The dose-rate at 1 metre from lead and steel blocks, measured at times from 1 hour to 1 year after being irradiated in a beam of 15 GeV protons are given. After decay times long compared to the irradiation time, steel activity is shown to decay as $t^{-1}$ whereas lead activity decays as $t^{-1.4}$. These empirical relations are used to develop expressions for the dose-rate after any irradiation and decay time. The faster rate of decay of the dose-rate from lead suggests that under certain conditions, induced activity dose-rates may be reduced by facing steel with lead. It is shown that, for example, the average dose-rate from lead would be only about one fifth of that from steel during a one-month shut-down, after being irradiated under the same conditions for a year or so in an accelerator.
In Fig. 1 are shown some measured dose-rates at 1 metre from steel and lead blocks which had been irradiated in a beam of 15 GeV protons. The irradiation times, beam intensities and block thicknesses are not the same for the two irradiations so that the absolute dose-rates are not directly comparable. What is of interest is the fact that at decay times long compared to the irradiation time, both curves go over to a power law dependence on decay time. For steel the slope of the log-log dose-rate decay plot is unity and for lead about 1.4.

With a knowledge of the conditions of the two irradiations the empirical power law can be used to predict dose-rates from steel and lead for any irradiation and decay time.

The straight line parts of the steel and lead dose-rate curves can be represented by:

\[ D = A t^{-n} \]

where \( t \) is the decay time. If the beam strength is \( \phi \) and the irradiation time \( T \), then

\[ A = k \phi T \]

where \( k \) is a constant for the material considered. The dose-rate expected for any other irradiation time \( T \) will be:

\[ D = k \phi \int_{0}^{T} (t + T)^{-n} \, dt \]
Integrating and putting in the numerical values given in the table below, the dose-rates from the lead and steel blocks can be expressed by:

\[
D(\text{lead}) = 1.0 \times 10^{-12} \Phi \left[ t^{-0.4} - (T + t)^{-0.4} \right] \text{rad/h}
\]

\[
D(\text{steel}) = 1.8 \times 10^{-13} \Phi \log \left( \frac{T + t}{t} \right) \text{rad/h}
\]

where \( t \) and \( T \) are in hours and \( \Phi \) in particles per second. The curves corresponding to these expressions have been plotted through the experimental points in Fig. 1 into the regions where the irradiation time is comparable with the decay time.

The steel block to which the expression above applies was only 2 cm thick. The most useful comparison between dose-rates from lead and steel would be for materials many gamma mean paths thick such that the gamma dose-rate is independent of thickness. The measured dose-rates would need a correction to apply to equilibrium thickness, of

\[
c = \int_0^X \frac{Be^{-\mu X}}{(X + 100)^2} dX
\]

where \( B \) is the dose build-up factor, \( \mu \) the linear narrow beam gamma absorption coefficient, and \( X \) the thickness of the block in cm.

For the lead block no correction is necessary as the block was already thick enough. For the steel it is estimated that the dose-rates would have been twice that measured had the steel block been very thick. Hence the dose-rates from lead and steel that should be compared are:

\[
D(\text{lead}) = 1.0 \times 10^{-12} \Phi \left[ t^{-0.4} - (T + t)^{-0.4} \right] \text{rad/h}
\]

\[
D(\text{steel}) = 3.6 \times 10^{-13} \Phi \log \left( \frac{T + t}{t} \right) \text{rad/h}
\]
The dose-rate ratio \( D(\text{lead})/D(\text{steel}) \) is plotted in Fig. 2 as a function of decay time for irradiation times from 1 h to 1 year. In an actual accelerator situation only dose-rates from materials that have been irradiated for a reasonable time will be of interest. The ratios given are of the dose-rates from thick targets irradiated with narrow beams. However, this ratio is expected to be the same for other geometrical conditions provided the steel and lead can always be considered thick compared to the gamma mean free path.

Evidently it is to be expected that if active regions of an accelerator were faced with about 2 cm of lead, then average induced radioactivity dose-rates would be reduced by a factor of about 3 during a maintenance period (\( \sim 3 \) days) and by a factor of the order of 5 during a longer machine shut-down of about 30 days. However, lead should be avoided in situations where it will be irradiated for only a few hours and in areas where access will be possible minutes after the machine is shut off.

It is of interest to note that the empirically derived expression for the dose-rate from steel is the same as that derived by considering the half-life distribution of possible isotopes produced by spallation\(^1\). Also the \( t^{-1} \) law for steel and \( t^{-1.4} \) law for lead can be compared with a \( t^{-1.2} \) law that has been commonly accepted for the decay of the dose-rate from mixed fission products\(^2\).

Details of the steel and lead irradiations

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (cm)</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Beam strength ( \varnothing ) (p/sec)</td>
<td>( 1.5 \times 10^{11} )</td>
<td>( 1.3 \times 10^{11} )</td>
</tr>
<tr>
<td>Irradiation time ( T ) (hours)</td>
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<td>5.28</td>
</tr>
<tr>
<td>Total number of protons (( \varnothing T ))</td>
<td>( 9.4 \times 10^{14} )</td>
<td>( 2.4 \times 10^{15} )</td>
</tr>
<tr>
<td>Curve parameters:</td>
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</tr>
<tr>
<td></td>
<td>( A )</td>
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<tr>
<td></td>
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<td>0.295</td>
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</table>
REFERENCES


FIGURE CAPTIONS

Fig. 1 Dose-rate measured at 1 metre from steel and lead blocks irradiated with 15 GeV protons.

Fig. 2 The dose-rate from lead compared to that from steel.
Fig. 2