
North American Tunneling '96

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ABSTRACT: The Yucca Mountain Site Characterization Project is the United States’s effort to confirm the technical acceptability of Yucca Mountain as a repository for high-level nuclear waste. A key part of the site characterization project is the construction of a 7.8-km-long, 7.6-m-diameter tunnel for in-depth geologic and other scientific investigations. The work is governed in varying degrees by the special requirements for “nuclear quality assurance,” which imposes uncommon and often stringent limitations on the materials which can be used in construction, the tunneling methods and procedures used, and record-keeping for many activities. This paper presents the current status of what has been learned, how construction has adapted to meet the requirements, and how the requirements were interpreted in a mitigating way to meet the legal obligations, yet build the tunnel as rapidly as possible. With regard to design methodologies and the realities of tunnel construction, ground support with a shielded Tunnel Boring Machine is discussed. Notable lessons learned include the need for broad design analyses for a wide variety of conditions and how construction procedures affect ground support.

1 PROJECT DESCRIPTION

1.1 Underground excavation

A key part of the Yucca Mountain Site Characterization Project (YMSP) is the Exploratory Studies Facility (ESF). The central feature of the ESF is a 7.6-m-diameter tunnel that is being excavated by a tunnel boring machine (TBM). The purpose of the tunnel is to gain access to the interior of Yucca Mountain in order to determine its suitability to be a repository for nuclear waste. The project is located 160 km northwest of Las Vegas, Nevada, and is situated on the southwest boundary of the Nevada Test Site.

Fig. 1 illustrates the Nevada Test Site ESF tunnel to be driven. Major parts of the tunnel work are as follows. The North Ramp is to be driven at about a 2% downgrade to reach the geologic formation of interest, a subunit of the Topopah Spring Member of the Paintbrush Tuff. A 60-m-long Starter Tunnel for the TBM was constricted by drill and blast in 1993. The main drift crosses, at a fairly flat grade, the Topopah Spring rock unit that would be the eventual repository location. The drive is completed by coming out of the mountain via the South Ramp to a second portal. The whole loop is about 7,800 m in length.

Several alcoves will be constructed for testing purposes and will be done by drill and blast and by mechanical means. Longer exploratory drifts on the order of 100's of m will be driven off the main loop to explore geologic conditions.

1.2 Geologic conditions

Tunneling is through volcanic rocks comprised of welded and nonwelded tuffs. For the initial portion, the North Ramp, the tunnel drive is against fairly flat-lying rock beds that dip 2’ to 15’ to the east. A key part of the project is to determine the character of the remaining faults at depth. One major fault structure near the North Portal, the Bow Ridge Fault, has been tunnelled through and consisted of a graben structure that is filled with substantially weaker tuffaceous material than is expected elsewhere in this tunnel. Soil-like in many ways this material is a very weak, friable rock. Deeper in the mountain, the Drill Hole Wash Fault was expected to be a major geologic structure, but was found to be only a minor structure at tunnel depth. Rock strengths are expected to vary up to 170 MPa. The tunnel is wholly above the static ground water table. For details on geology, see Buesch et al. (1994).
1.3 Tunneling equipment

The TBM with trailing gear was furnished by Construction Tunneling Services (CTS). The specifications for the TBM were provided by the YMP Architect Engineer (A/E) and were performance-based with a major emphasis on minimizing the potential for oil spills. A special feature is the geologic mapping gantry which was retrofitted to the trailing gear after tunneling had been started. This special equipment provides an approximate 55-m-long interval of tunnel for geologic mapping by project scientists. The TBM and trailing gear are shown in Fig. 2.

