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ACTIVATION DOSE RATE IN ACCSESS SCENARIOUS TO THE AREA BETWEEN DISK SHIELD AND TOROID

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ISTC Project #1800
II quarter (Jul.-Sep. 2001)

Abstract

The present note reports on the results obtained in evaluating activation dose rate for the access scenarios to the area between JDisk and Toroid and to the Big Wheel muon chambers.

Moscow, 30 October 2001

1. Introduction

Shielding and equipment are activated by elementary particles during LHC operation. Induced radioactivity depends on flux, energy spectra of particles, activation cross-section, concentration of target nuclei in the material, exposure time, and time after shut down.

Interactions of hadrons with stable nuclei produce most contribution to induced radioactivity. From the methodical point of view, its is convenient to divide the energy range onto two sub-ranges: (1) from thermal energies to 20 MeV, and (2) above 20 MeV. The point is that different processes of radionuclide production predominate in the energy ranges. At energy below 20 MeV, neutron induced reactions like (n,γ), (n,p), (n,α), and (n,2n) predominate. While, at energy above 20 MeV hadron induced reactions (x,Spall), were *X* is proton, neutron, Pi+, or Pi-, are most important. The division is also convenient due to different representation and availability of activation cross-sections. Neutron cross-sections are studied well for energy below 20 MeV as widely used in reactor applications. For energy above 20 MeV activation cross-sections are usually studied in less detail. As a rule, only proton cross-sections are studied well enough and used as a conservative estimation for other hadrons.

The note reports on the results achieved during the second phase of implementation of the ISTC #1800 project. The basic aim for the phase is simulating activation dose rate for access scenarios on the base of previously developed activation code and associated data sets [1].

The following results are given:

- Equivalent dose rate for the access scenario to the area between JDisk and Toroid - both with Beam Pipe in place and without Beam Pipe;
- Equivalent dose rate for the access scenario to the Big Weel muon chambers.

2. The simulations

Induced activity

It is convenient to use activation integral for calculation of induced activity. The integral, calculated per one target nuclear, shows the rate of a nuclear reaction:

$$q = \int_0^\infty \sigma(E)\varphi(E)\,dE\,,$$

where, ***σ(E)*** - activation cross-section, ***φ(E)*** - flux of particles.

Having solved the balance equation for the number of radioactive atoms, one could come to the formula for activity per unit volume

$$A_v = nq\big(1-\exp(-\lambda T)\big)\exp(-\lambda t) \qquad (1)$$

where λ is the decay constant, $\lambda = \ln(2)/T_{1/2}$ and $T_{1/2}$ is half life;
n - number of target nuclei per unit of volume;
T - is exposure time in the steady flux;
t - time after shut down.

In (1) we disregard the burning-out processes for both stable and target nuclei. The same expressions one could formulate for the daughter radioactive nuclei produced by radioactive decay of the radionuclide-product of nuclear reaction. Practically, it is enough to consider a mass-chain of three radioactive nuclei, as there is not a radionuclide with half decay exceeding few hours, which would have a longer mass-chain.

In the case the flux cannot be considered as steady in time, its possible to approximate it with a step-wise function of time. So that, the formula (1) will transform into the following:

$$A_{\mathrm{v}} = \frac{nq_{nom}}{W_{nom}} \left\{ \sum_{j=1}^{J} W_j \left(1 - \exp(-\lambda \Delta T_j)\right) \exp\left(-\lambda \ (t + T - \sum_{i=1}^{j} \Delta T_i) \right) \right\} \qquad (2)$$

where q_{nom} - is activation integral calculated for the nominal W_{nom} luminosity; W_j – luminosity during the time period ΔT_j; $T = \sum_{j=1}^{J} T_j$ - full exposure time.

Number of target nuclei per unit volume in formulas (1) and (2) are calculated using:

$$n = P\rho N_A / A, \qquad (3)$$

where, P - natural abundance of the isotope in natural material; ρ - density; N_A – Avogadro constant; A- atomic weight of the element.

Volume activity can be expressed in terms of contact dose rate - dose rate at the surface of a semi-infinite source uniformly contaminated with volume activity A_v.

