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Deep Tunnels in Poor Rock Conditions and High Water Head; How Much Can We Ask of TBM Technology?

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1.0 INTRODUCTION

The CPA Project is a major water conveyance and treatment system that is planned to augment deliveries of potable water to Metropolitan's "Central Pool" service area, and to western Riverside County, California. A primary goal for the CPA Project is to provide needed system capacity to meet long-term treated water demands. Additional benefits of the project include increased regional system flexibility and strengthened system reliability. The approved CPA Environmental Impact Report (EIR) identified the following program components:

- A new water treatment plant at Metropolitan's Eagle Valley property near Lake Mathews
- A 2 km long tunnel from Lake Mathews to Eagle Valley
- A 9 km long pipeline within the City of Corona
- An 18 km long tunnel, beneath the Cleveland National Forest
- A 4 km pipeline within the City of Irvine.

Conceptual design features of the 18 km long "Santa Ana Mountains" Tunnel include: an approximate 3.0 to 3.7 meters finished diameter; 0.3 to 1.0% overall slope (slope may be varied to optimize constructability); near watertight primary lining designed to external hydrostatic pressure of 300 to 400 meters; and a water-tight final lining. In July 2004, Metropolitan's Board authorized staff to re-evaluate the feasibility of the project, and specifically the Santa Ana Mountains tunnel. As a result, additional geotechnical investigations were undertaken to further investigate groundwater pressure along the tunnel alignment and the potential of restrictive groundwater inflow constraints during construction of the tunnel. The investigations included the drilling of two deep borings (750 meters and 700 meters) to reach the approximate tunnel depth, field and laboratory testing, and installation of observation wells.

2.0 PRELIMINARY GEOLOGIC CHARACTERIZATION

An alignment map and simplified interpretation of the tunnel geology is shown on Figure 1. As shown, it is anticipated that the Santa Ana Mountains Tunnel would encounter the following approximate distribution of geologic units (east to west) : 10 km Bedford Canyon Formation (Jbc); 1 km Santiago Peak Volcanics (Kvsp); and 7 km Tertiary and Cretaceous (weak) sedimentary rocks (T/K).

2.1 Ground Characteristics - Hard Rocks

Available data suggest that the Bedford Canyon Formation (Jbc) is typically thinly bedded, locally contorted, and highly fractured. Below the upper, more highly weathered zone, the Bedford Canyon Formation is expected to have very low hydraulic conductivity, however, localized sheared/faulted zones may exhibit higher conductivity. Intact rock pieces are expected to range in compressive strength from around 10 MPa to perhaps over 150 MPa. Accordingly, this ground is anticipated to range from "very blocky and seamy" to "crushed" [1]. Rock mass classification

