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Contractual Relationships: An Essential Ingredient of the Quality-Assurance System and Other Quality-Control Papers

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Transportation Research Record 762

page 17, column 2, reference 4
Change "1976" to "1966"

Transportation Research Record 778

page 36, column 2, line 20
Change "$6000" to "$660 000"

Transportation Research Record 790

page 74, column 1, Equation 1
Change to "$Y = b_0X_0 + b_1X_1 + b_2X_2 + b_3X_1^2 + b_4X_2^2 + b_5X_1X_2$"

page 75, column 1, Table 1
Change "Variable" column to
"Variable
X_0
X_1
X_2
X_1^2
X_2^2
R^2"

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page 2, column 2
Insert the following before the last paragraph:

"The speakers present papers that indicate how they have taken steps to reduce such adversary relationships in contractual work, and provide various evaluations of the resulting work. The various papers are placed in proper perspective to provide an overall introductory picture of the subjects to follow this introduction. Three teams of three authors each present viewpoints on three projects, and two authors add their thinking to the seminar."

"This seminar examines three other projects, each of which is addressed by three speakers with three different points of view, namely the owner's, the contractor's, and the engineer's or the Federal Highway Administration's representative. The projects are

1. West Virginia Department of Highways Quality Assurance Program;
2. Eisenhower Memorial Tunnel, Second Bore, in Colorado under Loveland Pass; and
3. Pittsburgh's South Busway.

"In addition we have

1. A paper by two researchers from Virginia.
2. Some thoughts by a service engineer of a large corporation who is constantly out in the field looking at all these problems and thus is in a position to observe what is going on."

Transportation Research Record 797

page ii, price should be $7.20

Transportation Research Record 816

page 34, Table 6, line 9, column "Realistic Saving"
Footnote b-Change to "0 to 3.8"
Change "Annual liters of fuel saved . . ." to "1000's of liters of fuel saved annually . . ."

page 29, column 1, line 21
Change "millileters" to "milliliters"

Transportation Research Record 834

page ii
Change subject areas to 13, 15, 25
Change mode to 01 only

Preprint Volume for the National Seminar on Portland Cement Concrete Pavement Recycling and Rehabilitation

page 94, column 2, last line
Change "a 0.241-cm (3/4-in.)" to "0.241-cm (0.095-in.) diamond sawblades at 1.9 cm (3/4 in.)"

page 96, column 2, paragraph 2, line 3
Change "(3/15-in.)" to "(3/16-in.)"

page 98, Figure 33, line 3
Change "apepar" to "appear"

page 98, column 2, line 5 below Figure 35
Change "(51,000 sq. yds.)" to "(57,000 sq. yds.)"

NCHRP Report 238

title page, author's name
Change "Shebr" to "Shelar"

NCHRP Synthesis of Highway Practice 66

page 5, caption for Figure 3
Change to ". . . as a type II . . ."

NCHRP Synthesis of Highway Practice 69

Foreword, page iv
Delete paragraph 3

page 13, Table 2, item 2.6
Change formula to $T_t = \Sigma P_i(t_i + \sqrt{h})$

page 41, column 2
Change formula to $T_t = \Sigma P_i(t_i + \sqrt{h})$

page 45, Table 15, title
Change to "GUIDELINES FOR SERVICE CHANGES: (Port Authority of Allegheny County)"

page 86, box under Toronto, item 2-6
Change formula to $T_t = \Sigma P_i(t_i + \sqrt{h})$

NCHRP Synthesis of Highway Practice 76

page 2, line 5
Change "$50" to "$25"

page 7, column 2
Change "i = 1" to "l = 1"

i=l to i=1

page 13, Table 9, under Pennsylvania
Change "10%" to "100%"

page 16, column 1, line 18
Change "$50" to "$25"

page 23, column 1, line 29
Change "$50" to "$25"

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Contractual Relationships—An Essential Ingredient of the Quality-Assurance System

EDWARD A. ABDUN-NUR

The quality-assurance system is described briefly as a total engineering or systems approach to quality assurance that comprises not only the technical facets of construction but also the nontechnical facets (political, legal, economic, social, environmental, and human) that should be part of all good engineering. It shows that contractual relationships that are a subsystem of the overall system have been traditionally an adversary relationship between the owner and contractor and thus have slowed the work and raised the cost. Frequently they have resulted in claims that were fought in courts. Defusion of such adversary relationships by equitable and fair specifications and contract documents and by engendering a team effort does away with all these negatives and, therefore, is advantageous to everyone concerned.

In a paper entitled, "What Is the Quality-Assurance System?" (1), I attempted to answer this question. Quality is defined as that of the finished project or structure, judged by how well it serves society physically, functionally, emotionally, environmentally, and, of course, economically--in other words, total quality.

This definition, because it is a total approach to quality, requires the systems approach to achieve it. What is the systems approach? The systems approach is more in the attitudes and ways of thinking than in formal procedures and methodology--it questions the obvious, it doubts long accepted conclusions until tested against others. Nothing is assumed to be true; every assumption is subject to inquiry.

Quality assurance, in its simplest terms, is a composite of everything that is done (studies, research, investigations, design, conclusions, communications, and feedback) to assure management that the right decisions are being made and that the right final things are being done. The earlier paper on the subject presented a chart, which is repeated here as Figure 1 (1). This shows graphically the high points of the quality-assurance system in construction.

DESCRIPTION

Initially, the need for some project is sensed by a politician or brought to his or her attention by interested groups, or, if a private project, the need for the project might be realized by the management of some company in order to carry out its work and growth most effectively. In our present day society, no matter how the idea gets started, one needs to keep in mind not only the technical and economic problems, but the human, environmental, and aesthetic factors, as well as legal, financial, and other miscellaneous items that have to enter the equation in order to be able to set up a time schedule and financing arrangements. The latter are the social factors that must be taken into consideration if the construction is to proceed smoothly and uninterrupted. If these factors are not carefully studied and planned and the various problems addressed and solved, then difficulties and delays will ensue and costs will escalate. It is essential, therefore, that the engineer get involved at this stage so that his or her input goes into the overall thinking. Otherwise, the engineer will inherit a project to design that ties one's hands behind one's back in many ways because he or she did not make sure that engineering ideas got into the overall thinking.

In essence then, quality assurance is a system that deals with the procedures for obtaining the quality level of construction needed for a project to perform the functions intended and to do so within the various human, social, environmental, and economic requirements and constraints. It encompasses the determining of the needs and will of the people or of an enterprise; political considerations; human, social, and environmental factors, and how these influence design, specifications, contractual relations, feedforward, production, quality control, sampling, testing, charting, inspection, decision making, and feedback; and the interactions of all these facets of the system with one another.

The details of how such a system should work can be found in the earlier paper (1) and need not be repeated. For this systems approach to be successful, communication becomes one of the most important facets of the whole. With proper communication everything moves smoothly and problems are solved, but without it, arguments develop and tempers get heated and often the work is delayed, costs escalate, and claims and counterclaims wind up in the courts, where only the lawyers will gain in the process.

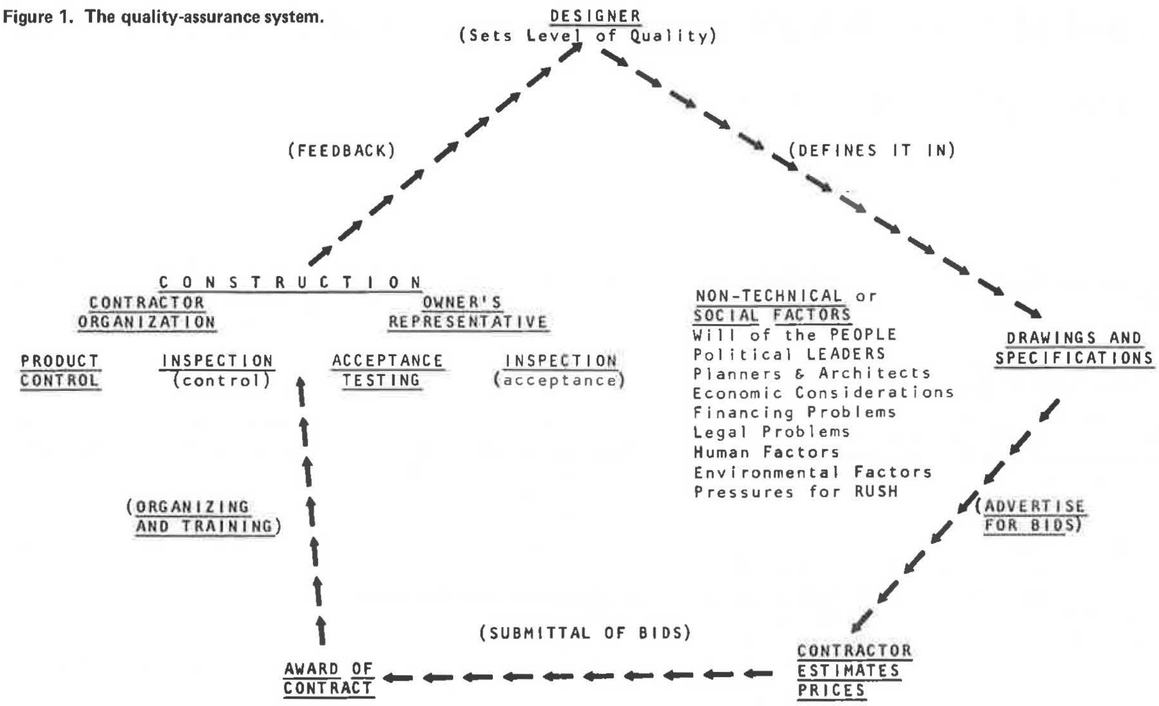
CONTRACTUAL RELATIONSHIPS

There is nowhere a greater need for smooth and effective communications for the success of the system than in the contractual relationships subsystem. One facet of contractual relationships brings up the question of how to reduce and defuse the adversary relationship that is so common in construction. This adversary relationship turns the work into a battlefield instead of what it should be--a cooperative effort between the owner and contractor, as a team, to get the job done most expeditiously and at the lowest cost consistent with the quality needed.

Some of the most important factors that lead to this adversary relationship are as follows:

1. The general practice of having specifications full of provisions such as, "as directed by the engineer," "as approved by the engineer," "as determined by the engineer," and "in order to satisfy the engineer," forces the contractor to bid more on the engineer than on the physical work. The engineer is left with the power to determine everything.
2. All contingencies are usually left to the contractor (the engineer even disclaims responsibility for the accuracy of information supplied in the contract documents, such as subsurface information that comes from the engineer's own investigations). This raises the cost, because the contractor has to allow contingencies for all this. Actually, rarely do all the contingencies come about, and thus the contractor is left with funds for contingencies that did not materialize and can increase his or her profit. It is much better to have the owner assume the contingencies and pay for them when they occur. This also saves arguments and heated tempers.

Figure 1. The quality-assurance system.



3. Arbitrary decisions by the owner's representatives are frequently made. These increase the cost because the contractor has been burned before and thus has allowed contingencies for such capriciousness.

4. Unrealistically tight limits that cannot be met realistically due to nature's variability abound in most specifications.

5. Bidding for the lowest price among unequal contractors results in poor work most of the time. A Hindu sage once said, "The bitterness of low quality remains long after the sweetness of low price is forgotten."

6. Specifications are meant to be a means of communication--that is, if they are clear and fair. Specifications should say what they mean and mean what they say; this is rarely the case. Jacobi wrote (2, p. 130):

> We should first try to establish communication, which leads to knowledge, which leads to trust, which leads to mutual respect....
>
> Once you get the communication, the trust, and mutual respect, one can at least see where individual positions differ and then find a common ground.

CONCLUSIONS

In the last few years I have reported on two projects where successful steps were taken to reduce the adversary relationship:

1. The Illinois Toll Highway, where there were some 65 contractors, hundreds of suppliers, and 24 consulting firms. It had less than one percent in claims, and all were settled through fair and friendly communications. This was because of team effort and realistic specifications that were in tune with nature. After all, nature does not read specifications.
2. Armco project 600, where the contractors turned back a portion of the money saved due to team effort and realistic specifications that were in tune with nature.

In closing, the Baltimore subway project has used approaches that have resulted in a cooperative relationship and smooth progress of the work. So, the trend appears to be for owners and contractors to work together as a team.

REFERENCES

1. E.A. Abdun-Nur. What Is a Quality-Assurance System? TRB, Transportation Research Record 613, 1976, pp. 51-55.
2. How the U.S. Performs on the World Stage. Fortune, Vol. 101, No. 10, May 19, 1980, pp. 124-130.

Quality Assurance—A System in Practice

G.W. STEELE AND F.T. HIGGINS, JR.

The trend toward rapid highway construction and maintenance operations has resulted in certain deficiencies in the classical specifications and procedures of past years. This has resulted in a decision to begin an ordered restructuring of the system then in existence. The objective was eventual establishment of a quality-assurance system that would be adequate for the department's needs and use the resources that would be made available. Major areas that have been substantially affected by the decision are briefly discussed. These areas include training, specifications, sampling and testing, information handling, and the owner-contractor relations. Changes noted that have been implemented in these areas include: (a) technician certification, (b) routine application of the concepts of probability, (c) clear definitions of the contractor's responsibility for quality control and the department's responsibility for acceptance, (d) use of contractor-developed data by the department, (e) development and application of rapid test and evaluation methods, and (f) the routine use of electronic data processing in daily operating procedures. Based on the favorable results obtained, performance specifications are workable, and the continued use of systems engineering techniques is the most practical way to maintain an overall course of action that is directed toward the achievement of our goal—a quality-assurance system that works in practice.

When we speak of a quality-assurance system we are actually speaking of a system that involves quality control, design, maintenance, planning, and environmental, social, and many other incidental factors that relate to human and natural resources (1-4). The total quality-assurance system can be illustrated as shown in Figure 1.

The role of quality assurance within this context is to verify, audit, and evaluate the quality factors that affect the design, specifications, production, construction, maintenance, and use of a product or service. Quality assurance used in this manner represents management's concern for quality as well as management's efforts to ensure quality.

Concern has been expressed during the past decade about the need for more homogeneous, rational, and significantly applicable decisions with regard to quality of highway construction and maintenance materials. Together with this concern has come considerable information and development of concepts. This concern and the attendant outgrowth of conceptual development resulted from the realization that the classical pre-1960 specifications and acceptance procedures were not sufficient for current highway construction and maintenance operations.

The state of the art of quality assurance and acceptance procedures for highway construction materials, current and predicted, has been addressed on a national level (5). Attention has been focused on a multitude of different, although related, approaches to improved quality and acceptance decisions. A few of those many different approaches involve such often heard terms as "rapid test method", "end-result specification", "statistical specification", and "automatic data processing systems approach". However, it has been the experience of the West Virginia Department of Highways that a combination of many of these various approaches is necessary in order to provide an efficient quality-assurance program. Our needs for the future require the development of systems that involved all of the factors shown in Figure 2.

It was recognized that a comprehensive quality-assurance system would have to be composed of two separate and distinct subsystems--that of process control and that of acceptance sampling, inspection, and testing. Process control is, of course, the responsibility of the producer of the product, that is, the contractor (see Figure 3). Acceptance inspection sampling and testing are the responsibility of the user, that is, the transportation agency (see Figure 3). Further, an optimized quality-assurance system must balance the need of the producer and user for a decision at the earliest practical time against the need for delaying a decision to the latest practical time.

PERFORMANCE SPECIFICATIONS

Accordingly, a quality-assurance system ceases to be strictly a project activity, because acceptance decisions must be made throughout the full range of the elements that comprise the system. Conversion to performance specifications seemed the best method to accomplish this. Also, the department thought that this conversion (from the classical pre-1960 specifications to performance specifications) should be an evolutionary process, rather than a revolutionary process. This approach, along with a permanent cooperative training program and regularly scheduled industry-department communication sessions have allowed the contracting industry to be prepared to accept its responsibility for the quality control of the production process.

Quality-assurance systems, as used by the West Virginia Department of Highways and as used in this paper, denote in general terms the following: a total procedure for the acceptance of highway construction or maintenance materials based on specification limits, statistical criteria for evaluation of central tendency and variability, input of process control and acceptance testing, and decision criteria--all evaluated by using automatic data processing equipment. The end-result decision produced by the system is one that culminates in required quality-control adjustments by the contractor and either increased or decreased levels of acceptance sampling and testing that are necessary to maintain an acceptable risk level for the department.

