200-400 GeV ACCELERATOR PROJECT RADIATION PROBLEMS

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1.1 Introduction

Chapter 12 of UCRL-16000 needs some revision to include new experimental and theoretical data and to take account of new design features of the Weston accelerator. Largely speaking, these changes will be in the nature of small corrections to the repdiction of Chapter 12. This paper illustrates how Chapter 12 should be revised. It is intended to revise the chapter after the Berkeley-CERN-Rutherford experiment has been analyzed.

A recent shielding experiment (autumn, 1966) carried out at CERN by a joint team consisting of personnel from Berkeley, CERN, and the Rutherford Laboratory will provide extensive data on neutron shielding, beam loss, radiation dose, particle spectra, and induced activity (BCR experiment). Analysis of the data obtained from this experiment is still continuing but indications of the results are now becoming clear and will be indicated in this paper.

For convenience, roughly the same layout as that for Chapter 12, UCRL-16000, is maintained and the two documents may be read side by side. Reference to the CERN 300 GeV design study report, SG64/15, is made where appropriate.

1.2 Maximum Permissible Levels of Radiation

The general statements contained in UCRL-16000 are still true and it is believed to be a good assumption that the I. C. R. P. recommended permissible levels of radiation will not be changed in the near future.

In the CERN 300 GeV design study report, reference is made to certain national regulations demanding more severe controls, by roughly a factor of three. It is not likely that the United States will follow the example of those countries who are, perhaps, "out of step" with I. C. R. P. The general opinion of experts in the field seems to be that the existing levels provide an adequate standard of safety both in terms of radiation workers and the general population. It is the opinion of radiation experts at SLAC that the decision (made in 1959 in a climate of hostile public opinion due to "fall-out" from nuclear weapons testing and following shortly after a reduction in permissible levels of radiation exposure) to introduce safety factors of approximately three would not be repeated. Reference in SG64/15 to exposure to the lens of the eye limiting whole-body exposure arose due to a wrong interpretation of a somewhat confusing paragraph in I. C. R. P. recommendations. In publication I. C. R. P. 9, this confusion has been resolved, and it is clear that both the eye and the body may be exposed to the same radiation environment.

1.3 Design Values for Radiation Levels

There is really no significant difference in the views of the CERN and Berkeley reports here. CERN adopted a single level of 0.8 millirem hr^{-1} whilst LRL proposed three separate areas, 0.25, 1.25, and 2.5 millirem hr^{-1}, around the ring top.

In view of the topography of the Weston site and the desire to site the laboratory office tower complex overlooking the injector and extracted beam region, general radiation levels in this region should be kept as low as possible. The larger the area in which radiation levels are reduced to below 0.25 millirem hr^{-1} at the ring top, the greater the flexibility there will be in siting future buildings near the experimental area. Since the cost of achieving reduction of radiation levels by a factor of ten in this general area is quite small (say, at a guess, $500,000), it should be done.

1.4 Beam Intensity and Beam Loss Assumptions

Radiation damage, induced activity, and neutron shielding will scale roughly as the beam power. At present, final decisions have not been taken on intensity or energy. For convenience, therefore, estimates have been made for two proton intensities, 1.5×10^{13} protons sec^{-1} and 10^{14} protons sec^{-1}, and at energies of 10, 200, and 500 GeV corresponding to the booster synchrotron and main ring stage 1 and stage 2 energies. No really convincing arguments have been put forward which justify radical changes in the beam extraction efficiencies assumed in UCRL-16000. It is perhaps more logical to assume an extraction efficiency of 90% for the booster synchrotron since only fast extraction will be used, and the figure of 85% refers to mixed fast and slow extraction. Since no high energy physics use of the booster synchrotron is anticipated, there is no need to introduce any additional safety factors.

Measurements of the beam loss distribution were made by the BCR shielding experiment, but the results have not yet been fully analyzed. Preliminary results indicate that 15% of the beam loss is contained within half a betatron wavelength of the target, the remaining 85% being somewhat randomly distributed around the ring. The bulk of the "distributed" loss occurs at 4-5 limited regions whose peak intensity is about 1% of that at the internal target. The table indicates the results of flux measurements made on the CPS straight sections with a thin target and beam clipper operating.

