VALUE ENGINEERING THE CONSTRUCTION OF LONG TUNNELS IN THE DOLOMITES OF NOTHERN ILLINOIS, UNITED STATES OF AMERICA

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ABSTRACT: Fermi National Accelerator Laboratory (Fermilab), a high-energy physics laboratory operated by the Universities Research Association for the US Department of Energy, is developing plans for the construction of accelerator tunnels.
The accelerator designs vary as a function of particles accelerated, technologies used and energies targeted. However, all accelerators require the excavation of long tunnels, up to 700 km in length, and tunnel costs represent a major portion of project budgets. This paper documents the findings of two studies undertaken to identify tunnel cost-drivers and outlines steps taken to initiate the "value engineering" of the tunnels.

1 INTRODUCTION

Since the demise of the Superconducting Super Collider project in the early 90s, the high-energy physics community has started developing plans for a new generation of particle accelerators. Multi-billion dollar accelerator projects on the drawing board include the Energy Tripler, the Very Large Hadron Collider and the Next Linear Collider (Holmes, 2000). Up to one third of the total cost of these projects is budgeted for the construction of the underground facilities. The cost of tunnel will have a major bearing on the overall viability of the accelerators, and supporters of these projects have been actively promoting the development of low-cost tunneling options. Early ideas fo lowering costs were based on the use of automated directional drilling and micro-tunneling technologies. The small-diameter, pipeline facility or "Pipetron" created by the application of these technologies was estimated to cost less than one third of the cost of a conventional tunnel housing (Friant et al., 1996). However, these pipeline ideas are beyond the state-of-the-art, and a baseline design, compatible with Today's Technology, was needed against which objective comparisons could be made and design decisions taken.

Having no in-house expertise in either tunnel design or construction, Fermilab enlisted the help of industry partners, Kenny Construction, and The Robbins Company (TRC) to help develop such a baseline. Kenny Construction was tasked to establish a state-of-the-industry cost estimate, consistent with the use of conventional tunneling technology and local construction practice. TRC was tasked to review the Contractor's tunnel driving methods and means and identify cost-reduction measures.

2 ESTABLISHING THE TUNNEL COST

To develop a cost estimate, Kenny Construction, an experienced local contractor, was given a contract scope for the construction of the Energy Tripler Facility, sited at depth in a dolomitic limestone (dolostone), and asked to deliver a detailed cost estimate (Lach et al. 1998).

2.1 Defining the Scope of the Underground Facility

The main criteria for the Energy Tripler are summarized in Table 1. The contract was scoped for delivery of a sub-horizontal, flat-floored, dry, stable tunnel aligned and sized to accommodate the installation and operation of an accelerator.

Table 1: Scope-of-Work for the Energy Tripler Underground Facilities

Item	Physicist-Required	Contractor-Preferred
Installation Shaft Diameter (No.4)	6.0 m	6.0 m
Egress Shaft Diameter (No.20)	None Required	1.8 m
Accelerator - Tunnel Length	34 km	
Injection Line - Tunnel Length	5.5 km (~90% Rock & ~10% Soil)	
Accelerator/Injection Tunnel Diameter	3.0 m	3.7 m
Accelerator/Injection Tunnel Floor	2.1 m	2.1 m
Allowable Water Inflow	125 l/min/km	
Completion Milestones	None Specified	

Distinction is made in the table between what the accelerator physicist required and what the Contractor preferred to build. The Contractor preferred to enlarge the diameter of the tunnel and added egress shafts. The tunnel diameter was enlarged to reduce constraints on in-tunnel work and accommodate a greater alignment tolerance during

excavation. Egress shafts were added to allow for the evacuation of the underground works in case of emergency. The water inflow criteria were set, in agreement with the Contractor, as being those achievable using normal cement-grouting techniques.
The injection line tunnels were inclined upward from the accelerator plane on a 4 per cent grade to pass through the overlying rock strata and glacial tills, and connect with an existing accelerator. The Contractor selected a common cross-section for both the accelerator and injection line tunnels.
The scope of the contract work did not include the excavation of any auxiliary openings, needed to house electrical and experimental equipment or off-site haulage of spoil. No time constraint was placed on the delivery of the facility. The Contractor was simply asked to organize and schedule the work to be performed cost-effectively.