The development of these systems could not have been successful without access to electronic data processing (EDP) equipment. Systems logic has been available to highway engineers and planners for several years. However, it was not until the relatively recent past that the hardware and software necessary to process and evaluate larger quantities of data on a near-real-time basis became available to an appreciable segment of the highway engineers who were principally concerned with quality assurance. Although the computer has been with us as a tool in highway departments since the mid-1950s, only in recent years has it been routinely used for the application of engineered systems (6).

Implementation of the conversion to performance specifications has been carefully programmed and practically paced. The pilot program for our quality-assurance system was initiated in late 1964 with the implementation of Highway Planning and Research (HPR) Project 18 (7-10). This project was designed to evaluate and define what was considered to be satisfactory materials construction and to provide practical performance specifications for consideration. This project has been completed and the above goals achieved.

We decided early that only through the concepts of probability could we hope to develop a

Figure 1. Elements of the quality-assurance system.

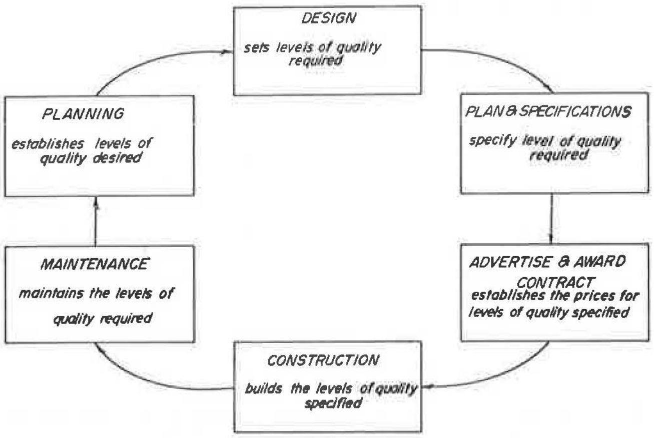


Figure 2. Quality assurance.

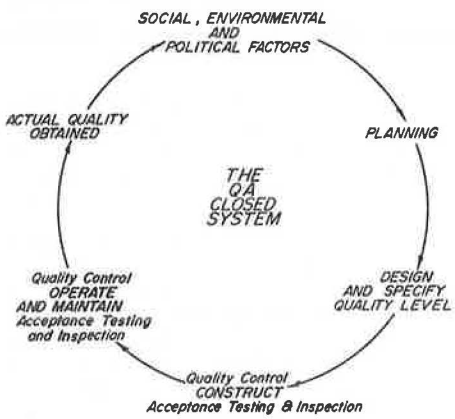
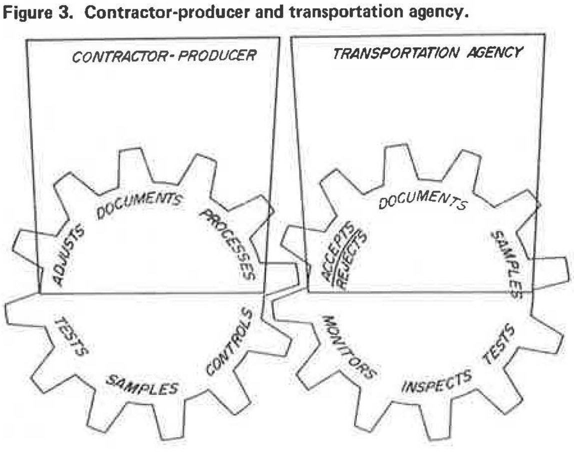


Figure 3. Contractor-producer and transportation agency.



satisfactory program. In developing these concepts, we recognized three basic considerations. These have been defined in various ways, but the following are perhaps the best known and most widely quoted (11):

1. What do we want?
2. How do we order it? and
3. How do we determine that we got what we ordered?

Some facts quickly became evident. The first was that we could not realistically define what we wanted in quantifiable terms. Although we had plenty of construction projects that could be judged fully acceptable from an engineering standpoint, we knew they had been accepted as substantially rather than as fully complying with the specifications under which they were constructed. Further, inspection and testing had been conducted under the traditional judgment procedures so that the resulting test data probably contained appreciable bias. Therefore, if a quantifiable system was to be adopted, we needed to know the true construction parameters of acceptable work under such a system.

The first priority, therefore, was to initiate a research program that had designed experiments to be conducted independently and on ongoing projects. Through these experiments, a realistic measure of the typical level and variability of the characteristics of our major construction and materials items was obtained. This information was then used to establish realistic, practical, and enforceable specification limits and acceptance procedures. These specifications focused on four major construction items--portland cement concrete, bituminous concrete, aggregate base course, and embankment construction.

All prototype specifications were field tested under the research program through experimental projects. Therefore, when finally adopted for general use, we knew we had a workable specification. The department's standard specifications since 1965 have been in a gradual state of evolution and change due to our research findings and the systems approach to our overall quality-assurance program. Current specifications give the responsibility for quality control to the contractor (3). He or she must have a qualified technician and develop a quality-control plan that details the type and frequency of sampling and testing that are deemed necessary to measure and control the various phases of the work. Current specifications also specifically state that acceptance inspection and testing is the department's responsibility. Our specifications are somewhat unique because the contractor's data may be used by department inspectors as part of their acceptance tests. This approach is fully consistent with the philosophy that the owner should perform only that inspection that is necessary to ensure that the consumer's risk is within acceptable limits (1). It should also be noted that most of the tolerances that currently appear in our specifications have been adjusted to more realistic levels as a direct result of our research findings.

From the beginning, we divided our quality-assurance system into two distinct functions:

1. Process control by the contractor and
2. Acceptance inspection and testing by the department (see Figure 3).

Competent industry and agency personnel are required to accept responsibility for their individual functions and produce complementary results. Training and recognition of such personnel are essential.

A cooperative program for the certification of technicians was initiated in 1965 (12,13). This was a joint industry-department effort, directed by a committee composed of representatives from both areas. In addition, the department has a program for the certification of several categories of inspectors. Also, in 1979 the department adopted a new classification based on the transportation engineering technician series administered by the Institute for Certification of Engineering Technicians.

A continuing annual training and certification process keeps the program up to date. The program has been well received and the use of a qualified technician by industry is now a specification requirement on all department projects.

Some contractor-producer organizations may feel that the costs associated with a contractor quality program are a disadvantage to their organizations. However, the greater majority of contractor-producer organizations that have contractual relations with us believe that the advantages far outweigh any disadvantages. They report that some of the more significant advantages are as follows:

1. Conflicts between the department and the contractor-producer are greatly reduced because there is no longer a question of test value validity and test results are available to the contractor-producer sooner,
2. The contractor-producer can control the number and quality of testing personnel necessary for control of the product and does not have to wait for the department technician to start production,
3. The contractor-producer is able to make better use of good but borderline materials by having control of the process, and
4. Faster test results and knowledge of trends allow more positive response by the contractor-producer; this results in less loss of production and a significant reduction in production or use of nonspecification material.

To further our communication with industry, periodic meetings are held with representatives of various producer organizations to discuss common problems and future developments. These meetings have provided a means for the review of proposed changes as the state of the art advances. The meetings encourage industry input in the development of specifications and quality-assurance systems. In addition, monthly meetings that include the department and the West Virginia Contractor's Association provide a vehicle for the discussion of problems, review of contractor- and department-proposed changes in procedures and specifications, and service as a springboard to allow for general discussion of quality-assurance associated problems.

TESTING ERRORS

In dealing with probability specifications it is necessary to analyze the inherent and assignable causes of error in testing and to eliminate as many of these assignable causes as possible. Our efforts in this regard have included development of standard sampling and testing procedures and extension of the Aggregate Materials Reference Laboratory (AMRL) and Cement and Concrete Reference Laboratory (CCRL) standard sample concepts to our field laboratory installations on a regular basis. Industry needs the same confidence in test data and is invited to participate in the testing. Also, any supplier, contractor, or manufacturer may send his or her quality-control personnel to our laboratory for consultation and comparative testing. This policy has proved very beneficial because it gives mutual confidence to all involved parties.

Improvements that reduce testing time are always helpful and our research in this area included designed experiments for the purpose of developing rapid methods of testing. Several methods have been developed and are now operational in the system. These include the early determination of potential strength of concrete cylinders by means of the maturity concept and an alternate capping procedure for concrete cylinders (14-16).

It was obvious from the beginning that the processing, evaluation, storage, and retrieval of data would become a major consideration. Under the relatively light work loads that had developed the conventional specifications, it was not uncommon for engineers at central headquarters to be intimately familiar with detailed data from every major project site. Under these conditions the human mind could make sound engineering judgments on a real-time basis. As the work load increased, it became necessary to make maximum use of EPD. Many factors were involved as we progressed toward optimization of this activity. Standardization of forms, documentation storage, retrieval, and distribution methods had to be approached so the end result would be workable. One innovation we use is the combining of a source document and the EDP input into a single item without the need for intermediate clerical processing. As data are developed in the field, they are recorded on 40-column punch cards by using a small portable punch board, or markscan forms, or directly on magnetic tape. All mediums are directly readable by the computer. We have become operationally dependent on EDP in our quality-assurance system.

SUMMARY

The steps that lead to where we are today started with the careful determination of the construction and materials characteristics associated with satisfactory work. This gives the answer to the first question, What do we want? The next step is the development of prototype specifications to be used experimentally on selected projects. Concurrently, close communication with and training of department and industry personnel are necessary so that they know what is expected. This provides the information necessary for development of specifications to answer the second question, How do we order it? and the third question, How do we determine that we got what we ordered?

Any summary would be incomplete, however, without restating the concept and underlying philosophy that governed our steps toward the current quality-assurance system. The final stage of creating a transportation facility from engineering concept to accomplished work usually involves the successful completion of a legal contract between the owner and the contractor. The owner is motivated by a desire to obtain a completed facility that complies fully with the contract documents or that exceeds the requirements in these documents and to achieve this end at minimum cost. The contractor is motivated by a desire to provide a completed facility that will satisfy the owner by means that will yield a suitable profit margin. These motivating factors, although they are fully compatible when viewed on an overall basis, can cause the adversarial factors of this relationship to be magnified to the detriment of both parties in the long run. Conversely, a cooperative approach between the two parties can lead to a greater probability of each realizing their individual goals (i.e., minimization of cost to the consumer and maximization of profit to the contractor). These basic motivators have, however, resulted in differing approaches by differing agencies in an attempt to obtain better contractual methods for achieving these desirable goals. In the usual case, monetary rewards, labeled by some a negative approach (i.e., the price adjustment downward for failure to achieve a specified quality in the product), have been placed in the contract documents. Such methods are workable and have been used widely at various times in the construction industry.

The debates over the positiveness or negativeness of such approaches have generally served only to obscure the real issues. One persuasive argument is that a bonus for good work is psychologically an excellent motivator; a good case can also be made that a cost reduction for deficient work is an equally persuasive motivator. In either case, the consumer must eventually pay the full cost of the product since it is elementary that a contractor cannot subsidize the contracting agency.

The intent of all such approaches, whether they result in increases or decreases in payment, is to provide legal mechanisms that will, by contract, reward the contractor whose quality equals or exceeds the specification requirements and to likewise place at a disadvantage in the construction market the contractor who provides a product quality level that is less than that specified. When this fact is recognized by all parties concerned, discussions of the various means by which this intent can be achieved are inevitably fruitful. We have moved consistently toward performance specifications. Our aim is to allow the contractor as much latitude in using optional materials and methods as possible so he or she can select the most economical ones. Performance specifications contain sampling plans and acceptance criteria so that all parties concerned know at the time of bidding the quality level required and how it is to be determined. Our specifications encourage the contractor to develop strong quality-control programs. Such programs provide timely information useful in controlling the project, especially in correcting deficiencies before they get out of control and in maintaining the optimum scheduling of the project.

Communication is an essential ingredient to mutual satisfaction with any legal contract. This should include those regular sessions for general discussion between user agencies and contracting industry as well as prebid and preconstruction meetings for specific projects. It is encouraging to note that contractors who have good quality-control organizations have indicated that an adequate quality-control program, properly administered, yields a net gain rather than a net loss (i.e., such a program improves potential profits).

CONCLUSIONS

Conclusions from our experience are as follows:

1. Performance specifications are workable, practical, and economical when properly implemented through systems-engineering techniques;
2. An agency that uses appropriate performance specifications can cause a decrease in the consumer's risk and generally can provide the opportunity for a decrease in producer's risk; in any event, the risk becomes manageable;
3. The contracting industry is fully capable and competent to provide the quality-control system necessary for production of a finished project that will meet the requirements of the plans and specifications; and
4. An agency that uses performance specifications can, by using an appropriate quality-assurance system, shift its activity emphasis to verifying the adequacy of the contractor's control systems as the principal means of ensuring that the specified facility is received.

In closing, we believe that we have demonstrated that the application of systems-engineering techniques has provided the way to achievement of our goal--a quality-assurance system that works in practice.

ACKNOWLEDGMENT

The contents of this paper reflect our views and we are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policy of the West Virginia Department of Highways or of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Process Control in Practice

R.W. THOMPSON

Our approach to process control is discussed for portland cement as this is the only phase of construction that we encounter. Our process-control system has been in existence since we first started to produce transit mix concrete in the late 1930s. Management took the position from the start that it would provide a quality product—to the point of overdesigning mixes to allow for some error in placement, handling, and testing. This was done and still is being done, to a lesser degree now, at the expense of the company. Changes in the concept of quality assurance introduced by the West Virginia Department of Highways in the mid-1960s, which were accepted by us in the early 1970s, have helped us to achieve and document goals of consistency in our manufactured product. Consistency was achieved by training technicians, setting up our own certified laboratory, maintaining complete control of our aggregates, testing cement from our suppliers, and, probably most important, switching from transit mix to an automated central mix plant. The sharing and use of test data collected by electronic data processing have been invaluable to us in our daily operating procedures. The raising of the iron curtain of communications from the owner to the contractor to us, the supplier, also contributed greatly.

Pfaff and Smith Builders Supply Company has been in business at the same location in Charleston, West Virginia, since 1902. It was founded to produce sand and gravel from the Kanawha and Elk Rivers for construction projects in the local area. Until the late 1930s it continued to produce sand and gravel and to sell wholesale products such as cement, plaster, and lath. Then, Pfaff and Smith entered the transit-mixed concrete market. The business remained basically the same until the early 1960s, when transit-mixed concrete gradually became the predominant product sold.

The first significant change in our operations came about in the early 1960s, when our dredge was modernized in order to produce higher-quality aggregates. We stayed current with the changing times by purchasing new transit mix trucks that allowed us to take on additional and larger jobs. During this period we encountered more stringent concrete specifications. This was also our initial introduction to process control.

QUALITY CONCRETE

During the mid-1960s we believed that we were producing good-quality concrete. Our aggregates were of good quality, cement appeared to be consistent, and the causes of problems in the field could usually be isolated as either the result of inconsistent testing procedures or the result of transit-mixer driver error. We were proud that we were often asked to furnish concrete after competitors had failed to meet specification requirements. We earned a good reputation and were thus able to sell quality concrete and service at a higher price. The reputation for quality and service at a higher price, although successfully sold to many local contractors, proved to be hard to sell to new contractors in our area. At this time we also realized that our gravity-fed transit mix plant was obsolete. It had been in continuous service for more than 30 years. We investigated conversion of the then-existing plant to a semiautomated plant, but this idea was quickly ruled out as too expensive and also this system would only meet the existing needs for plant capacity.

Next, we investigated the installation of a central mix plant. Although we believed that central mix was the way to go, the decision was delayed because it was very expensive, and we were uncertain that we could sell central mix concrete at the higher price needed to justify our investment. However, perhaps the main reason we delayed our decision was that preliminary plans for the Interstate system indicated that our property was in the path of one of the proposed routes.

Quality-Assurance Specifications

The West Virginia Department of Highways introduced their comprehensively rewritten standard specification in 1965. Area producers, already unhappy with the amount of concrete rejected on department of highway projects, viewed the new specifications with much apprehension. Meetings between producers and the department of highways usually ended with the attitude of near antagonism, at least from the producers' side.

