PNNL-27319

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

SuperCDMS Underground Detector Fabrication Facility

Cost and Feasibility Report

March 2018

Mark Platt[1,*]
Raymond Bunker[2,†]
Rupak Mahapatra[1]
John Orrell[2]

1. Department of Physics and Astronomy, and the Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
2. Pacific Northwest National Laboratory, Richland, Washington 99352, USA

Principle Investigator
†Corresponding Author: Raymond.Bunker@pnnl.gov

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.
(9/2003)

Acknowledgement

This work was supported in part by the U.S. Departement of Energy (DOE), Office of High Energy Physics; Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the DOE under Contract No. DE-AC05-76RL01830. Additionally, the authors would like to thank Jeter Hall and Richard Ford at SNOLAB for their contributions to this study. It is important to note that the contents of this report do not represent a commitment on the part of SNOLAB to establish or operate an underground facility for the fabrication of SuperCDMS detectors; SNOLAB does not necessarily agree to provide access to any of its personnel or facilities and does not guarantee the accuracy of the estimates and descriptions contained herein.

PNNL-27319

SuperCDMS Underground Detector Fabrication Facility

Cost and Feasibility Report

Mark Platt
Rupak Mahapatra
Raymond Bunker
John Orrell

March 2018

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

1. Introduction

The SuperCDMS SNOLAB dark matter experiment [1] processes Ge and Si crystals into fully tested phonon and ionization detectors at surface fabrication and test facilities. If not mitigated, it is anticipated that trace-level production of radioisotopes in the crystals due to exposure to cosmic rays at (or above) sea level (see, *e.g.*, Ref. [2]) will result in *the* dominant source of background events in future dark matter searches using the current SuperCDMS detector technology. Fabrication and testing of detectors in underground facilities shielded from cosmic radiation is one way to directly reduce production of trace levels of radioisotopes, thereby improving experimental sensitivity for the discovery of dark matter beyond the level of the current experiment.

There are three sequential stages in the creation of a fully functional SuperCDMS detector during which exposure to cosmic rays must be tightly controlled:

1. Growth of the single-crystal Ge or Si boules from which the detector substrates are cut,
2. Fabrication of the boules into individual detectors, and
3. Cryogenic testing of fully fabricated detectors.

In this report, we investigate the cost and feasibility to establish a complete detector fabrication processing chain (Stage 2) — similar to the facility in Ref. [3] — in an underground location to mitigate cosmogenic activation of the Ge and Si detector substrates. For a specific and concrete evaluation, we explore options for such a facility located at SNOLAB [4], an underground laboratory in Sudbury, Canada hosting the current and future experimental phases of SuperCDMS.

It is also important to consider the other two stages. We comment on general expectations for the sea-level-equivalent exposure associated with Stage 1, assuming that the single-crystal boules are grown by third-party vendors in surface facilities. As an example of what can be achieved, we site our recent experience acquiring low-activation crystals for the SuperCDMS SNOLAB experiment. We also note a recent effort to develop underground germanium-crystal growth. Finally, we do not explore reduction of cosmogenic exposure during testing of fully fabricated detectors (Stage 3) in this report, because it is already an active area of research; a project called CUTE is presently underway to establish a suitable underground testing facility at SNOLAB [5].

2. Fabrication Equipment

A description of the fabrication processes to transform single-crystal Ge or Si boules into functional SuperCDMS detectors can be found in Ref. [3], including crystal alignment, shaping, polishing, and sensor fabrication. Carrying out these procedures requires a long list of specialized equipment and associated utilities and infrastructure. In Appendix A, we have compiled a list of the fabrication equipment needed to establish an underground facility for fabrication of SuperCDMS-style detectors; hardware was specifically chosen for this purpose. The total cost is estimated at $2.1M.[1] Fabrication equipment costs are based primarily on (rounded) current market prices (*i.e.*, 2017 price quotes), but also on prior experience. The thin-

[1] Cost estimates are given in U.S. dollars and rolled-up estimates are rounded up to the nearest $100k.

film sputtering system dominates the cost estimate at $0.5M, followed by $0.25M for a plasma etching system and $0.23M for an x-ray diffraction machine (for crystal alignment).