Relative Source Strength	No. Straight Sections
0.5-1	2
0.1-0.5	1
0.05-0.1	1
0.01-0.05	11
0.005-0.01	6
$<$0.005	79

Only four straight sections had source strengths greater than 1% of that observed at the targets whilst approximately 80% of the straight sections had source strengths less than 0.5%.

Extrapolation of these data to a higher energy machine is not easy, in particular, the characteristic length of flux diminuation downstream of a target is not yet understood (we no longer believe the betatron wavelength to be relevant); and it has not yet been possible to correlate the spikes of beam loss around the accelerator with any physical cause, e.g., reduction in available aperture, etc. However, Ranft has recently carried out a Monte-Carlo calculation in which he estimated the neutron flux generated by a nuclear cascade in the CPS magnets and initiated by protons singly or multiply scattered from an internal target. Fair agreement with the BCR measurements is obtained and, hopefully, these calculations may be extended to higher energies.

1.5 Policy on Accelerator Maintenance

No changes from UCRL-16000.

1.6 Development of the High Energy Nuclear Cascade

1.6.1 Introduction — No change

1.6.2 Experimental Data — This section should now include references to more recent shielding experiments at Saclay, Rutherford, and CERN. Particular emphasis should be placed on measurements in the transverse direction.

1.6.3 Theoretical Calculations — References to the more recent work from ORNL and by Ranft should be included.

1.6.4 Energy Spectrum of Particles Produced by the Nuclear Cascade — More detailed discussion of the cosmic ray spectrum should be given. Results of spectrum measurements at CERN and Berkeley should be discussed.

1.6.5 Radiation Dose from a Cascade Spectrum
The results of 1.6.4 give definitive results here.

1.6.6 Buildup Factors — The confusion of this section should be cleared up by the BCR experiment.

1.6.7-1.6.8 Some small changes necessary.

SHIELDING

2.1 Introduction

No change needed.

2.2 Models Used to Estimate Strongly Interacting Particle Shielding Around the Booster and Main Synchrotrons

Final analysis of the BCR shielding experiment will, in principle, yield an exact solution to the neutron shielding problem. At the present time, analysis is not yet complete; but some indication of the results can be indicated.

The three models described in UCRL-16000 may now be replaced by a phenomenonological model (based largely on Model 2) where the flux at a point in the shield is given by:

$$\phi = \int_{-\infty}^{+\infty} \frac{B(x)\, S(z)\, \Theta(\theta)}{r^2} \exp\left(-\frac{l_{Fe}}{\lambda_{Fe}}\right) \exp\left(-\frac{l_E}{\lambda_E}\right) dZ.$$

where B(x) is a buildup factor and is a function of the path length through the magnet iron and earth.

S(z) is the source strength of an element of length dx at the vacuum pipe.

$\Theta(\theta)$ is the effective angular distribution of high energy particles close to the accelerator.

$l_E, l_{Fe}, \lambda_E, \lambda_{Fe}$ are the path lengths through attenuation lengths in the earth and iron respectively.

r is the distance from vacuum pipe to point in the shield.

The parameters of the buildup factors and angular distribution will be a function of primary proton energy and secondary particle considered.

λ_E, λ_{Fe} are effectively independent parameters.

During the BCR measurements of flux were made with a variety of threshold detectors at a motion of points inside the CPS tunnel and throughout the earth shielding. Our phenomenonological model is capable of fitting the measured fluxes to better than 30% and certain general statements may be made about the model parameters. If one allows the parameters to"float":

1. The attenuation length in earth is well defined.

2. The parameters of the angular distribution and buildup factor are not well defined.

More or less equally good fits can be obtained from different combinations of buildup factors and angular distribution. The physical explanation of this fact lies in the rapid degradation of the high energy protons close to the vacuum chamber and the consequent copious production of relatively low energy neutrons. Thus, provided there is some kind of conservation of the product:

$$B(x)\ \Theta(\theta)\ \exp\left(-l_{Fe}/\lambda_{Fe}\right)$$

adequate fits may be obtained. Certain constraints may be applied to the model parameters by choosing parameters for $\Theta(\theta)$ compatible with the angular distribution measured near an internal target and fixing λ_{FE}. Preliminary results indicate equally good fits for BCR data with B(x) = B (a constant).

