ATLAS project	Radiation in the USA15 cavern in ATLAS		
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ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE

CERN **EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

Radiation in the USA15 cavern in ATLAS

The USA15 cavern in the ATLAS experiment will contain most of the electronics for the experiment and it has to be accessible during the running of the LHC accelerator. A study of the predicted radiation levels in this cavern during high luminosity running has been made with the FLUKA program. Also reviewed is the radiation situation in the ATLAS surface building (SX1).

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Distribution List

1 Introduction

The ATLAS experimental cavern (UX15) is surrounded by other caverns, service ducts and access shafts as can be seen in Figure 1. The USA15 cavern next to the ATLAS experimental cavern is going to house most of the electronics in the experiment. This is a large cavern that is 20 m wide and 62 m long with electronic racks on two floors (see Figure 2). The floors are 1.8 m below and 3.6 m above the beamline. It is necessary that people can visit and work for long periods in this cavern, even during high luminosity running, without being exposed to large amounts of radiation from the experiment. From USA15 there are several service tunnels that lead to the experimental cavern (ULX16, UPX16, ULX14 and UPX14) and service ducts for cables (TE14 and TE16) as depicted in Figures 1 and 2. There is also a second cavern, called US15, in which some ATLAS electronics might be stored, but this cavern will not be accessible during LHC running.

A study was made by Ferrari et al. in 1995 [1-2] of the wall thickness between the experimental cavern and USA15, the plug thickness at the top of the two vertical shafts, the dose rate in the surface buildings and the lateral passage ducts. They concluded that the USA15 wall should be 2 m thick, giving a maximum dose equivalent rate in USA15 of ~3 μSv/h (see Figure 3). The ambient dose equivalent limit for a simple controlled area such as USA15 is 25 μSv/h [3]. In design studies, the CERN/TIS-RP group has recommended a design limit of 10 μSv/h. The predicted dose equivalent rate of 3 μSv/h in USA15 was therefore considered to be sufficiently low at the time.

While Ferrari et al. studied the attenuation in the wall and vertical shafts by using a FLUKA simulation, the passage ways and cable ducts into USA15 were investigated using so-called universal curves for radiation in a maze [4-5]. They concluded that the layout of all the service tunnels between the experimental cavern and USA15 gave an attenuation factor larger than a minimum requirement and that the dose rate in USA15 would therefore everywhere be below 10 μSv/h.

In 1999 a further study was undertaken [6] which focused on the attenuation of radiation through passageways and ducts. In this FLUKA study, a detailed description of the ATLAS experiment was not used. Instead, the particle spectra to be transported across the wall geometry were generated in a separate simulation, using a very simple target and concrete geometry. This method is clearly an approximation to the real situation but, for the investigation of attenuation of radiation in empty ducts and passageways, was considered reasonable. The calculated attenuation factors for the ducts were compared with that expected from the wall, given as 55 in [6]. The attenuation was considered satisfactory if greater than a 100. It was concluded that the radiation attenuation was sufficient in all the ducts and passageways (further details are given in Section 3 below).

Since these studies were performed, there have been three major changes that might impact radiation levels in the USA15 cavern.

1) Radiation levels in the experimental cavern have increased, typically by factors 2 to 3. This has been mainly due to “engineering realism” of the detector systems, shieldings and beamline equipment.
2) The size of the cavern assumed in the calculation by Ferrari et al. was smaller than the actual one. The distance between the beamline and the USA15 wall is now 16.7 m and not 13 m.
3) There have been several iterations of the trigger cable hole design. The number of holes has, for example, increased from 4 to 9. The current concern is not so much radiation coming through the holes, but rather an effective weakening of the wall due to an effective reduction in wall thickness.

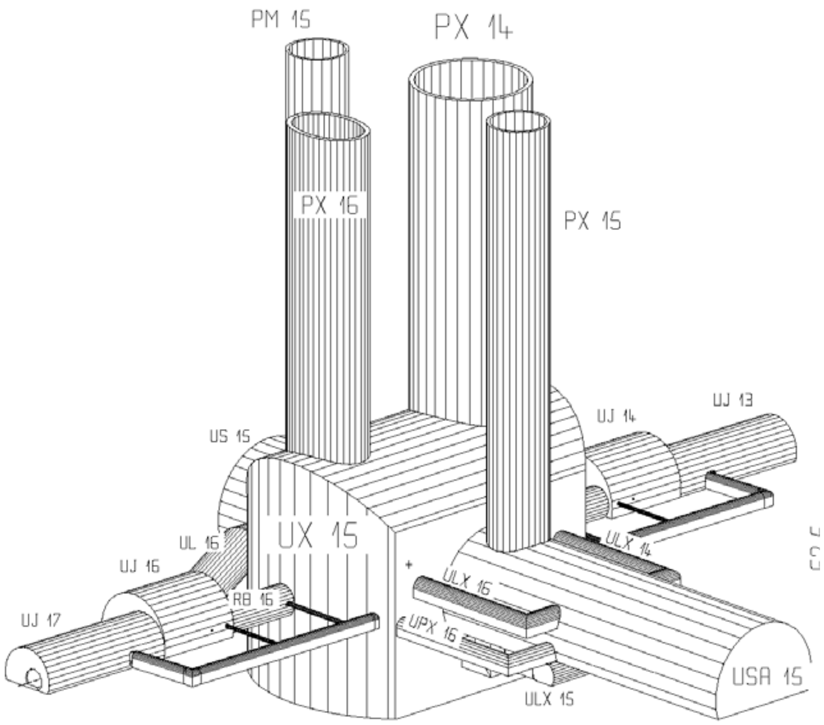

Figure 1. The caverns, access shafts and service tunnels that surrounds the ATLAS experimental cavern (UX15).

