ALUMINUM BEAM STOP FOR THE NEUTRINO-AREA DUMP-BOX

M. Palmer and R. Stefanski

October 1971

The dump-box in the Neutrino-Area must provide the capacity to dissipate full beam power for both short and long spill operation. Figure 1 is a schematic diagram of the dump-box. Beam stops and hadron shields will be brought into the box through a vacuum-door in five-foot long modules. The beam stoppers will be water cooled and constructed out of aluminum.

In this article we present the data that led to the selection of aluminum as beam-stop material for the neutrino-area dump-box. We consider the effects of energy deposition in the beam-stop material, thermal properties of the material, long term radiation effects on the material and the mechanical properties of the material. We also outline our schedule for developing beam-stop capability at the dump-box.

Energy Deposition; Heating the Beam-Stop

The temperature rise in a beam-stop exposed to beam power is determined by the rate of energy loss of the beam, the beam spot size, the radiation length of the beam-stop material, and the specific heat and density of the material.

The effects of each of these must be considered to determine the applicability of a material as beam absorber.

Energy deposition curves for high energy protons have been estimated by a number of authors[1,2] and Fig. 2 gives the results of two of these calculations. Calculations are also available from the Radiation Physics Section. These estimates are based on particle production models that have not been confirmed at NAL energies. Large uncertainties in the calculations still exist. However, some general conclusions can be made.

If $\frac{dQ}{dV}$ is the energy deposition in the material, then the temperature rise is given by

$$\Delta T = \frac{1}{c\delta}\frac{dQ}{dV} \tag{1}$$

where, c = specific heat

δ = density of material.

However, $\frac{dQ}{dV}$ is roughly proportional to density: a dense material will absorb the beam in a smaller volume than a light material. If we write

$$\frac{dQ}{dV} = K\delta \tag{2}$$

where K is the same for all materials, then

$$\Delta T = K/c \tag{3}$$

and the temperature rise for each material is determined by its specific heat. Table I gives the specific heat for some metals.

The assumptions represented by Eq. 2 ignored the effects of radiation length on the development of the cascade in the beam stop material. Ranft estimates that, at high energies, 56% of the energy deposited in the material is through π^o production.[2] Since π^o's decay rapidly into gamma rays, the radiation length of the material is important in determining the transverse development of the cascade. For a small beam spot the radiation length will be important in determining $\frac{dQ}{dV}$; in Eq. 2, $\frac{dQ}{dV}$ will also be a strong function of radiation length, and Eq. 3 would be incorrect. However, it is clear that $\frac{dQ}{dV}$, and therefore ΔT, will be smaller for materials with a large radiation length.

The smallest spot size anticipated at the dump-box would be about 0.5cm in diameter. Since the radiation length for some materials is much larger than this, it would be advantageous to use low Z materials to minimize dQ/dV in the beam absorber. Table I lists radiation lengths for various materials.

The desirability of choosing a material with high specific heat and long radiation length leads naturally to aluminum as a good choice. Beryllium would be a good candidate but it is too expensive and it is a toxic material. In the following sections we shall show that other properties of aluminum are also quite good.

Thermal Properties; Cool-Down Time of Beam Stop

The length of time required to cool a material after it is exposed to the beam is determined by the thermal conductivity of the material and by geometric effects. From the Fourier equation

$$\dot{Q} = k\nabla T \qquad (4)$$

where: $\dot{Q}$ = cal/cm^{2}sec

k = thermal conductivity

∇ = Laplace operator

T = temperature

Therefore, the rate at which thermal energy is removed from the material is directly proportional to the thermal conductivity of the material. Table I gives a list of some materials and their thermal conductivity. Copper and aluminum are high on the list.

In general, cooling proceeds more rapidly when the ratio of cooled surface to volume is larger. The effects of a low thermal conductivity of a material can be compensated by exposing a greater part of its surface to the cooling medium. Thus small steel balls will cool as rapidly as large copper balls. However, a large surface to volume ratio implies a large exposure of the cooling medium to the beam. In the case of a water cooled system, this entails a larger volume of radioactive water to deal with, larger volumes of H_2 generated and more elaborate controls on water conductivity. It might also require a high pressure system to push the water through the beam stop. It is therefore desirable to use a material with reasonably high thermal conductivity.

