The Sanford Underground Research Facility at Homestake

J Heise
Sanford Underground Research Facility, 630 East Summit Street, Lead, SD 57754
E-mail: jaret@sanfordlab.org

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 research opportunities in other disciplines such as biology, geology and engineering. A key component of the Sanford Underground Research Facility (SURF) is the Davis Campus, which is in operation at the 4850-foot level (4300 m.w.e.) and currently hosts two main physics projects: the LUX dark matter experiment and the MAJORANA DEMONSTRATOR neutrinoless double-beta decay experiment. In addition, two low-background counters currently operate at the Davis Campus in support of current and future experiments. Expansion of the underground laboratory space is underway at the 4850L Ross Campus in order to maintain and enhance low-background assay capabilities as well as to host a unique nuclear astrophysics accelerator facility. Plans to accommodate other future experiments at SURF are also underway and include the next generation of direct-search dark matter experiments and the Fermilab-led international long-baseline neutrino program. Planning to understand the infrastructure developments necessary to accommodate these future projects is well advanced and in some cases have already started. SURF is a dedicated research facility with significant expansion capability.

1. Introduction
Many disciplines benefit from access to an underground facility dedicated to scientific research, including physics, biology, geology, engineering, and a well-established science program is currently underway at the Sanford Underground Research Facility (SURF). The unique underground environment at SURF allows researchers to explore a host of important questions regarding the origin of life and its diversity, mechanisms associated with earthquakes and a number of engineering topics. A deep underground laboratory is also where some of the most fundamental topics in physics can be investigated, including the nature of dark matter, the properties of neutrinos and the synthesis of atomic elements within stars.

SURF is being developed in the former Homestake gold mine, in Lead, South Dakota [1, 2, 3]. Barrick Gold Corporation donated the site to the State of South Dakota in 2006, following over 125 years of mining [4], during which time over 600 km of tunnels and shafts were created in the facility, extending from the surface to over 2450 meters (8000 feet) below ground. The Laboratory property comprises 186 acres on the surface and 7700 acres underground, and the Surface Campus includes approximately 23,500 gross square meters (253,000 square feet) of existing structures. The South Dakota Science and Technology Authority (SDSTA) operates and maintains the Sanford Laboratory at the Homestake site in Lead, South Dakota with management and oversight by Lawrence Berkeley National Laboratory (LBNL).
Figure 1. The long section of the former Homestake Gold Mine, in which the dark lines represent vertical shafts and horizontal tunnels projected onto a NW to SE plane. This figure illustrates the 60 underground levels extending to greater than 2450 meters (8000 feet) below ground. For scale, the horizontal length of the projection is 5.2 km. The location of cross section is indicated in the inset.

In 2006, South Dakota philanthropist, T. Denny Sanford, gifted $70M to convert the former mine into a research laboratory and develop a science education facility. With these funds and a strong commitment from the State of South Dakota (appropriations of $42.2M to date), safe access to the underground has been reestablished and experimental facilities have been commissioned and certified for occupancy.

The initial concepts for SURF were developed with the support of the U.S. National Science Foundation (NSF) as the primary site for the NSF’s Deep Underground Science and Engineering Laboratory (DUSEL) [5]. With the National Science Board’s decision to halt development of a NSF-funded underground laboratory, the U.S. Department of Energy (DOE) now supports the majority of the operation of the facility. Support for experiments at SURF comes from both the NSF and DOE as well as other agencies such as the USGS and NASA. Elements of the Homestake DUSEL Preliminary Design Report [6] continue to be useful as the feasibility for portions of the original plan are investigated.

2. Facility Operations Infrastructure

Maintenance and operation of key elements of facility infrastructure enables safe access underground. Transportation of personnel and materials underground is accomplished using the two primary shafts, the Ross Shaft and the Yates Shaft. Pairs of hoists near both the Ross and Yates shafts move personnel and rock conveyances through the respective shafts. Pumping stations in the Ross Shaft allow ground water to be pumped to surface. Underground
ventilation is provided by the Oro Hondo fan as well as the fan at #5 Shaft, which bring fresh air underground via the Ross and Yates Shafts.

A key feature of the Sanford Laboratory is the capacity for redundancy. Redundant power, optical fiber and ventilation air are brought underground via both the Ross and Yates Shafts. Multiple emergency egress options are provided by Ross and Yates shaft (and separate compartments therein) as well as by ramp systems that connect numerous underground levels.

Initial rehabilitation of the surface and underground infrastructure focused on the Ross shaft that provides access to the majority of underground utilities, including the pumping system used to remove water from the mine. Contracted work in the Ross shaft started July 2008 and was completed by October 2008, after which SDSTA personnel continued with maintenance and renovations, including the removal of unused legacy piping (12 km) and power/communication cables (2 km). Started in November 2008, the Yates shaft initial renovation was completed in May 2012 with the installation of a new personnel conveyance and emergency braking system. The Ross Shaft provided primary underground access from the start of re-entry in 2007 until the Yates shaft was ready in May 2012. Personnel and materials are transported underground mainly using the Yates cage, which has dimensions 1.4 m wide \( \times \) 2.7 m tall \( \times \) 3.8 m long and has a maximum load capacity of 4540 kg (10,000 lbs); certain loads with widths of up to 1.7 m can be transported beneath the cage. The Yates cage schedule accommodates three shifts per day for science personnel, providing 24-hour access as needed. The maximum underground occupancy at SURF is determined by the number of personnel that can access a safe location in one hour. Based on the current configuration of the various conveyances, the current underground occupancy limit is 72 persons.

In order to provide increased capacity to support the construction and operation of future experiments, state and private funds have been allocated to perform extensive renovations in the Ross Shaft. Refurbishment of the Ross Shaft began in August 2012, and over 670 meters (2200 feet) of new steel and associated ground support has been installed as of the end of December 2014. A total of 1572 m (5159 ft) of new steel sets will be installed as part of the Ross shaft upgrade project, which is expected to be completed by mid-2017. Once the Ross shaft is completed, a renovation of the Yates Shaft will be scheduled.

