Empirical and Analytical Design of Large Openings at a Proposed National Underground Science Laboratory

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ABSTRACT

The famous Homestake gold mine in Lead, SD, closed recently after 125 years of operation. However, the mine may receive a new lease on life as a National Underground Science Laboratory (NUSL) supported by the National Science Foundation (NSF) and dedicated to high-energy physics experiments involving neutrinos. These experiments require the construction of many large underground chambers tens of meters wide at depths of over 2118 m. Construction of such large openings at such extreme depths has few precedents in civil-engineering-type construction.

The Spokane Research Laboratory has a long history of ground control research at the Homestake Mine and has supported NSF and the physics community in their efforts to develop a NUSL at Homestake or other suitable location. This paper will summarize underground science and describe proposed underground science laboratories in the United States, in particular the proposed NUSL at Homestake. Next, the paper describes an empirical design approach using the Q system of rock mass classification for these large openings. An initial site investigation that produced three good case histories is described. The actual support system used at the three sites agrees well with support recommendations from current support design charts, giving credibility to estimates of the classification parameters and Q. Feasibility of, and support requirements for, 25-, 50-, and 100-m spans are estimated in the anticipated rock mass. This analysis indicates that 25- and 50-m spans are probably feasible, but a stable 100-m span may be unachievable. The empirical predictions are then compared to detailed numerical analyses. The paper concludes with preliminary support recommendations and necessary site investigations needed to make a proposed NUSL a successful reality. These studies have been important input to NSF for their decisions on the technical feasibility of developing the proposed NUSL.

If NUSL is developed, it could enable scientific experiments in areas beyond high-energy physics. The laboratory could also enable research in rock mechanics, ground water hydrology, mining engineering, mine safety and health, and ground control.

INTRODUCTION

The physics community in the United States seeks to study nuclear processes in the sun, detect extragalactic supernova explosions, find missing dark matter in the universe, measure proton decay, and manufacture sensitive electronic materials.

What do these science studies have to do with rock engineering and ground control? The next generation of fundamental physics experiments requires construction of underground chambers larger and deeper than ever before. Scientific proposals under serious consideration at this time call for construction of large (50 m in diameter and 50 m high) chambers at depths in excess of 2100 m (*1*). Mining engineers have excavated temporary mine openings, such as nonentry stopes, of this size and at this depth; however, such openings push the envelope of current civil engineering and underground construction experience.

UNDERGROUND SCIENCE

Underground science spans several disciplines and seeks answers to fundamental questions in physics, astronomy, and cosmology, as well as in microbiology, geoscience, and materials science (*2*). Table 1 summarizes the wide range of scientific uses for a NUSL and, of relevance here, the size and depth requirements for the proposed experiments.

Many of the experiments involve the rapidly evolving field of neutrino physics. Neutrinos are fundamental neutral particles whose mass has not been determined. It is not clear if neutrinos are massless, as proposed in the standard model of particle physics, or if they have a very small, yet finite, mass, as suggested by quantum mechanics. Study of these infinitesimally small particles provides necessary insights into nucleosynthesis in stars, nova, and supernova, the fundamental structure of the universe and its ultimate fate, and details of the standard model of particle physics.

Study of these physics problems requires precise measurement of rare and/or very weak signals. Some detectors literally count atoms to indicate the occurrence of an event or a process. Two methods are generally available to experimentalists who measure rare and/or very weak signals. One is to boost the signal by making the detector bigger, and the other is to decrease noise with better shielding. In neutrino physics, the biggest source of noise is from

Table 1.—Science summary and laboratory space requirements at proposed NUSL (2)

Study topic	Depth, m	Size	Comments
Solar neutrinos	≥5000 mwe (about 2000)	500,000 m^3 (5 chambers, 50 m diameter, 50 m high)	The flux of electron neutrinos from nuclear reactions in the sun is less than that predicted by the standard solar model by a factor of 3. Resolving this dilemma provides crucial understanding of nucleo-synthesis, the standard model of particle physics and quantum mechanics.
Double beta decay	≥4000 mwe (about 1600)	≥4,500 m^3 (1 chamber, 20 m diameter, 15 m high)	Certain nuclei decay via an extremely rare process in which two electrons and two antineutrinos are emitted. In an even rarer process, the decay occurs without emitting antineutrinos. Observations of these exceedingly rare events will answer fundamental questions about the standard model of particle physics.
Dark matter	≥4000 mwe (about 1600)	≥4,500 m^3 (1 chamber, 20 m diameter, 15 m high)	Astronomers suspect that the major component of the universe's mass is dark matter, which cannot be seen because it does not emit or absorb light. Physicists are currently searching for massive neutrinos and weakly interactive massive particles (WIMP's) in the new field of dark matter research.
Nucleon decay	≥4000 mwe (about 1600)	≥900,750 m^3 (10 chambers, 50 m diameter, 50 m high)	Recent grand unification theories (GUT's) to link the weak, electromagnetic, and strong forces also predict that the proton should decay, although its lifetime is extremely long (10^{33} years or more). Detecting proton decay is one of very few ways to test GUT's directly.
Neutrino oscillations	≥4000 mwe (about 1600)	≥900,750 m^3 (10 chambers, 50 m diameter, 50 m high)	In the standard model of particle physics, neutrinos come in three flavors, electron neutrinos, muon neutrinos, and tau neutrinos. Evidence suggests that neutrinos will oscillate or convert to different flavors over time and that they possess a small but nonzero mass. The mechanics and implications of neutrino oscillations remain for discovery.
Supernova neutrinos	≥2000 mwe (about 800)	≥15,000 m^3 (1 chamber, 30 m diameter, 22 m high)	During a supernova, neutrinos carry away almost all (99%) of the ~10^{53} ergs released by the event. The emitted neutrinos carry critical information about the explosion mechanism itself and the formation of neutron stars and black holes.
Nuclear astrophysics	≥4000 mwe (about 1600)	≥6,000 m^3 (1 chamber, 20 m diameter, 20 m high)	Underground laboratories provide opportunities to study nucleosynthesis in nova, x-ray bursts, and supervnova and in the different phases of stellar evolution
Geoscience	All depths	Entire mine	Deep underground laboratories can be used to study groundwater flow, chemical transport processes, and rock deformation and failure processes. A dedicated laboratory enables large-scale, long-term, controlled experiments.
Microbiology	All depths	Entire mine	Unique microbial communities exist at least 2.8 km below the surface in extreme conditions of pressure, temperature, salinity, pH, and low energy and water availability. Deep underground excavations enable study of the subsurface biosphere, which has application to the search for life on other planets.
Materials science	All depths		Underground science experiments require new detector materials of extraordinary purity. The underground environment enables manufacture of new electronic materials free from damaging cosmic rays.

