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GUIDELINE AND RULES FOR INSTRUMENT SHIELDING DESIGN

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1. EXECUTIVE SUMMARY

Conservative estimates are presented of the contributions of the instruments to the annual doses in the auxiliary D and E buildings and in the campus area. These are compared to the dose constraints agreed with SSM and the calculated dose contributions from other parts of ESS, to ensure that the overall dose constraints are met. As a result, instruments are required to demonstrate compliance at TG3 with the following limits for their worst-case H1 scenarios and H2 events with a likelihood above one per year:

1. All instruments must design their cave and guide shielding so that the calculated area-averaged dose rates of all shielding surfaces, excluding the cave roof, are less than 0.5 μSv/hour. The averages must be performed separately for each of the four walls of the instrument cave, and for each 10m-long section of the guide shielding.
2. In order to comply with ESS-0001786 [2], the dose rate on the outer surface of the instrument shall not exceed 3 μSv/hour. To test for compliance, the calculated dose rate needs to be averaged over a 20×20 cm^2 area and multiplied by the appropriate safety factor.

Besides, for the other H2 events (i.e. H2 with a likelihood below one per year), the dose received by each individual per event shall not exceed 1 mSv.

Instruments which demonstrate compliance with these criteria shall be allowed to proceed with the call for tender for their shielding, assuming that there are no other, non-shielding-related, objections.

In order for each instrument to pass its Safety Acceptance Review (TG5), it will need to show that its instrument shielding design complies with an NSS-level dose budget which will be allocated before then. Based on the calculations presented here, the risk of non-compliance is deemed to be very low, provided all instruments satisfy the two requirements for H1 and H2 with a likelihood above 1 as stated above. The NSS management will therefore accept that project risk and take responsibility for the consequences of non-compliance.

Instruments which find that satisfying these constraints for their worst-case H1 or H2 with a likelihood above one scenario cause severe problems, may explore the option of performing an analysis of the expected durations of their various H1 and H2 with likelihood above one conditions, followed by appropriate verification to be agreed with the ESS Radiation Protection Group.

Instruments may create local blue controlled radiation areas on the cave roof, provided that access to such radiation areas is appropriately controlled.

2. INTRODUCTION

There is a clear need for all instruments to have well-defined requirements for the neutronic design of the shielding of their caves and guides. This is most urgent for the first eight instruments and, in particular, the subset of those eight which are located in E01 and can thus start installation work : BEER, CSPEC, BIFROST and MAGIC, as well as NMX, due to its proximity to the office and lab buildings in the campus area, and its potential for early installation. The instruments and building layouts are shown in Figure 1.

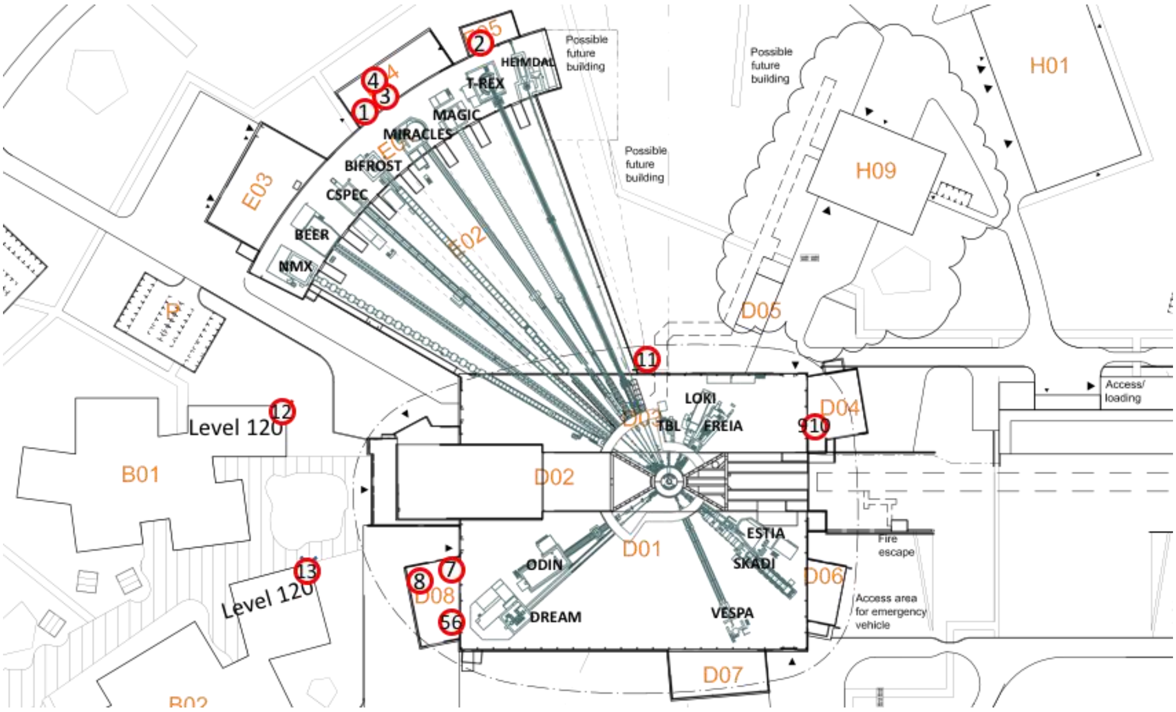

Figure 1 Layout of buildings and instruments. *The reference points at which the dose rate is calculated in this report are indicated with numbered red circles.*

Areas within ESS are divided into a series of non-designated or radiation areas as defined in [2]. Areas, such as office buildings are labelled as **non-designated** area. The agreed dose constraint for in non-designated areas at ESS is 100 μSv/year.

The instrument halls are **supervised** green radiation areas. The maximum permissible dose which could be received in one hour for a supervised area is 3 μSv based on an annual legal dose limit of 6 mSv [2]. Considering the ALARA principle, guidance to instruments is that cave and guide shielding must be designed to satisfy less than 3 μSv/hour as a contact dose rate, on the exterior of the shielding, for all H1 events, i.e. normal operations and H2 events with a likelihood above one per year. The effective dose to a worker from other H2 events shall not exceed 1 mSv.

When evaluating non-designated areas, we consider two types of ionising radiation to be potentially significant:

1. Fast neutrons (above 100 keV). At short distances, they can be considered to travel in straight lines, while at distances greater than about 100 m, they are better described as transported by multiple scattering in the air.
2. Gamma radiation. These can usually be considered to travel in straight lines and are attenuated by absorption in air.

Their relative contributions depend on several parameters, such as distance and intervening shielding elements. They can be estimated by handbook calculations or by Monte Carlo simulations. Calculated dose rates must be multiplied by a safety factor before comparison to the dose limits [3].

- The safety factor for handbook calculations is 3
- The safety factor for approved Monte-Carlo codes is 2

For comparison with the annual dose constraint in non-designated areas at ESS of 100 μSv/year, the calculated hourly dose rates are further multiplied by a baseline occupancy of 2000 hours/year and an occupancy factor of 10% or 65% depending on the type of area, as outlined in [13].

3. NON-INSTRUMENT CONTRIBUTIONS TO THE ANNUAL DOSE IN THE NON-DESIGNATED AREAS

The indoor non-designated areas which are closest to the experimental halls are those in the adjacent D and E buildings. A number of reference points have been identified there, representing plausible worst-case scenarios. They are marked with numbered circles in Figure 1 and Figure 2.