The average ground water inflow into the underground workings is approximately 730 gpm. After pumping ceased in June 2003 [7, 8], the mine filled with water until a high-water mark of 1381 meters (4530 feet) below surface was reached in August 2008. Sustained pumping resumed in June 2008, dropping the water level below the 4850-foot level (4850L) by May 2009, after being flooded for an estimated 16 months. Since April 2012 the water level is being maintained around the 1830-meter (6000-foot) level below surface. While the potential for accommodating deeper access exists, without a funded mandate to develop laboratory space below the 4850L, there is benefit in terms of cost and safety for maintaining the water level around the current level. If pumping now stopped, it would take an estimated 12–18 months to impact infrastructure on the 4850L.

A deep-well pump was installed July 2010 and is currently located about 1958 meters (6424 feet) below surface in #6 Winze, which extends from the 4850L to the deepest areas of the facility. Permanent stations employing 700-horsepower pumps are located on the 1250, 2450, 3650 and 5000 Levels in the Ross shaft. Water received at the surface Waste Water Treatment Plant (WWTP) is combined with Homestake-Barrick water and treated to remove iron that has leached from the mine workings and trace amounts of ammonia. The discharge capacity from the WWTP is roughly 2000 gpm using biological and sand-filter technologies.

Single-mode fiber optics cable is deployed throughout the facility and current network hardware provides inter-campus communication at 100–1000 Mbps. Redundant connections exist to the outside world, including commodity internet (“Internet 1”) at 1 Gbps and research internet (“Internet 2” via the state Research, Education and Economic Development (REED)
network) at 1 Gbps, which can be expanded to 100 Gbps with appropriate hardware upgrades. Redundant fiber pathways connect the surface to the 4850L via the Ross and Yates Shafts, and work in underway to ensure that the core network equipment is protected by uninterruptible power supplies and in most cases generator power. Researchers are making good use of the network infrastructure as illustrated in Table 1. In 2014, the average daily throughput was approximately 710 GB.

Table 1. Network traffic value increasing over time, indicating the evolution of science activities at SURF. The majority of the data transfers to date have been associated with the LUX experiment. "Internet 2" was used to route approximately 77% of the data.

| Year | Total Data Traffic (TB) |
|------|-------------------------|
| 2009 | 2.6                     |
| 2010 | 5.4                     |
| 2011 | 12                      |
| 2012 | 22                      |
| 2013 | 249                     |
| 2014 | 259                     |

3. Surface Science Facilities
In addition to the considerable underground extent at SURF, surface facilities exist at both the Yates and Ross surface campuses to facilitate science activities, including administrative support and office space, communication systems for education and public outreach, the WWTP for handling and processing waste materials and a warehouse for shipping/receiving. A number of spaces are currently being used for storage as well as experiment preparation and construction activities. Figure 2 shows the extent of the surface property.

While there are many surface amenities, three main facilities directly serve science needs: the Core Archive, the Sawmill and the Surface Laboratory, all of which are located at the Yates surface campus. Other surface buildings could be modified or renovated to meet specific needs.

3.1. Core Archive
Donated by Homestake-Barrick, SURF is the steward of 39,760 boxes of drill core rock\(^1\), which corresponds to 2688 drill holes with a total length of approximately 91 km. Homestake core holes extend to 3290 meters (10,800 feet) below surface. An additional 1646 m of core were added to the collection in Fall 2009 as part of the geotechnical investigations on the 4850L for DUSEL, and a further 770 m of core have also been collected for geotechnical investigations for the LBNF project in April 2014.

The SD Geological Survey has assisted with the development of an online database that so far includes 58,000+ entries, representing 1740 drill holes.

3.2. Sawmill
A former sawmill is currently being used by SURF personnel as well as researcher groups for various tasks. For instance, the MAJORANA collaboration is performing basic preparation, staging and construction activities in that facility.

\(^1\) Diamond drilling produces cylinders of rock of various diameters called drill core.
Figure 2. A plan view of the surface campus at SURF, which comprises 186 acres and includes approximately 23,500 m$^2$ (253,000 ft$^2$) of existing structures. Locations of the Ross and Yates shafts are indicated as is the main ventilation fan (Oro Hondo) and the Waste Water Treatment Plant (WWTP).

3.3. Surface Laboratory
Renovations were undertaken in 2009 in order to transform a former warehouse into a laboratory. Construction was completed in early 2010, resulting in approximately 190 m$^2$ of lab space in the top-most level of a four-story building as shown in Figure 3. The facility includes a cleanroom (5.6 m $\times$ 6.6 m with a 2.7 m ceiling height) and corresponding dedicated air handling and filtration system as well as a tank that can be used as a water shield (2.8 m diameter $\times$ 4 m high). The tank is installed in a recessed shaft in the center of the laboratory space. The laboratory was initially designed to meet the needs of the LUX experiment, but is now used to support multiple research groups. Additional renovations to accommodate the LUX-ZEPLIN (LZ) experiment are expected to begin as early as Summer 2015.

4. Underground Science Facilities
A number of levels required to support facility operations infrastructure can also accommodate research activities. However, the main infrastructure for the support of science activities has been developed on the 4850L with formal campuses located near both the Ross and Yates shafts.
4.1. 4850L Ross Campus

The 4850L Ross Campus includes the Ross Shaft and #6 Winze and encompasses a set of four existing excavations that were used as maintenance shops during mining activities. These former shops afford an economical means to implement experiments or other equipment in a timely manner. The layout is shown in Figure 4, including the location of the current electrical substation\(^2\) and generators. The two western shop areas are currently in use, whereas the two eastern shops are presently undergoing renovations.

Table 2. Footprint areas and volumes for the 4850L Ross Campus spaces. The volume for the NE area is derived from laser-scan data.

| Ross Campus Location       | Area (m\(^2\)) | Volume (m\(^3\)) |
|----------------------------|----------------|-----------------|
| NW (MAJORANA Electroforming) | 184            | 504             |
| NE (BHUC)                  | 297            | 707             |
| SE (CASPAR)                | 137            | 376             |
| SW (Refuge Chamber)        | 121            | 332             |
| **Total**                  | **739**        | **1919**        |

The NW shop area was renovated starting in December 2009 so that a cleanroom (3.7 m wide \(\times\) 12.2 m long, with an overall height of 3.1 m and an interior ceiling height of 2.5 m) for producing ultra-pure copper could be installed to support the MAJORANA experiment schedule.