2.2 Describing the Host Rock Mass

The host rock unit selected for housing the accelerator tunnel is the Galena-Platteville, the same unit that was proposed by Illinois for the siting the Superconducting Super Collider Project (Bauer and Gross, 96). The dolostone unit is between 100 and 120 meters in thickness. The intact rock is of intermediate strength, ranging from 80 to 120 MPa in uniaxial compressive strength, and is non-abrasive. Joint sets in the unit are sub-vertical, orthogonal and widely spaced. Bedding is generally less than one metre in thickness. In excavations, the rock mass is observed to be dry to moist. Based on site investigation work conducted for the Illinois Proposal for the Superconducting Super Collider, the Rock Mass Rating (Bieniawski, 1979) ranged from 72 to 87, corresponding to rankings of "good" to "very good" (Bauer et al., 1991). The rock mass is uniform across the region and it is conducive to excavation by both disc cutter and explosives.

2.3 Analyzing the Cost Estimate

To excavate the rock tunnel the Contractor elected to use two, new state-of-the-industry TBM-systems. Each system comprised a 3.7-m open Robbins TBM mounted with 432-mm diameter cutters. Muck evacuation was provided by a system of horizontal and vertical conveyors. Rock dowels were used for ground support. Grout and invert concrete work was performed after the TBM-drives had been completed.
The Contractor was not asked to include costs for items such as site investigation, land acquisition, design and construction management or identify any cost contingencies. The contract value was estimated at $167.5M . This cost included $30M profit and $24.9M in indirect costs. Indirect costs were associated with the administrative, managerial and financial elements of the project. The direct costs for the execution of work was $112.4M. Over 90% of the direct costs were associated with the construction of TBM tunnel in dolostone.
The distribution of direct costs for the accelerator tunnel excavation is shown in the pie chart in Figure 1. Grout and invert concrete costs are not included.

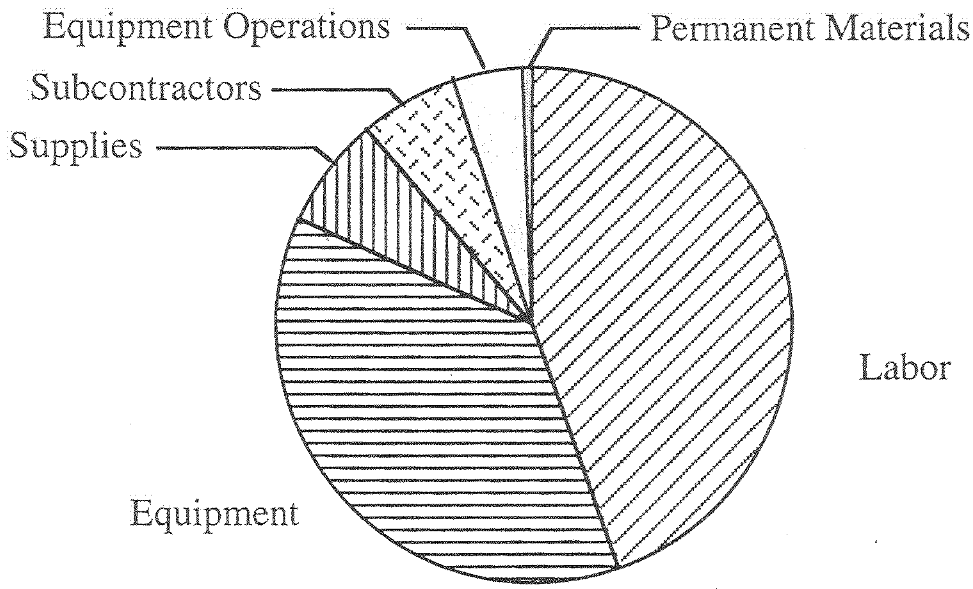

Figure 1: Distribution of Direct Costs for the Accelerator Tunnel

From the figure it can be seen that labor and equipment costs make-up over 80% of the total cost of excavating the tunnel. The relatively small contribution made by the other four factors reflects the stable and non-abrasive nature of the rock mass being mined.