During this period of transition, we declined to enter into substantial relations with contractors who were doing jobs under the specification of the West Virginia Department of Highways. For those jobs we did quote, we added up to one additional bag of cement to our cost of materials. In addition, a rule-of-thumb price of up to $4.00/yd^3 was added to the bottom line above the amount quoted to a commercial contractor for a like mix design.

As we neared the end of the 1960s, changing business conditions caused us to take a closer look at department of highways jobs. The Interstate system of roads to be built was coming closer to our area, which could mean more than 200 000 yd^3 of concrete for us. By this time our experience on department of highways jobs had improved and much less concrete was rejected. Test reports indicated good strength; however, we lacked consistency with wide ranges in strength, air, and slump.

Process Control

Good commercial laboratory facilities had not been available in our area, thus concrete test results were unreliable and costly. Therefore, we decided to set up our own laboratory and requested Cement and Concrete Reference Laboratory (CCRL) approval. This was perhaps the best decision made for our process control program. Within a couple of years we were able to effect a number of procedure changes that improved our process control.

Through our laboratory facilities and joint contractors-department of highways training programs, we have been able to train and hire personnel to handle our operations. We now have six certified concrete technicians who work in most phases of our operations:

1. One heads our dredging operation, where the aggregates are first taken from the river deposit;
2. One heads our laboratory;
3. One heads our sales department;
4. One heads our scheduling and dispatch operations;
5. One heads our equipment-maintenance program; and
6. One operates our central mix plant.

We believe that each of the above personnel has the end result in mind in decision making; therefore, our process-control program is maintained at a high level.

PLANT AUTOMATION

By 1972 the Interstate system had arrived in our area. Management realized two things:

1. If we wanted Interstate business, we had to have automated central mix; and
2. If we had automated central mix, we could meet department of highways specifications.

The decision was made to invest approximately $500 000 in a new, fully automated central mix plant to serve this potential market.

Central mix has enabled us to produce concrete to department of highways specification. In addition, it allowed us to reach a goal that we had thought was unobtainable for a producer such as ourselves (i.e., one who manufactures a diversification of mixes for multiple contractors). The goal was to meet the West Virginia Department of Highways' requirements for level 1 plant process control, which are as follows:

> All plants producing concrete that reasonably conforms to the specification requirements and that satisfies the following additional requirements will be considered to have level 1 process control:
>
> 1. The compressive strength of the concrete produced by the plant shall have a coefficient of variation of 0.15 or less and the average, compressive strength shall be equal to or greater than the specified requirement plus 2.5 standard deviations.
> 2. The air content of the concrete produced by the plant shall have a coefficient of variation of 0.18 or less, and the average air content shall not differ from the specified optimum value by more than one standard deviation.
> 3. The consistency of the concrete produced by the plant shall have a coefficient of variation of 0.20 or less, and the average consistency shall not differ from the specified optimum value by more than two standard deviations.
> 4. The plant shall maintain an adequate process control program for aggregate gradations.

CONCLUSIONS

Automated central mix has enabled us to realize some cost reduction for good process control. Within one year from opening our central mix plant we had reduced the cement content of 3000 lb/in^2, 6-bag, class B substructure concrete from a penalty content of 6.25 bags of cement to a reward content of 5.5 bags of cement. A three-year analysis of rejected concrete indicated that less than 0.5 percent of the rejections were destined for jobs for the department of highways.

Timely feedback of job information is vital if good process control is to be maintained. Once the communications barrier was overcome, we realized an improvement from most of our contractors in the ordering and scheduling of deliveries, which enables us to make better use of our equipment.

We consider concrete for department of highways' specification as preferred business and quote these jobs at or below rates for comparable commercial jobs.

SUMMARY

We look back at the 1970s as the time that we made great progress in our process-control program. It was an evolutionary rather than a revolutionary process that was guided by management direction. Central mix concrete is the only way we thought that we could maintain consistent process control. Even with central mix, we are not self sufficient. Communications, timely feedback of job conditions, and data furnished to us on a regular basis by the West Virginia Department of Highways enables us to indicate to our personnel how we are doing and the areas in which we need to concentrate. This sharing of information has enabled us to correct problems before they have a chance of getting out of control.

Overview of Quality-Assurance Program

JAMES P. DUNNE, JR.

Region 3 of the Federal Highway Administration (FHWA) recognized in the early 1960s that improvements were necessary in highway construction specifications in order to meet increased work loads. The quality-assurance system was determined to be our best approach. Our first step was to determine what the critical construction problems were. In 1965 we sponsored our first workshop on formal training for highway inspectors. In 1968 we held our first quality-assurance workshop. FHWA has also encouraged and participated with the state highway departments in administrative contracts, highway research projects, experimental projects, and demonstration projects to assist in the development of quality-assurance specifications. Indications are that the quality-assurance system is working in practice.

The region 3 Office of Construction and Maintenance of the Federal Highway Administration (FHWA) recognized in the early 1960s that improvements in highway construction specifications would have to be made to meet the expanded work load of the 1960s and 1970s in West Virginia. The quality-assurance system, as described in detail by Steele in a paper in this Record, was determined to be the best approach. A position was created within the office to promote the adoption of quality-assurance systems by the states in region 3. The first step was to determine what the critical construction problems were; management tools such as evaluations of various systems and coding were employed. During 1964-1966, we found that structural concrete, particularly bridge decks, and assignment to projects of a sufficient number of adequately trained inspectors were the items in most critical need of immediate attention.

With the cooperation of the highway departments and our divisions, we sponsored our first workshop on formal training for highway inspectors in 1965. Key state engineers and personnel associated with training attended. In 1966, a follow-up conference was sponsored by the state of Pennsylvania. The total effort was a tremendous success; all the highway departments either improved existing training manuals or developed new ones. In addition, all increased their winter training sessions and established a mutual program for the exchange of new training concepts.

In conjunction with the divisions and the state highway departments, we made a study of concrete controls from the inception of raw materials to the completed product. A formal 70-page report was published and distributed to the FHWA's Washington, D.C., office, states, and divisions for their review. This report was used as the basis for our first quality-assurance workshop, held in February 1968. As in the training workshops, the states' response was overwhelming: The completely objective approach to providing possible solutions to the concrete problems and the free exchange of ideas between states and FHWA were particularly noteworthy. Issues that received considerable attention were (a) control of water-cement ratio, air content, and plastic temperature; (b) use of trial mix methods in design; (c) acceptance of portland cement by certification; (d) gradation control of aggregates; and (e) testing of admixtures.

Since 1968, the region 3 quality-assurance workshop has become an annual event; the 15th was held in Harrisburg, Pennsylvania, in February 1981. This workshop was triregional. State highway departments, industry, and FHWA representatives from regions 1, 3, and 5 participated. This forum for encouragement of the development of quality-assurance systems has been beneficial to each of the highway departments in region 3.

The agency and our office have also encouraged and participated with the state highway departments in administrative contracts, highway research projects, experimental projects, and demonstration projects to assist in the development of quality-assurance specifications. Several of these have been described by Steele.

We have encouraged each state highway department to establish a time program or schedule that will lead to a total quality-assurance system for their construction specifications. Several states, including West Virginia, have developed a program that includes the research development, experimental use, education, and implementation phases of each specification area to be covered by a quality-assurance system.

The measurement of success of a quality-assurance system such as West Virginia's can be measured in several ways, such as work load. The West Virginia Highway Department used the same manpower in the 1970s as in the 1960s to meet a work load that was five times higher than that of the 1960s. Another measure of success is contractor response. The response of the contractors who have been involved in a quality-assurance system has, in our opinion, generally been positive, as outlined by Thompson in a paper in this Record.

NATIONAL NORMS

FHWA has recently published the 1979 Highway Condition and Quality of Highway Construction Survey (1). Although based on only a few bituminous paving projects from West Virginia, several comments with respect to the national data are noted. The quality levels were all above the 90 percent norm; many were 100 percent. The national data norm is somewhat lower than West Virginia's and lower than the 90 percent norm. The manpower distribution data indicate that the quantity per manhour exceeded the national data by a factor of two to four. The predominant classification for performing inspection and testing activities on the projects surveyed was the level-four technician. No engineers were reported on the projects surveyed.

The 1979 Highway Condition and Quality of Highway Construction Survey documents that the highway department, in its expanded program, is obtaining the level of quality desired with their existing technician-level inspection force. Although not everything is perfect, the above indicates that the noted quality-assurance system is working in practice.

ACKNOWLEDGMENT

The contents of this informal paper reflect my view and I am responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policy of the West Virginia Department of Highways or FHWA. This paper does not constitute a standard, specification, or regulation.

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Optimizing State-Contractor Relations for Improved Quality Assurance

WOODROW J. HALSTEAD AND CHARLES S. HUGHES

Differences in the performance of highways often occur, even when they are built to the same set of specifications and are subjected to similar environmental and load conditions. The differences may relate to unmeasured differences in materials and construction techniques, but they can also relate to the attitudes and skills of the people involved in building the roads. In particular, the relations between the representatives of the state (buyer) and the contractor (seller) can affect the quality of the work. Some of the potential causes of adversary relations between the state and the contractor are discussed and actions that can be taken to minimize or avoid such relations are suggested. The best course of action available to both the state, as the buyer, and the contractor, as the seller, is described as communication, competency, and cooperation. Good communication is established by preparing clear and complete specifications that take into account not only what is wanted but what is attainable at a reasonable cost. Competency must apply to both the buyer's and the seller's representatives, and all parties must recognize that their primary goal is to provide a good product and that a spirit of cooperation must prevail.

Different contractors and engineers, although they operate under the same set of specifications and comply with the specifications to the same degree, can produce highway facilities that perform differently under similar environmental and load conditions. The difference in performance may relate to unmeasured differences in materials and construction techniques, but more often they relate to the attitude and skills of the people who do the job. In particular, the relations between representatives of the state and representatives of the contractor affect the quality of the work. The effect of the relations is extremely difficult to quantify and, in fact, may not be quantifiable. However, it is important to review procedures and specifications to determine whether they are conducive to establishment of good state-contractor relations that will optimize the chances of securing the best possible results.

Since 1963, when a program of research and development was undertaken by the Federal Highway Administration, then the Bureau of Public Roads, to improve quality assurance in highway construction, the subject has been the focus of many treatises, workshops, and conferences. Almost everyone agrees that improvement is needed, but there are considerable differences of opinion as to how it should be brought about. Much of the controversy centers around the application of the principles of statistical probabilities in judging compliance to specifications and the extent to which end-result requirements can be applied as opposed to recipe or method requirements. Opinions vary from complete support of an end-result specification, based on statistical probabilities, to complete rejection of that approach in favor of a recipe specification, backed by engineering judgment. Both extremes, as well as intermediate specifications, have produced successes and failures. Consequently, one must concede that success cannot be guaranteed simply by designating the type of specification that shall be employed. It is necessary to consider all of the interacting factors and to establish, to the extent possible, the procedures and requirements most likely to produce the best results.

A review of some of the factors that affect state-contractor relations and how the relations may be optimized for improving quality-assurance techniques is the purpose of this paper.

PRINCIPLE OF VARIABILITY

Research conducted over the past 15 years has demonstrated the inherent variability of materials and construction. It is universally recognized that variations will occur around target values for all physical requirements. Much effort has gone into establishment of the amount of variation that can be considered normal for good engineering practice. The amount of variation that can be tolerated without seriously affecting the performance of a constructed facility has also been studied but to a lesser degree. In general, most measurable characteristics can be assumed to have a normal distribution, and the mathematically derived probabilities for the spread of test results can be reasonably applied as a basis for making decisions.

On the other hand, relatively little consideration has been given to ways to avoid an adversary relation between the buyer (state) and the seller (contractor). Whether or not such a relation develops depends primarily on psychological factors. In any contract, the opportunity for conflict or cooperation is present. Some organizations, either the buyer or seller, may intentionally choose to use one approach or the other to improve their position in the contract. In other cases, the psychological makeup of the buyer's or the seller's representative may decide which course is taken. Although the normal distribution curve may not strictly apply, variability occurs in the skills, attitudes, and, perhaps, even the honesty of people employed by both buyers and sellers. In relations between individuals or private companies as buyers and sellers, the less-than-desirable companies can often be spotted and ruled out on the basis of intuition or indirect evidence. However, when a public agency is involved, certain legal requirements establish restraints on the actions and decisions of that agency's representatives. These include the following:

1. Equal opportunity must be given to everyone to seek the contract;
2. Barring special circumstances, contracts must be awarded to the lowest-qualified bidder; and
3. All conditions of an established contract must be met.

Given these conditions, the public agency must not only prepare specifications and procedures that provide protection against the unqualified contractor, the requirements also must be established so that sufficient control can be exercised over the worst-qualified or least-cooperative contractor to ensure that a satisfactory product is obtained. Also inherent in the system is acceptance of the agency representative's opinion where judgment decisions are involved. In disputes, the contractor has recourse only to the courts if agreement cannot be reached by direct negotiations.

From an engineering viewpoint, the same restrictions and requirements are not necessary for all projects or all contractors. The work of a contractor of proven ability and good reputation does not need the same degree of inspection as does the work of someone of unproven ability or someone who may even be suspected of having less-than-ideal objectives. The problem for the public agency is to establish specifications and procedures that leave some degree of flexibility in the conduct of a project and in the amount of inspection and testing to be done and still comply with legal requirements.

ALTERNATIVE APPROACHES TO SPECIFICATIONS

A National Cooperative Highway Research Program (NCHRP) report reviews various aspects of quality assurance and their relation to the performance of highway facilities (1). The report emphasizes that performance is affected by many factors. Those considered are the following:

1. Political and economic requirements,
2. Traffic,
3. Environment,
4. Maintenance,
5. Materials,
6. Design,
7. Specifications,
8. Contractor performance,
9. Contractor procedures,
10. Control tests, and
11. Acceptance procedure.

The human factors of skill, cooperativeness, experience, and honesty may not enter heavily into some of these such as traffic or environment, but in others they may control how specifications are applied and create the atmosphere that determines the extent to which the job is successful.

Once the political and engineering requirements for a job have been determined and a design has been agreed on, plans and specifications must be drawn up. The manner in which these are written will influence subsequent buyer-seller relations.

Figure 1, taken from the NCHRP report (1), outlines typical steps in quality-assurance systems for highway construction. Of particular interest for this discussion are the specifications. These are shown to be either of the recipe or the performance type. Several performance, or end-result, types are depicted. The buyer-seller relations established by each of these various specifications will differ and such differences could affect the performance of the facility to be constructed.

Recipe Specifications

Recipe specifications put maximum control in the hands of the buyer's personnel. The seller is required to follow step-by-step procedures by using specified materials and equipment. A basic buyer-seller adversary relation is inherent in this type of specification, and the degree to which it can cause problems depends greatly on the attitudes and skills of both the state and contractor personnel.

Under ideal conditions, where experienced, highly skilled, and cooperative employees work together, excellent construction can be obtained and performance is optimized. On the other hand, such specifications generally leave many judgment decisions for the buyer's representative, and these can be the subject of much controversy. Adversary relations can develop to the extent that decisions could be arbitrary and not always in the best interest of securing high-quality workmanship.

Since the requirements of the recipe specifications are based on experience, often new methods or equipment are not allowed because the relation of performance to construction techniques is not known. This may lead to an inefficient and costly operation.

End-Result Specifications

Interest in end-result specifications was generated from the recognition that more than one approach or type of equipment can be used to attain satisfactory results in constructing elements of a highway or other transportation facility. End-result specifications are also a recognition that a seller's representative may be more knowledgeable and skilled than a buyer's representative with respect to construction of a facility or manufacture of a product. Consequently, this approach establishes the potential for a seller who has superior skills and equipment to provide better quality at a lower cost than can a seller who has lesser skills or less-efficient equipment.

The end-result principle is readily accepted for manufactured products that are used as components of a construction project. For materials such as portland cement concrete, asphalt, paint, and steel products, the seller is usually told only what the characteristics of the final product shall be and no attempt is made by the buyer to tell the seller how it is to be made. However, buyers (state, county, or city) are reluctant to accept totally end-result specifications for the completed product. This is true because adequate nondestructive tests for the finished product are not available. Also, complete knowledge of how to specify the characteristics of the finished product that relate to long-term performance under the expected service conditions is not available. Under an ultimate end-result approach, the buyer-seller relation could be expressed as, "You build it and I will check it out and decide if I will buy it after you have completed the job." This concept is not feasible if the product is a bridge or several miles of highway. An unacceptable product, in this case, creates almost as many problems for the public agency as it does for the contractor.