\(^2\) The capacity of the current electrical substation near the Ross shaft is sufficient for the planned new developments at the Ross Campus. LBNF will require a separate dedicated substation.
Figure 4. 4850L Ross Campus. Four existing excavations are labeled: NW, NE, SE, SW. The two western shop areas are currently in use, whereas the two eastern shops are presently undergoing renovations.

Figure 5. The MAJORANA electroforming laboratory at the 4850L Ross Campus. The cleanroom is located on the right-hand side.

After several phases of development, the laboratory area, complete with fire suppression system, was available for occupancy in March 2011 as shown in Figure 5. Production copper electroforming operations for the MAJORANA DEMONSTRATOR began in July 2011 and are expected to continue through Spring 2015.

Coincident with the start of the Ross Shaft rehabilitation in the fall of 2012, the SW area was converted into a safety Refuge Chamber that can accommodate 72 people (current maximum occupancy) for up to 96 hours. It includes air locks at the two entrances, compressed air, CO₂
Figure 6. The Refuge Chamber at the 4850L Ross Campus can accommodate 72 people for 96 hours. Amenities shown include first-aid kits, one of two CO$_2$ scrubbing units and a bank of compressed air cylinders as well as water and rations.

Figure 7. The Black Hills State University Underground Campus at the 4850L Ross Campus. Beneficial occupancy is expected in Summer 2015.

scrubbers, air conditioners, rations and communications. Some of the amenities are shown in Figure 6.

The NE shop will host the Black Hills State University Underground Campus (BHUC) that is intended to support multidisciplinary research from multiple institutions [9]. Installation of additional ground support was completed in December and shotcrete will be applied starting in January, with beneficial occupancy anticipated for Summer 2015. The main feature of the campus will consist of a 268-m$^2$ cleanroom as illustrated in Figure 7.
The Compact Accelerator System for Performing Astrophysical Research (CASPAR) will be installed in a laboratory area comprising 401 m$^2$, which includes the SE shop area as well as part of an adjoining tunnel. An existing accelerator at the University of Notre Dame will be transported to SURF and installed underground starting in Summer 2015.

The Compact Accelerator System for Performing Astrophysical Research (CASPAR) will be installed in the SE shop area of the 4850L Ross Campus. An existing accelerator at the University of Notre Dame will be transported to SURF and installed underground starting in Summer 2015.

4.2. 4850L Davis Campus
A state-of-the-art laboratory complex called the Davis Campus has been constructed at the 4850L near the Yates Shaft. The Davis Campus represents a $16M South Dakota commitment using state and private funds. New excavation for the Davis Campus took place during September 2009 – January 2011, during which time 16,632 tonnes (18,334 tons) of rock was removed. Rather than being transported to the surface, areas were identified on the 5000L (via the 4850L) for rock storage. Shotcrete was applied in both the Davis Cavern (average thickness 12.7 cm) and the Transition space (average thickness 8.9 cm). Laboratory outfitting began in June 2011 and was substantially complete in May 2012; pictures are shown in Figure 9. A final occupancy certificate was issued in July 2012, which specifies the maximum number of occupants to be 62 persons.

The two main experiments areas are the MAJORANA Lab/Transition space (43 m L x 16 m W x 4 m H) and the Davis Cavern (17 m L x 10 m W x 12 m H), as shown in Figure 10. Quoted dimensions are average values based on post-shotcrete laser-scan data. The Davis Campus footprint consists of 3017 m$^2$ (32,478 ft$^2$) total space as indicated in Table 3. While space is at a premium at the Davis Campus, two cutouts exist outside the clean space offering footprints of 30–33 m$^2$, with an average ceiling height of 3.7 m. These spaces could be made available to groups with modest equipment needs.

4.2.1. Davis Campus Monitoring Monitoring is conducted for a variety of gases at the Davis Campus. Due to the use of cryogens in various sections of the laboratory, a total of nine oxygen
Figure 9. Pictures of the Davis Campus in May 2012 after outfitting had finished: (left) Majorana Demonstrator Detector Room, (right) water shielding tank in Lower Davis for the LUX detector. A considerable amount of equipment has since been installed by both collaborations.

Figure 10. 4850L Davis Campus showing the main laboratory spaces and the proximity to the Yates Shaft, which is approximately 180 m from the main laboratory entrance. Majorana spaces are shown in blue whereas the LUX areas are red. The Davis Cavern offers two floors of laboratory space for LUX.

sensors are installed throughout the Davis Campus. Furthermore, a half-dozen portable gas testers sensitive to CO, H$_2$S, O$_2$ and CH$_4$ are also available throughout the campus. A fixed carbon monoxide monitor is located near the Yates Shaft, by the air intake for the Davis Campus. Separate heat and smoke sensors are installed in all areas of the Davis Campus.

A general facility alarm is activated throughout the Davis Campus in the event that any of the following occur: low oxygen, heat or smoke detected, fire suppression water is flowing or a manual pull station is activated. Currently, regular evacuations exercises are held biweekly, with more comprehensive scenarios conducted quarterly.

