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TOLERABLE SODIUM CONTENT IN THE CONCRETE OF THE FRONT END GALLERY (AREA 2)

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In an enclosure containing accelerator components in which high energy hadrons may be lost, remanent radioactivity is created by these hadrons and the extranuclear cascades initiated by them. This radioactivity causes an exposure rate that may render maintenance of the components difficult by reducing the occupancy time of the personnel in some areas to inconveniently short times.

Now, at any point in the enclosure, the total exposure rate is the sum of the exposure rates due to the radioactivation of the accelerator components and of the walls, floor and roof of the enclosure itself.

The remanent radioactivity of the accelerator component is dependent of the number and energy of the hadrons impinging on it. As a first approximation one assumes this radioactivity to be proportional to the hadron power loss. A study of the results given in reference 1, for 3 GeV and 200 GeV protons on steel, for a lateral shielding thickness of 100 g/cm^2 of steel (~5 inches) support this "rule of thumb".

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The accelerator components to be located in the gallery are going to be mainly magnets. In the design of conventional magnets there is little choice of component materials. The core is low carbon steel, the coils are made of copper. In addition, the beam losses cannot be limited. With incident proton currents of 1.5 x 10^{13} p/sec at 200 GeV, one may expect localized losses of one to ten kilowatts of secondary neutrons and off momentum charged hadrons. The exposure rates from these areas to the personnel can only be controlled by the use of local shielding such as steel or lead.

The hadrons exiting from the steel shields will enter the walls of the enclosure. Obviously there is a simple geometrical relationship between the hadron fluxes causing the radioactivation of the steel and of the walls. The estimate of the tolerable sodium content of the walls will be based on that simple fact.

The exposure rate from the walls will then be a function of the hadron fluxes as well as the chemical composition of the concrete.

In the area where NAL is being built, the lowest cost concrete consists of portland cement, water, crushed limestone and sand. This is very fortunate because the local limestone is nearly sodium-free. A typical analysis[(2)] of this type of concrete may give,

	oxygen	52.5% by weight	*	silicium	2.3% by weight
*	calcium	23.0		hydrogen	.8
	carbon	10.0	*	iron	.7
*	magnesium	9.9	*	aluminum	.6
					99.8% by weight.

At this moment it is necessary to emphasize the fact that the above results are typical but also vary greatly from sample to sample. Limestone varies in composition as a function of quarry and along each excavation. The sand and gravel defy any analysis since they come from rocks which had been swept ages ago by the glaciers. It is only possible to predict the composition of the concrete if the limestone and sand are first stockpiled in their respective quarries, then analyzed, and finally the concrete is mixed using them. Fortunately the chemistry of the portland cement is such that their formulation is less variable and sodium is a poison to be avoided.

Of the elements shown in the above analysis, the starred ones may be the source of long-lived radioactive nuclides by either neutron capture or by spallation. An element not listed above is sodium. This sodium that appears as a contaminant has a large cross-section for neutron capture.

The ^{23}Na (n,γ) ^{24}Na is the greatest single source of remanent exposure from the concrete. ^{24}Na has 1.37 and 2.75 MeV gammas, and a h -life of 15 hours.

Calculations[(3)] show that the radiative neutron capture reaction in sodium is the most important single reaction leading to concrete remanent exposure rate. Actually, in a concrete containing 1% sodium by weight, this reaction is fifteen times more important than all others. One hour after beam shut-down, essentially all the exposure rate from the concrete is due to ^{24}Na. These calculations[(3)] are in good agreement with measurements made by P. Gollon[(4)] and W. Gilbert, et al.[(5)] in all cases except magnesium where the Mg (hadron, spallation) ^{24}Na, is overestimated by a factor of three. The two measurements[(4,5)] are in excellent agreement with each other. Hence, one feels confident using Armstrong's results[(3)] in estimating the contribution to the total remanent exposure rate by the radioactivity created in the walls.

The calculations[(3)] mentioned above were carried out for the following geometry,

1) monochromatic protons uniformly lost on the axis of a 40 g/cm^2 (~5 inch) steel cylinder,
2) the steel cylinder is coaxial with a cylindrical void in an infinite block of concrete.

Although this geometry is not real, it allows a building designer to approximate an answer to the following crucial question,

what is the effect of the sodium content of the concrete on the total exposure rate to a worker at two feet from a magnet, one hour after beam turn off and after an infinitely long irradiation time?

Note that a shorter irradiation time such as one month would make the wall contribution twice as important as in the case of an infinitely long irradiation. This is so because the steel would not have reached saturation of its longer lived radioactivities.

Note also that in the case of the geometry described above, the exposure rate from the walls is,

1) uniform inside the void,
2) inversely related to the radius of the void and equal to the exposure rate at the wall itself.

Then, from Armstrong's paper we get,

$$\frac{\text{Exp. rate in contact with steel } (r = 2 \text{ in})}{\text{Exp. rate from wall } (\text{Na content} = 1\%,\ r = 7.5 \text{ ft})} = 11$$

for a cooling time of 1 hour, and an infinite irradiation time.

However, a more reasonable average distance between the worker and the steel would be 22 inches, while at the front of the gallery a more representative radius would be 6 feet. Then, for the same conditions,

$$\frac{\text{Exposure rate from steel}}{\text{Exposure rate from wall}} = 11 \times \frac{(2/24}{(7.5/6)} = .73$$

This means that the worker would be getting ~58% of his dose from the wall! To reduce the exposure rate from the wall, we must reduce the sodium content of the concrete.

A possible choice is that the exposure rate from the wall be 20% of the total exposure rate. This would mean, $\frac{\text{Exposure rate (Fe)}}{\text{Exposure rate (wall)}} = 4$ or a decrease of the exposure rate from the wall by a factor of 5.5. Since most of the sodium-24 comes from the (n,γ) reaction, this reduction in exposure rate implies a reduction of the sodium content of the concrete from 1% to (1/5.5)% = 0.18%.

Hence, it is recommended that the average sodium content in the concrete of the front gallery (Area 2) be kept at 0.2%.

There are, of course, some questions not easy to answer with respect to the validity of using Armstrong's calculations in the front end gallery. Let us discuss them.

1) The calculation was made for an infinite line source. The actual loss will be a short line. These short lines have a length that approaches a few gallery-widths. Hence, the calculation overestimates only slightly the thermal

neutron flux and the sodium-24 formation.

2) The calculation was made for three GeV protons and the typical hadrons that will be lost by momentum selection will range from a few tens to two hundred GeV. The main energy transport through a thick shield is due to particles that entered the shield nearly normal to its thickness or were created in the shield itself in that direction. Since the mean transverse momentum is about 0.3 GeV/c, the general shapes of the energy spectra of the outgoing hadrons should be generally similar for thick shields. Thus, the ratios of radionuclide densities and the nuclear species at the outer edge of the steel and entrance to the concrete should remain essentially independent of primary hadron energy. Still, the calculation was for a "thin" shield (2 in. of steel) which would tend to harden the spectrum and de-emphasize the sodium-24 formation with respect to the spallation of iron. Hence, one is taking a risk in accepting a value as high as 0.2% for the sodium content. Should this be found later to be too high, one may either increase the local shield or use local thermal neutron shields(6) over the concrete.

Actually, large variations in the magnesium and aluminum content of the concrete could produce a small change in the tolerable sodium content(7). However, from the experience gained during the mixing of the low sodium concrete for the booster enclosure, it is only necessary to specify and analyze the sodium content.

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