3. Infrastructure

SNOLAB's existing underground infrastructure is impressive and generally better equipped than most universities to accommodate a fabrication facility of this type. Electrical power, compressed air, nitrogen, supply water, other gases, waste water, chemical (and acid) waste, and pump exhaust are all handled routinely in the SNOLAB experimental spaces. Additionally, SNOLAB infrastructure also extends to ES&H, with well-established safety protocols and on-site training programs. A list of standard utilities required to operate the fabrication equipment is provided in Appendix B, almost all of which are already available underground at SNOLAB.

The fabrication facility will require a total space of approximately 1200–1400 ft^2, which naturally divides into two roughly equal parts that need not be physically connected: (1) a clean area with a dedicated ~360 ft^2 class-100 cleanroom for sensor fabrication work; and (2) a less clean area for crystal alignment, shaping and polishing. All of SNOLAB is already a class-2000 cleanroom, and the staff have extensive experience creating cleanrooms inside of this already clean space.

Acid exhaust and radon are the most challenging aspects of the underground infrastructure. Some stages of detector fabrication are radon-sensitive, and the radon level in underground spaces is generally elevated relative to surface labs. The average radon level at SNOLAB has been measured to be ~130 Bq/m^3 [6], approximately 10× higher than at existing SuperCDMS detector fabrication facilities. Consequently, active radon mitigation must be considered. Typical strategies include:

1. Storage of parts in nitrogen-purged cabinets,
2. Working in nitrogen-purged glove boxes,
3. Soft-walled tents continuously flushed with low-radon air, and/or
4. Conducting work inside a dedicated low-radon cleanroom.

Equipment needed to implement #1 is already included in the total cost estimate indicated in Sec. 2. Because detector fabrication spans a period of many days, it is already necessary in existing above-ground facilities to protect detectors from radon overnight and on weekends; so use of strategy #1 is assumed underground as well. In general, strategy #2 is not practical for SuperCDMS detector fabrication because the work requires a high degree of dexterity and/or large pieces of equipment, both of which are either too difficult or too costly to effectively implement inside a glove box.

Strategy #3 might be considered for the crystal alignment, shaping and polishing area. SNOLAB already compresses surface air and pipes it underground for general use, with a radon level ~20× lower than underground. However, this surface air has a limited available flow rate: ~100 ft^3/min. During high-usage periods, a compressor located underground supplements the supply with underground air, which leads to an increased radon level. Alarms and carefully planned protocols would be needed to ensure that a satisfactory level of radon mitigation is achieved.

Strategy #4 will be implemented underground at SNOLAB in an aluminum cleanroom as part of the SuperCDMS SNOLAB project [7] — to protect the detector payload during installation into the SuperCDMS cryostat. This cleanroom will be too small to accommodate the class-100 space needed for sensor fabrication; however, it provides a useful model for implementation of radon mitigation. Based on prior experience with similarly designed systems, we estimate a total radon infrastructure cost of $0.5M: half for purchase ($150k) and installation ($100k) of the cleanroom and half for the purchase ($150k) and installation ($100k) of the radon-filter hardware.

Finally, we estimate an overall infrastructure cost of ~$1M to prepare the underground space(s) prior to installation of the fabrication equipment and cleanroom. This is a rough estimate that will need to be reevaluated when the specific underground locations for the fabrication facility are identified. In particular, this includes labor and M&S for purchase and installation of additional acid- and pump-exhaust plumbing, which will need to be run to a central location within SNOLAB to join with existing exhaust lines. The location of the fabrication spaces and their proximity to the existing facilities will have a major impact on the facility's infrastructure cost. If a space can be located near the existing facilities, the overall cost and effort could be substantially less. The $1M estimate also includes labor and M&S to install dedicated electrical breakers, to extend existing compressed-air and water utilities, and to install a fume hood within the sensor-fabrication cleanroom — including any additional design work required to make the fume hood compatible with a low-radon design.