An array of extensometers is installed to monitor ground motion and convergence at the Davis Campus – data collected so far indicate nothing unexpected. Geotechnical interpretations were performed using drill core and other rock mechanics studies [10].
Table 3. Footprint areas and volumes for the 4850L Davis Campus spaces. The volumes are derived from post-shotcrete (where appropriate) laser-scan data with finished flooring.

| Davis Campus Location            | Area (m²) | Volume (m³) |
|---------------------------------|-----------|-------------|
| LUX                             | 375       | 1976        |
| MAJORANA DEMONSTRATOR           | 300       | 1279        |
| Low-Bkgd Counting               | 33        | 140         |
| Common Science                  | 244       | 980         |
| Other/R&D Science               | 63        | 253         |
| Facility Infrastructure          | 508       | 2063        |
| Access Drifts                   | 1494      | 4664        |
| **Total**                       | **3017**  | **11,354**  |

4.2.2. Davis Campus Services  Services provided throughout the Davis Campus include fire sprinklers, potable and non-potable (industrial) water, lighting (including emergency lighting), ventilation and air conditioning. A building management system provides controls throughout the Campus. Cooling is provided with two redundant 50-ton (633-MJ) chillers supplying chilled water to three air handling units that provide ventilation to separate campus spaces. Chilled water and a facility air compressor are also available for experiments to connect equipment directly. A dedicated 1500 kVA substation provides sufficient capacity for the experiment and facility needs, with margin for future expansion (e.g., LZ and any scaling of the MAJORANA DEMONSTRATOR). Emergency power for lighting is provided with batteries in the lighting system to provide immediate light, while a standby diesel generator near the campus provides up to 24 hours of power to all safety systems in the campus. This includes water pumps in the nearby Yates shaft to prevent water from rising into the campus spaces. Three separate air handling units provide multi-stage air filtration for the Davis Campus clean spaces and establish relative pressure balances to help maintain appropriate relative levels of cleanliness. Starting in July 2014, the intake air for the Davis Campus clean area air handling system was pre-processed using a dedicated dehumification system.

4.2.3. Davis Campus Cleanliness  Cleanliness at the Davis Campus is maintained through a combination of transition zones and protocols as well as dedicated cleaning staff. When supplies and equipment are brought from the dirty space into the clean space, items either need to be suitably enclosed or cleaned in the facility entrance Cart Wash. Personnel typically enter through a series of rooms where outer coveralls and dirty-side gear are removed in favor of corresponding clean items. Laundry services are also available in the clean space. The facility design includes two sets of personnel showers, but so far they have not been necessary.

When the laboratory is occupied, particle counts (>0.5 μm per cubic foot) in all main common areas are below 10,000/ft³. The MAJORANA collaboration follows additional gowning protocols to achieve ultra-low cleanliness levels in their laboratory spaces. Particle counts have been monitored at the Davis Campus since September 2012, and a summary of cleanliness states throughout various areas is presented in Table 4.

Dust from the air-handling unit filters as well as floor sweepings have been collected and routinely analyzed for more than 6 months. The main activity contributions appear to be from ²¹⁰Pb and ⁷Be. For example, in situ dust has the following average levels: ~1 ppm U, ~2 ppm Th and 1–2% K [11].
Table 4. Median particle count levels in various Davis Campus laboratory locations during occupied periods. Additional cleanliness protocols are instituted in the MJD areas.

| Davis Campus Location                  | Particle Count (0.5 μm/ft³) |
|----------------------------------------|------------------------------|
| Entry/Lockers (MJD)                    | 790                          |
| Common Transition Hallway              | 2320                         |
| Common Corridor                        | 3240                         |
| Davis Cavern, Lower (LUX)              | 3400                         |
| Davis Cavern, Lower (CUBED)            | 720                          |
| Davis Cavern, Lower (BLBF)             | 490                          |
| Davis Cavern, Upper (LUX)              | 400                          |
| Detector Room (MJD)                    | 100–400                      |

5. Facility Characteristics
A number of specific properties that define and influence capabilities for various underground laboratory spaces are reviewed in the sections below, including the geographic coordinates, geology and rock overburden characteristics as well as radon and radioactivity considerations.

5.1. Coordinates
Initial survey work in 2010 projected the Universal Transverse Mercator (UTM) coordination system (Zone 13 North, NAD83 datum with 2002 Epoch) underground to benchmarks on the 4850L. Projected Easting (x) and Northing (y) coordinates for various underground locations are presented in Table 5. Future surveys in support of the long baseline neutrino initiative will improve on these preliminary efforts.

5.2. Geology and Rock Overburden
When considering the muon flux at key laboratory spaces on the 4850L, six geological formations are important to consider: Grizzly, Flagrock, Northwestern, Ellison, Homestake and Poorman. The Yates Member (Unit) is the lowest stratigraphic unit of the Poorman Formation and is important for developments on the 4850L; other geological formations also have amphibolite manifestations that are accounted for in the analysis below. In addition, tertiary Rhyolite dikes occur throughout the rock mass.

The surface topology varies significantly throughout the laboratory property as shown in Figure 11. Using average rock densities and a 3-dimensional geological model [13] in addition to recent topological surveys, estimates of the rock overburden for various locations are summarized in Table 6. Errors in the vertical rock depth are expected to be modest (±10 m). To estimate the overburden uncertainties associated with the geological model, rock formation contact boundaries were adjusted for several locations based on the relative information about their locations in order to maximize and minimize the total density-scaled depths. Density errors (1–6%) were also factored in using ±1 σ (standard deviations), and contributed the majority of the uncertainty. However, in addition to simply quantifying the measurement error, the uncertainties also characterize density variations due to differences in mineralogy in a given rock formation. As a result of the combination, the average uncertainty in the water-equivalent overburden values was estimated to be ∼4% for most of the locations; the overburden error for the 800L location is lower at roughly ∼2.5%. In addition to the vertical overburden depth values, the rock density averaged over a 45-degree cone (determined by sampling the model at several
Table 5. Coordinates estimates for various locations of interest. Both UTM and geographical coordinates are presented. U.S. survey feet are converted to meters.