Preliminary results for ring top shielding using an analytical model have been reported in UCID-10199 which were somewhat lower than the shield thicknesses quoted in UCRL-16000. Further analysis by Gilbert indicates values intermediate betwen the two.

In view of the short time before the final analysis will be completed, new specifications for shielding have been drawn up using the latest data available. These specifications will provide a good guide for cost estimating but may change marginally. Three useful formulae are given to estimate shielding. Because of simplifications they are only accurate to about 100 gm cm^2 and apply only over a limited range (typically the ranges of energy and intensity for the proposed accelerators).

Shielding in Quiet Areas

A convenient formula for estimating earth shielding above quiet areas is:

$$\underset{(\mathrm{gm\ cm^{-2}})}{t} = 250 \log_{10} M - 1750$$

where M is a parameter given by:

$$M = \frac{piE}{RD}$$

p = fraction of beam not extracted
i = beam intensity (p sec^{-1})
E = beam energy (GeV)
D = dose rate at shield surface (millirem hr^{-1})
R = mean accelerator radius in meters.

E(GeV)	i (psec^{-1})	p %	R meters	D Millirem hr^{-1}	M	t gm cm^{-2}	t meters earth (ρ =1.7 gm cm^{-3})
10	1.5×10^{13}	1	100	0.25	6×10^{10}	945	5.55
10	10^{14}	1	50	0.25	8×10^{11}	1232	7.25
200	1.5×10^{13}	2	1000	0.25	2.4×10^{11}	1088	6.4
200	10^{14}	2	1000	0.25	1.6×10^{12}	1300	7.65
200	1.5×10^{13}	2	1000	1.25	4.8×10^{10}	920	5.40
200	1.5×10^{13}	2	1000	2.5	2.4×10^{10}	845	4.95
500	10^{14}	2	1000	0.25	6.0×10^{16}	1405	8.25

Shielding in Target Areas

A similar formula for generating target station shielding (where point source intensities are applicable) is:

$$t = 320 \log_{10} N - 2750$$

where $N = \underline{piE}$

E(GeV)	i (psec^{-1})	p %	D (millirem hr^{-1})	t gm cm^{-2}	Meters Earth
10	1.5×10^{13}	10	0.25	1655	9.8
10	10^{14}	10	0.25	1925	11.3
200	10^{14}	15	0.25	2390	14.1
200	10^{14}	15	0.25	2515	14.8

Beam Line Shielding

It is convenient to estimate beam line shielding on the basis of point loss expected along the beam. The parameter N of formula 2 is therefore relevant. Close-in shielding will, in general, be used and a correction to the estimates of formula 2 must be made because of the reduced geometrical dilution. Adequate provision may be made by using:

$$t = 320 \log_{10} N - 2500$$
(gm cm^{-2})

Summary

Table XIII-VIII of UCRL is revised and the overhead earth shielding above the synchrotrons given in lb ft^{-2} (rounded upwards to the nearest 50#) assuming a final circulating intensity of 10^{14} $psec^{-1}$.

Specifications for Total Neutron Shielding Above 10 GeV and 500 GeV Synchrotrons

Accelerator	Location	Dose Rate (millirem hr^{-1})	Total Overhead Shield Required (lb ft^{-2})
10 BeV	General	0.25	2550
10 BeV	Regions above first septum magnet, kickers	0.25	3950
10 BeV	Regions above second septum magnet, kickers	0.25	3250
500 BeV	General	1.25 0.25	2550 2900
500 BeV	Regions above first septum magnet, kickers	0.25	5200
	Regions above later septum magnets	0.25	4450

3. Induced Activity and Shutdown Gamma Fields

3.1 Introduction and Qualitative Description of the Activity Model

Small changes necessary here in beam-loss model. Ranft Monte-Carlo calculations should be mentioned and the work of Barbier.

3.2 Shutdown Gamma-Radiation Field in the Brookhaven AGS

3.2.1
3.2.2 } No change needed.
3.2.3

3.3 Application of the Cascade-Activity Model to Injector and Main Synchrotron Magnet

Review of calculation necessary for new magnet design when fixed is necessary.

