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Systems and Cost Analysis for a Nuclear Subterrene Tunneling Machine

A Preliminary Study

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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J. H. Altseimer

Work supported in part by a grant from the National Science Foundation, Research Applied to National Needs (RANN).

SYSTEMS & COST ANALYSIS FOR A NUCLEAR SUBTERRENE TUNNELING MACHINE

- A PRELIMINARY STUDY -

by

J. H. Altseimer

ABSTRACT

The basic system components of large rock-melting Nuclear Subterrene Tunneling Machines (NSTMs) have been conceptualized and defined for a preliminary tunneling cost estimate and comparison with costs using tunnel-boring machines (TBMs) and other conventional tunneling techniques. Two initial types of NSTMs are considered: Type I, peripheral kerf-melting penetrators plus centrally located rotary cutters for soft ground and rock; and Type II, kerf-melting penetrators plus multiple, hot rock-fracturing penetrators for very hard rock. Tunneling costs for NSTMs are very close to those for TBMs, if operating conditions for TBMs are favorable. However, for variable formations and unfavorable conditions such as soft, wet, bouldery ground or very hard rock, the NSTMs are far more effective. Estimates of cost and percentage use of NSTMs to satisfy U.S. transportation tunnel demands indicate a potential cost savings of 850 million dollars (1969 dollars) through 1990. An estimated NSTM prototype demonstration program cost of $100 million over an eight-year period results in a favorable benefit-to-cost ratio of 8.5. The NSTM systems are characterized by large capital costs compared to conventional TBMs. However, many higher-cost items and components are expected to have long service lives and will be used for more than one tunnel project instead of writing off the tunneler after each project as in current TBM practice. The cost of thermal energy for rock melting is not a large percentage of the total project cost.

I. INTRODUCTION

A. Study Objectives

The general study objective, considering the present early stage of Subterrene concept development, was to establish a clear indication of the cost effectiveness of Nuclear Subterrene Tunneling Machines (NSTMs) as applied to national demands for large tunnels. To achieve the above, three specific objectives were established: first, to develop technically sound conceptual designs; second, to make a cost comparison with the conceptual NSTMs on the one hand and tunneling with Tunnel Boring Machines (TBMs) and conventional excavation methods, on the other; and third, to determine the benefit-to-cost ratio for a projected major Subterrene development program costing $\sim \$100 \times 10^6$ over an eight-year period.

B. Subterrene Program Background

The need for innovative approaches to the solution of major problems in excavation and tunneling technology has been summarized in recent publications by the Underground Construction Research Council and the National Academy of Sciences.[1,2] A research and development program in excavation technology, based on rock-melting, is being conducted at the Los Alamos Scientific Laboratory (LASL).[3,4] In addition to identifying many potential applications, this program has indicated that the Subterrene concept can offer, through an integrated tunneling system, solutions to the multiple problems in the three important areas of conventional tunneling technology:

- Forming the hole.

- Maintaining wall integrity and forming a primary support.
- Removing the debris.

The program has also indicated that the rate of penetration in varying geological formations can be predicted and is relatively insensitive to the material being melted.[5] In addition, the input power requirements for small-diameter, electrically heated Subterrene devices are easily handled with conventional equipment, as has been substantiated by LASL laboratory and field tests.[6] A recent study of current tunneling systems and economics indicated the areas in which a Subterrene system could significantly contribute to advancing the tunneling and excavation technology.[7] The study also contains an extensive and selected bibliography and should be considered as complementing this report.

While electric heating appears to be quite practical for small Subterrene devices, a nuclear-powered subsystem was assumed to be most feasible for the sizes considered in this report. A detailed technical and cost-tradeoff study to establish crossover points between electric and nuclear systems has yet to be conducted, but indications are that a demand of ~ 10 MW (electric) may be the level above which practical considerations of power supply and distribution become unattractive for an electrically heated system. This demand is in the approximate power-level range needed for the smallest tunnel considered in this report. A cost advantage of the nuclear subsystem is offered by the fact that thermal energy is applied directly to the rock and that the circuitous procedure of an electric system can be avoided in which thermal energy is generated, converted to electricity (at an efficiency of ≈ 30%), and then converted back to thermal energy at the rock-melting penetrator bits. Another advantage is that the nuclear subsystem can make the tunneling system almost completely self-sufficient, minimizing external expenses such as large specially installed power lines to the tunnel portal. Other characteristics that make a nuclear subsystem feasible are: (1) compactness, i.e., reactor diameters of 1 to 2 m, thus fitting into even a small 4-m tunneling machine; (2) lack of rotating or moving components except control rods or drums; (3) low containment pressures due to the use of heat pipes to transfer heat out of the reactor core; and, (4) sufficiently long component operational lifetimes to be useful for this application.

The chemical generation of heat has been considered in a report by Hanold.[7] It was found to be unattractive for various operational and environmental reasons and therefore was not considered for this study.

C. General System Assumptions

A circular tunnel cross section was assumed for convenience in calculating power requirements and to facilitate the comparison with TBMs which are, of necessity, circular. No economic advantage was taken from the fact that NSTMs can form noncircular cross sections, which could minimize the excavation volume and automatically incorporate features such as utility line gangways or partially finished roadway surfaces.

The finished tunnel diameters* studied ranged from 4.0 m (~ 13 ft) upward. The minimum diameter of 4.0 m was chosen because the required melting power (≈ 7 MW) appears high enough for economical use of nuclear devices and because the envelope is clearly large enough for their accommodation at this stage of development. No maximum-diameter limitations for NSTMs have yet been established. Any such limitations would probably result from practical considerations external to the NSTM equipment. Such a constraint might result from excessive tunnel support requirements due to large structural span dimensions.

Two basic NSTM design concepts were considered in this preliminary study. Both were chosen because they appear to be logical progressions from existing technology incorporating the new nuclear Subterrene designs, and both require only partial melting of the working face. (Applications in which the excavation face is almost or completely melted will be examined at a later date as well as many other conceivable design variations.) The two concepts considered are illustrated in Figs. 1 and 2. The conceptual designs are:

- Type I--uses a peripheral kerf penetrator to form the tunnel wall, whereas the main excavation face is removed by mechanical rotary cutters. This device is intended for use in softer formations.

*Throughout this report the finished tunnel diameter refers to the inner diameter of the completed tunnel, including final support lining.

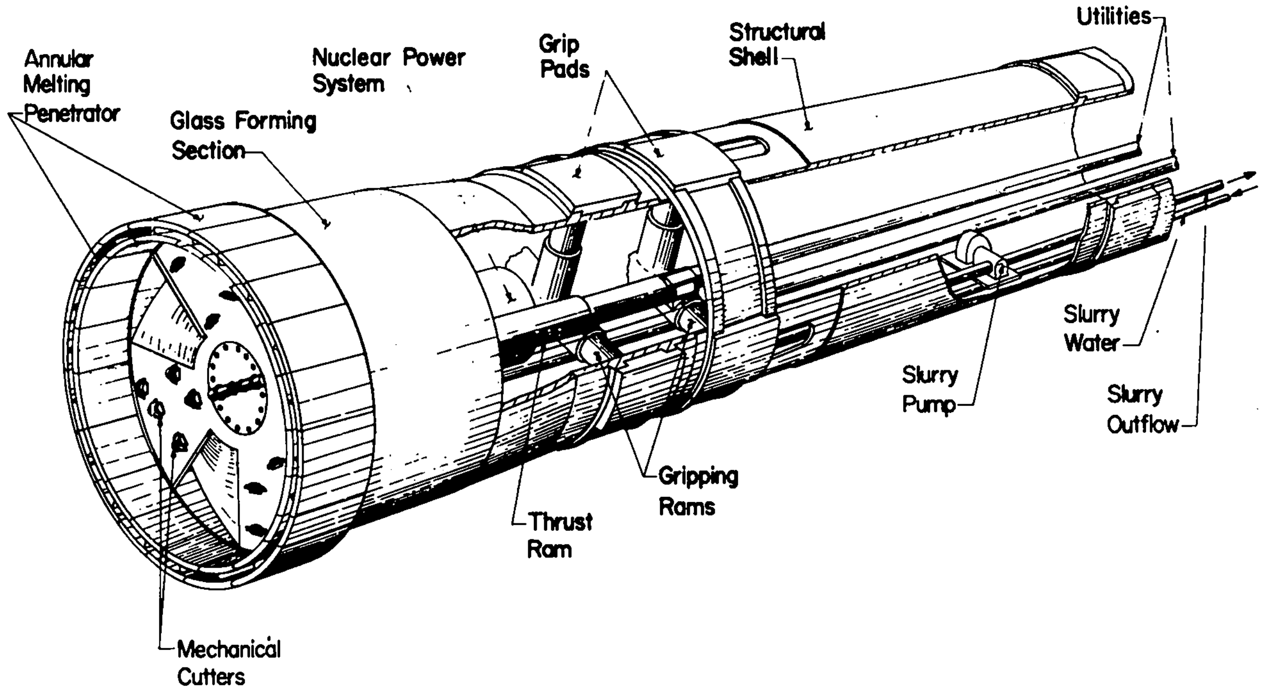

Fig. 1. Conceptual design of Type-I NSTM with peripheral kerf-melting penetrator and mechanical central-face cutter.