| Location                      | UTM Coordinates Easting (m) | UTM Coordinates Northing (m) | Geographic Coordinates Latitude | Geographic Coordinates Longitude |
|-------------------------------|-----------------------------|-------------------------------|---------------------------------|---------------------------------|
| 4850L Davis Campus            |                             |                               |                                 |                                 |
| LUX Detector                  | 599527                      | 4911873                       | 44° 21' 11.88'' N               | 103° 45' 04.27'' W              |
| MJD Detector                  | 599516                      | 4911838                       | 44° 21' 10.75'' N               | 103° 45' 04.77'' W              |
| Entrance Cutout               | 599531                      | 4911781                       | 44° 21' 08.92'' N               | 103° 45' 04.15'' W              |
| 4850L Ross Campus             |                             |                               |                                 |                                 |
| MJD Electroforming            | 598939                      | 4911087                       | 44° 20' 46.70'' N               | 103° 45' 31.33'' W              |
| BHUC                          | 598962                      | 4911085                       | 44° 20' 46.65'' N               | 103° 45' 30.31'' W              |
| CASPAR                        | 598939                      | 4911045                       | 44° 20' 45.36'' N               | 103° 45' 31.39'' W              |
| 4850L Other                   |                             |                               |                                 |                                 |
| LBNF (10 kt Cavern)           | 599236                      | 4911041                       | 44° 20' 45.07'' N               | 103° 45' 17.96'' W              |
| LBNF (30 kt Cavern)           | 599223                      | 4910960                       | 44° 20' 42.44'' N               | 103° 45' 18.62'' W              |
| Expt Hall (Generic)           | 599437                      | 4911408                       | 44° 20' 56.88'' N               | 103° 45' 08.86'' W              |
| Other                         |                             |                               |                                 |                                 |
| 800L (Muon site [12])         | 598928                      | 4911221                       | 44° 20' 51.07'' N               | 103° 45' 31.74'' W              |
| 2000L (Muon site [12])        | 598764                      | 4912928                       | 44° 21' 46.47'' N               | 103° 45' 37.98'' W              |

discrete points through the cone volume) is presented for various underground locations as a way of characterizing the effective overburden over a broader extent. Geochemical composition data for various formations are available from sources such as the USGS [14] and others.

5.3. Radioactivity and Radon

SURF strives to provide the lowest possible radioactivity environment for experiments hosted within the facility. This commitment had been integrated into the site preparation process from the early days of the facility design, and carried over to the realization of the 4850L Davis Campus laboratories. These efforts include site and environmental characterization including rock radioactive measurements, use of low-radioactivity construction materials, and regular monitoring of environmental factors, including airborne radon.

The natural abundance of U/Th/K in Homestake rock is generally low, especially in certain geological formations such as the Yates Amphibolite, which have been measured to contain sub-ppm levels of U/Th. Samples from other formations such as the Rhyolite intrusions can be 30–40× higher as illustrated in Table 7. While not as low as the host Yates Amphibolite rock, the lowest-activity construction materials for the Davis Campus were selected from a large number of samples [15, 16, 17].

Long-term underground radon data have been collected since 2009 and at the Davis Campus since July 2012, shortly after outfitting was completed. Aside from the normal facility ventilation that brings fresh air underground via the Ross and Yates shafts, no extraordinary steps have been taken to mitigate underground radon levels. Some research groups employ a type of purging system to reduce radon locally for their equipment. As seen at other underground laboratories,
Figure 11. Topological contours for the opening of a 45-degree cone overlaid on top of an outline of the 4850L (shown in blue), centered on the Davis Campus. Various cardinal coordinates are indicated with red lines. The Open Cut is a prominent feature on the surface toward the west. Contour lines indicate 6-meter (20-foot) elevation changes.

Figure 12. 3D geological model showing rock cone above the 4850L centered on the Davis Campus as well as the surface topology. The colored section represents different rock formations in the 45-degree cone; the gray outline represents the extent of a 60-degree cone. The vertical lines show the locations of the Ross and Yates shafts.
Table 6. Rock overburden estimates for various underground locations at SURF, using a 3-dimensional geological model [13] and including depths scaled by density to give the meters of water equivalent (m.w.e.). The average rock density is based on a 45-degree cone centered above the specific site. The data reflect considerable variations in surface topology as well as geology. Properties related to the locations of recent muon flux measurements are also included. Uncertainties on the rock depth values are estimated to be ±10 meters, whereas the estimated uncertainties in the density-scaled overburden values are ∼4%; the overburden error for the 800L location is lower at roughly ∼2.5%.

| Location | Vertical Rock Overburden (m) | Average Cone Density (g/cm$^3$) |
|----------|-----------------------------|-------------------------------|
|          | Vertical Rock Overburden (m.w.e.) |                      |
| 4850L Davis Campus |                         |                               |
| LUX Detector | 1466 | 4210 | 2.85 |
| MJD Detector | 1477 | 4260 | 2.86 |
| Entrance Cutout | 1494 | 4300 | 2.85 |
| 4850L Ross Campus |                         |                               |
| MJD Electroforming | 1503 | 4290 | 2.81 |
| BHUC | 1503 | 4380 | 2.83 |
| CASPAR | 1499 | 4170 | 2.81 |
| 4850L Other |                         |                               |
| LBNF (10 kt Cavern) | 1384 | 3910 | 2.82 |
| LBNF (30 kt Cavern) | 1375 | 3840 | 2.82 |
| Expt Hall (Generic) | 1189 | 3390 | 2.80 |
| Other |                         |                               |
| 800L (Muon site [12]) | 283 | 770 | 2.73 |
| 2000L (Muon site [12]) | 624 | 1700 | 2.74 |

A seasonal dependence is becoming apparent in the Davis Campus trends, with higher radon levels observed during the summer months May through September. The total average radon concentration over the monitoring period (883 days) at the Davis Campus is approximately 310 Bq/m$^3$ with a low baseline of 150 Bq/m$^3$ during the winter months. Brief excursions above 1000 Bq/m$^3$ have been observed, typically correlated with known events such as ventilation fan maintenance or when the Yates and/or Ross shafts are partially covered.

