Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

WHAT PROMPTS CONSTRUCTION INNOVATION?

By Clyde B. Tatum,[1] M. ASCE

ABSTRACT: Current and expected challenges on large engineering and construction projects demand innovative methods for improved performance. Analyses of several examples of innovative engineering and construction techniques for nuclear generating plant projects as presented. The findings based on those analyses identify not only conditions that favor innovation, but also those that appear to restrict the use of new techniques. The writer suggests guidelines for industry professionals and researchers to follow, in order to promote engineering and construction innovation.

INTRODUCTION

Many segments of the U.S. construction industry and many individual projects continue to apply familiar construction techniques with little innovation. The decline in overall international competitiveness of the U.S. construction industry results, in part, from that static approach. However, certain conditions present on individual projects do promote innovation and also realize substantial cost and schedule savings. What factors characterize an innovative versus a static approach?

The present paper describes six innovative construction methods from nuclear generating plant projects and uses those examples to identify conditions that foster construction innovation. Despite the small sample, the findings from that analysis can help construction companies to create a climate fostering innovation, assist individual project managers and owners to encourage technological advancement, and suggest topics for future research.

OPPORTUNITIES FOR ENGINEERING AND CONSTRUCTION INNOVATION

Revised engineering designs, which can reduce quantities of construction material and the degree of difficulty of the project, present an important opportunity for innovation on construction projects. The high-cost influence (27) of early engineering decisions makes consideration of innovative designs critical. Value engineering is one method that fosters innovative approaches, by offering a critical analysis of functional requirements for a facility and selection of the least-cost alternative that meets those requirements (3). This method opposes the engineer's tendency to routinely apply design standards and experience from previous projects rather than investigate innovative approaches with potential cost savings.

Construction technology involves the methods, processes, and materials used to construct the facility (7). Opportunities for cost and schedule savings frequently exist. Possible improvements include: (1) Devel-

[1]Assoc. Prof. of Civ. Engrg., Stanford Univ., Stanford, Calif. 94305.

Note.—Discussion open until February 1, 1985. To extend the closing date one month, a written request must be filed with the ASCE Manager of Technical and Professional Publications. The manuscript for this paper was submitted for review and possible publication on January 4, 1984. This paper is part of the *Journal of Construction Engineering and Management,* Vol. 110, No. 3, September, 1984. ©ASCE, ISSN 0733-9364/84/0003-0311/$01.00. Paper No. 19103.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

opment of new construction methods or sequences; (2) application or extension of methods or techniques originally developed to meet other requirements; (3) development and application of new equipment or tools; and (4) scale-up or refinement of existing methods.

Taken independently, important opportunities for improvement in both engineering and construction merit serious consideration. However, the synergistic effect of considering combined innovations in engineering and construction frequently offers very large project benefits (8,11). These activities are highly related; minor changes in one may produce substantial changes in the other. This high dependency across disciplines can decrease the efficiency of either engineering or construction activities if they are not integrated. The integration of engineering and construction planning and task completion (35,36) produces important opportunities for cost and schedule savings.

The following sections describe several engineering and construction innovations used on power plant projects. They illustrate the potential for advancing the technology, while decreasing cost and schedule duration using integrated engineering and construction planning.

Site Development Activities

Site conditions and building configurations on power plant projects may require innovative construction methods to maintain schedules. The need for alternate approaches on power plant projects frequently results from the combined effects of two requirements: (1) Design configurations involving extensive excavation and subsurface structure construction to meet structural design criteria or to satisfy plant arrangement; and (2) the construction schedule benefits of simultaneous work on several buildings, including those adjacent to the structures requiring deep foundations. Innovations in site development and building foundation construction may also avoid the expensive waterproofing and backfill required on many projects.

Reactor Building Freeze Wall.—One nuclear project used a freeze wall technique for reactor building construction (16,29). This structure, approximately 150 ft by 100 ft (30 m × 45 m) in plan, required a building excavation approximately 70 ft (21 m) in depth (Fig. 1). High groundwater levels and the high permeability of the in situ material required special techniques for foundation excavation. Use of conventional dewatering and slope layback would have delayed construction of the turbine generator pedestal and the turbine building.