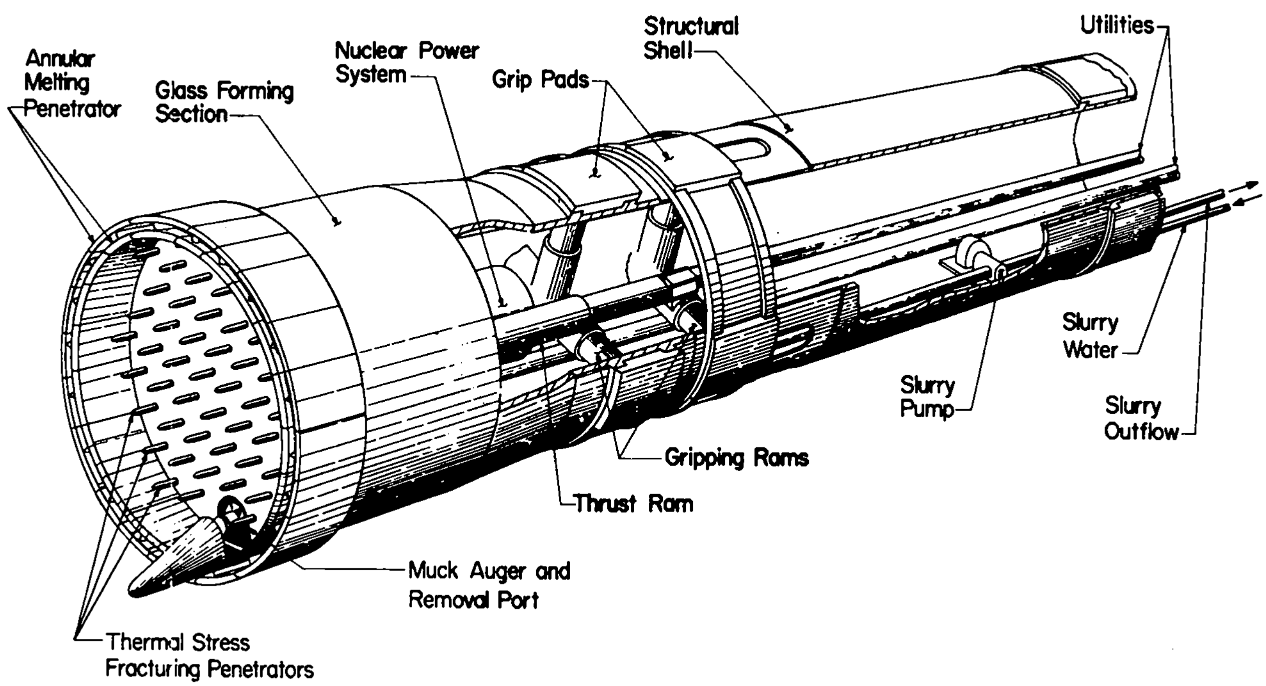

Fig. 2. Conceptual design of Type-II NSTM with peripheral kerf-melting penetrator and central-face thermal fracturing penetrators.

- Type II--uses a similar kerf-melting device, but the rotary cutters are replaced by an array of hot penetrators which thermally crack and fragment the rock at the working face. This concept is applicable to very hard rock.

The important advantages in soft-ground tunneling of the Type-I NSTM concept have been emphasized by Hanold.[7] The potential ability of the peripheral kerf melter to continuously seal, stabilize, and support the soil of the tunnel wall immediately behind the NSTM as the tunnel hole is formed is a major breakthrough in tunneling technology. However, the kerf-melting penetrator designs are not limited to the annular, extended-surface types illustrated; this is discussed later in the text.

D. Future Study Plans

The NSTM design and economic models, and cost evaluations, will be expanded and refined as experimental data and firmer design data become available. The General Research Corp. computer program[8] for estimating excavation costs is being acquired and is expected to be especially useful for obtaining TBM and conventional costs. To provide an increasingly realistic NSTM cost model, more information will be required in the fields of rock-glass liner formation and structural characteristics; reactor design; nuclear fuel; heat pipes; heat-distribution losses; component lifetimes and reliabilities; tunnel advance rates; assembly, maintenance, and diassembly cycles; and the ability of the NSTM to accommodate wide geological variations. Tradeoff studies will be made between important parameters in the excavation, materials handling, and support operations; and labor, equipment, and materials cost estimates will be refined. Excavation demand information will be updated as data from a broader base become available from a projected U.S. tunneling-demand survey by the National Academy of Sciences - National Academy of Engineering.[9]

II. DESCRIPTION OF NSTM SYSTEM ANALYZED

A. Summary of Assumptions and Subsystem Choices

The following is a brief list of assumptions and subsystems that were chosen to facilitate the preliminary cost analysis for large-diameter tunnel construction projects using the two conceptual types of NSTMs shown in Figs. 1 and 2:

- The NSTMs are peripheral kerf-melting types.
- NSTM tunneling costs are compared to costs accrued by using TBMs and conventional methods only, for both rock and soft ground. Cut-and-cover and immersed-tube methods were not considered.
- Tunnel sizes studied range from about 4-to 12-m finished diameter.
- Tunnel cross-section configurations for the NSTM are not restricted. However, for calculational convenience, circular cross sections are used.
- The NSTM average operational sustained advance rate is 0.423 mm/s = 1.5 m/h, which is equal to 36.5 m/day (≈ 120 ft/day ≈ 5 ft/h).
- Thermal energy for rock melting is obtained from a nuclear reactor system installed in the NSTM.
- Liquid-metal heat pipes are used to transfer heat from the reactor core to a heat reservoir and then to the rock-melting penetrators.
- The NSTM-generated glass tunnel liner is strong enough to eliminate the need for any other form of temporary support. The liner thickness is 4% of the finished tunnel diameter (~ 0.5 in. per foot of tunnel diameter) for unfavorable conditions and is 2% of finished tunnel diameter for very hard rock (e.g., basalt).
- The permanent tunnel liner consists of the glass plus a usual concrete liner, with overall thickness equaling 8% of the tunnel diameter for all earth and rock conditions.
- Because the temporary glass liner is a structurally sound tunnel support there is no need for rapidly installing a permanent liner. Therefore, the tunnel contractor is free to either choose the most economical liner schedule or to employ an innovative continuous concrete liner process such as the Extruded Liner System described by Parker and Semple of the University of Illinois.[10]
- The rock-melt glass liner, reactor containment structure, cutter drive motor, tunnel air, etc., are water-cooled.

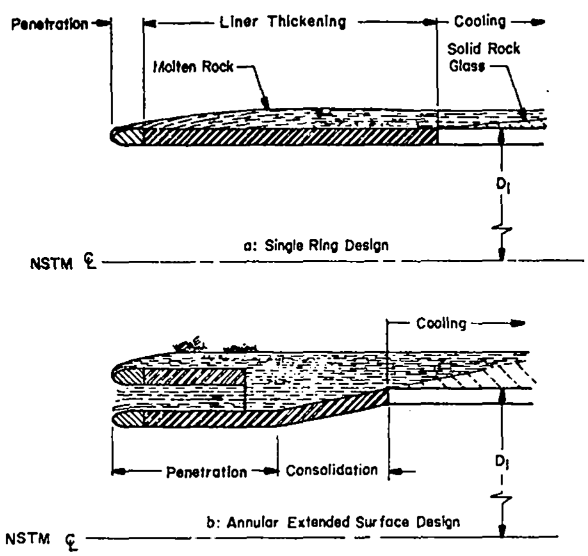

Fig. 3. Two types of kerf-melting penetrator designs.

- Closed-loop cooling-water circuits are used, with filtering and cooling accomplished at the tunnel portal.
- Electric power for other than rock-melting use is generated at the portal utilizing heat scavenged from the cooling water.
- The excavation face is sealed by a peripheral seal and a face structural diaphragm.
- Muck removal is by the hydraulic-slurry method using muck lines which penetrate the face diaphragm.
- Utility lines are continuously extended to accommodate NSTM advance by means of a trailing-line extender assembly.
- A manned control center is located in the tunnel as a component at the aft end of the NSTM.

B. Technical Description of Major Subsystems and Their Operation

1. Kerf Penetrator

Two types of kerf penetrator bit subsystems could be considered, as illustrated in Fig. 3. The single-ring penetrator, Fig. 3a, is (1) structurally simple, (2) requires a long, trailing kerf-melting section to develop a thick kerf liner, and (3) is most applicable in very sound rock requiring only a thin peripheral liner. The characteristics of the annular, extended-surface arrangement, Fig. 3b, are: (1) heat flow to the outside wall can be minimized to just allow the machine to move through rock at the desired rate, (2) heat flow can be maximized to the annular space where heat losses to surrounding rock can be minimized, and (3) the extended heat-transfer surfaces result in a higher permissible advance rate when thick liners are being considered. The annular, extended-surface type was chosen for calculating power requirements for this report. Both kerf-penetrator system designs need further detailed study and other design concepts will undoubtedly emerge as the technology develops.

2. Nuclear Subsystem and Power Requirements

The nuclear subsystem will be completely sealed and will include heavy biological radiation shielding and a massive, armored shell. Heat will be transferred through the shielding and armor by heat pipes into a heat-distribution reservoir. Control rods will be actuated by water-cooled electric actuators. The reactor will operate at relatively low internal core pressure and the shielding, containment, and armor walls will be protected by water-cooling. The nuclear subsystem will be replaceable, if necessary, in case of a malfunction. Fuel life is estimated at 9000 h while the remainder of the system will have at least a lifetime of 90000 h.

To obtain an estimate of thermal power requirements, the thermal properties of typical tuff and basalt materials[11] were used with the following properties, conditions, nomenclature, and units:

	Symbol	Tuff	Basalt
Rock density, kg/m^3	ρ_i	1400	2800
Rock glass density, kg/m^3	ρ_g	2600	2800
Specific heat, J/kg K	c	1000	1000
Heat of fusion, J/kg	ΔH_L	418×10^3	418×10^3
Melting temperature, K	T_m	≈ 1470	≈ 1420
In-situ temperature, K	T_i	290	290
Average melt temperature, K	T_{avg}	1570	1570

Tunnel finished inside diameter	D, m
Glass liner inside diameter	D_i, m
Glass liner outside diameter	D_o, m
Glass liner thickness	$t_\ell = \frac{(D_o - D_i)}{2}$, m

Average advance rate	V, m/s
Glass liner cross sectional area	A_g, m^2
Useful heat flow rate into the rock	$\dot{E}_{use}$, MW
Total reactor thermal power	$\dot{E}_{total}$, MW

The glass lining thickness needed to provide safe temporary support is a function of the specific project. Considerations of liner thickness may include such variables as overburden pressure, type of ground, water flow, geologic consistency, and tendency to swell. Due to these imponderables, tunnel designers have used empirical rules that are apparently conservative enough to have withstood the test of time. According to one such rule, the permanent concrete lining should have a thickness of 80 mm/m (1 in./ft) of tunnel diameter.[12] For a temporary liner thickness, using glass, it was assumed for this study that a thickness equal to ~ 40 mm/m of tunnel diameter (0.5 in./ft ≅ 0.04 x D) would be adequate in unfavorable ground and that 20 mm/m of diameter (0.25 in./ft ≅ 0.02 x D) would apply for favorable RQD conditions.* Then, using (0.04 x D) as the lining thickness, the diameter and glass liner cross-sectional area relationships applicable to soft rock or ground are:

$$D_o = D + 2\ (0.08\ D)$$

$$D_i = D + 2\ (0.04\ D)$$

$$A_g = \frac{\pi}{4}\ (D_o{}^2 - D_i{}^2) = 0.1407\ D^2.$$

Solving for $\dot{E}_{use}$, the power required is:

$$\dot{E}_{use} = A_g\ V\ \rho_g\ C\ (T_{avg} - T_i) + A_g\ \rho_g\ \Delta H_L$$

and, using the tuff properties previously defined,

$$\dot{E}_{use} = 620\ D^2\ V,\ MJ/s \equiv MW.$$

The various losses of thermal power which could occur around the peripheral kerf penetrator bits were estimated and are shown in Fig. 4, itemized in Table I, and further illustrated in Fig. 5a. Then, including losses equal to 40%, the thermal total power source required is:

*The RQD (Rock Quality Designation) is a rating scale of rock quality introduced by D. U. Deere[13] and is based on specific geologic factors as observed during analysis of core samples.