4. Staffing & Operations

Significant time and effort are required to create *and* startup a fabrication facility of this nature; establishing the infrastructure and installing the equipment is just the beginning. Due to the complex nature of the equipment, considerable time and effort are needed for development and validation of fabrication processes. Based on Mr. Platt's prior experience in the semiconductor industry, as well as his experience establishing the microfabrication facility at Texas A&M University (described in Ref. [3]), we estimate that the initial installation and startup project to establish an underground fabrication facility at SNOLAB will take 2 to 3 years. Staffing during this startup period is estimated at 4.0 FTE:

- 1.0 FTE – Managing engineer/supervisor
- 2.0 FTE – Fabrication technicians
- 1.0 FTE – SNOLAB facilities technician

Staffing thereafter to operate the facility would be similar during active detector fabrication. However, with the general infrastructure established, only a fraction of the SNOLAB facilities technician would be needed; staffing during normal operations would likely be <3.5 FTE overall.

Additional operating costs (not including labor) after the initial startup period are expected to be modest. A detailed estimate is provided in Appendix C; operating costs are estimated at $70.5k per year, covering various detector-fabrication consumables such as chemicals, thin-film targets, and cleanroom gear. This assumes that SNOLAB will cover the cost of general utilities (*e.g.* electricity), as they do for other hosted experiments.

5. Cosmic-ray Exposure Budget

The ultimate goal of hosting detector fabrication in an underground laboratory is to minimize exposure of detectors to cosmic rays. A useful figure of merit is the number of sea-level-equivalent days of exposure. The current SuperCDMS SNOLAB project aims to limit sea-level-equivalent exposure to less than 60 days, which approximately breaks down as follows:

1. Crystal growth, shaping and initial shipment – 20%
2. Sensor fabrication – 40%
3. Detector testing & final shipment – 40%

With an underground detector fabrication facility and utilizing the aforementioned CUTE facility for detector testing, contributions from the latter two stages are reduced to effectively zero. Further, (in this case) the first stage estimate assumes that the crystal boules are diced and shaped by a vendor in a surface facility, which need not be the case. Additionally, it includes a lengthy shipment from crystal growers in Europe to the SuperCDMS detector fabrication facility at Stanford University in California.

At the time of this writing, the SuperCDMS SNOLAB project has completed the first stage in the detector fabrication processing chain. The realized sea-level-equivalent exposure was 7–8 days, with roughly equal contributions from: (1) growth and shaping of the crystals by a European vendor, and (2) shipment from Europe to California in a shielded container.[2] The underground facility outlined in this report includes equipment to shape crystal boules into individual detector substrates. Based on the recent SuperCDMS experience, this would shave ~1.5 days off of the Stage 1 exposure. Assuming the boules are grown by the same vendor and that they will be shipped in the shielded shipping container, an additional reduction of ~0.5 days may be possible because the shipping route from Northern Europe to SNOLAB is shorter than to California. Overall, this suggests that a total exposure budget of 6 days is feasible, corresponding to an order of magnitude improvement relative to the SuperCDMS SNOLAB project goal. If there were a suitable crystal grower in closer proximity to SNOLAB, an additional factor of 2 reduction is conceivable.

During the finalization of this report, we became aware of the GEMADARC effort[3] — supported by the National Science Foundation Partnerships for International Research and Education Program (NSF PIRE) — to develop the means to grow detector-grade Ge crystals underground. In principle, this would mitigate the Stage 1 cosmic-ray exposure. Of course, if crystal growth were to occur in a different underground facility than the one hosting the detector-fabrication and -testing capabilities, some surface transport would be required. Regardless, the GEMADARC partnership points to a broader community desire for underground detector production.

[2] This shielded shipping container was originally constructed and used to protect enriched-germanium detector crystals for neutrinoless double-beta decay searches. The design is described in Ref. [8] and studied in Ref. [9]. While housed within the shielded container, the effective sea-level-equivalent exposure is 10× less.