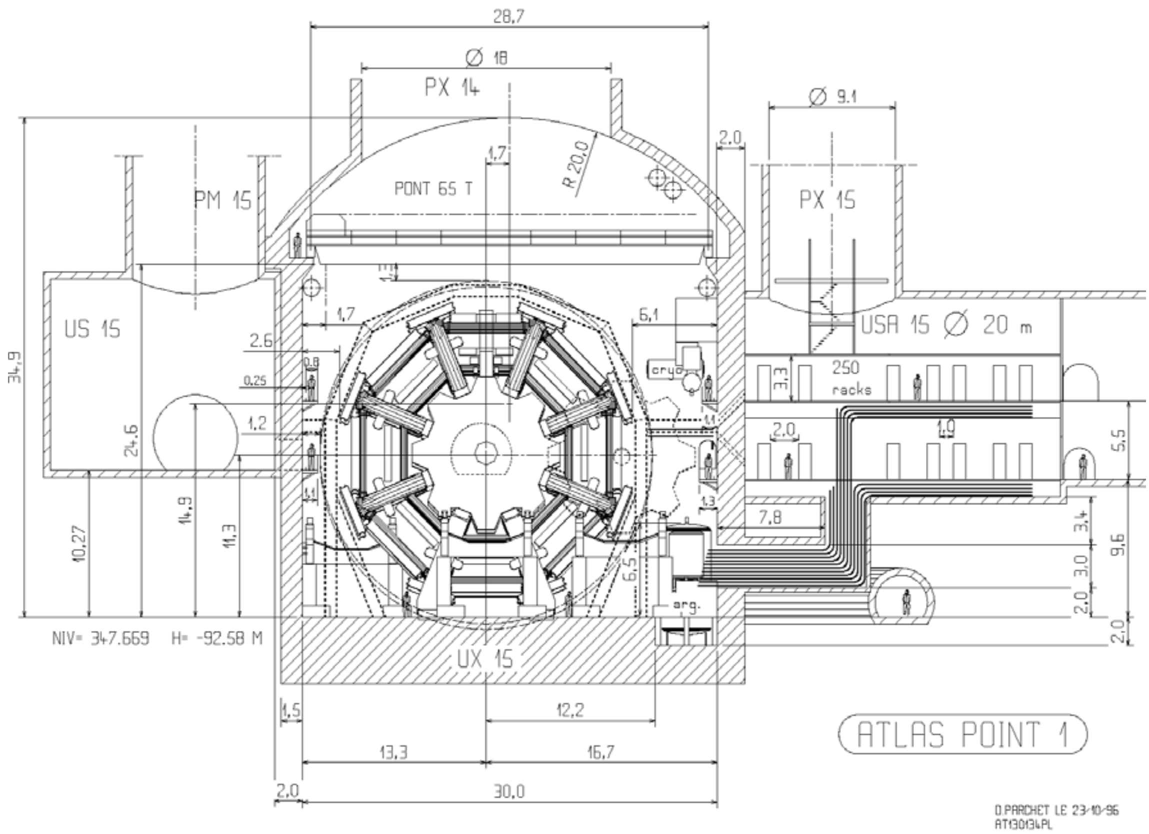

Figure 2. Cross section of the ATLAS experimental hall UX15, the electronics cavern USA15 and the US15 hall.

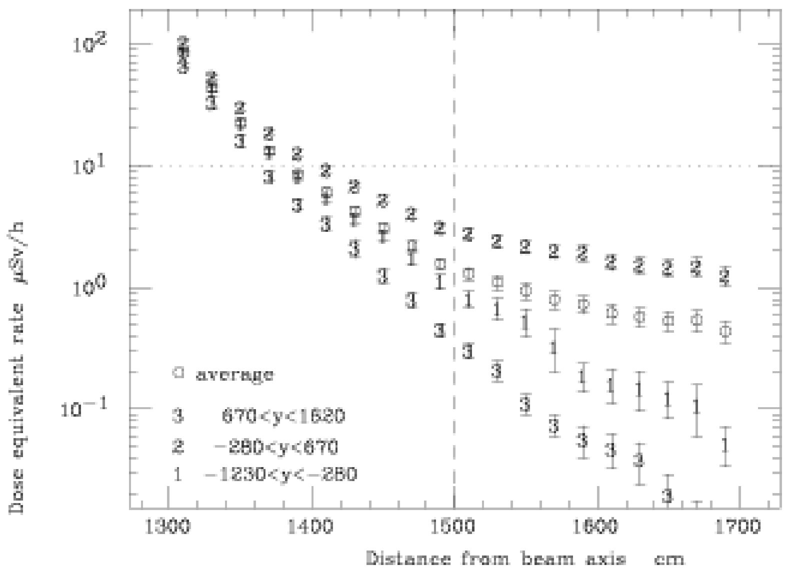

Figure 3. Ambient dose equivalent rate versus the distance from the beam axis [1]. It is assumed that the wall starts at a distance of 1300 cm from the beamline. The results are given for three vertical slices and have been averaged over the full horizontal length of the wall.

Furthermore, it is expected that the Swiss/French radiation authorities will reduce the yearly dose limits. CERN will probably follow suit, and reduce the yearly limits from 15 mSv to 6 mSv. This implies a reduction of the limits for a simple controlled area from 25 μSv/h to 10 μSv/h.

Therefore, it is important to review the radiation situation in USA15 due to these changes. This has been done in two steps:

1) The ATLAS radiation background simulations using FLUKA2002 [7] were updated to include the USA15 cavern. The simulation includes a recent description of the detector, beamline and shielding. In this study, new "absolute" numbers for the effective dose across the cavern wall into USA15 were obtained. In order to reduce simulation time, the trigger cable ducts were not included in these simulations.
2) The impact of the trigger ducts on the weakening of the wall was then assessed using the method and files of G. Stevenson as described in [6].

2 Review of the Radiation Environment

Following on from the work of the ATLAS radiation taskforce, full FLUKA simulations of the radiation backgrounds were performed using a relatively recent and realistic ATLAS geometry and material description, extended to include USA15. A cylindrical cavern wall geometry was used to reduce simulation time and particle biasing was implemented across the wall since it is otherwise impossible to obtain sufficient statistics of particles in the USA15 cavern. The inner radius of the cavern wall was furthermore increased from the old value of 13 m to 16.7 m.

All results were obtained under the assumption of a beam luminosity of 10^{34} cm^{-2} s^{-1}. High energy neutrons were identified in the original studies as the most important component of the radiation field for dose rates in USA15 and Figure 4 shows the neutron fluences for energies greater than 10 MeV. The weak part of the shielding inside the end-cap toroid is evident from this plot. The forward shielding for ATLAS has been significantly reduced since the geometry in this study was constructed, but with little consequence on the cavern fluences and it is the plume of high energy neutrons coming out from the endcap toroid and hitting the edge of the USA15 cavern that is the greatest concern (USA15 ends at Z=1000 cm).