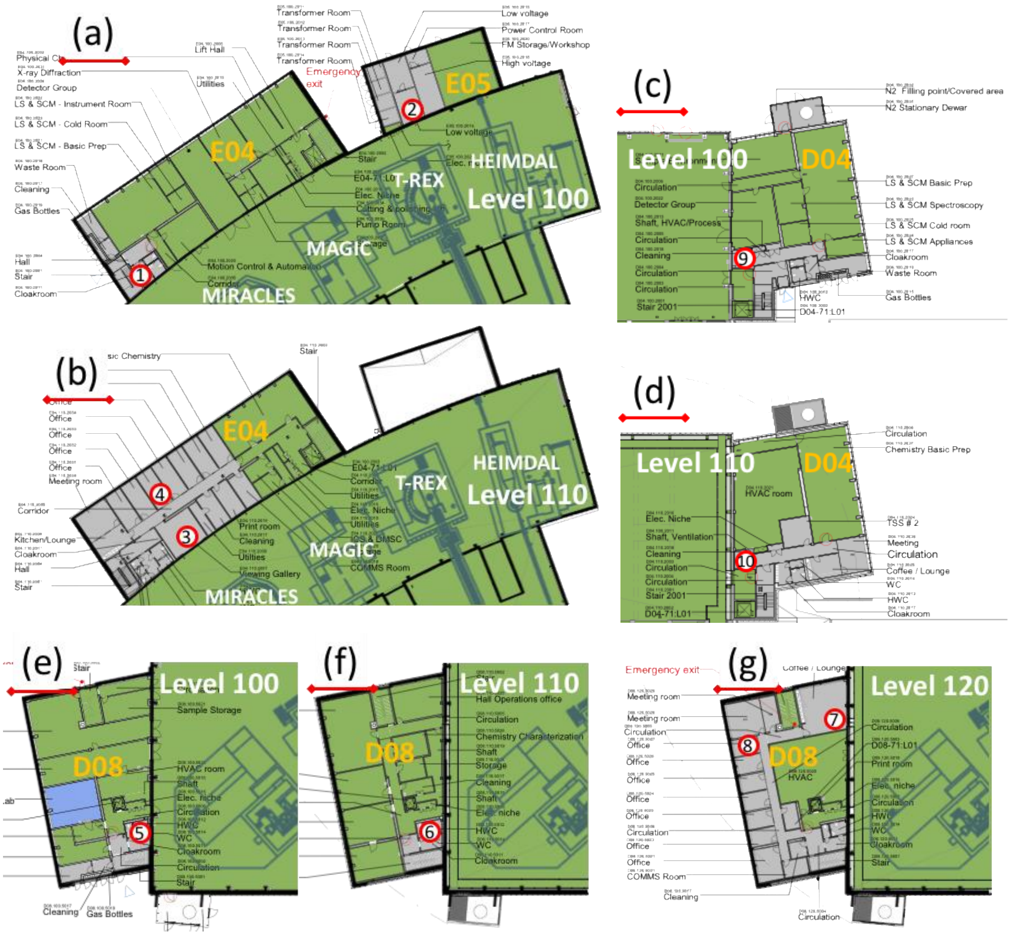

Figure 2 **Reference points chosen in the buildings adjacent to the experiment halls.** *(a) & (b) E04 and E05, (c) & (d) D04, (e)-(g) D08. Level 100 is the ground floor, while levels 110 and 120 are the floors above. Supervised areas are shown in green, while non-designated areas are shown as grey. The red bars are 10 m long and are shown for scale.*

The reference points shown in Figure 2 have been chosen to represent the worst-case scenarios of the auxiliary buildings E03, E04, E05, D04, D06, and D08. D07 is not considered, as its internal layout is not yet known, and the entirety of the building is currently expected to be a supervised area.

In addition to the ten reference points in the D & E buildings, three other reference points have been chosen, one outside the buildings and two in the campus area, labelled 11 to 13 in Figure 1. In all cases, they are placed at 1 m above the floor (or ground) height, so as to simulate the torso of a person standing or sitting at a desk. Their descriptions are summarised in Table 1.

Table 1 Description of Reference Points.

Reference Point	Description
1 (E04)	Closest indoor point at level 100 to the instruments in E01
2 (E05)	Closest indoor point at level 100 to the instruments in E01
3 (E04)	Closest indoor point at level 110 to the instruments in E01
4 (E04)	Closest high-occupancy point to the instruments in E01
5 (D08)	Closest indoor point at level 100 to the instruments in D01/D03
6 (D08)	Closest indoor point at level 110 to the instruments in D01/D03
7 (D08)	Closest indoor point at level 120 to the instruments in D01/D03
8 (D08)	Closest high-occupancy point to the instruments in D01/D03
9 (D04)	Closest indoor point at level 100 to the accelerator, target and bunker
10 (D04)	Closest indoor point at level 110 to the accelerator, target and bunker
11 (outdoors)	Closest outdoor point to the accelerator, target, bunker and instruments
12 (B01)	Closest and highest point in campus area to the instruments in E01
13 (B02)	Closest and highest point in campus area to the instruments in D01/D03

Choice of reference points in the closest non-designated areas to the instruments. Reference point 11 is at 4 m to the E02 wall, at the foot of an 11° slope leading up to the E02 wall, and at 1 m to the D03 wall. Reference points 12 and 13 are chosen to be on the top floor, so as to maximise the view of the instruments.

The various contributions to the expected annual dose at these reference points are listed in Table 2. For each reference point, the dose numbers are calculated for the occupancy factor shown.

Table 2 All ESS contributions to the annual dose at the reference points

Table 2 All ESS contributions to the annual dose at the reference points

Reference Point	Occupancy factor	Accelerator [μSv/year]	Target (incl. ACF) [μSv/year]	Bunker [μSv/year]	Instruments Calculation / Budget [μSv/year]
1 (E04)	10%	2 × 0.6	3 × 0.1	2 × 0.3	3×18.4 / 97.9
2 (E05)	10%	2 × 0.6	3 × 0.1	2 × 0.3	3×31.9 / 97.9

Table 2 All ESS contributions to the annual dose at the reference points

Reference Point	**Occupancy factor**	**Accelerator** [µSv/year]	**Target (incl. ACF)** [µSv/year]	**Bunker** [µSv/year]	**Instruments Calculation / Budget** [µSv/year]
3 (E04)	10%	2 × 0.6	3 × 0.1	2 × 0.3	3×26.0 / 97.9
4 (E04)	65%	2 × 3.9	3 × 0.5	2 × 1.8	3×103.1 / 87.1
5 (D08)	10%	2 × 1.2	3 × 3.4	2 × 1.0	3×8.3 / 85.4
6 (D08)	10%	2 × 1.2	3 × 3.4	2 × 0.9	3×8.4 / 85.6
7 (D08)	10%	2 × 1.2	3 × 3.5	2 × 0.8	3×7.4 / 85.5
8 (D08)	65%	2 × 7.8	3 × 5.5	2 × 5.2	3×27.4 / 57.5
9 (D04)	10%	2 × 20	3 × 1.6	2 × 1.0	3×4.8 / 53.2
10 (D04)	10%	2 × 20	3 × 1.6	2 × 0.8	3×4.8 / 53.6
11 (outdoors)	10%	2 × 3.0	3 × 2.7	2 × 5.8	3×34.0 / 74.3
12 (B01)	65%	2 × 1.7	3 × 0.9	2 × 2.9	3×38.4 / 88.1
13 (B02)	65%	2 × 1.7	3 × 1.0	2 × 2.2	3×15.2 / 89.2

Contributions to the annual dose constraint at the reference points for a baseline occupancy of 2000 hours/year, multiplied by the occupancy factors shown. The calculations of the non-instrument contributions are described in Appendix 1, and are shown here multiplied by the applicable safety factors. The last column shows the calculated contributions from the instruments, as well as the remaining dose budget, once the other contributions are subtracted from the dose constraint

As can be seen in table 2

Table 2 All ESS contributions to the annual dose at the reference points

, there is considerable variation in the degree of compliance with the dose constraint for the various reference points, which is colour-coded in the table.

