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Heating of Target Cell Components by Secondary Particles Produced by the LAMPF Proton Beam

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HEATING OF TARGET CELL COMPONENTS BY SECONDARY PARTICLES
PRODUCED BY THE LAMPF PROTON BEAM

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Patrick A. Thompson

ABSTRACT

The 1 mA 800-MeV proton beam at LAMPF contains 800 kW of energy. Calculations have been made of the amount of heat produced by the absorption of secondary particles in some of the magnets in Target Cell No. A-2. For thick targets the total energy released in this target cell is of the order of 500 kW and the amount absorbed by each of the three magnets considered of the order of 100 kW. These numbers are sufficiently large that they must be carefully considered and appropriate cooling supplied. The recommendation of this note is to shield the magnets as much as practical and to provide water cooling for the yoke of the magnets. It is also recommended that the thickest target to be considered for use in Target Cell No. A-2 under 1 mA beam conditions be 6 cm of Al_2O_3 (which is referred to as the "standard maximum target"). The gain by going to thicker targets is probably not worth the added cost in terms of cooling capacities. The results developed in this paper are mainly devoted to Target Cell No. A-2; however, a few cases have been run for the biomedical channel and the muon channel results can be scaled for the biomedical beam line. Target Cell No. A-1 has similar problems which are not considered herein.

1. INTRODUCTION

The proton beam at LAMPF has a design intensity of 1 mA at 800 MeV. When this beam interacts with a production target a great deal of energy is removed from the primary beam. This energy loss occurs through several channels: (1) dE/dx scattering in the target, which heats up the target and may through thermal radiation result in heating of nearby components such as vacuum windows, (2) multiple scattering of the proton beam, which may result in significant proton fluxes striking the downstream mainline beam components, and (3) protons scattered through large (compared to multiple scattering) angles and interaction products, which can produce heating of secondary beam line components. The intensity of the beam is high enough that the power dissipated may be of the order of hundreds of kW. Some of the power will be carried off by rather penetrating particles, further complicating the problem of shielding it. This particular paper considers the magnitude of and possible solutions to

the problems generated by processes (2) and (3). In the consideration of interaction products, only protons, neutrons, and charged pions are considered. The errors introduced by neglecting the contribution from other particles are small compared to the uncertainties inherent in a calculation of this sort. The problem of activation is closely related to the problem of heating considered here, and indeed one can get rough estimates of activation by multiplying the heat generated by the appropriate constants (dependent upon activation product of interest). The results of detailed computer calculations are believed to be accurate to $\pm 20\%$ and are obtained in the following way:

1. From the input target parameters the length of the target in collision lengths is obtained. From this number, the number of interactions is computed (see Appendix for formulae). This number is compensated for the dE/dx loss before the collision. At the same time, the length of the target in radiation lengths is computed; from this,

one calculates the amount of multiple scattering. The two numbers together give the total in this target cell.

2. From the results of a nuclear cascade code supplied by D. Cochran,¹ by interpolation, and multiplication by the number of interactions, one obtains the spectrum for the given target as a function of angle.

3. The energy lost as a function of depth at this specific angle is calculated in the following way:

a. The neutrons are treated with an empirical formula that fits Alsmiller's² calculations.

b. The proton energy loss is assumed to be the sum of dE/dx plus the loss that a neutron of the same energy would undergo. Specifically, the dE/dx is multiplied by the fraction of protons which have reached a given depth without interaction; and the neutron equivalent loss is multiplied by the proton energy divided by the initial proton energy. The combination of these gives results in agreement with Alsmiller's calculations for total dE/dx of protons.

c. Pions are treated in the same manner as protons except that when a pion is stopped its mass (for π^- or its mass less 50 MeV for π^+) is added to the energy loss.

4. For a given component the above steps are performed for five angles spanning the component. The integration over the component is then performed by taking a 100 points distributed over it. The power deposited at each of these points is found by interpolation within the five angles calculated. The contribution from multiple scattering is calculated directly for each point. The whole calculation takes about 35 seconds of 6600 CP time.

5. Assuming that the beam illuminates the target uniformly and that the target is cylindrical in shape with a diameter of 1 cm, the average distance that a particle travels before leaving the target is calculated. The energy lost in this region is calculated in the same manner as the rest of the calculation. This energy loss is not shown in the printout but it does reduce the calculated energy deposited in the magnets. The size of this loss can be as much as 30% at some angles. (This

correction was omitted in an earlier version of the program.)

6. Approximations used. The correct solution to this problem would be to use a full-scale Monte Carlo shielding code such as DTF-IV (USAEC Report LA-3373, Los Alamos Scientific Laboratory, 1965). The amount of computer time required to carry these calculations to the depth required and for the number of cases considered would be prohibitive. Thus, the neutron energy loss has been approximated with analytic fits to Alsmiller's calculations and the proton loss with a home-brewed mixture of the above neutron data and dE/dx for charged particles. Also the energy for the decay and/or capture products of the pions has been assumed to be deposited locally, whereas the 52 MeV positron has a range of some 25 gm/cm². This latter is a negligible effect.