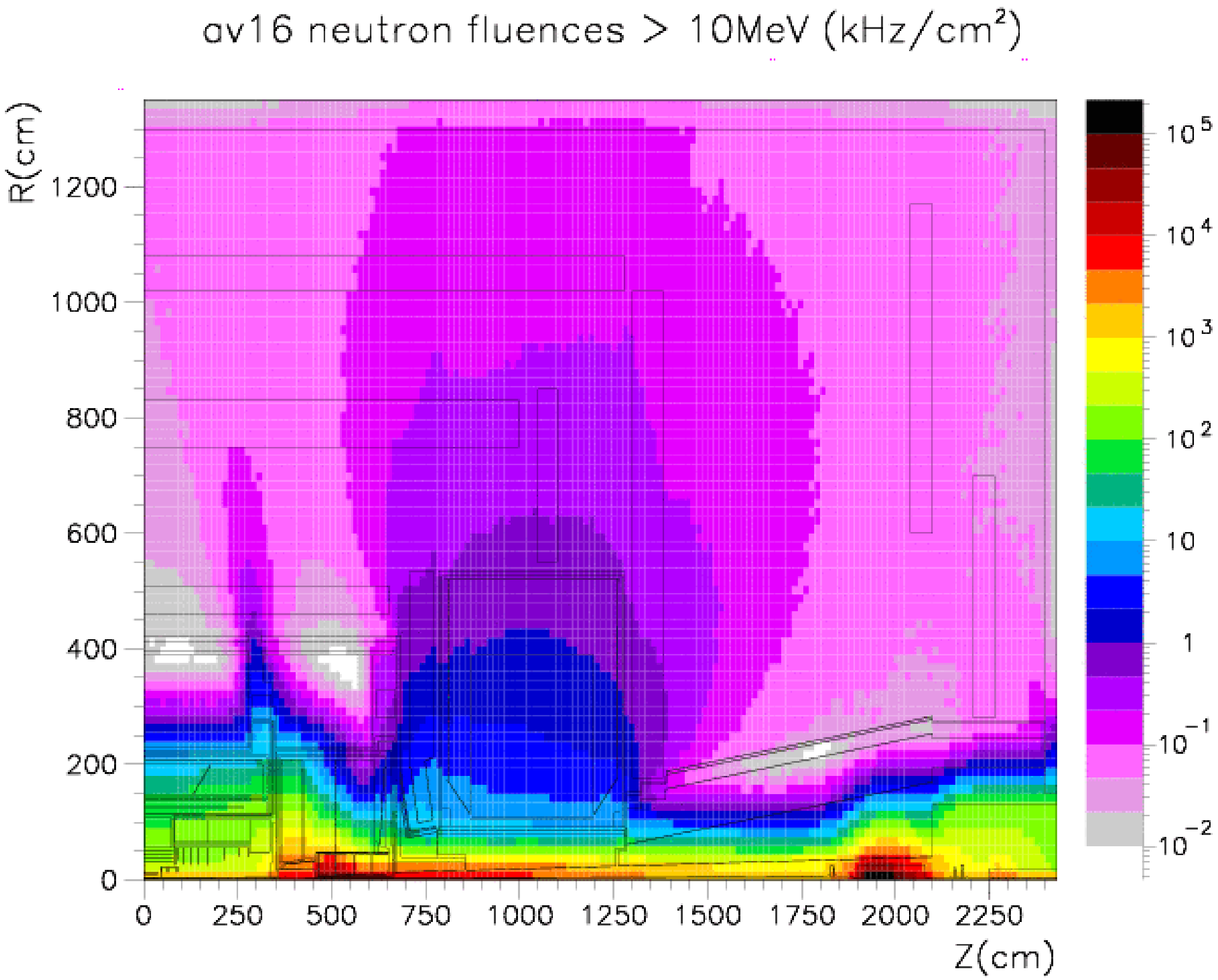

Figure 4. The plot shows one quarter of the ATLAS experiment and the fluences in kHz/cm^2 of neutrons with an energy larger than 10 MeV.

The particle fluences have to be converted into an effective dose and this is done by multiplying the fluences with an energy dependent conversion factor. The conversion factors depend on the particle type and on the direction of the particles. The doses presented in this note were calculated with the use of conversion factors estimated by Pelliccioni [8-9] (for a description of how the factors were obtained see [9]) and the worst possible geometry of the incoming radiation was assumed in order to have a conservative estimation. Previous studies used “ambient dose equivalent” factors which give a 10% lower dose than the factors used in the present study.

Figure 5 shows the conversion factors that were used in the present FLUKA simulation for neutrons, protons, muons and photons. Neutrons and photons have the largest fluence in USA15 but since the conversion factor for neutrons is one order of magnitude larger than that for photons, it is neutrons that dominate the dose rate in USA15.

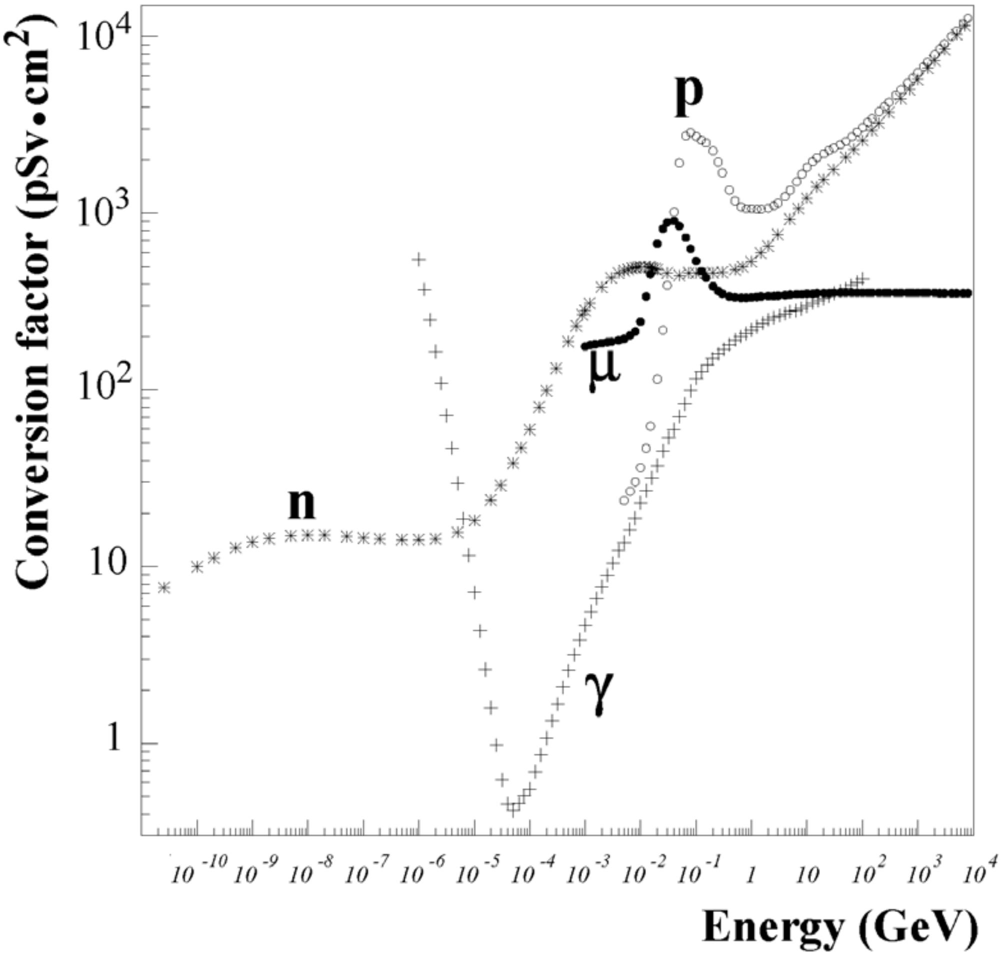

Figure 5. The factors that were used in Fluka to convert particle fluence to effective dose.