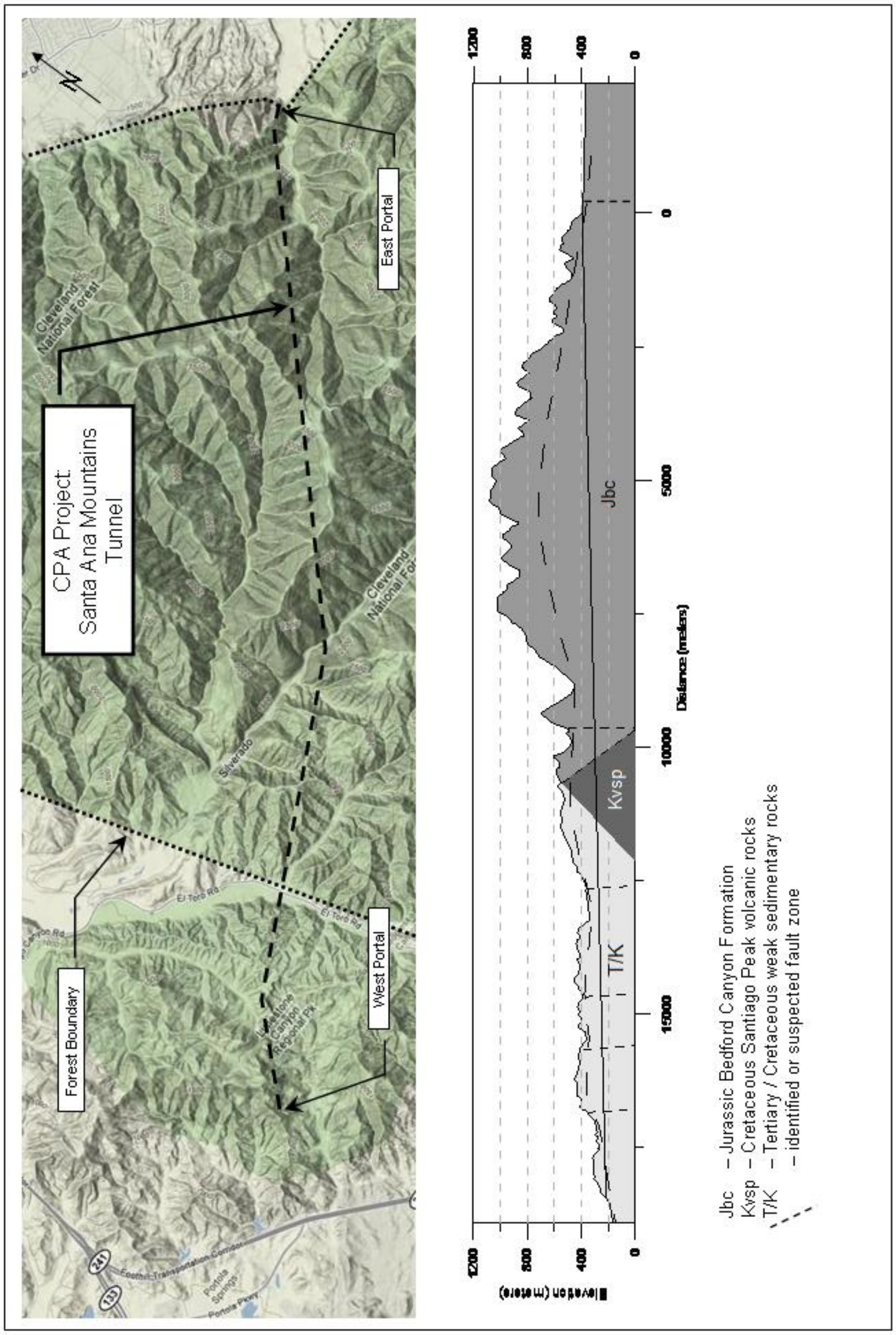

Figure 1
CPA Santa Ana Mountains Tunnel Alignment Map And Simplified Tunnel Profile

schemes indicate the Bedford Canyon Formation would typically be classified as “poor” to “very poor ground” in the RMR system [2], and “extremely poor ground” in the Q System [3]. Outside of fault zones, GSI [4] values may be in the range of 30 to 40. It is anticipated that, based on ground cover and hydrostatic head, the Bedford Canyon Formation will tend to exhibit raveling behavior, with block falls or rock mass shear failures. Where ground cover is high, this material will likely exhibit squeezing behavior or significant convergence due to stress redistribution. Locally, at sheared zones, which appear to be common, severe squeezing may occur. As a result, the excavation method (i.e. a shielded TBM) will need to incorporate positive measures to control overbreak from the face and crown. In addition, the TBM will need to have adequate shove force to overcome squeezing ground.

The Santiago Peak Volcanics (Kvsp) are anticipated to be typically thickly bedded to massive, and much less fractured than the Bedford Canyon Formation. The rock strength is anticipated to be significantly stronger. Therefore, the ground is expected to be dominantly “blocky and seamy”, with typical ground behavior ranging from “stable” to “local block falls”. The potential for water inflows is anticipated to be higher in the volcanics (as compared to the Bedford Canyon Formation), therefore pre-excavation grouting (as needed to control inflows) is likely to have more benefit. Pre-drainage can be considered, but might require substantial flows to obtain a significant benefit.