[3] Germanium Materials and Detectors Advancement Research Consortium; http://pire.gemadarc.org.

6. Summary

We conclude that it is indeed feasible to build a detector fabrication facility in SNOLAB. The existing SNOLAB infrastructure is almost ideal for hosting such a facility. Further, the SNOLAB scientific and technical staff have a well-developed understanding of our concerns with respect to controlling exposure to other environmental factors (*e.g.*, radon and dust). There is also an existing relationship between SuperCDMS and SNOLAB, with some of the scientific staff participating as official collaborators. These factors, together with the collocated cryogenic testing facility (CUTE), make SNOLAB the only logical choice for an underground fabrication facility for SuperCDMS detectors. We estimate a total cost of $3.6M for equipment and infrastructure to install and commission the facility, not including the 4.0 FTE of personnel required to complete the startup project over a 2–3 year period. Thereafter, staffing can be reduced to 3.5 FTE during operation of the facility, with a yearly M&S budget of ~$70.5k (not including the cost of the Ge or Si crystals).

Appendix A – Equipment List

The following list includes major equipment needed for fabrication of SuperCDMS-style detectors. Most cost estimates are based on 2017 price quotes and all amounts are in U.S. dollars. In a few cases, purchase of new equipment would be cost-prohibitive and thus it is recommended that used equipment be procured. Infrastructure costs — class-100 cleanroom, radon mitigation system, and pump and acid exhaust lines — are not included here.

Process	Equipment	#	Price	Total
Metals despoition	Thin-film sputtering system	1	$500,000	$ 500,000
Dry etching	Reactive ion etching system	1	$250,000	$ 250,000
Crystal alignment	X-Ray diffraction machine	1	$230,000	$ 230,000
Dry etching	Used scrubber	1	$150,000	$ 150,000
Feature inspection	Used scanning electron microscope	1	$150,000	$ 150,000
Photolithography	Thin-film mask aligner	1	$115,000	$ 115,000
Crystal polishing	Interferometer	1	$100,000	$ 100,000
Film hieght	Optical profilometer	1	$ 80,000	$ 80,000
Side shaping	Bonding machine for sacrificial discs	1	$ 60,000	$ 60,000
Photolithography	Optical inspection microscope with PC image capture	1	$ 55,000	$ 55,000
Photolithography	Spin rinse dryer	1	$ 50,000	$ 50,000
Crystal shaping	Lapping machine	1	$ 47,500	$ 47,500
Side Shaping	Mill for core drilling and other work	1	$ 37,500	$ 37,500
Wire Bonding	Wedge wire bonder	1	$ 35,000	$ 35,000
Photolithography	Spin coater	1	$ 32,500	$ 32,500
Dry etching	Explosion-proof gas cabinet	2	$ 16,000	$ 32,000
Photolithography	Used wet bench	1	$ 13,500	$ 13,500
Photolithography	Acid fume hood	1	$ 12,500	$ 12,500
Crystal polishing	Used multi-spindle polsihing machine	1	$ 10,000	$ 10,000
Environmental monitoring	Particle counters	2	$ 5,000	$ 10,000
Sensor fabrication	Chiller	1	$ 8,500	$ 8,500
Face alignment	Face alignment fixture (custom machining)	1	$ 8,400	$ 8,400
Sensor fabrication	DI water treatment system	1	$ 7,500	$ 7,500
Environmental monitoring	Radon detectcor	1	$ 7,000	$ 7,000
Photolithography	Vibration isolation table	1	$ 5,500	$ 5,500
Face shaping	Linear feed fixture (custom machining)	1	$ 4,800	$ 4,800
Sensor fabrication	Work tables/desks	3	$ 1,200	$ 3,600
Side Shaping	Mill accessories and hardware	1	$ 3,000	$ 3,000
Photolithography	Spin coater chucks (custom machine work)	3	$ 960	$ 2,880
Crystal polishing	Nitrogen dry box	1	$ 2,750	$ 2,750
Sensor fabrication	Nitrogen dry box	1	$ 2,750	$ 2,750
Heavy etching	Eyewash station	2	$ 1,250	$ 2,500
Side Shaping	Core drilling fixture (custom machine work)	1	$ 2,400	$ 2,400
Photolithography	Ultrasonic bath with heater	1	$ 2,350	$ 2,350
Crystal polishing	Work bench	2	$ 1,175	$ 2,350
Photolithography	Substrate oven >150 C	1	$ 2,100	$ 2,100
Crystal alignment	Radiation survey meter	1	$ 2,000	$ 2,000
Crystal polishing	Laboratory sink	1	$ 2,000	$ 2,000
Photolithography	Ultraviolet monitor	1	$ 1,600	$ 1,600
Photolithography	Hot plate with stir	3	$ 600	$ 1,800
Side Shaping	Side grinding fixture (custom machine work)	1	$ 1,440	$ 1,440
Heavy etching	Emergency shower	1	$ 1,350	$ 1,350
Crystal polishing	Spindle adaptors (materials & machining)	4	$ 250	$ 1,000
Approximately 25 other items, each <$1k				$ 11,512
Total			**$**	**2,061,582**