- Green: within dose budget
- Red: exceeds dose budget

In the next two sections, we will present the method of calculation of the instrument dose rates and then study the worst-case reference points, resulting in establishment of the requirements for the instrument shielding needed to bring the calculated dose rate at all reference points into compliance with the dose constraint.

4. CALCULATED DOSE CONTRIBUTION FROM INSTRUMENTS

Different instruments contribute differently to the dose rate at the various reference points. This depends on several factors, including their distance, the nature of the radiation (fast neutrons (above 100 keV) or gammas), and the presence of intervening shielding structures. Table 3 summarises which instruments are judged to contribute significantly to the dose rate at each reference point, which calculation method has been employed, and the resultant calculated value.

Table 3 Calculated instrument contributions at the reference points

Ref. Point	Total	LOKI	FREIA	ESTIA	SKADI	**VESPA**	**DREAM**	**ODIN**	NMX	BEER	CSPEC	BIFROST	MIRACLES	**MAGIC**	**T-REX**	**HEIMDAL**	**Test BL**
1	18.4					0.1	0.1	0.0	0.0	0.8	2.4	7.7	5.8	0.5	0.5	0.3	0.2
2	31.9					0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.0	21.4	7.6	0.2
3	26.0					0.1	0.0	0.0	0.0	0.4	1.1	3.8	16.6	2.4	1.0	0.5	0.2
4	103.1					0.3	0.3	0.3	0.0	2.0	4.2	11.2	52.4	16.8	10.1	4.5	1.0
5	8.3			0.0	0.0	0.3	5.3	2.1						0.1	0.1	0.0	0.3
6	8.4			0.0	0.0	0.3	5.4	2.1						0.1	0.1	0.0	0.3
7	7.4			0.0	0.1	0.3	4.6	1.6						0.1	0.1	0.1	0.5
8	27.4			0.2	0.3	1.6	12.3	7.7	1.0	0.3				0.6	0.6	0.3	2.4
9	4.8	0.7	0.9			0.7	0.2	0.2						0.2	0.2	0.2	1.5
10	4.8	0.8	0.9			0.7	0.2	0.2						0.2	0.2	0.2	1.5
11	34.0	3.8	0.0			0.5	0.3	0.4						0.0	0.0	28.0	1.0
12	38.4					0.6	0.8	0.7	16.3	8.7	3.9	3.0	1.6	0.3	0.8	0.4	1.3
13	15.2			0.3	0.3	0.5	1.7	1.3	3.7	2.4	1.2	1.0	0.6	0.2	0.4	0.2	1.2

Calculated contribution in μSv/hour of each instrument to the various reference points. White: no contribution. Yellow: gamma radiation only. Red: fast neutrons via sky-shine only. Blue: gamma radiation and fast neutrons via direct view. Purple: gamma radiation and fast neutrons via sky-shine.

The colour code in Table 3 describes which instruments are estimated to contribute to the radiation dose at that reference point and through which mechanism:

- White: the instrument is not judged to contribute significantly to the dose rate at that reference point. This is the case for instruments which can contribute mainly by direct line of sight and where intervening shielding elements, such as another instrument cave or the target station high bay, prevent radiation from travelling there in a straight line.

- Yellow: the instrument contributes only via gamma radiation to that reference point. They are assumed to travel in straight lines and are attenuated by air. A contact dose rate on the shielding surface of 1.5 μSv/hour is assumed, arising purely from gamma radiation.
- Red: the instrument contributes only via fast neutron sky-shine to that reference point. Gamma radiation is assumed to contribute negligibly as intervening shielding elements prevent direct line-of-sight. Sky-shine is the transport via multiple scattering of fast neutrons and is modelled using a distance dependence of $\exp(-R/600m)/R^2$ from [7], which is applicable for distances greater than about 100 m. A contact dose rate of 1.5 μSv/hour is assumed, arising purely from fast neutrons.
- Blue: the instrument contributes by both gamma radiation and fast neutrons to that reference point. Due to the short distance to the reference point, the fast neutron contribution is modelled in the same way as the gamma contribution, i.e. travelling in straight lines, though not attenuated by air. A contact dose rate of 1.5 μSv/hour is assumed, originating from gamma radiation and fast neutrons equally.
- Purple: the instrument contributes by both gamma radiation and fast neutrons to that reference point. Due to the larger distance to the reference point, the fast neutron contribution is modelled as sky-shine. A contact dose rate of 1.5 μSv/hour is assumed, originating from gamma radiation and fast neutrons equally.

Instruments whose guide systems close the direct line-of-sight within the bunker are considered not to have a significant fast neutron dose emitted from their shielding. Their shielding design is generally driven by the prompt gammas emitted from their guide, resulting in a fast-neutron dose which is more than an order of magnitude lower. Instruments with significant fast-neutron transport out of the bunker are named in bold in Table 3. Their contribution to the dose rate is calculated for all reference points, as fast-neutron transport via sky-shine does not require direct line-of-sight to the shielding surface and can propagate over large distances.

Radiation escaping from a shielding surface is expected to be preferentially emitted in the direction perpendicular to the surface. This is usually described by weighting it with the cosine of the angle relative to the surface normal [7]. The gamma radiation contribution has been modelled in this way, as has the fast-neutron contribution in the cases where there is direct line-of-sight between the instrument and the reference point. A more detailed description of the calculation is provided in Appendix 2.

5. WORST-CASE REFERENCE POINTS: RESULTING REQUIREMENTS ON INSTRUMENTS

Reference points where the instruments are shown in Table 2 to be compliant with the dose budget do not need to be further considered here. The non-compliant reference points are numbers 4, 8, 11 and 12 and are highlighted in Table 2 and Table 3. This section will consider how to deal with them. At the worst-case reference point 4, the calculated dose rate integrated over all instruments and multiplied by the safety factor of 3 exceeds the available dose budget by a factor of 3 or more. Table 4 summarises the situation and proposes how best to resolve the issue.