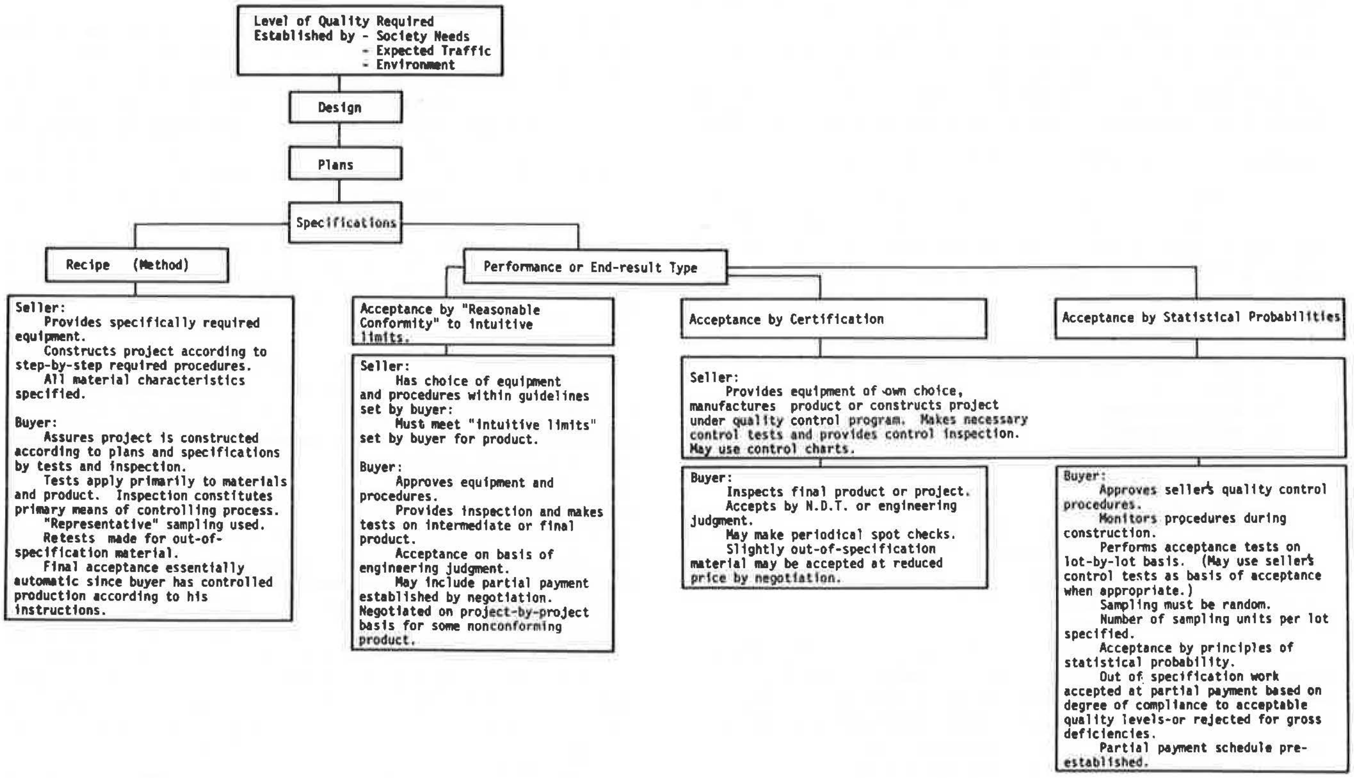
The alternative is to establish a system of lot-by-lot acceptance during each stage of construction. Sellers must be allowed as much freedom as possible to establish their own techniques. Buyers must provide inspection and final quality-assurance tests to ensure compliance to requirements. The manner in which the requirements are established, the provisions for determining whether or not the work complies to the specification, and the provisions for resolving questions concerning nonconforming work establish the conditions under which buyer-seller relations function. These will have a considerable effect on whether such relations are those of a partnership (that is, work toward a common goal of a good job accomplished without unnecessary delays or costs) or those of adversaries who each jockey for position and conditions favorable to his or her own ends.

POTENTIAL CAUSES OF ADVERSARY RELATIONS

Proliferation of Specifications

Contractors may be required to perform a certain operation for which they can find no reason; and, in fact, the reason may be obscure if not nonexistent. The requirement may have been included to prevent a practice that resulted in poor performance on one project. The intention in the specification may have been good; however, the consequence to the seller may seem to be harassment. When this happens frequently, the specifications cease to be objective and instead tend to be punitive and negative. The undesirable is stressed instead of the desirable, and a negative tone can be set for the entire contract.

Figure 1. Typical steps in quality-assurance systems for highway construction.



By the Book

Many traditional specifications have been written in exact terms with an unwritten understanding that some leeway in interpretation or variability in application can be had, depending on specific conditions at the project. However, some buyer's representatives may stick precisely to the specification book. This usually occurs when the representative is inexperienced or has been censured for employment of common-sense practices on a previous job. The result is that the seller is saddled with cost and inefficiencies, which translate into a poor buyer-seller relation. Nit-picking, instead of good, objective practices, can become a primary aspect of the inspection procedures.

Too-Close Bidding

At times a contractor may not allow sufficient profit margin and is tempted to cut cost by using low-quality materials, less-than-precise operations, or both. Once this occurs, the buyer's representative looks very closely at the contractor's practices and may tend to become overly cautious or restrictive. A loss of trust may occur under these conditions.

Price-Adjustment Systems

No contractor enjoys the thought of receiving less than the full bid price for an item or a project. However, if one assumes that a specification details an acceptable product and describes how the acceptable product will be determined, some recourse should be available to the buyer when that acceptable product is not provided. Removal or reconstruction may be possible, but in some cases it may be more advantageous to the buyer and less costly to the seller to leave the product in place and receive a reduced payment. The reduction in payment should be commensurate with the decreased performance of the product.

A possible feature to help offset negative reactions to a price-adjustment system is to have it operate both positively and negatively. The concept is controversial and may not be applicable in all situations. There are at least two occurrences that make positive price adjustments untenable. First, there are public agencies that have constitutions that make it illegal to increase the payment above the bid price. The other case would occur when the property measured is such that improvement to it would not necessarily improve the performance. In this situation, pay beyond the stated quality level is certainly questionable economically.

However, there are properties that, if improved over what is determined to be an adequate quality level, can provide performance over and above that expected. In these cases, it seems logical to pay more for additional improved performance.

ESTABLISHMENT OF OPTIMUM RELATIONS

In order to establish conditions and a climate for good relations, both the buyer and seller must recognize certain principles and adopt policies based on a fair deal for everyone.

The buyer must

1. Establish material specifications based on realistic requirements that take into account the inherent variability in materials and normal processes;

2. Establish construction specifications that spell out in advance the acceptance procedures to be applied, including price adjustments where applicable;

3. Provide for cooperative resolution of unforeseen problems;
4. Provide for correct sampling and testing techniques and assign well-trained personnel as inspectors on the job; and
5. Give prompt decisions concerning the acceptability of materials or items of construction.

The seller must

1. Set realistic targets for material properties and construction processes that ensure a high degree of confidence that the quality asked for is being provided (operations designed to be just good enough to get by will always be a source of problems),
2. Not take advantage of loopholes such as the absence of inspection or a lack of requirements that allow inferior materials to be used, and
3. Provide knowledgeable personnel who can recognize the conditions necessary for good results and apply corrective measures if the process goes out of control.

SUMMARY

In summary, both the buyer and seller have two courses open to them. The negative course of action available to the seller (contractor) might be described as circumvent, cajole, and cry. That is, if a requirement appears costly to live up to, the seller can look for ways to adjust the material or cut corners to lower costs. The buyer's representative can be cajoled into accepting materials or construction that might be questionable. If this fails, he or she can then complain or appeal for exceptions.

A similar negative course of action by a buyer can be described as coercion, criticism, and condemnation. The buyer can attempt to make the seller live up to the letter of requirements and timetables when there are good and justifiable reasons for delays or when unforeseen circumstances have indicated a need for reconsideration of the requirements. He or she can adopt an attitude of criticism--always be on the lookout for any action that might be questioned. The buyer can also condemn any insignificant deviation from requirements and thus cause unnecessary interruptions and delays.

Obviously, neither of these negative courses of action is desirable and would most likely result in inadequate performance of the product and high costs because of litigation and replaced or reworked components.

The positive alternative available to both the buyer and the seller is to adopt the principles of communication, competency, and cooperation. Good communication is established through clear and complete specifications. Requirements must take into account not only what is wanted but also what is attainable at a reasonable cost and within a reasonable period of time. The responsibilities of each party must also be clearly understood. Competency must apply to both the buyer's and seller's representatives. They must be able to recognize deviations from the normal that can lead to problems. Finally, a spirit of cooperation must exist. Representatives of both the buyer and seller need to recognize that their primary goal is to construct a good facility. The buyer's representative is not out there just to see that the buyer is not cheated, nor is the seller's representative there only to reduce costs whenever possible so as to increase profits.

The positive approach--communication, competency, and cooperation--will optimize state-contractor relations and ensure that the best quality is attained with the materials and techniques specified with fairness to both parties and maximum benefit to the public.

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Summary of Contractual Relations: An Essential Ingredient of the Quality-Assurance System

RICHARD L. DAVIS

Since competition is so much a part of life in our society, it is easy to understand how adversary relationships develop. Adversarial relations are disruptive and costly in the construction field. It is in the interest of all parties to try to reduce the waste from this friction through improved communication and understanding. It is very helpful to the completion of the job if each party is competent and cooperative.

Competition is such an important factor in the economic system of the United States that it is not surprising that it is carried to the point that it is counterproductive at times. One area in which competition often becomes excessive is in the buyer-seller relation. This relation can start out as a healthy effort by the representatives of both parties to protect the interests of their principals, but it sometimes deteriorates to the point where the representatives become adversaries. People can become so involved in the adversarial nature of this activity that they lose sight of the more important effort to produce something of value. This can be particularly true in the construction field, where the adversarial relation can increase costs and delay the completion of vital projects.

It is essential that the parties involved learn those factors that are truly important to the success of a given construction project and not allow wasteful controversy to negate its completion. Controversy is encouraged by confusion and misunderstanding about the variation in test methods and their application to specifications. Great care should be exercised in the selection of the properties that will be used to control the work and the test methods that will be used to measure those properties. A price is paid for every property measured and consideration should be given as to whether the gain in control of the project through the use of a test method is worth what it costs. These costs include not only the direct cost of testing but also the cost increases that the variation of the test method adds to the interpretation of the test results through misunderstandings and confusion on the job.

An example might help to clarify this relation. Some years ago, a state highway department was writing a specification requirement for controlling the variation of asphalt content in bituminous mixtures. They decided that a specification limit of ±0.3 percent would be set for asphalt content of bituminous concrete. I pointed out that the major component of variation is due to the distribution of the various individual pieces of aggregate. In other words, the asphalt content of large pieces of aggregate is much lower than that of smaller pieces of aggregate. Therefore, the asphalt content of a test portion rises or falls with the number of large pieces of aggregate that it contains. This is a chance variation that had been shown to have 95 percent probability limits of ±0.5 percent for bituminous concrete of the type specified. I pointed out that about 20 percent of the test results would be outside the specification limits of ±0.3 percent due to chance causes in the measuring system. This was something about which the contractor could do nothing. The state highway department said that they wanted to set a goal for contractors to strive to attain.

I went back after one paving season and asked how the ±0.3-percent specification was working. I was told that it was performing very satisfactorily. On examining the test results, a little more than 20 percent of them were outside the specification limits. No action had been taken in connection with any of the out-of-specification material. This specification was, in fact, not a specification because no mechanism was set up for eliminating any material no matter how far out of the specifications it might be. If a specification is to be written, it is important to set the limits so that they are meaningful and realistic in relation to the testing and sampling variation.

Abdun-Nur, in a paper in this Record, spoke eloquently of the need to focus on the whole process of obtaining quality in a contract or project. He urged us not to be sidetracked into only a portion of the quality picture or into fruitless controversy or adversary relations. He emphasized the importance of considering the total system for controlling quality.

Steele and Higgins, in another paper in this Record, emphasized the importance of being fair. Under our system of open bidding, unfairness nearly always results in higher costs, often without compensating benefits. They also stressed keeping channels of communications open in order to improve performance and save money.

Thompson, also in a paper in this Record, spoke of the importance of the contractor's knowing how to produce a quality product at a high level of productivity. He also spoke of the fact that the contractor could put all of his or her efforts into increasing productivity and quality under a properly devised quality system. Waste or increased costs are the result of a poor quality system, where the contractor cannot meet the required specifications no matter what he or she does because the specifications were improperly devised.

Dunn, in a paper in this Record, spoke of a proper quality-assurance program from the point of view of the Federal Highway Administration. He commented that the West Virginia Department of Highways used the same work force in the 1970s as in the 1960s to meet a work load that was five times higher than that of the 1960s. Further, although perfection was not achieved, the quality-assurance system is working in practice.

Halstead, also in a paper in this Record, spoke of optimizing state-contractor relations from the research point of view. He spoke of the problems that can arise between an engineer and contractor and how each can diminish them through reasonableness and conciliation.

Contractual Requirements and Design Philosophies Employed to Minimize Adversary Relationships: Eisenhower Memorial Tunnel, Second Bore

PHILLIP R. McOLLOUGH

The Colorado Department of Highways awarded a contract to construct the first bore of the Eisenhower Memorial Tunnel on October 3, 1967. The tunnel was opened to traffic on March 8, 1973, two years behind schedule and had a cost overrun of approximately 125 percent. Substantial difficulty was encountered in constructing the tunnel due to the bad ground conditions that existed in the eastern half of the tunnel. A redesign was necessary and the project contract was modified to a cost contract to complete the eastern portion of the tunnel. Not only did the ground conditions deteriorate, but the working relationship between the owner and contractor developed into a classical adversary relationship. With the previous construction history indelibly impressed in the owner's mind, steps were taken in June 1973 to develop a design to complete the facility by driving the second bore. Considerable attention was given to development of a workable design and equitable contract provisions that would share and minimize risks involved. The second bore contract incorporated equitable contract provisions along with two new provisions that provided for the establishment of a project review board to handle major construction disputes and escrow documents (contractor's bid documents) to serve as a basis for evaluating the contractor's bid. The escrow documents would also facilitate equitable settlement of major construction disputes. The contract for the second bore was awarded to the joint venture contractor of Peter Kiewit Sons Company and Brown and Root on August 11, 1975. The contract was completed successfully nine days early, within budget, and approximately three percent under the engineer's estimate. The contract and its provisions, along with the design, helped to produce an outstanding product.

The Eisenhower Memorial Tunnel, located on Interstate-70 approximately 95 km (60 miles) west of Denver, passes under the Continental Divide at the elevation of 3350 m (11 000 ft). The twin 2700-m (8900-ft) tunnels carried 8200 average daily traffic in 1973 and will carry about 14 000 average daily traffic in the year 2000.

As early as the 1930s, highway planners realized that a vehicular tunnel would be the ultimate answer for handling the projected traffic volume across the Colorado Rockies. Due to steep grades, sharp curves, severe winter conditions, and maintenance problems of conventional high mountain passes, the tunnel alternative was investigated. Preliminary sites were examined, and in 1943 a small bore was tunneled beneath Loveland Pass. However, extensive problems arose that illustrated the need for further studies. The result of these studies culminated in the selection of the route that follows the Straight Creek Valley, and the pilot bore along this route was completed in 1964.

Construction of the first bore and ventilation buildings started March 13, 1968, at the west portal. The project was opened to traffic March 8, 1973. The project encountered many difficulties and gained notoriety when construction costs escalated from $54 million to $108 million and completion was delayed by approximately two years.

Early in the project a number of problems were encountered with foundation materials in the west ventilation building. Many claims were submitted during this time from the subcontractor via the prime contractor to the owner.

Tunneling of the west heading proceeded relatively smoothly while the ventilation buildings were under construction. After driving 1325 m (4350 ft) on the west heading, a chamber was constructed for the installation of the shield. Simultaneously, the east heading was started and driven approximately 550 m (1800 ft) before severe structural deformation problems began to occur.