Appendix B – Utilities

Included here is a list of standard utilities required to operate detector fabrication equipment. Almost all of these are already available underground at SNOLAB. Utilities not yet accounted for in this list are those associated with radon scrubbing for the class-100 cleanroom. Utilities required for the planned SuperCDMS SNOLAB radon filter (as in Ref. [6]) include ~100 amps of 208 VAC and ~10 amps of 120 VAC power, ~4 gpm of chilled water, and compressed air for valve actuation.

Process	Equipment	120VAC [Amps]	208VAC [Amps]	Air [psig]	Dry N2 [psig]	Exhaust	DI water [gpm]	City water [gpm]	Other
Alignment	X-ray diffraction machine	15							
Alignment	Radiation survey meter	5							
Shaping	Lapping machine		15					1	1 gpm waste water
Side Shaping	Mill: core drilling, other work		30	90					CDA for part blow off
Side Shaping	Waste pump	1.7						0.5	.5 gpm waste water
Side Shaping	Bonding machine	7		30				0.25	.25 gpm waste water
Heavy etch	Eyewash Station							Yes	
Heavy etch	Emergency Shower							Yes	
Polishing	Polishing machine				30				N2 for crystal blow off
Polishing	Interferometer	5							
Polishing	Inspection Microscope	1.5							
Polishing	Nitrogen Dry box	3			12 cfh				Boil off nitrogen
Polishing	Sink						0.5		.5 gpm waste water
Fabrication	Cleanroom ULPA filters	96							2' x 4' HEPA panel X 20
Fabrication	Cleanroom Air Coditioning	51.5							Clean room air handler
Fabrication	Cleanroom lights	5							7 LED light panels
Fabrication	Chiller		15						single phase
Fabrication	Chemical storage Acid					yes			Acid fume exhaust
Fabrication	Water treatement system	3						0.25	
Fabrication	DI Pump	1.3							
Fabrication	Nitrogen dry Box	3			12 cfh				Boil off nitrogen
Deposition	Sputtering system		60	90	30	yes			Pump exhuast not toxic
Photolithography	Substrate oven >150 C	13							
Photolithography	Spin coater	6		90		yes			
Photolithography	Thin-film mask aligner	10		60	30				Vacuum for chuck
Photolithography	Ultraviolet monitor	15							
Photolithography	Vibration Isolation Table			90					
Photolithography	Hot plate with stir	10							
Photolithography	Wet bench (solvents)	15		90	30	yes	1	1	2 gpm waste water
Photolithography	Acid fume hood	15			30	yes			Acid fume exhaust
Photolithography	Microscope	10							
Photolithography	Ultrasonic bath with heater	5							
Photolithography	Spin Rinse Dryer		15	70	30	yes	2		N2 output to exhaust
Dry Etch	Reactive ion etcher		30	90	30	yes			Toxic exhaust to scrubber
Dry Etch	Explosion-proof gas cabinet	15		90	30	yes			cabinet exhaust
Dry Etch	Scrubber		20						
Wire Bonding	Wire bonder	10			30				
Wire Bonding	Small vacuum pump	2							
Film hieght	Optical Profilometer	15							
Radon counter	Radon detector	5							
Particle counter	Particle counter	1.5							
Approximate Totals		**345.5**	**185**	**90**	**30**		**2**	**2**	