The construction planning team for the project evaluated several excavation alternatives, including conventional layback of slopes, sheet pile walls, and freeze wall excavation. The evaluation required a tradeoff between uncertain technical feasibility and schedule duration.

The team selected the freeze wall method because of important schedule advantages. This technique involved ringing the excavation with 270 shafts drilled to the full excavation depth. Circulation tubes for refrigerated brine were placed in a drilling slurry inside each of the shafts forming an elliptical freeze wall, approximately 6 ft (2 m) thick. The excavation proceeded by light track equipment, once the refrigeration established the freeze wall. Despite limited difficulties with wall seal and

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

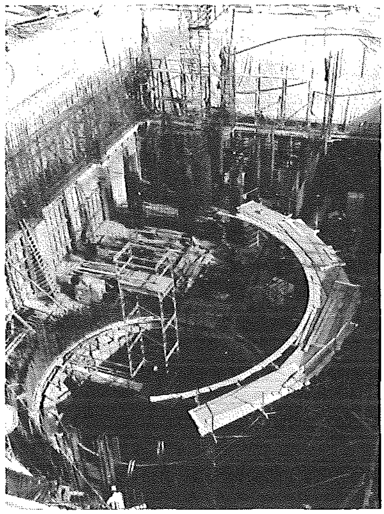

FIG. 1.—Reactor Building: Freeze Wall Construction

water in the excavation, the technique performed as expected. The structural integrity of the wall allowed close-in placement of large lifting equipment for removal of excavated material and for construction of the building mat and substructure.

Combination Structure Neat Line Excavation.—The restricted site area available for a two-unit nuclear project resulted in innovation in engineering and construction of the large combination structure. Because of highly-varied topography, the site required extensive excavation, limiting the plant island area and forcing innovation in building foundation design and construction.

The project planning team considered several alternatives for the 320 by 300 ft plan (100 × 90 m), having an excavated depth of approximately 65 ft (20 m) (Fig. 2). Feasible options included: (1) Conventional dewa-

FIG. 2.—Combination Structure: Neat Line Excavation

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

tering and slope layback; (2) slurry wall construction and subsequent use of the retaining wall as an exterior form; and (3) neat line excavation with dewatering by a collection and gravity drainage system.

The team selected the neat line alternative because of both schedule and cost advantages. This option provided superior access to the combination structure, eliminated the need for waterproofing, and allowed work to begin earlier than was expected on adjacent buildings. These benefits offset three major disadvantages of the approach: (1) Safety concerns expressed by regulatory agencies and craft unions; (2) unique features of the dewatering system resulting in increased licensing review; and (3) requirements for more expensive one-sided concrete form work.

The method selected required a specific sequence of construction activities: (1) Line drilling the entire foundation perimeter; (2) ripping and removing the sandstone material; (3) installing vertical half-round collectors, a horizontal header, and a tunnel system for dewatering; (4) shot creting the exposed sandstone surface; (5) constructing inspection manholes at the excavation corners; and (6) placing the substructure wall concrete directly against the shot crete and the vertical collectors. A geotechnic consultant completed extensive geological mapping of the sandstone faces prior to shotcreting. The excavation design also required an extensive instrumentation system, including surveyed reference points, borehole extensiometers, inclinometers, and piezometers to monitor both the slope stability and the ground-water levels.

The neat line method met all objectives. The excavation allowed close-in placement of large lifting equipment and simultaneous work on adjacent building structures. The slope proved stable. The gravity dewatering system also assisted in building dewatering during construction. With the exception of access ramps to each structure, this excavation method eliminated the costly soil cement backfill necessary to duplicate both static and dynamic properties of in situ materials. Implementation of this technique required extensive discussions with contractors, regulatory agencies, and craft unions, concerning the in-depth analysis and safety of the excavation.

