Supporting Capabilities For Underground Facilities

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Abstract. The 2021 particle physics community study, known as "Snowmass 2021", has brought together particle physicists around the world to create a unified vision for the field over the next decade. One of the areas of focus is the Underground Facilities (UF) frontier, which addresses underground infrastructure and the scientific programs and goals of underground-based experiments. To this effect, the UF Supporting Capabilities topical group created two surveys for the community to identify potential gaps between the supporting capabilities of facilities and those needed by current and future experiments. Capabilities surveyed are discussed in this report and include underground cleanroom space size and specifications, radon-reduced space needs and availability, the assay need and other underground space needs as well timeline for future experiments. Results indicate that future, larger experiments will increasingly require underground assembly in larger, cleaner cleanrooms, often with better radon-reduction systems and increased monitoring capability for ambient contaminants. Most assay needs may be met by existing worldwide capabilities with organized cooperation between facilities and experiments. Improved assay sensitivity is needed for assays of bulk and surface radioactivity for some materials for some experiments, and would be highly beneficial for radon emanation.

INTRODUCTION

Underground experiments require significant supporting capabilities, including above-ground and underground cleanrooms, radon-reduction systems, and low-background assays. These capabilities are required to create and maintain a low-radioactive environment for the operation of radiation-sensitive experiments such as those used in rare event searches, dark matter and neutrino physics. To assess the needs of future experiments for supporting capabilities, a survey was sent to all current and future underground experiments. Another survey was sent to all current and planned underground facilities to assess existing and planned infrastructures. Eleven current experiments, 20 planned experiments, and 16 facilities completed the surveys. Their responses are discussed in the following sections along with a summary of the topical group report for the Snowmass 2021 process [1].

FACILITIES FOR LOW-RADIOACTIVITY FABRICATION AND ASSEMBLY

In low-radioactive-background experiments sensitive to ionizing radiation, background from exposure to environmental-levels of radioactive isotopes is problematic. Here we consider cleanrooms and environments with reduced-radon air as supporting capabilities to mitigate these background sources.

Cleanrooms and radon-reduced cleanrooms

Exposure of selected radio-pure detector materials to airborne contaminants (dust and radon) at any stage during storage, handling and detector assembly could result in their surface contamination, through the deposition of dust particulates (containing ^{238}U, ^{232}Th and ^{40}K) and radon progeny plate-out [2, 3, 4, 5]. The higher level of mine dust and airborne radon in many underground spaces increases the level of contamination of the detector surfaces by these particulates compared to above ground if dedicated cleanroom spaces are not used. While radon progeny will directly plate-out onto the detector material surfaces, ambient dust will also deposit onto the surfaces, and later on, emanates radon which could travel to the detector active volumes and yield daughter decays in the active volumes during data-taking period. One of these progeny is ^{214}Pb, which will emit naked betas leading to a continuous ER background down to the signal energy window for dark matter detectors (e.g. liquid xenon detectors). Of particular concern to these surface contaminations, is the long lived ^{222}Rn daughter, the ^{210}Pb ($t_{1/2} = 22.3$ year), whose deposition onto the detector surfaces will contribute to the experiment nuclear recoil (NR) and electron recoil (ER) backgrounds long after the initial plate-out via its beta decay [3, 4, 5, 6], alpha decay [7, 8, 9, 10] and recoiling daughters [3, 9, 11, 12, 13, 14, 15] which will interact with the detector materials and detector active volumes. Dust on or in sensitive detectors can also compromise detector operation in some cases (e.g. by causing electrical shorts or sparking [16]).

Remedial cleaning of the detector surfaces after the assembly is complete in order to remove these problematic surface contaminants is not always practical and effective. Due to nuclear recoil momentum, decay daughters are generally embedded tens of nm into the detector material surfaces after the initial parent depositions. The contaminants are therefore not easily removed with remedial cleaning after the assembly is complete. Techniques such as acid etching or electropolishing may be performed in some cases with relatively good efficiencies at removing some of the implanted radon daughters (^{210}Pb, ^{210}Bi, ^{210}Po) [10, 17, 18, 19, 20, 21]. The best approach remains the prevention or a strong mitigation against the deposition of these surface contaminants onto the detector material surfaces.

Until now, detectors for underground experiments were often assembled in a cleanroom laboratory above ground and then transported underground to finalize the assembly. As the need for bigger detectors arises for the future of these experiments, more, larger underground clean areas will be needed for detector assembly, as transport of very large assembled detectors from the surface will become more difficult. Underground clean areas will also be increasingly needed for material storage, screening facilities and detector development such as crystal growth for solid state detectors.