For high-Z targets some of the beam will be multiple scattered out of the target before it can interact. In the extreme case of the 12-cm-tungsten target, this might redistribute of the order of 20% of the power into the forward direction.

II. GENERAL DISCUSSION

Before presenting the detailed results for specific cases, it is worthwhile to summarize some general properties of the problem. The results presented in this section can be used as rules-of-thumb to estimate cases not covered in detail in the next section.

A. Probability of Interaction

The first thing to consider is the probability that an incident proton will cause a nuclear interaction in a given target. For our case one must also consider the energy at which this interaction occurs (i.e., a 400-MeV proton interaction will produce lower energy secondaries than an 800-MeV one). The number of interest is essentially the fraction of the incident energy (assumed to be 800 MeV) which is converted into secondaries. This is plotted in Fig. 1 as a function of the thickness of the target in collision lengths. For reference, collision lengths for various materials are given in Table I. To obtain the power reradiated one multiplies the fraction given in Fig. 1 by the initial beam power (nominally 800 kW).

TABLE I
PROPERTIES OF TYPICAL TARGET MATERIALS

Material	Z	A	Density (gm/cm ²)	Collision-----Length (gm/cm ²) (cm ⁻¹)	Radiation-----Length (gm/cm ²) (cm ⁻¹)
C	6	12	1.8	60.4 33.6	43.3 24.2
Al ₂ O ₃	~10	~20	4.0	72.0 18.0	30.0 7.5
Al	13	27	2.7	79.2 29.3	24.3 9.0
Fe	26	56	7.9	101.2 12.2	13.9 1.8
Cu	29	64	9.0	105.4 11.8	13.0 1.5
W	74	184	19.3	150.8 7.8	6.8 0.4

Reference: Particle Properties, April 1972, Rosenfeld, et al.

Fig. 1. Fraction of interactions as a function of target thickness.

B. Multiple Scattering

The basic formulae for multiple scattering are well known and are given in the Appendix. For a thick target one must consider some additional complications:

1. The energy of the emerging scattered proton will not be its initial energy, thus reducing the power distributed by multiple scattering.
2. Because of this reduction in energy the multiple scattering will be increased.

These two effects are of opposite sign and for the cases of interest cancel to better than 2%. They are ignored. Also a large portion of the incident beam will undergo an interaction and hence must be subtracted before making the multiple scattering calculation. To calculate the multiple scattering contribution, I have assumed a 30-mr aperture in

Fig. 2. Fraction of incident beam power appearing as multiple scattered protons for selected target materials.

the beam line quadrupole. (Obviously to get a meaningful result one must choose some angle.) Figure 2 displays the results of these calculations, where the multiple scattering is expressed as a fraction of the incident beam power. Comparing Figs. 1 and 2 one can see that the proton beam is most efficiently used by a target of low-Z.

C. Energy Spectrum

The spectrum of the secondary particles as a function of angle is important because it determines the depth that the radiation will penetrate. The dominant secondary particles are neutrons and protons. (Large numbers of electrons are produced but their energy and range are so low that they are not important.) The spectra are similar in shape for the neutrons and protons and are rather independent of target material. The main change with target

material is the increase in the ratio of neutrons to protons as a function of increasing Target Z. Proton spectra¹ from an iron target are shown in Fig. 3.

Fig. 3a. Secondary proton spectrum from an iron target for angles from 20 to 180°.

Fig. 3b. Secondary proton spectrum from iron target for angles from 1 to 9°

NOTE: Vertical scale is $\times 10$ that of Fig. 3a.

D. Power Distribution as a Function of Angle

The most important parameter in estimating the power absorbed by a particular component is the total radiated power incident upon the component. The actual details of this distribution are somewhat complex in that it depends upon the target thickness and material. For purposes of making estimates Fig. 4 is provided. This figure shows the energy distribution as a function of angle for some possible target materials. The curve contains only the contribution from secondary neutrons and protons. (The contribution from π 's, etc., is less than 10%.) It does not include the contribution

Fig. 4. Total power as a function of angle.

from multiple scattering of the incident beam. As can be seen from this curve the power drops almost three orders of magnitude between the forward and backward directions. The curve is plotted for 100% interactions and should be multiplied by the fraction of interactions for a particular target given in Fig. 1.

E. Power Distribution as a Function of Depth

The power absorbed as a function of depth depends on both the energy and type of particles incident. Some typical curves are given in Fig. 5. These curves are plotted for normal incidence upon iron at a distance of 100 cm and include the effects of π flux. For all cases considered, the power per gram is a maximum at the surface due to the large low energy flux; for angles less than 30° there is a significant flux of high energy protons which produce the break in the curve at 50 to 100 gm/cm². For angles above about 30° this effect disappears and one sees simply a rapid drop-off for the first portion due to the attenuation of the low energy charged particles followed by the characteristic neutron tail.

