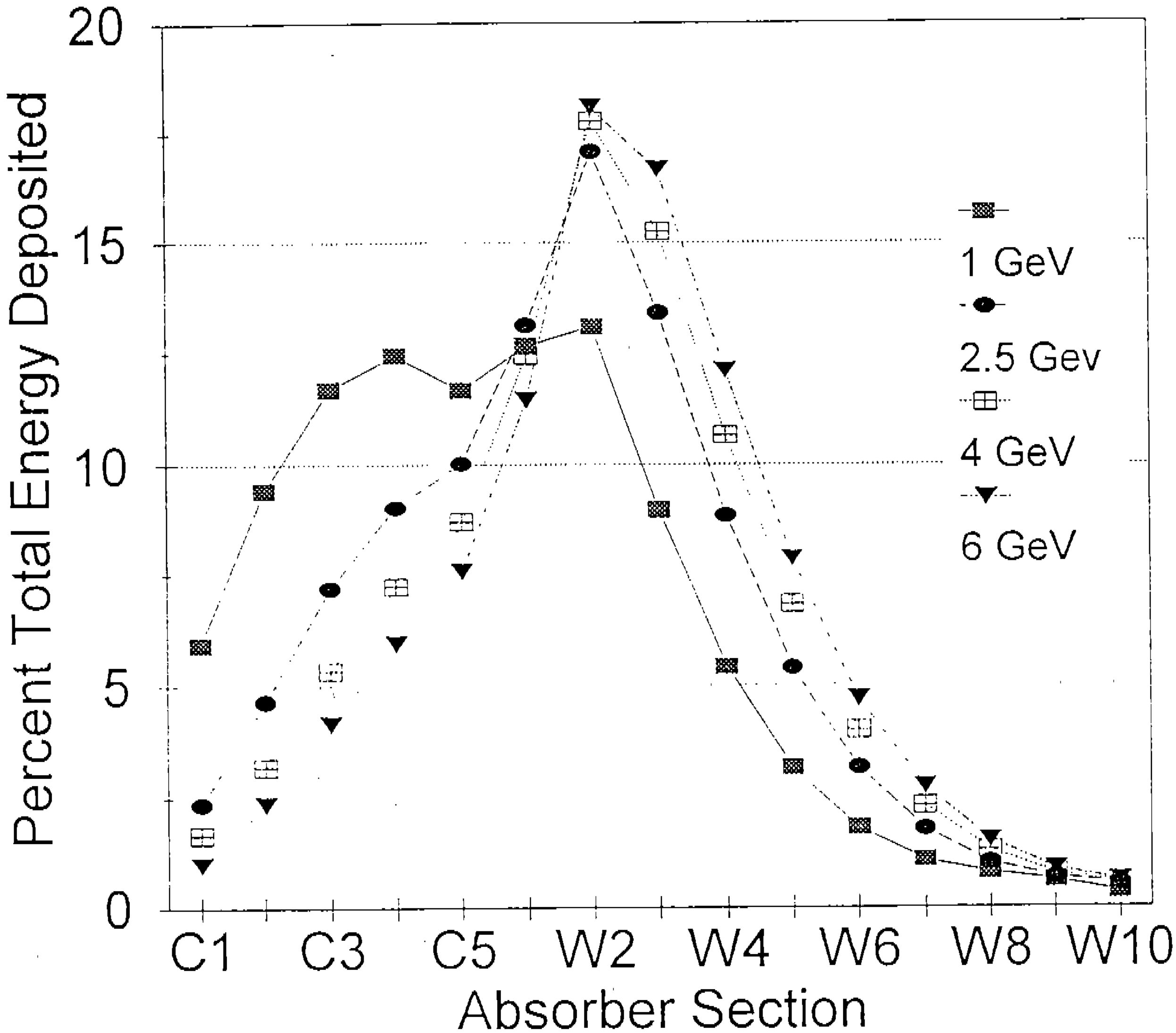


Figure 2. The percent of total beam energy deposited in the beam-dump absorber plates for several different incident beam energies. "C" indicates on of the 5 carbon absorbers, "W" indicates the associated tungsten absorber.