Other efforts to characterize physics backgrounds (e.g., muons, neutrons, gamma rays) in various underground areas were carried out by various research groups. Historically, the differential muon flux was measured by collaborators on the Homestake chlorine experiment [18]. More recently, since the mine was reopened as a laboratory, other groups have gathered data over several years [12, 19, 20]. Results from recent neutron flux measurements collected on the 4850L are expected in an upcoming publication as are results related to the cosmic ray muon flux measured at the Davis Campus.
Table 7. Partial U/Th/K assay results for relevant SURF rock samples as well as key construction materials used at various laboratories [15, 16, 17].

|                        | Uranium (ppm) | Thorium (ppm) | Potassium (%) |
|------------------------|---------------|---------------|---------------|
| **4850L Davis Campus** |               |               |               |
| Yates Amphibolite Fm (Majority) | 0.22          | 0.33          | 0.96          |
| Rhyolite Dike          | 8.75          | 10.86         | 4.17          |
| Shotcrete – Low Activity | 1.52          | 2.17          | 0.55          |
| Shotcrete – Standard   | 2.00          | 3.35          | 1.23          |
| Shotcrete – Finish Coat | 1.62          | 3.08          | 0.79          |
| Masonry Blocks         | 2.16          | 3.20          | 1.23          |
| **4850L Ross Campus**  |               |               |               |
| Poorman Fm (Majority)  | 2.58          | 10.48         | 2.12          |
| Siderite/Grunerite Ironstone | 0.41          | 2.30          | 0.25          |
| Shotcrete – Standard   |               |               |               |
| Shotcrete Surface Coating | Under investigation |

6. Current Science Program

Science efforts that started in 2007 during re-entry into the facility have grown steadily over the years. Building on the legacy of the Ray Davis chlorine solar-neutrino experiment [21] that began in 1965 at the Homestake Mine, twenty-six research groups have conducted underground research programs at SURF. Measurements have been made and samples collected from elevations ranging from surface to the 5000L, investigating topics in physics, geology, biology and engineering. A total of eighteen research programs are considered active as summarized in Table 8, which includes a brief description of each group as well their respective locations. The list includes the two main physics efforts underway at Davis Campus, as well as the two low-background counters. There has also been significant interest from additional groups across all disciplines.

6.1. Large Underground Xenon (LUX)

The LUX experiment [22] is conducting a direct search for weakly interacting massive particles (WIMPs) using 370 kg (118 kg fiducial) of purified xenon inside an ultra-pure titanium cryostat that is immersed in a water tank containing 272,550 liters (72,000 gallons) of purified water. Following collisions in the liquid xenon volume, a strong electric field moves ionization electrons into the gas space at the top of the detector, and a total of 122 PMTs collect scintillation light from interactions in both xenon volumes.

Members of the LUX collaboration have been active onsite at SURF since December 2009, when preparations began for detector assembly at the Surface Laboratory. After completing detector assembly and operational testing on surface, LUX began their transition underground to the Davis Campus in May 2012. With strong support from SURF personnel, the fully-assembled LUX detector was successfully transported underground from the Surface Laboratory in the Yates cage and into the Davis Cavern – stringent limits on acceleration and tilt were not exceeded. The LUX space at the Davis Campus includes a cleanroom and a control room, which are separate from the main lab space. The SURF water purification system and a storage area for liquid nitrogen are located near the LUX equipment but outside the clean environment.
Table 8. Current scientific research programs at the Sanford Laboratory. Locations in bold indicate current installations or the subject of current focus; those in italic are imminent.

| Experiment | Description | Locations | References |
|------------|-------------|-----------|------------|
| **Physics** |             |           |            |
| Large Underground Xenon (LUX) | Dark matter using Xe | Surface, **4850L** | [22, 23] |
| MAJORANA DEMONSTRATOR | Neutrinoless double-beta decay using Ge | **Surface, 800L, 4850L** | [24, 25] |
| Center for Ultra-low Bkgd Experiments in the Dakotas (CUBED); also Bkgd Characterization | Low-bkgd counter, isotope separation; also bkgds: muon, neutron, gamma, radon | **Surface, 800L, 2000L, 4550L, 4850L** | [12, 19, 20, 26] |
| Berkeley Low-Bkgd Facility | Neutron bkgds | **4100L, 4850L** | [27] |
| Compact Accelerator System for Performing Astrophysical Research (CASPAR) | Cleanliness tests | **Surface, 4850L** | [29] |
| Long-Baseline Neutrino Facility (LBNF) | Seismic characterization for gravity-wave research | **Surface, 4850L, 300L, 800L, 1700L, 2000L, 4100L** | [30, 31] |
| **Geology** |             |           |            |
| Geoscience Optical Extensometers and Tiltmeters (GEOX™) | Optical fiber applications, tiltmeters | **2000L, 4100L, 4850L** | [32, 33, 34, 35], [36] |
| USGS Hydrogravity | Local gravity for water tables, densities | **Surface, 300L, 4100L, 4850L** | [37] |
| Petrology, Ore Deposits, Structure (PODS) | Core archive and logs, geologic mapping | Surface, **800L** | [38, 39, 40] |
| Transparent Earth | Seismic monitoring/properties, melt studies | **2000L, 4100L** | [41, 42, 43] |
| **Biology** | (Samples collected informally have also resulted in publications [44]) | | |
| Biodiversity (BHSU) | Microbiology | Surface, **300L, 2000L, 4100L, 4550L, 4850L** | [45, 46, 47] |
| Biofuels (SDSMT) | Biofuels | **4550L, 4850L, 5000L** | [48, 49, 50, 51], [52, 53, 54, 55] |
| Lignocellulose (SDSU) | Biofuels | **1700L, 4850L** | [56, 57] |
| Syngas (SDSMT) | Biofuels | **4850L** | [58, 59, 60] |
| Life Underground – NASA Astrobiology Institute | Water in drill holes, geomicrobiology | **Surface, 800L** | [61] |
| **Engineering** | | | |
| Xilinx, Inc. | Chip error testing | **4850L** | |
The LUX collaboration published results in October 2013 from their first underground data run [23] and started a longer run (nominally 300 live days) in October 2014. LUX is expecting to complete their experimental program in 2016.

6.2. MAJORANA DEMONSTRATOR (MJD)

The MAJORANA collaboration is investigating neutrinoless double-beta decay using a detector called the DEMONSTRATOR consisting 40 kg of germanium in two ultra-pure copper cryostats and a compact shield constructed from lead, copper and high-density polyethylene. MAJORANA expects to use up to 30 kg of enriched $^{76}\text{Ge}$. The main technical goal of the DEMONSTRATOR is to confirm that the ambitious purity requirements for a tonne-scale detector are achievable [24, 25]. The group also plans to test a controversial claim for the detection of neutrinoless double-beta decay.