Table 4 Dose rates for the reference points in non-compliance with the instrument dose budgets

	Ref. Pt. 4	Ref. Pt. 8	Ref. Pt. 11	Ref. Pt. 12
LOKI			3.8 μSv/yr	
FREIA			0.0 μSv/yr	
ESTIA				
SKADI				
VESPA	0.3 μSv/yr	1.6 μSv/yr	0.5 μSv/yr	0.6 μSv/yr
DREAM	0.3 μSv/yr	12.3 μSv/yr	0.3 μSv/yr	0.8 μSv/yr
ODIN	0.3 μSv/yr	7.7 μSv/yr	0.4 μSv/yr	0.7 μSv/yr
NMX	0.0 μSv/yr	1.0 μSv/yr		16.3 μSv/yr
BEER	2.0 μSv/yr	0.3 μSv/yr		8.7 μSv/yr
CSPEC	4.2 μSv/yr			3.9 μSv/yr
BIFROST	11.2 μSv/yr			3.0 μSv/yr
MIRACLES	52.4 μSv/yr			1.6 μSv/yr
MAGIC	16.8 μSv/yr	0.6 μSv/yr	0.0 μSv/yr	0.4 μSv/yr
T-REX	10.1 μSv/yr	0.6 μSv/yr	0.0 μSv/yr	0.8 μSv/yr
HEIMDAL	4.5 μSv/yr	0.3 μSv/yr	28.0 μSv/yr	0.4 μSv/yr
Test BL	1.0 μSv/yr	2.4 μSv/yr	1.0 μSv/yr	1.3 μSv/yr
Total	103.1 μSv/yr	27.4 μSv/yr	34.0 μSv/yr	38.4 μSv/yr
New Limit	0.5 μSv/hr	0.5 μSv/hr	0.5 μSv/hr	0.5 μSv/hr
New Total	34.4 μSv/yr	9.0 μSv/yr	11.3 μSv/yr	13.1 μSv/yr
New Total × 3	103.1 μSv/yr	26.9 μSv/yr	34.0 μSv/yr	39.4 μSv/yr
Budget	87.1 μSv/yr	57.5 μSv/yr	74.3 μSv/yr	88.1 μSv/yr

The lines for each instrument are calculations corresponding to a dose rate of 1.5 μSv/hr over all shielding surfaces. Proposed new area-averaged dose rate limits are shown in the *top line of the boxed area. The resultant calculated annual dose, obtained by appropriately scaling down the contributions of each instrument, is compared to the available dose budget for the four worst case reference points, after multiplying by the applicable safety factor.*

As shown in the boxed area of Table 4, a dose rate of 0.5 μSv/hr results in near-perfect compliance with the dose budget for all reference points. We recall that the calculations shown here assume a dose rate of 1.5 μSv/hr over all shielding surfaces. It is thus reasonable to expect that the area-averaged dose rate will be significantly lower, provided the averaging is performed over a sufficiently large area. We therefore formulate a new requirement for instrument shielding:

For all instruments, the calculated dose rate averaged over all external surfaces of their cave walls and guide shielding must be below 0.5 μSv/hour.

The requirement applies to the worst-case H1 scenarios and H2 events with a likelihood above 1 per year of the instrument calculated using approved Monte Carlo code. The area-averaging should be performed independently for the four walls of the cave (front, rear, left, right) and for each 10m-long section of the guide shielding, averaged over both vertical and horizontal surfaces. The requirement does not apply to the cave roof.

This will result in compliance with the dose budget for reference points 8, 11 and 12 and near-compliance for reference point 4. A study was performed of various, more complex schemes which would impose less stringent limits for reference points 8, 11 and 12, with more stringent limits for selected instruments contributing to reference point 4, so as to bring the calculated dose rates into compliance for all reference points, while relaxing requirements where possible. After due consideration, it was felt to be more achievable and simpler to impose a uniform dose-rate requirement for all instruments. This also makes the analysis less sensitive to the specific choice of reference points made here.

There are good reasons to believe that these area-averaged dose rate requirements will not be difficult for the instruments to meet. The instrument shielding is designed to reduce the dose rate at any point on its external surface to below 3 μSv/hour for H1 scenarios and H2 events with a likelihood above one per year. In order to satisfy this requirement, they will be calculated using approved Monte Carlo code to provide a dose rate below 1.5 μSv/hour at all points over their full surface.

The calculations presented here assume that the shielding is calculated to emit radiation at a dose rate of 1.5 μSv/hour over its full surface, whenever the accelerator is operating. There are two principal reasons why this will overestimate the dose rate at the reference points, even when the accelerator is operating at its full nominal power of 5 MW:

1. The dose rate will not be uniform over the shielding surface. For any realistic shielding design, the area-averaged dose rate will be significantly lower than 1.5 μSv/hour. Preliminary calculations indicate that for a typical shielding design, the area-averaged dose-rate is lower than the peak dose rate by a factor of 3-5.

2. The dose rate will not be constant in time. Since the shielding is designed to deal with the worst-case H1 scenarios and H2 events with a likelihood above one per year, the time-averaged dose rate will on most instruments be much lower.

The formulation of this new requirement takes credit for only the first of the two points above. In order to avoid causing undue budget pressure, some instruments may wish to explore the second point: performing an analysis of the expected durations of their various H1 conditions and H2 events with a likelihood above one per year, calculating their area-averaged dose rate for each condition, and estimating the full-year contribution, by weighting the various contributions by their accumulated duration during the year. This may be of particular interest to HEIMDAL, DREAM and ODIN whose T0 chopper will, during normal operations, significantly reduce the downstream dose rates.

If this approach is taken, verification of the accumulated durations of the various H1 conditions (normal operation) and H2 events with a likelihood above one per year needs to be estimated on-line, allowing a running check of the full-year area-averaged dose rate. This will be used to estimate if the projected end-year dose limit will be exceeded and hence if action needs to be taken during the year. Area monitoring, set up by the Radiation Protection group, will control the respect of the limit for the supervised area. Exceeding the limit will result in a shutdown of the instrument (e.g. closing the beam shutter) or an alarm reported to instrument team.

The effect at the reference points of allowing an increased dose rate on the cave roof has been studied (see Appendix 3) and found to be negligible for calculated contact dose rates up to 12.5 μSv/hour. Cave roofs are therefore not covered by the above requirement.

Though not all instruments are covered by the analysis presented in Table 4, the primary 0.5 μSv/hour requirement for the area-averaged dose rate is applied to all instruments. This is an application of the ALARA principle, but it also represents a pragmatic way of dealing with uncertainties relating to possible future changes to the internal layout of the auxiliary D and E buildings, notably that of D07 which is not considered here, as well as the addition of further instruments beyond the first fifteen. Such changes will have to be monitored closely, and their impact on the analysis presented here evaluated to ensure compliance with the dose constraint for workers in non-designated areas.

6. FURTHER CONSIDERATIONS FOR DESIGNING SHIELDING FOR INSTRUMENTS

In the spirit of providing helpful guidelines for designing the instrument shielding, we here address a number of separate topics which represent relevant implementations of the ESS Radiation Protection Handbook and underlying documents [9].

6.1. Shielding area for calculating the contact dose rate

When calculating the dose rate at the shielding surface using Monte Carlo code, the result must be integrated over a finite area for comparison to the relevant dose rate limit. We here specify that the area to use is 20×20 cm^2. This applies to both supervised (green) and blue controlled radiation areas.

6.2. Contribution to the annual dose at the site boundary

The dose rate requirements at the site boundary are similar to those for the campus area. However, the reference points where they are determined for SSM [5] are about 4 times further away from the instruments than the campus area. This more than compensates for the greater occupancy factor (5400 hours/year, total annual target operation) which applies there. The site boundary conditions are therefore not considered to result in additional constraints to the instrument shielding.

6.3. Creation of local blue controlled radiation areas

Instruments may designate parts of their caves and other areas (e.g. part or all of the cave roof) as blue controlled radiation areas while the beam shutter is open. This will increase the maximum permissible continuous dose rate to 25 μSv/hour in those areas. The same safety factors apply. In order to do so, access to these areas must be controlled by suitable protective and administrative measures to be approved by the Radiation Protection Group.