Any radionuclide emitting ***I*** gamma rays with different energy E_{0i}, MeV, and absolute intensity n_i, photons per decay, will produce contact dose rate $\dot{H}$, Sv/h:

$$\dot{H} = \frac{2\pi \Gamma_H A_v}{\mu^{S}_{en,m}(\bar{E})\rho} 3600 \cdot 10^4, \qquad (4)$$

where $\mu^{S}_{en,m}(\bar{E})$, cm^2/g, - mass energy attenuation coefficient for average energy $\bar{E}$ emitted by the radionuclide; ρ- is density of material, g/cm^3.

$\Gamma_{H,}$ $\frac{\mathrm{Sv} \cdot \mathrm{m}^2}{\mathrm{Bq} \cdot \mathrm{s}}$, – so-called "gamma-factor", which is constant for the radionuclide:

$$\Gamma_H = \frac{\sum_{i=1}^{I} \left(E_{0i} n_i \mu^{tiss}_{en,m}(E_{0i}) w\right) 1.602 \cdot 10^{-13}}{4\pi}. \qquad (5)$$

where $\mu^{tiss}_{en,m}(E_{0i})$ - mass energy attenuation coefficient for energy E_{0i} emitted by the radionuclide in the biological tissue, m^2/kg;
w= 1 Sv/Gy - tissue weighting factor for photons;
Factor 1.602E-13 is used to transform energy E_{0i} from MeV to Joles.

If the source contains more than one radionuclide, then the contact dose will be the sum for all the radionuclides.

Another value, which can be used for characterization of emitting power of a radioactive source, is the so-called "gamma-equivalent", which is a product of gamma-factor by activity. Gamma-equivalent is equal to the dose from a point-wise radionuclide source with activity A at the distance 1 m. For example, volume gamma-equivalent can be calculated with the formula

$$k_{e,v} = A_v \Gamma_v \qquad (6)$$

There exists a direct relation between the gamma-equivalent and contact dose rate:

$$\dot{H} = \frac{2\pi\, k_{e,v}}{\mu^{S}_{en,m}(\bar{E})\rho} 3600 \cdot 10^{4} \qquad (7)$$

The described methods for simulation of induced activity and dose characteristics (contact dose rate and gamma-equivalent) have been implemented in the ACTIVATION-2 code [2,3]. Additionally, the code allow to calculate a distributed volume source which is used in the study as input for simulation of photons transport with radiation transport codes DOT-III [4] and MCNP [5]. The ACTIVATION-2 code is equally applicable for study of both low energy neutrons and high-energy hadron activation if relevant group activation cross-sections libraries are available.

Dose rate

Both simple engineering methods and radiation transport codes are used in the present study for simulating of dose rate fields. Engineering methods are based on simplification of a real geometry and radiation source distribution that allows an analytical solution. A complex geometry can be represented as a set of sources of simple shape and dose rate will be the sum over the sources. Implementation of engineering methods, in some cases, allows to get rather a precise estimation for dose rate. For example, formula (7) gives absolutely correct results in the case of uniformly contaminated semi-infinite source. Though applicability of every particular method is limited and its use must be justified on case-by-case basis. If geometry is complex enough or radiation source is not uniform, the only way to get correct solution is to use venerable codes for simulating radiation transport in real geometry. In this study we use DOT-III two-dimensional discrete ordinate radiation transport code and MCNP-4A Monte-Carlo code.

To estimate dose rate from Beam Pipe we use the following engineering method.

The Beam Pipe was modeled as a set of point-wise sources positioned along the Z-axis and dose rate in a point (Z_0,R_0) is sum of contributions over all the sources:

$$\dot{H} = 3600 \sum_i \frac{k_{e,m}(z_i) m(z_i)}{(z_i - Z_0)^2 + (R_0)^2}, \qquad (8)$$

where $\dot{H}$ - equivalent dose rate, Sv/h,

$k_{e,m}(z_i)m(z_i)$ is gamma-equivalent of source *i*, Sv.m^2/s;

$k_{e,m}(z_i)$ - specific gamma-equivalent, Sv.m^2/(s.kg),

$m(z_i)$- mass of the source, kg,

At that the doses will be slightly conservative as no attenuation of gamma radiation in the Beam Pipe was taken into account. Beam Pipe itself is a thin stainless tube (0.8 mm) and attenuation of gamma radiation in it is negligible. There are flanges in the place of conjunction between Beam Pipe sections. Cross-section of each flange is 14x14 mm. Consequently dose rate may be overestimated in the region close to the flanges by some 10%. Besides this method does not allow calculating surface doses because dose rate at the surface of a point source is infinitely high.