Fig. 5. Power absorbed as a function of depth.
Target: 6-cm carbon
Absorber: iron

III. DETAILED CALCULATIONS FOR TARGET CELL NO. 2 AND BIOMED TARGET

This section discusses and presents the results of computer calculations of the heating of target cell components. Table II and Fig. 6 summarize the physical dimensions of these components. In general, calculations have been performed for the target cell magnets with no shielding and then with a 20-cm tungsten shield and a 40-cm iron shield. For the muon channel the 40-cm iron shield is not practical. The shields have been assumed to taper as shown in Fig. 6. In most cases this taper is not important; however, for the muon and P^3 channels, the taper on the edge closest to the beam is very important because of the rapid increase in power in the forward direction. The bores of the shields have also been assumed to be tapered so as to subtend the same solid angle as the bore of the component which they are shielding. Finite target size is not taken into account.

Figure 7 shows the computed angular distributions for the targets considered. These distributions include the contribution from the multiply

Fig. 6. Elements of Target Cell No. 2.

Fig. 7a. Power per steradian for selected targets.
Theta = 0.7° to 7.0°

scattered incident proton beam. Table III gives the parameters of the proton targets considered.

Tables IV through VII give the results for each component and configuration calculated. The quantities tabulated are the total power absorbed by the object in kilowatts and the maximum and minimum power densities on the front surface. The numbers are not accurate beyond one significant figure. Additional

Fig. 7b. Power per steradian.
Theta = 7.0° to 140°

figures have been included for symmetry. For each beam line three cases have been considered: the components as originally designed with no shield, the same configuration with the addition of a 20-cm tungsten shield, and with a 40-cm iron shield.

A. Muon Channel: Table IV

The muon channel is at a reasonably good angle, however the large size of the first magnet and the short distance to the target increase the heat load substantially. The radiation incident in this direction is not as penetrating as that for the more forward components. Thus, significant improvements can be realized with a rather thin (14 cm) tungsten shield -- which is all that will physically fit. In addition, the muon channel is unique in that the coils are concrete insulated. This insulation is probably rather heat sensitive -- presumably if it gets hot it loses water and eventually strength. How well this concrete is cooled by the copper coils is not certain; in many places on the existing coils the concrete is in poor mechanical and hence thermal contact with the coils.

TABLE II
PHYSICAL DIMENSIONS OF COMPONENTS CONSIDERED

TARGET CELL No. 2		Width (cm)	Height (cm)	Bore (cm)	Distance from Target	Thickness (cm)	Material
Component	Angle (degrees)						
μC_W	65	74	74	16	32	20	Tungsten
$\mu QM01$	65	114	114	25	52	84	Iron
$\mu QM02$	65	114*	114	25	160	86	Iron
$P^3 C_{Fe}$	20	41	49	12	72	40	Iron
$P^3 C_W$	20	52	63	16	92	20	Tungsten
$P^3 QM01$	20	64	80	20	117	63	Iron
$P^3 QM02$	20	64	80	20	180	63	Iron
TCT C_{Fe}	0	49	65	16	204	40	Iron
TCT C_W	0	56	72	18	224	20	Tungsten
TCT QM01	0	64	80	20	250	65	Iron
TCT QM02	0	64	80	20	320	65	Iron
BIOMED C_W	70	44	68	20	31	14	Tungsten
BIOMED QM01	70	92	140	27	64	36	Iron
BIOMED QM02	70	92	140	27	128	39	Iron

*NOTE: The computer program actually assumes that the second quadrupole completely fills the shadow of the first quadrupole in each beam line. Thus, the dimensions used in the calculation are larger (by the ratio of the radii) than those given in the table above. Since the power absorbed in the second magnet is always greatly reduced from that in the first and since it cannot be calculated that accurately, this effect can be ignored.

TABLE III
TARGET PARAMETERS

Material	Z	Length (cm)	Density	X/X ₀	X/L _{col}	θ_{ms} (degrees)	RTAR	Nuclear Power (kW)	Mult. Scat. (kW)	Total (kW)
Mo	42	0.6	10.2	0.62	0.05	0.77	0.049	39.3	5.4	44.7
C	6	6.0	1.8	0.243	0.178	0.48	0.163	130.0	0.0	130.0
Al ₂ O ₃	10	6.0	4.0	0.80	0.331	0.88	0.280	224.1	12.7	236.8
C	6	12.0	1.8	0.486	0.356	0.69	0.298	238.0	1.1	239.1
Al ₂ O ₃	10	12.0	4.0	1.60	0.662	1.25	0.477	381.9	61.3	443.3
Cu	29	12.0	9.0	8.223	1.015	2.82	0.621	497.1	200.3	697.5
W	74	12.0	19.3	33.611	1.538	5.71	0.748	598.6	157.0	755.6

NOTES:

X = target thickness in gm/cm²

X₀ = radiation length

L_{col} = nuclear collision length

θ_{ms} = rms multiple scattering angle

RTAR = fraction of incident beam power appearing as secondary particles (does not include multiple scattering)

Nuclear Power = power appearing as secondary particles

Mult. Scat. = power carried off by multiple scattered proton beam (assuming 30 mr quadrupole aperture)