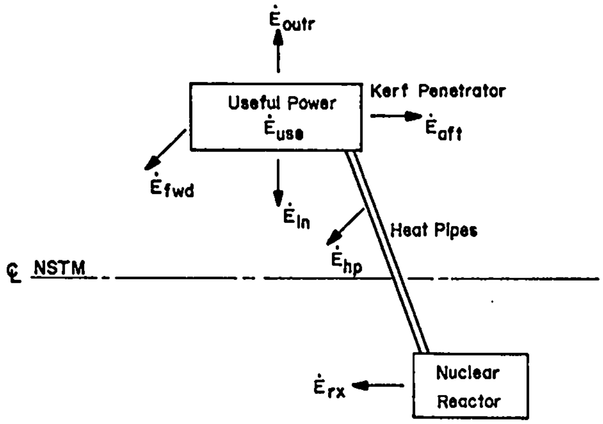

Fig. 4. Schematic of heat fluxes related to penetrator, heat pipes, and reactor subsystems.

$$\dot{E}_{total} = \frac{\dot{E}_{use}}{0.6}\ D^2\ V = 1030 \times D^2\ V,\ MW.$$

The above power requirement is shown graphically in Fig. 6 for an advance rate V = 0.423 mm/s (5 ft/h). This advance rate is equal to that already achieved during small-scale penetration tests.[6] The goal of the current Subterrene project is a target advance rate for the NSTM of 1.0 mm/s (11.8 ft/h = 283 ft/day).

The loss to the surrounding rock around the penetrator (Table I) is estimated to be 20% of $\dot{E}_{total}$. As will be shown later, another 21% will be lost to the rock during the glass liner cooling process, making a total of 41% of $\dot{E}_{total}$. This radial dissipation of power will not heat the rock to any

TABLE I

ESTIMATED PERIPHERAL KERF-MELTING PENETRATOR SYSTEM AND REACTOR HEAT LOSSES

Heat Loss Contribution	Symbol	Estimated Fraction of Total Reactor Power
Loss forward and inward into rock face	$\dot{E}_{fwd}$	0.01
Radial outward heat-flow loss into surrounding rock	$\dot{E}_{outr}$	0.20
Loss aft into cooler machine structure	$\dot{E}_{aft}$	0.10
Loss radially inward	$\dot{E}_{in}$	0.01
Loss from heat pipes	$\dot{E}_{hp}$	0.04
Losses to reactor containment	$\dot{E}_{rx}$	0.04
	Total Fraction of Losses	0.40

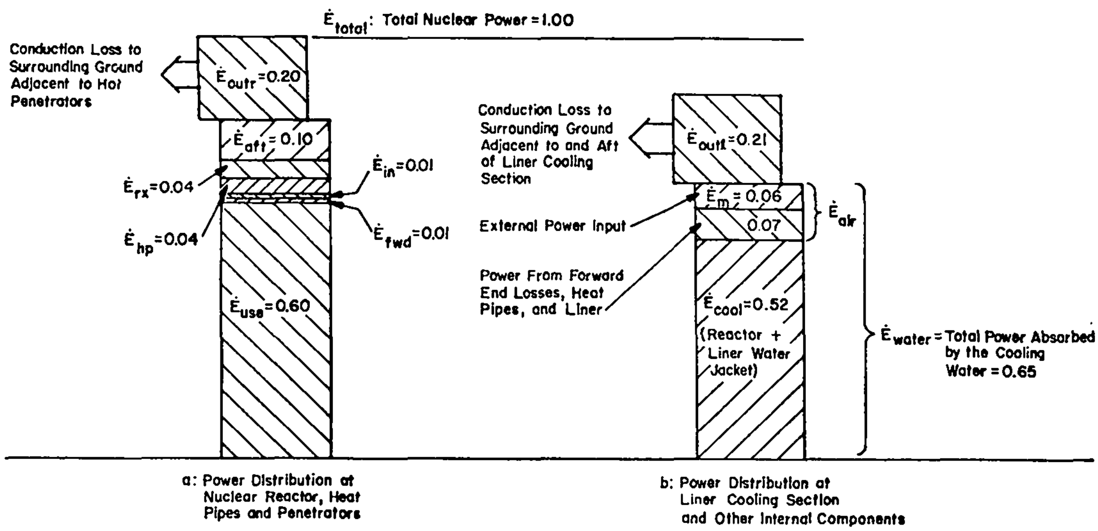

Fig. 5. Power distribution for a Type-I NSTM.

significant distance from the tunnel-liner outside diameter. To illustrate this point, consider the case of a 7.3-m tunnel in tuff with a reactor power output of 23.4 MW. The energy dissipated to the rock could be stored in a 1-m-thick annulus outside the tunnel liner, with the 1470-K rock-melting temperature at the inner radius and the 290-K rock in-situ temperature at the outer radius. In basalt, the above annular thickness would only be 0.5 m.

3. Face Removal

a. Type-I NSTM

The Type-I NSTM concept (see Fig. 1) uses a rotary cutter assembly to remove the face soil and rock inside the melted peripheral kerf. The rotary design is assumed to be similar to the cutters now being used in TBMs. However, the effectiveness and useful life of the cutter assembly in the NSTM is expected to be better than in a TBM. Carstens[14] has pointed out the generally accepted fact that the outside gage cutters, in comparison to the interior cutters, account for the greatest share of the total cutter cost, ranging from 30 to 60%. In the NSTM, the usual gage cutters and their problems will be eliminated completely, the peripheral rock being taken care of by the kerf-melting penetrators. In competent rock the kerf penetrator aids the cutters in two other ways. First, the rock in the peripheral area of the rotary cutter head is thermally spalled and cracked by the kerf penetrator. Second, this rock is subject to some heating and hence some lessening of strength. In loose soils a rotary head suitable for such strata will be used, operating in the significantly advantageous situation of a stabilized tunnel bore provided by the NSTM with its continuously formed glass lining.

The cutter drive motor will be located aft of the face-seal structural diaphragm and thus will be in a favorably clean environment. If necessary, the motor can be cooled by a line branching off of the main water-cooling system. Suitable entryways for

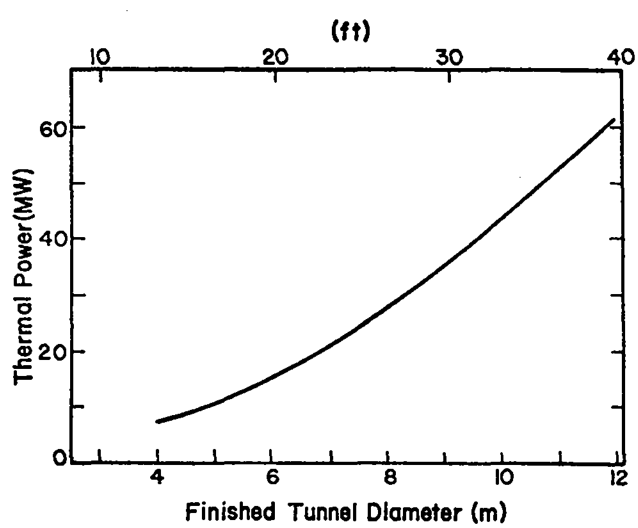

Fig. 6. Reactor thermal power vs finished tunnel diameter.

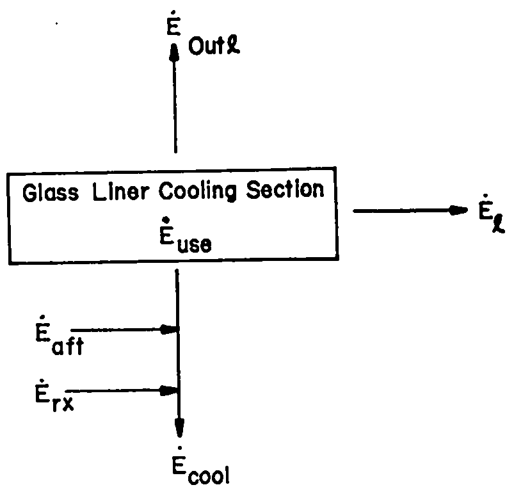

Fig. 7. Schematic of heat fluxes related to glass liner cooling section.

cutter removal or changes and general maintenance must be provided in the face seal structure.

b. Type-II NSTM

The Type-II concept (shown in Fig. 2) substitutes an array of spike-like rock-melting penetrators for the rotary cutters of the Type-I assembly. The Type-II concept is applicable to very hard rock, the rock being fragmented by thermal-stress fracturing. This design, while theoretically sound, still contains many yet-to-be resolved parameter optimizations, such as penetrator spacing, power, size of each penetrator, and adaptability to geologic variations.

The total rock penetration and fragmentation power for the Type-II NSTM, is assumed equal to that of a Type-I machine (see Fig. 6). Type-II in basalt and with a liner thickness equal to 0.02 D, requires a useful liner power, $\dot{E}_{use}$, equal to 0.55 $\dot{E}_{use}$ of Type-I in tuff. The remaining 0.45 power fraction is used for the spike penetrator bits and redistributed heat losses in the Type-II machine.