However, in addition to considering the rate at which thermal energy is removed from the material, it is instructive to consider the temperature of the material and the rate at which it decreases under the influence of a cooling medium. In a water-cooled system it is desirable to operate below temperatures of 100°C, especially for a fast spill. As shown in the previous section, materials with a high specific heat will operate at lower temperatures. But consider also a specific example of a 2" slab which is heated by a beam incident perpendicular to the face of the slab. If the temperature at the center of the slab increases by ΔT, and if both faces of the slab are cooled, then

$$T = T_{H_2O} + \Delta T \quad e^{-t/\tau} \qquad (5)$$

where, T = temperature of slab

T_{H_2O} = temperature of cooling medium

t = time in sec. after the beam is turned off.

$\tau = 3.1 \frac{\delta c}{k}$ = 2.8 sec for Cu
3.7 sec for Al.

It is evident in this example that the cool-down time of the material, given by τ, is related to thermal conductivity and, also, the heat capacity, $c\delta$, of the material. Therefore, although copper cools faster than aluminum, the difference in cool-down time is not as great as would be predicted on the basis of thermal conductivity alone. In addition, since the specific heat is high, ΔT is likely to be less for aluminum to begin with.

We conclude, therefore, that the use of a material of high thermal conductivity is desirable, but that other effects may well be paramount. Since aluminum has a reasonably high thermal conductivity, it is a good candidate as beam stop material. Although copper would give a better cool-down time, its residual radioactivity would be high as is shown in the next section.

Residual Specific Activity

The beam stop in the dump-box can be removed or replaced to accommodate different beam configurations or to insert special loads for beam-stop experiments. The handling procedures are simplified if the residual radioactivity of the material is kept at a minimum. Radioactive isotopes are generated as spallation products of the interactions of beam particles with nuclei in the beam stop. Lighter materials are, therefore, advantageous since fewer spallation products are feasible. Table II gives some long-lived nuclei, their cross-sections, half-lives and residual radioactivity after one month of running at full beam intensity in copper and aluminum. Two effects are evident in comparing copper and aluminum: 1) In aluminum only the lighter isotopes are produced and 2) in aluminum the production of Be^7 and H^3 is much less than in copper. So again we have good reason to use a lighter material such as aluminum as beam-stop material.

Long-term exposure to radiation tends to make materials stronger and more brittle, but the effects are not large. Thermal conductivity, mass density and elastic constants are unaffected at room temperature and above.[3]

Mechanical Properties of Metals

Table I lists some of the mechanical characteristics of various materials. Because of the consideration in the previous sections, however, aluminum is the only material we hope to use and we concentrate on its properties.

For a water-cooled system it is important to use a material that can withstand erosion reasonably well. Aluminum has been used in water-cooled systems at SLAC with good success. Also, aluminum does not corrode, because it develops a hard film of aluminum oxide on its surface.

Aluminum is easy to machine and aluminum welding techniques have been developed and are widely used.

The mechanical strength of aluminum as given by its yield point and tensile strength is reasonably high. The ability of the material to withstand the thermal shocks it will be exposed to will depend, however, on the details of the mechanical design of the beam stop. As an example, consider a situation in which the beam is dumped into a large solid aluminum block. The heated core will be constrained by the cold metal around it and will not be able to expand. The stress developed is given by

$$S = 2\alpha Y \, \Delta T \qquad (6)$$

where S = stress in PSI

α = coefficient of linear expansion $= 2.4 \times 10^{-5}\,{}^{\circ}C^{-1}$

Y = Young's modules for Al - 10^{7}PSI

ΔT = temperature chance in $^{\circ}$C.

Then: $S/\Delta T = 480 \frac{PSI}{^{\circ}C}$.

Therefore the aluminum would approach its yield joint with only a 10°C temperature increase. This estimate is probably over-pessimistic, since it does not allow for the ductility of the material. However, large thermal stresses must be considered in the beam-stop design.

Disadvantage of Low Density Material

A low density material requires excessive length to fully attenuate the beam. From Fig. 2 it is evident that about 90% of the beam power is absorbed in seven absorption mean free paths. This corresponds to about four feet of copper and 13.6 feet of aluminum. Since handling requirements dictate that car loads be no longer than five feet, it is apparent that at least two aluminum cars would be required.

The beam-stop cars must be backed up with neutron shielding cars which will be made of steel. Whatever beam power is not dissipated in the beam stop will serve to heat up the steel shielding cars. If only one aluminum beam stop car is used, the shield car immediately behind it will heat up at a rate of $100^{\circ}C\ hr^{-1}$ (10^{-13}pps). This rate is excessive and would require that some water cooling be provided for the shield car.