Appendix C – Operating Costs

Detector fabrication is performed in batches, with each batch requiring ~2 months of fabrication time. The following list details M&S consumed during fabrication of a single batch, totaling just under $12k. The total yearly operating cost (not including labor) is therefore ~$70.5k.

Description	Price	Quantity	Total
Aluminum etchant	$ 240.00	8	$ 1,920.00
Photoresist stripper	$ 100.00	16	$ 1,600.00
Developer	$ 85.00	16	$ 1,360.00
Hydrogen peroxide	$ 45.00	16	$ 720.00
Methanol	$ 100.00	6	$ 600.00
Clean supplies	$ 550.00	1	$ 550.00
Si thin-film target	$ 1,800.00	0.2	$ 360.00
Al thin-film target	$ 1,750.00	0.2	$ 350.00
Al target	$ 1,750.00	0.17	$ 291.55
DI water	$ 140.00	2	$ 280.00
Hydrofluric acid	$ 260.00	1	$ 260.00
Pump rebuild	$ 1,450.00	0.17	$ 241.57
W thin-film target	$ 1,200.00	0.2	$ 240.00
Photoresist	$ 480.00	0.5	$ 240.00
Nitric acid	$ 235.00	1	$ 235.00
Polishing slurry	$ 125.00	1.5	$ 187.50
Glass ware	$ 160.00	1	$ 160.00
Sulfuric acid	$ 70.00	2	$ 140.00
DI water	$ 140.00	1	$ 140.00
Acetic acid	$ 265.00	0.5	$ 132.50
Carboys	$ 260.00	0.5	$ 130.00
Hydrofluric acid	$ 260.00	0.5	$ 130.00
Skirts	$ 3.20	40	$ 128.00
Acetone	$ 32.00	4	$ 128.00
Filter paper	$ 736.00	0.17	$ 122.62
Sulfuric acid diluted	$ 30.00	4	$ 120.00
Acid protection gear	$ 100.00	1	$ 100.00
Polishing pad (course)	$ 30.00	3	$ 90.00
Polishing slurry	$ 90.00	1	$ 90.00
Hydrocloric acid	$ 40.00	2	$ 80.00
Polishing slurry	$ 70.00	1	$ 70.00
Carboy for acid disposal	$ 260.00	0.25	$ 65.00
Polishing pad (fine)	$ 30.00	2	$ 60.00
2Propanol	$ 30.00	2	$ 60.00
SF6 for reactive ion etch	$ 535.00	0.1	$ 53.50
Wafers	$ 17.50	3	$ 52.50
Substrate boats	$ 175.00	0.25	$ 43.75
Wafer shippers	$ 7.00	6	$ 42.00
Microscope bulb	$ 250.00	0.17	$ 41.67
Polishing pad (felt)	$ 20.00	2	$ 40.00
Acetone	$ 35.00	1	$ 35.00
Crystal boxes	$ 20.00	1	$ 20.00
Foil	$ 4.00	4	$ 16.00
2Propanol	$ 30.00	0.5	$ 15.00
Dicing tape	$ 90.00	0.1	$ 9.00
Total cost per crystal batch (~2 month period)			$ 11,750
Total cost per year	**$ 11,750**	**6**	**$ 70,501**

Appendix D – Additional Notes

During the course of this study, the authors consulted with SNOLAB staff to better understand how well existing SNOLAB infrastructure and utilities align with the needs of a SuperCDMS detector fabrication facility. A few specific challenges were highlighted, which we document here for posterity's sake:

- Hydrofluoric Acid (HF): HF has been used in the past underground at SNOLAB (so it is possible); however, it is nonstandard which means there will be overhead in HF-specific training, personal protection equipment, separated storage, transport underground, waste, maintaining the antidote cream, etc.