energy cosmic rays that easily penetrate the earth's atmosphere and hundreds of meters of rock. Better shielding requires thousands of meters of rock, thus the need for large, deep underground science laboratories.

EXISTING AND PROPOSED UNDERGROUND SCIENCE LABORATORIES

The first underground science laboratory was the 600-ton solar neutrino detector installed by Davis on the 4850-ft level of the Homestake Mine (*3*). From this beginning, other underground science laboratories have been developed at the Soudan Mine in Minnesota, the Kamioka Mine in Japan, the Creighton Mine near Sudbury, Ontario, the Waste Isolation Pilot Plant in New Mexico, the Gran Sasso highway tunnel near Rome, the Mont Blanc tunnel between Italy and Switzerland, and the Baksan Laboratory in the northern Caucasus Mountains of Russia. Figure 1 shows the characteristics of current underground science laboratories in terms of depth expressed as meters of water equivalent (mwe) and the cosmic ray muon flux expressed as counts per square meter per year.

Gran Sasso, at a depth of 3899 mwe, is currently the deepest available general-purpose underground science laboratory. To lead the world in pioneering underground science study, the U.S. physics

Table 2—Characteristics of proposed sites for a national underground science laboratory in the united states (*4*)

Site and location	Access	Depth, m	Shielding, mwe	Underground development costs	Operating costs/year	Site geology	Possible development time for large new detectors, years
1. Homestake Mine, Lead, SD	Vertical shafts and ramps	Up to 2600	Most likely 6700 up to 7200	$83 M to $159 M	$3.8 M	Multiple rock types; mostly metamorphic	1 to 3
2. San Jacinto, Palm Springs, CA	Horizontal drift	Over 2000	Most likely 6500 up to 7000	$115 M to $161 M	$2.3 M	Igneous rock batholith	5
3.Soudan Underground Physics Laboratory, St. Louis County, MN	Vertical shaft	710	2200		$1 M	Multiple rock types; mostly metamorphic	5
4. Carlsbad Underground National Laboratory (Waste Isolation Pilot Plant), NM	Vertical shaft	Up to 1300	Up to 3200	$64 to $104 M	$2 M to $10 M	Layered sedimentary rocks, salt and potash	
5. California - Nevada border	Horizontal drifts	Over 2000	Up to 6000			Green-field sites; site-specific geology varies	5 +

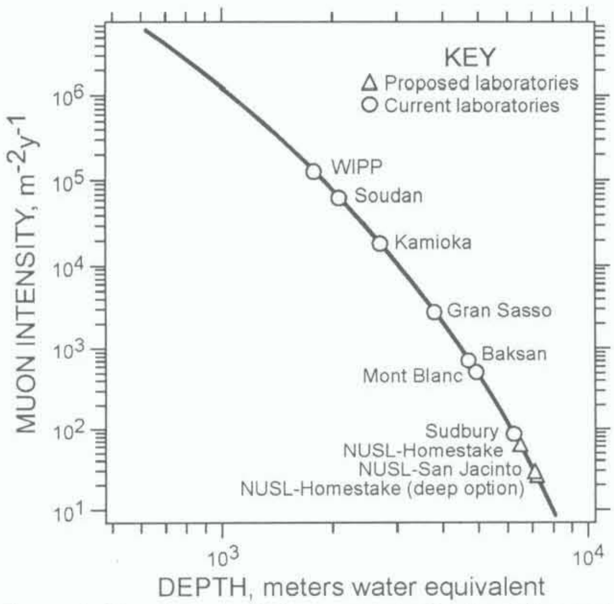

Figure 1.–Cosmic ray shielding and depth of existing and proposed underground science laboratories (after *1*)

community wants to establish a National Underground Science Laboratory (NUSL) at a depth of 7000 mwe. A Technical Assessment subcommittee investigated four prime sites for a NUSL in the United States, as well as several other possibilities (*4*). The subcommittee identified 28 individual factors relevant to site selection. Table 2 summarizes select characteristics of these sites with particular relevance to the rock mechanics and ground control. The Homestake site was favored because of its shorter time-scale for achieving significant scientific results, lower development costs, and lower inherent uncertainties because of geologic factors. The San Jacinto site is also favored because of its horizontal access and lower operating costs. Decisions are still pending on NUSL wherever it is ultimately built.