TABLE IV
TOTAL POWER ABSORBED AND MAXIMUM AND MINIMUM LOCAL POWER DENSITIES FOR MUON CHANNEL

Component	Parameter	Target =	0.6 cm Mo	6 cm C	6 cm Al ₂ O ₃	12 cm C	12 cm Cu	12 cm W	Configuration
QM01	P _{total}		5.4	21	35	39	66	74	unshielded
	P _{max}		0.2	0.7	1.0	1.3	2.3	2.1	
	P _{min}		0.02	0.1	0.2	0.3	0.2	0.2	
QM02	P _{total}		0.04	0.1	0.2	0.3	0.5	0.6	
	P _{max}		0	0	0	0	0	0	
	P _{min}		0	0	0	0	0	0	
C _W	P _{total}		4.7	19	32	35	57	64	14-cm tungsten shield
	P _{max}		0.9	3.4	5	6.2	9.0	9.5	
	P _{min}		0.08	0.6	0.9	1.1	0.9	0	
QM01	P _{total}		1.3	4.6	7.8	9.5	16	19	
	P _{max}		0.01	0.05	0.08	0.09	0.2	0.2	
	P _{min}		0	0	0	0	0	0	

Results are given for two different configurations: (1) bare magnets without shielding, and (2) magnets protected by a 14-cm tungsten collimator. The results are given for the first two components in the line in each case.

P_{total} = total power absorbed by the device in kilowatts.

P_{max} = maximum power density on the front surface in watts/cm³.

P_{min} = minimum power density on the front surface in watts/cm³.

TABLE V
TOTAL POWER ABSORBED AND MAXIMUM AND MINIMUM LOCAL POWER DENSITIES FOR P³ CHANNEL

Component	Parameter	Target =	0.6 cm Mo	6 cm C	6 cm Al ₂ O ₃	12 cm C	12 cm Cu	12 cm W	Units	Configuration
QM01	P _{total}		5.0	22	36	40	63	82	kW	unshielded
	P _{max}		0.13	0.5	0.9	0.9	1.4	3.0	watt/cm ³	
	P _{min}		0.05	0.2	0.3	0.3	0.5	0.5	watt/cm ³	
QM02	P _{total}		0.3	1.1	1.8	1.9	3.3	3.7	kW	
	P _{max}		0	0.01	0.01	0.01	0.02	0.2	watt/cm ³	
	P _{min}		0	0	0	0	0	0		
C _W	P _{total}		4.4	20	32	36	60	77	kW	20-cm-tungsten shield
	P _{max}		0.4	1.5	2.6	3.1	4.0	9.5	watt/cm ³	
	P _{min}		0.1	0.5	0.8	0.8	1.4	1.3	watt/cm ³	
QM01	P _{total}		1.0	4.5	7.3	8.1	13	16	kW	
	P _{max}		0.04	0.2	0.3	0.3	0.5	0.8	watt/cm ³	
	P _{min}		0	0.01	0.02	0.02	0.04	0.04		
C _{Fe}	P _{total}		4.7	21	34	38	61	82	kW	40-cm-iron shield
	P _{max}		0.4	1.4	2.4	2.8	3.8	9.1	watt/cm ³	
	P _{min}		0.1	0.4	0.8	0.7	1.2	1.2	watt/cm ³	
QM01	P _{total}		0.8	3.2	5.2	5.8	9.6	11	kW	
	P _{max}		0.02	0.1	0.2	0.2	0.3	0.6	watt/cm ³	
	P _{min}		0	0.01	0.01	0.01	0.03	0.03	watt/cm ³	

Results are given for three different configurations: (1) bare magnets without shielding, (2) magnets protected by a 20-cm-tungsten shield, and (3) magnets protected by a 40-cm-iron shield. The results for the first two components are given in each case.

P_{total} = total power absorbed by the device in kilowatts

P_{max} = maximum power density on the front surface in watt/cm³

P_{min} = minimum power density on front surface

For the operation of the muon channel, we have requested consideration of a 12-cm-tungsten target, which generates three times the heat in the target cell triplet as the "standard maximum target" of 6-cm of Al₂O₃. I believe this problem should be ignored for the following reasons:

1. This thick target will be used only when the beam is at 100 μ A or less;

2. Lack of this target will not hurt the muon channel more than 5%.

Under this constraint the total power loading of the first component is 40 kW, and the fluctuation in power density across the front surface is about 7:1.

TABLE VI
TOTAL POWER ABSORBED AND MAXIMUM AND MINIMUM LOCAL POWER DENSITIES
FOR TARGET CELL TRIPLET

Component	Parameter	Target =	0.6 cm Mo	6 cm C	6 cm Al ₂ O ₃	12 cm C	12 cm Cu	12 cm W	Units	Configuration
QM01	P _{total}		3.5	16	26	28	140	130	kW	unshielded
	P _{max}		220	125	160	160	15	2.7	watt/cm ³	
	P _{min}		...	0.1	0.3	0.3	0.4	0.9	watt/cm ³	
QM02	P _{total}		0.2	0.7	1.2	1.3	2.0	2.0	kW	
	P _{max}		...	0	0	0	0.01	0.01	watt/cm ³	
	P _{min}		...	0	0	0	0.01	0.01		
C _W	P _{total}		2.8	13	21	23	126	120	kW	20-cm-tungsten shield
	P _{max}		520	310	370	380	33	5.8	watt/cm ³	
	P _{min}		0.07	0.3	0.5	0.6	0.9	2.1	watt/cm ³	
QM01	P _{total}		0.08	3.4	5.5	6.1	19	16	kW	
	P _{max}		130	76	90	91	4.0	0.6	watt/cm ³	
	P _{min}		0.015	0.04	0.06	0.08	0.1	0.3	watt/cm ³	
C _{Fe}	P _{total}		2.9	13	22	23	130	120	kW	40-cm-iron shield
	P _{max}		380	247	260	280	23	4.0	watt/cm ³	
	P _{min}		0.05	0.2	0.3	0.3	0.7	1.5	watt/cm ³	
QM01	P _{total}		0.5	2.3	3.8	4.1	10	8.8	kW	
	P _{max}		110	73	90	93	2.7	0.3	watt/cm ³	
	P _{min}		0.01	0.03		0.05	0.09	0.2	watt/cm ³	