Concrete Construction

The large size of structures required for nuclear projects, combined with the many unique and severe design criteria, result in challenging concrete construction requirements. Engineers and constructors of nuclear plants developed many innovative approaches for completing these structures in accordance with demanding schedules (33). This section describes three innovative approaches as examples for further analysis of innovative processes in construction.

Reactor Bottom Head Construction.—Three conditions forced an analysis of innovative means for constructing the prestressed concrete reactor vessel (PCRV) bottom head on a nuclear generating station project (23). First, the schedule required the shortest possible duration for this work. Second, the PCRV foundation, a support ring, involved extremely high densities of reinforcing steel and precise construction tolerances and a five-month schedule duration. Third, the PCRV bottom head involved several long duration operations, including liner erection, penetration

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

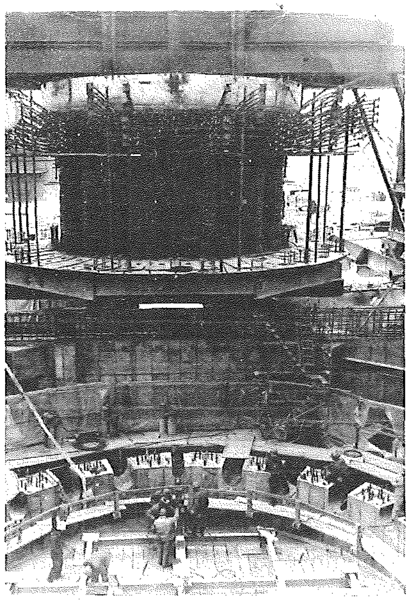

FIG. 3.—Reactor Vessel Bottom Head Move-In

installation, reinforcement placement, and precise positioning of embedments. These conditions required changes from traditional practices of in-place, sequential erection and concreting.

The planning team for this project evaluated several alternatives for bottom head construction. These included: (1) Building in place; (2) partial yard assembly and placement with lifting equipment; and (3) extensive yard assembly for transport and setting by specialized rigging equipment.

The alternative selected involved assembling the bottom head and installing reinforcing steel and other embedments up to a total weight of 400 ton (363,000 kg). This allowed yard assembly of the bottom head in parallel with support ring construction in place. The constructor then transported the assembly approximately 190 ft (57 m) and lowered it approximately 20 ft (6 m) into place using a modified stator lifting rig (Fig. 3). This innovation resulted in a schedule savings of approximately 3 months compared to sequential work in the 2 major elements.

Slip Form Construction of Reactor Building Shield Walls.—Managers for many types of structures have applied slipform construction techniques. Several nuclear projects have used this method; each application presents new requirements because of evolving design criteria. At a two-unit project, several technical requirements forced consideration of alternate construction techniques. The differences between this project and past ones included: (1) High seismic design accelerations; (2) large numbers of penetrations located in several linear groups in the wall; (3) high construction loading; and (4) precise penetration location requirements. Construction requirements for short schedule duration and for early start of containment vessel erection following shield wall con-

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

struction also suggested innovative techniques.

After evaluating several conventional forming techniques, the project engineering and construction team selected the slipform method (19). The high densities of reinforcing steel, the large numbers of penetrations, and the stringent location tolerances required several innovations in using slipform construction technology.

The contractor developed advanced form designs, with interior trusses for form work rigidity, to meet the construction tolerances. The high densities of reinforcing steel surrounding multiple penetrations presented severe problems. The innovative solution involved preassembly of "penetration towers" including the sleeves and large quantities of supplemental reinforcing steel surrounding these openings. This allowed timely installation of the combined assemblies, rather than individual placement of complex reinforcing which would have delayed slip form progress. The slipform techniques shortened the schedules from approximately 6 months to 21 and 17 days for the two shield walls (Fig. 4).

Precast Turbine Generator Pedestal.—Pedestals for turbine generators on nuclear projects require large and extremely rigid structures. Sizes may range up to 65 ft (20 m) high with an operating deck thickness of up to 12 ft (3.5 m). Engineering and construction requirements for the turbine generator pedestal dictate erection sequences for the condensor and other turbine building equipment. Conventional construction techniques for turbine generator pedestals involve extensive shoring and restrictions to parallel construction activities.