In order to satisfy the very low background requirements, the MAJORANA collaboration has set up a laboratory at the 4850L Ross Campus to produce the world’s purest electroformed copper, which is then machined at a dedicated machine shop at the Davis Campus. The MJD electroforming process begins with minimally-processed oxygen-free high conductivity copper nuggets (99.999%), with typical properties: $U = 1.25 \mu\text{Bq/kg}$, $Th = 1.10 \mu\text{Bq/kg}$ and yield strength of $\sim 50 \text{ MPa}$. MJD electroformed copper averages $U = 0.17 \mu\text{Bq/kg}$, $Th = 0.06 \mu\text{Bq/kg}$ with yield strength 70–100 MPa (work hardened). The average growth rate for electroformed copper is relatively slow at approximately 1 mm/month, and MJD expects to produce roughly 2860 kg of the material for the DEMONSTRATOR.

The MAJORANA collaboration began work onsite starting in November 2010 with deliveries of equipment (including the first germanium detectors) and then with preparations for the electroforming cleanroom. Production of electroformed copper began in July 2011 and about eight months later in March 2012 the group started to move equipment into the Davis Campus. The majority of the detector shield is complete, including 3400 cleaned and stacked Pb bricks and some of the inner copper sheets. MJD is currently collecting background data from germanium crystals in a prototype (commercial-copper) cryostat. Completed assembly and the start of commissioning for the first production module with 20 kg of high-purity germanium (mostly enriched in $^{76}\text{Ge}$) is expected in early 2015, with the second production module expected to be completed in late 2015. The full MAJORANA experimental program with both production cryostats could extend into 2019.

6.3. Center for Ultra-low Background Experiments in the Dakotas (CUBED)

Initially created as a South Dakota Governor’s Research Center administered through the University of South Dakota, CUBED involves physics researchers and others from the majority of universities in the state [26]. In addition to increasing the South Dakota academic involvement in SURF research, the center maintained a focus on areas of interest congruent with planned SURF experiments, such as crystal growth, low-background counting and stable isotope separation.

CUBED has set up a low-background counting laboratory in a dedicated room in the Lower Davis Cavern of the 4850L Davis Campus. The system allows direct-gamma counting using a 1.3-kg high-purity n-type germanium crystal (60% relative efficiency), resulting in 0.06–0.1 ppb sensitivities to U/Th as summarized in Table 9. Installation of the germanium counter began in April 2013 and was finished a year later in April 2014 when the complete shield was established: 72 oxygen-free high conductivity copper bricks, a stainless steel enclosure for purging radon using boil-off nitrogen and approximately 500 lead bricks that were cleaned and coated in borated paraffin. Assays of community samples began in October 2014. A subsequent reconfiguration of the detector shield carried out in December 2014 has resulted in a further 25% reduction in the rate of background events compared to the original performance. The CUBED low-background...
counter is expected to move to a separate dedicated cleanroom at the 4850L Ross Campus in Summer 2015.

Another CUBED project, the isotopic separation and ultra-purification (ISUP) project, is underway at the Surface Laboratory, where the separation of stable isotopes is being investigated. Initial tests are being performed with CO$_2$, with plans to also study N$_2$, Ar, Kr and Xe. Installation began in May 2014 with commissioning and full operation in September 2014. Studies are expected to be completed in May 2015.

A main CUBED focus involves crystal growth, and SURF personnel have provided a cost estimate to develop a laboratory to support underground crystal growth. Funding is being sought.

6.4. Berkeley Low-Background Facility (BLBF)

After operating since the 1980s, LBNL counting operations at the Oroville Dam$^3$ ended in February 2014. The site was decommissioned and the HPGe detector and shield materials were shipped to SURF in March. Starting in May, the detector and shielding were installed at a dedicated laboratory within the 4850L Davis Campus, next door to the CUBED low-background counter. After a brief period of commissioning and background testing in June, the counter was back online for receiving samples in July [27]. In total, the implementation at SURF took less than 6 months. Since July, eleven community samples have been counted on behalf of the MAJORANA and LZ collaborations.

The BLBF counter is a 2.1-kg p-type coaxial germanium crystal (85% relative efficiency), resulting in 0.01–0.3 ppb sensitivities to U/Th (see Table 9). Compared to the original Oroville installation, background rates measured at SURF indicate a performance improvement of approximately 30%, mainly due to shield configuration improvements. The BLBF low-background counter is expected to move from the Davis Campus to a separate dedicated cleanroom at the 4850L Ross Campus in Summer 2015.

|                | Uranium (ppt) | Thorium (ppt) | Potassium (ppb) |
|----------------|---------------|---------------|-----------------|
| CUBED          | 60            | 100           | 25              |
| BLBF           | 10            | 30            | 20              |

6.5. Experiment Implementation Process

SURF has developed a formal process for implementing experiments [62]. Requirements include an experiment planning statement, a memorandum of understanding, appropriate insurance as well as a decommissioning plan. If necessary, financial responsibilities for both SURF and the experiment are documented in a general services agreement. Safety reviews are commensurate with the scale of the project. SURF personnel are available to serve in various roles, including acting as a guide in the underground environment, providing logistical support as well as participating in the work planning process.

$^3$ The Oroville Dam was the original site of the UCSB/LBL double-beta decay experiment.
7. Future Science
The future offers many scientific opportunities for underground science that can be pursued at SURF. Both the nuclear physics and high-energy physics communities are developing strategic plans for the future of their respective fields, and projects that are planned for SURF figure prominently [63]. Near-term expansions are underway and there exist options to significantly expand the facility footprint to accommodate additional endeavors. The locations of existing and future experiments are shown in Figure 13.

7.1. Black Hills State University Underground Campus (BHUC)
As mentioned previously, Black Hills State University is developing an underground campus at the 4850L Ross Campus, including a cleanroom that will host a variety of research activities. Approximately 75% of the BHUC cleanroom space is envisioned to be a low-background assay laboratory operated at Class 1000, while the remaining 25% of the laboratory will be reserved for research that does not require a high level of cleanliness. Space in the cleanest laboratory area dedicated to performing low-background assays is expected to house 8–9 instruments, possibly including more than a half-dozen high-purity germanium detectors and the associated shielding and access systems as shown in Figure 14. The area outside the cleanroom will be used for storage as well as other research activities.

