SSC-N-438
December 1987

Activation of Air in the SSC Complex

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I. Introduction

The question has been raised concerning whether there may be problems with radioactivity in the air in the SSC complex of tunnels and experimental areas. This note reports a set of simplified calculations which indicate that the SSC is safe; specified general population limits of isotope activities are not exceeded. The areas where radioisotopes are produced and where concentrations may approach significant values are within interlocked enclosures and are not accessible to the general public at anytime. The isotopes which are produced with the greatest specific radioactivity concentrations are also short-lived, with characteristic decay time constants on the order of ten minutes. The assumptions made in these estimates are important and should be reviewed in the context of final accelerator and experimental hall parameters.

II. Areas of Concern

There are three areas where radiation can lead to radioactivity of air nuclei. The first is in the tunnels generally where beam-gas scattering may lead to a constant rate of beam loss per unit length of the accelerator. Most of the beam path length is contained in magnets, although in the experimental cluster regions there may be considerable lengths of unshielded beam pipe. The buildup of radioactivity of long-lived isotopes in these areas is limited by the rate of air circulation in the tunnels.

The second areas of concern are the vicinities of beam scrapers and collimators. These are localized regions, and again the activation levels depend on the rate of beam lost, the shielding (diameter) of the collimators, and on the rate of air flow in the beam tunnel where they are located.

The third areas of interest are the experimental, or interaction halls. Here one must make assumptions concerning the size of the hall, the nature of the detector, and in some cases the air circulation. We consider here a high luminosity, low β example as the significant case. A totally hermetic detector would have no hadrons in air (the full path length would be contained in the detector). Correspondingly, a totally unshielded IR with high luminosity would lead to more air activation than the case calculated here.

The beam absorbers were not considered. Beam will be brought to them in vacuum and no air is to be circulated through or close to them.

III. Assumptions

Three references were of particular value in preparing this note. They were the "Shielding Calculations..." of Van Ginneken et al.,[1] the SSC "Report of the Task Force on Radioactivation,"[2] and a CERN report on "Radioactive Gas... Production by... High Energy Accelerators..." by Petermans and Baarli.[3] Reference was also made to SSC reports on radiation issues,[4, 5] and to the SSC Conceptual Design Report.[6]

For beams interacting with residual gas a beam-gas lifetime of 300 hours was assumed [2]. This corresponds to a loss rate of 7×10^8 per second (each ring) or 9 interactions (cm s)$^{-1}$ with the nominal beam of 1.4×10^{14} p, or 23 (cm s)$^{-1}$ with 4×10^{14} p [2]. The rings are assumed mostly covered with magnets with an iron (equivalent) radius of 13.5 cm, although several percent of the beam path may be in a bare pipe.

Note that this assumed beam intensity includes a safety factor of three times the SSC design current.

The tunnel has a cross-sectional area of 6 m^2, based on 10 ft diameter minus the areas subtended by the magnets and the floor. Ventilation is assumed to be provided by the air circulation fans noted in the Conceptual Design Report [6] of 13000 cfm maximum (3 $m^3 s^{-1}$) for each 8 km section of tunnel, pumping at the center. This would move air at a velocity of 0.5 m/s. However, when personnel are not in the tunnel the air circulation will be slower, assumed here to be by a factor of 10.

For purposes of this note then, a flow rate in the tunnel of 0.05 m/s (5 cm/s) is assumed.

In the Report of the Task Force on Radioactivation [2] the beam lost on various collimators and scrapers is taken to be 10^{15} protons per year maximum, corresponding to 5×10^7 interacting protons per second. Again, this corresponds to a beam current of three times the design values.

The collimators and scrapers are assumed to be iron (or equivalent absorber) of 35 cm radius. The location of the collimators is in the standard 10 ft diameter tunnel, with air circulation as noted above.

The high-luminosity experimental areas are assumed to be in halls of 20,000 m^3 volume. Presumably the secondaries will go directly into detectors except at small angles where they will emerge from the beam vacuum and strike collimators which shield the low-β quadrupoles. The average total charged-particle multiplicity has been predicted to be about 100. For these calculations we have assumed that 40 secondaries go through air at small angles; 20 forward and 20 backwards. Their path length in air is taken as 20 meters, the distance to the first collimator.