At one nuclear project, the desire to use a shop tubed condensor resulted in the need to handle 100 ton (90,700 kg) tube bundle assemblies. The condensor pit elevation, approximately 12 ft (4 m) below grade, made yard assembly and move-in of the condensor extremely difficult. These factors combined to require innovative approaches in design and construction of the pedestal.

Other projects have used heavy steel formwork to span between pedestal legs or embedded trusses to eliminate shoring requirements. The project team evaluated these options but identified difficulties in meet-

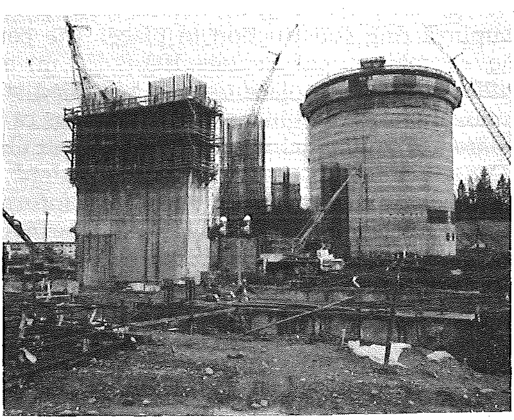

FIG. 4.—Shield Wall Slipform Construction

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

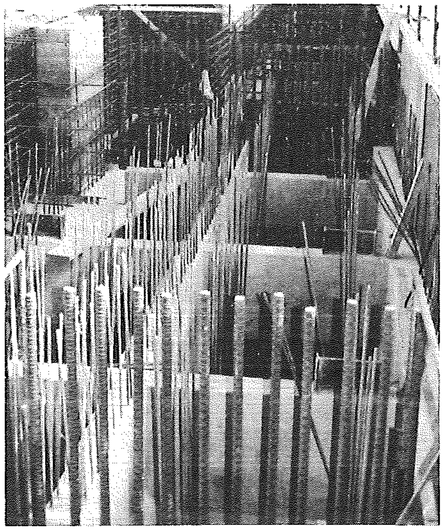

FIG. 5.—Precast Turbine-Generator Pedestal Construction

ing design criteria and in potential interferences with reinforcing steel and other embedments.

The innovation selected involved precasting large girder assemblies (up to 150 ton or 136,000 kg) in the contractor's yard, hauling to the turbine building, and setting in place with the overhead crane (12). These girders provided stay in-place forms. The contractor then installed reinforcing and other embedments, and completed the 2,500 cu yd (1,900 m^3) pedestal deck placement (Fig. 5). This technique allowed erection of the steam condensor in place, using the overhead cranes to handle the large tube bundles.

Heavy Rigging

Nuclear projects require setting very large vessels; this activity frequently forms the project critical path. Individual reactor vessels or steam generators may weigh up to 1,000 ton (907,000 kg). General arrangements of plant buildings frequently create difficult access configurations for the large vessels. This section describes the actions taken at one project to meet these demands.

This project faced scheduled pressures to set three large vessels with minimum time duration and minimum disruption of collateral work activities. The reactor building location, surrounded by the reactor auxiliary building, required innovative construction techniques. Work within the reactor building, proceeding on a three-shift basis, involved complex concrete construction. The high density reinforcing steel and embedments, combined with the complex configuration of the internal structures, created high labor intensity for this work. The congested conditions made material handling both to and within the building extremely complex.

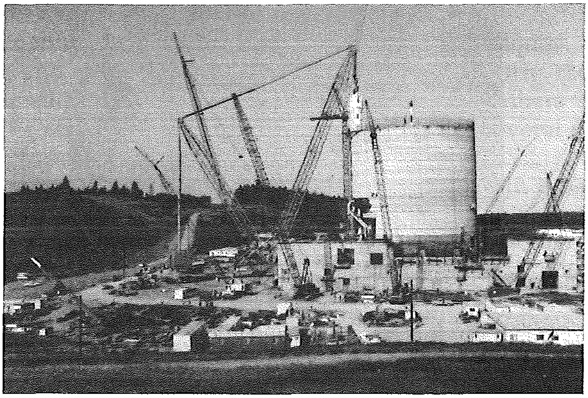

FIG. 6.—NSSS Vessel Setting Using Large Mobile Crane

The construction team considered several alternatives in planning this heavy rigging operation. Conventional approaches included construction of large temporary structures and use of lifting devices to raise, transport, erect, and set the vessels. Each of these conventional approaches required extensive disruption of concrete construction activities in both the reactor building and the adjacent structures.