NUSL AT THE HOMESTAKE MINE

The Homestake Mine in Lead, SD, is an underground gold mine with workings extending to over 2,460 m below the surface. Mining began in 1876 and continued for 125 years until December 2001 when the company decided to cease operations permanently. As shown in figure 2, access to the mine is via the Ross and Yates shafts that extend to the 4850-ft level. The No. 6 shaft and other internal shafts plus a ramp system provide access to lower levels up to 2460 m deep.

The Homestake Mine has a rich history of mining innovation, ground control, and rock mechanics. Vertical crater retreat mining and cable bolting of large stopes was applied at the Homestake Mine in the 1970's (*5-6*). Extensive rock mechanics studies resulted in calibrated numerical models of large stopes and shaft protection pillars (*7*). Nonentry stopes over 50 m wide have been developed routinely.

Present underground science experiments take place in a chamber near the bottom of the Yates shaft on the 4850-ft level. This chamber near the bottom of the Yates shaft houses a solar neutrino detector containing 600 tons of perchlorethylene (dry-cleaning fluid). The proposed NUSL chambers could be developed around the 7400-ft level, also shown on Figure 2. Proposed detectors for the most ambitious experiments would require development of 10 chambers, each about 50 m in diameter and 50 m high. Figure 3 shows a conceptual arrangement for these detector chambers off the No. 6 shaft. Each chamber would be approximately a vertical cylinder with hemispherical ends.

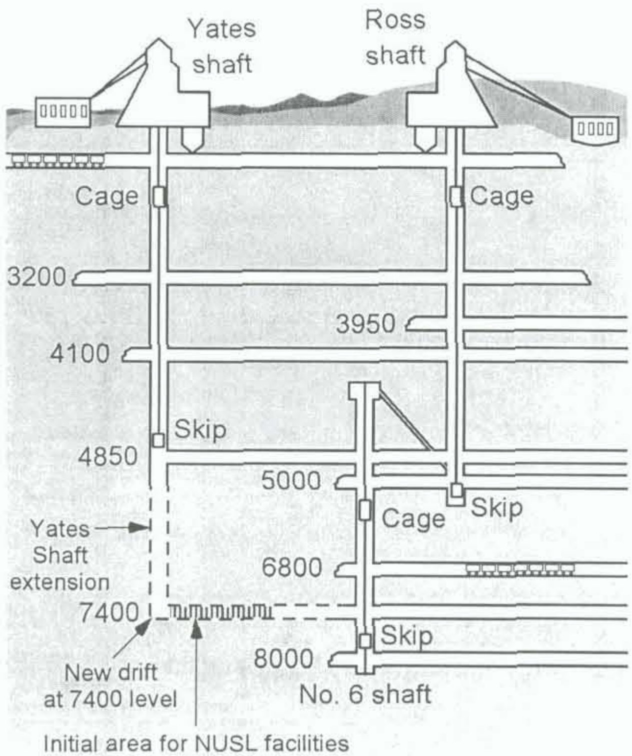

Figure 2.–General schematic of Homestake Mine showing proposed location of NUSL facilities (after *1*)

EMPIRICAL ANALYSIS OF LARGE DEEP UNDERGROUND CHAMBERS

Almost all mining at the Homestake Mine has occurred in the Homestake Formation with some development in the Poorman Formation. Proposed NUSL chambers will be developed in the Yates Member of the Poorman Formation, where little development work has been done. Although mining experience in the Yates Member is limited, what is known clearly indicates its excellent quality for underground construction.

Initial characterizations were performed at three sites using the Q system of rock mass classification to assess the feasibility of constructing large openings in this rock and determine support requirements.

- The rock at site 1 at the 6950-ft level is mainly Homestake with some Poorman. Certain areas are highly stressed and fractured because of nearby stoping . Steeply dipping bedding planes are the major discontinuity at this site. It appears that these bedding planes are tightly healed; however, in highly stressed areas, the spacing between open bedding planes is 5 to 10 cm. The continuity of these bedding planes is low, and most cannot be traced more than 1 m. Occasional joints with random orientation were also observed. These joints can be traced for 3 to 6 m or more and are tight, smooth, and contain no filling material. The estimated number of bedding planes, joints, and fractures per cubic meter is about 16.

- The rock at site 2 (between the 6950- and 7100-ft levels) is the most heavily jointed rock observed at the Homestake Mine. This site is also in the Homestake and Poorman formations. Steeply dipping bedding planes are spaced 15 to 30 cm apart, and again, high stress conditions resulting from nearby stoping may have opened these discontinuities, which are otherwise tightly healed. A poorly developed joint set was observed with spacings of about 30 cm and a continuity of 3 to 6 m. These fractures are tight, rough and contain a hard filling (probably quartz). The estimated number of bedding planes, joints, and fractures per cubic meter is about 12.

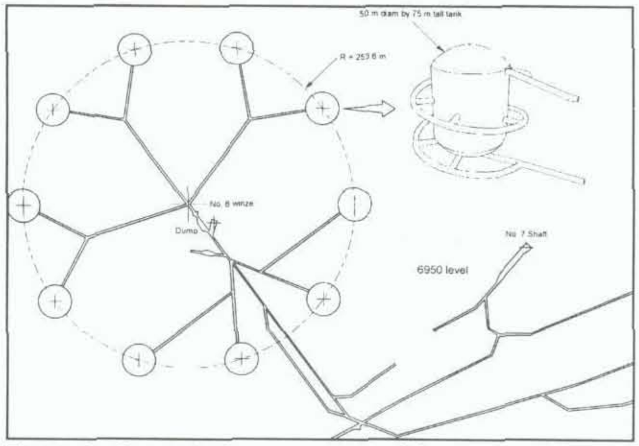

Figure 3.–Conceptual arrangement of large, deep detector chambers at a NUSL at Homestake (Laurenti, personal communcation, 2002).