4. Glass Liner Cooling

The glass liner will be cooled in two ways. Liner heat will be dissipated radially outward into the surrounding rock and will also flow radially inward into the liner water-cooling system. The structural characteristics of the liner will be determined by the cooling process, from average rock-melt temperatures to about 900 K. If the NSTM were completely automated, high wall temperatures might be permissible at the aft end of the machine. However, water could be used to cool the wall down to about 305 K (90° F). Local refrigeration and cool air circulation systems installed inside the NSTM could provide adequate working conditions. Final wall-cooling could be accomplished by a water-cooled air circulation system as explained later. Considering only the heat absorbed by the water flowing through the reactor and the liner coolant jacket, $\dot{E}_{cool}$, five heat flows are involved, shown schematically in Fig. 7. Three, $\dot{E}_{use}$, $\dot{E}_{aft}$, and $\dot{E}_{rx}$, were defined previously and are equal to 0.60, 0.10, and 0.04 of $\dot{E}_{total}$, respectively. The other two heat flows are: $\dot{E}_{out\ell}$, the heat flow radially outward into the surrounding rock, and $\dot{E}_{\ell}$, which is residual heat in the glass liner after the liner water-cooling section has moved on. The quantities $\dot{E}_{out\ell}$ and $\dot{E}_{\ell}$ are estimated to be 0.21 $\dot{E}_{total}$ and 0.01 $\dot{E}_{total}$, respectively. Then, the water heat load from the liner and reactor is,

$$\dot{E}_{cool} = \dot{E}_{use} + \dot{E}_{aft} + \dot{E}_{rx} - \dot{E}_{out\ell} - \dot{E}_{\ell}$$

$$= (0.60 + 0.10 + 0.04 - 0.21 - 0.01)\ \dot{E}_{total}$$

$$= 0.52\ \dot{E}_{total}.$$

5. Air Cooling and Circulation

The air cooling and circulation subsystem is shown schematically in Fig. 8. This subsystem will cool the wall to a final low temperature by flowing air in direct contact with the wall. The air will also absorb heat generated in the forward sections of the NSTM, e.g., at the cutter drive motor or muck machinery and will provide for a reasonably low temperature inside the NSTM for personnel. The circulating air can be replenished as necessary by means of an air utility line from the portal. The circulating air, kept in motion by an electric-motor drive fan, is continuously cooled in a water-cooled heat exchanger.

6. Total Water Heat Load

It is estimated that the various machines within the NSTM generate a thermal power load, $\dot{E}_m$, equivalent to 0.06 $\dot{E}_{total}$. This amount -- added to estimated values for $\dot{E}_{fwd}$, $\dot{E}_{hp}$, $\dot{E}_{in}$, and $\dot{E}_{\ell}$ (the heat in the liner absorbed by the circulating air) --

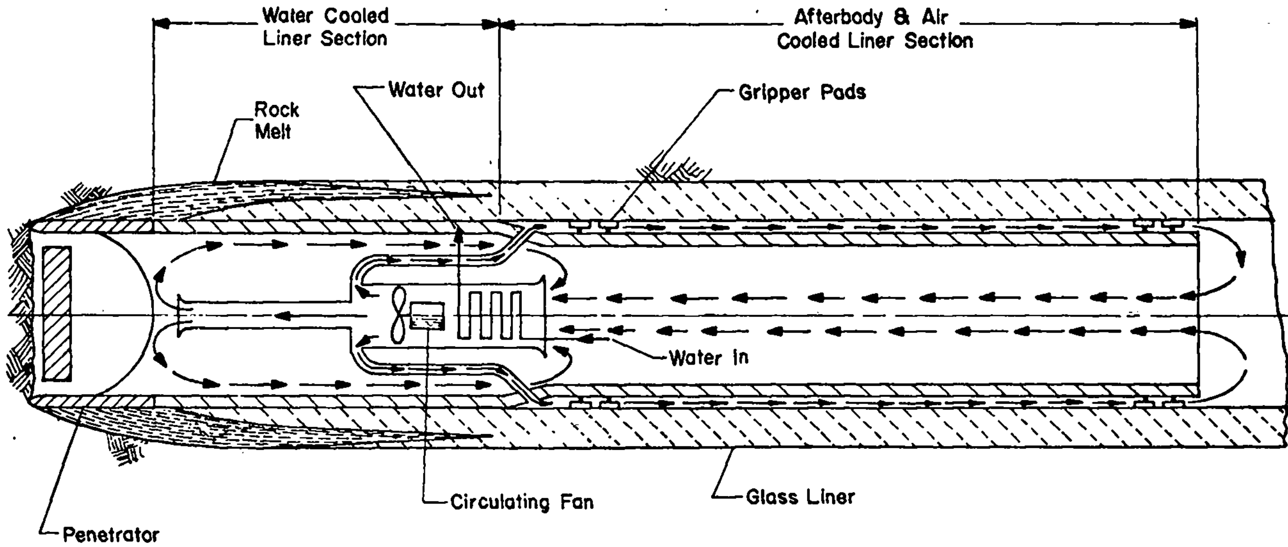

Fig. 8. Schematic of air cooling and circulation subsystems.

equals the total heat load absorbed by the cooling water in the air-circulating system and is called $\dot{E}_{air}$ (see Fig. 5b for an illustration of the above power distributions).

Then,

$$\dot{E}_{air} = \dot{E}_m + \dot{E}_{fwd} + \dot{E}_{hp} + \dot{E}_{in} + \dot{E}_\ell$$
$$= (0.06 + 0.01 + 0.04 + 0.01 + 0.01)\dot{E}_{total}$$
$$= 0.13\ \dot{E}_{total};$$

and, the total heat load into the cooling water is:

$$\dot{E}_{water} = \dot{E}_{cool} + \dot{E}_{air}$$
$$= (0.52 + 0.13)\ \dot{E}_{total}$$
$$= 0.65\ \dot{E}_{total}.$$

7. Hydraulic Slurry Muck Removal

Complementary to the water systems used for cooling the glass liner and the NSTM equipment, is the hydraulic slurry muck removal system. It is assumed that part of the cooling water can be diverted to fluidize the muck. In very favorable circumstances the resultant water outflow from the tunnel might be discarded and fresh water pumped in. However, for cost purposes, it is assumed that closed circuits are needed with only some makeup water supplied as necessary. At the portal, portable dry-cooling towers will reduce the water temperature to a level adequate for recycling. The water will also be filtered and cleansed before reuse. Some water-cooling circuits will be isolated from the muck-contaminated circuit to avoid fouling certain critical coolant-flow passages.

8. Portal Power Subsystem

As noted in Section II-B-6, above, the cooling water returning to the portal carries heat equivalent to about 65% of the reactor heat release. Most of this heat will be dissipated through the cooling towers emplaced at the portal. However, it is also assumed that a portal power subsystem (PPS), extracting energy from the cooling water, will generate the electricity needed for NSTM components other than the penetrators. This power will be obtained with an organic Rankine-cycle power system because of the relatively low water temperatures available. Power generation and water cooling can be done, e.g., with subsystems illustrated in Fig. 9.

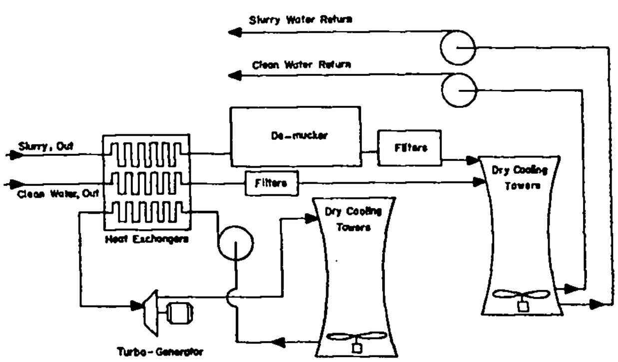

Fig. 9. Schematic of portal power and cooling subsystems.

Thus, except for startup, shutdown, emergency, and other miscellaneous power requirements, most of the NSTM operation could be approximately sustained solely by the nuclear reactor power.

9. Sealed Excavation Face

The NSTM system with its close fit around the kerf penetrators and the glass liner cooling section is ideally suited to a sealed and pressurized working-face operation. Thus, the problems of water and gas inflow into the tunnel, except in extreme cases, are eliminated when the machine is operating. Minimal leakage would normally be expected through the glass-lined walls aft of the penetrators. To further improve the face seal, a peripheral sealing device could be easily incorporated. A diaphragm bulkhead structure could be used to seal the central face area. The only operational openings would be those used to feed the muck into the slurry crushers and grinders for subsequent pumping to the portal for disposal, and access to the rotary cutter head for maintenance and cutter changes.

10. Thrusters, Grippers, and Guidance

As projected in Figs. 1 and 2, the main structural component of an NSTM is a cylindrical shell housing the various subsystems. Thruster-actuators push axially on the main cylindrical structure and react against radially expanding gripper pads. Two sets of gripper pads are located at forward and aft stations, respectively. One set of each pair can be gripping while the other shifts forward to take a new advance position. Machine guidance is possible by adjusting the radial extension of the various gripper pads. It is assumed that only very gradual changes in direction will be required with the types of NSTMs studied. Hydraulic actuators can be used because of the low temperatures inside the NSTM. The system is basically that in use for most TBMs.

11. Utility Lines and In-Tunnel Transportation

The main water-cooling lines have already been described. Other general-purpose utility lines will be required for such needs as fresh air, auxiliary power, and communications. For extension of all lines that cannot be unreeled conveniently, it is projected that a line-extender assembly will be mounted on a trailer towed behind the NSTM. Because of the smoothness of the glass-lined tunnel walls and floor either railed or wheeled vehicles can be used.

12. Control Center

A fully instrumented, cooled, control center mounted at the aft end of the NSTM is anticipated, from which the reactor and heat-transmission operation as well as the various other excavation processes can be manually monitored.

III. COST ANALYSIS

A. NSTM Cost Estimates

The two initial designs of NSTM systems described in Section II were used for cost estimating purposes. One general economic characteristic of the NSTM system is the fact that it is much more capital-intensive than conventional and TBM excavation equipment. Whereas, in past excavation projects, it was customary to write off a tunneling machine after a single project; much of the equipment for NSTM excavation systems will be used until its operational lifetime will have been reached. Fortunately, costly Subterrene components are not exposed to the harsh conditions that components in, e.g., TBMs have to endure. For example, the nuclear energy system in the NSTM will be completely enclosed and contained. Similarly, the heat pipes will be enclosed. Also, dust and debris will be contained in the forward face cavity of the NSTM, and trailing equipment and utility lines will encounter only relatively clean and smooth glass-lined tunnel walls. However, certain components, e.g., rotary cutter assemblies, rock grinders, and crushers in the hydraulic slurry disposal system, will still be limited to more traditional operating lifetimes.

With NSTMs, the tunneling contractor will be faced with higher capital investments than with conventional equipment; i.e., the cost of capital will increase and must be accounted for in the overall cost of a tunneling project. A firm might raise capital by various means, e.g., by selling stocks or bonds, drawing on reserves, or taking a loan.[15] To arrive at a cost-of-capital effect on overall cost in a simple manner the procedure presented in the following discussion was used.