Dose rate fields from JDisk and Toroid were calculated with DOT radiation transport code and DLC-23/CASK cross-section library [6]. It is known that a discrete ordinate code like DOT can result in significant inaccuracy being implemented for geometry with localized source surrounded with low-density material like air due to the so-called "ray-effects", especially when a full symmetric angle mesh of low order is used. Usual way to cope with ray-effects is to use a biased angle mesh. Though choose of a particular biased mesh should be justified by comparison with a method free of ray effects— either engineering, in simplified geometry, or with Monte-Carlo method in real geometry. In order to estimate the related inaccuracy of DOT results, we done calculations in real geometry with MCNP code. Angle mesh with 100 directions biased towards detector was found to be the most correct for the particular problem.

3. Input data

In order to calculate specific induced activity one should know:

- flux of incident particles;
- concentration of target nuclei;
- cross-section of nuclear reactions producing radioactive nuclei;
- operation scenario: time of operation ***T*** and time of cooling ***t***.

Fluxes

Fluxes in the region 0<R<12 m, 0<Z<24 m, together with a readback procedure, were produced by Mike Shupe with GEANT/GCALOR. The following data available [7]:

- Fluxes on 10 cm x 10 cm grid

1. High energy neutrons above 20 MeV;
2. Fast neutrons - 2.19 MeV to 20 MeV;
3. Intermediate neutrons - 3.78 keV to 2.19 MeV;
4. Moderated neutrons - 0.414 eV to 3.78 keV;
5. Thermal neutrons - 10E-5 to 0.414 eV;
6. Protons above 20 MeV;
7. Pi minus above 20 MeV;
8. Pi plus above 20 MeV;
9. Stars, threshold 50 MeV.

- Neutron spectra on 100 cm x 100 cm grid, 61 energy groups.
- Charged hadron spectra on 50 cm x 50 cm grid, 21 energy groups:

1. protons,
2. π- pions,
3. π+ pions.

The data was calculated for baseline geometry of February 2001. Totally, 1505 events were processed.

Cross-sections

Cross-sections of nuclear reactions producing radioactive nuclei are usually available in form of data libraries.

Historically, neutron cross-sections, ranging from thermal energies up to 20 MeV, are studied rather well, because they are extensively used in fission reactor applications. There are number sources available, e.g ENDF, JANDL, IRDF.

Calculated proton cross-sections for threshold reactions are available up to energy 200 MeV from MENDL-2 data library [8]. Proton reaction data up to energy 10 GeV are also available in the form of experimental or calculated data compilations for a limited list of materials [9,10].

Cross-section data set for protons was prepared in the same energy group structure as fluxes. By now the data set includes Be, C, N, O, F, Al, Ar, Ti, Mn, Fe, Ni, Cu, Au. For other elements we use cross-sections of material with a most close atomic number. For example, in the study we use cross-sections for Mn instead of Cr, Cu instead of Zn, and Au instead of Pb.

There were no pion activation cross-sections data found so far. For the purpose of this study, proton cross- sections are used for all hadrons with energy above 20 MeV. The estimation is rather valid for neutrons and results are certainly conservative for pions (up to 30%), that can be concluded from the energy dependence of hadrons inelastic cross-sections.

Geometry

For the purpose of this study the version of GEANT/GCALOR geometry description file of February 2001 was used to define material composition of JDisk and Toroid.

- JDisk materials were taken cast iron, brass (90% Cu, 10% Zn), and aluminum alloy. Description of geometry is given in Table 1.
- Toroid materials were taken cast iron, brass (90% Cu, 10% Zn), aluminum alloy 5000, Polyethylene with Li, and Lead. Description of geometry is given in Table 2.
- Beam Pipe materials was taken stainless steel. Geometry was adopted from drawings LHCVC1T_0002 B, LHCVC1A_001 B, and LHCVC1J_001. Description of geometry is given in Table 3.

Access scenarios had been formulated by V.Hedberg [11]. The distance between JDisk and shifted Toroid was taken 570 cm for the relevant scenario. The distance between JDisk and shifted muon chambers was taken 106 cm.

Concentrations

Concentrations of target nuclei for activation calculations were taken from [12]. Table 3 summarizes concentrations of elements assumed in the present study.