The increase in dose rate at the various reference points when converting the cave roofs to blue controlled areas, has been evaluated and is found to be negligible. For more information, see Appendix 3.

6.4. Accident scenarios

The dose rates discussed here relate to H1 events, i.e. scenarios which occur during normal operation of the instrument and H2 events with a likelihood above one per year. Other H2 events are off-normal events with a likelihood of occurrence greater than once every 100 years but lower than once every year.. They are hence anticipated to occur during the lifetime of ESS. Instrument shielding needs to be designed to attenuate the dose rate from all H1 events and H2 events with a likelihood above one per year to below 3 μSv/hour and should, as far as possible, do the same for other H2 events. It is up to the instrument teams to individually define their H1 and H2 scenarios and argue for which H2 scenarios should be dealt with by passive shielding.

H2 events (i.e. H2 events with a likelihood below one) which result in a dose rate above 3 μSv/hour – hence exceeding the dose rate limit of a supervised (green) area - are dealt with by imposing a limit to workers of 1 mSv per event. Such events are thus dealt with on a per-event basis, and should not be considered to contribute to the annual dose budgets at the reference points which are discussed here. Nor do they affect the considerations for the classifying local areas as blue controlled areas by the Radiation Protection Group.

6.5. Instruments beyond the first fifteen instruments

For most of the reference points, additional instruments are not considered to result in significant increases in dose rates. Considering the worst-case reference points individually:

- Reference point 4: E01 cannot house any additional instruments beyond the first 15. An extension of E01 to allow for new instruments using beamports W9-W11 would not significantly increase the dose rate here, as their contribution is expected to be similar to that of BEER and NMX
- Reference point 8: This is dominated by ODIN and DREAM on beamports S2 and S3, respectively. Beamport S1 is foreseen for a short instrument in order to avoid obstructing access to the large sliding door in the ODIN cave. An instrument there will thus contribute little to this reference point. Future instruments on beamports S4-S11 and in the East sector will all be significantly further away than ODIN and DREAM and their view to the reference point will be mostly obstructed by the ODIN and DREAM cave shielding. In addition, the area-averaged dose rate limit of 0.5 μSv/hour results in a calculated total dose which is only half of the dose budget, even after applying the safety factor of 3. There is thus ample room for dose from additional instruments.
- Reference point 11: There is space for several additional instruments in the North hall. Again, since the area-averaged dose rate limit of 0.5 μSv/hour results in a calculated total dose which is less than half of the dose budget, even after applying the safety factor of 3, there is ample room for dose from additional instruments. If, against expectation, this results in too large an increase to the dose rate at this reference point, it may need to be fenced off to prevent access.
- Reference point 12: E01 cannot house any additional instruments. Additional instruments in the South and East sectors will not contribute significantly to this reference point, as they will be largely shielded from direct view by the target station high bay. In addition, since the area-averaged dose rate limit of 0.5 μSv/hour results in a calculated total dose which is less than half of the dose budget, even after applying the safety factor of 3, there is ample room for dose from additional instruments.

Upgraded or new instruments replacing the current fifteen instruments will need to comply with similar area-averaged dose rate requirements. In addition, we recall that the accelerator power will be significantly lower than 5 MW in the early years of operation, allowing time to study the situation with regular radiological surveys carried out by the ESS

Radiation Protection Group and add additional shielding where identified and required during operations, if necessary.

7. REFERENCES

[1] ESS-0057612 Radiological Zoning D and E Buildings
[2] ESS-0060903 ESS Handbook for Radiation Protection. Chapter 2. General Radiation Protection Rules
[3] ESS-0019931 ESS Procedure for designing shielding for safety
[4] ESS-0063681 ESS accelerator skyshine dose rate maps during normal operations
[5] ESS-0068567 NSS handbook assessment for the contributions of the NSS work areas to the dose at the site boundary through skyshine
[6] ESS-0065565 Handbook assessment of the contribution of the target station to the dose at the site boundary through skyshine
[7] A guide to radiation and radioactivity levels near high energy particle accelerators, A.H. Sullivan (1992)
[8] ESS- 0239723 ESS Handbook for Radiation Protection. Chapter 7. Radiation Monitoring
[9] ESS-0131289 ESS Handbook for Radiation Protection – Table of Content
[10] ESS-0416081 Neutronic design of the bunker wall and roof
[11] ESS-0134533 Dose assignment in the offices for zoning discussion
[12] Dose contributions from NMS to office areas, internal report, P.M. Bentley (2018)
[13] ESS-1095920 Occupancy factors for non-designated areas
[14] ESS-0051492 Radiation Shielding of the Active Cells Facility

8. DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue with contributions from RP group	Ken Andersen	2020-02-04

9. APPENDIX 1: CALCULATION OF NON-INSTRUMENT DOSE RATES AT THE REFERENCE POINTS

Table 5 Non-instrument contributions to the annual dose at the reference points

Reference Point	Occu-pancy factor	Distance to TCS	Accelerator [μSv/year]	Target [μSv/year]	Active Cells Facility [μSv/year]	Bunker [μSv/year]
1 (E04)	10%	180 m	2 × (0+0.6)	3 × (0.04+0.04)	0	2 × (0+0.30)
2 (E05)	10%	180 m	2 × (0+0.6)	3 × (0.04+0.04)	0	2 × (0+0.30)
3 (E04)	10%	180 m	2 × (0+0.6)	3 × (0.04+0.04)	0	2 × (0+0.28)
4 (E04)	65%	187 m	2 × (0+3.9)	3 × (0.24+0.24)	0	2 × (0+1.82)
5 (D08)	10%	96 m	2 × (0+1.2)	3 × (0.28+0.16)	3 × 3	2 × (0+1.02)
6 (D08)	10%	96 m	2 × (0+1.2)	3 × (0.28+0.16)	3 × 3	2 × (0+0.90)
7 (D08)	10%	90 m	2 × (0+1.2)	3 × (0.33+0.19)	3 × 3	2 × (0+0.80)
8 (D08)	65%	102 m	2 × (0+7.8)	3 × (1.54+0.94)	3 × 3	2 × (0+5.20)
9 (D04)	10%	57 m	2 × (0+20)	3 × (1.07+0.50)	0	2 × (0+0.98)
10 (D04)	10%	57 m	2 × (0+20)	3 × (1.07+0.50)	0	2 × (0+0.84)
11 (outdoors)	10%	45 m	2 × (0+3.0)	3 × (1.89+0.82)	3 × 0.6	2 × (0+5.80)
12 (B01)	65%	147 m	2 × (0+1.7)	3 × (0.53+0.42)	0	2 × (0+2.86)
13 (B02)	65%	142 m	2 × (0+1.7)	3 × (0.58+0.45)	0	2 × (0+2.21)

Contributions to the annual dose constraint at the reference points for a baseline occupancy of 2000 hours/year, multiplied by the occupancy factors shown. For Accelerator, Target and Bunker, the calculated dose rate is shown as the sum of two terms: gamma radiation and fast neutrons, respectively. The calculation for the Active Cells Facility is scaled with an occupancy factor of 100%.

9.1. Accelerator

The contribution from gamma radiation is expected to be negligible. Figure 3 shows a map of the fast-neutron dose rate originating from the accelerator, taken from [4].