Coincident with detailed planning of this work, heavy rigging technology advanced with the introduction of lift cranes having substantially increased capacities. This new technology added a further alternative of vessel setting by mobile crane from the yard. After a detailed technical assessment and comparison of cost and schedule under the two major alternatives, the construction team elected to use the advanced technology. The contractor successfully completed this operation and satisfied cost and schedule objectives (34). The advanced lifting equipment (Fig. 6) allowed setting the three vessels on three successive weekends with minimal disruption of other construction operations.

Other Examples

The construction literature includes descriptions of several other innovations on large power plant projects. Among these are: (1) Use of reinforced earth in a heavily-loaded retaining bulkhead (6); (2) use of a circular cofferdam to allow construction of a second unit in close physical proximity to an operating first unit (4); (3) special techniques in containment structure construction (24,26); and (4) steel containment vessel erection (22).

Each of these innovations included a specific technical problem forcing a study of alternatives, a joint engineering and construction involvement in both formulating and evaluating alternatives, and adequate time to consider innovative techniques and plan their implementation. Although each involved risk and required the solution of minor problems as the work progressed, the project benefits justified the use of this advanced technology.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323

CONDITIONS FAVORING INNOVATION

Although the projects described in this paper form a very small sample, they do suggest that certain project conditions may favor construction innovation. In general, the selected projects characterized by major innovation displayed several common aspects. However, there were several conditions present on some but not all projects, while other factors were absent on all projects. The innovation literature also provides further insight regarding process and conditions favoring technological advancement.

Common Conditions for Innovation.—The projects differed in scope, schedule duration, and fundamental design criteria. However, they shared several common characteristics in situation and management. Among these were:

1. Engineering and construction requirements challenged current technology on each of the projects. Technical or schedule requirements exceeding past projects forced a questioning of conventional approaches. These demands resulted in the evaluation of revised equipment or methods.
2. The project plan required mobilization of a construction planning team with sufficient lead time to develop a detailed construction schedule, to plan construction methods, and to provide input to the engineering and procurement activities supporting the planned work approaches (8,35,36).
3. The schedule allowed adequate time for detailed planning and evaluation of several alternative construction methods and equipment.
4. Managers staffed the planning team with a mix of experienced and entry level personnel, including an energetic individual willing to serve as a "champion" (28) for the proposed innovation.
5. The organizations included project management personnel with a willingness and ability to make objective cost and schedule comparisons and tradeoffs in evaluating possible innovations. These comparisons used project, rather than engineering or construction, priorities in selecting designs and methods.
6. The project engineering and design team displayed a willingness and positive approach regarding the evaluation of alternative construction methods which could require changes in specifications and drawings.
7. Managers established effective interdisciplinary coordination within the design team to allow the early identification and resolution of problems in one discipline resulting from changes in another.
8. Large construction operations gaining significant management attention, rather than smaller scale work activities that are frequently repeated, dominated this small sample of construction innovations.

Conditions Present on Some Projects.—A portion of the projects exhibited the following conditions related to the technological innovation: (1) New technology in the field was available (34); (2) the same firm served as designer and constructor or construction manager (35,36); and (3) the selected method or equipment was successfully used on a past project at a substantially smaller scale. These conditions appeared to assist in both identifying and selecting new technologies.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

Absent on All Projects.—The following work conditions, although frequently found on engineering and construction projects, were absent on all of the projects in this sample of innovative construction methods: (1) Adversary contractual relationships; (2) rigid use of standard requirements or design guides; (3) budgets preventing evaluation of several alternatives; (4) unwillingness to take risks; and (5) rigid barriers to engineering and construction communication.