Operation scenario

For the purpose of this study there is no need in detail specifying LHC operation history. It is assumed, for the short term operation scenarios (less than one year), that LHC is operated at high luminosity during T and then is shut down during time t. For long-term operation scenarios, 120 days per year run at high luminosity was assumed and the rest of the year LHC is shut down.

4. Results

Equivalent dose rate fields for the studied access scenarios were calculated for T=30 days, 100 days, 5 years, and 10 years; time after shut down is 1 day, 5 days, and 100 days. Dose rate is given in μSv/h.

Equivalent dose rate fields in the area between JDisk and shifted Toroid (fig. 1) with beam Pipe in place are given in Table 5 and, without Beam pipe (fig.2), in Table 6. Both high energy hadron and low energy neutron activation was taken into consideration.

Equivalent dose rate fields resulted from high-energy hadron activation in the area between JDisk and shifted muon chambers (fig. 3) are given in Table 7 and from low energy neutron activation in Table 8.

Equivalent dose rate field from individual components— JDisk (fig.4), Toroid (fig.5), and Beam pipe (fig.6) are given in tables 9-14. Dose rate resulted from hadron and low energy neutron activation are given in separate tables.

It is known that a discrete ordinate code like DOT can result in significant inaccuracy being implemented for geometry with localized source surrounded with low-density material like air due to the so-called "ray-effects". In order to estimate the related inaccuracy, some calculations were done for the same geometry with MCNP code. Equivalent dose rates resulted from activation of JDisk by low energy neutrons calculated with both DOT and MCNP are given in Table 15. Ray effect shows itself by unphysical oscillation of dose rate. The closer to the source (JD surface) the less inaccuracy resulted from ray effect. In the region close to the beam pipe (0< R< 100 cm), where the dose rate is high, the difference do not exceeds 40%. In the region 100 cm< R< 425 the difference may be within 2. Though dose rate level in this region is less than 1 μSv and may be considered as insignificant. So that, DOT together with chosen gamma-ray transport cross-section library, space mesh, and angle mesh allows to get satisfactory results and its use for multiple calculation is justified, as calculation of the same problem with MCNP takes much more computation time.

5. Conclusions

Levels of equivalent dose rate in the access scenario into the region between Jdisk and shifted Toroid are significant. Maximum dose rate is at the front surface of JD plug and reach 2.7 mSv/h (Table 5 -- T=10 year, t=1 day). At the locations most close to the Z-axis, the contact dose rate ranges from 0.3 mSv/h up to 1.8 mSv/h in 5 days after shutdown. In these regions high-energy hadrons produce predominating contribution to the total dose rate. Though low energy neutrons activation contributes 2-20% on the front surface of JD plug for various exposure and cooling time assumptions.

Contribution from the Beam Pipe turned out to be rather high (see Tables 5-6). It is comparable with contribution from activation of JD Plug and exceeds activation of Toroid. More precise estimation is absolutely necessary for the Beam Pipe, as here only estimation was made. The estimation is based on not yet finalized design and, that is more important, hadron fluxes had been calculated with a rather rough space binning along the R-axis.

Dose rate in the access scenario to the Big Weel muon chambers are much less than in the previous scenario. Maximum dose rate is at the side surface of JD plug and may reach 0.5 mSv/h (Table 7, 8 -- T=10 year and t=1 day). Though, at the distance 1 m along R the dose rate do not exceed 30 μSv/h in 5 days after shutdown. Contribution tho the total dose rate of activation induced by low energy neutron does not exceed 50-60% in 1 day after shutdown and 20-30% for 5 and 100 day after shut down.

6. Acknowledgements

The authors would like to thank M.Shupe for calculation of hadron fluxes and V.Hedberg for many useful discussions.