Need and availability

In many cases, next-generation experiments will require cleanrooms with radon reduction features. A few such facilities exist (e.g., in Gran Sasso, at SNOLAB and at SURF as seen in Table II). We anticipate further development of such unique supporting capability at different facilities will be necessary. Here we evaluate the existing and future supporting facility needs for cleanroom and reduced radon together.

Indeed, the larger future detectors requiring lower levels of radon-daughter plate-out will also necessitate larger cleanrooms underground with even lower radon concentrations. For the cleanroom ISO class, the standard ISO-6 (class 1000) currently available in different facilities across the world is sufficient for many experiments but not for all experiments. Some experiments have requested to improve the class of these cleanrooms to an ISO-5 (class 100) for further suppression against dust fallout onto the detector material surfaces during the assembly stage as shown in the Figure 1 summarizing the cleanroom needs for future experiments. Table I lists the cleanroom sizes and ISO class available in underground and surface laboratories worldwide while Table II lists the current low-radon cleanrooms worldwide along with additional reduced-radon spaces with radon concentrations reduced to lower than outside air.

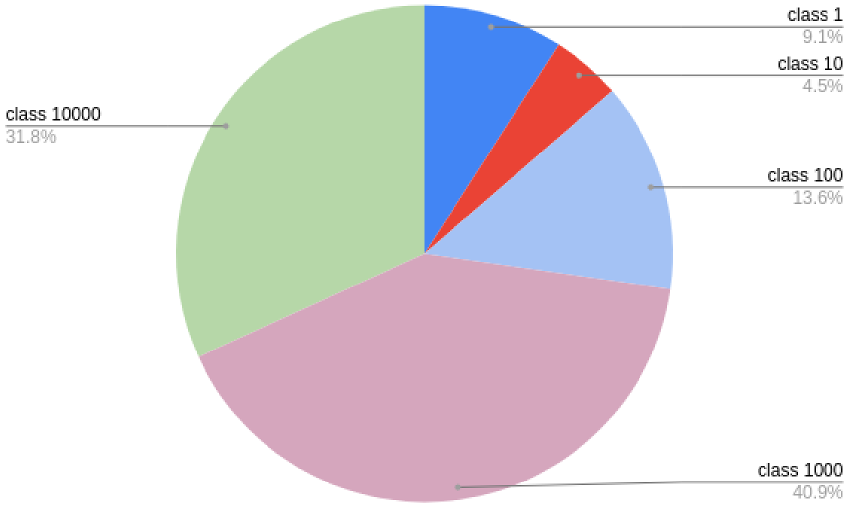

FIGURE 1. Cleanroom class requested by future underground experiments.

TABLE I. Cleanroom spaces for underground facilities.

Laboratory	Depth (mwe)	CR Areas (m^2)	CR ISO Class
Boulby, UK.	2805	800	ISO 7
Canfranc, Spain	2400	70, 30	ISO 5-6
Gran Sasso, Italy	3100	13	ISO 7
Gran Sasso, Italy	3100	86, 32	ISO 6
Gran Sasso, Italy	0	325	ISO 6
Gran Sasso, Italy	0	62	(in progress)
SNOLAB, Canada	5890	4924	ISO 6-7
SNOLAB, Canada	5890	3159	ISO 6-7
SURF, SD, U.S.	0	37	ISO 6
SURF, SD, U.S.	0	55	ISO 5-6
SURF, SD, U.S.	4300	140, 56, 53, 41	ISO 5-6
SURF, SD, U.S.	4300	52, 18	ISO 6-7
SURF, SD, U.S.	4300	163, 142, 33, 33	ISO 7
SURF, SD, U.S.	4300	236	ISO 8
Y2L, Korea	1750	46, 46	ISO 7
Yemilab (under construction), Korea	2800	23	ISO 5
Yemilab (under construction), Korea	2800	80, 20	ISO 7
Kamioka Observatory, Japan	2700	66	Not relayed
PNNL, U.S.	38	5×19-60	ISO 6-7

In general, these facilities have been built to meet the needs of specific near-term experiments. Future experiments such as liquid noble detectors tend to need reduced-radon cleanrooms with areas 100–200 m^2, while several next-generation experiments (such as DarkSide-LowMass and future phases of NEXT) require lower radon concentrations (1–5 mBq/m^3) than are currently available. These lowest radon concentrations desired are at, but not beyond, the capabilities of the most sensitive radon monitors so far produced.