For the basic equipment-cost estimations the NSTM was categorized by identifying basic subsystems, and operational lifetimes were assigned to each. The estimated capital cost of each subsystem was amortized over time periods of approximately

TABLE II

EXAMPLE OF TYPE-I NSTM EQUIPMENT COSTS, 7.3-m (24-ft) DIAMETER, 23.4-MW POWER
(Costs Based Upon 1972 Dollars)

NSTM Subsystem	Lifetimes: Amortization, yr	Lifetimes: Actual, h	Capital Cost, M$	8% Interest on Remainder, M$	Salvage Value, M$	Cumulative Cost, M$	Cost per Advance (V=1.523 m/h), $/m	Cost per Advance (V=5 ft/h), $/ft
Kerf penetrators	1	4500	1.500	0.120	(0.150)	1.470	214.3	65.3
Mechanical cutters	1	4500	0.800	0.064	---	0.864	126.0	38.4
Slurry grinder, pumps, and pipes	1	4500	0.150	0.012	---	0.162	23.6	7.2
Liner cooling surface	1	4500	0.750	0.060	(0.075)	0.735	107.2	32.7
Nuclear fuel	2	9000	0.702	0.085	---	0.787	57.4	17.5
Heat pipes	5	20000	0.300	0.076	(0.030)	0.346	11.3	3.5
Mechanical cutter drive	5	20000	0.200	0.050	---	0.250	8.2	2.5
Nuclear system less fuel	20	90000	4.194	4.349	---	8.543	62.3	19.0
Water coolant system	20	90000	0.150	0.156	(0.015)	0.291	2.1	0.6
Air circulating system	20	90000	0.150	0.156	(0.015)	0.291	2.1	0.6
Thruster and grippers	20	90000	0.100	0.104	---	0.204	1.5	0.4
Control center	20	90000	0.250	0.259	---	0.509	3.7	1.1
		Subtotal	9.246	5.491	(0.285)	14.452	619.7	188.8
Air, power, and water utility lines	1	4500	0.100	0.008	---	0.108	15.7	4.8
Portal power and cooling	20	90000	1.300	1.348	(0.130)	2.518	18.4	5.6
		Subtotal	1.400	1.356	(0.130)	2.626	34.1	10.4
		Total	10.646	6.847	(0.415)	17.078	653.8	199.2
Totals Referred to 1969 Dollars [16]			9.339	6.006	(0.364)	14.981	573.5	174.7

twice the operational life of the subsystems; i.e., the actual use-to-calendar time ratio is 0.50. Capital-equipment funds were borrowed with interest charges of 8% of remaining capital, paid off over the various amortization periods. Certain components made of relatively expensive materials were assigned a 10% salvage value. These include kerf-melting penetrator slabs, heat pipes, glass-liner cooling surface slabs, water-cooling jacket, air circulating system located in the NSTM, and the portal power and water-cooling systems. Finally, costs in dollars per tunnel length were calculated by assuming an average NSTM advance rate of 0.423 mm/s (5 ft/h). Table II summarizes typical estimated costs for a Type-I NSTM (kerf-melting plus mechanical cutter) designed to produce a tunnel with a finished diameter of 7.3 m (24 ft) at a nuclear power level of 23.4 MW (thermal power). These estimates are referred to 1972 dollars. To refer to 1969 dollars, an overall inflation factor of 14% is used from 1969 to 1972.* The inflation rate for the excavation equipment analyzed might very well be considerably higher, but this effect was not studied. Summary total equipment cost in 1969 dollars for

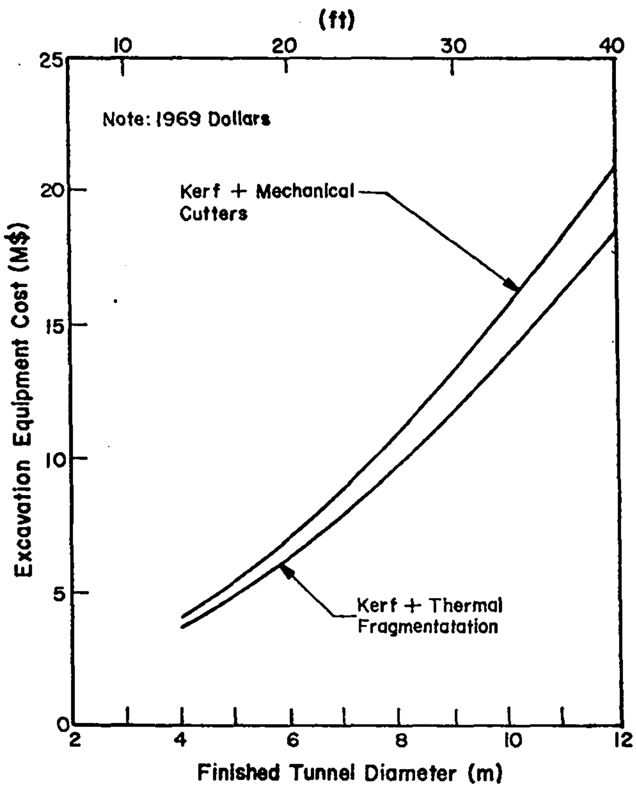

Fig. 10. NSTM excavation equipment costs vs finished tunnel diameter.

*Overall national inflation rate for that period as published by the U.S. Department of Commerce.[16]

TABLE III

BASES FOR EQUIPMENT COST AND LIFETIME ESTIMATES

Item	Basis
1. Heat pipes and penetrators	LASL experience since 1963. Conservative assumptions: lithium/molybdenum pipes at 200-to 400-MW/m^2 capacity. Penetrator costs based on use of molybdenum, tungsten, and other refractory parts at average cost of 22 \$/kg (10 \$/lb).
2. Nuclear components	High-temperature gas-reactor electric utility costs[17] multiplied by factor of 6 to allow for compact size needed for NSTM. NSTM reactor equipment costs are \$180/kW and fuel costs are 3.35 mills/kWh, both based on thermal power (not electric) and on 1972 dollars.
3. Mechanical cutter	Tunneling machine costs per Ref. 14 range from \$250,200 to \$1,225,000 in 1969 \$, the latter value being for a 21-ft-diam tunnel. For this study, a baseline 7.3-m-(24-ft-) diam machine cost of \$1,000,000 (1972 \$) was selected to cover cost of cutter wheel and structural mount, with \$200,000 included for the drive motor.
4. Muck removal	Costs given by Holmes and Narver, Inc.[18] and those derived from COHART[19] for current conveyor systems were studied. It was concluded that the COHART costs could be conveniently used to represent future slurry systems without affecting the overall results significantly.
5. Portal power and cooling	Power-industry-type costs were used conservatively enough to cover additional costs for a mobile system and setup. Typical costs of turbine and electric equipment are 66 to 84 \$/kW, based on 1973 dollars.[17]
6. Control center	A cost of \$250,000 was assumed for all sizes using similar electronics. This compares with \$150,000 for completely automated controls for the LASL 370-MW nuclear space engine.
7. Other components	Because many miscellaneous smaller components were not detailed and their cost effects were obviously small, order-of-magnitude estimates only were made.
8. Operating lifetimes	For the penetrators, mechanical cutters, slurry components, liner cooling surfaces, and utility lines, a lifetime of 4500 h was estimated for future components considering the relatively favorable NSTM environment. For the hot penetrating surfaces, a 4500-h lifetime was deemed feasible. This is indicated by small-scale LASL tests where, under very harsh conditions, a maximum hot-wall erosion rate of 13 μm/h (0.0005 in./h) was measured. For the nuclear fuel, a 9000-h period between refueling operations is consistent with nuclear power-plant practice. High-temperature heat pipes have been operated well over 10,000 h, and a doubling of their lives to 20,000 h is not considered too difficult. Electric utility practice assumes a 30-year lifetime with some maintenance. The long-lived components in this study were assumed to have a lifetime of only 10 years.
9. Scaling procedures	Scaling on size from a 7.3-m-diam tunnel baseline was done by assuming that costs varied with the square of the tunnel diameter except for the nuclear system for which a square-root relationship was used. As noted earlier, control-center costs remained fixed.

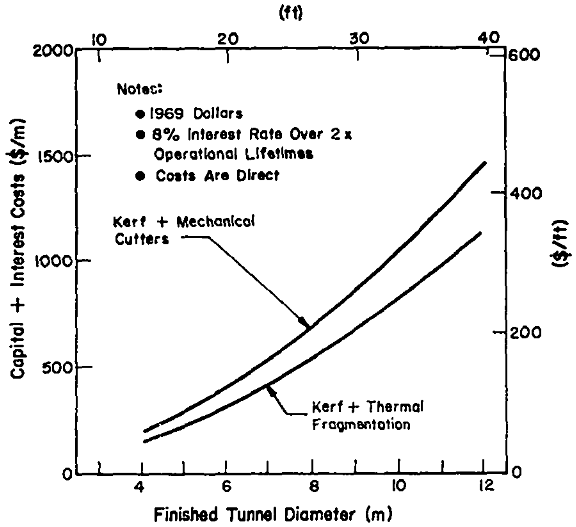

Fig. 11. NSTM excavation equipment plus interest costs per unit tunnel length vs finished tunnel diameter.

the two types of NSTM systems are plotted in Fig. 10, and Fig. 11 displays similar data in a cost-per-unit tunneling length basis.

Table III lists the bases for the cost estimates used to establish the values summarized in Table II. In general, very conservative estimates were made for all nonconventional subcomponents of the NSTM. However, the experience in refractory-metal material and fabricating costs gained thus far in the project was factored into these estimates. The subcomponents that are based upon conventional equipment technology were costed by using existing data for such equipment as extensively as possible.

Direct NSTM operating costs were estimated by using data derived from the COHART computer program for conventional and machine costs (based upon 1969 dollars)* as a base to arrive at reasonable conventional or TBM-type direct cost items and adjusting these values for NSTM costs. These COHART data were supplied by Foster.[19] Tables IV and V summarize typical results of these operating-cost estimates. The tables show the percentage contribution to the total in each case of the major project processes: excavation, materials handling, and supports, as well as labor, equipment, and materials distribution. It can be seen that the cost distribution for NSTMs is markedly different from conventional or TBM costs;

*The cost reference base was chosen as 1969 dollars because the COHART program data base utilized this reference.

TABLE IV

TYPICAL COST DISTRIBUTION FOR MAJOR EXCAVATION ELEMENTS OF A 7.3-m-(24-ft) DIAMETER TUNNEL

Earth Conditions	Type Machine	% of Total Project Costs: Excavation	Materials Handling	Support and Liners
Medium rock	Type-I, NSTM	48	31	21
Hard rock	Type-II, NSTM	43	32	25
Medium rock	TBM	38	30	32
Soft ground, Variable	Type-I, NSTM	47	22	31
Soft ground, dry	TBM	19	23	58

for the NSTM a greater cost percentage is concerned with excavation and less with supports and liners. This difference is ascribed to higher NSTM excavation equipment costs and to associated lower costs for liners and supports.