Results are given for three different configurations: (1) bare magnets without shielding, (2) magnets protected by a 20-cm-tungsten shield, and (3) magnets protected by a 40-cm-iron shield. The results for the first two components are given in each case.

P_{total} = total power absorbed by the device in kilowatts

P_{max} = maximum power density on the front surface in watt/cm³

P_{min} = minimum power density on the front surface in watt/cm³

B. P³: Table V

The P³ channel is at a more forward direction, but a larger distance from the proton target and hence the power loading is about the same as the muon channel. The energy of the incident radiation is higher requiring thicker collimators. There is, however, somewhat more room.

For the first element the total power is 50 kW or less and the variation across the front surface is approximately 3:1. The standard shields do a reasonable (5x) job of reducing the power. The requirements on distortion from uneven heating are somewhat higher for this line than for the muon channel.

TABLE VII (a)
TOTAL POWER ABSORBED AND MAXIMUM AND MINIMUM LOCAL POWER DENSITIES FOR BIOMED CHANNEL

Component	Parameter	Target =	0.6 cm Mo	5 cm C	5 cm Al ₂ O ₃	Units	Configuration
QM01	P _{total}		2.0	7.5	10	kW	unshielded
	P _{max}		0.09	0.3	0.5	watt/cm ³	
	P _{min}		0.02	0.14	0.16	watt/cm ³	
QM02	P _{total}		0.24	0.8	1.1	kW	
	P _{max}		---		less than 0.01	watt/cm ³	
	P _{min}		---		less than 0.01	watt/cm ³	
C _W	P _{total}		1.5	5.7	7.8	kW	15-cm-tungsten shield
	P _{max}		0.7	2.6	3.5	watt/cm ³	
	P _{min}		0.14	1.1	1.4	watt/cm ³	
QM01	P _{total}		0.3	1.1	1.6	kW	
	P _{max}		0.01	0.02	0.03	watt/cm ³	
	P _{min}				less than 0.01	watt/cm ³	

Results are given for two different configurations: (1) bare magnets without shielding, and (2) magnets protected by a 15-cm-tungsten shield. The results for the first two components are given in each case.

P_{total} = total power absorbed by the device in kilowatts

P_{max} = maximum power density on the front surface in watt/cm³

P_{min} = minimum power density on the front surface in watt/cm³

C. Target Cell Triplet: Table VI

The target cell triplet is in the worst position from the standpoint of nuclear heating. In particular for thick targets the multiple scattered incident proton beam will hit the magnet. The radiation hitting the magnet is predominantly 800 MeV and hence, the "standard" collimators do not work very well (less than 5x). The total power for the first element is less than 50 kW. There is extreme (> 100:1) fluctuation in power density across the front face.

D. Biomed: Table VII

The biomed beam line is located at 70° relative to the proton beam and hence is in a good location as far as radiation is concerned. The maximum

power for the targets considered is less than 10 kW. It is possible, since this channel is designed for low energy π^- , that they might consider a high-Z thick target. Detailed calculations have not been made for this target but by inspection of the calculations for the muon channel, it appears that such a target would produce less heating than the 5-cm Al₂O₃ target considered. With such low maximum power levels it would probably be feasible to run the channel with no heat shielding at all. Calculations were done only for a 15-cm-tungsten shield which provides a factor of 8 reduction. Calculations were also done for the heat load of the TCT in the biomed target cell for a 5-cm-Al₂O₃ target. These were done both with and without a 100-cm-collimator.

TABLE VII (b)
TOTAL POWER ABSORBED AND MAXIMUM AND MINIMUM LOCAL POWER DENSITIES FOR BIOMED CHANNEL TCT

Component	Parameter	Target =	5 cm Al ₂ O ₃	Units	Configuration
QM01	P _{total}		47	kW	unshielded
	P _{max}		120	watt/cm ³	
	P _{min}		0.4	watt/cm ³	
QM02	P _{total}		1.8	kW	
	P _{max}		32	watt/cm ³	
	P _{min}		0.04	watt/cm ³	
C _{Fe}	P _{total}		130	kW	15-cm-tungsten shield
	P _{max}		12	watt/cm ³	
	P _{min}		0.2	watt/cm ³	
QM01	P _{total}		5.6	kW	
	P _{max}		0	watt/cm ³	
	P _{min}		0	watt/cm ³	

Results are given for two different configurations: (1) bare magnets without shielding, and (2) magnets protected by a 100-cm-iron shield. The results are for the first two components and are given in each case.

