A DUSEL Facility for Assay and Acquisition of Radiopure Materials

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Abstract. FAARM is an acronym for a low background counting facility at the proposed DUSEL laboratory at the Homestake mine in South Dakota. Detailed plans for the 4850' level facility are presented, as well as plans for associated technologies and integration activities.

Keywords: Low Background Counting, radiopurity, DUSEL, AARM, screening, backgrounds, underground science

PACS: 01.50.Pa, 23.40.Bw, 98.80.-k, 96.50.sb, 01.55.+b

THE GOALS OF AARM

In preparing for the Deep Underground Science and Engineering Laboratory (DUSEL), the NSF funded a number of studies centered on the technology and experiments which would be housed there. One of these S4 proposals is the Assay and Acquisition of Radiopure Materials (AARM). The AARM collaboration includes representatives from those experiments which require low background siting and materials, in particular those concerned with dark matter, neutrinoless double beta decay, low energy neutrino detection and production, and elements of biology and geology. The goal is to articulate an integrated program to define necessary technologies and capabilities, which must be available when DUSEL starts operations, as well as the R&D program needed to develop technologies providing enhanced sensitivities. The plan must result in on-site facilities capable of providing assay and ultra-clean materials support for the initial suite of science experiments, as well as integration tools to share data, exchange equipment, train personnel, optimize screening throughput (both on-site and off-site), foster new collaborations in areas of geology, biology and homeland security, and identify new users in other research fields. Under the three-year S4 proposal, we are committed to:

- Characterize radon, neutron, gamma, and alpha/beta backgrounds at Homestake.
- Develop a conceptual design for a common, dedicated facility (FAARM) for low background assay.
- Assist in the creation of common infrastructure required to perform low background experiments.
- Perform targeted R&D for ultra-sensitive screening and water shielding.

Design of the FAARM will optimize economy of scale (combining ultra-sensitive and production screening in the same room) and take advantage of common infrastructure (such as purification plants and water shield engineering). To this end, the best option is a dedicated, water-shielded room at the 4850' level. We constrained the design to fit within one third of a standard lab module. Within this dedicated and centrally located FAARM will reside the following common technical capabilities identified as needed by the initial suite of DUSEL experiments:

- <u>*Gamma Screening*</u> - HPGe detectors of varying sensitivity and segmentation.
- <u>*Alpha, Beta, and Rn Counting*</u> - Both commercial pre-screeners and more sensitive new technology that is currently being developed. Radon emanation chambers and systems.
- <u>*Ultra-sensitive Immersion Tank*</u> - A large-scale screener using liquid scintillator to provide counting capabilities for large samples or materials.

Associated with the FAARM at either the same level or shallower depths will be

- *Underground Storage of Ultra-pure Materials* - Storage of clean materials such as cryogens, water, noble liquids and gases, copper, lead and germanium.
- *Underground Ultra-pure Material Production Facilities* - Expected materials include electroformed copper, Kr removal, and some detector fabrication. Also includes access to a clean machine shop and special fabrication tools such as EDM machines and laser welders.
- *Access to Mass Spectrometry* - The means to obtain sensitivities at the sub-microBq/kg level, employing existing mass spec facilities. Requires ultra-clean reagents and wet-lab facilities.
- *NAA and RNAA Screening* - The ability to facilitate neutron activation and radiochemistry NAA measurements. The RNAA measurements require wet lab capabilities. They both require dedicated HPGe detectors with moderate sensitivity either outside the shielded FAARM at the 4850-ft. level or at the 300-ft. level for easy access.

These elements do not exist on their own. In order to fully utilize the capabilities outlined above, organizational structures are needed which allow for the prioritization of samples, programs and R&D, exchange of technologies and expert personnel, expansion of the user base, and smooth running of the facility. These have been identified as:

- *Materials Database* - Web-accessible open database of all materials screened, their contamination levels, production details, and expected use.
- *Assay Capabilities* - Web-accessible scheduling tools with the sensitivities and characteristics of all machines and processes available to the user, including techniques only available offsite (Mass Spec, Irradiation for NAA, chemical assay).
- *Code Repository* - Updated and maintained software for the operation and interpretation of screening data, cosmogenic activation and shower production, nuclear cross sections, etc.
- *Integrative Activities* - Workshops and networking activities to foster continued research into new low background techniques, international and cross-cutting collaboration, and extension into other research areas.