The effective dose rate in μSv/h, in the region of the wall between the UX15 and USA15 caverns, is given in Figure 6 as a function of the radial distance from the beamline. The average over the full length (|Z| < 10 m) of the USA15 wall is compared with the central region (|Z| < 2 m) and the "side regions" (8 m < |Z| < 10 m). The effective dose in the "side regions" is approximately twice that of the central region (~4 μSv/h versus ~2 μSv/h), reflecting the variation of the high energy neutron component along the wall (see Figure 4).

Shown in Figure 7 are neutron spectra, averaged over the entire USA15 wall, for the three cases corresponding to 1) the experimental cavern side of the wall, 2) the middle of the wall and 3) the USA15 side of the wall. The 1/E spectrum below ~1 MeV is typical of neutron spectra in a concrete environment. The high energy neutrons at ~100 MeV are attenuated with a nuclear interaction length / density of 50 cm which is typical of high energy neutron attenuation in concrete. The lowest energy bin corresponds to thermal neutrons, and extends down to 10^{-11} MeV.

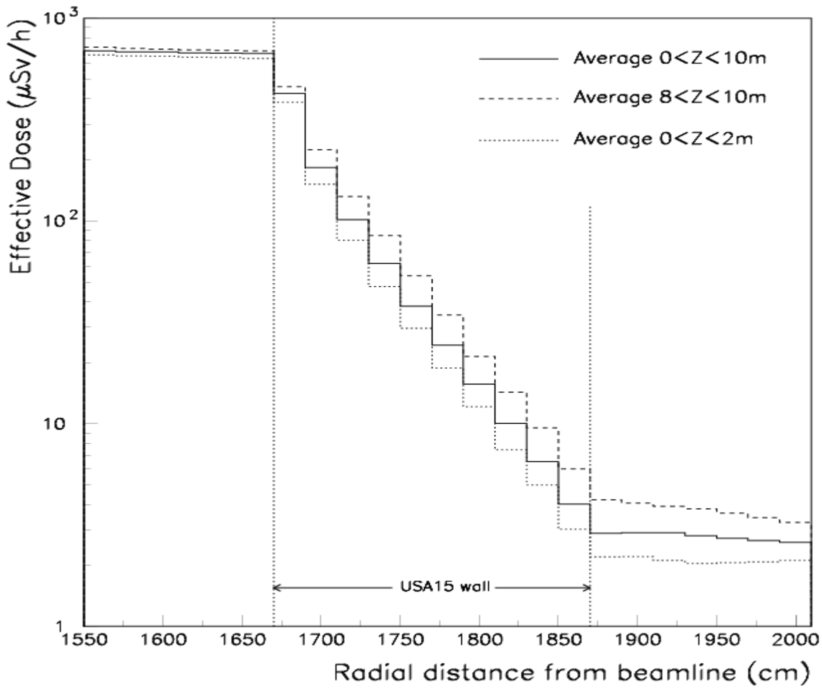

Figure 6. The effective dose rate in the region of the wall between the experimental cavern (UX15) and USA15. A cylindrical UX15 cavern with a radius of 18.7 m was assumed in this calculation. The dose rate is given for three different Z-regions corresponding to the whole USA15 wall and the side and central regions of the wall.

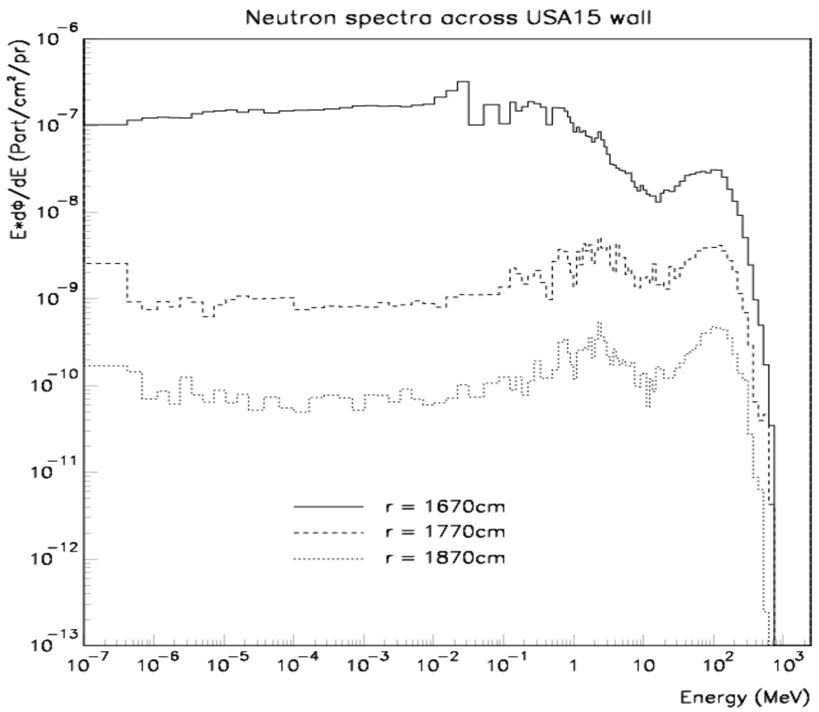

Figure 7. The plot shows the neutron energy distributions for three different distances to the beamline. These correspond to the experimental cavern side of the wall (r=1670 cm), the middle of the wall (r=1770 cm) and the USA15 side of the wall (r=1870 cm).

It is of interest to investigate the effect on the effective dose in USA15 by new additional layers of material either in USA15 or on the experimental side of the cavern. This has been done for 20 cm thick layers of 1) Boron-doped polyethylene in the USA15, 2) Steel in the USA15 and 3) Steel in the experimental cavern. The results are shown in Figure 8. The largest decrease of the radiation is obtained by adding steel shielding in the experimental cavern. The high energy neutrons are in this case first attenuated in the steel and then moderated by the concrete wall. It is interesting to note that 20 cm of steel in the USA15 does not help. This is because of the interactions and cascades of high energy neutrons in the steel, with no subsequent moderation. The 20 cm of boron doped polyethylene in USA15 reduces the effective dose by nearly a factor of two.