The COHART data were available as raw direct costs to which factors had to be applied to account for profit, overhead, and regional cost effects. According to Wheby and Cikenek[20] the computer data are based on 1969 dollars and on Chicago prices. By referring to pertinent mid-1969 issues of the Engineering News Record (ENR) publications with data available for prices in 22 major U.S. cities, it was estimated that for typical tunneling projects the cost index used in COHART, based on arithmetic averages for the 22 cities, is about 5% less than for Chicago only. Therefore, an approximate cost index of 1.00 was deemed satisfactory.

For regional factors (which take into account, e.g., labor union regulations, militancy, and other costly restrictions), Wheby and Cikenek present a scale ranging from 1.0 to 3.0 with 1.1 applying over much of the U.S. They list a factor of 1.5 for the Northeast Corridor, excluding New York City. In this study, a factor of 1.3 was estimated to apply to overall U.S. tunnel projects.

TABLE V

TYPICAL PROJECT COST DISTRIBUTION BY LABOR, EQUIPMENT, AND MATERIALS FOR A 7.3-m-(24-ft) DIAMETER TUNNEL

Earth Conditions	Type Machine	% of Total Cost: Labor	Equipment	Materials
Medium rock	Type-I, NSTM	42	42	16
Hard rock	Type-II, NSTM	44	37	19
Medium rock	TBM	51	21	28
Soft ground, Variable	Type-I, NSTM	33	49	18
Soft ground, dry	TBM	43	16	41

TABLE VI

COST FACTORS APPLIED TO NSTM AND COHART DIRECT COSTS TO ARRIVE AT NATIONAL AVERAGE COSTS

	NSTM	COHART
Cost index	1.00	1.00
Profit	1.06	1.09
Overhead	1.27	1.27
Regional	1.30	1.30
Net	1.75	1.80

A 27% overhead rate and a 9% profit are recommended in Ref. 20. In the NSTM case, for which the large equipment capital costs are assumed to consist of borrowed capital plus 8% interest, a contractor profit of 6% was allowed.

The factors applied to the COHART data are summarized in Table VI.

B. Comparisons With Conventional and TBM Costs

Data on conventional and machine-tunneling costs were compiled for comparison with Subterrene costs. Although the cost spread is broad and the desired consistency of the data is sometimes difficult to obtain, the general magnitudes and trends of these costs were identified.

Costs versus tunnel-diameter data for rock tunnels are shown in Fig. 12. The three curves designated ① were taken directly from Spittel et al.[21] and represent equations and estimations from actual tunnel data. The sensitivity to type of geology is represented by RQD (Rock Quality Designation)[13] values from 100 down to 25%. Two variables that were not taken into account by Spittel are rock strength and abrasiveness. Their effect on the estimates is not clear because rock with an RQD = 100% is not necessarily very hard or abrasive. To more clearly define cost characteristics of cutters, rock strength and/or abrasiveness should be considered. Data designated ② for conventional excavation were extrapolated from Baker et al.[1] by taking lower-bound excavation-only costs and then dividing by 0.35 to obtain approximate total costs.

Data denoted by ④ were estimated from COHART program data.[19] It was assumed that these data were representative of medium-strength rock, i.e., rocks with an average compressive strength of 135 MN/m^2 (20000 lbf/in.^{2}). Carstens[14] concluded on the basis of actual cost data that rock compressive strength was the best readily available parameter for correlating cutter costs. Using factors estimated from Ref. 14, the data denoted ④ were scaled up to the two curves marked σ = 275 MN/m^2 (40000 lbf/in.^{2}) and σ = 345 MN/m^2 (50000 lbf/in.^{2}) to arrive at an estimate of the significant additional costs which occur due to increased cutter wear in very hard rock. These latter curves are designated ③ .

If we compare the NSTM data with the other data in Fig. 12, we see the following: At RQDs of 75 and 100%, the cost curves denoted ① are significantly lower than those for the NSTM. However, for less favorable rock conditions, e.g. RQD = 25%, the NSTM is competitive and even a little superior. It has already been noted that the data plotted as ① did

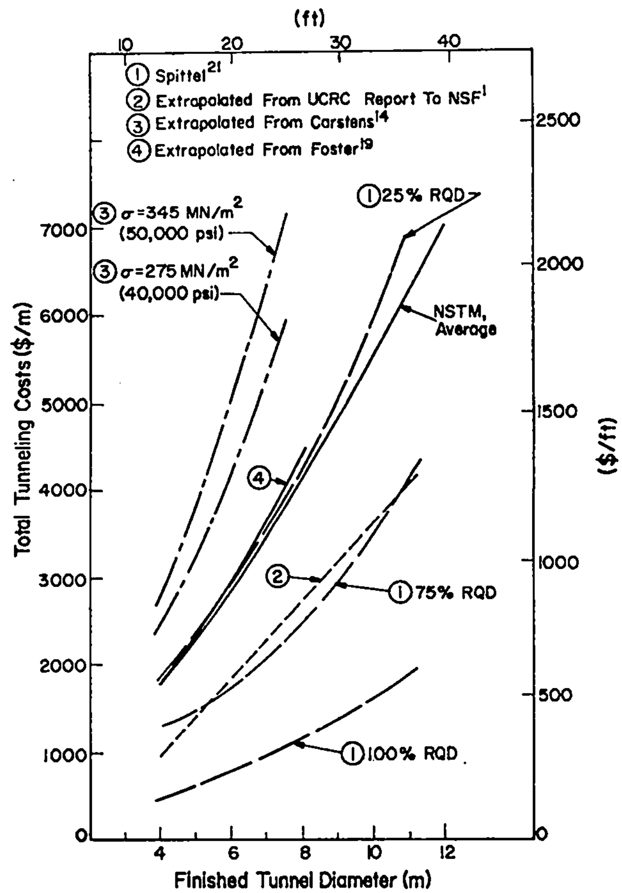

Fig. 12. Costs vs tunnel diameter for rock tunnels.

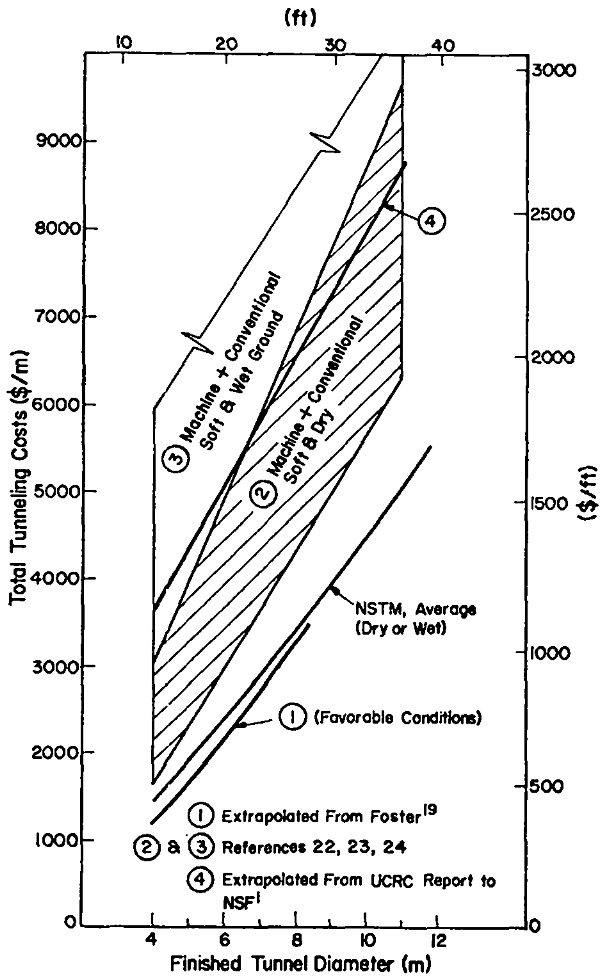

Fig. 13. Costs vs tunnel diameter for soft-ground tunnels.

not consider rock strength or abrasiveness as variables and that the effect of these rather important cost parameters is somewhat hidden. Nevertheless, the data for RQDs of 75 and 100% show that, at this stage of the economic evaluation, there are undoubtedly some projects in very favorable rock conditions where other simpler and more traditional techniques will compete with the currently projected NSTM systems.

However, the advantages of NSTMs become important if we consider very hard rock, i.e., with compressive strengths of 200 to 345 MN/m^2 (30,000 to 50,000 psi). For example, at a tunnel diameter of 7 m (23 ft) and at rock strengths of 275 and 345 MN/m^2, the NSTM costs would be 66 and 54%, respectively, of those resulting from a rotating cutter machine. The cost effectiveness becomes gradually even better as tunnel size increases.

The NSTM compares unfavorably to the costs labeled ②, which are minimum costs in rock using conventional methods and are based on actual data. However, for urban usage, the NSTMs would have important practical advantages because they would avoid the environmental problems caused by drill-and-blast techniques.

Fig. 13 shows cost data for soft-ground excavation. Data labeled ① are estimated from the COHART computer program.[19] The data designated ② and ③ summarize actual data for both conventional and machine techniques and were extracted from OECD, Fenix and Scisson, A. D. Little, and Virginia Department of Highway sources.[22,23,24]

The lower bounded data ② are for soft, dry ground with the data above labeled ③ being for soft, wet ground. The spread of these data illustrates the strong influence of geologic variations on costs. It also illustrates the need for the development of new equipment that is less sensitive to the often encountered, but not necessarily anticipated, geologic variations. Data ④ are extrapolated from the UCRC report to NSF[1] and seem to correlate well with ② and ③. These values were obtained by dividing Ref. 1 data, for the excavation process only, by 0.35 to obtain overall tunnel costs.

Comments pertinent to the comparison of NSTM costs with the soft-ground cost data shown in Fig. 13 are as follows. The NSTM estimates are nearly identical to the COHART estimates, Curve ①. However, both estimates fall far below historical data, Curves ②, ③, and ④. These indicate that tunneling problems, e.g., geologic variations, are perhaps not correctly anticipated by COHART. If we were to assume an additional multiplying factor to account for unanticipated earth conditions, the COHART data should be higher than the NSTM costs. The NSTM estimate shown is meant to cover both soft, wet, running, bouldery ground as well as soft, dry conditions and, thus, already discounts geological variations. Roughly, it appears conservative to conclude that the NSTM would reduce average soft-ground tunnel costs by ~ 50%.