Insights from Studies of Innovation.—Studies of innovation suggest the most favorable types of organization structure and climate (32,37). Peters and Waterman (28) argue that small independent teams, known as "skunk works," produce superior results.

A study sponsored by the Organization for Economic Cooperation and Development (OECD) considered the influence of industrial structures, size, and sophistication of national markets in identifying the conditions for successful innovation (25). The study identified three essential components: scientific and technological capability, market demand, and a transformation agent. The findings suggested that both large and small firms play essential roles in advancing technology, and that these roles are complementary, interdependent, and dynamic.

Other studies of innovation in the manufacturing industries concluded that: (1) Over half of the important innovations studied stemmed from independent inventors or small firms (13,14,15,20); (2) the majority of R&D projects and innovations are not very costly (31); (3) management of innovation is a corporate-wide task (5,25); and (4) innovation requires manufacturing and marketing integration (1,2,17,18).

Twiss (38) reviewed several studies of innovation and identified the following factors contributing to success: (1) A market orientation; (2) relevance to corporate objectives; (3) an effective selection and evaluation system for R&D project; (4) effective management and control of research projects; (5) a source of creative ideas; (6) an organization receptive to innovation; and (7) commitment by one or a few individuals. These studies included those granted Queen's Awards (21), pairs of similar projects (one successful and the other less so) (14), and projects abandoned during development (30).

Conclusions and Practical Applications

The present paper describes several types of engineering and construction innovations for large power plant projects, in an attempt to promote an understanding of what factors prompt construction innovation. Based on this small sample of projects, the writer has attempted to identify types of innovative conditions favoring the development and use of advanced techniques. Although not focused on construction, other studies of innovation also offer helpful insights. Findings in each of these areas (design, construction, and management) lead to both practical applications for industry professionals and suggestions for future research.

Types of Innovations.—The foregoing projects illustrate several types of innovations: (1) Changes in construction methods or sequences; (2) expansion or new application of a special technique; (3) scale-up of previous method; (4) change in design to accomplish the same function at lower cost, in a manner similar to value engineering; (5) simplification

J. Constr. Eng. Manage., 1984, 110(3): 311-323

of design requirements and construction operations; (6) changes in planned construction methods to allow more favorable engineering techniques; and (7) use of alternative materials or equipment. This variety suggests that managers should require investigation of all possible opportunities for use of advanced technology.

Project Situation and Innovation.—The examples of innovation in the study sample allow an interesting identification of conditions present on some or all projects present on different projects, or absent on all projects. A comparison of the conditions present on different projects supports the conclusion that 3 project conditions strongly favor construction: (1) Strong and unbiased management commitment to select the technologies that best support project goals; (2) early involvement of representatives with the authority to commit each segment of the project organization influenced by the innovation; and (3) effective information flow within the project team to identify and resolve problems resulting from new technologies.

Prior studies of innovation in other types of business suggest that: (1) Organization structure and climate influence the development and use of advanced technology; (2) market demands and conditions strongly influence the process; and (3) relevance to corporate objectives is essential. Although there are no empirical data available regarding the applicability of those conclusions to innovation in construction, studies of several other types of industries also support those same conclusions.

Practical Applications.—Managers seeking to improve innovation performance either in construction firms or on specific projects should establish the commitment, involvement, and information flow suggested by the aforementioned projects. Creating a climate in which traditional approaches are questioned is one way that will satisfy those conditions.

Early construction involvement and knowledge of the owner's desires, competitor's activities, and supplier's advances also appear helpful in promoting innovation. Finally, recognition by management of the opportunities and returns provided by the use of advanced construction technology should stimulate an increased emphasis on innovation in corporate objectives.

Opportunities for Future Research.—The conclusions from this limited sample of large generating station projects suggest important opportunities for future research to improve the rate of technological advancement in the U.S. construction industry. First, a framework to classify construction technology will assist in identifying and analyzing innovative procedures. This framework should include the resources, methods, and operations that comprise any specific construction technology. It should permit the determination of state-of-the-art technologies, as well as the identification of potential improvements in construction.