On December 6, 1969, the east heading advance was halted. Heavy loading resulted in unexpected convergence and deformation of the steel support sets in the east heading. Extensive remedial work such as rock bolting, buttress concrete, shotcrete, grouting, rock reinforcement, and jump sets were eventually required to stabilize this heading. Three months prior, excavation that used a full face shield was stopped in the central section of the mountain because the shield developed mechanical problems. This method was later abandoned.

For the next year underground construction was at a standstill while discussions ensued among the owner, contractor, consultants, and Federal Highway Administration (FHWA) engineers on methods of resolving construction problems.

On September 5, 1969, the contractor notified the owner that underground conditions existed that were beyond the scope of the contract and claimed that a breach of contract existed. A redesign of the tunnel was necessary to accommodate the difficult geological conditions encountered and the original unit-price contract was renegotiated to a cost contract to complete the tunnel portion of the project. As a result of negotiations, the owner became intimately involved with the contractor's organization and problems because the owner paid the costs directly of completing the underground work by using the multiple-drift method. In other words, the owner's supervisory personnel had to transfer their attention from payment of bid items and documentation to concern with all aspects of costs and construction methods involved. This partnership produced the desirable effect of immediately improving relations between the owner and the contractor. On January 7, 1971, construction resumed.

The owner's involvement in the first bore project varied markedly before and after renegotiation of the original contract. The owner's staff became substantially more involved in construction and administrative matters, which are generally and historically assigned to the contractor in the original contract. It was interesting to observe the improved cooperation between the owner and contractor. As a result, the work progressed at a substantially improved rate and the adversary relationships that had previously existed were, in some cases, greatly diminished or nonexistent.

Due to the success of the renegotiated contract, the multiple-drift method, and other refinements to the tunneling methods, the holing-through occurred on March 1, 1972, and the tunnel was officially opened to traffic March 8, 1973.

PROJECT PLANNING

Planning and design work started on the second bore of the Eisenhower Tunnel in June 1973. It was decided to use the in-house capabilities of the department of highways to accomplish the planning and design of the second bore. The consulting firm of Leeds, Hill, and Jewett of San Francisco was engaged to assist the department's designers on an as-needed basis in planning, design, specification preparation, and construction of the project. I was assigned the task of coordinating the planning and design efforts.

All information relative to the construction history of the first bore was reviewed in considerable detail by the design and planning group. Considerable time was employed in analyzing why the construction of the first bore met with severe difficulty and what factors contributed to those problems. Particular attention was given to the adversary relationship that developed during the construction of the first bore. The planning group concluded that the following elements should be addressed in the design, contract, and specifications for the second bore as well as in other contracts that would be used to complete the entire facility:

1. Type and number of contracts,
2. Advertising period,
3. Contract time and working hours,
4. Disclosure,
5. Safety,
6. Prequalification,
7. Contingencies and exculpatory language,
8. Payment for materials on hand,
9. Mobilization,
10. Labor adjustments,
11. Adjustment of material costs and adjustments for changes in common-carrier rates,
12. Escrow documents,
13. Cost accounting,
14. Dispute resolution,
15. Detailed plans,
16. Financing, and
17. Other elements.

The planning group considered other related elements separately that were deemed important to the administration of the contract for the second bore, such as the following:

1. Staffing of the owner's construction team,
2. Qualification of the owner's construction team,
3. Authority and lines of communication for the construction team, and
4. Training of project inspectors.

CONTRACT

The planning group considered several types of contracts that ran the gamut from a cost contract, at one extreme, to a fixed-price contract, at the other. It was concluded that the unit-price contract would be the most appropriate, considering the constraints imposed on governmental agencies. However, it was believed that the historic unit-price-cost contract typically used by government agencies could be modified to promote more equitable sharing of risks between the owner and contractor. Thus, a more equitable unit-price contract was employed for the construction of the second bore.

Number of Contracts

The planning group noted the difficulty experienced by both the owner and contractors in handling and coordinating the single large contract employed for construction of the first bore. These difficulties existed in the areas of providing space for each contractor in a very limited work area at the tunnel portals, coordination and sequencing of the work, materials procurement, and labor disputes. In light of these problems and in recognition of advantages of stage financing to construct the entire second-bore facility, the planning group concentrated on clearly defining and separating the total work necessary to construct the facility. The following contracts were decided in the sequence shown:

1. Ventilation and electrical equipment procurement and installation in the portal ventilation buildings; this project was designated as I-70-3(82);
2. Tunneling, concrete lining, and tunnel drainage; this project was designated as I-70-3(81);
3. Bridge construction east portal tunnel approach; this project was designated as I-70-3(80);
4. Finishing work in the tunnel including installation of tile walls, suspended ceiling, and ventilation ducts, safety curbs, tunnel paving, electrical conduit, wiring, cabinetry, and mechanical equipment (i.e., carbon monoxide sampling equipment); this project was designated as I-70-3(83);
5. Paving tunnel approach roads; this project was designated as I-70-3(84); and
6. Landscaping work at the tunnel portals and the east and west approaches to the tunnel along I-70; this project was designated as I-70-3(85).

Although this paper is principally concerned with the tunneling contract (number 2), it is important to note that many of the provisions and concepts of the tunneling contract were used in contract numbers 1 and 4.

Prospective bidders for the contract for the second bore were advised of the number and sequence of all projects planned. This information was listed in subsection 105.07 of the project specification.

Advertising Period

The planning group recognized that the shorter advertising period (3-4 weeks) customarily used by the owner on highway contracts was not appropriate in considering a tunneling project of this magnitude. Consequently, a 6-week advertising period was eventually employed due to the time constraints that had developed by the summer of 1975. However, the consensus of opinion of the planning group was that a 12-week advertising period would have been more appropriate and desirable.

Contract Time and Working Hours

This provision of contracts is one of the most-important facets that should be determined through thorough analysis by the designer and construction personnel. All too often contract times are set based on little or no analysis.

In the interest of developing realistic and reasonable contract times for the entire project, the owner's design and construction group scheduled all contracts and related work activities on the basis of reasonable construction rates and floattime that were achieved during construction of the first bore. Construction rates available from other tunnels were also considered. Thus, the tunneling contract time for the second bore was established at 940 working days or approximately 3.5 years. This type of procedure was used in setting the contract times for all contracts.

In setting contract times for this contract, additional explanation is necessary to convey the owner's reasoning based on conclusions reached during the construction of the first bore. The owner noted several circumstances during construction of the first bore that were worthy of consideration in setting the contract time and in developing the contract-specification provisions.

During the first bore construction, when the contractor was compelled to conduct many work activities in close proximity to one another, there was a greater exposure of all work force in those congested areas to accident. By being a bit more liberal in setting the contract time, a contractor could minimize this exposure of the work force by reducing the work activities in a given location and thus reduce the congestion and promote greater safety for the work force.

It was observed that, when the first-bore contractor worked a three-shift, seven-day week, the work force would work the premium time shifts on the weekends and then be absent during the straight time shifts during the week. Absenteeism on Mondays and Tuesdays ran as high as 45 percent. A general decrease in productivity was also evident on the weekend shifts. In addition, the contractor, although adequately equipped with the numbers and type of equipment to conduct the work, was hard pressed to maintain the equipment due to the lack of adequate maintenance time imposed by the scheduled seven-day workweek.

A general observation concluded that the supervisory personnel of both the owner and contractor were overly fatigued by the seven-day workweek and the adverse environment at this location [i.e., the 3350-m (11 000-ft) elevation and generally nine months of snow and subzero temperatures]. The contract time for the second bore was set at 940 working days based on a mandatory five-day workweek. The contract time requirements are listed in subsection 108.06 of the project specifications.

DISCLOSURE

The owner's planning group recognized that prospective bidders for the second bore should have available all possible information that related to the design and construction of the first bore as well as that developed for design of the second bore.

The design and construction group assembled, filed, and recorded two complete copies of virtually every report, photograph, article, as-constructed plan, and engineering construction record available. This information was made available to all contractors during the prebid period at a prebid room located at the division headquarters in Denver.

The owner's prebid room was manned by knowledgeable construction personnel and a procedure was employed so that a list of available information was provided to the bidders, who could then request to review any of the documents in the prebid room and order copies of those documents that they desired.

The prebid room also contained one geological model and a construction model that depicted the owner's design for the second bore. A list of information available to bidders was listed in section M-16 of the project specifications.

SAFETY

The planning group unanimously endorsed the development of plan and specification provisions that would promote safety during construction, such as the workable design details evident in the project plans and specification provisions that would pay the contractor directly for safety-related items. Further, the planning group thought that the owner should promote safety where possible in a direct way and thereby eliminate some of the contingency risks associated with the items of work.

Specification provisions that relate to project safety were incorporated in the second bore contract as follows:

Specification	Provision Number	Unit
First aid attendant	625	Hour
Ambulance driver		Hour
Ambulance attendant		Hour
Furnish ambulance		Each
Traffic control supervision	614	Day
Flagging	614	Hour
Pedestrian overpass	521	Each
Rock reinforcement	211	Each

One can readily conclude that the construction group employed on the first bore felt that the owner could and should provide greater emphasis on project safety by participating directly in the costs as well as by addressing safety aspects in the design of the tunnel structure.

PREQUALIFICATION

The planning group recognized the need for employing a highly competent contractor who had an adequate organization and resources, including personnel, to accomplish this difficult project. The group thought that prospective bidders should have a substantial track record of successful completion of similar tunnels of this size, length, and difficulty to be eligible to bid on work for the second bore. Subsequently, specification subsection 102.01 was prepared and included in this contract.

CONTINGENCIES AND EXCULPATORY LANGUAGE

Inasmuch as the general use of exculpatory language employed historically in contracts was of little if any value and could contribute to the development of the adversary relationship, the planning and specification groups diligently endeavored to preclude this type of language from the plans and specifications.

Further, the group recognized that certain types of work would be difficult to define and quantify for bidding purposes, and the decision was made to direct the contractor to conduct this work on a force-account basis, as provided by specification subsection 109.04. Items of work directed to be completed on a force-account basis were as follows:

Item	Estimated Cost ($000s)
On-the-job trainee	16.8
Erosion control	100.0
Construction monitoring	140.0
Furnish employee shuttle bus	25.2
Trial testing for rock reinforcement	4.2
Miscellaneous work	70.0

Payment for Materials on Hand

The planning group recognized the need for a contract provision that would allow payment for permanent materials procured by the contractor. This contract provision (specification subsection 109.07) was included as an aid to assist in the financing of the project.

Mobilization

A mobilization item, specification section 626, was included to assist in financing the project.

Labor Adjustments

The project planning group recognized the need for inclusion of a labor adjustment provision to provide relief and minimize this risk (see subsection 109.09 in the specifications). At this time (1973-1975), inflation was running rampant and, in consideration of the duration of this contract, it was decided that a contractor could not reasonably assess this risk. Therefore, a specification provision, patterned closely in concept to that used by the U.S. Bureau of Reclamation in federal contracts, was employed.

A review of the labor adjustment payments made to the contractor reveals the following:

Year	Labor Adjustment Payments ($)
1975 (August)	0, not eligible
1976	0, not eligible
1977	314 000
1978	991 924
1979	363 974
Total	1 669 898

The total of the labor adjustment payments represents 90 percent of the actual escalation incurred by the owner during the allowed escalation period. Adjustments for labor costs were not allowed during the first 545 calendar days of the contract. The total amount of labor adjustment allowed represented 1.62 percent of the contract amount bid.

Adjustment of Material Costs and Adjustments for Changes in Common-Carrier Rates

A provision for adjustment of selected material costs was deemed appropriate for inclusion into the contract based on the inflationary trends (1973-1975), shortages of various steel shapes, and energy-dependent products. In general, American Association of State Highway and Transportation Officials (AASHTO) guidelines were used with some modification. Materials determined to be eligible for cost adjustments were structural steel, reinforcing steel, gasoline, diesel fuel, liquid petroleum gas, and electrical power (refer to specification subsection 109.10). The following tabulation reflects the material adjustment costs through July 1979:

Item	Material Cost Adjustment ($)
Structural steel	856 434
Reinforcing steel	101 721
Gasoline	26 971
Diesel fuel	34 540
Liquid petroleum gas	84 647
Electrical power	228 196
Total	1 332 509

This total amount of allowed material cost adjustment represents 1.30 percent of the contract amount bid.

A provision that would allow adjustment for changes in the common-carrier rates was included as part of the contract. This provision is normally included in all Colorado highway contracts (refer to specification subsection 109.08). This adjustment amounted to $50 054 during the life of the contract.

ESCROW DOCUMENTS AND COST-ACCOUNTING SYSTEMS

In consideration of the complexity of this project, the risks involved, and the construction history of the first bore, a provision was included in this contract to require the contractor to submit to the owner virtually any and every piece of information used to arrive at the bid. It was required that the unit prices for each bid item be supported and separated into a cost breakdown that consisted of labor, equipment, material, on-project fixed costs, and off-project fixed costs. Since mobilization was a separate bid item in this contract, it was supported by the same type of cost breakdown as specified for all other unit price items.

The owner's reasoning for requiring submission of the contractor's bid documents was to establish and ensure that the basis of bid would be available for review to facilitate determination of just and fair compensation in the equitable settlement of major disputes that might arise during the course of construction.

The owner and others remember the unavailability of such documents during the construction of the first bore. Also, the escrow documents documented the basis of a bid and provided a means of evaluating the contractor's bid proposal.

The owner established procedures to ensure that the contractor's bid documents would be maintained confidential, such as storage in a bank safe deposit box with access attained only by mutual consent and presence of designated officials for the contractor and the Colorado Division of Highways.

Appropriate portions of the escrow documents were reviewed on occasion to facilitate adjustments made in accordance with specification subsection 104.02, "alteration of character or quantities of work". This use greatly facilitated this type of adjustment.

The contractor, although not obligated to do so, volunteered to make the documents available to members of the project review board in the event of a dispute where resolution of the dispute could be facilitated through use of the documents.

On completion of the project and agreement to final payment, the escrow documents were jointly removed from the safe deposit box by the owner's representative and the contractor's project manager and returned to the contractor.

A cost-accounting system was required by project specification subsection 108.03 to be maintained by the contractor. The cost-accounting system would assimilate costs incurred on a current basis and would be structured to identify costs of labor, equipment, materials, fixed costs on-project site, fixed costs off-project site, and other costs. These cost records were available to the engineer as required for monitoring project costs.

One can readily see how the escrow documents and the cost-accounting system could be used to quantify costs and facilitate determination of just compensation in the event of a claim or major dispute during the course of work.

DISPUTE RESOLUTION

The need for an outside, nonbiased authority to facilitate resolution of project disputes was demonstrated during construction of the first bore.

Provisions were incorporated into the contract for the second bore to provide for a three-member review board to resolve disputes that might arise during construction. The board consisted of three authorities in the construction field who were contracted with individually by both the owner and contractor to monitor progress of the construction and to hear disputes between the owner and contractor. The board routinely visited the project at 90-day intervals for joint briefings by the contractor and owner. Approximately 15 meetings were held at the site for routine briefing purposes and resolution of three disputes that involved claim amounts of approximately $580 000.

The costs of using the project review board amounted to approximately 0.045 percent of the contractor's bid price for construction of the project and approximately 8.06 percent of the amount of claims presented to the board. The cost of the review board was shared equally by the owner and contractor.

The concept of the review board worked well on this contract and was very effective in settling the disputes that arose during construction of the project. The owner's construction personnel thought that the presence of the review board probably precluded the development of other disputes during the construction. In other words, the review board's presence, in addition to the stature of the individual board members, exerted an unwritten stabilizing influence over both the owner's and contractor's supervisory personnel, which precluded the potential for development of the adversary relationship.

Specification subsection 105.17 was also included in the tunnel finish contract and electrical-mechanical contracts.

DETAILED PLANS

The owner's planning group concluded that the plans for this project should be carefully and completely detailed to convey the owner's and designer's intent for a workable, buildable design. Thus, the project plans and specifications were developed accordingly. The contractor followed the plans and specifications in constructing this project, and few revisions were necessary.

CONCLUSION

The contract and contract provisions for this project were very workable. The contract came in within budget, slightly under the contract time allowed, and 3 percent under the engineer's estimate. The adversary relationship common to most contracts did not develop. Substantial credit must be given to the contractors, Peter Kiewit Sons Company and Brown and Root, for their outstanding organization and management of the project and to the department of highways' consultant, Tom Lang of the firm Leeds, Hill, and Jewett, Inc., for his expertise during design and construction.