TABLE VII

COST CONTRIBUTION OF THERMAL ENERGY ON A DIRECT COST BASIS

(1969 Dollars)

Type Ground & NSTM	4.1-m-diam Tunnel Total Cost, \$/m	4.1-m-diam Tunnel Fuel + System Cost, \$/m	4.1-m-diam Tunnel Thermal Energy Cost, %	10.7-m-diam Tunnel Total Cost, \$/m	10.7-m-diam Tunnel Fuel + System Cost, \$/m	10.7-m-diam Tunnel Thermal Energy Cost, %
Rock, Type I	1040	46.7	4.5	3460	188	5.4
Hard Rock, Type II	1020	46.7	4.6	3380	188	5.6
Soft Ground, Type I	810	46.7	5.7	2800	188	6.7

C. Energy Costs and Refueling Considerations

The thermal energy for penetrating rock for both Type-I and Type-II NSTMs was considered to be the same. For the kerf-and-mechanical cutter case (Type-I) all the energy is used to develop a thick temporary liner. Where the kerf-and-thermal fragmentation penetrators (Type-II) would be used, the rock conditions would be such as to require less liner thickness. Thus, the thermal energy to the kerf penetrators would be reduced and the energy saved would be diverted to the thermal fragmentation penetrators in the central-face area.

The nuclear fuel costs used in this report include the external costs of refueling. It was assumed that specialized nuclear reactor industries would handle all nuclear-related aspects of the excavation project. This would include reactor system manufacture, installation, on-the-job operation, maintenance, safety, and long-distance transportation.

No attempt was made to detail cost effects of recovering some thermal energy from the cooling water so as to generate electricity for running the slurry pumps, air circulating fans, cutter drive motors, etc.

Table VII summarizes the contribution of the costs of the nuclear fuel plus the nuclear subsystem needed to convert the fuel into thermal energy. On a basis of percentage of overall tunneling costs, the thermal energy varies from 4.5 to 6.7%. It should be remembered that the temporary liner thicknesses assumed for this study are very conservative, and affect the power required and costs directly. Nevertheless, the cost contribution of thermal energy is certainly not dominant.

Power costs can be expressed in another manner, i.e., in terms of costs per kWh. Fig. 14 compares purchased electric power costs from two sources with those used in this study. The NSTM data shown are for Type-I NSTMs and for 4- and 12-m-diam tunnels. The bar at the left of the figure represents rates in dollars/kWh(e) as quoted for Los Alamos, NM,[25] whereas the bar in the middle is a national average rate estimated by Hanold.[7] These two rates are 0.014 and 0.020 \$/kWh(e), respectively. These data are based on power delivered to existing transmission terminals near the tunnel portal and do not take into account special hookup costs. Also, 100% conversion efficiency from electricity to heat is assumed. A factor to be considered is the regional aspect of electric power costs, which can vary significantly depending on location. For nuclear-supplied thermal power (delivered directly to the working face), costs range from 0.006 to 0.011 \$/kWh (thermal) depending on tunnel size.

D. NSTM Development Benefit-to-Cost Ratios

No detailed estimates of overall future excavation demands for the world or the U.S. were

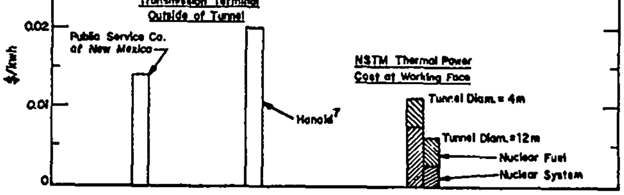

Fig. 14. Typical electric and NSTM thermal power costs.

TABLE VIII

PROJECTED U.S. TUNNELING EXPENDITURES

Time Period	Average Expenditures, B $* Transportation Only	All Tunneling Except Mining
1970-1979	5.1	34
1980-1989	9.3	65

* Based on 1969 dollars.

readily available. However, large future demands are anticipated in such activities as geothermal energy, mining, scientific studies, waste disposal, water redistribution, utility conduits, high-speed transportation, and urban facilities like airports, power plants, manufacturing plants, gas storage, housing, etc. Some recent projections for U.S. tunneling demands compiled by the U.S. Department of Transportation (D.O.T.) were obtained from Foster.[19] These projections can be used to show benefit-to-cost ratios based on NSTM savings indicated previously. They are shown in Table VIII. Ref. 19 also indicated that the percentages of the total excavation demands for rock and soft-ground tunnels are close to 50 and 20%, respectively, with the remaining 30% of the total consisting of cut-and-cover and immersed-tube demands.

Estimated Subterrene characteristics and program costs are summarized as follows: The program will lead to a feasibility demonstration of a prototype NSTM, at which time the technology will be available to industry. The program will cost about 100 million in 1969 dollars and will cover an eight-year period. After demonstration the industrial implementation of NSTMs will take place in a linear manner over a four-year period. The above process is illustrated in Fig. 15. The dotted lines indicate the early technology transfer from laboratory to industry. This is an important concept of the program proposed by LASL, wherein it is planned to: (1) cooperate with industrial firms interested in furthering the R&D effort of the Subterrene concept, (2) train key industrial technical personnel by encouraging them to work directly on the LASL team, and (3) award LASL subcontracts to industry to accomplish key elements of prototype fabrication.

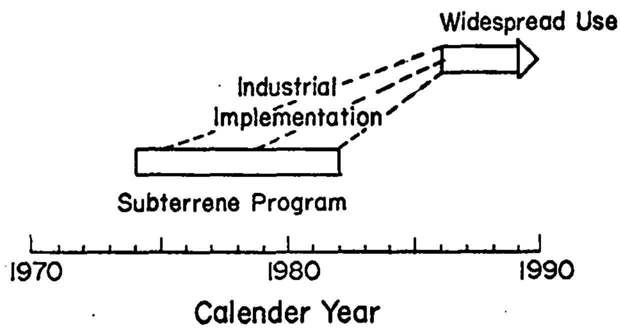

Fig. 15. Schedule for NSTM prototype demonstration and concept implementation.

In Section III-B, wherein NSTM vs TBM and conventional costs were discussed, an example of typical hard-rock costs showed NSTM cost savings of 34 and 46% over TBMs. Also, drill and blast methods are very undesirable in most urban environments and probably will be eliminated in many future projects. For soft ground, Fig. 13 showed that NSTM costs might very easily be less than half those of other methods. On the basis of these considerations the conclusion was reached that projects, excluding those where rock and soil conditions are very favorable for TBM or conventional methods, could be done at cost savings of 30 and 50% for rock and soft ground, respectively, if NSTMs are used.

Two more estimates are needed to arrive at a final benefit-to-cost ratio; both relate to the percentage of tunneling where NSTM systems show cost savings. These are estimated to be 50 and 75% for hard-rock and soft-ground tunnels, respectively. All cost assumptions are summarized in Table IX.

TABLE IX

NSTM COST ASSUMPTIONS AND BENEFITS TO CY 1990 BASED ON TRANSPORTATION DEMANDS ONLY

Type Tunnel	Fraction of Total, %	Demands Available to NSTM 1982 to 1990, B$	Fraction Assumed Done by NSTM, %	Average Savings, %	Benefit, B$
Rock	50	2.79	50	30	0.42
Soft Ground	20	1.17	75	50	0.43
				Total:	0.85

Net transportation benefit-to-cost ratio $= \frac{0.85}{0.10} = 8.5.$

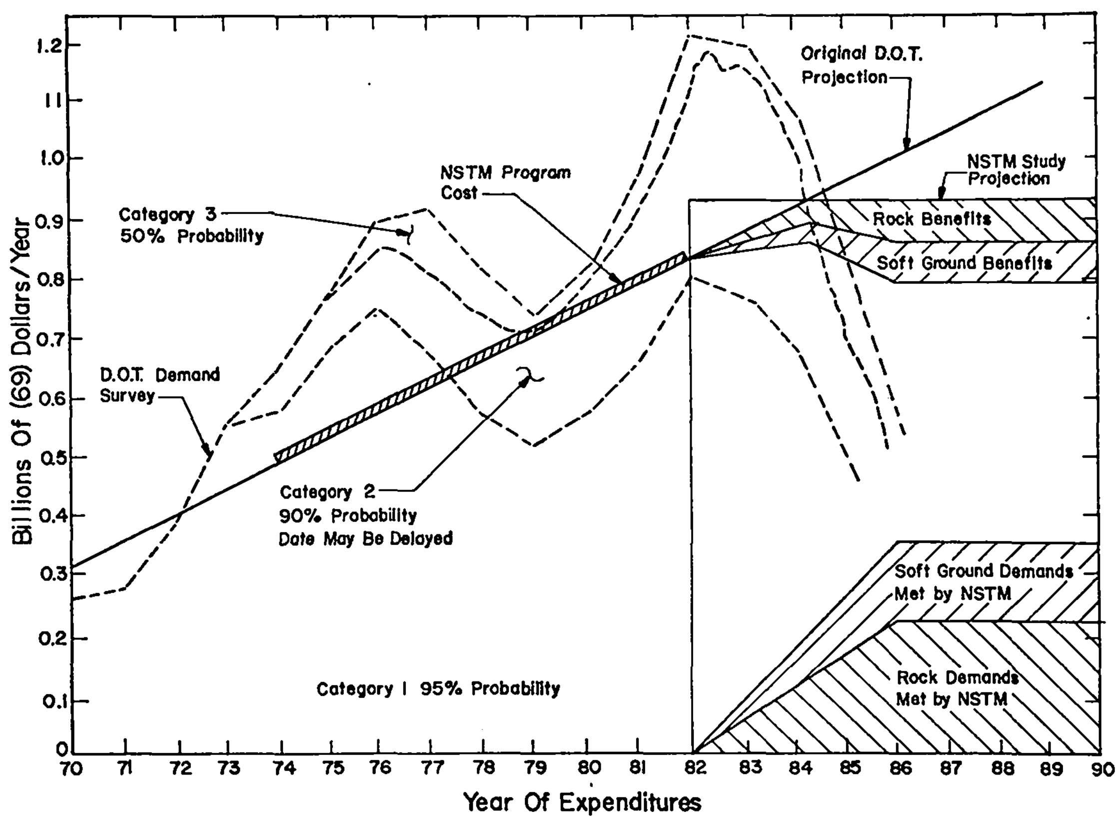

Fig. 16. Department of Transportation demand data and NSTM benefits.

