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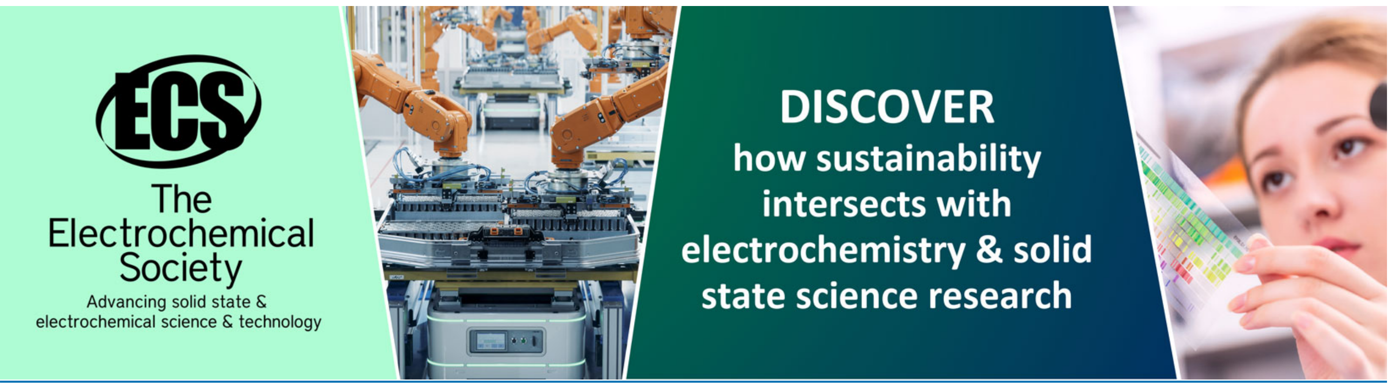

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The Sanford Underground Research Facility

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Abstract. The former Homestake gold mine in Lead, South Dakota, has been transformed into a dedicated facility to pursue underground research in rare-process physics, as well as offering unique research opportunities in other disciplines. The Sanford Underground Research Facility (SURF) includes two main campuses at the 4850-foot level (4300 m.w.e.) – the Davis Campus and the Ross Campus – that host a range of significant physics projects: the LUX dark matter experiment, the MAJORANA DEMONSTRATOR neutrinoless double-beta decay experiment and the CASPAR nuclear astrophysics accelerator. Furthermore, the BHUC Ross Campus laboratory dedicated to critical material assays for current and future experiments has been operating since Fall 2015. Research efforts in biology, geology and engineering have been underway at SURF for 10 years and continue to be a strong component of the SURF research program. Plans to accommodate future experiments at SURF are well advanced and include geothermal-related projects, the next generation direct-search dark matter experiment LUX-ZEPLIN (LZ) and the Fermilab-led international Deep Underground Neutrino Experiment (DUNE) at the Long Baseline Neutrino Facility (LBNF). SURF is a dedicated research facility with significant expansion capability, and applications from other experiments are welcome.

1. Introduction

The Sanford Underground Research Facility (SURF) is a unique facility built on rich legacies in both mining and transformational science to serve a variety of research disciplines, including physics, biology, geology and engineering [1, 2]. In particular, a deep underground laboratory enables investigations into some of the most fundamental topics in physics today, including the nature of dark matter, the properties of neutrinos and the synthesis of atomic elements within stars.

Opened July 2007, SURF just celebrated 10 years as a dedicated science facility, which would not have been possible without generous donations from the Barrick Gold Corporation (owner of the Homestake Mining Company), South Dakota philanthropist, T. Denny Sanford, as well as strong support from the South Dakota legislature. Since 2012, SURF operation has been funded by the U.S. Department of Energy through sub-contracts with various national laboratories (initially LBNL and since October 2016 via Fermilab).

In total, the SURF facility consists of more than 600 km of tunnels and shafts extending from the surface to over 2450 meters (8000 feet) below ground. Of the 29 underground elevations that are currently accessible, six have been identified as key levels for science activities: 300L, 800L, 1700L, 2000L, 4100L, 4850L. The Laboratory property comprises 223 acres (expanded in May 2017) on the surface and 7700 acres underground, and the Surface Campus includes approximately 26,088 gross square meters in structures (expanded in May 2017) that were for the most part inherited from Barrick.

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2. Facility Operations Infrastructure

Maintenance and operation of key elements of facility infrastructure enable safe access underground. Two main shafts – the Ross and Yates – provide redundant routes for power and network services as well as for the transportation of personnel and materials. Additional shafts are dedicated to ventilation, providing air-flow at a rate of approximately 510,000 m^3/hr, with over 40% directed to the 4850L. Air-flow is expected to increase significantly to support LBNF excavation expected to begin mid-2019. Various air handling units and chiller systems provide the required air flow inside laboratory spaces as well as condition the environment to meet experiment temperature and relative humidity requirements.