Because the ultimate goal of reduced-radon cleanrooms is to mitigate and assess the level of radon-daughter plate-out onto detector surfaces, additional monitoring of the radon daughter plate-out is also needed in many cases (especially since such plate-out rates depend not only on the radon concentration but also on the material charge and geometry). Such monitoring is typically achieved through a distribution of witness plates measured with low-background alpha detectors. Desired sensitivities for many experiments are lower than 0.1 mBq/m^2 activity of ^{210}Po during a full construction period, implying that monitoring that can provide direct short-term feedback of use must be modestly better than the best sensitivity currently available. [21, 22]

For these future detectors' development and assembly, multiple-sites monitoring of the dust concentration within the cleanrooms as well as the dust fallout rate over time is also requested. Particulate detectors should be distributed in strategic areas to sample the air within the room over time with prompt feedback. Collection vials or witness plates should also be distributed in these areas to be measured with ICP-MS or optical and/or x-ray fluorescence microscopy to enable an accurate modelling and tracking of the dust content within the room and its deposition onto the detector materials (which can be confirmed later with tape-lift measurements). The lowest requirements on dust fallout rate is at the level of 100 ng/cm^2 over the duration of experiment assembly for inner detector surfaces with a requirement of $\sim 10^{-17}$ g (U,Th) /cm^2 on U and Th from dust. These requirements are modestly smaller than the sensitivity of the current microscopy techniques for dust deposition but may be met for long-lived isotopes using ICP-MS [23].

Other underground support needs

Experiments require additional specialized underground support to allow fabrication and assembly of detectors, or to allow experimental science requirements to be met during operation. These support capabilities include underground storage of detector materials, on-site (including possibly underground) machining, and glove boxes for even cleaner detector assembly. These capabilities may require reduced radon environments, as may the detector shielding

TABLE II. Radon-reduced spaces for underground facilities.

Laboratory	Depth (mwe)	CR Area (m^2)	CR ISO Class	Rn Concentration (mBq/m^3)	Other Areas
Canfranc, Spain [24]	2400	70	ISO 5-6	<5	1 mBq/m^3 to experiments
Gran Sasso, Italy	3100	13	ISO 7	10	
Gran Sasso, Italy	3100	86	ISO 6	50	
Gran Sasso, Italy	3100	32	ISO 6	50	
Gran Sasso, Italy	0	325	ISO 6	(in progress)	
Gran Sasso, Italy	0	62	ISO 6	(in progress)	
Kamioka Obs., Japan	2700				50 mBq/m^3 to SuperK tank
Modane, France [25]	4800	16		(planned)	15 mBq/m^3 to experiments
SNOLAB, Canada	5890		ISO 6	(in progress)	
SURF, SD, U.S.	4300	45	ISO 7	100	
SURF, SD, U.S.	0	55	ISO 5-6	500	
Y2L	1750	46	ISO 7	1000	HPGe array room
Yemilab (planned) [26]	2800	23	ISO 5	planned	planned
Yemilab (planned) [26]	2800	80	ISO 7	planned	planned
U. Alberta, Canada [27]	0	100	ISO 5	100	
SD Mines, U.S. [28, 29]	0	15	ISO 5-6	20	

configurations.

On-site underground fabrication facilities are necessary to prevent cosmogenic activation of detector and shielding parts. Such facilities may provide benefit to multiple underground experiments at a site. Underground electroforming of copper parts can result in $>10\times$ lower radioactivity than the cleanest commercially available copper, and so is planned for experiments such as CDEX [30], NEWS-G [31], LEGEND [32], NEXT [33], and nEXO [34, 35]. Experiments such as SBD [36, 37] and SuperCDMS [38] would also benefit from electroplating of clean copper onto pre-machined copper pieces [39, 40]. Underground electroforming capabilities exist at SURF, Canfranc, and PNNL, and facilities are planned for Boulby and SNOLAB. Additional underground crystal growth and fabrication of Ge detectors (to reduce the cosmogenic production of tritium) would also be beneficial for multiple experiments [40, 41, 42], but there are no such facilities currently due to their significant cost. Several labs (SURF, SNOLAB, and Gran Sasso) have underground machine shops. More extensive underground machine shops for general use would benefit future experiments.