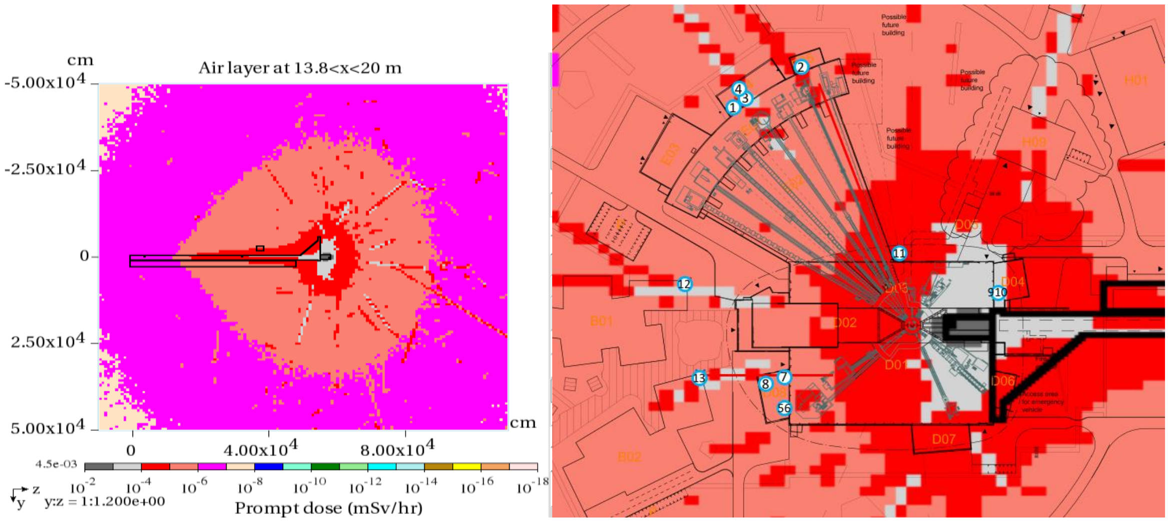

Figure 3 **Fast-neutron dose rate from the accelerator at 5 MW.** *Left: Fig. 7 from [4], showing a map of the fast-neutron dose rate from the accelerator at a height of 13.8-20m above ground level. Right: The same dose rate map, rotated, scaled and overlaid with the building layout showing the location of the reference points.*

By reading off the contour labels, we can extract the calculated dose rate. For reference points 1-4, 5-8, 9-10 and 11 the calculated dose rates are 3e-6, 6e-6, 1e-4 and 3e-5 mSv/hour, respectively. For reference points 12-13, The dose rate value is taken from table 1 of [4] for reference point G1 [5] which is equivalent to buildings B01/B02, and calculated by simulation to be 1.32e-3 μSv/hour. These values are then converted to an annual dose rate for the baseline occupancy of 2000 hours, multiplied by the occupancy factors shown in Table 5.

9.2. Target

For the contribution from gamma radiation, we use the expression given on page 5 of [11]:

$$D_T = \left(\frac{R_m}{R_{rp}}\right)^2 \left(D_n + D_\gamma e^{-\lambda_{air}(R_{off}-R_m)}\right) \quad (1)$$

setting the fast-neutron contact dose rate D_n to zero and the gamma contribution D_γ to 0.75 μSv/hour. R_m is the effective radius of the target monolith of 6 m, R_{rp} is the distance to the reference point and λ_{air} is the inverse attenuation length in air of ln(10)/300m.

For the fast-neutron contribution, we use the result presented in [6] of 6e-8 mSv/hour at 300 m from the target station, rescaled to the distances from the target centre to the reference points, using a distance dependence of exp(-R/600m)/R^2 from [7].

9.3. Active Cells Facility

For reference points 5-8 and 11, we also include a contribution from the Active Cells Facility (ACF) which is calculated to provide a dose rate of 3 μSv/hour on contact of the ACF exterior walls [14]. Assuming a target radius of 1.5 m and an inverse square scaling with distance, this will result in an annual dose of 3 μSv/year for the reference points in D08 and 0.6 μSv/year for reference point 11. As outlined in [13], an occupancy of 2000 hours/year is used for the ACF since it is in operation throughout the year.

9.4. Bunker

The fast-neutron contribution to the reference points has been calculated by using Monte Carlo simulation. It uses the same number of instruments and beamport configuration as the bunker report [10], i.e. 26 instruments distributed over all instrument sectors with generally very conservative assumptions for the beam size and fast-neutron spectrum.

A calculation of the gamma contribution indicates that it is about a factor of 100 less intense than the fast-neutron contribution and can hence be ignored. The report on the calculations for dose rates in non-designated areas rising from bunker sky-shine is planned to be released in 2020.

10. APPENDIX 2: CALCULATION OF DOSE RATES FROM INSTRUMENTS TO THE REFERENCE POINTS

All instrument shielding is assumed to emit radiation at a dose rate of 1.5 μSv/hour uniformly over its surface. The instrument shielding is designed to satisfy the dose rate requirement of 3 μSv/hour with a safety factor of 2, as it is being designed using approved Monte Carlo codes. A contact dose rate of 1.5 μSv/hour thus represents the largest permissible calculated number.

The tables below use the same colour coding as Table 3:

- White: no contribution
- Yellow: contribution only via gamma radiation using the solid angle of the shielding surfaces viewed from the reference point, attenuated by air.
- Red: contribution only via fast-neutron sky-shine, using the distance scaling of exp(-R/600m)/R^2 from [7].
- Blue: contribution via both gamma radiation and fast neutrons. Both are calculated using the solid angle of the shielding surface viewed from the reference point (as for the yellow table cells), though only the gamma radiation is attenuated by air.
- Purple: contribution via both gamma radiation and fast neutrons. The gamma radiation contribution is calculated using the solid angle of the shielding surfaces viewed from the reference point, attenuated by air (as for the yellow table cells), while the fast-neutron contribution is calculated by sky-shine (as for the red table cells).

The cases for applying these different methods are summarised in Table A2.1

Table 6 Use cases for methods for calculating radiation dose rates

	Reference point is within LOS of the instrument shielding		Reference points is outside LOS of the instrument shielding
Guide system blocks fast-neutron transmission out of the bunker	Only gammas		No contribution
Guide system transmits fast neutrons out of the bunker – instruments named in blod	Ref.pt. < 100m: gamma + direct fast neutrons	Ref.pt. > 100m: gammas + fast neutrons by sky-shine	Only fast neutrons by sky-shine

Colour-coded summary of the use cases for the various ways of calculating the radiation dose rates.

The calculated contributions due to gamma and fast-neutron radiation, respectively, are shown in and Table 8 below.