The TBM designed and built by CTS is a shuffle-shoe machine. This machine has four large grippers that work in sets of two, a horizontal and vertical set. The two sets of grippers "float," i.e., the two shoes of each set are tied together by four gripper cylinders and tied to the cutter head/forward shield with two propel cylinders on each shoe. The grippers are not connected to any framework on the TBM. The two sets of grippers can either be operated independently (shuffle-shoe mode) or in combination (full grip mode). The cutter head is driven by 12 two-speed 186 kW (250 hp) electric motors. Electric motors were specified to reduce hydraulic equipment in the tunnel. The motors are two-speed and are operated at 1800 and 900 rpm. For more details on the TBM, see Morris and Hansmire (1995).
2 TUNNEL DESIGN

2.1 Design approach

A substantial portion of the tunnel design work has been performed in accordance with a program of Nuclear Quality Assurance (NQA-1) design controls and procedures for those design features classified as important to nuclear safety. While nuclear waste will never be handled in the ESF, a program decision was made in the mid-1980's to integrate the ESF with the potential repository. This decision resulted in the requirement for the design of the primary, surface-to-subsurface access openings for the ESF to be consistent with the requirements for repository accesses. The repository will utilize these primary accesses for functions such as waste transport to the subsurface so the location and support of these openings is driven by repository needs.

Key aspects of NQA-1 design, relative to standard commercial design, include rigorous documentation of the design basis for items to be constructed so that a technically qualified person reviewing the design some 10 to 20 years in the future is able to fully understand the basis for conclusions reached by the original designer. Termed "traceability," documentation of the design bases in analyses must fully support construction specification language and drawings in a manner that demonstrates "flowdown" of program level requirements included in regulatory documents to the as-constructed product. The extensive records generated as a result of this process will eventually be used to support applications to the Nuclear Regulatory Commission (NRC) for licenses to construct, operate, and eventually close the repository.

Designs are subject to extensive reviews by all affected program participants, ranging from scientific personnel who will perform site suitability tests in the ESF to construction staff responsible for building it. All comments must be documented and formally resolved prior to issuance of the design. Design changes can be made quickly in the field so long as the change is "bounded" by the appropriate design analysis and is formally documented in accordance with governing procedures. Otherwise, the analysis must be revised, reviewed, and approved in the same manner as the original design before a change can be implemented in the field. The preparation of broad bounding analyses to support construction needs for uncertain geologic conditions represents a significant lesson learned on the project.

Design and construction of the ESF to NQA-1, or "Q" standards have been implemented in two primary areas: 1) tunnel ground support, and 2) control of construction activities that could potentially impair the ability of the site to isolate waste or that could interfere with, or render inconclusive, tests that are to be conducted to determine the suitability of Yucca Mountain as a nuclear waste repository.

Ground support design is conservatively classified Q based on the assumption that a major rockfall could either directly (by breaking open a waste package being transported through the opening) or indirectly (cause a control system failure) contribute to a release of radiation. Waste isolation and test interference controls include a ban on the use of epoxy resin based rockbolting systems and timber lagging for steel sets (the introduction of hydrocarbons is thought to increase the potential for accelerated corrosion of waste packages due to microbial action), as well as limitations on the use of shotcrete or similar materials that could interfere with geological mapping and geochemical tests.

Other waste isolation and test interference controls on construction activities include restrictions on the amount of construction water that can be used, enhanced maintenance requirements and spill cleanup procedures to minimize the amount of oils and other equipment operating fluids that are spilled or leak onto rock surfaces in the tunnel, and a requirement for all construction water used underground to be traced with a marker compound, lithium bromide (LiBr), so that the "introduced" water can be differentiated by project scientists from naturally occurring, in-situ moisture. Similarly, air for scientific drilling is traced with sulfur hexafluoride (SF₆). See Morris and Hansmire (1995) for more discussion of the special limitations on materials.

2.2 ESF ground support design

The intent of the tunnel is to explore geologic conditions. Thus, only minimal ground support or lining is used so that scientific observations are maximized to the degree possible while maintaining a safe work area. The ground support design is flexible and intended to give as much latitude to the tunnel constructor as possible in dealing with as-encountered geologic conditions. Rock reinforcement is the primary design and consists of 3-m-long Swellex™ or Williams™ rock bolts on a 1.5-m pattern for the best ground, and grading to about a 1-n pattern for ground of poorer rock quality. See Fig. 3.
TRAVELING MAPPING GANTRY
CONVEYOR SYSTEM
VENTILATION SYSTEM

FIG. 2
TUNNEL BORING MACHINE WITH TRAILING GEAR

FIG. 3
TYPICAL GROUND SUPPORT DESIGN WITH ROCK REINFORCEMENT
Welded wire fabric and 250-mm channel are used for rockfall protection. The initial design for poorer ground uses 200-mm steel sets (W8 x 31 structural steel members as manufactured in the United States) with steel lagging. A lightweight, 150-mm steel set (W6 x 20) is to be used eventually as an alternative to 200-mm steel sets or rock bolting. See Bonabian (1995) for details regarding ground support of the 7.6-m-diameter tunnel.