- Site 3 is in the Yates Member. Rock at this site is massive with no or few joints. The estimated number of bedding planes, joints, and fractures per cubic meter is less than 4.

The rock quality designation (RQD) of the rock at these sites was estimated from the number of joints per cubic meter. All three sites are dry. Compressive strength of the intact rock at sites 1 and 2 is in the range of 70 to 140 MPa, while the compressive strength of the Yates Member appears to be about 200 MPa.

Q is calculated as—

$$Q = \frac{RQD}{J_N} \frac{J_R}{J_A} \frac{J_W}{SRF}$$

where RQD = rock quality designation.
J_N = number,
J_R = joint roughness number,
J_A = joint alteration number,
J_W = joint water reduction,
and SRF = stress reduction factor.

Table 3 summarizes rock mass classification parameters, Q, recommended support systems, and the actual support system used. At site 1, Q equals 1.0, and the equivalent span is 2.5 m. At site 2, Q equals 0.9, and the equivalent span is also 2.5 m. At site 3, Q equals 60, and the equivalent span is 3.1 m. Figure 4 shows these three observations on Barton et al.'s chart (*8*), which gives support recommendations as a function of span and Q. The actual support system used at the three sites agrees well with the recommended support systems, giving credibility to estimates of classification parameters and Q.

Table 3.—Rock mass classification data, Q, support recommendations, and actual support used for three sites at Homestake Mine

Parameter	Site 1	Site 2	Site 3
Joints/m^3 (J_V)	16 (13 + 3)	12 (7 + 5)	<4
RQD = 115 – 3.3 J_V	60	75	85 (reduced from 100 for unknown joints)
Joint set number, J_N	3 (one joint set + random joints)	4 (2 joint sets)	0.75 (massive, no or few joints)
Joint roughness number, J_R	1 (smooth, planar)	1 (smooth, planar)	4 (discontinuous joints)
Joint alteration number, J_A	1 (unaltered joint walls)	1 (unaltered joint walls)	0.75 (tightly healed joints)
Joint water reduction, J_W	1 (dry)	1 (dry)	1 (dry)
Stress reduction factor (SRF)	20 ($\sigma_c/\sigma_1 < 2.5$)	20 ($\sigma_c/\sigma_1 < 2.5$)	10 ($\sigma_c/\sigma_1 > 2.5$)
Q	1.0	0.9	60
Excavation support ratio (ESR)	1.6 (permanent mine opening)	1.6 (permanent mine opening)	1.6 (permanent mine opening)
Span, m	4	4	5
Equivalent span, m	2.5	2.5	3.1
Required (9)	Category 4, rock bolts, 1.3-m spacing, 50 mm shotcrete	Category 4, rock bolts, 1.3 m spacing, 50 mm shotcrete	No support required
Required support (8)	Category 25, untensioned bolts, 1-m spacing, chain link mesh	Category 25, untensioned bolts, 1-m spacing, chain link mesh	No support required
Actual support used	Friction bolts,1-m spacing, chain link mesh	Friction bolts, 1-m spacing, chain link mesh	Spot bolting with mechanical anchor bolts, friction bolts, 1.5-m spacing, chain link mesh