2.2 Ground Characteristics - Weak Rocks

The Cretaceous and Tertiary sedimentary rocks (T/K) consist largely of silty sandstones with strengths ranging from a few MPa to about 20 MPa, and are expected to be easy to excavate with a TBM, and have adequate stand-up time for the installation of primary support. The ground is anticipated to exhibit “firm” behavior for the most part, possibly with some “slabbing” in formations that are more well-bedded. There is a potential for local flowing ground within zones of crushed rock, at fault zones, and within sedimentary layers with low fines content. Based on the interpreted conditions, tunnel advance rates within weak rock can be significantly higher than in the hard rocks. Some difficulty may occur at fault zones, but such zones are not anticipated to be common. Recent experience on Metropolitan’s Riverside Badlands Tunnel illustrates the potential for high advance rates (on the order of 60 m/day) in similar soft rock formations. On the Badlands Tunnel, it was not uncommon to achieve 300 meters of advance in a week. However, it is noted that the Badlands Tunnel was supported with expanded precast concrete segments that were neither bolted or gasketed. At this time, it is not envisioned that the Santa Ana Mountains tunnel would use expanded segments, but the potential for their use could be further evaluated during design studies. It is likely that the use of expanded segments (i.e. which do not control seepage into the tunnel), would depend on the potential for developing adverse effects to local groundwater resources.

2.3 Fault / Shear Zones

Very weak sheared rock and fault gouge (with significant clay content) indicates a high potential for squeezing at many locations along the 18-km long Santa Ana Mountains tunnel. Some of these locations will coincide with faults and lineaments that have been mapped at the surface. Additional faults/shears should be expected to occur at locations that cannot be predicted from surface mapping or exploration drilling. The tunnel boring machine (TBM) will need to be configured to handle this type of ground, and construction practices will need to be adjusted to avoid getting the TBM stuck. Locally, it may be possible to reinforce weak, raveling ground, by pre-excavation grouting ahead of the machine. However, the success of such efforts will depend on the characteristics of the ground (i.e. the feasibility of grout penetration into the ground) under the ground and groundwater pressures present. Pre-drainage ahead of the TBM is another option that may be useful.

2.4 Groundwater Inflows

Low inflows are generally anticipated within the Bedford Canyon Formation, based on the results from three deep borings. Fault / shear zones are a potential exception to this, and they may yield high flows. Probe drilling ahead of the tunnel seems a likely requirement to identify such zones before they are encountered in the tunnel. Inflow rates are anticipated to be higher within the Santiago Peak Volcanics. With some exceptions, inflows are anticipated to be minor within the weak sedimentary formations, because most of these weak rocks have moderate to low primary permeability and little fracture permeability. However, local conglomerate units may have relatively high primary permeability and thus are a possible source of heavy inflows. Therefore, probing and pre-excavation grouting may be required to control water, at least locally, in the weak rock formations. It is assumed that the tunnel would be mined from two headings, and therefore the expected low inflows from the Bedford Canyon Formation would be a positive factor for the (downhill) tunnel drive from the east end. Inflows to the tunnel driven from the west may be higher, but would be easier to handle because that heading would be mined uphill.

2.5 Potential for Gas

A potentially significant issue that requires further investigation is the potential for hazardous gas. It is anticipated that most of the sedimentary (soft) rocks present will not contain hazardous gas. However, local coal beds are reported, and shale units could be gassy. In addition, it appears likely that the Bedford Canyon Formation will contain some hydrogen sulfide gas. Design phase investigations would address this issue though a detailed investigation program.

3.0 TUNNEL LININGS

It is anticipated that a relatively low groundwater inflow criteria will be imposed during the excavation and support of the Santa Ana Mountains tunnel, and that the final tunnel lining will need to be watertight to groundwater inflows. These criteria restrict the types of compatible tunnel liners that might be used. Similar inflow criteria were imposed on the tunnel lining system designed and utilized for the Arrowhead Tunnels Project in Southern California. This lining system proved successful with respect to watertightness and constructability, and is currently believed to be the most feasible type of lining system for the Santa Ana Mountains Tunnel.

For the Arrowhead project, the primary lining was constructed during the TBM excavation phase and was composed of bolted and gasketed, pre-cast reinforced concrete segments. This primary lining was designed for ground loads, temporary construction hydrostatic heads and anticipated TBM thrust loads. Measurements of seepage and groundwater pressure following tunnel excavation indicate the primary liner has an overall equivalent porous-medium hydraulic conductivity on the order of 10^{-8} cm/s. This relatively watertight initial lining was generally less permeable than the surrounding rock mass. The annulus between the ground and the primary liner was backfilled with an initial phase of cement grout to provide structural confinement to the segments. A second phase of backfill grouting was used to fill voids, and aid in sealing the annulus from water flows toward the tunnel face. The concrete segments had an internal diameter of 4.5 meters and were about 330 mm thick. The segments had a minimum 28 day compressive strengths of 6,000 or 8,000 psi, depending on the external groundwater pressure.