ACKNOWLEDGMENT

I wish to thank the Federal Highway Administration Division, Region, and Headquarters for their participation during the development of the design and specifications and the division assistance during construction. It is also appropriate to acknowledge the valuable reference the National Academy of Sciences has provided through the report, Better Contracting for Underground Construction. Complete provisions on the contract for the second bore of the Eisenhower Memorial Tunnel can be obtained from my office.

Minimizing Adversary Contractual Relationships for the Eisenhower Memorial Tunnel, Second Bore

H. RAY POULSEN, JR.

The Colorado Division of Highways awarded the contract for the Eisenhower Memorial Tunnel, second bore, in August 1975, and the project was completed on schedule in June 1979. This difficult underground construction project was built without major claims or delays. The contract included the changed-condition clause and other provisions for cancellation, quantity variation, and time extension. The contract included new provisions for this state government agency, including a provision for the establishment of a review board for settlement of claims and disputes. A second provision was the requirement that contractor's bid documents be presented with the bid and held in escrow for use in determining adjustments. The division's design for the tunnel was well done and the division maintained responsibility for the design. The contract kept contractual adversary relations to a minimum. It was well administered by the division and the work was well managed by the contractor. Reasonable people, working under this contract, successfully accomplished a difficult project.

Construction contracting is a service profession; it is one of the few businesses that, by and large, functions on a directly competitive basis. When a contractor signs and seals the bid, he or she is committed to perform a service for a specified amount. In this act, he or she wagers (a) that his or her appraisal of the conditions and requirements is sufficiently accurate, (b) that his or her judgment of the cost of accomplishing the work is sufficiently correct, (c) that his or her organization and resources are sufficiently strong, and (d) that his or her physical and mental health are adequate to accomplish the work on time and at a cost that results in a reasonable profit.

The contractor must assess the risks involved in the work for each bid and prepare a proposal that includes a profit margin that is consistent with such risk. This is difficult to do and varies with every job. The degree of variance in the work and the amount of risk is greater in underground construction than in general construction or building construction. A contractor must, therefore, include substantially more markup on underground or tunneling bids than on building bids.

Due to the higher risks in underground work and the resulting higher markups, owners have realized that fair contract provisions that minimize some of the risks can result in lower bids and savings in project costs. The Colorado Division of Highways devised such a contract for the Eisenhower Memorial Tunnel, second bore.

Contractual relationships become people relationships; an adversary relationship, in my opinion, is one that exists between opponents. We certainly endeavor to maintain relations that will not hinder our performance. Yet, our human nature leads us to assume the adverse or opposing view when we expect that another person's position may harm us.

When a potentially harmful situation develops, we react to protect ourselves. One immediate reaction is to watch what we say. This is often done by lessening the pressure to coordinate fully, or worse yet, by avoiding full, free discussion and review of our problems with the opponent. The result, of course, is inadequate communication. Communication is probably the most important part of any relationship. A decrease in communication, the exchange of information, has an immediate effect on a construction job--requirements are misunderstood, work may have to be removed and rebuilt, and delays occur while clarifications are obtained. Costs go up, production and level of quality go down, and time goes on. All of these results are bad for both the contractor and the owner. It is then apparent to me that we should remove as many potentially harmful provisions from our contracts as possible. At the same time, we should maintain and add provisions for the reasonable protection of the parties in an equitable manner.

The contract for the second bore included provisions for price and time adjustment for delays, adjustment of alteration of character or quantities of work (including changed-conditions clause), and a review board. The review board consisted of three experts in the field organized to hear and decide on claims for adjustment and disputes in a nonbinding arbitration procedure. The contract provided for payment adjustments for escalated costs of labor (partial), energy, and specific major materials. The division accepted the responsibility for its design. These provisions (and several additional equitable provisions) removed many of the problem areas that precipitate adverse relations during the performance of the contract.

The following comments are offered regarding some of the provisions included in the division's contract that do significantly minimize contractual adversary relationships. The last paragraphs of this text offer suggestions on items of lesser magnitude that could further improve contractual relationships on similar projects.

CANCELLATION OF CONTRACT (Subsection 108.09)

This provision reads as follows:

> The division reserves the right to cancel this contract or any part thereof if it is determined

to be in the best interests of the state. Should the chief engineer find that it would be in the best interest of the state to terminate the contract, written notice to that effect will be issued to the contractor 30 days prior to cancellation. Such termination shall be subject to the following:

Where units of work have been completed, they may be paid for at the unit bid price or the contractor may be paid on a force-account basis. On lump sum bid items that are only partially completed, payment may be made in the proportion that the completed work bears to the total bid price; however, where the work performed by the contractor is of such a nature that some units of work have been completed and other units have not been completed and it is impossible to separate the costs betwen the completed units and uncompleted work, the contractor will be paid for the necessary preparatory and other work accomplished on the force-account basis.

The division will reimburse the contractor on an actual cost basis for acceptable materials obtained for the project but not incorporated in the work.

The intent of this provision is to provide a method of equitable settlement with the contractor. Loss of anticipated profits shall not be considered.

It is also the intent of this provision that a settlement for the work performed shall not relieve the contractor or his surety from responsibility for defective work and/or materials on the completed portion of work nor for labor and materials as expressed in the surety bond.

The title to all property accruing to the division by reason of termination of this contract shall immediately vest in the division, and the contractor shall execute and deliver to the chief engineer, or his representative, all papers necessary to transfer title.

The chief engineer or his representative shall be given full access to all books, correspondence, and papers of the contractor relating to this contract in order to determine amounts to be paid on account of the termination of work.

The complexity of our society with regard to politics, the economy, energy, and ecology can be cause for cancellation of a contract. The above provision removed the risk as to how a cancellation would be handled and how the partial performance would be paid for.

PRICE AND TIME ADJUSTMENT FOR DELAYS (Subsection 108.10)

This provision reads as follows:

(a) If at any time during the performance of this contract evidence develops that there will be delays due to reasons unknown to and beyond the control of the contractor, the contractor shall notify the division in writing within 20 days of such development.

(b) In addition, if the delay persists and causes an increase in the cost of, or the time required for, the performance of any part of the work under this contract, the contractor shall notify the division in writing of such increase. Such notice should include the contractor's proposal for an adjustment in the contract price, time, or both.

(c) Upon receipt of the contractor's proposal the parties shall negotiate an adjustment in price, time, or both if the division determines such increase is justified.

(d) Such increases in time if allowed shall be in addition to that authorized pursuant to subsection 108.06.

This provision offers relief to the contractor for a variety of possible high-risk situations. The provision is considerably broader than the typical force majeure clauses of other contracts. Subsection 108.06 deals with determination and extension of contract time.

ALTERATION OF CHARACTER OR QUANTITIES OF WORK (Subsection 104.02)

This provision reads as follows:

(a) At any time during the progress of the work, the division may make such increases or decreases in quantities and such alterations in the work within the general scope of the contract, including alterations in the grade or alignment of the road or structure or both, as may be found to be necessary or desirable. Such increases or decreases and alterations shall not invalidate the contract nor release the surety. The contractor shall accept the work as altered, the same as if it had been a part of the original contract.

(b) Alterations of plans or of the nature of the work will not involve or require work beyond the termini of the original proposed construction until a covering supplemental agreement acceptable to both parties has been executed.

(c) Unless increases or decreases in quantities and alterations in plans materially change the character of the work to be performed or the cost thereof, the altered work shall be performed as a part of the contract and will be paid for at the same contract prices as for other parts of the work. Adjustment other than provided below will not be made in the contract unit price for any item that has materially changed if neither party requests an adjustment in the contract unit price for that item. The term materially change (herein) for purposes of intent under the contract shall be construed to apply only to the following circumstances and corresponding adjustments:

1. When the character of the work, as altered, materially differs in kind or nature from that involved or encountered in the original proposed construction, adjustments to contract unit bid prices may be made to compensate for either increased or decreased direct costs of performing the work.

2. When the total amount of increase or decrease in quantity of a major contract bid item affected by the work as altered varies from the total for those same individual items in the contract bid schedule by more than 20 percent, the contract unit bid price will be adjusted as provided for in [subsection] 109.03.

3. When a minor contract item is increased to an amount exceeding 6 percent of the cost of the contract, computed from the original contract

price and estimated quantity, the contract unit bid price will be adjusted as provided for in [subsection] 109.03. A minor contract item may be decreased by any amount without affecting the contract.

4. A change order may be requested by either the division or the contractor for an alteration involving an increase or decrease of more than 25 percent of the total cost of any individual contract item.

Change orders for increased work shall apply only to the quantity of work performed in excess of 125 percent of the original proposal quantity.

Change orders for decreased work shall apply to the quantity of work actually performed. The adjusted cost for decreased work shall not be greater than 75 percent of the contract bid cost for the work or item.

(d) If the character of the work or the unit costs thereof are materially changed, as above defined, and if written requests for adjustment are received within a reasonable period of time after the qualifying condition can be determined, an appropriate adjustment will be made in the order authorizing the work. Any adjustment will be as provided for under subsection 109.04, which allows for payment either at an agreed unit price or on a force-account basis.

(e) Claim made by the contractor for any loss of anticipated profits because of any such alteration, or by reason of any variation between the approximate quantities and the quantities of work done, will not be accepted.

(f) Payment for work occasioned by changes or alterations will be made in accordance with the provisions set forth in subsection 109.03 of these special provisions. If the altered or added work is of sufficient magnitude as to require additional time in which to complete the project, such time adjustment will be made in accordance with the provisions of subsection 108.06.

(g) Changed-condition clause: should the contractor encounter or the division discover during the progress of the work subsurface or latent physical conditions at the site differing materially from those indicated in this contract, or unknown physical conditions at the site of an unusual nature, differing materially from those ordinarily encountered and generally recognized as inherent in work of the character provided for in the contract, the engineer shall be promptly notified in writing of such conditions before they are disturbed. The engineer will thereupon promptly investigate the conditions and if he finds they do so materially differ and cause an increase or decrease in the cost of, or the time required for, performance of the contract, an equitable adjustment will be made and the contract modified in writing accordingly.

This provision sets out a settlement or adjustment procedure necessary to reduce risks of losses due to quantity variations. It also provides the owner with procedure for changes that may be necessary to handle unforeseen problems. The changed-conditions clause is similar to that of the standard federal contract--it is certainly one of the most effective provisions yet in reducing contingency costs in bids for underground work. Subsection 109.03 deals with compensation for altered quantities and subsection 109.04 deals with extra and force-account work.

CLAIMS FOR ADJUSTMENT AND DISPUTES (Subsection 105.17)

This provision reads as follows:

Claims for adjustments and disputes shall be handled according to the following procedures:

(a) Notification of dispute: If the contractor objects to any decision or order of the engineer, the contractor shall ask, in writing, for written instructions from the engineer. While waiting for the written instructions, the contractor shall proceed without delay to perform the work or to conform to the decision or order. Cost records of the work shall be kept in accordance with subsection 109.04. Within 10 days after receipt of the written instructions, the contractor shall file a written protest with the engineer, stating clearly and in detail the basis of the objection.

(b) Determination of dispute: The engineer will consider any written protest and make his decision. The decision, in writing, shall be furnished to the contractor. This decision shall be final and conclusive subject to written appeal by the contractor requesting a review board. The appeal must be instituted within 30 days of the date of receipt of the engineer's decision. Pending final decision of a dispute, the contractor shall diligently proceed with the work as directed.

Should the contractor appeal the engineer's decision, the matter will be referred to a review board consisting of one member selected by the division and one by the contractor, the two to select a third member. The contractor and the engineer shall each be afforded an opportunity to be heard by the review board and to offer evidence. All matters brought before the review board will be reported to the chief engineer.

The decision of the review board shall govern unless the chief engineer shall determine that such decision is not in the best interest of the state, in such instance he may override the board's decision. The division and the contractor shall each be responsible for one-half the review board's fees and reasonable expenses.

This provision as written in the specifications prompted a question from the prospective bidders at a prebid conference held by the division approximately three weeks prior to the bid date. The question and answer, as set out in a letter from the division to the planholders, reads as follows:

Q. Under subsection 105.17 appeals can be taken to a review board from any decision of the engineer involving contract questions and controversies. The decision of the board will be final and conclusive; except, the engineer can overturn or reverse any such decisions upon his determination that such decision would not be in the best interest of the state. The best interest of the state is a nebulous and uncertain standard for the exercise of authority of such potential. Preferably the review board decisions should be final and conclusive. However, if the engineer is to be given authority to overrule

> or reverse any such decisions, the grounds for doing so should be specific.
>
> What are the specific standards by which the engineer will base his decision to overrule the board?

A. The last paragraph of subsection 105.17 is clear in providing that the chief engineer is the only person who can override the decision of the review board. It should be noted that the review board's findings are not binding upon the chief engineer or the state of Colorado. However, the findings of the review board will be very persuasive and accorded great weight.

In my opinion, this answer confirms that the Colorado Division of Highways intended that the maximum authority permitted by law be vested in the review board. In the event of an override by the chief engineer that could not be accepted by the contractor, legal action in the courts would be undertaken. In that event, the decision of this board of reputable experts in the industry would have to be accorded considerable weight by the court. Irrespective of the decision, the court time and costs should be reduced by the advance preparation.

Members of the review board were selected and contracts for their services were executed soon after award of the prime contract. It was agreed that the board would meet at the job site approximately quarter-annually to maintain a thorough knowledge of the project status and be apprised of any potential problems. I think that the frequency of meeting could be reduced on less-complicated contracts but seemed about right at Eisenhower. The board provided prompt decisions on the few disputes presented to it. These prompt decisions saved time and money for both contractor and owner.

The existence of a functioning review board could lead to wasted efforts in settling minor differences. The board's time should be allocated to major disputes. The contractor and owner should work diligently to settle routine minor disputes between themselves at the lowest possible level.

The board did minimize contractual adversary relationships on this project. The success was enhanced by a general desire by all the participants to make it work. I believe that nonbinding arbitration provisions such as this can become a major improvement in similar large, high-risk contracts throughout our industry. These provisions are not desirable in routine contracts for low-risk work because I doubt that they would reduce significantly the time or cost for settlement of claims or disputes in that work.

ESCROW DOCUMENTS (Subsection 102.07)

This provision reads as follows:

> Each bidder shall submit with his proposal complete documentation clearly itemizing and separating costs for each contract item, except the contract item "fixed fee", contained in the proposal. Costs used to determine each unit price shall be separated and identified as costs of: labor, equipment, materials, fixed costs--on project site, fixed costs--off project site, and any other costs included must be specifically identified.
>
> (a) The documentation shall include copies of all quotes, memoranda, narratives, or any other information used to arrive at the bid prices contained in the bid schedule and shall be clearly marked with the appropriate bid schedule item reference number. For purposes of identification all such supporting documentation will be known as the escrow documents.
>
> (b) The escrow documents shall be submitted in a sealed container along with the sealed envelope containing the proposal and will be clearly marked with the bidder's name, date of submittal, and project number and titled escrow documents. The escrow documents shall be accompanied with an affidavit signed by the bidder, stating that he has personally examined the contents of the escrow document container and has found that the documents are in the container and are correct and complete. Escrow documents of the apparent successful bidder shall be examined in his presence for adequacy and accuracy prior to award. After award of the contract, the escrow documents of all other bidders will be returned unopened.
>
> (c) The escrow documents of the successful bidder will be returned at such time that the contract is completed and final settlement has been achieved.
>
> (d) Escrow documents shall be stored at a location and in a manner agreeable to the division and the contractor.
>
> Escrow documents may be examined any time deemed necessary by the chief engineer to determine the contractor's bid concept. This examination may be required for payment purposes for any and all contract items, subject to the following requirements:
>
> 1. Examination of documents shall be made by those specifically delegated by the chief engineer and a contractor representative.
> 2. These documents are considered proprietary and confidential in nature and shall be treated as such by those designated to review them. These documents, or any of the contents thereof, shall not be made available to any person or persons not herein designated without the specific consent of the contractor.

This provision requires disclosure of the bidder's confidential estimation procedures. Most contractors consider the procedures and information used in an estimate to be a closely guarded secret. Is it possible for a public agency to ensure that the information in the documents will not be disclosed? Also, the preparation of the documents in the form requested and in the limited time available prior to bid increases bidding costs for each bidder.