IV. Calculations

The proton interactions give rise to a nuclear-electromagnetic cascade in matter. Total absorption of the energy of a proton leads to about 20,000—30,000 nuclear interactions, or "stars." These nuclear interactions result in final state nuclei, some of which may be radioactive. For air the inelastic cross sections of interest are N-oxygen: 292 mb, N-nitrogen: 265 mb, and N-argon: 566 mb [7]. Other constituents of air are unimportant.

Cross sections for different isotopes of interest were taken from the CERN report, [3] and the yield of each isotope was found from the ratio of the corresponding cross section to the appropriate oxygen, nitrogen, or argon cross sections weighted by the appropriate fraction in air. The fraction F_i of stars in air resulting in a particular isotope i is then given as follows:

$$F_i = 0.79\,\frac{\sigma_{iN}}{265} + 0.20\,\frac{\sigma_{iO}}{292} + 0.01\,\frac{\sigma_{iA}}{566}$$

where σ_{iN} is the cross section in millibarns for production of isotope i by high-energy nucleons on nitrogen, etc.

Isotopes of interest, and corresponding values of F are listed in Table I, where the partial cross sections are taken from Reference 3. Although these values for F are derived for nucleons and the nuclear cascade is dominated by pions, it is reasonable to assume that F would be substantially the same for pions.

Van Ginneken [1] has plotted cascade curves for carbon, and these have been used to assess the number of stars in air. In particular, the number of stars produced in carbon per radial centimeter, integrated over z and per interacting proton is plotted. A centimeter of carbon corresponds to 2.2 g cm^{-2} of carbon. The average path length in air radially from the beam in the tunnel is $\sqrt{6/\pi} \cong$ 1.4 m, or 0.18 g cm^{-2}. Hence the radial star density in air is taken to be 0.18/2.2 = 8.2×10^{-3} that in carbon.

For beam which interacts in the wall of the beam pipe, the radial star density is taken to be the $r = 0$ intercept value for carbon, or 460 per cm. When this is reduced to a star density per unit radial mass density (grams per square centimeter), and multiplied by the mass path length in air, the number of stars produced in the tunnel air per interacting proton, N_{SO} is:

$$N_{SO} = 0.082 \times 460 = 38 \text{ stars per proton}.$$

If the proton interacts within a magnet of radius 13.5 cm (Fe) the radial star density on the surface of the iron is reduced by a factor of 3.62, or exp(13.5/10.5), from Van Ginneken's curves. [1] It may be assumed that the radial star density in air is reduced by a corresponding factor from the unshielded case. This assumption should be verified by calculation, but is certainly adequate for the present calculation. The number of stars produced per proton interacting within the magnets, N_{SM} is given by

$$N_{SM} = N_{SO}/3.62 = 10 \text{ stars per proton}.$$

The beam scrapers and collimators are taken to be 35 cm in radius of iron, or iron equivalent. This reduces the radial star density by a further factor of $\exp(21.5/10.5) = 7.7$, so that the numbers of stars in air per proton interacting in a collimator, N_{SC} is given by

$$N_{SC} = N_{SO}/27.8 = 1.4 \text{ stars per proton}$$

For the interaction halls the number of stars was taken to be the total path length of hadrons in air, $20{\times}40 = 800$ m, divided by the mean free path in air for nucleons, 700 meters. This would give 1.14 stars per interacting proton. The figure may be high because the mean free path of mesons is greater than that for protons, but it may be low because it neglects albedo from the face of the shield and radial loss out of the lateral sides of the shield (as in the collimator case above). A very conservative value for the number of stars per *pp* interaction in the high-luminosity IR regions, $N_{SI} = 2$.

These values of N are summarized in Table II.

The concentration of a particular isotope in the air will depend on the rate of production per unit volume of air and on its decay properties. The number of decays per unit volume of air, R_i of that isotope is then the concentration divided by the decay mean life τ_i; if this is to be determined at a time t following exposure this rate will fall as $\exp(-t/\tau_i)$.

If the lifetime of the isotope is short compared with the exposure time of air to the source, equilibrium between production and decay is established and R_i at machine turnoff does not depend on τ_i. If τ_i is long compared to the exposure time T, the concentration of the isotope and hence R_i will grow with T.