The final lining for the Arrowhead Tunnels is watertight. In lower head areas, the final lining was steel pipe, whereas in areas of high external head, the final liner was a reinforced concrete cylinder pipe (RCCP). The steel cylinder on the outside of each pipe section was welded to an adjacent section of pipe to form a continuous, impermeable seal against groundwater intrusion. The annulus between the primary liner and the final liner was backfilled with cellular cement grout for the RCCP and standard backfill grout for the steel lining. The internal diameter of the final lining is about 3.5 meters. The final liner is designed to carry the full external groundwater pressure without relying on the segmental lining.

3.1 Groundwater Pressures

For the Santa Ana Mountains tunnel, the groundwater pressure on the tunnel lining system constitutes the largest design load. Based on current information, the maximum groundwater pressure along the Santa Ana Mountains Tunnel alignment would exceed current tunnel lining technology for a watertight tunnel. This will necessitate testing and evaluations (beyond that which was performed for the Arrowhead Tunnels), to develop a lining that is applicable to the CPA project. The selection of a hydrostatic design criterion for the primary lining can recognize that, during tunnel excavation and prior to the installation of the final liner, the groundwater levels are temporarily lowered by tunnel drainage resulting from heading inflows and small, localized leaks through the primary liner. Therefore, the primary lining may not be subjected to the maximum pre-construction groundwater pressure. The maximum pre-construction pressure at Arrowhead was about 335 meters, but the segments were designed for a head of 275 m. The actual maximum head measured on the Arrowhead segments during construction was less than 185 meters, due to less than full groundwater recovery, which is not likely to occur until after the final lining is installed and backfilled. The groundwater head on the segments for the Santa Ana Mountains tunnel will also be lower than the pre-construction conditions for the same reasons. A detailed study of the potential drawdown of the groundwater level for the CPA tunnel has not been made, but based on the Arrowhead experience it is assumed that the groundwater head on the segments will be on the order of 300 to 400 meters. After the excavation is complete and the final liner is installed, groundwater inflow into the tunnel will be halted and the groundwater will recover to pre-mining levels.

3.2 Primary Lining

The precast concrete segment design for CPA can be adjusted for higher groundwater levels by increasing the concrete strength and steel reinforcement. The maximum structural capacity required for the Santa Ana Mountains tunnel segments can be achieved by increasing the minimum concrete compressive strength to about 9,000 psi or greater. Similar to the Arrowhead segments, reserve capacity should be maintained to resist exceptional TBM thrusts, since cracking of the segments can allow groundwater seepage. At this time, it appears likely that the thickness of the CPA segments could be limited to 330 mm so as to avoid them being unwieldy in a tunnel of this diameter. Although the tunnel diameter could be increased to make thicker segments easier to handle, increasing the tunnel diameter is not desirable because it would increase excavation and final lining costs. Because currently there is no prior experience with bolted and gasketed precast concrete segments subject to the magnitude of groundwater pressure present on the CPA project, the design will need to be verified through a testing program carried out during the design phase (similar to that which was performed to confirm design assumptions for the Arrowhead project). The testing program should verify the structural design of the concrete segments, watertightness of the gaskets and compatibility of the compressed gasket to the edge strength of the segment. It may also be necessary to work with proprietors to develop a gasket that will meet the demands of the design.

3.3 Final Lining

To optimize the final lining design, several classes of RCCP can be used for different levels of groundwater head. The highest class of RCCP will need to carry approximately 450 meters of groundwater head, which is about 120 meters higher than what was designed for on the Arrowhead Tunnels project. This class of RCCP will require a concrete compressive strength exceeding 7,000 psi and steel reinforcement modified from the Arrowhead RCCP. If possible, the RCCP lining cross-sectional thickness should not be increased. Doing so would increase section weight, handling costs and significantly increase manufacturing costs. A composite lining composed of the RCCP with a structural backfill outside of the RCCP to enhance its structural performance may be considered for areas of the tunnel with the highest head, which is limited to the area beneath the high ridge of the mountains. Welded steel pipe (WSP) is not considered a viable final lining option for the highest head reaches of the tunnel, because of manufacturing and constructability concerns. Under the highest head conditions (i.e. over about 250 meters), the steel pipe thickness would need to be in excess of 5 centimeters, and this presents difficulties in manufacturing the steel pipe and welding the joints in the field. WSP would be considered for areas of low head (less than about 150 meters), such as the portals and the western portion of the project (under the foothills) where groundwater heads are much lower.