The documents were used during this project primarily to confirm the basis for adjustments claimed by the contractor. The documents did provide security for the division and were a factor in minimizing contractual adversary relationships in this instance.

In my opinion, a provision for escrow documents as above should rarely be included in a construction contract. The provision may cause a decrease in the number of bidders because of the concern for disclosure. Disclosure of the documents or improper use of the documents could result in an adverse effect on contractual relationships.

SUGGESTIONS FOR IMPROVEMENT

Time is of the essence. Typically, the Eisenhower contract provides that the contractor pay liquidated damages in the event of late completion. This provision is reasonable to maintain an emphasis for timely completion by the contractor. A similar emphasis for timely settlement and payment by owner should be included in future contracts. This provision could be written in various ways. One alternative would be a provision for the owner to pay interest on the amount due from the time the cost was incurred until it is paid to the contractor. Such provision would encourage prompt payments and reduce the contractor's financing costs. The long-term results from such a provision should be lower bid prices.

Mobilization items generally reduce the contractor's financing cost and increase the owner's financing costs. Mobilization items encourage bids from firms that are inadequately financed and have insufficient in-house depth of supervision to undertake a project of this nature (the strict prequalification requirement eliminated this concern at Eisenhower). The Eisenhower mobilization item was good in that the amount was not preset by the division. The savings in cost were diminished, however, by the inclusion of demobilization and the payment schedule. The schedule provided that 10 percent of the mobilization item amount would be paid with the final payment. I suggest that demobilization be eliminated from the item in future contracts.

Force-account items were planned by the division in the Eisenhower contract. The items provided an estimated dollar amount to be spent for erosion control, avalanche control, and trial testing for rock enforcement. Provision for these highly variable items on a force-account basis reduced the risk for the contractor and created a lower price by eliminating contingency cost in the bid. The force-account approach gave full flexibility and control for this work to the division, which is good. Payments to the contractor for force-account work in this contract and, in general, in the industry are not good. The schedule interference of force account and bid item work and the general supervision efforts are significant costs that force-account markups did not cover adequately. Also, equipment rental and operating costs in this contract and in the industry, in general, are not adequately paid. A joint effort by the owner and contractors to establish force-account rates and markup prior to bid could produce a more satisfactory basis.

SUMMARY AND CONCLUSIONS

This major underground construction project was completed on time at a price less than the owner's original estimate. The contractor's cost was reasonably close to the estimate. Total claims processed on this contract were less than one percent of bid amount. The claims were settled within 14 months after completion of the field work.

The following are my conclusions:

1. The changed-condition clause included in the contract is a cornerstone in minimizing contingency costs in bid prices. The alteration, cancellation, and delay provisions also reduce these costs.
2. The nonbinding arbitration or review board provision for claims and disputes was very successful. Similar provisions should be considered for large, high-risk jobs. The provision should not be provided for routine, average-risk work.
3. The escrow-documents provision in the contract gave owner confirmation of contractor's bid pricing. This confirmation aided in the settlement and adjustments for quantity variations. The escrow documents cost bidders extra and the possibility of disclosure is a major concern to contractors. The escrow documents provision would not normally minimize contractual adversary relationships.
4. Further improvements in similar contracts could be made with provisions for faster payment and improved mobilization and force-account specifications.

The Colorado Division of Highways contract for the Eisenhower Memorial Tunnel, second bore, was more desirable to bid than most. The contract provisions were more equitable than most. The contract minimized adversary contractual relationships.

Minimizing Potential for Adversary Contractual Relationships During Construction of Eisenhower Memorial Tunnel

A.J. SICCARDI

Some hold the viewpoint that the engineer, especially in public construction, must be ever alert to attempts by the contractor to seize on some advantage in the execution of contracts to the detriment of the public. Certainly, the engineer's first loyalty in the preparation of plans and specifications and the administration of the contract is to the public. However, the referenced viewpoint leads to a basic distrust between the contract parties and creates an adversary relationship during execution of the contract, which serves neither party and may lead to unnecessary and bitter litigation to settle disputes. The contract needs to be fair to both parties: the engineer should recognize that the contractor properly seeks to make a reasonable profit, and the contractor should acknowledge that the work should meet owner expectations of value and be a good-specification product. Underground construction holds special potential for generating adversary relations because the risks are generally greater than those that arise from other highway construction. Attention is needed in the preparation of such contracts to ensure an equitable sharing of risks without vitiating the basic premise of the competitive bidding process. Several innovations were built into the construction contract for the eastbound bore of the Eisenhower Memorial Tunnel, including among other features the inclusion of an impartial review board into the administrative process for settling differences, special prebid qualifications for the contractors, the require-

ment for escrow documents in support of the contractor's bid proposal, the judicious use of escalation provisions, and special design efforts.

The bidding of a project on any highway contract involves a great amount of risk for the contractor, but in the case of an underground tunnel the risks can be extraordinary. Regardless of the amount of subsurface investigation performed by the highway agency, simple economics will prevent so thorough an investigation as to preclude any unknowns. As a result, there will need to be considerable extrapolation from the known data both by the engineers and the contractors. Necessarily, then, the contractor, in preparing a bid for handling this construction risk, must gamble on the amount of bid contingency to be included in a bid so as to ensure the ability to complete the contract successfully with a reasonable profit for the effort. In the competitive bidding system, too high a contingency for risk makes it likely that the contractor will not be the low bidder and, conversely, too low a contingency for risk may result in not only the low bid but also a high potential for little or no profit if, in fact, he or she is able to complete the project at all. The quality-assurance system used by a state highway agency in putting together its plans, specifications, and estimate (PS&E) for any project, especially tunnel projects, and approved by the Federal Highway Administration (FHWA) will greatly influence a contractor's proposal for performance of the work.

Quality assurance is normally defined as the systematic use of performance requirements, design criteria, specifications, production-control procedures, and acceptance plans for materials, processes, or products to ensure prescribed properties or characteristics of an end product. It is fair to say that, as the highway engineer ponders and applies this general definition to projects, he or she tends not to include the contractor as a part of the system. A little reflection, however, will make it clear that those elements of any quality-assurance system concerned with creating quality, that is, the completion of a quality product in conformance with the plans and specifications, is primarily the responsibility of the contractor. Further, the contractor is responsible for production-control procedures, and therefore, an important and integral participant in the total system. If an adversary contractual relationship is to be minimized, if indeed it need exist at all, there needs to be a recognition of the fact that no specification, no matter how well written, can be expected to be 100 percent perfect. Quality assurance, as it relates to specification compliance and the production of a quality end product, is the goal of a system action.

Elements of the quality-assurance system, insofar as highway projects are concerned, include planning, design, production of plans and specifications including consideration of human and environmental factors, advertisement and award of contract, and construction and maintenance of the highway. Three principal parties are concerned with federal-aid contracts--the state highway agency, the contractor, and FHWA. Only two parties, however, are parties to the contract itself. The FHWA is not a party to the contract and, therefore, no contractual relationship exists between the contractor and FHWA, and neither has contractual rights that can be enforced on the other. The role of FHWA is to review and approve or disapprove of a state decision. Thus, FHWA's decisions normally should not have any impact on the contractor. However, indirectly at least, because of the state's desire to minimize the number of FHWA decisions that result in nonreimbursement to the state of expenditures made, FHWA's decisions often have an impact on the contract and its administration when it is anticipated that claims and disputes will arise out of the contract and that it may become necessary to settle a contract claim presented by federal-aid contractors to state highway agencies. If a state incurs costs as a result of work performed by it or its contractors that is not in conformity with the approved plans and specifications or approved amendments thereto, then it is not entitled to reimbursement from FHWA. Indeed, FHWA is not legally authorized to reimburse such costs. A primary goal, therefore, of the state highway agency and FHWA is to produce a clear, concise, and precise set of contract documents in order to keep disputes at a minimum and, as a result, to minimize the need for contract claims. Such a goal led to the inclusion in the PS&E for the Edwin C. Johnson (second) Bore of the Eisenhower Memorial Tunnel, along Interstate-70 in Colorado, of a number of new contractual concepts from those normally included in Colorado state highway contracts. The focus of this paper will be to review certain of those concepts as they impacted on the construction subsystem of quality; specifically, the bidding process, the advertisement and award, and the construction phases.

Normally we think most about contractor process-control activities and state activities that relate to the acceptance sampling, testing, and inspection of materials and their placement in the project. These activities are essentially the quality-control and the quality-acceptance features in the construction phase of a project. These features in the construction subsystem conjure the image of using the tools of statistical quality control and sampling theory. There are, however, other concerns in the construction subsystem, and the thrust of this paper is concerned with understanding the contract and the relationships it creates between the two principal actors.

By definition, a contract is an agreement between two or more persons that creates an obligation to do or not to do a particular thing. Its essentials are competent parties, subject matter, legal consideration, mutuality of agreement, and mutuality of obligation. The writing that contains the agreement of the parties, which includes the terms and conditions of the agreement, serves as the proof of obligation. The construction subsystem is, in fact, broader than the actual product produced and the statistical tools that have been adapted to that phase of the system. It also includes the phases of development of plans and specifications, advertisement and award, and engineer-contractor relations as the mutual agreement and obligations to perform are carried out.

It is appropriate, therefore, to begin an analysis of this subject with a look at the design subsystem. Design, as a term of art, relates to the conception of a plan or scheme in one's mind that is intended for subsequent execution. The plans, of course, become the representation of that design, and the specifications are a series of detailed statements concerned with the various elements of the plan. A contractor in public sector work is not normally connected with the design subsystem element or with the development of the later system element of PS&E, at least in the U.S. system of contracting. This is not always the case in the private sector. Also, in many instances, contractors are used in the design phase to critique design proposals as to their practicability and economy for construction.

There was no involvement in this subsystem phase by contractors during development of PS&E for the Eisenhower Memorial Tunnel. The contractor under-took to perform the construction of the tunnel for a fixed price. In point of fact, the contract is more accurately identified as a unit-price contract, not a fixed-price contract, in that payment was made to the contractor on the basis of work actually performed according to items identified and bid on in the bid documents. The contractor, of course, is in pursuit of an independent business and undertakes to do a specific thing. Obviously, this undertaking must produce a profit, which the contractor naturally will attempt to maximize. The state personnel, on behalf of the public, will be charged with administering the project so as to ensure completion in reasonably close conformance with the PS&E, and this effort may tend to conflict with the goal of the contractor.

From these apparently divergent perspectives, one generally assumes that an adversary relationship will and must exist between the parties. Actually, such a relationship need not, and should not, be the case. Both the engineer and the contractor are interested in getting the work done. The latter, not having been a party either to the conceptual design or its development, must rely on good-faith relationships between the engineer and himself. The contractor must also rely on the very critical advertisement and award subsystem element to get a clear and concise translation of the design quality levels required in order to yield the desired end product. In this instance, a proposal of approximately $102 million was made by the successful contractor, a joint venture of Peter Kiewit Sons Company and Brown and Root. The contract was to extend for a period of 3.5 years. The offer to perform such an undertaking involved risk management on the part of the contractor. In a relatively short but longer-than-normal period for advertisement and award (six weeks), the contractor had to indemnify systematically the company's exposure to risk of loss, and make decisions that were all but clear as to the best methods for handling these exposures. The bottom line was profitability. The only basis the contractor had for assessing the risks was the plans and specifications that had translated the design concept into a basis for a written contract. This paper deals only with the mining and excavation contract; however, that contract was only one of six major contracts involved in the Eisenhower tunnel before its completion. This was the largest and, no doubt, the most-important contract and, therefore, warranted special features. However, some of the concepts initiated in this contract were carried into the contracts for mechanical, electrical, and final lining.

In these days of departments that are organized functionally, with emphasis on division of labor and specialization of work tasks, those persons assigned by the highway agency to administer the construction contract often are not parties to the design development phase of a project. Fortunately, in this instance, Phillip McOllough, who later was to direct the construction of the project, was a lead figure in directing the design process. This fact alone, in my judgment, created the basis from which a sense of fairness in dealing with the on-the-scene representatives of the contractor could be developed. The contract relationship between McOllough and Peter Kiewit Sons Company, specifically Ray Poulsen, was to prove to be extremely successful. This judgment is based on the fact that the project was, in fact, completed on time, essentially as budgeted, and without significant claims by the contractor as the obligations were performed under the contract.

How did it happen? McOllough has outlined in a paper in this Record the ideas built into the contract in an effort to maximize good relations. In addition to the special prequalification to screen out inexperienced contractors, the longer-than-usual period for advertisement and award, and other features described by McOllough, there were three ideas (apart from the personnel assigned to the project) that were most responsible for minimizing adverse contractual relationships during this project. The three included (a) the use of a review board, (b) the provision in the contract for materials escalation clauses, and (c) the escrow document. Special philosophies toward the design element also contributed.

REVIEW BOARD

Perhaps the most significant change in the state's standard contract provisions was the inclusion in the administrative process for this project of a procedure for the processing of claims for adjustments and disputes by a review board. The board was to serve as an impartial arbiter of those situations in which the contractor may have been directed by decisions of the engineer to perform work tasks but in which the contractor had some objection. The use of the term arbiter is not totally correct in that the board had no power to decide the matter, only a power to evaluate and to recommend to the engineer a proposed settlement of the objections or dispute. Such a constraint on the power of the board was necessary to comply with the state law that prohibited the delegation of such a power by the chief engineer to say nothing of FHWA's viewpoint in this matter.

The essential provisions in the specifications that provide for the board and its makeup are as follows:

> 105.17 Claims for Adjustments and Disputes
>
> (b) Determination of dispute: The engineer will consider any written protest and make his decision. The decision, in writing, shall be furnished to the contractor. This decision shall be final and conclusive subject to written appeal by the contractor requesting a review board. The appeal must be instituted within 30 days of the date of receipt of the engineer's decision. Pending final decision of a dispute, the contractor shall diligently proceed with the work as directed.
>
> Should the contractor appeal the engineer's decision, the matter will be referred to a review board, consisting of one member selected by the division (state highway agency) and one by the contractor, the two to select a third member. The contractor and the engineer shall each be afforded an opportunity to be heard by the review board and to offer evidence. All matters brought before the review board will be reported to the chief engineer.
>
> The decision of the review board shall govern unless the chief engineer shall determine that such decision is not in the best interest of the state, in such instance he may override the board's decision. The division (state highway agency) and the contractor shall each be responsible for one-half the review board's fees and reasonable expenses.

Note that the wording of the specifications created some doubt in the mind of the ultimately successful contractor. During the period of advertisement and award he felt compelled to raise a question at the prebid conference as to the basis on which the chief engineer might overrule the decision of the board. Admittedly, the words, "not in the best interest of the state," are vague and have the potential for arbitrariness on the part of the chief engineer. The contractor's interpretation, as I understand it, was that overriding of the board's decision would be almost impossible according to the plain language of the specifications, save for a decision that might be outside the limits of the law. The state, the contractor felt, should not have an advantage any more than should the contractor. In my judgment, such a contract could be entered into by the state if delegation of the chief engineer's responsibility were possible to that extent. This would amount to binding arbitration on the part of the state. FHWA would, however, be forced to reserve judgment on automatic federal participation in the board's decision, because legally, FHWA requires that a responsible employee of the state highway agency be in control of the project management. This is viewed as a non-delegatable function. For practical purposes, such a reservation by FHWA most likely would have the effect of a state proceeding with great caution in this area regardless of the merits of such an agreement.

This, then, raises the question as to whether the provision in the specification accomplished the purpose that was envisioned. If the contractor perceived that the chief engineer would review every board decision in detail, then the effect would be perceived as business as usual and no real progress concerning the inclusion of this feature can be claimed. Fortunately, few disputes developed in the mining portion of the total project, and there were no occasions on which the chief engineer was given cause to override the board nor were there occasions that resulted in FHWA's nonparticipation. But the issue is a real one and must be given careful thought should a similar provision be used in another contract. Such a provision is valuable and has a place in the highway contracting process.

The makeup of the board to ensure at least a perceptible measure of impartiality is, perhaps, another area open to the potential for disagreement between the state highway agency and FHWA. In addition to the legal constraints on the power of a board to decide, such a board could not flourish nor even perform in a minimally satisfactory way if its recommendations for settlement were not well reasoned and founded on a contractual base. No matter how well founded is the claim factually, if a proposed settlement is not based on a contractual provision, it is difficult to support. A thorough knowledge of the project and its progress by the board is necessary, as is an understanding of the contract and a commitment of impartiality.