DESIGN OF THE 4850' LEVEL ASSAY FACILITY: FAARM

Design of FAARM optimizes economy of scale (combining ultra-sensitive and production screening in the same area) and takes advantage of common infrastructure (such as purification plants and water shield engineering at DUSEL). It is designed to be a self-sufficient laboratory, which will service the needs of all experiments over the life of DUSEL. It is therefore enclosed in its own building with a separate safety system and infrastructure, including plumbing, air handling and waste management. The floor plan layout is shown in Figure 1. The overall dimension of the facility is 25 m x 17 m, in compliance with guidelines for fitting into the DUSEL lab modules at the 4850' level. In order to maintain the cleanliness of the facility, entry to the lab is through the two locker rooms which include shower and gowning facilities. Equipment passes through the cart access interlock, which includes a cleaning station. The goal is to maintain a 10,000 class clean room protocol throughout the building, with tighter standards in the inner tunnel lab, some assembly areas, and in the immersion tank top-loading clean room.

The main water shield and screening laboratory (including control room) is at the ground level. Stairs lead to a second floor, which is level with the top of the water shield. A hatch and crane lifts materials and equipment to the second floor, and a monorail provides transport to the clean room above the water shield. The second floor provides sample storage and preparation space with wet benches and fume hoods, as specified by microbiology and geochemistry users, as well as some radiochemistry. There is an enclosed shop for small jobs requiring clean machining and a radon-free room for sensitive assembly and storage needs. The radon scrubber, local water processing system, and HVAC support are located outside the facility walls on a fenced balcony above the first floor. The exterior building provides the isolation required to meet clean room specifications and enable graded radon mitigation protocols, while sharing a standard lab module with other experiments. If FAARM were to be housed in a dedicated space, the civil construction could be relaxed and only certain spaces, such as the clean room above the ultra-sensitive immersion tank, would be enclosed.