Polyethylene shielding in ATLAS is typically doped with boron since its high cross section for thermal neutron capture means it is efficient in stopping thermal neutrons. In order to evaluate the effectiveness of the boron doping a further simulation was performed using pure polyethylene. The comparison is presented in Figure 9. The difference between the two is within statistical uncertainties, suggesting that the thermal neutron component does not contribute significantly to effective dose and that the main effect of the polyethylene is due to the moderation of high energy neutrons to lower energies where the fluence to effective dose conversion factors are smaller.

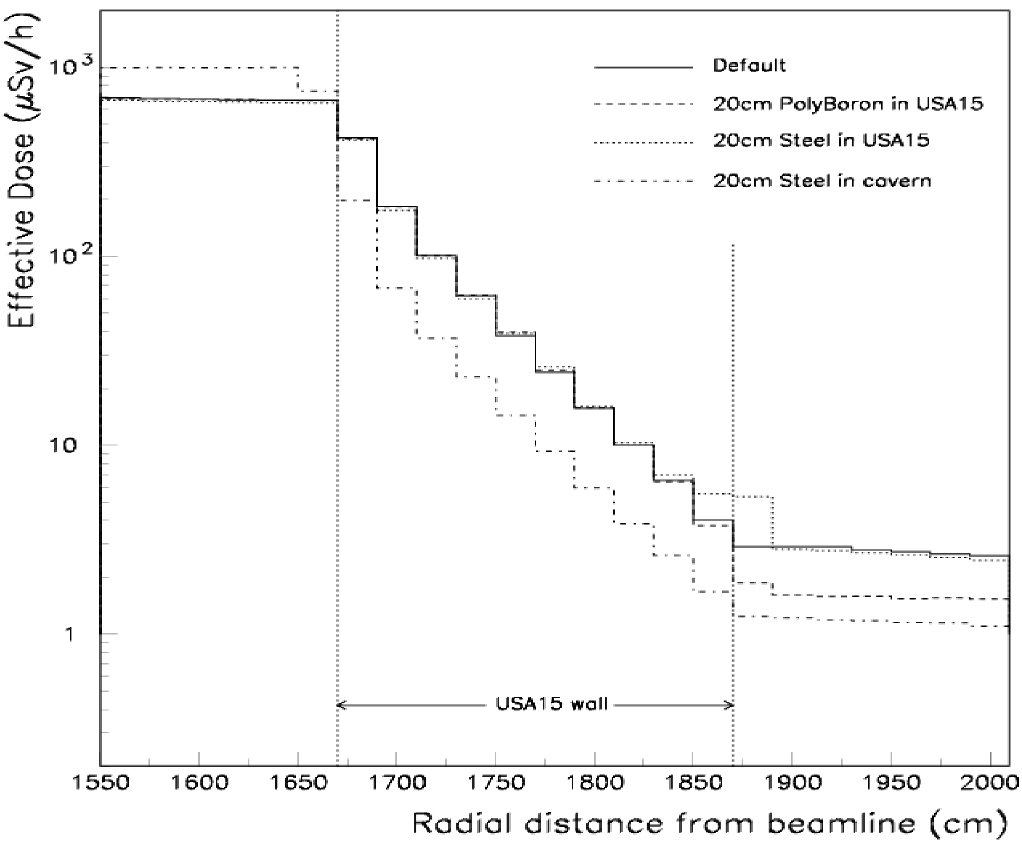

Figure 8. The effective dose rate in the region of the wall between the experimental cavern (UX15) and USA15. The dose rate is given for the standard 2 m thick default concrete USA15 wall and for a wall reinforced by a 20 cm thick steel layer on the UX15 or the USA15 side and by a 20 cm thick layer of boron doped polyethylene.

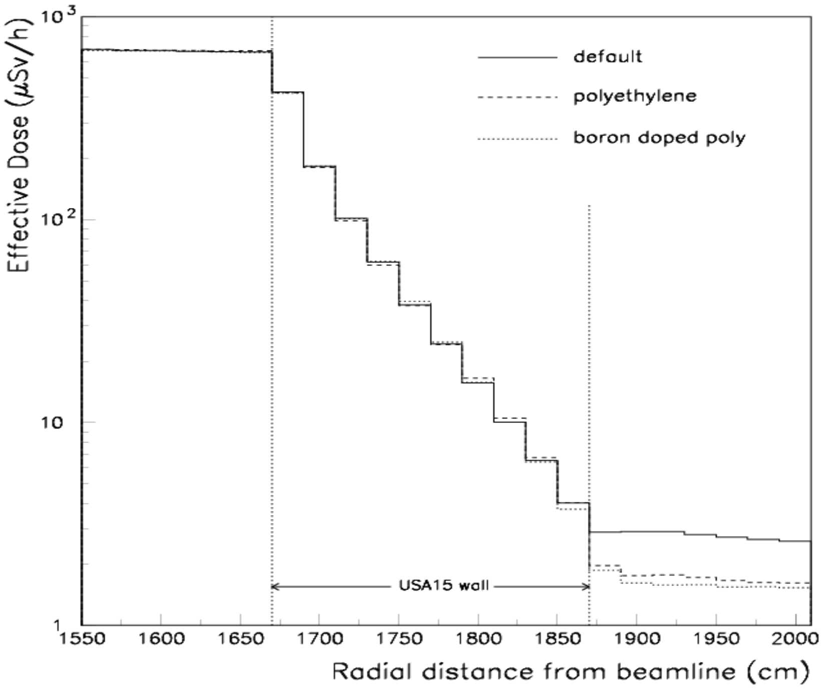

Figure 9. The effective dose rate in the region of the wall between the experimental cavern (UX15) and USA15. The dose rate is given for the standard 2 m thick default concrete USA15 wall and for a wall with an additional 20 cm thick layer of either pure polyethylene or boron doped polyethylene.

The effect of the composition of the concrete in the wall was also studied. Different concrete gave small differences in the predicted dose rate in USA15 (< 5%). The concrete wall is steel reinforced. This reinforcement corresponds to an average steel thickness of 3 cm. This would decrease the radiation in USA15 but this is cancelled out by the fact that the wall is not exactly 2 m thick but 1.92 m.

3 Impact of trigger cable ducts

Rollet, Potter and Stevenson made a study in 1999 using FLUKA96 [6] of the effect of the access labyrinths and service tunnels on the radiation levels in USA15. In order to simplify the calculations, the pp interactions in LHC were replaced by a 100 GeV proton beam hitting an axial cylindrical iron target with a 5 cm radius and the ATLAS experiment was replaced by a concrete cylindrical shell of 5 m radius and 50 cm thickness. The particles leaving the shell were written into a source file. In a second step, the source file was used by another FLUKA program which contained a detailed description of the ATLAS cavern and its service ducts. The sensitivity of the calculations was increased by biasing the particle transport through the cavern walls and by re-directing particles going into uninteresting regions to the regions under study. For more details about the programs see [6].