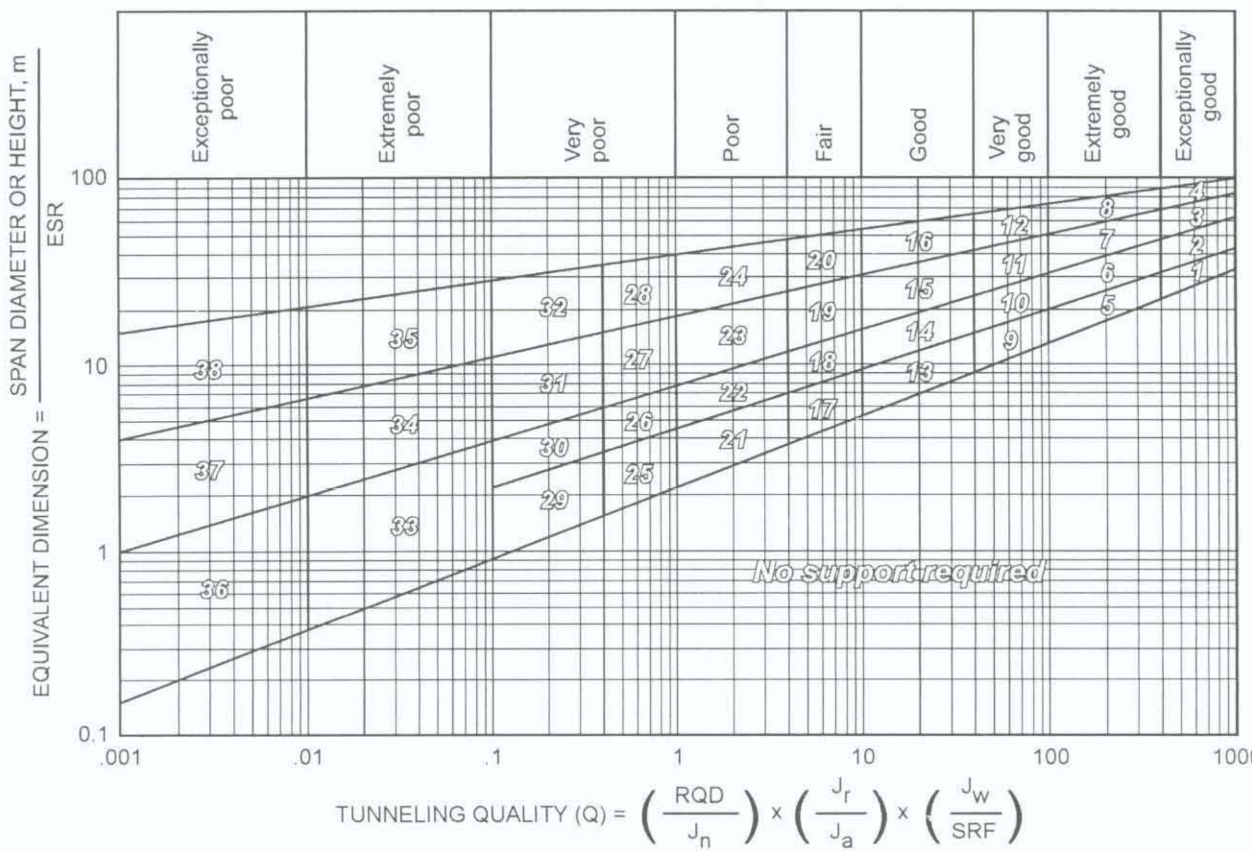

Figure 4.—Required support for different span and rock mass quality (after 8)

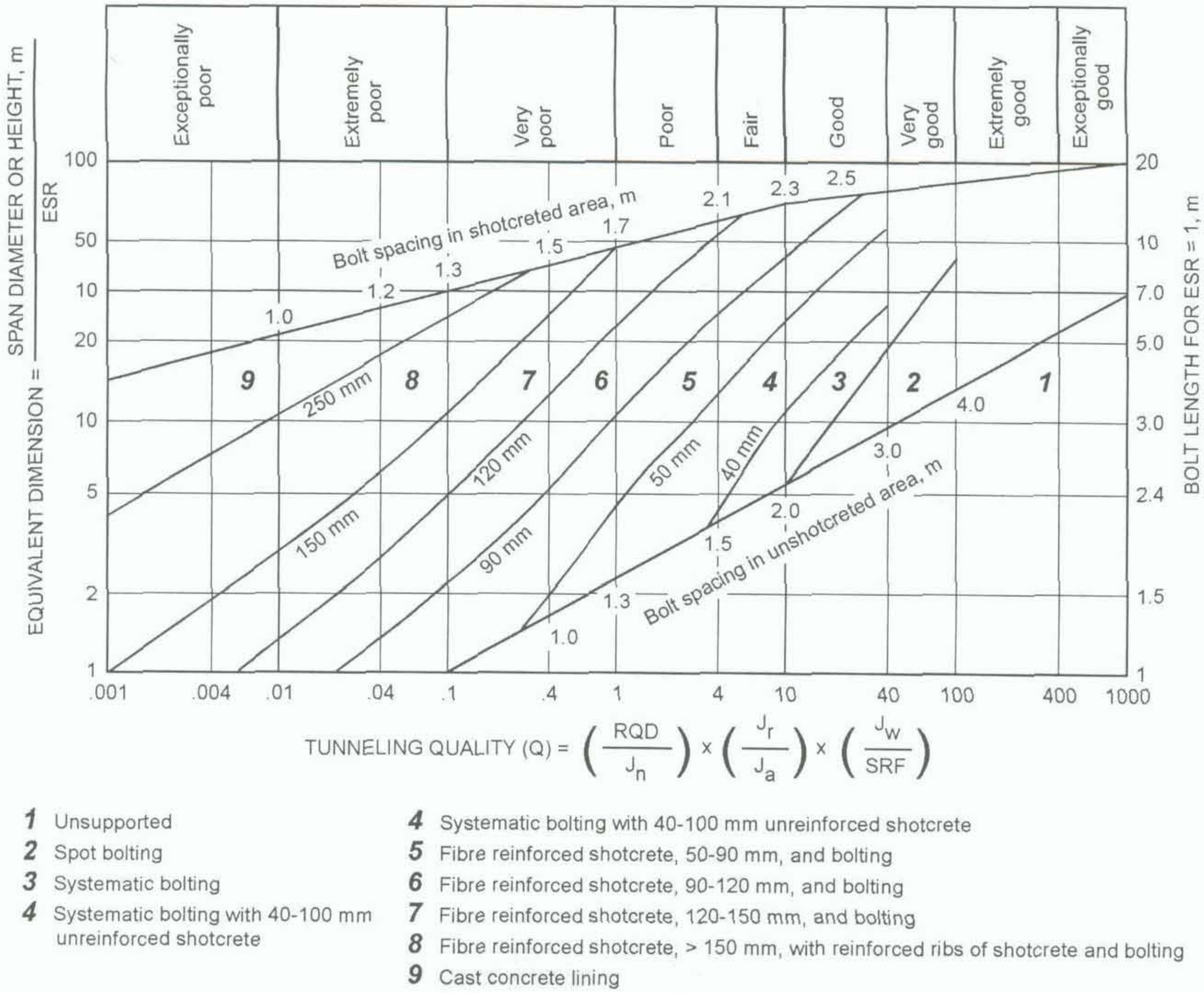

Figure 5.—Required support for different span and rock mass quality (after 9)