7.2. Compact Accelerator System for Performing Astrophysical Research (CASPAR)
An underground facility is under development at the 4850L Ross Campus to study the stellar nuclear fusion reactions responsible for the production of elements heavier than iron, especially via the slow neutron-capture nucleosynthesis process (s-process). The Compact Accelerator System for Performing Astrophysical Research (CASPAR) collaboration seeks to study (α,n) reactions at stellar energies relevant for helium and carbon burning [64]. CASPAR will use an existing 1-MV Van de Graaff accelerator from the University of Notre Dame capable of producing high-intensity (~150 μA) proton and helium beams with energies between 200 keV and 1 MeV. A specialized windowless gas target system for 22Ne and 13C is also being developed at the

Figure 13. The 4850L of SURF highlighting the existing and proposed experiments.
The initial CASPAR scientific program is expected to take 5–8 years to complete, with a broader program that is expected to last for over a decade. Potential future federal funding could allow for expansion to include additional elements that were originally planned for the Dual Ion Accelerators for Nuclear Astrophysics (DIANA) project [65].

7.3. LUX-ZEPLIN (LZ)
In July 2014, the LUX-ZEPLIN (LZ) proposal was one of two direct-search generation-2 dark matter experiments selected for funding by the U.S. DOE division of High Energy Physics. The LZ detector will employ approximately 10 tonnes of liquid xenon (~6 tonnes fiducial or ~45× LUX fiducial), and will rely on modest upgrades to existing SURF infrastructure, including the Surface Laboratory for detector assembly and underground space at the 4850L Davis Campus where the LUX experiment is currently operating. In particular, no new excavation will be required, and LZ will be able to reuse the water shielding tank used for LUX with the addition of an improved background veto system consisting of gadolinium-loaded linear alkyl-benzene liquid scintillator, as shown in Figure 15. LZ sensitivity is projected to be approximately 100× better than the anticipated LUX 300-day result (underway), with sensitivity of $2 \times 10^{-48}$ cm² for its full 1000-day exposure.

Detector assembly at the Surface Laboratory could begin as early as mid-2015. Underground production data-taking is scheduled to begin 2019 and will nominally last 5 years.
Figure 15. Schematic of the LUX-ZEPLIN experiment at the 4850L Davis Campus. Existing infrastructure is shown such as the ductwork, the water shielding tank (lower center) and the control room (upper right). LZ will require all available space in the Davis Cavern, including rooms (lower left) currently used by the two low-background counters.

7.4. Neutrinoless Double-Beta Decay
The MAJORANA collaboration is investigating performing the next-generation neutrinoless double-beta decay experiment on the 4850L at SURF. If the combination of rock overburden and veto is determined to be sufficient, scaling up to order $\sim 200$ kg from the current DEMONSTRATOR may be possible at the Davis Campus but ultimately a new laboratory may be needed.

7.5. Long Baseline Neutrino Facility (LBNF)
Neutrinos propagated over long distances (> 1000 km) allow for investigations into fundamental physics, touching on such compelling unanswered puzzles as neutrino mass hierarchy and CP violation (matter/antimatter asymmetry) as well as many other topics.

For many years, the U.S. has been developing an experiment called the Long Baseline Neutrino Experiment (LBNE) [66] that is transforming into the Long Baseline Neutrino Facility (LBNF). While the project design has undergone many iterations (consideration of water Čerenkov technology and an initial detector installation on the surface), the latest design consists of a large liquid argon detector (or detectors) located underground at the 4850L of SURF that would observe neutrinos generated approximately 1300 km away at Fermilab using an upgraded accelerator beam (up to 2.4 MW). The detector mass could be staged in various ways (e.g., 10 kt, 30 kt, etc.) to reach a nominal fiducial mass of 40 ktonne (total mass $\sim 60$ ktonne). Some simulations to quantify backgrounds due to cosmic ray muons have already been performed [67].

International partners are required to ensure the success of such an ambitious project, and a process is currently underway to consolidate interested researchers into a single Fermilab-led experiment. The new proto-collaboration is referred to as the Experiment at the Long Baseline Neutrino Facility (ELBNF) and is expected to include the majority of researchers from existing collaborations such as LBNE (90 institutions and 500+ collaborators) and the Long Baseline...
Neutrino Oscillation (LBNO) European experiment [68]. A Letter of Intent defining the new collaboration has been drafted [69] and will be presented to the Fermilab Program Advisory Committee (PAC) in January 2015.

Geotechnical studies have already commenced, and the first construction efforts associated with LBNF could begin as early as FY16 when shaft services and some aspects of a waste-rock handling system could be installed. Underground excavation could begin as soon as the Ross shaft rehabilitation is completed, expected to be mid-2017.

7.6. Future Expansion

Space is currently available for modest R&D efforts, including cutouts at the Davis Campus (30–33 m$^2$) and laboratory space at the BHSU Underground Campus. While it may be possible to utilize a few other existing excavations on the 4850L and other relatively deep levels, most practical existing excavations will soon be occupied. Some spaces that are currently occupied may become available again in 5–10 years.

New excavations of order 11,500 cubic meters (15,000 cubic yards) of rock could be performed prior to the completion of the Ross Shaft rehabilitation; however, once a waste-rock handling system is installed to support the LBNF project very large excavation projections become possible. Based on the DUSEL preliminary design, a generic Experiment Hall is included on Figure 13 as a placeholder to accommodate a tonne-scale neutrinoless double-beta decay experiment and/or a generation-3 dark matter experiment. Nominal dimensions are 20 m W × 24 m H × 50–100 m L displacing 45,900–85,600 cubic meters (60,000–112,000 cubic yards) of rock, including access tunnels, over-break and rock swell. Other configurations and locations are also possible.

8. 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 2.5 years. The LUX and MAJORANA experiments are well established and there are current 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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