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Table 1

JD geometry and materials taken for calculations

##	Zmin	Zmax	Rmin	Rmax	Material
1	669.5	671.5	12.8	93	Iron
2	668.5	671.5	389	423	Iron
3	671.5	674.5	33	100	Iron
4	671.5	674.5	100	275	Polyethylene +Li
5	671.5	674.5	411	423	Polyethylene +Li
6	674.5	676.5	33	275	Iron
7	676.5	684.5	33	423	Iron
8	671.5	680	12.9	33	Brass
9	680	730	13.5	33	Brass
10	730	780	14.5	33	Brass
11	780	852.5	15.5	33	Brass
12	684.5	730	33	38	Iron
13	730	780	33	38	Iron
14	780	852.5	33	38	Iron
15	684.5	690	38	74.3	Brass
16	690	700	38	74.3	Brass
17	700	710	38	74.3	Brass
18	684.5	690	74.5	147.67	Brass
19	690	695	74.3	114.45	Brass
20	695	700	74.5	88.67	Brass
21	684.5	695	147.67	154.67	Polyethylene +Li
22	690	697	114.45	147.67	Polyethylene +Li
23	697	702	114.45	121.45	Polyethylene +Li
24	695	702	88.67	114.45	Polyethylene +Li
25	702	707	88.67	95.67	Polyethylene +Li
26	700	707	74.3	88.67	Polyethylene +Li
27	684.5	700	154.67	157.67	Lead
28	697	700	121.45	154.67	Lead
29	700	705	121.45	124.45	Lead
30	702	705	95.67	121.45	Lead
31	705	710	95.67	98.67	Lead
32	707	710	74.3	95.67	Lead
33	710	735	38	75.85	Brass
34	735	783	38	80.2	Brass
35	710	735	75.85	82.85	Polyethylene +Li
36	735	783	80.2	87.2	Polyethylene +Li
37	710	735	82.85	85.85	Lead
38	735	783	87.2	90.2	Lead

Table 2

JT and Toroid geometry and materials taken for calculations

##	Zmin	Zmax	Rmin	Rmax	Material
1	854.2	880	16.6	81.5	Brass
2	880	910	17.2	81.5	Brass
3	910	940	17.7	81.5	Brass
4	940	970	18.2	81.5	Brass
5	970	1000	18.8	81.5	Brass
6	1000	1050	19.6	81.5	Brass
7	1050	1100	20.5	81.5	Brass
8	1100	1150	21.5	81.5	Brass
9	1150	1200	22.5	81.5	Brass
10	1200	1250	23.5	81.5	Brass
11	1250	1283	24.5	81.5	Brass
12	854.2	880	81.5	86.5	Lead
13	880	910	81.5	86.5	Lead
14	910	940	81.5	86.5	Lead
15	940	1000	81.5	86.5	Lead
16	1000	1283	81.5	86.5	Lead
17	785	854.2	81.5	86.5	Lead
18	793	1283	87.5	91.5	Iron
19	1283	1291	24.7	86.5	Brass
20	809	1257	92.5	94.5	Aluminum
21	787	809	91.5	123.5	Polyethylene +Li
22	1257	1279	91.5	123.5	Polyethylene +Li
23	787	1279	524	530	Aluminum
24	869	873	107.5	400	Aluminum
25	1193	1197	107.5	400	Aluminum
26	787	794.5	123.5	524	Aluminum
27	785	854.2	40	81.5	Brass

Table 3

Beam pipe geometry taken for calculations

##	Section	Element	Zmin	Zmax	Mass of SS, kg
1	VA	Bellows	853.5	864.7	0.45
2		Tube	864.7	868.6	0.06
3		Flange	868.6	870	0.9
4	VT	Flange	870	871.4	0.9
5		Tube	871.4	1046.5	2.8
6		Tube	878.5	1039.3	3.5
7		Tube	1046.5	1278.7	5.2
8		Flange	1278.7	1300.7	3
9	VJ	Flange	1300.7	1302.9	0.9
10		Tube	1302.9	1320.7	0.4
11		Bellows	1320.7	1332.1	0.4
12		Tube	1332.1	1392.8	1.3
13		Bellows	1392.8	1404.2	0.4

Table 4

Concentrations of elements in materials, %

Element	Cast iron ASTM A 48 Class 40	Poly. + Li	Aluminum 5000 Series Alloy	Bronze Commercial 220	Chemical Lead, UNS L51120	Stainless Steel 304
H		0.13				
Li		0.05				
C	3.5	0.82				0.08
Mg			4.5			
Al			94.8			
Si			0.4			
Ti			0.15			
V						
Cr	0.45		0.25			19
Mn	0.9		1			2
Fe	95		0.4		0.002	71
Co	0.015(*)					0.2
Ni	0.2					10.5
Cu	0.4		0.1	90		
Zn			0.25	10		
As					0.002	
Zr						
Mo	0.1					
Ag					0.02	
Sn					0.002	
Sb					0.002	
Pb					99.9	