There are two access tunnels (UPX14 and UPX16) between USA15 and the experimental cavern on the ground level of USA15 and two more access tunnels (ULX14 and ULX16) between the first floor of USA15 and the experimental cavern (see Figure 1). Figure 10 shows the result of the calculations of the radiation in these tunnels [6]. The radiation is reduced by a factor 100,000 in the long tunnel on the ground floor and a factor 8,000 in the shorter and wider tunnel on the first floor.

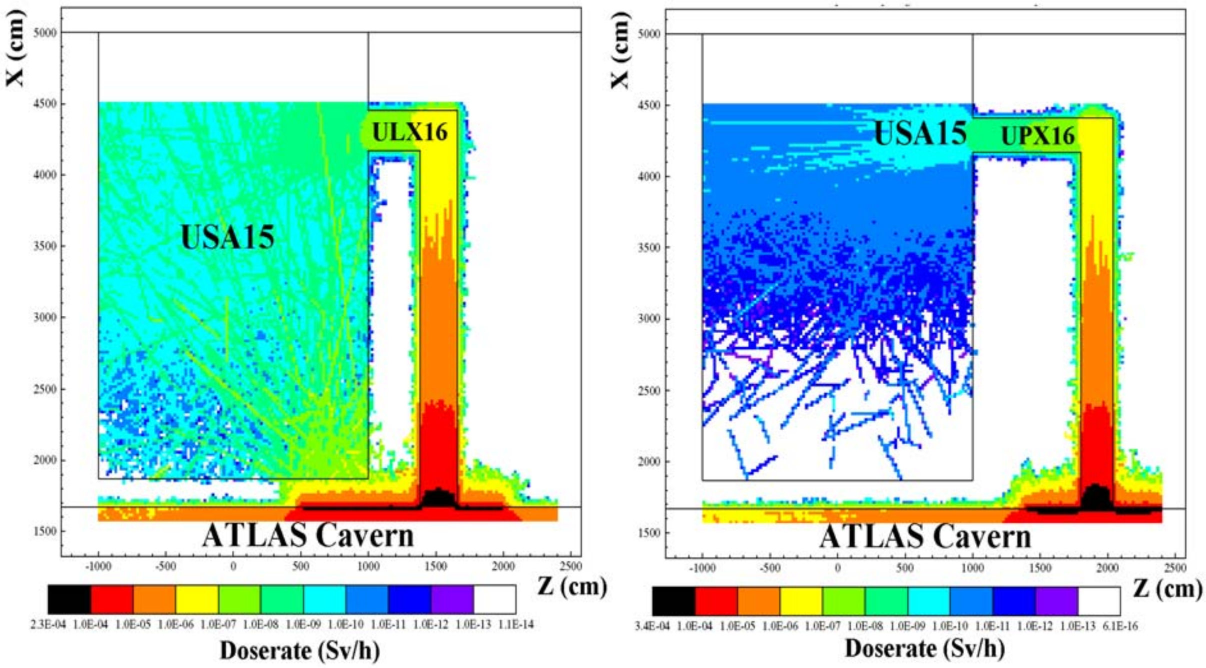

Figure 10. Top view of the ambient dose equivalent rates in the service tunnels ULX16 and UPX16 which go from the ATLAS cavern to the USA15 cavern [6].

Figure 11 shows the result of the calculation by Rollet et al. of the large service tunnel (ULX15) between the elevator and the ground-floor of the cavern and the two large cable ducts (TE14 and TE16) between the cavern and USA15. The reduction factor for the service tunnel is 6,000 and for the cable duct it is 1,200 (without cables).

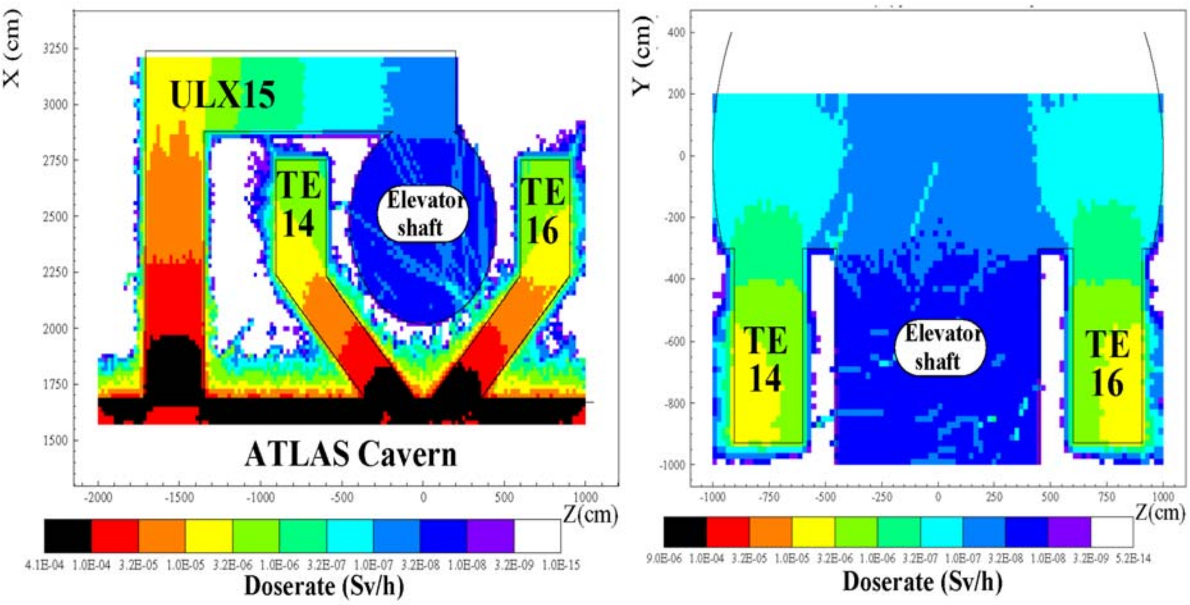

Figure 11. Left: Top view of the ambient dose equivalent rate in the large service tunnel (ULX15) between the elevator and the ground-floor of the cavern and the two large cable ducts (TE14 and TE16) [6]. Right: Side view of the dose rate in the two large cable ducts (TE14 and TE16) [6].

A calculation was also made of the weakening of the USA15 wall due to the holes for the trigger cables (see Figure 12). These go through the wall at an angle so that they do not point at the interaction point and the number and design have changed several times. At the time of the report by Rollet et al. one intended to have four holes for the trigger cables but nine different holes were made in the final design. The reduction factor of the holes was estimated to be only a factor of 250 (without cables) and so the trigger holes were regarded by Rollet et al. as the weakest part of the various ducts going into the USA15 cavern.