P_{total} = total power absorbed by the device in kilowatts

P_{max} = maximum power density on the front surface in watts/cm³

P_{min} = minimum power density on the front surface in watts/cm³

The triplet receives a total of 47 kW without the collimator and 12 kW with.

IV. HEATING OF CONCRETE FLOOR

Because of structural weakening from water loss, concrete is vulnerable to overheating; it is important to consider how much the concrete floor beneath the target cell will be heated by nuclear radiation. The results of these calculations are presented in Table VIII. The units and notation are the same as those used for the individual beam line components. It should be noted that the calculations have been done with the assumption of a 30-cm-thick layer of iron covering the concrete. Without this covering the power levels are rather high; it is important that this covering not have large holes in the vicinity of the target.

The conductivity of concrete is low (0.5 BTU/hr-ft-°F).³ With the power levels given in Table

VIII, if there is no iron shielding, the temperature rise of the concrete may be of the order of 100°C.

For example, assume a uniform power density of 0.004 watts/cc down to a depth of 50 cm. Then

$$\Delta T = \frac{PH^2}{2kA}$$

$$P = 4 \times 10^{-4}, \quad H^2 = 2.5 \times 10^3$$

$$k = 2.5 \times 10^{-3}, \quad A = 1.0$$

$\Delta T = 200^\circ\text{C}$. Admittedly, the actual geometry is rather complex, but the above numbers are representative.

V. DISCUSSION OF COOLING

The first step in considering the cooling problem is to establish a criterion for the maximum allowable temperature. A somewhat arbitrary limit is 100°C for water-cooled components and 200°C for air-cooled. These will produce distortions in the

TABLE VIII
HEATING OF CONCRETE FLOOR

Material	Length	P _{total} (kW)	P _{max} (watt/cm ³)	P _{min} (watt/cm ³)	Target
Mo	0.6	1.5	0.02	0.	iron
		0.2	0.	0.	concrete
C	6.0	5.7	0.08	0.04	iron
		0.8	0.	0.	concrete
Al ₂ O ₃	6.0	9.1	0.1	0.02	iron
		1.3	0.	0.	concrete
C	12.0	10.0	0.1	0.03	iron
		1.4	0.	0.	concrete
Cu	12.0	17.0	0.2	0.04	iron
		2.8	0.	0.	concrete

NOTES: Peak power density occurs at about 65°.
Power integrated over an area 240 by 240 cm.
Power density at 90° approximately 75% of maximum.

yoke of a few hundredths-of-an-inch which is probably as much as can be permitted.

A. Convection

The simplest solution to the problem would be to ignore it and say that when the magnets get hot enough they will cool themselves by conduction, convection, and radiation. Because of the temperature limits imposed above, radiation cooling will be ignored. Table IX lists the amount of convection cooling calculated (with the able assistance of K. Meier, MP-6) from the formulae in Jakob's work.⁴ A cubical magnet has been assumed. The heat transfer goes roughly as the 1.25 power of the temperature, so if one allows the full 200°C rise for a 3-ft.-cube magnet, one can get 10 kW of cooling. This is inadequate for a large component by itself but marginally adequate for a component with a thick shield.

B. Conduction

The conduction of the air is negligible. The conduction of solid components is worth considering. First, consider the stands for the magnets -- a typical stand will have three 1-in.-diam jack screws with a length of about 2 in. The impedance of this piece of steel is approximately 1°C/watt, or 0.3°C/

TABLE IX
HEAT TRANSFERRED BY CONVECTION

Temperature Rise (degrees F)	Length of side of cube (feet)	Log ₁₀ (Gr Pr)	Heat Transfer BTU/hr	kW
100	1	8.17	630	0.2
	2	9.07	2800	0.8
	3	9.60	6750	2.0
200	1	8.47	1400	0.4
	2	9.37	7200	2.1
	3	9.90	16000	4.6

watt for all three legs. Thus, the maximum power which can be dealt with in this manner is 0.6 kW. Some heat may be carried off by the beam pipes, however, these are generally stainless steel and rather thin and long. It is possible that significant cooling could be accomplished by heat transfer to the coils which are water-cooled. Unfortunately, the insulation of these coils is a poor conductor of heat and the mechanical contact between the coils and the yoke is also poor. It is not possible to calculate this heat loss to any useful accuracy -- a guess would be that it is not significant.

C. Miscellaneous Methods

Very brief consideration has been given to forced convective cooling, addition of heat fins, addition of conduction paths, etc. This is outside my competence but most of these methods seem more trouble than they are worth.

D. Water Cooling

The most direct method of cooling the magnets is to use water cooling. The heat transferred by this method is easily calculated and the temperature rise accurately predictable. Aside from the construction and engineering effort involved, this is the best way.

E. Target Cell as a Whole

In addition to the individual components, one must consider the total heat developed in the target cell. Reference to Table III indicates that with the maximum "standard target" this is about 250 kW. R. Macek, MP-6, has brought it to my attention that dissipating this heat by conduction through the steel shielding will not work, e.g.,

If one assumes a shield consisting of a hollow sphere of iron with inside radius 3 feet and outside radius 20 feet, the temperature rise is 400°C. Due to cracks between shielding blocks and the fact that half of the "sphere" is actually concrete the actual temperature rise will be much more.