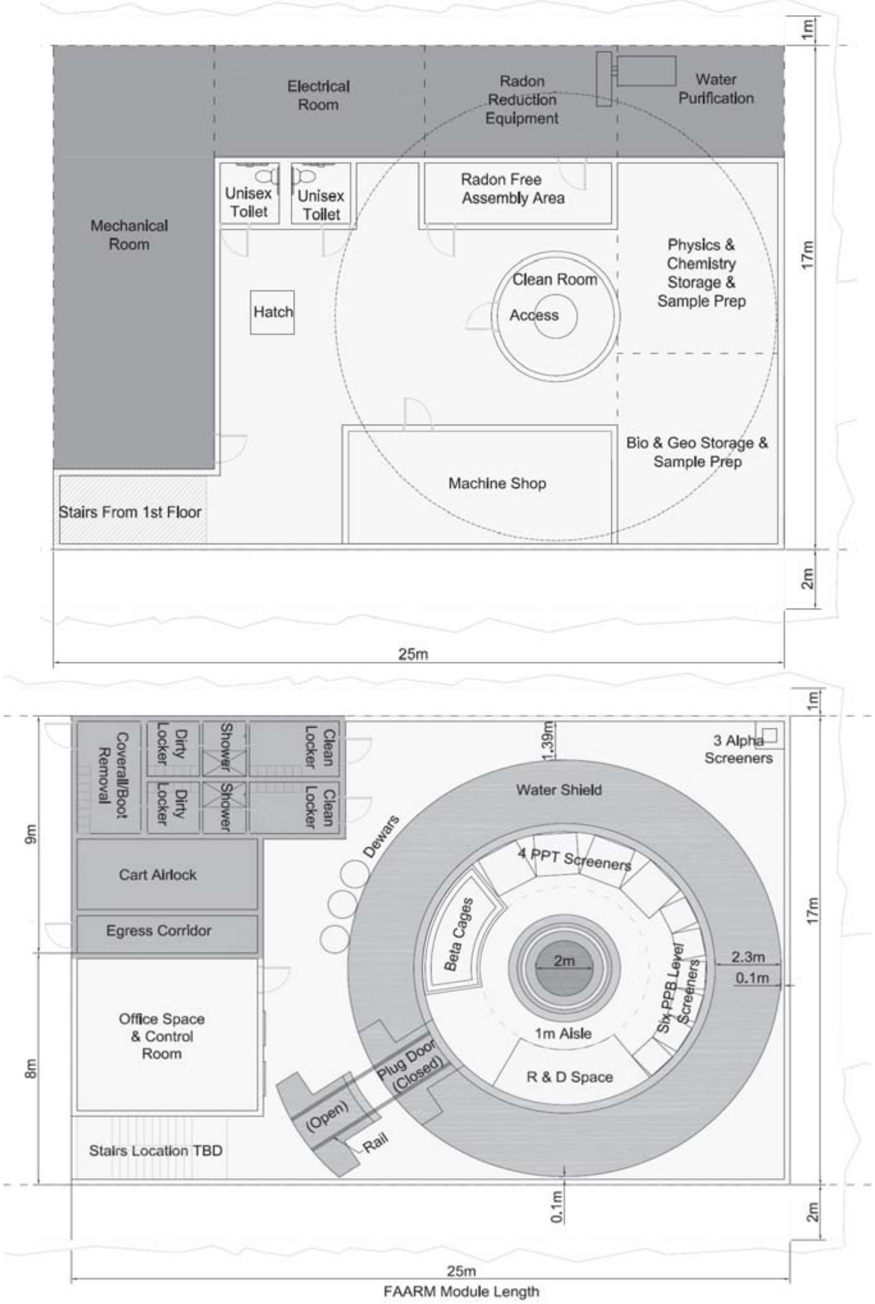


FIGURE 1. Floor plan for the DUSEL 4850' level Facility for Assay and Acquisition of Radiopure Materials, or FAARM.

The water shield is the most important aspect of the design and has been optimized for cost and space. The rendering in figure 2 shows how it fits into the facility. The size of the shield is ~15m diameter and ~8m height, but the final dimension will depend on the radioactivity level of the surrounding rock and construction, as well as the cavern lining (shotcrete or spray-on vinyl). The required water is expected to come from the LBNE water system at the 4850' level, but there will be local processing to improve and maintain the cleanliness of the water. The right circular cylinder design can be easily constructed on-site by contractors who build such tanks at remote sites for the ethanol industry. Rectangular shapes and site-filling designs came out at twice and three times the cost. These tanks can be built of stainless steel or carbon steel with an interior lining. At the moment, there is no financial incentive to use the carbon steel option.