Figure 12. Left: The holes for the trigger cables on the ATLAS side of the USA15 wall. Middle: The holes for the trigger cables enters the USA15 cavern under the floor boards at ground level and the first floor. Right: The entrance of the UPX14 tunnel in USA15.

Since the design of the trigger holes has been changed and the original calculation did not give the same large safety reduction factors for the trigger holes as for the other ducts, the calculation of these holes has now been redone. The geometry of the holes was first measured by surveyors [10] in order to get the correct description of the holes. A new FLUKA source file as described above was produced containing 10000 interactions and the present trigger hole design was implemented in the FLUKA program used in the second stage of the calculation. The strategy of the new calculation was somewhat different from that used by Rollet et al. since a comparison was made of the dose rate levels behind a wall with and without trigger holes, instead of calculating the reduction factor of the radiation in the holes.

The result of the new calculation is given in Figure 13 which shows the effective dose rate levels just behind the wall inside USA15. The calculation has been made with and without trigger holes. It is clear from the plot that some regions behind the trigger holes will see an increase of radiation and two critical regions that are behind the holes and on the ground-level were defined (the dashed boxes in Figure 13). The height of these regions is similar to that of a person standing on the ground floor. The increase of the dose rate in the critical regions was only 14% when trigger holes were added to the simulation (the statistical error of each bin in Figure 13 was about 3%). In some regions just in front of the holes the radiation could double but this was below the false floor and in a small area that could in principle be shielded further. The holes were assumed to be empty in this calculation and the cables should decrease the dose rate behind the trigger holes even further.

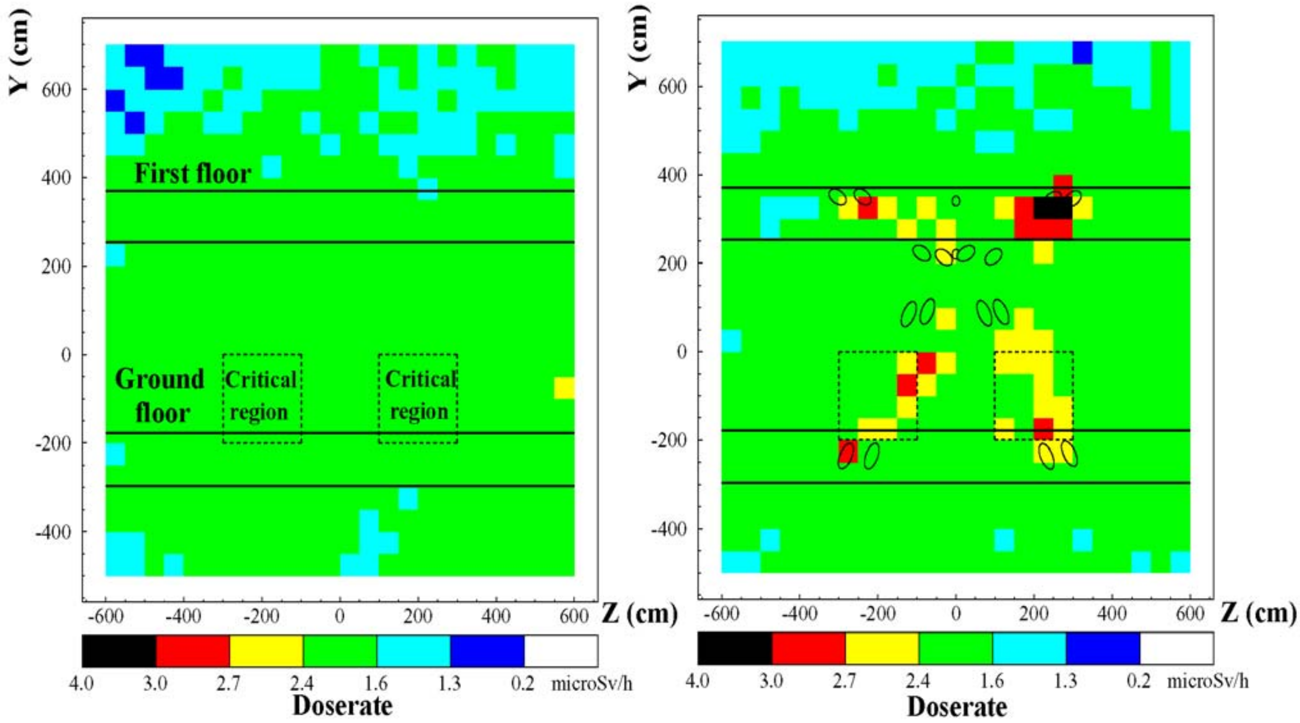

Figure 13. **Left: The effective dose rate in the USA15 cavern in front of the wall without trigger holes. The floors and the critical regions are indicated as full and dashed lines respectively. Right: The dose rate in the USA15 cavern in front of the wall with trigger holes. The enter and exit points of the trigger holes in UX15 and USA15 are indicated in the plot.**

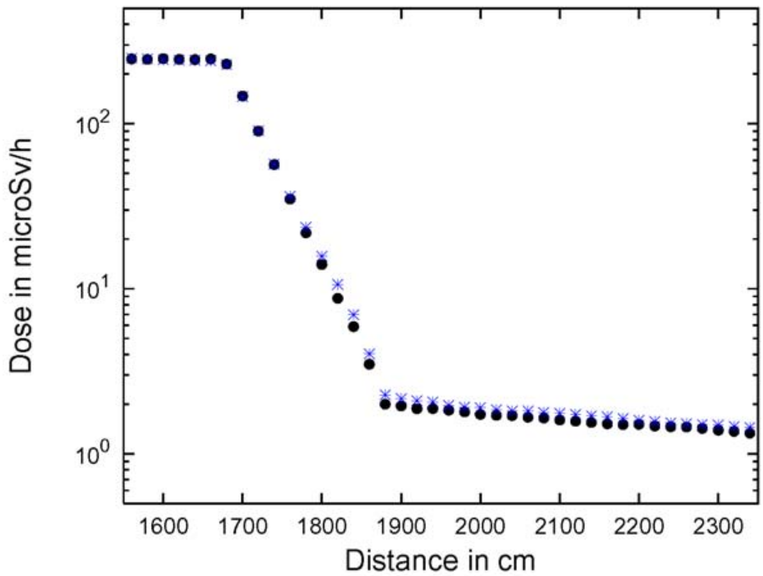

Figure 14. **The effective dose rate in the critical regions as a function of the distance from the beamline. The circles are for a wall without trigger holes and the crosses are for a wall with trigger holes.**

Figure 14 shows how the dose rate in the critical regions varies with the horizontal distance to the beamline. The difference between the situation with and without holes in the wall is small. Note also that the dose rate decreases only slowly as the distance to the wall inside USA15 increases.