Thus, water cooling should be provided to dissipate a total of 250 kW. If water cooling is provided for the magnets (approximately 160 kW) then the target cell cooling need only make up the deficit.

If for example, some components are allowed to cool themselves by convection, this heat load still must be removed from the target cell.

V. SHIELD THICKNESSES

One way to reduce the amount of heat intercepted by a magnet is to place a shield in front of it. In the calculations some representative shields have been considered. The actual shields used will have to be based on the physical space limitations, cost, etc. To aid in estimating the effects of shields of different thicknesses than those calculated, Table X lists the approximate thicknesses of shields of different materials needed

to reduce the power absorbed by the magnet by factors of 5, 10, and 20. The thickness needed varies with angle because of the change in spectrum.

TABLE X
SHIELDING THICKNESS (in centimeters) AS A
FUNCTION OF SHIELDING FACTOR AND ANGLE

Material and Shielding Factor		0°	10°	20°	40°	60°	90°
Iron	5X	29*	34*	31*	29	21	18
	10X	42	48	43	41	30	26
	20X	54	63	58	54	39	35
Tungsten	5X	19*	28*	19*	17*	13*	11
	10X	27	41	27	25	18	16*
	20X	35	53	36	33	24	21

Lead, copper, and steel are all roughly the same as iron.

*These values are closest to the actually calculated values. The accuracy of the estimated thicknesses in any column decreases with increasing distance from the asterisked numbers. In general, the accuracy is about 1-1/2 significant figures.

VI. CONCLUSIONS AND RECOMMENDATIONS

The power levels that will be produced are high enough that they must be given serious consideration. Even at 10% of design beam the levels can not be ignored. It is recommended that for full beam the thickest target considered be 6 cm of Al_2O_3 or the equivalent. Thicker targets cause large increases in heat load (and induced radioactivity) without a significant increase in pion production. The biomed channel is of course a special case and it may be advantageous to consider a thick high-Z target for this area. It is also recommended that the cooling of components be done by direct water cooling, and that the magnets, except for the biomed channel, be shielded. It is also necessary to provide cooling for the bulk shielding and protection for the concrete floor. The detailed values are tabulated below.

Target Cell No. 2

Maximum Full Beam Target: 6-cm- Al_2O_3

Total Power Dissipated: 240 kW

Recommended Target Cell Cooling: 150 kW (100°F rise 25% over-design)

μ Channel

14-cm-tungsten shield

Total Power: 32 kW

Recommended Cooling: 40 kW (100°F rise 25% over design)

Magnet: QM-01

Total Power: 8 kW

Recommended Cooling: 12 kW (50°F rise 50% over design)

P³ Channel

40-cm-iron shield

Total Power: 34 kW

Recommended Cooling: 40 kW (100°F 25% over design)

Magnet: QM-01

Total Power: 5 kW

Recommended Cooling: 8 kW (50°F rise 50% over design)

Target Cell Triplet (downstream only -- upstream has negligible heating)

40-cm-iron shield

Total Power: 22 kW

Recommended Cooling: 28 kW (100°F rise 25% over design)

Magnet: QM-01

Total Power: 4 kW

Recommended Cooling: 6 kW (50°F rise 50% over design)

Biomed Channel

Total Target Cell Power: 240 kW

Recommended Cooling for Target Cell: 250 kW (100°F rise 25% over design)

Magnet QM-01 (no shield suggested)

Total Power: 10 kW

Recommended Cooling: 15 kW (100°F rise 50% over design)

REFERENCES

1. D. Cochran, private communication.
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3. E.R.G. Eckert and R. M. Drake, Jr., *Heat and Mass Transfer*, p. 508 (McGraw-Hill, New York) 1959.
4. M. Jakob, *Heat Transfer*, p. 529 (John Wiley and Sons, New York) 1949; also Ref. 3, p. 308.
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APPENDIX FORMULAE USED

I. GENERAL PROPERTIES

$$Z/A = 0.538 \approx 0.01568 \sqrt{Z}$$

$$\text{Collision Length} \approx 26.5 A^{1/3} \text{ gm/cm}^2 \equiv L_{\text{col}}$$

$$C = 0.150 (Z/A) \text{ used in } dE/dx \text{ calculation} \quad (R)$$

$$I = 1.3 \times 10^{-5} Z \text{ MeV} \quad \text{used in } dE/dx \text{ calculation} \quad (R)$$

$$1/X_0 = 0.0013959 \frac{Z(Z+1)}{A} \left[\log \left(\frac{183}{Z^{1/3}} \right) \right] \frac{1.0}{1.0 + 0.1 \left(\frac{Z}{82} \right)^2}$$

$$\theta_{\text{ms}} = 0.0172 \sqrt{\frac{X}{X_0}} \quad (\text{for 800-MeV protons}) \quad (R)$$

$$F_{\text{TAR}} = \exp(-X/L_{\text{col}}) \quad (\text{percent of incident beam which does not interact})$$

$$R_{\text{TAR}} = 1.0 - \exp(-X/L_{\text{col}}) - 0.0156 (X/L_{\text{col}})^2$$

(fraction of incident beam power which interacts; the X^2 term allows for dE/dx losses in the target).