Table 4.—Support recommendations for three opening widths at NUSL with Q = 60

Parameter	Span = 25 m	Span = 50 m	Span = 100 m
Excavation support ratio (ESR)	1 (large civil cavern)	1 (large civil cavern)	1 (large civil cavern)
Equivalent span, m	25	50	100
Required support (9)	Category 4, systematic bolting, 40-50-mm shotcrete	Category 4, systematic bolting, 40-50-mm shotcrete	No recommendations
Required support (8)	Category 11, tensioned bolts, 2 - 3-m spacing	Category 12, tensioned bolts, 2 - 3-m spacing	No recommendations

The rock conditions at site 3 may be similar to those expected at major NUSL facilities. Based on a Q of 60, support system requirements for spans of 25, 50, and 100 m were estimated. These spans are indicated on figure 4, and table 4 summarizes support recommendations. Spans up to 50 m are feasible with modest support requirements; however, a span of 100 m is beyond the experience base of the empirical method, and no recommendations are given. Such a wide opening may be impractical. Review of the data points used to develop figure 4 shows clearly that spans above 50 m are beyond the experience base and may be impractical. Figure 5 is a more up-to-date design chart for rock support as a function of span and Q. Again, spans up to 50 m appear feasible with modest support requirements.

A cursory review of the underground construction literature provided few examples of similar size and span to those proposed at the Homestake NUSL. Nieto (*10*) summarizes the general characteristics of large underground chambers in rock. Uses for these chambers include as powerhouses, storage facilities for materials and fuel, subway stations, crushing and mining facilities, and military tests. Underground powerhouses are typically excavated at a depth of 100 to 800 m. Storage facilities range from shallow to 500 m. Depths of subway stations are typically at shallow depths (up to 50 m). Widths range from 14 to 50 m; lengths extend up to 500 m; and heights range from 3 to 50 m. Provost and Griswold (*11*) describe the power plant chamber at NORAD within Cheyenne Mountain in Colorado. This chamber is about 22 m wide in competent granite. Cording and Deere (*12*) discuss another 22-m-wide opening for the Dupont Circle Metro Station in Washington, D.C. Bock (*13*) describes three other Washington, D.C., Metro stations that are 18 m wide and supported by 7-m-long rock bolts. This bolt length is about 40% of the opening width. The rock type at these stations is typically granitic gneiss cut by occasional shear zones and other discontinuities. Boisjoly et al. (*14*) describe an underground powerhouse in Quebec, Canada, having a width of 24 m.

To summarize, underground construction literature provides some examples of large underground chambers with spans up to 50 m. Beyond that width, experience appears to be limited, at least in the United States.

NUMERICAL ANALYSIS OF LARGE DEEP UNDERGROUND CHAMBERS

In addition to the empirical analyses of wide spans, preliminary numerical analyses of the large underground chambers at the proposed NUSL were also completed. Extensive rock mechanics studies at the Homestake Mine in support of mining activities enabled these analyses. The modeled room was a 50-m-high cylinder with 50-m-diameter hemispheres representing the mine roof and floor and a volume of 163,624 m^3. In constructing a FLAC3D model (*15*), one-eighth symmetry was used to reduce the size of the finite-difference mesh, which consisted of 140,800 zones shaped like extruded annulus sectors having a 2.3-m radial thickness and an extruded length of 2.5 m (figure 6). Sector dimensions were reduced to approximately 1.5 m for one computer run to confirm that the mesh size was small enough to estimate the depth of failure into the rock mass. The initial in situ stress state used in these analyses was based on stress measurements made in the 1970's and 1980's at the Homestake Mine. Measurements between 930 and 2256 m in the mine resulted in a linear stress formula dependent on depth below the mine surface (*7*). The initial stress state in the model was achieved by applying the three orthogonal stresses at the finite-difference mesh boundary seven radii from the rib of the cylindrical room and iterating to equilibrium.