To provide increased capacity to support future experiments, extensive renovations are being performed in the Ross shaft. Since beginning in August 2012, new steel supports and associated ground support have been installed through roughly 97% of the total length. The entire upgrade project is expected to be completed in 2018.

3. Surface Science Facilities

SURF facilities support research activities both on the surface as well as underground. On the surface, science activities are facilitated in a number of ways, but the principal facility that directly serves science needs is the Surface Laboratory, which provides approximately 210 m^2 of lab space (265 m^2 total) in the top-most level of a four-story building. The Surface Laboratory facility includes a cleanroom that was installed in 2009 (37 m^2, originally used by LUX) as well as new systems installed in 2017 to support LUX-ZEPLIN (LZ) detector assembly activities, including a new metal, low-radon cleanroom (55 m^2) served by a radon-reduction system fabricated by Ateko capable of providing air-flow at a rate of approximately 300 m^3/hr.

The main infrastructure for the support of science activities underground has been developed on the 4850-foot level (4300 meters water equivalent) with multi-laboratory campuses located near both the Ross and Yates shafts. Near the Yates shaft, a laboratory complex called the Davis Campus has been operating since 2012. It has a footprint (1015 m^2 science, 3017 m^2 total) consisting of clean laboratory spaces that are typically maintained around Class 3000 or lower. The 4850L Ross Campus includes four existing excavations that were used as maintenance shops during mining activities with a footprint consisting of 1148 m^2 (science) and 2645 m^2 (total). Initial occupancy of the Ross Campus was in 2011 followed by new laboratories in 2015.

4. Laboratory Characterization

A geologic model has been constructed to incorporate the complex surface topology as well as the six main geologic formations plus other features that characterize the underground environment. Previously published [2] overburden density values were calculated using several discrete points. Results from a more sophisticated analysis using the relative rock formation volumes weighted by the average formation densities for a variety of cone angles are summarized in Table 1.

SURF and other groups have collected data characterizing the facility in terms of various radioactive backgrounds. The Davis Campus is hosted in Yates Amphibolite rock, which is relatively low in radioactivity: 0.22 ppm U, 0.33 ppm Th and 0.96% K. The Poorman rock formation surrounding the Ross Campus is slightly higher in natural radioactivity: 2.58 ppm U, 10.48 ppm Th and 2.12% K [5, 6]. Long-term underground radon data have been collected at various locations. In particular, the total average radon concentration over the monitoring period at the Davis Campus (1936 days) is approximately 300 Bq/m^3, with a low baseline of 150 Bq/m^3. For the same period, the average radon concentration at the Ross Campus is approximately 500–600 Bq/m^3. Brief excursions above 1000 Bq/m^3 have been observed at both campuses, typically correlated with maintenance and ventilation changes. Other efforts to characterize physics backgrounds in various underground areas were carried out by various research groups: muons [4, 7], neutrons [8] and gamma rays [9].

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Table 1. Overburden rock density estimates at different cone angles for various underground locations at SURF, using a 3-dimensional geological model [3]. Angles are relative to the vertical above the specific site. Overburden density errors are estimated to be <1%.

Location	**Rock Overburden (m.w.e)**	**Overburden Density** **0 deg**	**15 deg**	**30 deg (g/cm^3)**	**45 deg**	**60 deg**
4850L Davis Campus						
LUX/LZ Detector	4210	2.870	2.898	2.848	2.833	2.828
MJD Detector	4260	2.882	2.892	2.848	2.832	2.828
4850L Ross Campus						
MJD Electroforming	4290	2.853				2.821
BHUC	4380	2.916				2.821
CASPAR	4170	2.783				2.820
4850L LBNF Campus						
Chamber 1	3980	2.791				2.818
Chamber 2	3860	2.755				2.817
Chamber 3	3810	2.760				2.816
Chamber 4	3830	2.782				2.815
Other						
800L (Muon site [4])	770	2.729				2.717
2000L (Muon site [4])	1700	2.725				2.754

5. Current Science Program

As interest grows from the scientific community, the formal process for implementing experiments at SURF has also matured [10]. To date, thirty-eight groups have conducted research programs at SURF, including efforts at elevations ranging from the surface to the 5000L. A total of twenty-three research groups are currently active.

The Large Underground Xenon (LUX) [11] experiment performed a direct search for dark matter at the 4850L Davis Campus using 370 kg of xenon housed within an ultrapure titanium cryostat, which was immersed in an ultrapure 270-tonne water shield. The LUX detector stopped data collection in May 2016 and held world-leading sensitivity for ∼3.5 years over most of the WIMP-mass region. The LUX experiment was decommissioned in 2017.

