Summary Remarks

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•WE ARE indebted to Day for his informative description of present nuclear excavation technology. The potential of this technique for such large projects as the interocean canal staggers the imagination. I can only assume that the development of "clean" nuclear explosives has progressed to a point where radiation effects are no longer a problem.

When one considers the advances that have been made in tunneling machines during the past 10 years, Williamson's projections for the future seem very conservative. On the other hand, I am not optimistic that any really significant advances can be made by simple improvements in the engineering design of cutters and bearings. I think that some innovative approach will be necessary to achieve advances of any magnitude. In particular, I am hopeful that some of the research we in the Department of Transportation are doing will provide a dramatic increase in boring machine capabilities, as well as permit economical operation in the harder rock formations. Specifically, we are exploring the possibility of chemically or thermally weakening rock ahead of the cutter blades. It is well established that chemical treatment or heat will weaken rock strength, but a major question remains as to the practicality of such methods in a tunnel environment and the cost benefits to be realized. We hope to have some answers to this soon.

Standardization of machines is a worthwhile goal. Unfortunately we have no organizational mechanism for deciding on diameters and other factors that might be associated with standardization.

A rather interesting point was made by Irwin et al. in their statement that smooth tunnel walls produced by tunneling machines may hide poor internal conditions and thus provide a false sense of security that might lead to liner design error. This certainly highlights the need for post-excavation geologic exploration.

Another issue raised, which I consider to be rather controversial at this time, is whether lining should be placed immediately after excavation or after stress relaxation has taken place. One might argue that forces on the liner will be less after stress relaxation and therefore could be of lighter design. On the other hand it has been well established that shotcrete, for example, is most effective when placed immediately after excavation so as to assist the development of arching action before degradation of the rock structure occurs.

I also found interesting the comment by Irwin et al. that it is not always necessary or desirable to explore on the "tunnel line" and that outcrops and other evidence, properly evaluated, can result in valid conclusions as to the subsurface geology.

The theme expressed by Irwin et al. that machine tunneling requires more comprehensive exploration is certainly valid, as has been borne out through several experiences in which unexpected bad ground necessitated removal of the boring machine at considerable expense.

Geologic uncertainty is of course reflected as a cost of risk in contractors' bids. The greater the uncertainty is, the higher the cost. On the other hand, geologic exploration also costs money. At some point the law of diminishing returns must govern the economic trade-off, so that some reasonable limit to the extent of geologic exploration can be established. I know of no hard and fixed rules to the game, and each case must certainly be viewed on its own merits.

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I should like to add to the comments by Deere et al., with regard to the need for secondary lining in transportation tunnels. While steel sets, shotcrete, or segments may be quite satisfactory for urban transit systems, the aerodynamic losses that would result from using these types of final liners in advanced high-speed intercity systems would preclude their use. In these latter systems liner surfaces must be smooth and have a low friction coefficient. Since such systems would probably be below the water table, liner systems must also be capable of handling water pressures and leakages.

Shotcrete is a relatively new liner method in this country but is gaining wide acceptance. One disadvantage is that the resulting surface is not smooth or uniform. We see a definite requirement for someone to devise a placement method that incorporates an automatic troweling feature so as to provide a uniform cross section and smooth surface.

I concur with the authors that field observation is needed to determine the behavior of actual tunnels both during and after construction. Much can be accomplished by theoretical analyses of support systems, but empirical data are necessary to confirm and expand our theoretical knowledge. The University of Illinois, under Department of Transportation sponsorship, is now developing a program for instrumenting on-going projects for this purpose. It is hoped that similar programs will be developed by other tunnel construction agencies so as to provide a well-documented storehouse of data on various kinds of tunnel designs and geologic situations.