Summary

The advantages of aluminum outweigh the disadvantages of using two beam stop cars. It is our intent, when full beam power is available, to use two aluminum beam stoppers, backed up by two steel neutron shields. In the initial operation of the accelerator, however, we will use one beam stop car and one neutron shield. This will suffice during the initial learning phase to test our ideas on handling procedures for the cars; our ability to make water, gas and electrical connections within the dump box; and our ability to operate a beam stop within a vacuum environment. Should we find that the aluminum beam-stop is insufficient, we can then proceed to design a beam stop made of heavier material.

References

[1] NAL Technical Memo, TM-218, M. L. Stevenson.

[2] Rutherford Laboratory Preprint, RPPIN 20, J. Ranft.

[3] Billington, Douglas; Radiation Damage in Solids; Princeton University Press.

U. S. Office of Naval Research; The Effects of Radiation on Materials; Reinhold Publishing Company.

TABLE I

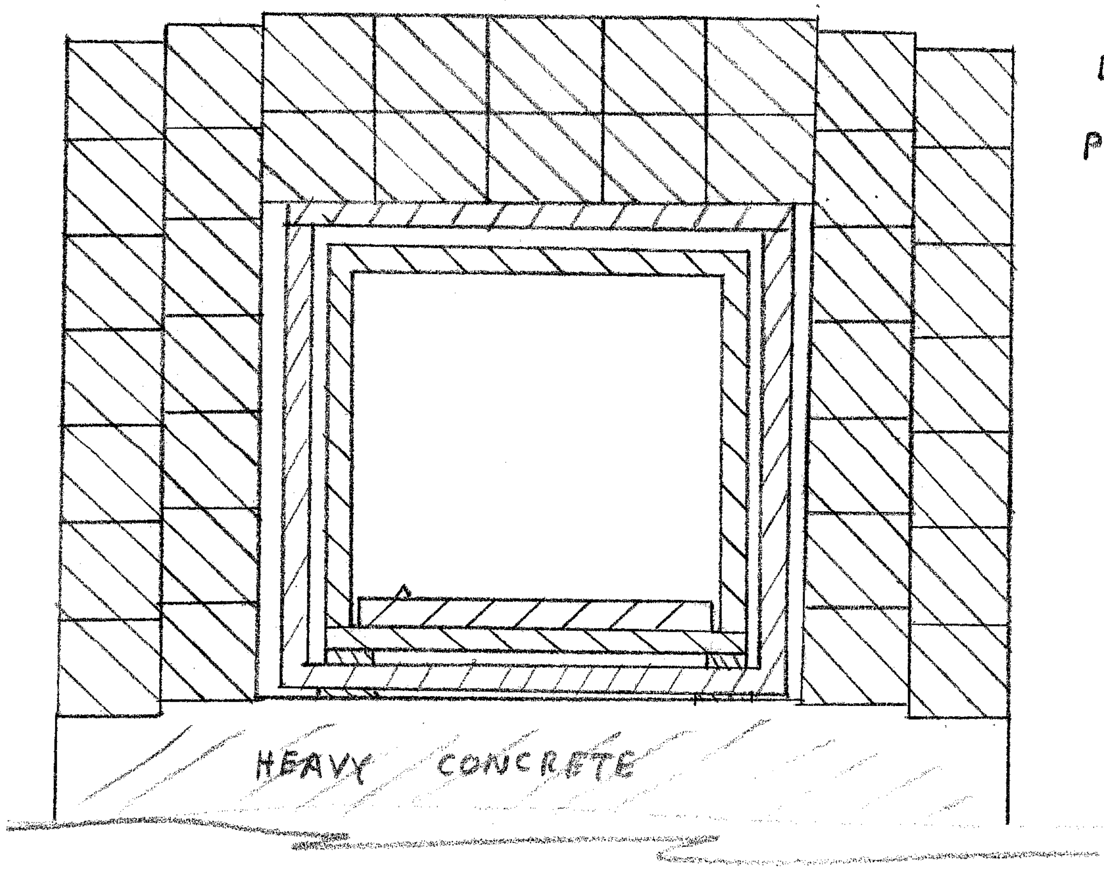
	Specific Heat	Thermal Conduct-ivity	Melting Point	Density	Radiation Length	Collision Length	Elongation Const.	Young's Modules	0.2% Yield Point	Tensile Strength
	Cal/gm°C	Cal/cm °Csec	°C	gm/cm^3	gm/cm^2	gm/cm^2	$10^{-6}°C^{-1}$	10^6PSI	10^3 PSI	10^3PSI
Bc	0.45	0.38	1277	1.85	66.0	55.0	11.6	44.0	40-60	60-90
C	.165	.057	3727	2.26	43.3	60.4	+0.06 -0.8	4.4	-	$(\sim 2 \frac{kgm}{mm^2})$
H_2O	1.0	.0014	-	1.00	35.7	57.2	-	-	-	-
Al	.215	.50	660	2.70	24.3	79.2	25.	10.0	5-21	13-24
Ti	.126	.038	1668	4.51	15.1	-	8.7	15.0	80	95
Fe	.11	.18	1537	7.86	13.9	101.2	12.1	29.0	8-40	18-60
Cu	.092	.94	1083	8.96	13.0	105.4	16.6	17.0	5	32
W	.033	.397	3410	19.3	6.8	150.8	4.6	50.0	-	18-20 (sinter-ed ingot)