A. Distributed Beam Loss

For the case of beam loss in the magnets (and beam pipe), with dP/dz the proton loss rate in protons per meter per second, R_i is given by

$$R_i = N_{SM} \frac{dP}{dz} F_i/A \qquad \tau_i << T$$
$$R_i = N_{SM} \frac{dP}{dz} F_i \left(\frac{T}{\tau_i A}\right) \qquad \tau_i >> T$$

With air circulation at 10% the rate during occupancy, the exposure time of air in the tunnel will be about one day, or 8×10^4 seconds. The maximum beam loss rate dP/dz taken from Reference 2, is 28 protons per cm^2 second, or 2.8×10^3 m^{-1}s^{-1}. A loss rate of 9×10^2 protons m^{-1} s^{-1}, corresponding to the design beam intensity, is also considered. The tunnel cross sectional area A is 6 m^2.

The activity in sections of tunnel with unshielded beam pipe will be given by the same expression with N_{SO} replacing N_{SM}. For simplicity, it is expedient to take N_{SO} over a length of tunnel shorter than that over which the magnets are shielded by just the ratio N_{SM}/N_{SO}, so that the overall activity may be taken as twice the above values. Then the rate must be multiplied by a factor of two again to take account of two beams. So the expressions used are:

$$R_i = 4\ N_{SM} \frac{dP}{dz} F_i/A \qquad \tau_i << T$$
$$R_i = 4\ N_{SM} \frac{dP}{dz} F_i \left(\frac{T}{\tau_i A}\right) \qquad \tau_i >> T$$

The activities of the isotopes considered are tabulated in Table III for dP/dz corresponding to a 300 hour beam life time and 1.3×10^{14} protons per beam. They are also tabulated for 3 times the design beam, or 4×10^{14} protons per beam.

B. Beam Loss on Collimators

In the case of beam losses on collimators and scrapers, a loss at a particular point is considered, although only one of the two beams is considered at each azimuth. The exposure time relevant here is the time for air to flow across the beam loss area, given by dz/v_{air}. The beam loss per unit length is integrated over z for the values used, so that

$$R_i = N_{SC}\ P_c\ F_i/(v_{air}\ \tau_i\ A)\,.$$

For all isotopes of interest, $\tau_i \gtrsim L/v_{air}$, where L is the length of the major part of the cascade, or about 10 meters, and v is 0.05 meters per second.

Values for P_c of 1.6×10^4 and 5×10^7 protons per second were considered, corresponding to a high value for the design parameters [6] and a scaled-up intensity [2]. Values of R_i are given in Table IV for both examples.

C. Interaction Regions

Beam interaction rates P_I corresponding to the SSC design luminosity of 10^{33} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, or 10^8 per second, and to a hypothetical order of magnitude increase, to 10^9 per second, are used to find values of R_i, using $N_{SI} = 2$ as discussed above and an experimental hall volume V of 2×10^4 m^3. It is assumed that the air in the hall is circulated by the same 13,000 cfm (3 m^3/s) blowers, running at 10% speed, as assumed in the beam tunnel case. Then the exposure time, T, to the beam will be $2\times10^4/0.3$, or 6.7×10^4 seconds, quite comparable to the tunnel air circulation (Case A, above). The produced isotopes are presumed to mix uniformly in the hall volume V.

The isotope activity concentrations R_i are therefore given by

$$R_i = N_{SI}P_IF_i/V \quad , \qquad \tau_i << T$$
$$R_i = N_{SI}P_IF_i/(\tau_i\phi) \quad , \qquad \tau_i >> T\,.$$

where ϕ is 0.3 m^3 per second, the blower exhaust rate. The results of these activity rates are in Table V.

V. Discussion

It is apparent that there is no air activation difficulty presented by the SSC when operating at its design values and even at hypothetical increased beam and luminosity values. Other isotopes produced from interactions in argon were examined and found to have lifetimes, production cross sections, and safe exposure limits which made them less significant that ^{39}Cl tabulated here. It should be noted that ^{41}A is not included in the tables as there is no easy estimate for the rate of formation from thermal neutrons. It may be observed, however that, at 600 mb thermal neutron cross section, the mean free path of a thermal neutron for capture in argon is 60 km. Nitrogen has a much greater (1.6 b) capture cross section. The ^{41}A activity level should nevertheless be addressed.