The net benefit-to-cost ratio is 8.5 when based only on average projected transportation-tunnel excavation demands up to CY 1990. Fig. 16 plots the original D.O.T.-projected transportation-tunneling demand* in billions of dollars per year (1969 dollars) to CY-1990 and some results of a later D.O.T. survey of demand which are categorized into 50, 90, and 95% probabilities of actual implementation. The demand curves show a rapid decrease after 1983, which (according to D.O.T.) is due to lack of planning beyond a ten-year lead time by government organizations and not to any expected actual decrease in need for transportation excavation projects.** The various shaded areas in Fig. 16 show the $100 million cost for prototype demonstration, the demands which were assumed as being met by NSTMs for both rock and soft-ground projects and, at the upper right, the benefits that would accrue from savings by use of NSTMs. Benefit-to-cost ratio is, of course, the integrated benefit area divided by the program cost area. These curves also emphasize that additional benefits will accrue if the project had been initiated earlier and shortened in duration.

E. Effect of Advance Rate on Tunneling Costs

The effect of changes in advance rate from the baseline rate of 36.5 m/d was studied. It was assumed that capital costs and design remained the same as those of the baseline configuration but that the system efficiency either increased or decreased to produce the change in penetration rates. The results are summarized in Fig. 17 where the ratio of tunnel cost at other rates to baseline tunnel project cost is plotted against advance rate. The point where the benefit-to-cost ratio would equal zero is at a cost ratio of 1.375, at an advance rate of 22 m/d (3 ft/h), which is well below the baseline rate of 36.5 m/d (5 ft/h). During penetration tests

*The average demands listed in Table VIII correspond to the data in Fig. 16 designated "Original D.O.T. Projection."

**A detailed study of past U.S. tunnel project history and development of more accurate and comprehensive methods of surveying future demands may reveal a basic cyclic trend.

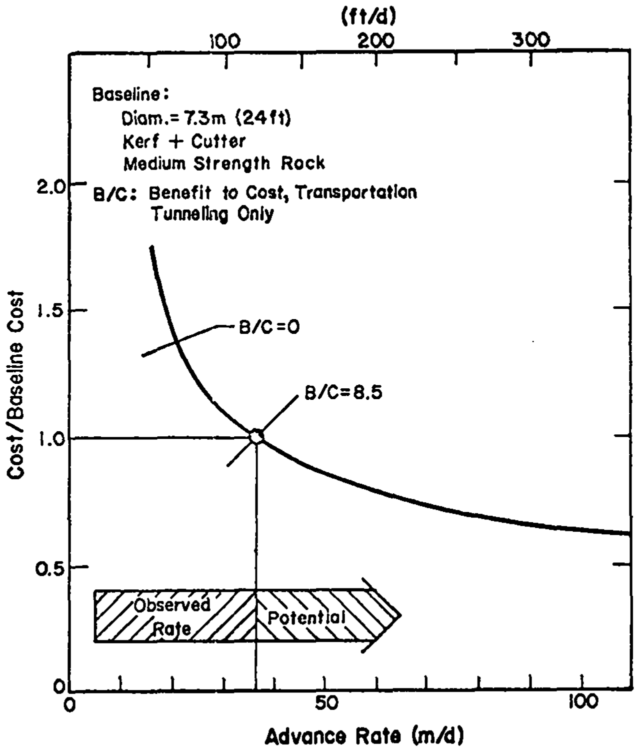

Fig. 17. Effect of advance rate on costs.

of small consolidating penetrators at LASL, rates of 24 m/d were generally recorded and, for short times, were as high as 36.5 m/d; however, at that time, no attempt was made to sustain such rates. Los Alamos Scientific Laboratory experimental experience suggests that a rate of 36.5 m/d is readily achievable and that higher rates are possible, as indicated in Fig. 17.

If the advance rate were twice the baseline value, i.e., about 80 m/d (~ 260 ft/day), an additional 30% savings may result. However, at some as yet undetermined high advance rate the cost may reach a minimum and then increase with further increases in advance rate. This may well be caused by a tradeoff with increasing costs of equipment, e.g., slurry pumps, piping, and crushers, increased cutter wear, longer glass-liner cooling sections, a larger nuclear power system, and larger portal power and coolant equipment. When this occurs a new system concept will become necessary. Such a new system might take advantage of full face melting as indicated by projected long life of melting penetrators (4500 h appears possible). Also, methods of lowering

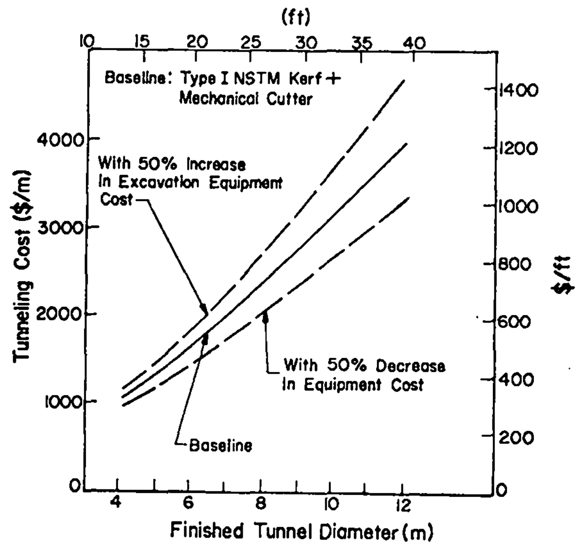

Fig. 18. Effect of ± 50% variation in NSTM excavation equipment costs.

the rock-melting temperature and reducing the viscosity of the melt should be given consideration.

F. Effect of ± 50% Excavation Equipment Cost Perturbation

A perturbation of ± 50% on excavation equipment costs around the baseline case was studied; results are shown in Fig. 18. The overall effects on tunnel project cost were ± 9 and ± 17% for tunnel diameters of 4.1 and 10.7 m, respectively. The upper-limit cost variations, if they occurred, would reduce the benefit-to-cost ratios to between 5 and 6 based on transportation-tunneling demands to 1990. Thus, we may conclude that results would not be affected significantly, even if equipment costs used in this study were greatly in error, e.g., by 50%.

G. Other Benefits Not Quantified In This Study

The benefit-to-cost ratio discussed to this point included only the excavation demands for transportation, i.e., average of 9.3 billion dollars for the period 1980-1989. As was shown in Table VIII, an additional 56 billion dollars of excavation demand is foreseen during that time period for other tunneling projects, excluding mining. Thus, with the inclusion of these additional demands, the benefit-to-cost ratio could become considerably larger.

Conceivably, as experience is gained with the glass liner, the concrete structural wall inside the glass liner could be eliminated or greatly minimized. This would result in further savings in support costs. Another NSTM advantage that should be kept in mind is offered by the fact that the NSTM can advance through the earth with a minimum of disturbance, thus maintaining the inherent strength of the surrounding strata and, in fact, enhancing their integrity by the cementing action of the solidifying glass. Emphasizing this point Cording and Deere,[27] discussing tunnel support loadings, point out that liner loadings can be rather low even in highly fractured rock, if the joints are tight and irregular and if initial loosening is prevented.

Technology spin-off benefits from NSTM development could include high-temperature abrasion-resistant materials and high-temperature, high-heat-flux, long heat pipes; such heat pipes could be useful in high-temperature chemical processes, e.g., coal gasification. Another spin-off or parallel development could be that of small electrically powered penetrators for installation of underground utility lines, for exploration of natural resources, or for mining. One of the most important Subterrene applications could be the deep penetration into the earth's crust to tap geothermal energy[26] for such purposes as water desalination, surface heating, and electric power generation.

IV. CONCLUSIONS

The designs and characteristics of two large Nuclear Subterrene Tunneling Machines (NSTMs) were postulated and their cost-effectiveness for future transportation tunnel projects was analyzed. Both designs are first-order extensions of present Tunnel Boring Machine (TBM) technology and visualize the addition of a peripheral kerf-melting penetrator, which will form a continuous temporary support by lining the tunnel walls with rock glass. High cost-effectiveness is projected for both soft-ground and very-hard-rock tunneling. Contributing to this projection is the anticipation that NSTMs will be relatively insensitive to variable and unexpected formation changes.

The major results of the study are:

- The preliminary economic analysis indicates excellent cost benefits for the development of NSTM systems. Estimating that unfavorable excavation conditions would be encountered at least 50% of the time in rock and 75% of the time in soft ground, and using the best available estimates for hard-rock and soft-ground excavation demands in only the transportation sector up to CY 1990, the benefit-to-cost ratio for a Subterrene development program is 8.5. Many other potential benefits outside of transportation applications could increase this ratio significantly.
- Additional benefits will accrue if research and industrial implementation are accelerated. LASL program plans are based on early transfer and availability of the technology to industry.
- As an initial step, large NSTMs using the peripheral kerf-melting bit concept can be integrated into technically sound excavation systems.
- For a conservative temporary glass-liner wall thickness equal to 4% of tunnel diameter, the nuclear thermal power requirements are 7 and 63 MW for 4- and 12-m-diam tunnels, respectively.
- The cost of the thermal power required to melt the rock is only about 4 to 7% of the total excavation project cost.
- NSTMs are capital-intensive systems as compared to the labor-intensive TBMs.
- Penetrator material costs appear to be the highest cost item, on a cost-per-unit tunnel length basis, followed by the cost for mechanical rotary cutters used to fragment the central areas of the excavation face.
- The total costs for excavation, materials handling, and supports and liners, using NSTMs, are very close to those for TBMs when ground conditions are favorable. However, the advantages of NSTMs become outstanding in unfavorable ground conditions such as in very hard rock and, particularly, in soft, wet, running, or bouldery ground.
- Very high advance rates may require design extensions beyond the two NSTM concepts analyzed in this study.

Additional investigations in the following areas are needed:

- Continue more detailed preliminary design studies of NSTM tunneling system.

- Develop more specific future tunneling demand data (both in the U.S. and overseas); including sizes, geological conditions and variations, project locations, applications, and schedules.
- Study other NSTM designs which will encompass full-face melting designs and include removal of molten rock from the tunnel.
- Develop system concepts and costs for Electric Subterrene Tunneling Machines (ESTMs) and compare with NSTMs and TBMs.
- Evaluate the details of the supply and cost problems of exotic components such as refractory penetrator bits.
- Determine the most likely benefits achievable by actively pursuing R&D related to TBM and conventional methods, and compare with ESTM and NSTM benefits.
- Study the environmental and social impact of ESTM and NSTM full-scale implementation.
- Adapt COHART or the General Research Corp. computer program to obtain additional useful cost study data.
- Conduct investigations and tests to verify glass wall properties and their wall-support characteristics.
- Study effects on the overall system design of greatly increasing the advance rate.
- Initiate failure-mode analyses, conduct maintainability studies, and develop component life data.

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