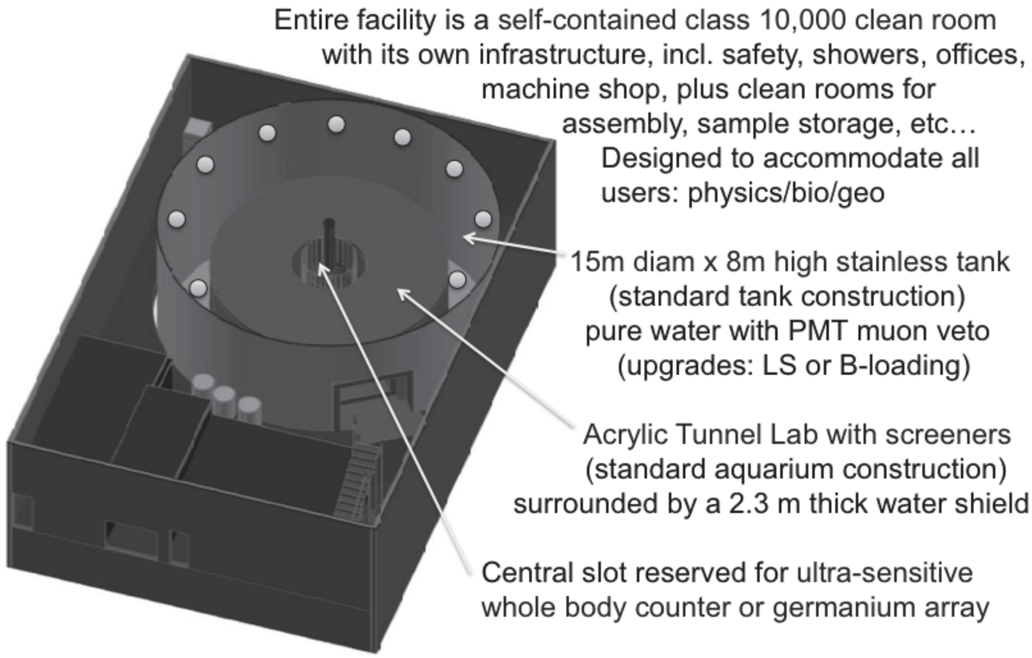


FIGURE 2. Rendering of FAARM, showing the water shield and inner tunnel lab.

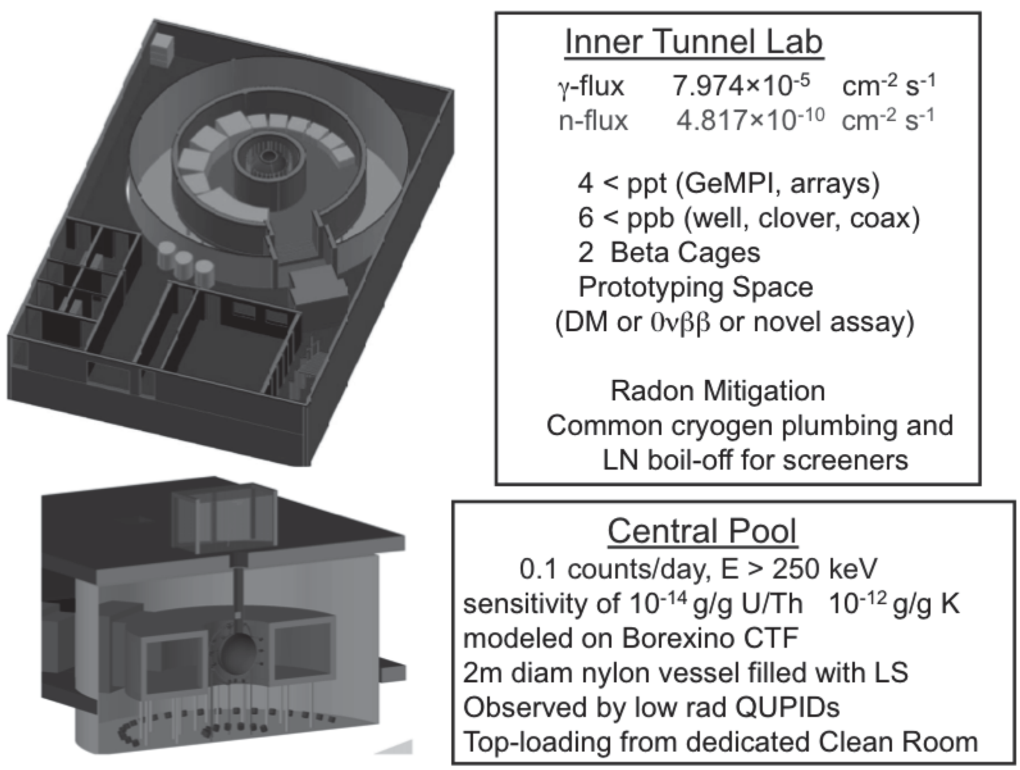
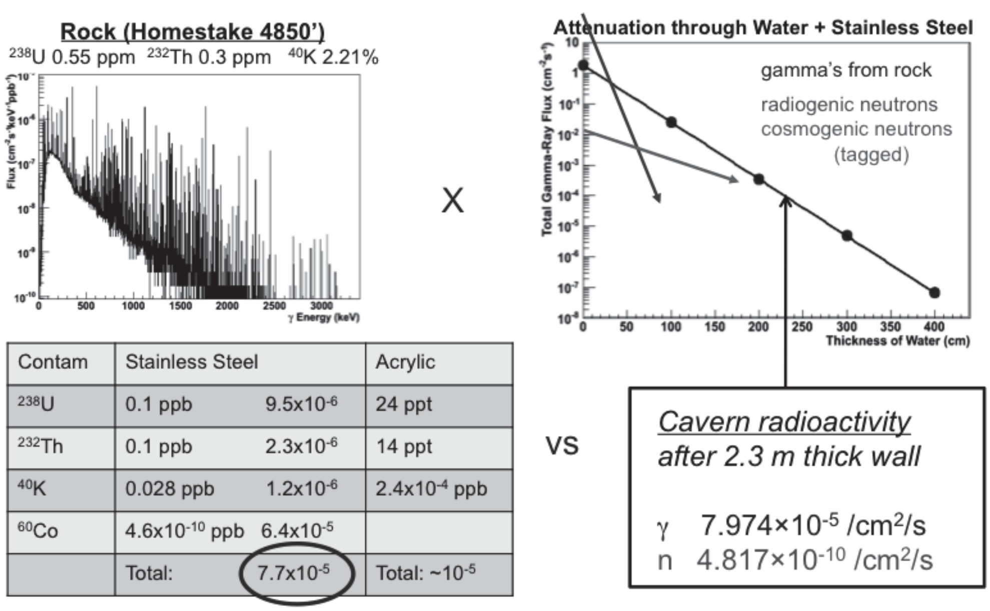