3.4 Thermal-Neutron Production and Enclosure-Wall Activation

New work of CERN should be discussed.

3.5 Activation of Enclosure, Air, Water, and Dust

New numbers can be generated from fluxes scaled from CERN measurements. No great changes are expected.

3.6 Conclusions and Maintenance and Personnel Exposure

Some discussion of the radiation experience at CERN and BNL should be included.

4. Radiation Damage

4.1 No large changes.

4.2 Can be rewritten to include the relevant BCR data.

(Addendum) Radiation Exposure to Vacuum Chamber and Magnet Coils

4.2.1 Introduction

Measurements of the high energy neutron flux and γ dose rate at the surface of the CPS vacuum chamber enable better estimates of the radiation exposure to components close to the vacuum chamber of a high energy accelerator.

4.2.2 Measurement at CERN

Measurements were made at the surface of the vacuum chamber with threshold detectors (e.g., sulphur, measuring flux of neutrons greater than 3 MeV in energy) and T. L. D. (Li^7F, measuring the γ dose rate).

Close to a target the neutron flux was 6.6×10^8 n cm^2 sec^{-1} with a circulating intensity of 10^{12} protons sec^{-1}. The dose rate given by :

D_γ [γ dose rate (rads hr^{-1}) $\approx 6.2 \times 10^{-4}$ ϕ (n cm^2 sec^{-1})

where ϕ is the flux determined by a sulphur detector.

(This proportionality between γ dose rate and neutron flux is somewhat dependent upon local conditions, e.g., quantity of material present, etc., but the standard deviation on this constant is about 25%.)

The total dose deposition rate, D, is given by:

$$D = D_\gamma + D_n$$

and assuming the mean energy of neutrons to be between 1-10 MeV, then:

$$7.2 \text{ n cm}^2 \text{ sec}^{-1} \equiv 1 \text{ millirem hr}^{-1}$$

whence $\quad 1 \text{ n cm}^{-2} \equiv 3.88 \times 10^{-8} \text{ rem.}$

A crude assumption is to assume epoxy resins to be tissue-like, whence:

$$1 \text{ rem} = (QF) \times 1 \text{ rad}$$

where QF is a Quality Factor about 5 (from memory).

$$\text{Thus } 1 \text{ n cm}^{-2} = \frac{3.88 \times 10^{-8}}{QF} \text{ rads}$$

$$\approx \underline{\underline{7.75 \times 10^{-9} \text{ rads}}}$$

$$1 \text{ n cm}^{-2} \text{ sec}^{-1} \simeq 3.6 \times 10^3 \times 7.75 \times 10^{-9} \text{ rads hr}^{-1}$$

$$\simeq \underline{2.75 \times 10^{-5} \text{ rads hr}^{-1}}$$

Finally then:

$$D \text{ (rads hr}^{-1}) = [6.2 + .3] \times 10^{-4} \phi \text{ (n cm}^2 \text{ sec}^{-1})$$

Thus

$$D \text{ (rads hr}^{-1}) = 6.5 \times 10^{-4} \phi \text{ (n cm}^2 \text{ sec}^{-1})$$

Note: The dose deposition close to the vacuum chamber is almost entirely due to γ-rays and charged particle ionization.

This is the inverse of the situation in the earth shielding. In order to allow for spurious situations seen to exist around the CPS, the constant 6.5×10^{-4} should be increased somewhat to preclude the possibility of a disastrous estimate. Hence, finally we will use:

$$D\ (\text{rads hr}^{-1}) = 10^{-3}\ \phi\ (\text{n cm}^{2}\ \text{sec}^{-1})$$

A more useful number is the dose to the vacuum chamber per year per unit beam power (p GeV sec^{-1}).

$$\text{Thus}\quad D\ (\text{rads yr}^{-1}) = \frac{10^{-3} \times 6.6 \times 10^{8} \times 365 \times 24}{10^{12} \times 25}$$

$$= \underline{\underline{2.3 \times 10^{-4}\ \text{rads yr}^{-1}/\text{p GeV sec}^{-1}}}$$