3 REDUCING THE COST OF THE EXCAVATED TUNNEL

Although several key tunnel design criteria need further definition, it is already apparent that the viability of these accelerator projects will be enhanced if the cost of tunnel excavation can be reduced. Based on this fact, Fermilab sponsored TRC to review the Contractor's proposed TBM-system and identify modifications or operational improvements that could be made to reduce the costs. Additionally, TRC was asked to comment on equipment costs and identify areas of research and development that they though might lead to reduction in tunneling costs in the future.

3.1 Modifying the Contractor's System

Based on a review of the Contractor's estimate, TRC identified several sub-system modifications that could be made to improve productivity and reduce the direct and indirect costs of construction. The predicted performance impacts of these modifications, in Penetration Rate – Utilization space, are shown in Figure 2 as a series of system upgrades.

Upgrade 1 improved the cutterhead Penetration Rate through the use of a state-of-the-art, high power machine. The net result of this upgrade was to increase Penetration Rate from 6 to 10 meters per hour, by increasing the penetration per revolution, and the speed of cutterhead rotation. In estimating the net gain in Advance Rate, the positive influence of the upgrade on Penetration Rate was partially offset by a reduction in Utilization, due to the increased percentage of wait time, accumulated between thrust cylinder strokes.

Upgrade 2 increased Utilization by eliminating the between-stroke stoppages through the incorporation of double thrust cylinders and continuous conveyors.
Upgrade 3 increased Utilization by improving the reliability of critical sub-systems through the adoption of monitoring and preventive maintenance programs. TRC's aim here was to increase the Time Between Failure and reduce the Time To Repair parameters of operation by monitoring critical sub-systems and identifying pre-cursors of failure. If a sub-system malfunction is identified before failure, preventative maintenance or replacement can be planned and undertaken during scheduled maintenance periods, a common practice in the mining industry (Bleazard et al). Such systems have already been installed on both new and secondhand TBM-systems (Lach et al, 2001).