VI. Cosmic Rays

If all of the SSC beam energy at design intensity were deposited in air, there would be $2\times 6.7\times 10^{16}$ protons per year $\times 20,000$ GeV/proton or about 2.7×10^{21} GeV per year, an average of 8.5×10^{13} GeV per second. This would produce about 1.2×10^{14} stars per second.

For reference the SSC oval of 83 km encompasses an area of about 550 km^2. Cosmic rays continually bombard the Earth's atmosphere; they are almost all nuclei, with 80% protons. The energy spectrum falls rapidly, and the absolute flux is given by 1.8 $E^{-2.7}$ nucleons (GeV cm^2 s sr)$^{-1}$. This flux is cut off at the low end by the Earth's magnetic field at a value depending on geomagnetic latitute but equal to about 2 GeV over the U.S. This flux may be integrated over solid angle and energy to give a total energy flux, in round numbers this is about 5 GeV/cm^2 sec. Almost all of this energy is dissipated in the atmosphere, producing therefore about 10 stars per cm^2 sec in air nuclei (about 2 per GeV, a more nearly correct value at low energies). This corresponds, over the 550 km^2 area of the SSC oval, to 2.7×10^{13} GeV per second, or about 5.5×10^{13} stars per second.

Consequently the continual flow of cosmic rays produces about half as many radioactive isotopes in the atmosphere as the full design SSC beams would if totally dissipated in air over the area encompassed by the SSC orbit!

It goes without saying that there is no reason to dump the SSC proton beams in the air, and many of the cosmic ray interactions are high in the atmosphere. Nevertheless these figures may place the potential hazard of the SSC in somewhat clearer perspective.

Recently there has been concern raised about levels of ^{222}Rn in buildings, and the question of the buildup of radon in the SSC has been raised. This may well dominate the SSC tunnel air exposure, and may determine the rate of ventilation. Of course radon will be very site specific.

Conclusions

The radioactivation of air in the SSC tunnel and experimental halls should pose no hazard to laboratory personnel. Activity levels are at or below exposure limits for the general population even at the time of beam turnoff for design operating conditions. Limits are more nearly approached for beam levels elevated above design values, and some cooling off time (up to 30 minutes) could be recommended in special cases.

The methodology sketched here may be extended to other possible situations, such as catastrophic beam losses.

One isotope not studied here is ^{41}A, produced by thermal neutron activation of atmospheric argon. While there is no reason to be concerned, a further look at argon is desirable for completeness.

The conclusions here are in accord with the observations at CERN and Fermilab, that air activation is generally not a radiation health hazard except in the vicinity of intense direct beams passing through air.

REFERENCES

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Table I

Isotopes Produced in Hadron-Air Collisions

Isotope	Mean Life τ (seconds)	Production Cross Sections σ_i (mb)[1] Nitrogen	Oxygen	Fraction of Stars in Air Producing this Isotope: F_i[2]	MPC μCi[3]
^{3}H	5.5×10^{8}	35	40	0.131	0.2
^{7}Be	6.7×10^{5}	8.5	8.2	0.031	4×10^{-2}
^{11}C	1.75×10^{3}	14	12	0.050	6×10^{-2}
^{13}N	8.74×10^{2}	5.5	2.5	0.018	5×10^{-2}
^{15}O	1.75×10^{2}	0	35	0.024	4×10^{-2}
^{39}Cl	4.80×10^{3}	20.9 (Argon)		3.7×10^{-4}	3×10^{-2}
^{41}A	9.49×10^{3}	— (Argon)[4]		—	4×10^{-2}

(1) Cross sections from reference 3.

(2) F_i defined in text.

(3) Maximum permissible concentrations for the general population exposure from reference 3 in accordance with ICRP recommendations.

(4) ^{41}A is formed by thermal neutron capture on atmospheric Argon.