2.3 Use of steel sets in ESF

The need to refine the ground support design for highly jointed rock was driven not only by geologic conditions but also by the use of the TBM. The original design assumed that direct ground support (steel sets) would only be needed in conditions of very low rock quality, such as in fault zones or the near soil-like conditions at the Bow Ridge Fault described earlier. It became apparent later that steel sets would better facilitate construction in moderately to extensively fractured geologic conditions where rockbolt reinforcement might have otherwise been appropriate if construction were by drill and blast.

The advantages of the steel set approach under highly jointed rock conditions is illustrated in Figs. 4 and 5. As shown in Fig. 4, steel sets can be safely assembled under cover of the tail shield at the rear of the TBM and subsequently expanded out to the tunnel profile as the shield clears the set location. Lagging or interlocking wire mesh is installed to span the space between the sets situated just inside and just outside of the shield, thereby offering protection from falling rock as the machine advances. This approach facilitates continued, safe TBM advance concurrent with support installation, invert segment installation, rail installation, etc., to the extent that erection of the support and installation of the other materials can keep pace with the rate of advance.

Alternatively, as shown in Fig. 5, a rock bolting approach in similarly jointed ground would have required that the work area under and around the tail shield of the TBM be kept clear of personnel while the machine advanced to preclude injury from rock falling out of the crown as the shield moves forward. This approach would have required that the TBM advance be stopped to complete the installation of each row of rockbolts, any supplemental bolts, and wire mesh. Because of rock dislodged during the bolting cycle, installation of segments and rail would have had to wait until the area was bolted and fallout material had been manually cleared away and placed on the cleanup conveyor. Then installation of the invert segments could have been performed, after which personnel would have been moved out of the tail shield area and boring could resume for another 1.0 to 1.5 meters until clearing the location of the next row of rock bolts. Besides other problems associated with equipment damage that would have been suffered as a result of the rock falling out of the crown area (numerous hydraulic lines and cylinders would have been exposed to falling hazards), this approach would have reduced boring to a cyclical operation, defeating the relatively high production rate potential offered by a properly used TBM. The efficiency of operations would have been severely impacted if a rigorous rock bolting program were attempted in closely jointed ground as depicted on the figures.

3 TUNNEL PROGRESS

3.1 Geologic conditions and tunneling

The ESF design has been long in development and changes during construction are ongoing. This report statuses tunneling aspects as of early November 1995. For the current work under way, final designs for ground support were started in 1993 and were initially issued for construction in 1994. Design refinements have taken place since as described above. The TBM equipment was substantially in place as of August 1994. Tunneling did not start in earnest until the end of 1994, however, as a result of procedural delays. Substantial time and effort was required to get procedures in place, make some equipment modifications, and deal with somewhat difficult tunneling under unusual procedural working conditions. Once started, the tunneling progress has been in roughly four phases described as follows.

The first phase was the initial boring starting at the end of the Starter Tunnel. Tunneling to 200 m into the mountain was difficult because it was necessary to go through moderate to highly jointed rock under low stress. The result was routinely occurring, large fallouts in the crown. Some very large fallouts were encountered and backfilling was required behind the fully lagged lining. In such instances it was not possible to propel the TBM off of the vertical grippers since they must react between one another and the ground to develop a reaction for the propulsion force. There were also TBM steering problems at the start of tunneling which were attributed to the equipment and were subsequently corrected. It was a time of learning for the entire project and the work was done.
FIG. 4 STEEL SET SUPPORT IN HIGHLY FRACTURED GROUND

FIG. 5 ROCK BOLT SUPPORT IN HIGHLY FRACTURED GROUND
with the utmost concern for safety. Progress was slow. Steel sets were installed throughout on 1.22 m centers.