4.0 CONSTRUCTION CONSIDERATIONS

4.1 Tunnel Excavation

Mechanized excavation of the tunnel with a TBM is required for the installation of a bolted and gasketed concrete segmental lining, which appears to be the most appropriate primary liner type for the Santa Ana Mountains tunnel. The use of a TBM is often cost effective for driving tunnels of this length, due to the high advance rates than can be achieved relative to conventional methods. Given the length of the Santa Ana Mountains tunnel, more than one tunnel heading should be considered, to reduce the construction schedule and overall project costs. There is also the risk of major TBM maintenance (requiring several months for repairs) associated with an 18 km tunnel drive. Dividing the tunnel into two 9 km tunnel drives would significantly reduce this risk. For the CPA project, the efficiency of the TBM will be dependent primarily on its compatibility with handling groundwater inflows and variable ground conditions. The broader the ground conditions and the more frequently they change, the slower the overall TBM progress rate will be.

4.2 TBM Capabilities for Water and Muck Handling

The current state-of-the-art rock TBM capable of handling large volumes of water inflow is a hybrid TBM with a slurry/hard rock combined muck handling system. Primarily the TBM operates in "open mode" in a similar fashion to a shielded rock TBM with muck belt conveyance. The combined muck and water are separated by an initial coarse slurry separation plant on the TBM trailing gear. The remaining water is pumped out of the tunnel through slurry lines for final separation. The coarse muck is hauled out of the tunnel in muck cars or by conveyor. When it is necessary to seal out high groundwater inflows the TBM can be operated in "closed mode". The current state-of-the-art for a slurry TBM of the required diameter is likely about 6 to 8 bars of pressure at the head, while operating in closed mode, and 10 bars when the TBM is not in operation. Maximum "closed mode" operating and static pressures are increasing in response to unique project needs, and a slurry TBM is being designed and fabricated that can operate at approximately 12 to 17 bars, although perhaps for limited time periods. In closed mode, the TBM is designed to completely handle the muck within the slurry system and break down the rock within a rock crusher, to sizes that can be pumped. Typically the TBM advancement rate, operating in closed mode, is significantly less than in open mode. These TBM's typically are costing $14 to 18 million (USD) for in-tunnel equipment and $2 to 3 million (USD) for outside tunnel muck/slurry handling equipment.

Slurry TBM technology is the principal means for water collection and conveyance from the tunnel heading. The water handling system needs to be able to move water from the cutterhead to the back of the TBM, away from the segmental ring build area. It is imperative that water inflows do not intrude on the ring build area to allow the ring to be assembled quickly and ensure that the gaskets are clean. Gaskets contaminated with soil or mud will not seal properly and will result in increased tunnel leakage. The water handling system must be able to deal with sudden in rushes of water (flush flows) and allow the TBM to mine efficiently with inflows of upwards of 150 lpm into the cutterhead area. Slurry systems can be effective provided that the rock is not highly abrasive. Abrasive conditions can wear the slurry system quickly, resulting in frequent downtime and repairs on exposed surfaces. However, the rock types along the Santa Ana Mountains tunnel are not expected to be highly abrasive. Within the last 10 years, TBM technology has increased significantly and future advances will enhance the constructability of the CPA project, and possibly reduce current cost estimates.

4.3 TBM Design for Anticipated Ground Conditions

A broad range of ground conditions may be encountered in the tunnel alignment. However, a given TBM will generally perform optimally in a relatively narrow range of ground conditions. If the rock is very strong, the TBM may be designed for efficient mining of the strong rock, but will be less effective in mining poor quality rock. The opposite can also be true. For the CPA project, the best performance may be achieved by tailoring the TBM to address the intensely fractured rock conditions which are currently estimated to comprise nearly 60 percent of the alignment. For these conditions, a shielded TBM is critital. Rock conditions are much too weak and variable for side grippers to be effective, so a main beam is probably not feasible.