Secondly, the studies of innovations in other industries suggest that a similar investigation of technological advancement in construction is merited. Critics may judge this task unchallenging. Despite opposition, the U.S. construction industry includes examples of many types of technological advancements deserving investigation. This research should describe the process at the industry, firm, and project levels and should determine the major differences between the progressive and the static.

Finally, researchers should investigate relationships between research

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

strategy, business strategy, and innovation performance. Studies by the Business Roundtable (7,9,10) indicated that managers will invest in construction R&D only when the potential returns exceed that of product or process advancement. Investigating the role of strategy could assist in identifying these returns.

Industry professionals, government policymakers, and researchers each have a role in improving U.S. construction innovation. Foreign competitors demonstrate the opportunity and feasibility of technological advancement. The actions suggested in this paper should increase U.S. construction cost effectiveness and, thereby, improve the international competitiveness of our basic and construction industries.

Appendix.—References

1. Abernathy, W. J., Clark, Kim V., and Kantrow, A. M., *Industrial Renaissance Producing A Competitive Future for America*, Basic Books, Inc., New York, N.Y., 1983.
2. Ansoff, H., and Stewart, J., "Strategies for a Technology-Based Business," *Harvard Business Review*, Nov.–Dec., 1967.
3. Barrie, D. S., and Mulch, G. L., "The Professional CM Team Discover Value Engineering," *Journal of the Construction Division*, ASCE, Vol. 103, No. CO3, Proc. Paper 13199, Sept., 1977, pp. 423–435.
4. Burket, J. P., and Kuo, H. J., "St. Lucie No. 2 Foundation Construction," *Journal of the Construction Division*, ASCE, Vol. 107, No. CO2, Proc. Paper 16315, June, 1981, pp. 398–404.
5. Burns, T., and Stalker, G., *The Management of Innovation*, Tavistok Publications Ltd., U.K., 1966.
6. Bush, R. Y., Ghadiali, B. M, "Reinforced Earth Used At the Palo Verde Nuclear Plant," *Journal of the Construction Division*, ASCE, Vol. 107, No. CO1, Proc. Paper 16113, Mar., 1981, pp. 121–126.
7. Business Roundtable, *Construction R&D In a Research Program and Strategy to Foster Technology Advancement in the U.S. Construction Industry*, A Report of the Construction Technology Area of the Construction Industry Cost Effectiveness Project, 200 Park Ave., New York, N.Y., Nov., 1981.
8. Business Roundtable, *Integrating Construction Resources and Technology Into Engineering*, Report B-1, 200 Park Ave., New York, N.Y., Aug., 1982.
9. Business Roundtable, *Technological Progress in the Construction Industry*, Report B-2, 200 Park Ave., New York, N.Y., Aug., 1982.
10. Business Roundtable, *Construction Technology Needs and Priorities*, Report B-3, 200 Park Ave., New York, N.Y., Aug., 1982.
11. Business Roundtable, *More Construction For the Money*, 200 Park Ave., New York, N.Y., Jan., 1983.
12. Shetty, R., and Ellis, G., "Partially Precast Turbine-Generator Pedestals Eliminate Shoring," *Energy Business*, Third Quarter 1982, pp. 16–21.
13. Enos, J., *Petroleum Progress and Profits: A History of Process Innovation*, MIT Press, Cambridge, Mass., 1962.
14. Freeman, C., *Success and Failure in Industrial Innovation*, Center for the Study of Industrial Innovation, University of Sussex, 1972.
15. Freeman, C., "Science and Economy at the National Level," in *Problems of Science Policy*, OECD, Paris, 1968.
16. Habush, A. L., "Construction and Site Work," *Nuclear Engineering International*, Dec., 1969.
17. Hayes, R. H., and Wheelright, S. C., "Link Manufacturing Process and Product Life Cycle," *Harvard Business Review*, Jan.–Feb., 1979, pp. 133–140.
18. Hayes, R. H., and Wheelright, S. C., "The Dynamics of Process Product Life Cycles," *Harvard Business Review*, Mar.–Apr., 1979, pp. 127–136.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