The plot can be compared with Figure 6 which shows the same thing for a full FLUKA simulation of the ATLAS experiment. The absolute rate in the experimental hall is a factor of three higher in the full ATLAS simulation but only 50% higher inside USA15. The reason is that the full simulation predicts a larger amount of soft radiation in the experimental hall and this radiation cannot penetrate the wall.

4 Radiation levels in the surface building

The discussion above has been limited to the radiation levels in USA15 but there is also a concern about the radiation level in the ATLAS surface building (SX1). This building is connected to the experimental cavern via two large vertical shafts (Figure 1). The largest of these shafts (PX14) has a diameter of 18 m and the smallest (PX16) a diameter of 12.6 m. The top of the shafts are covered by 100 cm thick concrete plugs during LHC running. The surface building is classified as a supervised area in which the ambient dose equivalent rate should be less than 2.5 μSv/h [3], with TIS-RP recommending a design limit of 1.0 μSv/h.

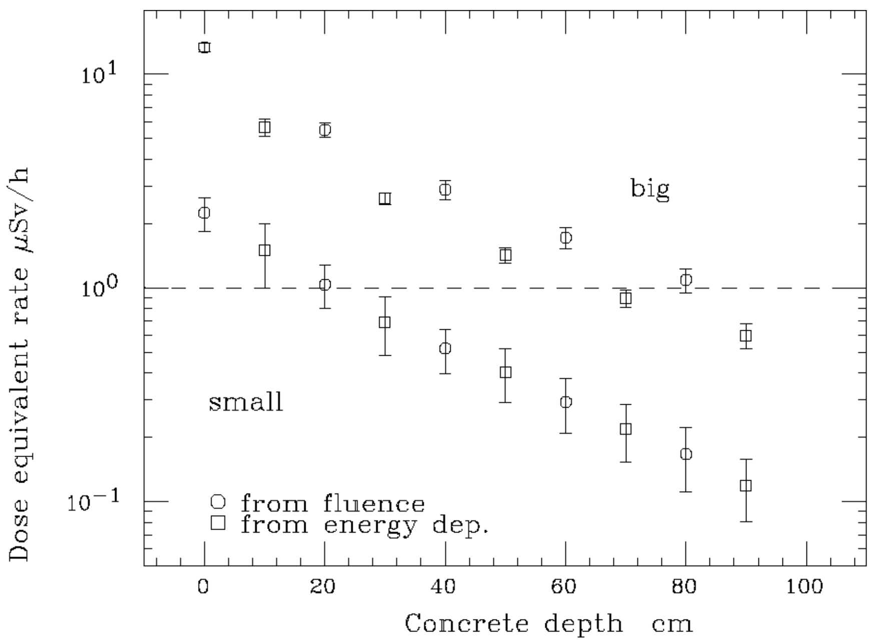

Figure 15. The dose equivalent rate in the surface building as a function of the thickness of the concrete plugs for a large and a small vertical shaft as described in the text [1].

Ferarri et al. calculated the dose equivalent rate in the surface building with the FLUKA program in 1995 [1-2]. No new FLUKA study has been performed in the re-evaluation presented in this note. The method used by the Radiation Task Force (RTF) to estimate the dose rate in USA15 has instead been adopted [11]. The RTF in its study took the old dose rate prediction for USA15 by Ferrari et al. and scaled it with a conservative estimate of the increase since 1995 of hard neutron radiation into the cavern walls, giving a factor 2.7. Another factor taking into account a larger UX15 cavern was also applied. In this way the RTF estimated a maximum dose equivalent rate of 5 μSv/h in the USA15 cavern, consistent with the new results presented in Section 2.

A similar approach has now been applied to update the old predictions of the dose equivalent rate in the surface building. The starting point is the calculation of the dose rate in SX1 as a function of the thickness of the plugs (Figure 15) [1]. The calculation by Ferrari et al. was made for one large shaft (25 m x 29 m) and one small shaft (9.4 m x 13.6 m). Figure 15 gives a prediction of a dose equivalent rate of about 0.5 μSv/h in SX1 for the large shaft and a 100 cm thick plug. The size of the large shaft is, however, not 25 x 29m as in the old calculation since it has been reduced to a circular shaft with a diameter of 18 m. The universal attenuation factor for radiation in a shaft is proportional to $d/\sqrt{A}$ where d is the length of the shaft and A is its cross-section area [4-5]. This expression can be used to estimate that the radiation in the present large shaft should be reduced by a factor 0.67 compared to the older larger shaft. Taking the conservative factor of 2.7 increase of the hard neutron radiation into account one ends up with a prediction of 0.9 μSv/h for the dose equivalent rate in the surface building.

5 Conclusions and recommendation

1) The effect of the weakening of the wall by the trigger holes is small (14%). When these holes are filled their impact will be even smaller. The trigger holes are therefore not a source for concern.
2) More important is the variation of the effective dose in USA15 along the wall. The prediction is 4 μSv/h at the edges of the USA15 cavern due to the plumes of hard neutron radiation coming out of the endcap-toroids, and 2 μSv/h in the central region where the trigger holes are located. The predicted effective dose values are normalised assuming a luminosity of $10^{34}cm^{-2}\ s^{-1}$.
3) If 10 μSv/h will be the new ambient dose equivalent limit for defining a simple controlled area, then ATLAS is below this limit with a safety factor of 2.5.
4) An extra 20 cm of polyethylene moderator in USA15 reduces the effective dose by a factor of two. This is because neutrons are moderated to lower energies, giving lower radiological damage. Doping with boron does not help much because thermal neutrons do not contribute significantly to the effective dose.
5) Using a shielding material such as steel helps only if it is placed on the experimental side of the cavern. It could be noted that there is a lot of steel structures on the experimental side of the wall (stairs, gangways etc..) which were not included in this study. However, when averaged over the wall their effect is expected to be small.
6) The prediction of the dose equivalent rate in the surface building is now 0.9 μSv/h, which can be compared with the ambient dose equivalent limit for a supervised area of 2.5 μSv/h. If this limit is lowered in the future or if the present calculation is an underestimate, ATLAS could be forced to take measures to deal with the situation. More concrete blocks can of course also be put on top of the plugs but that would limit the movement of material in the surface building.

Recommendation:

Even if the present study does not predict a dramatic increase of the radiation in USA15 compared to the design study, it is the opinion of the authors that a 20 cm deep zone on the USA15 side of the wall should be reserved for polyethylene. ATLAS could otherwise find itself in a difficult situation if the limit for a simple controlled area is reduced or if the luminosity is increased.

A polyethylene layer would not be very costly or difficult to install in USA15 but polyethylene is a fire hazard and it might be prudent to wait with the installation until measurements of the equivalent dose rate at low luminosity running have been carried out. One can then see if the polyethylene will be needed at high luminosity running.

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