TABLE II

	Nuclide Produced	σ	$\tau_{1/2}$	Activity after 1 mo.
		mb	yrs.	curies
Copper:	Co^{60}	14	5.27	5-
	Fe^{55}	17	2.9	12
	Na^{22}	2.9	2.6	2
	Be^{7}	165	(53.4 da.)	1830
	H^{3}	202	12.3	33
Aluminum :	Na^{22}	17	2.6	9.
	Be^{7}	9	(53.4 da.)	71.
	H^{3}	45	12.3	9

NATIONAL ACCELERATOR LABORATORY ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	EXP FAC	ν-LAB		

SUBJECT	NAME	
DUMP-BOX NEUTRINO LAB	R. STEFANSKI	
	DATE	REVISION DATE
	4/29/71	



DUMP BOX PROFILE

PLAN VIEW

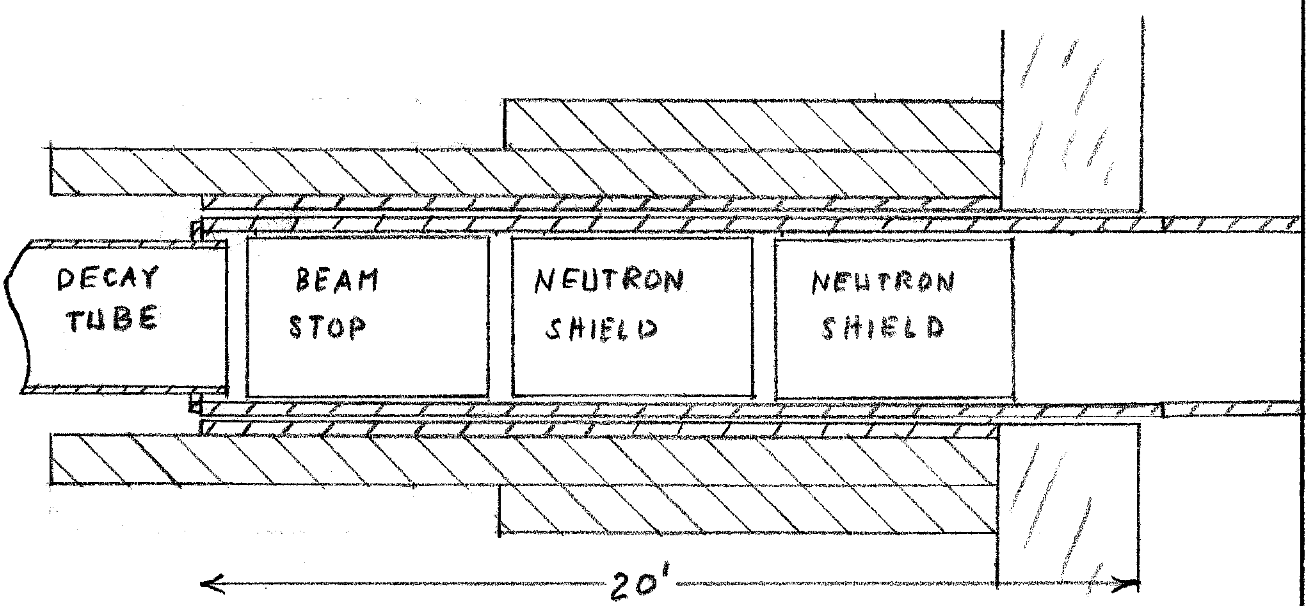


FIG 1

NATIONAL ACCELERATOR LABORATORY ENGINEERING NOTE	SECTION EXP FAC	PROJECT ν LAB	SERIAL-CATEGORY	PAGE

SUBJECT	NAME	
ENERGY DEPOSITION	R. STEFANSKI	
	DATE 4/28/71	REVISION DATE

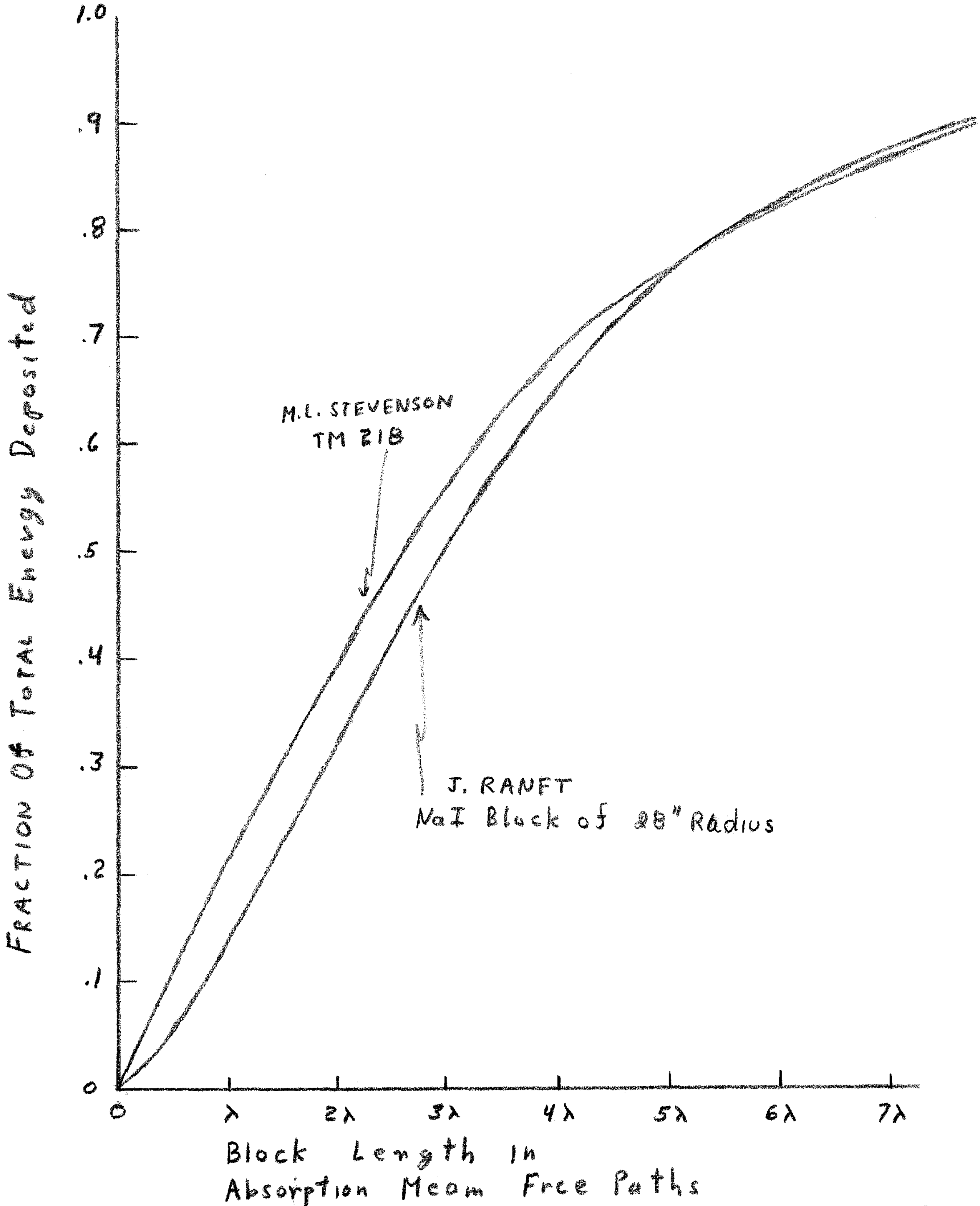


FIG 2