Most underground sites have plenty of non-cleanroom space available for storage of materials that do not need to be kept in clean conditions. Such long-term storage is important for letting cosmogenic activation decay away in materials of detectors used for rare-event searches. Most experiments need only modest storage within cleanroom spaces. Some of this storage must be in low-radon volumes in order to mitigate radon-daughter plateout onto parts. Such storage is most easily achieved by bagging materials in radon-impermeable bags or vacuum-tight canisters, and/or placing in gloveboxes or cabinets that are purged with low-radon gas, typically liquid nitrogen boil-off. Radon concentrations at or below 0.1 mBq/m^3 are achievable with such purges. [43, 44]. Several experiments require plants for water purification and radon removal (from the water), scintillator purification and degassing, or chemical spaces with fume hoods. SNOLAB in particular has excellent facilities for such liquid material purification. Finally, several experiments require isotopic purification, with some of these needed to be sited underground, such as Te for SNO+.

DETECTOR MATERIAL ASSAY NEEDS

For each rare-event search detector, materials are carefully assayed and selected for their radiopurity to comprise the detectors and their shielding. The surveyed current and planned experiments relayed a variety of needed sensitivities for sample assays, with most next-generation experiments aiming for $\sim$100 nBq/kg assay capability for inner detector materials. However, KamLAND-Zen [45] related their requirement of achieving on the order of 1 nBq/kg. A complementary suite of assay capabilities, including High Purity Germanium (HPGe) Gamma-Ray Spectroscopy, Inductively Coupled Plasma Mass Spectrometry (ICP-MS), alpha screening, and radon emanation is required to determine which radionuclides are present in a material and at what levels, especially since decay chains are often not in secular equilibrium [46, 47].

TABLE III. Current low background HPGe systems. Some sensitivities in our survey were not recorded.

Facility	Depth (mwe)	Number HPGe	Sensitivity [U], [Th] (mBq/kg)
Berkeley Low Background Counting Facility, U.S. [49]	15	1	6 – 24
Boulby Underground Laboratory, UK [50]	2805	6	< 0.1 – 1
Canfranc, Spain [51]	2400	7	0.1 – 1
China Jinping Underground Laboratory [52]	6720	3	1
Gran Sasso, Italy [53, 54]	3100	8	0.016 – 15
Kamioka Observatory, Japan [55, 56]	2700	5	< 1
LAFARA Underground Laboratory, French Pyrénées [57]	220	5	Not relayed
LLNL Nuclear Counting Facility, U.S.	10	3	Not relayed
Modane, France [58, 59]	4800	2	0.4 – 4
Pacific Northwest National Laboratory, U.S. [60, 61]	38	14	Not relayed
SNOLAB, Canada [62]	5890	6	0.04 – 0.35
SURF, SD, U.S. [63]	4300	6	0.05 – 0.7
Vue-des-Alpes Laboratory, Switzerland [64, 65, 66]	620	1	< 0.1
Y2L / Yemilab, Korea [26, 67, 68]	1750/2800	3	0.05 - 0.5
SD Mines, U.S.	0	2	200 – 2000

High-purity germanium gamma-ray spectroscopy

Gamma-ray spectroscopy using HPGe detectors has historically been the workhorse of low background efforts and is sensitive down to $10\,\mu\mathrm{Bq\,kg^{-1}}$ levels to ^{232}Th and ^{238}U. Counting times for these detectors are routinely on the order of 1–2 weeks, with some up to a month in duration. Samples must be of sufficient mass to collect emission statistics but also must fit within the shielding of the detectors, which vary in size. HPGe gamma-ray spectroscopy is a non-destructive assay technique, so it can be used to assay final components. For samples of smaller mass and activity, Neutron Activation Analysis (NAA) sometimes may be used [48]. Samples are first activated in a reactor, and then analyzed over a few weeks using HPGe detectors. This technique is effectively destructive to a low background sample as the sample is unusable after it is activated.

As shown in Table III, there are currently over 60 HPGe detectors serving underground experiments worldwide (and there are numerous HPGe detectors at additional underground laboratories not listed). If each detector counts a sample for two weeks and each detector requires four weeks of calibrations and background checks per year, the world-wide capability for ultra-low background counting is approximately 1,400 samples per year. Experiments need on average 100 samples counted per year, so there appears to be enough worldwide capacity for HPGe assays. However, limits of sensitivity for currently available HPGe detectors may not reach the levels required by the most inner materials in the next generation of dark matter and neutrinoless double-beta decay experiments. Current detector limits are on the order of $10\,\mu\mathrm{Bq\,kg^{-1}}$, about two orders of magnitude worse than needed for some materials. HPGe detectors with improved sensitivity (such as multiple-crystal detectors [68]), or other assay techniques with improved sensitivity, will be needed to provide assays for next-generation experiments. Furthermore, we cannot realize the full efficiency of having all world-wide detectors subscribed with the current model of each experiment "owning" detectors. World-wide collaboration among low background counting labs is needed to fully realize the potential.