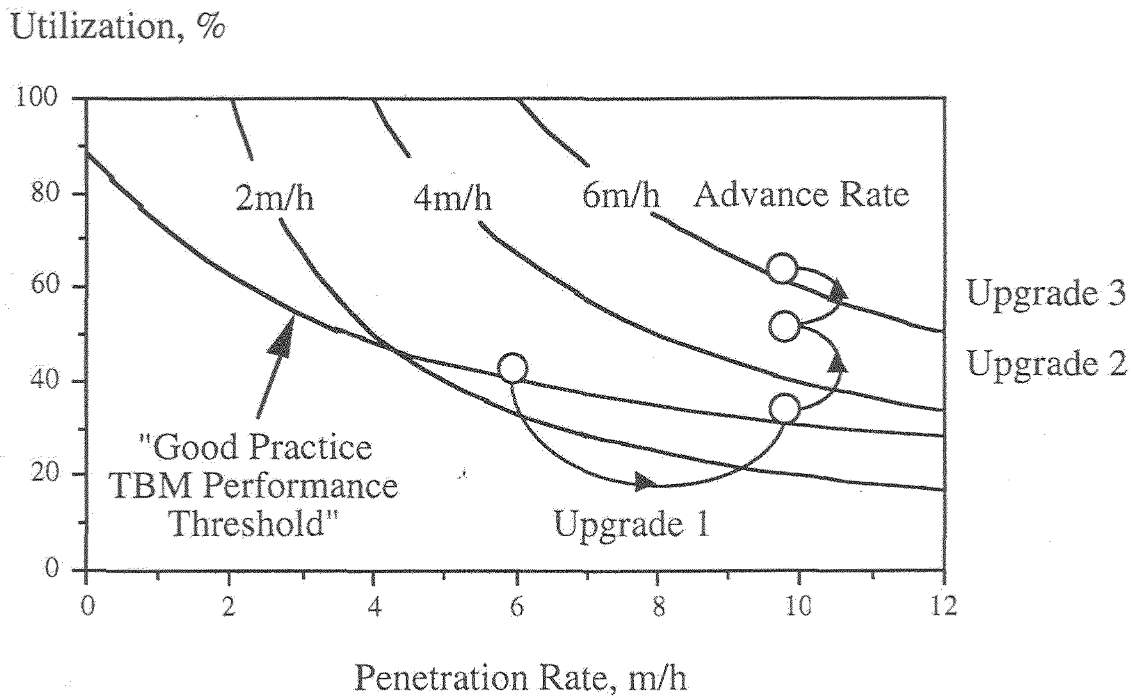

Figure 2: TBM-System Upgrades - Improvements in Performance

The potential for improving the overall TBM-system performance can be gauged through reference to the Advance Rate contours and the good practice threshold plotted on the graph. The performance anticipated by the Contractor, before upgrade 1, is slightly above the upper operating threshold observed in industry for a TBM-system operating in a stable rock mass (Laughton, 1998). At this threshold, the TBM-system is not unduly delayed by either support installation ("support –bound") or spoil evacuation ("muck-bound"). TRC project that the state-of-the-industry performance can be more than doubled, to over 6 m/h, by implementing their recommendations. Increasing the advance rate would proportionally reduce the direct labor costs and other time-dependent cost elements.

TRC also noted that the Contractor's TBM crew size was more than double that used for comparable operations in other regions of the world, such as Scandinavia. TRC recommended reductions in crew size through the adoption of multi-tasking work plans and through the automation of tasks such as track-laying, utility extension, equipment monitoring and rock support installation.

3.2 Designing and Contracting Strategies for Low Cost Tunnel Excavation

The improved monitoring and maintenance described in Upgrade 3 would not only lead to improvements in the Utilization of the TBM-system but would also enhance equipment longevity. An increase in longevity would allow the system to be used to mine longer tunnels and lead to a reduction in amortization rates per unit length of tunnel mined. A reduction in unit amortization could be achieved by intelligent planning of the contract(s) scopes and timing. Were a refurbished TBM-system used instead of a new system, equipment amortization costs could be reduced by as much as 50% (Peach, 1988). The possibility of secondhand equipment being used on any given contract would be further enhanced if acceptable design options were identified during the tender period. Adding flexibility to the design, as tendered for bid, would enhance the bidding contractors' ability to explore lower cost solutions based on the use of owned equipment and minimize the need for any costly equipment modifications or purchases. These strategies were successfully employed on the Texas site of the Superconducting Super Collider (Laughton, 1989).

3.3 Implementing The Robbins Company Recommendations

The tunneling industry is relatively conservative in its use of new technology. Underground innovation is a high-stakes gamble that can only be justified when the probability of success is high and/or the benefits of success are substantial. An attraction of the equipment upgrades, suggested by TRC, is that their adoption does not introduce a high degree of "performance uncertainty" into the total system. The upgrades represent an evolution in the capabilities of the existing system, and should be readily managed by a competent mining contractor familiar with TBM operations.
The impact of the upgrades on TBM-system performance and costs will vary considerably from site to site, and the system's designer will need to evaluate, in detail, specific rock mass and operational criteria. In particular, the Utilization improvements projected by TRC, in Upgrades 2 and 3 will only be forthcoming if the total system, including logistics, mucking and support operations, can keep pace with the elevated levels of Penetration Rate, predicted by TRC.
Reductions, and ultimately the elimination, of labor from the tunneling process are to be anticipated in the future. Multi-tasking is already being undertaken in some parts of world, primarily in the excavation of stable rock masses, where focus is on the logistics and organization of equipment at the heading rather than the support and treatment of rock. The remote operation of mining equipment is already being practiced at some

mines, with operators capable of controlling multiple pieces of equipment from the comfort and safety of a home office. Fully automated rock tunnel operations are also being envisaged. Focus here is currently on the development of intelligent drill-and-blast operating units that will be capable of working in the harsh underground mining environment without any need for human intervention (Cohen and Hervé, 1998).

4.0 CONCLUSIONS

In the near-term, there appear to be several viable options for reducing the costs of accelerator tunnels in the homogeneous dolostone that underlie the Fermilab region. In the paper, productivity improvements are identified that could more than halve both direct labor and equipment costs. Successful integration of these recommendations into the tunneling operation could result in costs being reduced by a factor of two. Future progress in remote and automated operation could further enhance this cost reduction factor.

It is readily acknowledged that few tunnel equipment innovations have proven successful. However, the upgrades of the existing system proposed here are relatively low-risk, low-cost ventures that could provide a high return on investment. Responsibility for implementing the upgrades should lie with those with the most relevant experience and qualification: the contractors and equipment manufacturers.

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