Intensely fractured or highly altered rock will contribute to adverse ground behavior, such as crown, wall, and face instability with limited standup time, flowing or raveling ground, and squeezing ground. The difficulties of these ground behaviors can be compounded by the operational characteristics of the TBM. For instance, weak or highly altered rock can be broken down to a fine material during excavation. If this material is not efficiently removed from the TBM head by the mucking system, the finer materials can accumulate around the TBM shield and will pack on the outside of the TBM. This occurrence typically results in difficulty in steering the TBM, increased TBM thrusts, and possible entrapment of the TBM, causing significant delay and reduced TBM efficiency. If ground treatment (such as pre-excavation grouting) is deemed necessary to mitigate the instability of weak ground or muck packing around the shield, TBM efficiency is reduced even further. Avoiding this requires a TBM cutterhead designed to control face stability and raveling/caving conditions. To overcome these challenging ground conditions and behaviors, the following will be key issues to be considered for TBM design:

- The TBM should be capable of operating in both open and closed modes. The machine should be designed for maximum closed mode pressure at the time the project is bid.

- The muck handling should be compatible with high water inflows and weak ground, and be able to efficiently collect the material under all conditions, and remove it from the tunnel without impacting the ring build area.

- The TBM should have high thrust and torque capacity to overcome high ground loads (perhaps from squeezing) or muck packing conditions, and free the cutterhead if it becomes jammed by unstable ground.

- The TBM shield should be configured to minimize the effects of ground and material interaction on the TBM operations. This would include minimizing the shield length, using a tapered shield, having the ability to place lubricants outside of the shield, and having the ability to flush out material from the annulus back toward the cutterhead.

- A closed-face cutterhead should be provided to control the ground at the tunnel face when the TBM is operated in open mode.

- The TBM should be able to maintain line and grade in variable ground including weak ground and in curves, and control roll using a bi-directional cutterhead.

The anticipated ground conditions, and the TBM characteristics for handling such ground conditions, are significant challenges. The Arrowhead TBMs partially addressed these issues, but improvements are needed to increase advance rates and reduce the instances of the TBM getting stuck. An advantage for the CPA project is that the current project schedule provides the tunneling industry with time to research and test TBM designs for handling difficult ground and groundwater conditions.

4.4 Probe Hole Drilling and Pre-Excavation Grouting

Because of the variable ground conditions, the systematic advancement of probe holes ahead of the tunnel face will likely be required to look for inflows that could exceed the water handling capability of the TBM under normal operation. Probe holes would also be used to detect areas of weak, unstable (potentially squeezing) ground. In some instances, pre-treatment of the ground through temporary drainage and pre-excavation grouting may be needed to address the potential for unfavorable inflows and ground conditions. However, to reduce costly delays when such conditions are found in the probe holes, it is preferable that the TBM operations first be modified to be more compatible with the anticipated water inflows or ground behavior, such as operating the TBM in “closed” or “pressurized” mode. Only when the conditions are likely to exceed the capability of the TBM in its modified operation, should pre-treatment of the ground be attempted. The goal of pre-treatment should be to reduce the potential inflows and/or ground instability to levels that can be managed by the TBM in its modified operation. Drain holes can be particularly helpful in this respect. In addition to reducing the driving head, which may destabilize a weak rock mass, and draining compartmentalized groundwater, drain holes can also be used to reduce high hydrostatic pressures within the TBM cutterhead when it is operated in “closed” mode.

5.0 CONCLUSIONS

As discussed above, the CPA project presents significant design and construction challenges, some of which will require research and testing to determine new methods to meet the challenges that are beyond the current state-of-the-art, in particular:

- Squeezing ground conditions may occur in significant portions of the highly fractured Bedford Canyon Formation, and especially within fault/shear zones

- The permitting requirements (required by the U.S. Forest Service) for water inflow will likely be stringent

However, with recent advances in technology and a project schedule that provides the tunneling industry with time , it appears that the challenges presented in constructing the CPA project can be met. Therefore, the feasibility studies concluded that there appear to be no insurmountable impediments to tunnel constructability.

6.0 REFERENCES

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