4.2.3 Dose Rate Estimate for Proposed High Energy Accelerator

E(GeV)	i (p sec^{-1})	(%)	Dose Rate (rads yr^{-1})
10	1.5×10^{13}	10	3.4×10^{9}
10	10^{14}	10	2.3×10^{10}
200	1.5×10^{13}	10	6.9×10^{10}
200	10^{14}	10	4.6×10^{11}
500	1.5×10^{13}	10	1.7×10^{11}
500	10^{14}	10	1.1×10^{12}

$$\text{Dose Rate (rads yr}^{-1}) = 2.3 \times 10^{-4}\ \eta\ E\ i$$

where η = fraction of beam interacting at a point; E = beam energy (GeV); i = beam intensity (protons sec^{-1})

c.f. estimate in UCRL-16000: 5.6×10^{3} rads yr^{-1} for $i = 1.5 \times 10^{13}$ $E = 200$ $\eta = 0.15$ to be compared with the present estimate: 10^{10} rads yr^{-1}.

4.2.4 Dose Distribution Around Ring

A summary of measurements of beam loss distribution at the CPS is tabulated below:

Source Strength Relative to Target	% St. Sections
0.5-1	2
0.1-0.5	1
0.05-0.1	1
0.01-0.05	11
0.005-0.01	6
< 0.005	79

4.2.5 Risk to Magnet Coils and a Vacuum Chamber

We assume:

1. Dose rate estimate of paragraph III.

2. Maximum permissible exposure to coils close to vacuum chamber (or vacuum chamber) 2×10^9 rads

3. Desirable life time 10 yrs. giving a maximum dose rate of 2×10^8 rads yr^{-1}.

10 GeV Booster

% Magnets	Stage 1 Dose Rate	Stage 2 Dose Rate
2	$1.7\text{-}3.4 \times 10^9$	$1.2\text{-}2.3 \times 10^{10}$
1	$3.4 \times 10^8 - 1.7 \times 10^9$	$2.3 \times 10^9 - 1.2 \times 10^{10}$
1	$1.7 \times 10^8 - 3.4 \times 10^8$	$1.2 \times 10^9 - 2.3 \times 10^9$
11	$3.4 \times 10^7 - 1.7 \times 10^8$	$2.3 \times 10^8 - 1.2 \times 10^9$
6	$1.7 \times 10^7 - 3.4 \times 10^7$	$1.2 \times 10^8 - 2.3 \times 10^8$
79	$< 1.7 \times 10^7$	$< 1.2 \times 10^8$

Conclusion

At stage 1, 95% of the magnets will have a lifetime of 10 years using polyester materials. 2% of the magnets may fail in 1 year's operation.

At stage 2, 85% of the magnets will have a lifetime of 10 years, 12% a lifetime between 1-10 years and 3% will have to be specially fabricated.

200 GeV Main Ring

% Magnets		Stage 1 Dose Rate (Rads Yr^{-1})	Stage 2 Dose Rate (Rads Yr^{-1})
2		$3.5\text{-}7 \times 10^{10}$	$2.3 \times 10^{11} - 4.6 \times 10^{11}$
1		$7 \times 10^{9} - 3.5 \times 10^{10}$	$4.6 \times 10^{10} - 2.3 \times 10^{11}$
1		$3.5 \times 10^{9}\text{-}7 \times 10^{9}$	$2.3 \times 10^{10} - 4.6 \times 10^{10}$
11		$7 \times 10^{8}\text{-}3.5 \times 10^{9}$	$4.6 \times 10^{9} - 2.3 \times 10^{10}$
6		$3.5 \times 10^{8}\text{-}7 \times 10^{8}$	$2.3 \times 10^{9} - 4.6 \times 10^{9}$
79	(39)	3.5×10^{8}	$4.6 \times 10^{8} - 2.3 \times 10^{9}$
	(17)		$2.3 \times 10^{8} - 4.6 \times 10^{8}$
	(23)		2.3×10^{8}

At stage 1, roughly 80% of the magnet coils will have a lifetime of 10 years. Something like 10% a lifetime between 5-10 years, 5% a lifetime of 1 year, and 5% less than one year and would have to be specially designed.

At stage 2, only about 25% of the magnets would have a lifetime of 10 years and an additional 20% might have a lifetime of more than 5 years. 35% will have a lifetime between one and five years. 20% of the magnets around the main ring need special consideration.

4.3 No large changes necessary.