$$\sigma_v \quad = \quad 28.28\ h,$$

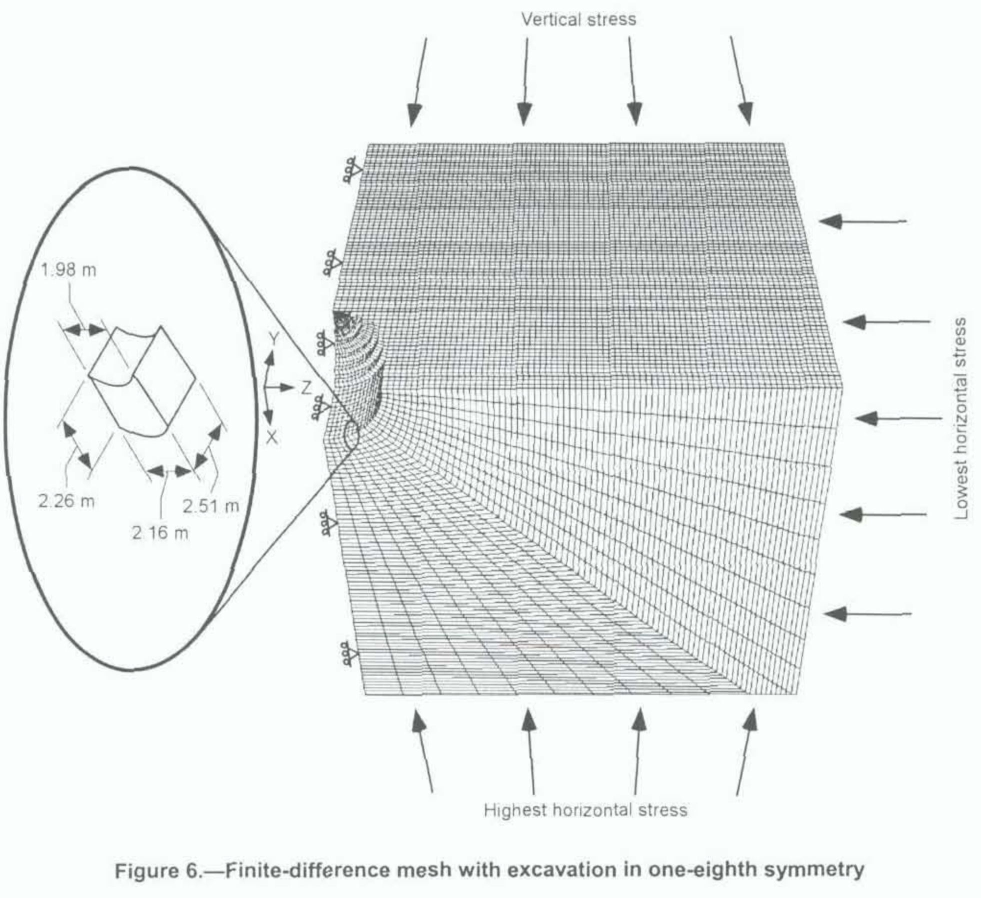

Figure 6.—Finite-difference mesh with excavation in one-eighth symmetry

$\sigma_{h1} = 14{,}327.8 + 11.99\ h,$
$\sigma_{h2} = 834.3 + 12.44\ h,$

where h = depth in meters,
σ_v = vertical stress in kilopascals (kPa),
and σ_{h1} and σ_{h2} = horizontal stresses in kPa.

The room was assumed to be excavated in a homogenous, isotropic rock mass constructed between existing levels below 2118 m. The average depth between levels was used for parameter h to calculate initial stresses. A Mohr-Coulomb failure criterion defined by cohesion and angle of internal friction was used to limit the elastic behavior of the material or the strength of the rock mass. Because there was a limited amount of material property information on the Yates Member, three values for cohesion were used—12.2, 18.3, and 24.4 MPa. These values represent 50%, 75%, and 100% of average strengths calculated from unconfined compressive strength test results conducted on specimens from the Poorman Formation and a value of 30° for the angle of internal friction. The field-scale unconfined compressive and tensile strengths in the Poorman Formation (42.3 and 6.58 MPa, respectively) were 50% of the average laboratory values. They were obtained by monitoring the loss of borehole extensometer anchors during mining of large vertical crater retreat stopes between 2118 and 2164 m deep at the Homestake Mine (*5*). These extensometers were also used to calibrate a three-dimensional, finite-element program, resulting in a field-scale modulus of deformation equal to 23,615 MPa, or 25% of average laboratory values. This value was used in the finite-difference analyses.

Two specimens were prepared for unconfined compression tests and five specimens were prepared for Brazilian tensile tests from a grab sample of rock from the Yates Member. The specimens were approximately 1 by 0.5 m. Their average tensile strength was about the same as the average tensile strength of rock from the Poorman Formation, but the unconfined compressive strength was more than two times the value for the Poorman Formation. This implies that 24.4 MPa is about half the cohesion value for the Yates Member and, based on these tests, is a reasonable estimate of the field, or rock mass, value of cohesion. It is important to emphasize that these specimens may not represent the entire Yates Member. A thorough site investigation is essential to characterizing the rock more accurately. The high strength of the laboratory specimens combined with their elastic-brittle behavior when loaded to failure indicate that Yates rock may be prone to rock bursting.

Results from the finite-difference model indicate that the maximum depth of failure into the rock around the cavity is 10 m and occurs in the lower roof (figure 7*S*). The maximum yield width in the room's rib is 6.8 m. Yield zones in the y-z plane through the origin are similar in shape, but not as extensive as yield zones in the x-y plane. If the centroid of the chamber is located 2141 m below the surface in rock equal in strength to that of the Poorman Formation, the model calculates yield zones in both the lower roof