Table 7 Calculated instrument contributions due to gamma radiation

Ref. Point	Total	LOKI	FREIA	ESTIA	SKADI	**VESPA**	**DREAM**	**ODIN**	NMX	BEER	CSPEC	BIFROST	MIRACLES	**MAGIC**	**T-REX**	**HEIMDAL**	**Test BL**
1	17.9								0.0	0.8	2.4	7.7	5.8	0.5	0.4	0.3	
2	30.2								0.0	0.0	0.0	0.0	0.6	1.8	20.5	7.3	
3	25.3								0.0	0.4	1.1	3.8	16.6	2.2	0.8	0.4	
4	97.7								0.0	2.0	4.2	11.2	52.4	15.3	8.9	3.7	
5	6.8			0.0	0.0		5.0	1.9									
6	7.0			0.0	0.0		5.0	1.9									
7	5.7			0.0	0.1		4.2	1.4									
8	19.1			0.2	0.3		10.7	6.6	1.0	0.3							
9	1.8	0.7	0.9													0.1	
10	1.8	0.8	0.9													0.1	
11	32.1	3.8	0.0											0.0	0.0	27.4	0.9
12	35.8								16.3	8.7	3.9	3.0	1.6	0.5	1.2	0.6	
13	14.5			0.1	0.3	0.3	2.1	1.7	3.7	2.4	1.2	1.0	0.6	0.2	0.5	0.2	

Calculated contribution in μSv/hour of each instrument to the various reference points by gamma radiation, assuming 1.5 μSv/hour contact dose from gammas on all shielding surfaces. Applies to all colours except red.

Table 8 Calculated instrument contributions due to fast-neutron radiation

Ref. Point	Total	LOKI	FREIA	ESTIA	SKADI	**VESPA**	**DREAM**	**ODIN**	NMX	BEER	CSPEC	BIFROST	MIRACLES	**MAGIC**	**T-REX**	**HEIMDAL**	**Test BL**
1	1.9					0.1	0.1	0.0						0.6	0.6	0.4	0.2
2	32.5					0.1	0.0	0.0						2.1	22.3	7.8	0.2
3	4.5					0.1	0.0	0.0						2.5	1.1	0.6	0.2
4	36.9					0.3	0.3	0.3						18.3	11.4	5.3	1.0
5	8.8					0.3	5.6	2.4						0.1	0.1	0.0	0.3
6	9.0					0.3	5.7	2.4						0.1	0.1	0.0	0.3
7	8.0					0.3	5.1	1.9						0.1	0.1	0.1	0.5
8	28.3					1.6	13.9	8.8						0.6	0.6	0.3	2.4
9	3.3					0.7	0.2	0.2						0.2	0.2	0.3	1.5
10	3.3					0.7	0.2	0.2						0.2	0.2	0.3	1.5
11	30.9					0.5	0.3	0.4						0.0	0.0	28.7	1.1
12	4.2					0.6	0.8	0.7						0.4	0.3	0.2	1.3
13	4.9					0.8	1.3	0.9						0.3	0.3	0.2	1.2

Calculated contribution in µSv/hour of each instrument to the various reference points by fast-neutron radiation, assuming 1.5 µSv/hour contact dose from fast neutrons on all shielding surfaces. Applies to all colours except yellow

The dose rate values shown in Table 3 are obtained by combining the data in and Table 8. The calculations were performed as follows:

10.1. Yellow

Only gamma radiation contributes to the reference point from this instrument. It is evaluated for each instrument by calculating the solid angle of its shielding viewed from the reference point. This method is employed for instruments whose external shielding walls have a direct line-of-sight to the reference point, ignoring building structures which are judged to have negligible shielding properties. The calculation is expressed as:

$$D_i = O \times d_\gamma \sum_j \frac{\Delta\Omega_j}{2\pi} \cos\theta_j \, e^{-\frac{r_j}{r_{air}}} \tag{2}$$

where D_i is the contribution to the dose rate at the reference point from instrument i, O is the occupancy of the reference point, d_γ is the assumed contact dose rate of gamma radiation on the surface of the instrument shielding of 1.5 µSv/hour, and $\Delta\Omega_j$ is the calculated solid angle of the instrument shielding viewed from the reference point, which is evaluated for the different parts of the instrument *j*, each at a distance r_j from the reference point. The solid angle is reduced by intervening shielding elements which block the direct view. The guide shielding for the long instruments (those in E01) was split into parts of 20m in length, for the instruments in D01 each part was 10m in length, while the cave was treated as a single part in all cases. θ_j is the angle of the surface normal to the shielding surface, relative to the direct line from the reference point. The cosine dependence describes the preferential emission of radiation in the direction perpendicular to the surface [7].

The dimensions of the instrument caves and guide shielding were taken from the EPL database. Instrument caves with complicated shapes were approximated by rectangles.

This method is used for instruments which do not transport fast neutrons out of the bunker through their guide system and for reference points which allow a direct line-of-sight to exterior of the instrument shielding.

To illustrate the method, Figure 4 shows the calculation of the solid angles and surface angles for the case of T-REX seen from reference point 4. In this case, the dose rate is dominated by the cave contribution and the guide shielding is neglected. Figure 5 shows the calculation of the solid angles and surface angles for the case of BEER seen from reference point 12, where the guide and cave contributions are both significant and where the angles are calculated at several positions along the length of the guide and cave.

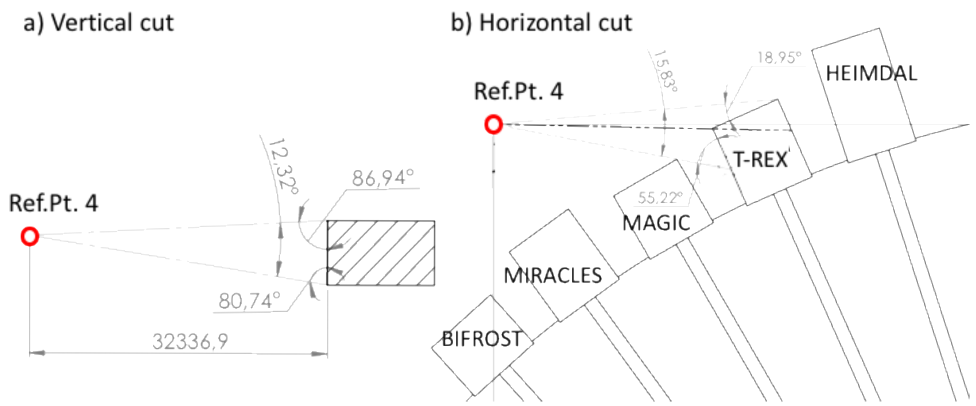

Figure 4 *Calculation of the solid angles $\Delta\Omega_i$ and the surface angles ϑ_i for the example of T-REX seen from reference point 4*