FIGURE 3. Cutaway view of the inside of the water shield, showing the location of the screeners in the toroidal inner tunnel lab and the top-loading immersion tank at the center.

The purpose of the water shield is to provide inexpensive, hydrogenous common shielding for sensitive screeners, while creating ultimate shielding for the innermost ultra-sensitive immersion counter. By being located at the 4850' level, it can share common water purification infrastructure with other DUSEL experiments that are planning dedicated water shields. There are four major design elements: (1) an active, shared water volume observed by phototubes for the identification of muons and neutron activation products, as well as passive attenuation of external gammas and neutrons; (2) a laboratory space inside the water shield for housing sensitive beta and gamma screeners; (3) an ultra-sensitive immersion system at the center, capable of performing large sample counting; and (4) space inside the same water shield for R&D and prototyping of detectors for future DUSEL experiments.

The water shield thickness of 2.3 m was chosen after simulation showed that this would reduce the gamma background from the cavern rock to approximately the same level as contaminants within the shield itself (figure 4). This is an acceptable level for a facility which has limited space and budget. For input, the Geant4 simulation used a gamma spectrum obtained from concentrations of uranium, thorium, and potassium measured in samples of the Homestake rock (germanium spectroscopy by Al Smith, Berkeley Oroville facility). Over the next year, more detailed simulation will map out the background levels for all screeners inside the tunnel lab. While additional copper shielding may be required for the most sensitive screeners, the water shield cuts down the background significantly for all screeners, creating a much more cost effective solution than individual lead shielding. For the most sensitive samples, a muon veto is also necessary, despite the depth. Adding phototubes to the water shield is a cost-effective way to add this functionality.



Contam	Stainless Steel		Acrylic
^{238}U	0.1 ppb	9.5×10^{-6}	24 ppt
^{232}Th	0.1 ppb	2.3×10^{-6}	14 ppt
^{40}K	0.028 ppb	1.2×10^{-6}	2.4×10^{-4} ppb
^{60}Co	4.6×10^{-10} ppb	6.4×10^{-5}	
	Total:	7.7×10^{-5}	Total: ~10^{-5}

FIGURE 4. Optimization procedure to determine the minimum thickness of water between outside of stainless steel tank and inner tunnel lab. Geant4 Simulation using Homestake rock measurements as input (top left). Attenuation of gammas from the rock through a water shield of varying thickness (top right). Gamma levels due to contamination in the steel and acrylic itself (bottom left) compared to the level achieved after 2.3 m of water (bottom right).