The Majorana collaboration is investigating neutrinoless double-beta decay at the 4850L Davis Campus using the Majorana Demonstrator (MJD) detector [12, 13], which consists of 44 kg of germanium detectors (approximately 30 kg enriched in ^{76}Ge) within two ultrapure copper cryostats protected by a 66-tonne shield comprised of layers of copper, lead and HDPE with an active muon veto. The Majorana group is currently transitioning from commissioning to production operation and plans to continue operations through 2020. The Majorana Demonstrator electroforming facility that operated at the Ross Campus since 2011 was decommissioned in 2017.

The Compact Accelerator System for Performing Astrophysical Research (CASPAR) [14] collaboration is using a 1-MV Van de Graaff accelerator to study reactions at stellar energies associated with the slow neutron-capture nucleosynthesis process (s-process). The accelerator was relocated from the University of Notre Dame in the summer of 2015 to an underground laboratory at the 4850L Ross Campus. The beamline has been assembled and commissioning is underway following first beam in May 2017 and an initial operations announcement in July 2017. The group expects to begin taking physics data within the next six months.

Black Hills State University has developed an underground campus at the 4850L Ross Campus. The main feature of the laboratory is a 74-m^2 cleanroom that hosts multidisciplinary research activities [15]. Space in the cleanest section of the laboratory area dedicated to performing low-background assays currently hosts five instruments (plus another one outside the cleanroom), for which capabilities are summarized in Table 2. The cleanroom has space to house up to 10 instruments.

Table 2. Low-background counter sensitivities for a sample of order ∼1 kg and counting for approximately two weeks.

Detector (Group)	**Ge Crystal**	**[U] mBq/kg**	**[Th] mBq/kg**	**Install Date**	**Status**
Maeve (LBNL)	2.2 kg (ϵ=85%)	0.1 (∼10 ppt)	0.1 (∼25 ppt)	BHUC: Nov 2015 SURF: May 2014	Production assays
Morgan (LBNL)	2.1 kg (ϵ=85%)	0.2 (∼20 ppt)	0.2 (∼50 ppt)	BHUC: Nov 2015 SURF: May 2015	Production assays
Mordred (USD/CUBED, LBNL)	1.3 kg (ϵ=60%)	0.7 (∼60 ppt)	0.7 (∼175 ppt)	BHUC: Jul 2016 SURF: Apr 2013	Production assays
SOLO (LZ/UCSB, Brown)	0.6 kg (ϵ=35%)	0.6 (∼50 ppt)	0.3 (∼75 ppt)	BHUC: Feb 2016 (from Soudan)	Production assays
Dual HPGe (LBNL,BHSU, UCSB)	2×2.1 kg	∼0.01 (∼1 ppt)	∼0.01 (∼1 ppt)	BHUC: Jul 2017	Commissioning
Ge-IV (Alabama, USD)	2.0 kg (ϵ=111%)	< 7.4 (<600 ppt)	< 2.4 (<600 ppt)	BHUC: Oct 2017	Initial install

6. Future Science

The future offers many scientific opportunities for underground science at SURF. Upgrades are underway, expansion plans are being developed and there exist options to significantly expand the facility footprint to accommodate additional endeavors.

The LZ detector [16, 17] will employ approximately 10 tonnes of liquid xenon (∼50× LUX fiducial) with a projected sensitivity 100× better than the final LUX result. The entire xenon inventory is on contract, and the majority has been delivered to SLAC for purification. Necessary SURF surface infrastructure upgrades have been completed and underground modifications are scheduled to begin later in 2017, with completion projected by mid-2018. Detector assembly at the Surface Laboratory is expected to begin in 2017, with underground installation anticipated in 2019 followed by operation in 2010. The nominal data run is 5 years.

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The Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) [18, 19] is the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States. Led by Fermilab, LBNF will provide facilities at two locations: accelerator facilities at Fermilab to create the neutrino beam as well as facilities at SURF to support the DUNE detectors that will investigate neutrino properties (oscillations, CP violation, mass hierarchy), nucleon decay and supernovae using a total of 70 ktonnes (40 kT fiducial) liquid argon on the 4850L. Geotechnical studies on the 4850L were completed in the spring of 2014, and an initial test-blast program was completed in the spring of 2016. A groundbreaking ceremony for LBNF was held in July 2017, and underground construction will begin mid-2018 with the main excavation to commence in 2019 and last roughly three years. The current design for the underground laboratory envisions four detector chambers, each 20 m wide $\times$ 29 m tall $\times$ 70 m long and able to accommodate a 10-kT liquid argon detector.

7. Summary
SURF is a deep underground research facility, dedicated to scientific uses. Research activities are supported at a number of facilities, both on the surface and underground. Two campuses on the 4850L accommodate a number of leading efforts, and in particular the 4850L Davis Campus has been successfully operating for over 5 years. Several experiments are well established and there are robust capabilities for low-background counting. Many expansion possibilities are on the horizon and a number of key experiments in the U.S. research program are developing plans for installation at SURF.

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