The well documented Bow Ridge Fault was encountered in the second phase and it was located as expected at about 200 total m into the mountain. The fault per se was only meters in length and posed no excavation problems except substantial ground was lost above the machine coming out of the fault—much like what might happen by over excavation in a soft ground tunnel. Backfilling of the void was required. Tunneling with the fundamentally hard rock TBM was possible, however, in the near soil-like conditions. Runs did not occur through the face when no mining was taking place. The soft rock had substantial stand-up time as had been exhibited in a major test trench above the tunnel before construction. The lower parts of the bedded materials were often weak. Steering was sometimes difficult and getting enough reaction to shove the TBM was sometimes difficult if the vertical grippers could not be used. This condition existed for approximately 100 m in length.

In the third phase, a hard rock tunnel section for about the next 100 m was the most difficult to date. Geologic maps identified this as the Imbricate Fault Zone. The imbricate faults are a closely spaced series of nearly parallel and overlapping minor faults oriented in the same direction. Prior to tunneling there was no precedent for what the tunnel conditions might be like. No special ground support, like steel sets, were anticipated. Geologic mapping indicated a series of faults with apparently minor displacement in comparison to the nearby Bow Ridge Fault which had slipped on the order of 100 m. The reality of this was that the rock had through-going joints, the manifestation of the relatively minor rock movements (faults). Under low stress like that encountered at the start of tunneling, block fallouts were common and numerous. The conservative approach was to install steel sets for reasons as discussed earlier in Section 2.3.

Truly good tunnel ground conditions were not encountered until the fourth phase about 1300 m into the mountain. Once beyond the faulted area, rock jointing and overall rock mass quality was considerably higher than for most of the previous tunneling. With the installation of the conveyor in July 1995, the anticipated higher rates of tunnel advance were achieved. Ground support consisted of a minimal pattern of rockbolts with welded wire fabric and channels. Spot bolting was occasionally required. Over 1500 m of tunnel have thus far been excavated with only rockbolt, wire mesh, and channel ground support.

3.2 Tunnel advance

TBM progress as of November 4, 1995 was considered overall very favorable in view of all of the physical and procedural difficulties at the start of tunneling. Achievements are summarized as follows:

- Best 8-hour shift: 23 m
- Best 24-hour day (3 shift operation): 50 m
- Best 5-day week: 149 m
- Total progress: 2,630 m

TBM tunneling has progressed to near the end of the curve as shown in Fig. 2.

As tunneling has continued, three alcoves on the order of 3.7 m by 3.7 m in cross section and from 37 m to 60 m in length have been excavated (see Fig. 2). Alcove 1 was excavated in 1994 by drill and blast in the Starter Tunnel. Alcove 2 was excavated by drill and blast. A few days of TBM downtime was required to turn under and start driving generally a single round a day to minimize impacts on TBM tunneling. Alcoves 3 and 4 were excavated with an Alpine Miner AM 50 road header in softer, nonwelded tuff. They were excavated after the subsurface conveyor was installed and little to no interference to TBM tunneling was required. Plans are being made to excavate a test area for conducting thermomechanical test in situ and an exploration drift to Ghost Dance Fault (see Fig. 2).

As of this writing, plans are uncertain for the extent of underground mining that will take place. TBM tunneling will continue to respond to site characterization requirements that are currently in evolution. More drifts are expected to be excavated from the TBM tunnel for geologic and testing purposes. Excavation in the Calico Hills formation, the formation below the potential repository horizon, is also being considered to verify and to increase knowledge of the geologic conditions in the Calico Hills tuff obtained through surface-based investigations. A shaft on the order of 400 m deep and suitable for rapid sinking and development is envisioned.

4.0 CONCLUSIONS

The final design of the ESF was started in early 1992, only a short time before beginning construction on the portal pad started in November 1992.
Considering that this project constitutes one of the first large-scale applications of an NQA-1 design control approach for final design and construction of a major underground facility, the learning curve has remained nearly vertical in an effort to provide cost-effective, just-in-time design that does not overly constrain construction. One key to making this happen has been the development of broader ranging analytical design bases that not only provide the design solution presented in construction specifications and drawings, but go beyond the specified approach to bound other scenarios that could present themselves as construction proceeds. The results are positive in that substantial progress has been made while meeting many special requirements.

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REFERENCES