- Electrical: the electrical demands for the fabrication equipment are not small, at about 30 kW at 120 VAC installed. This should be fine, but to save on both cost and space, purchase of equipment that can operate at 600 VAC (3-phase) should be considered — and with correct product approvals (*e.g.*, CSA electrical stamps). Also, all of this power must come out as heat somewhere; specific consideration will need to be given to ensure sufficient cooling via air and/or chilled water.

- Chemical Hood: at the time of this writing, SNOLAB is in the process of installing a fume hood, but it will not be suitable for HF or frequent use with strong acids. The issue is that it is complicated to vent the hood to a safe location, which requires an 8" diameter pipe — run 500 ft through the lab and external drifts — out to a vent raise. A chemical- and acid-resistant pipe would be costly; for the current hood installation the plan is to use galvanized pipe, making the hood suitable for general purpose light use only. It may be possible to upgrade the vent pipe, but an additional dedicated acid-resistant pipe would be needed if the fabrication equipment requires a chemical hood to be located in close proximity (which is does). An additional consideration is safety equipment (*e.g.*, eyewash and shower), which can be costly to install.

- Chemical Waste: current activities underground at SNOLAB already generate a decent amount of chemical waste (*e.g.*, one experiment is planning to generate continuous 380 liter batches of liquid chemical waste for a few months); so in principle, accommodating the detector fabrication facility would be a straightforward matter of paying the company that is currently in use by SNOLAB to dispose of the waste — at something like $500 per cubic meter. Strong acids would need to be neutralized, which would require additional materials and labor. SNOLAB has an existing setup for neutralizing caustic waste, which suggests ~$1-2k per cubic meter of caustic waste.

References

[1] R. Agnese *et al.* (SuperCDMS Collaboration), Projected sensitivity of the SuperCDMS SNOLAB experiment, *Physical Review D* **95** (2017) 082002; doi:10.1103/PhysRevD.95.082002.

[2] S. Cebrian, Cosmogenic activation of materials, *International Journal of Modern Physics A* **32** (2017) 1743006; doi:10.1142/S0217751X17430060 (or arXiv:1708.07449).

[3] A. Jastram *et al.*, Cryogenic Dark Matter Search detector fabrication process and recent improvements, *Nuclear Instrumentation Methods A* **772** (2015) 14–25; doi:10.1016/j.nima.2014.10.043.

[4] N.J.T. Smith, The SNOLAB deep underground facility, *European Physical Journal Plus* **127** (2012) 108; doi:10.1140/epjp/i2012-12108-9.

[5] P. Camus *et al.*, CUTE Project: Conceptual Design Report; *see also* W. Rau, CUTE – A Cryogenic Underground TEst facility at SNOLAB, *poster presentation at TAUP2017 conference*: https://indico.cern.ch/event/606690/contributions/2591553/.

[6] SNOLAB User's Handbook Revision 2 (2006); http://snolab2008.snolab.ca/snolab_users_handbook_rev02.pdf.

[7] J. Street, R. Bunker, E.H. Miller, R.W. Schnee, S. Snyder and J. So, Radon Mitigation for the SuperCDMS SNOLAB dark matter experiment, *AIP Conference Proceedings* **1921** (2018) 050002; doi:10.1063/1.5018995.

[8] I. Barabanov *et al.*, Cosmogenic activation of germanium and its reduction for low background experiments, *Nuclear Instrumentation Methods B* **251** (2006) 115–120; doi:10.1016/j.nimb.2006.05.011.

[9] E. Aguayo, R.T. Kouzes, J.L. Orrell, D.J. Reid and J.E. Fast, Optimization of the Transport Shield for Neutrinoless Double-beta Decay Enriched Germanium, *Pacific Northwest National Laboratory Technical Report* No. **PNNL-21302** (2012); doi:10.2172/1039848.

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

Proudly Operated by Battelle *Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)

www.pnnl.gov