An upgrade path also exists, where the water is replaced with either boron-loaded liquid scintillator or gadolinium-loaded water plus wavelength-shifter. This would enable neutron detection, not only for background rejection of higher energy cosmogenically-produced neutrons that can penetrate the shield, but also for long-lived capture processes that are harder to associate with the initial muon track. By continually operating the upgraded shield as a neutron monitor over many years, FAARM will be able to provide valuable benchmark information for cosmogenic simulations, which are currently limited by the paucity of data.

Sensitive screeners will be located inside a toroidal inner screening laboratory which forms a tunnel within the water shield (see cutaway view in figure 3). The toroidal geometry which reserves a central shared water space for the most sensitive detector saves valuable space, uses the same water system and phototubes, and avoids the cost of an additional containment tank. The walls of the torus laboratory, especially the inner one that faces the immersion tank system, need to be constructed of radiopure material. Acrylic tunnel design is a staple of large public aquariums and this expertise is being tapped. The support structure below the tunnel will have to withstand both compressive forces when the water shield is empty and buoyant forces when filled. The door is shown as a movable plug, but may instead be a fixed shield labyrinth. Entrance to the inner lab would then be via a simple over-pressure entrance interlock to maintain a higher degree of cleanliness and radon mitigation within the inner lab.

At least four of the installed gamma screeners will be large-crystal, high-purity germanium counters capable of ppt sensitivities, while a set of ppb-capable germanium detectors in various configurations (well, clover, coaxial, etc) will cover other gamma spectroscopy needs. For beta counting, we anticipate using two *beta cages*[1], at least one of which will already be in use at Soudan by that time. The beta cage is a low-background multi-wire proportional chamber using neon gas at atmospheric pressure. Samples are placed inside the chamber so that the full track from emitted electrons can be measured. Space within the inner lab will also be reserved for detector R&D and prototyping for future experiments. This provides unique shielded underground space for new technologies which otherwise would be unable to afford the type of shielding required to extend their sensitivities and determine their feasibility.

Some screening capability will be in the FAARM, but not inside the inner lab. For example, the XIA corporation currently builds the most sensitive alpha counters in the world. They will benefit from an underground, radon-mitigated location, but do not require the water shield as they have their own veto planes. We have set aside FAARM space outside the inner lab for two XIA alpha counters. Dedicated screeners may also be brought to the lab by, for example, researchers doing microbial research using radioactive tracers. Where they are operated will depend on their sensitivity requirements.

The center of the water shield would house a large volume assay chamber similar to the Borexino counting test facility, or CTF[2]. While we chose an existing technology in order to provide a good cost estimate and schedule, it is the location which makes it special; the ultimate assay function can take advantage of the maximal shield thickness. The assay chamber is accessed by a hermetic top deck with a nitrogen purge between the liquid surface and deck for handling and insertion of counters and samples into the active volume. Another option for the same location might be a segmented germanium array with coincident counting and pulse shape discrimination. It can also be imagined that upgrades and replacements can occur as detector technology advances.

The current plan calls for a two-meter diameter transparent vessel filled with liquid scintillator (e.g. linear alkylbenzene, LAB). Samples are lowered through the neck of the liquid scintillator vessel. The vessel can be made of nylon, in which case it will be assembled in a dedicated clean room at a participating institution, in the same way the CTF vessel was assembled (the original company still has the raw materials). Alternatively, a high purity silica sphere will be explored. Signals from samples immersed in the scintillator will be observed by low radioactivity photodetectors (costed for QUIPIDs[3]). The photodetectors are hung on a titanium frame inside the water shield, but outside the scintillator vessel.