$$F_{\text{MS}} = \exp(-X/L_{\text{col}}) \exp(-0.03/\theta_{\text{ms}}^2) \quad (\text{the fraction of incident beam power which is multiple scattered through an angle greater than } 30 \text{ mR}).$$

$$\text{SCAT}(\theta) = \frac{F_{\text{TAR}}}{\pi \theta_{\text{ms}}^2} \exp\left(-\left(\frac{\theta}{\theta_{\text{ms}}}\right)^2\right) \quad \left(\begin{array}{l} \text{fraction of} \\ \text{incident beam} \\ \text{scattered per} \\ \text{steradian at the angle } \theta. \end{array}\right) \text{ This is the calculation for multiple scattering only.}$$

NOTE: The (R) refers to Ref. 5. The other formulae in this section are either well known or were developed by the author as approximations to numerical data.

II. ENERGY LOSS EQUATIONS

A. Neutrons

$$dE/dX|_N = \frac{710}{L_{\text{col}}} \exp(-2.3 \sqrt{C_H^2 + S^2 X_u^2})$$

$$\text{where } X_u = \frac{X}{\sqrt{2} L_{\text{col}}} - \Delta \quad X = \text{depth in gm/cm}^2$$

$$\Delta = 0.37 + 6 \times 10^{-4} E_n \quad E \text{ in MeV.}$$

$$C_H = 1.56 + E_n(-2.09 \times 10^{-3} + 1.07 \times 10^{-6} E_n)$$

$$S \begin{cases} = 0.34 + \frac{0.2}{(0.01E)^{1.736}} & X_u > 0 \\ = 1.5 - E \cdot 10^{-3} & X_u \leq 0 \end{cases}$$

This is an approximate fit to Alsmiller's calculations² with an accuracy of 50%.

B. Protons

For protons the energy deposited consists of two components:

1. the dE/dx loss due to electromagnetic interactions in the medium, and

2. the nuclear interaction loss arising from the interactions of the protons with the nucleus.

The method adopted has been to combine these two in a plausible arrangement which gives the correct total energy deposited. (Presumably, for this application, errors in the distribution of energy are not as important as the total energy.) The formula used for dE/dx is given below:

$$\left. \frac{dE}{dx} \right|_{EM} = \frac{2 C m_e}{\beta^2} \left\{ \log \left[\frac{4 m_e^2 \beta^4}{(1-\beta^2)^2} \right] - 2 \beta^2 \right\} \quad (R)$$

$$E(x) = E_0 - \int \frac{dE}{dx}$$

$$\text{TOTAL } \left. \frac{dE}{dx} \right|_p = \left. \frac{dE(x)}{dx} \right|_{EM} \cdot e^{-\frac{x}{\sqrt{2} L_{col}}} + F(E_0, E(x - \sqrt{2} L_{col})) \left. \frac{dE_0}{dx} \right|_N$$

where: E_0 is the initial proton energy

$E(x)$ is the proton energy degraded by passage through x gm/cm²

$F[E_0, E(x - \sqrt{2} L_{col})]$, F has the following properties:

1. $E_0 > 350$ MeV

$$\begin{aligned} F &= \frac{E(x - \sqrt{2} L_{col})}{E_0} \text{ for } 0 < E(x - \sqrt{2} L_{col}) \leq E_0 \\ &= 1 \text{ for } E(x - \sqrt{2} L_{col}) \geq E_0 \\ &= 0 \text{ for } E(x - \sqrt{2} L_{col}) \leq 0 \text{ where } E(x - \sqrt{2} L_{col}) = \\ &\quad E(x - \sqrt{2} L_{col}). \end{aligned}$$

2. $E_0 < 350$ MeV

$$F = 1 \text{ for } E(x - \sqrt{2} L_{col}) \geq E_0 \text{ and } E(x) > 0$$

$$F = \frac{E(x - \sqrt{2} L_{col})}{E_0} \text{ for } 0 \leq E(x - \sqrt{2} L_{col}) < E_0 \text{ and } E(x) > 0$$

$$F = 0 \text{ for } E(x) \leq 0.$$

The purpose of the function F is to compensate for the fact that the amount of energy produced in a nuclear interaction depends upon the energy of the proton which produces it. Empirically, it turns out that the best results are obtained by using the energy of the proton when it produced the shower which is roughly $\sqrt{2} L_{col}$ earlier in the material. It also turns out to be desirable to cut off the shower for initial energies less than 350 MeV at the end of the proton range rather than $\sqrt{2} L_{col}$ later as is done with the higher energy protons. This system is not particularly elegant or exact, but it produces energy depositions in agreement with better calculations up to 30 gm/cm² (as deep as the detailed calculations went), a total energy deposition equal to the incident energy and is fairly plausible. It is also computationally simple.

The charged pions are treated in the same manner as the protons (with corrections being made for the lower mass and the energy deposited at the end of the range by capture or decay). The neutral pions, electrons, and heavy charged particles are ignored.