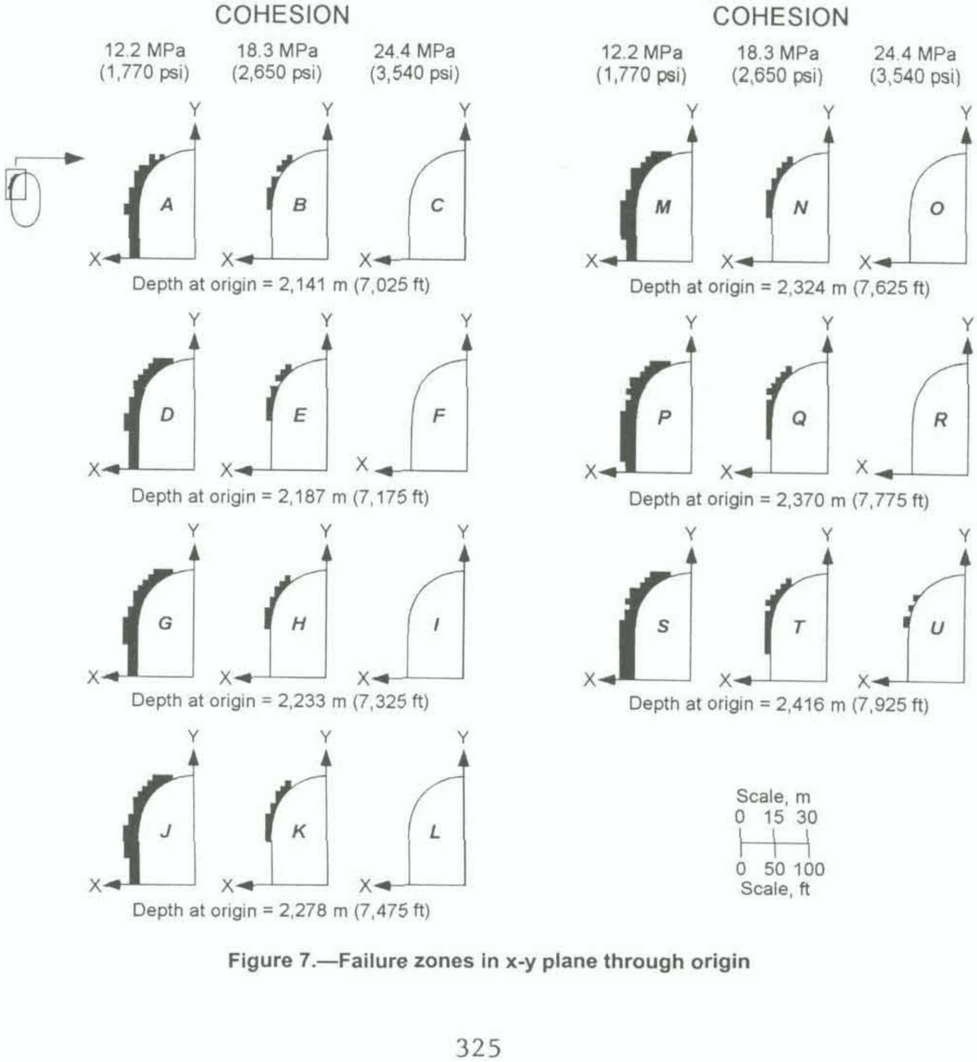

Figure 7.—Failure zones in x-y plane through origin

and ribs (figure 7*A*). Previous mining experience confirms that a stope 24 m wide, 30 m long, and 46 m high excavated with the vertical crater retreat method at 2141 m suffered some caving, but remained open when the roof was supported with cable bolts (*5*). Conversations with mine personnel indicated that large structures (45.7 m high, wide, and long) have been excavated, but are unstable at depths of 2416 m. These observations, combined with the finite-difference results, imply that 2141 m may be the deepest 50-m-wide opening that can exist in the Poorman or Homestake formations without encountering stability problems (figure 7*A*, *S*). However, if the rock strength of the Yates Member is approximately twice that of the Poorman Formation, as initial laboratory tests indicate, then failure will be limited around the room constructed in Yates rock even at 2416 m underground (figure 7*U*). Results could differ if the Yates rock has anisotropic material properties.

Failure zones were initiated where redistributed stresses became concentrated near the lower roof of the chamber and propagated into the ribs as mining depth increased. The thickness of the failure zone diminished to zero near the apex of the hemispherical roof because the arched opening eliminated a wedge of material of a type that often fails and requires support.

SUPPORT OF LARGE DEEP UNDERGROUND CHAMBERS

Empirical methods suggest that systematic bolting with tensioned bolts on 2- to 3-m centers and 40 to 50 mm of shotcrete are required to support a 50-m-span in a rock mass where Q = 60. Bolt length should be at least one quarter of the span (*16*).

For structure-controlled failure, we assume a worst-case rock wedge with dimensions of 15 by 15 m at the base, 15 m high, and weighing about 3100 tonnes. We also assume double-strand cable support with capacity of 40 tonnes. Support of this rock wedge requires about 78 double-strand cables over the 15- by 15-m area, which implies a spacing of about 1.7 m.

For stress-controlled failure, we designed based on the 10-m-deep failure zone found from numerical stress analysis. The weight of the 10-m-deep failure zone is about 27.5 tonnes/m^2. Assuming double-strand cable support with capacity of 40 tonnes requires one cable per 1.45 m^2 or a spacing of about 1.2 m.

CONCLUSIONS

The stability of a 50-m-wide opening with a volume of 163,624 m^3 was analyzed using empirical rock characterization techniques and the numerical model FLAC3D. Empirical methods show that a 50-m opening is feasible with ordinary rock support. A likely support system is double-strand cable bolts with 40-tonne capacity, 15-m length, and 2-m spacings. The numerical models calculated zones of plasticity around the opening at all depths below 2141 m. The maximum extent of the failure zone was 10 m. A support system to contain this failed material consists of double-strand cable bolts with 40-tonne capacity, 15-m length, and 1.2-m spacings. Such a support system is obviously feasible. Based on these preliminary analyses, there are no apparent geotechnical showstoppers for a NUSL at the Homestake Mine.

Observations of instability in large stopes by mine personnel at 2438 m underground suggest that 2141 m may be the deepest level at which a room spanning 50 m can be mined and maintained in rock with strengths equal to those of the Poorman and Homestake formations. If the rock strength obtained from the specimens of Yates rock are representative of the entire formation, then construction of large rooms may be possible at levels below 2141 m in this host rock, but may raise rock bursting concerns.

Proposals to develop a NUSL at Homestake or San Jacinto or elsewhere call for expenditures on the order of $100,000,000 for underground development. The U.S. National Committee on Tunneling Technology (*17*) recommended expenditures of about 3% of estimated project cost for geotechnical site investigations for any major underground civil construction, such as underground power stations or metropolitan tunnels. Therefore, any NUSL site may need about $2 to $3 million for exploratory tunnels, core drilling, instruments, testing, and analyses to develop an adequate engineering design prior to beginning construction.

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