Such a whole body counter has been proposed before[4] as a general-purpose screener which can detect minute amounts of radioactivity and can handle large samples. It is especially good for bulk gammas; the energy resolution is moderate (ΔE = 8% at 1 MeV) and the photon efficiency becomes greater than 50% above 1 MeV. Betas and alphas from surface contamination can be detected from bare samples directly immersed in the scintillator. Reactive samples can be placed inside nylon bags. As long as they thinner than 50 mm, only the alpha sensitivity will be lost. It would be possible to distinguish betas from gammas via event reconstruction and alphas by pulse shape analysis. For this to work, the LAB must be purified to 10^{-16} g/g U/Th and 10^{-14} g/g K. This level, though stringent, has been achieved for liquid scintillator.

COST AND SCHEDULE

We prepared a complete resource-loaded schedule. The resulting cost for FAARM can be broken down into three categories: \$3M for the water shield and inner lab, \$2.5M for the immersion tank, and \$3M for the building and its infrastructure, assuming that DUSEL provides power, water, and ventilation to the outside of the building. This includes the scientific labor involved in the commissioning and quality assurance of elements such as the phototubes, nylon vessel, data acquisition, etc., as well as the engineering design work and contracted assembly of large elements such as the water shield, tunnel lab, and civil construction. It is therefore obvious from the breakdown, that a third of the cost could be recovered if the FAARM were located in a dedicated excavation from which to manage cleanliness and radon reduction, rather than building a shell around itself.

Assuming a DUSEL funding profile that releases MREFC money in 2014 and has cavern locations prepared by 2017, we would have beneficial occupancy by January 2018. Screeners originally located in the Davis cavern and

Soudan will be moved into the FAARM over the course of a year, maintaining maximum screening throughput at the remote locations in a staged manner. The stages of our project are as follows:

Before Module is ready, but after money is allocated

- Detailed engineering-level design
- Obtain bids, contracts and permits and hire contractor
- Assemble and test water purification system
- Procure radon system from Ateko (year lead time)
- Choose photodetectors, screening and testing, bids
- Purchase photodetectors and electronics, perform calibration and quality assurance
- Procure nylon and build dedicated clean room
- Build nylon vessel in clean room

Once module is ready and radon < 100 Bq/m^3 (ventilation, rock coating)

- Install Ateko in module, operate temporary radon-free room for sensitive materials
- Water tank assembly under direction of contractor
- Ateko moved to final location inside FAARM
- Beneficial occupancy one year later.

Establish moderate cleanliness protocols immediately after Beneficial Occupancy

- Clean entire lab as soon as possible
- Clean and coat interior of shield, install cables, plumbing, air, cryogen system
- Initial water fill and test plumbing – drain and clean
- Install Water Shield Photomultiplier tubes – fill shield, operate and calibrate phototubes
- Comission data acquisition and shield – take data for long muon run - drain

Establish tight cleanliness protocol, including showers and radon mitigation

- Measure particulate level and radon to confirm – commission monitoring
- At least one sensitive HPGe moved to FAARM as bkgd monitor
- Install nylon vessel and QUPIDs (test and calibrate)
- Fill Immersion Tank with liquid scintillator
- Install nitrogen blanket, clean room – scintillator purity studies with QUPIDs
- Fill shield – Combined Water + scintillator test: take data for long background run
- Install rest of screeners and commission Immersion Tank.

CONCLUSIONS

The AARM collaboration has completed a conceptual design of a low background facility for the assay of radiopure materials which can fit within the cost and space requirements of a new DUSEL lab located at the Homestake mine. Such a common use facility, which services the needs of the underground science community, provides a cost effective alternative to single-experiment screeners in multiple locations. Since FAARM will not be available until mid-2018, it is important to begin an early screening program to aid in the design and construction of the initial suite of experiments and to advance assay technology. If done in a coordinated manner, this can form the nucleus of an integrated training and reallocation plan, whereby distributed sites already serving the community (e.g., Kimballton, Soudan, WIPP, Oroville, etc.) participate in early screening and then move toward a more unified center at DUSEL. Since FAARM will be operated by local technicians and overseen by researchers, this early screening effort can be used to develop a trained staff.

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