Mass spectrometry

Complementary to HPGe screening are various forms of mass spectrometry. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) provides some of the lowest detection limits (sub-ppt, or $0.01\,\mu\mathrm{Bq\,kg^{-1}}$) [69, 70, 71] available for ^{232}Th and ^{238}U as well as other isotopes of interest to the low-background community [72, 73]. While ICP-MS can also detect ^{40}K, interference effects with Ar species produced in the Ar plasma tend to reduce its sensitivity, with ppm levels achieved typically and state-of-the-art instrumentation able to achieve ppb to ppt levels [74]. One advantage of ICP-MS over HPGe detectors is in the measurement speed. Once the sample is prepared, ICP-MS takes minutes to analyze one sample, whereas the HPGe detector may take weeks. Additionally, smaller sample sizes are required with

ICP-MS. If laser ablation is utilized, ICP-MS can be a location-specific technique, although this mode of operation requires more complicated calibration techniques typically including the development of certified matrix-matched standards [75, 76]. A disadvantage of ICP-MS is in the preparation of the sample (if laser ablation is not used). Optimizing a sample preparation technique for each new material can be time-consuming. Since digestion or ablation are required, the technique is destructive. Most of the underground facilities surveyed either have 1–2 ICP-MS systems on site at their surface facilities, or have relationships with nearby labs for use of their ICP-MS systems. Most of these ICP-MS systems are located in cleanroom facilities with dedicated sample-preparation areas. The experiments surveyed either plan to use these systems or have located other systems within their collaborating institutions.

Alpha screening

Many alpha detectors have negligible backgrounds reduced by operating them underground, but backgrounds of the most sensitive detector for α screening, the XIA UltraLo-1800 [77], with a sensitivity to surface ^{210}Po $< 0.1\,\mathrm{mBq\,m^{-2}}$ [21] are reduced by operation underground by about a factor of 3 [22]. Despite this fact, relatively few underground sites (Boulby, Kamioka, PNNL, and Y2L [78]) have underground XIA detectors; one will be moved underground at SNOLAB soon. Most experiments require surface-alpha sensitivity that may be achieved with the XIA, but improved sensitivity is needed by Argo and is important for many experiments wishing to ensure that assembly occurs within the background requirements, rather than resulting in a need to etch or replace materials after assembly.

Radon emanation assays

As described in [79], emanation of radon provides an important radioactive background for most underground physics experiments, so screening candidate materials for Rn directly [80, 81, 82] is an important support for such experiments. Although radon emanation assays do not have improved sensitivity underground, many experimental systems requiring emanation assays are too large and/or fragile to move to an above-ground site for assay, and assaying as-built systems underground may be advantageous (see e.g. [46]). For these reasons, several underground laboratories, including Kamioka, SNOLAB, Boulby, and Canfranc, have radon emanation systems on-site, while SURF has the capability to harvest radon on-site for measurement nearby at South Dakota Mines [46].

The amount of radon emanation capacity worldwide appears sufficient for future experiments so long as this capacity may be efficiently exploited. However, for many experiments, improved radon emanation assay sensitivity would be useful, as many measurements of individual materials at the limit of sensitivity may easily add up to total radon emanation higher than the experiment requirements. Furthermore, ambiguities in interpretation from radon emanation measurements at room temperature when applied to experiments at low temperatures provide a need for future facilities for radon emanation at low temperatures.

CONCLUSIONS

Future, larger experiments will increasingly require underground assembly with stricter radioactivity requirements. There will need to be larger, cleaner cleanrooms, often with better radon-reduction systems and increased monitoring capability for ambient contaminants. Methods to assay dust deposition and radon-daughter plate-out will need to be improved. There will be increased need for underground machine shops.

Most assay needs may be met by existing worldwide capabilities with organized cooperation between facilities and experiments. Improved assay sensitivity is needed for assays of bulk and surface radioactivity for some materials for some experiments, and would be highly beneficial for radon emanation.

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