19. Hsieh, M. C., and King, J. R., "Slip Forming of Heavy Reinforced Concrete Shield Building," *Journal of the Construction Division,* ASCE, Vol. 108, No. CO1, Proc. Paper 16879, Mar., 1982, pp. 63–73.
20. Jewkes, J., Sawyers, D., and Stillerman, R., *The Sources of Invention,* St. Martin's Press, London, 1958.
21. Langrish, E., *Wealth From Knowledge, A Study of Innovation in Industry,* The MacMillan Co., New York, N.Y., 1972.
22. Lebre, R. N., "Construction of FFPF Containment Vessel and Lock," *Journal of the Construction Division,* ASCE, Vol. 102, No. CO2, Proc. Paper 12177, June, 1976, pp. 325–334.
23. Nerses, H. M. G., and Tatum, C. B., "Fort St. Vrain PCRV Bottom Head Construction," *Journal of the Construction Division,* ASCE, Vol. 101, No. CO2, Proc. Paper 11394, June, 1975, pp. 391–402.
24. Olyniec, J. H., "Bellefonte Primary Containment Structure," *Journal of the Construction Division,* ASCE, Vol. 107, No. CO4, Proc. Paper 16699, Dec., 1981, pp. 679–694.
25. Organization for Economic Cooperation and Development, *The Conditions for Success in Technological Innovation,* OECD, Paris, 1971.
26. Paulson, K. L., "Construction of Post-PWR Containments," *Journal of the Construction Division,* ASCE, Vol. 102, No. CO1, Proc. Paper 11981, Mar., 1976, pp. 213–225.
27. Paulson, B. C., Jr., "Designing To Reduce Construction Cost," *Journal of the Construction Division,* ASCE, Vol. 102, No. CO4, Proc. Paper 12600, Dec., 1976, pp. 587–592.
28. Peters, T. J., and Waterman, R. H., Jr., *In Search of Excellence,* Harper and Row, New York, N.Y., 1982.
29. Pienado, C. O., Plaehn, J. L., and Way, W. J., "Fort St. Vrain Prestressed Concrete Reactor Vessel—Progress of Construction," Preprint 1068, ASCE Annual and Environmental Meeting, Chicago, Ill., Oct. 13–17, 1969.
30. Reekie, W. D., *On the Shelf,* Center for the Study of Industrial Innovation, 1971.
31. Seiler, R., *Improving the Effectiveness of Research and Development,* McGraw-Hill Book Co., New York, N.Y., 1965.
32. *Successful Industrial Innovations,* National Science Foundation, Washington, NSF 19-17, Washington, D.C., 1969.
33. Tatum, C. B., "Innovations in Nuclear Concrete Construction," *Journal of Construction Engineering and Management,* ASCE, Vol. 109, No. 2, Paper No. 17997, June, 1983, pp. 131–145.
34. Tatum, C. B., "Heavy Rigging for Nuclear Projects," *Journal of Construction Engineering and Management,* ASCE, Vol. 109, No. 1, Paper No. 17772, Mar., 1983, pp. 48–60.
35. Tatum, C. B., and Teague, F. G., "Managing the Engineering/Construction Interface for Improved Project Performance," *1981 Proceedings of the Project Management Institute—INTERNET Joint Symposium,* Sept. 28, 1981, Boston, Mass., pp. 157–169.
36. Tatum, C. B., and Rezak, W. D., "Integrated Planning Shortens Schedules and Reduces Costs," *Power Engineering,* Vol. 83, No. 1, Jan., 1979, pp. 54–57.
37. *Technological Innovation: Its Environment and Management,* U.S. Department of Commerce, Washington, D.C., Jan., 1967.
38. Twiss, B. C., *Managing Technological Innovation,* 2nd ed., Longman, London, 1980.

Downloaded from ascelibrary.org by Mississippi State Univ Lib on 07/05/19. Copyright ASCE. For personal use only; all rights reserved.

J. Constr. Eng. Manage., 1984, 110(3): 311-323