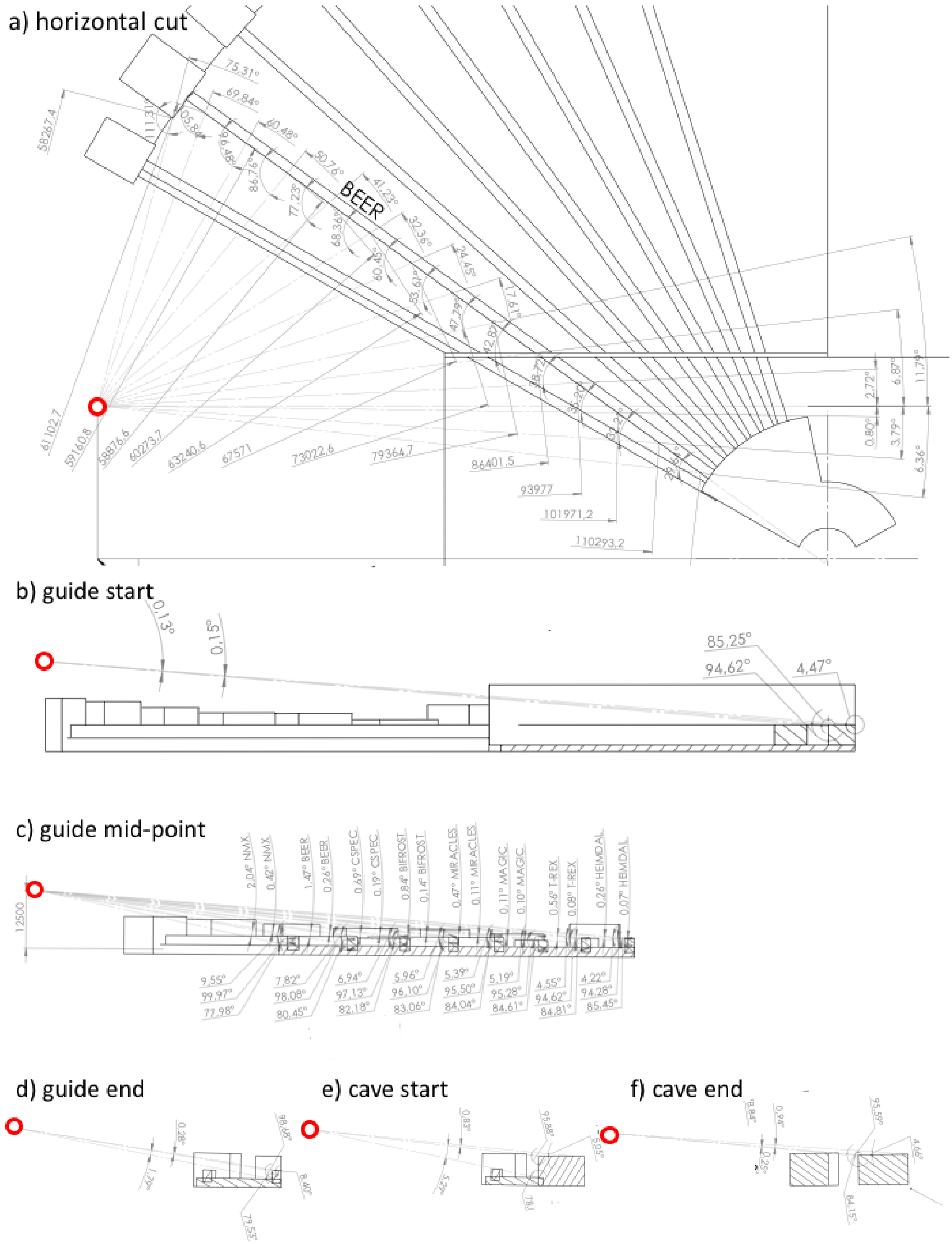

Figure 5 *Calculation of the solid angles ΔΩ$_i$ and the surface angles ϑ$_i$ for the example of BEER seen from reference point 12. a) horizontal cut, b)-f) various vertical projections*

10.2. Red

Only fast neutrons contribute to the reference point from this instrument. It is evaluated by sky-shine using the method in [5], with the same surface areas and source locations used there. This is based on an approximation for fast-neutron sources at a distance of more than 100m, described in the Sullivan handbook [7], which scales the dose emitted at the surface of the shielding with the area of the surface and with a distance scaling of exp(-R/600m)/R^2. A uniform surface dose of 1.5 μSv/hour arising from fast neutrons is assumed for all shielding surfaces.

Only instruments whose guide systems allows a direct line-of-sight from a point outside the bunker to the fast-neutron source in the target monolith are considered to emit significant dose rates of fast neutrons. There are seven of them and they are named in bold in the tables. Of these instruments, DREAM, ODIN and HEIMDAL will have T0 choppers which will effectively prevent fast neutrons from exiting the bunker during normal operations. The calculations do not take the T0 choppers into account and will therefore significantly overstate the fast-neutron contribution from these instruments during normal operations.

This method is used for the instruments named in bold in the tables and for reference points which are further away than about 100 m and do not allow a direct line-of-sight to the shielding.

10.3. Blue

Both gamma radiation and fast neutrons contribute to the dose rate at the reference point from this instrument. Both contributions are calculated using the solid angle of the shielding viewed from the reference point, as expressed in Equation 1 and illustrated in Figure 4 and Figure 5. For the fast-neutron component, the factor describing the attenuation by air is omitted, as it is essentially negligible. A uniform contact dose rate of 1.5 μSv/hour is assumed, originating from gamma radiation and fast neutrons equally. No credit is taken for T0 choppers.

This method is used for the instruments named in bold in the tables and for reference points which are closer than about 100 m and allow a direct line-of-sight to the shielding.

10.4. Purple

Both gamma radiation and fast neutrons contribute to the dose rate at the reference point from this instrument. The gamma contribution is calculated using the solid angle of the shielding viewed from the reference point, as given in Equation 1. The fast-neutron component is calculated by sky-shine as for the cells labelled in red. A uniform contact dose rate of 1.5 μSv/hour is assumed, originating from gamma radiation and fast neutrons equally. No credit is taken for T0 choppers.

This method is used for the instruments named in bold in the tables and for reference points which are further away than about 100 m and allow a direct line-of-sight to the shielding.

11. APPENDIX 3: EFFECT AT REFERENCE POINTS OF BLUE CONTROLLED AREAS ON CAVE ROOFS

Some instruments have expressed interest in converting parts of their cave roof to blue controlled areas, in order to simplify the cave design, improve accessibility and convenience, and to save money on shielding. This would allow them to increase the calculated dose rate from 1.5 μSv/hour to 12.5 μSv/hour in those areas. In order to check the influence that this might have on the non-designated areas, we have increased dose rate on the full surface of all the cave roofs, except the test beamline, to 12.5 μSv/hour. The result is shown in Table A3.1 below.

Table 9 Effect of allowing blue controlled areas on the cave roofs

Reference Point	Level	Occupancy factor	Total with 1.5 μSv/hour on all surfaces	Total with 12.5 μSv/hour on cave roods
1 (E04)	100	10%	18.4 μSv/year	18.4 μSv/year
2 (E05)	100	10%	31.9 μSv/year	31.9 μSv/year
3 (E04)	110	10%	26.0 μSv/year	26.0 μSv/year
4 (E04)	110	65%	103.1 μSv/year	103.2 μSv/year
5 (D08)	100	10%	8.3 μSv/year	8.3 μSv/year
6 (D08)	110	10%	8.4 μSv/year	8.4 μSv/year
7 (D08)	120	10%	7.4 μSv/year	7.6 μSv/year
8 (D08)	120	65%	27.4 μSv/year	28.5 μSv/year
9 (D04)	100	10%	4.8 μSv/year	4.8 μSv/year
10 (D04)	110	10%	4.8 μSv/year	4.8 μSv/year
11 (outdoors)	100	10%	34.0 μSv/year	34.0 μSv/year
12 (B01)	140	65%	38.4 μSv/year	39.4 μSv/year
13 (B02)	110	65%	15.2 μSv/year	15.4 μSv/year

Effect at the reference points of converting all cave roofs (except the test beamline) to blue controlled areas.

It is seen that the effect of converting all the cave roofs to blue controlled areas is only noticeable in some of the areas above level 100, as expected. It results in at most a 4% increase in the total instrument contribution to the dose rate at the reference point, and for most reference points it is much smaller. This is essentially negligible. We therefore conclude that we can allow the conversion of cave roofs to blue controlled areas without additional requirements related to the non-designated areas.