Table II

Stars Per Interacting Proton

Stars in air taken from carbon data of Van Ginneken et al.[1]

Proton Interaction Site	Stars in Air, N_S, Per Interacting Proton
Unshielded beam pipe in 10 ft. diameter tunnel	$N_{SO} = 38$
Beam dipole magnet, $r_{Fe} = 13.5$ cm in 10 ft. diameter tunnel	$N_{SM} = 10$
Collimator or scraper, $r_{Fe} = 35$ cm in 10 ft. diameter tunnel	$N_{SC} = 1.4$
Beam-beam interaction in IR balls, 20 m air path	$N_{SI} = 2.0$

(1) Reference 1.

Table III

Air Activation from Distributed Beam Losses

Isotope	Radioactivity Design Current$^{(3)}$	$R^{(1)}$ μCi/m^3 3× Design $^{(3)}$	MPC$^{(2)}$ μCi/m^3
^{3}H	3.2×10^{-6}	9.6×10^{-6}	2×10^{-1}
^{7}Be	6.3×10^{-4}	1.9×10^{-3}	4×10^{-2}
^{11}C	7.9×10^{-3}	2.5×10^{-2}	6×10^{-2}
^{13}N	2.8×10^{-3}	9.1×10^{-3}	5×10^{-2}
^{15}O	3.8×10^{-3}	1.2×10^{-2}	4×10^{-2}
^{39}Cl	6×10^{-5}	1.9×10^{-4}	3×10^{-2}

(1) $R_i = 40 \frac{dP}{dz} F_i \; (8\times10^4/6\tau_i)$ for ^{3}H, ^{7}Be

$R_i = 40 \frac{dP}{dz} F_i \; (1/6)$ for ^{11}C, ^{13}N, ^{15}O, and ^{39}Cl.

(2) Maximum Permissible Concentration; general

(3) $\frac{dP}{dz} = 8.9$ (design), 28 (3× design) protons lost (cm s)$^{-1}$.

Table IV

Air Activation from Beam Interactions in Collimators

Isotope	Radioactivity Design Current(3)	$R^{(1)}$ μCi/m^3 3X Design(3)	MPC(2) μCi/m^3
^{3}H	4.8×10^{-7}	1.5×10^{-6}	2×10^{-1}
^{7}Be	9.4×10^{-5}	2.9×10^{-4}	4×10^{-2}
^{11}C	5.8×10^{-2}	18×10^{-2}*	6×10^{-2}
^{13}N	4.2×10^{-2}	13×10^{-2}*	5×10^{-2}
^{15}O	2.8×10^{-1}	8.6×10^{-1}*	4×10^{-2}
^{39}Cl	1.6×10^{-4}	8.6×10^{-4}*	3×10^{-2}

(1) $R_i = \frac{1.4}{6 \times 0.05} P_c \left(\frac{F_i}{\tau_i} \right)$

(2)Reference 3

(3) $P_c = 1.6 \times 10^7$ (design), 5×10^7 (3X design) protons per second lost on colllimator

*A cooloff periof 10–30 minutes could be required before tunnel entry if these high losses were experienced.

Table V

Air Activation from High-Luminosity Collision Halls

Isotope	Radioactivity Design Luminosity	$R^{(1)}$ μCi/m^3 3× design Luminosity	MPC[2] μCi/m^3
^{3}H	4.3×10^{-6}	4.3×10^{-5}	2×10^{-1}
^{7}Be	8.4×10^{-4}	8.4×10^{-3}	4×10^{-2}
^{11}C	1.4×10^{-2}	1.4×10^{-1}*	6×10^{-2}
^{13}N	4.9×10^{-3}	4.9×10^{-2}*	5×10^{-2}
^{15}O	6.5×10^{-3}	6.5×10^{-2}*	4×10^{-2}
^{39}Cl	1.0×10^{-4}	1.0×10^{-3}*	3×10^{-2}

(1) $R_i = \frac{2}{\phi} P_i \left(\frac{F_i}{\tau_i}\right)$ for ^{3}H, ^{7}Be

$R_i = \frac{2P_i}{V} F_i$ for ^{11}C, ^{13}N, ^{15}O, ^{39}Cl

$\phi = 0.3$ m^3/s; $V = 2\times10^4$ m^3; $P_I = 10^8$ s^{-1} (design)

(2) Reference 3

*A cooloff periof 20–30 minutes could be necessary for very high luminosity operation