The board for this project included Charles McGraw, retired president of Utah Construction Company, who died during the progress of the tunnel and was replaced by Nixon F. Crossley (state selection); A.A. Matthews, retired principal of a consulting engineer firm that bears his name (contractor selection); and B. Palmer King, retired attorney for the bureau of reclamation.

The specifications for the project provided that, if the contractor objected to any decision or order by the engineer, he or she must proceed without delay after requesting instructions in writing to perform the work or to conform to the decision or order, and maintain cost records of the work in accordance with subsection 109.04, reproduced here in the interest of completeness:

109.04 Extra and Force Account Work

Any extra and force-account work performed without notification to the engineer will not be paid for.

Extra work performed in accordance with the requirements and provisions of subsection 104.03 will be paid for at the unit prices or lump sum stipulated in the order authorizing the work, or the division (state highway agency) may require the contractor to do such work on a force-account basis to be compensated in the following manner:

(a) Labor: For all labor and foremen in direct charge of the specific operations, the contractor shall receive the rate of wage (or scale) agreed upon in writing before beginning work for each and every hour that said labor and foremen are actually engaged in such work.

The contractor shall receive the actual costs paid to, or in behalf of, workmen by reason of subsistence and travel allowances which are the result of a collective bargaining agreement or other employment contract generally applicable to the classes of labor employed on the work.

An amount equal to 45 percent of the sum of the above items will also be paid the contractor to cover overhead, additional bond, property damage and liability insurance, workmen's compensation insurance premiums, unemployment insurance contributions, social security taxes, and profit.

In addition to the 45 percent stated above, the actual amount of fringe benefits will be paid to the contractor for those work classifications which carry fringe benefits resulting from collective bargaining agreements or as required by U.S. Department of Labor wage schedules. (Fringe benefits are those payments made by the contractor to a third party, trustee, or directly to the employee to cover such things as, but not limited to, health and welfare, pensions, vacations, and apprenticeship program.) The 45 percent loading factor shall not apply to fringe benefits paid to a third party, trustee, or to the workman.

(b) Materials: For materials accepted by the engineer and used, the contractor shall receive the actual cost of such materials delivered on the work, including transportation charges paid by him (exclusive of machinery rentals as hereinafter set forth), to which cost 25 percent will be added for handling and profit.

(c) When extra work on a force-account basis is performed by a subcontractor on the project in accordance with the provisions of an extra work order, a percentage based on the following table will be allowed as additional to the percentages in (a) and (b) above, to reimburse the prime contractor for the administrative expenses incurred in connection with the work. Bid items in the original contract are not to be considered.

To \$1000--10 percent,

Over \$1000 to \$10 000--\$100 plus 5 percent of excess over \$1000,

Over \$10 000--\$550 plus 3 percent of excess over \$10 000.

Approval of this additional percentage will be made after receipted invoices are furnished by the contractor.

The subcontractor will not be permitted to load billings except as outlined in (a) and (b) above.

(d) Equipment: For any machinery or special equipment (other than small tools) including fuel and lubricants, plus transportation costs, the use of which has been authorized by the engineer, the contractor shall receive rental rates as established and published by the division (state highway agency) for this project. Rates for equipment used but not listed in the project rental rate manual will be established by using the formula set up in the rental manual.

For a review board to be effective, it is necessary, as has been previously stated, that, as a group and individually, they be informed and knowledgeable concerning the progress of the work. Accordingly, individual contracts were prepared with each of the three review board members. The contracts included a requirement for regular meetings at the project site within a time frame not to exceed 90-day intervals. Either party (i.e., the state or the contractor) by contract was to have the discretionary power to call the board into service by written communication to meet for special problems that arose during the contract and that required resolution. The intent of the contract was that the board should submit a singular report of its findings concerning any matters brought before it; however, provision for dissenting views was included so as to provide the chief engineer with as much data as possible from which to accept or reject the board's report. Each board member was required to place in the record a report of the routine project inspections and meetings to include only factual information in accordance with his or her perspective but not to contain conclusions or recommendations, presumably to minimize bias in the event of dispute proceedings.

The review board concept is intended to offer an objective look at problems. The concern of FHWA is that, in agreeing to such a concept for the adjudication of claims by such a board, the findings of the board may be conclusive under state law or by provisions of the contract as to a dispute between the contractor and the state, but it is not conclusive between the state and FHWA insofar as federal-aid reimbursement is concerned. In the interest of a relatively harmonious relationship between the state and FHWA, we attempt to make our decisions compatible with the policies and laws of the state; specifically, in this instance, to accept the findings of the review board and ultimately those of the chief engineer as our own. This approach proceeds from the position that legal problems that arise in highway construction contracts generally involve mixed issues of law and engineering, and settlement of those questions within the equitable adjustment provisions of the contract, which is a key to settlement of issues, is appropriate where possible to avoid unnecessary and lengthy recourse to the court system. Following a general principle of contract law, the specifications written by the state would be interpreted against the state where ambiguity was found to exist. In all probability, the contractor interpretation (that override authority should exist only in cases where decisions of the board are based on illegalities) would prevail were the argument to be tested. Thus, it is appropriate, perhaps, that it may have been more desirable for reference in the specification to "not in the best interest of the state" to have been further defined and replaced by a reference to decisions based on illegal premises. Alternatively, the state must assume risk of potential for nonreimbursement of what the board perceives to be a legitimate settlement if this type of board is to cause the contractor to perceive a lowering of risk and thus a likely area for submitting a lesser contingency in the bid as a result of this feature. In a project such as the Eisenhower Memorial Tunnel, there is potential for large settlements even in small disputes because of the repetitive nature of the work in the tunnel, and then an objective review board has much merit.

The review board met routinely on at least 14 occasions throughout the life of the project and was called on to review and recommend settlement of four disputes. From my perspective, this relatively small need for the board signifies a successful project, but the degree to which that success should be attributed to the presence of the board is difficult to assess. A board composed, as it was, of representatives selected by the parties has the potential for becoming an adversary proceeding in itself. Ideally, the selected representatives, who presumably bring to the board perspectives that are consistent and compatible with viewpoints of the parties by whom they were selected, can rise above such a narrow approach and exhibit a degree of freedom from any bias on those occasions when it is called on to act. My perspective is that members of such a board should be agreed on by both parties; however, all members should come from a subset of a larger number of nominations by the parties rather than as was the basis in this contract. I hasten to add that in the Eisenhower Memorial Tunnel project no basis surfaced for either supporting my perspective or for supporting the board makeup as it was constituted. To be sure, the presence of a board made up of knowledgeable and respected persons associated with the contracting and legal professions appeared to have a deterrent effect on the filing of claims. This statement is made without any intent to detract from the superb qualifications of both the contractor and the state, in this instance, to administer the contract. Nevertheless, an accumulation of data is available to the board during its routine visits to the project. The data become factual data to each member, somewhat personal in nature, from which the board can draw when a dispute does arise.

I have come to believe in the concept of a board; however, with the caveat that such boards need not and should not become commonplace in highway construction contracts. The concept is most useful in large and complicated contracts, especially in the mining, excavation, mechanical, and electrical aspects of tunnel work because of the specialized nature of that work and the probability that the state will not have the expertise readily available to evaluate the propriety of a contractor's claim. The fears of FHWA, in this instance at least, that the owner is at the mercy of the members of the board and that, emotionally, such boards tend to favor the views of the contractor, did not materialize. The findings of the board were clearly set out in the reports it prepared. In only one instance was it necessary to return to the board for a clearer articulation of how its decision followed from the contract and from the factual data as reported and from which its recommendations for settlement flowed.

ESCALATION CLAUSES

Another important innovation in this contract, which had an effect of minimizing a potential adversary relationship, was the inclusion of escalation clauses for materials and labor. Highway law, as codified in Section 112 of Title 23, U.S. Code, requires that the construction of each project, "shall be performed by contract awarded by competitive bidding, unless the secretary shall affirmatively find that, under the circumstances relating to such project, some other method is in the public interest." Certainly this project was bid competitively. Two contractors submitted bids, Healy-Ball-Granite-Greenfield and Peter Kiewit Sons Company and Brown and Root, Inc., in a joint venture, in respective amounts of $102 988 770 and $102 800 000. Yet, when a contract is expected to extend over a period of more than three years,

Table 1. Computation of labor escalation.

Item	Amount ($)		
	Tunnel Laborer	Carpenter	Clerk-Typist
Federal wage-scale basic rates[a]	6.75	7.85	
Actual cost basic rates[a]	7.00	8.10	3.50
Federal wage-scale on review date[a]	7.10	8.05	
Contractor pay-scale on review date[a]	7.25	8.60	3.75
Federal wage-scale change[b]	+0.35	+0.20	
Contractor pay-scale change[c]	+0.25	+0.50	+0.25

[a]Amount includes fringe benefits.
[b]The percentage change is +0.052 percent for tunnel laborer and +0.025 percent for carpenter.
[c]The percentage change is +0.036 percent for tunnel laborer, +0.062 percent for carpenter, and +0.71 percent for clerk-typist.

especially in inflationary times, it is appropriate and in the public interest to provide some degree of protection to the contractor against a rapid cost spiral of the most inflationary and unstable items. Presumably such an approach returns to the public the cost of excessive caution on the part of the contractor.

Since all contractors begin with the same awareness, the compromise to competitive bidding is small, if indeed it exists at all. Provisions for adjustments beyond those included in the state's normal practice were included in the contract through the following contract subsections:

109.09 Adjustment of Labor Costs

Adjustments for increase or decrease of labor costs will not be made during the first 545 calendar days of the contract.

On the first year anniversary date of the contract, the labor rates, including fringe benefits, being paid at that time by the contractor for each labor classification employed shall be recorded. These rates shall become the "actual cost--basic rates."

On the first-year-anniversary date of the contract, the labor rates, including fringe benefits, specified by the federal requirements wage schedule for the region applicable to Clear Creek and Summit Counties for each labor classification employed shall be recorded. These rates shall become the "federal wage scale--basic rates."

On the 180th calendar day from the first-year-anniversary date of the contract and on each succeeding 180th calendar day thereafter, the labor rates being paid by the contractor for each classification employed will be reviewed. In the event there is any change from the "actual cost--basic rates," payments to the contractor will be adjusted as hereinafter provided.

The percentage of change in actual rates paid by the contractor for each labor classification will be determined.

The applicable federal wage schedule rates in effect on the review date will be compared with the "federal wage scale--basic rates" and the percentage of change determined for each labor classification.

Effective with the first payroll paid following the review date, monies due the contractor will be adjusted for change in labor costs as follows:

(a) Monthly payments of monies due the contractor will be adjusted by the lesser of the monetary amounts arrived at by:

1. Computation in accordance with subparagraphs (b), (d), and (f) below as applied to applicable hours of work.
2. Computation in accordance with subparagraphs (c), (e), and (f) below as applied to applicable hours of work.

(b) Ninety percent of the percentage change in the federal wage scale rates from the "federal wage scale--basic rates" for each labor classification that has incurred changes will be determined.

(c) Ninety percent of the percentage change in rates, being paid by the contractor, from the "actual cost--basic rates" for each labor classification that has incurred changes will be determined.

(d) The percentages derived in subparagraph (b) above will be applied to the applicable "federal wage scale--basic rates" for each labor classification that has incurred changes.

(e) The percentages derived in subparagraph (c) above will be applied to the applicable "actual cost--basic rates" for each labor classification that has incurred changes.

(f) For personnel of the contractor's labor force that are not included in the applicable federal wage scale (e.g., supervisor, engineers, administrative personnel, clerical personnel) the allowable percentage of adjustment for any classification shall not exceed the lesser percentage computed in accordance with subparagraphs (b) and (c) above for laborer (tunnel).

(g) Monetary adjustments made in accordance with the provisions of this subsection will not be considered when computing retainage to be withheld by the division (state highway agency).

(h) Adjustment example: [Table 1 shows the adjustment example.]

Allowable escalation adjustment payable to the contractor on payrolls paid subsequent to the review date (until next review date) will be

Laborer (tunnel): 0.90% x 0.036% = 0.0324%; 0.0324% x $7.00 = $0.23 (adjusted to nearest full cent).

Carpenter: 0.90% x 0.025% = 0.0225%; 0.0225% x $8.10 = +$0.18 (adjusted to nearest full cent).

Clerk typist: 0.90% x 0.036% = 0.0324%; 0.0324% x $3.50 = +$0.11 (adjusted to nearest full cent).

(Note: The adjustment will apply to overtime rates as well as straight-time rates and will apply to all hours worked and paid.)

109.10 Adjustment of Material Costs

In calculating unit bid prices for pay items contained in the proposal, exclusive of the item for fixed fee, the bidder shall use material procurement costs (f.o.b. project site) as follows:

(a) Structural steel @ $660.00/ton: This item shall be limited to structural steel used for excavation support and shall not include structural steel used for other purposes such as jumbo fabrication, etc.

(b) Reinforcing steel @ $320.00/ton: This item shall cover all reinforcing steel used on the project, including that reinforcing steel used for rock support.

(c) Gasoline @ $0.382/gal:

(d) Diesel fuel @ $0.330/gal:

Items (c) and (d) shall cover all gasoline and diesel fuel used by equipment assigned to the project.

(e) Liquid petroleum gas (LPG) @ $0.30/gal: This item shall cover all LPG used on the project including that gas used for heating tunnel ventilation air.

(f) Electrical power:
1. Energy used:
   First 20 000 kW•h @ $0.015 48/kW•h
   Next 60 000 kW•h @ $0.013 68/kW•h
   Next 200 000 kW•h @ $0.012 78/kW•h
   Next 220 000 kW•h @ $0.011 10/kW•h
   Over 500 000 kW•h @ $0.009 86/kW•h
2. Demand charge:
   First 100 kW @ [lump sum] $237.00
   Next 200 kW @ $1.98/kW
   Next 200 kW @ $1.86/kW
   Over 500 kW @ $1.63/kW
3. Fossil fuel cost adjustment:
$0.001 433/kW•h used.

This item shall cover all electrical power used on the project.

Upon procurement of materials listed above, appropriate adjustments will be made to monies due the contractor. These adjustments will be in the amount of the difference between cost actually paid by the contractor and the cost as computed by using the unit prices designated above. These adjustments may be an increase or a decrease.

The purchase price to be paid by the contractor for any and all of the above listed materials and the quantities to be purchased must have prior approval by the engineer.

The provisions of this subsection shall not apply to any materials not listed herein.

The contractor will be required to file a statement executed by, or on behalf of, the person, firm, association, or corporation to whom such contract is to be awarded, certifying that such person, firm, association, or corporation has not, either directly or indirectly, participated in any collusion, or otherwise taken any action to influence the price paid for materials procured under this subsection, so as to create an inequitable cost to the division (state highway agency). This statement shall contain the form prescribed in subsection 106.03(b)5. The original of such statement shall be filed with the division (state highway agency) for each adjustment of prices.

Once again, the magnitude and duration of the project led the state to a determination that a departure from the normal contract was appropriate; FHWA concurred in that determination. I had some misgivings as to the appropriateness of whether an adjustment of labor costs as determined by a percentage equivalent to the percentage of change for each labor classification in the wage schedule should be included in the contract. Also, FHWA had a long-standing policy not to approve cost-escalation clauses for labor because wage rates are at least partially under the control of contractors. However, during the period of advertisement and award, we were aware of the following:

1. Labor negotiations for all major unions were to be conducted subsequent to the award, and predictability of union demands and ultimate agreements was virtually impossible;
2. Labor agreements were being shortened in time period because of inflationary pressures on the economy; and
3. Crafts disputes could occur more readily in tunnel undertakings than under most highway contracts.

Contract agreement was reached to include such a labor escalation clause, and the compromise was to not provide for adjustments during the first 545 calendar days of the project but to provide for a review and adjustment of rates thereafter. As indicated in the reproduced portion of the pertinent specification, labor escalation was based on the applicable federal wage schedule determination for the project and keyed to an areawide wage scale. The escalation was pegged at 90 percent of the actual escalation after the initial nonescalation period to ensure some degree of commitment by management to reasonably bargain during negotiations.

The outcome of the labor escalation through July 1979 was in an approximate amount of $1 669 800. If we assume that approximately one-third of the bid cost of $102.8 million was for labor (approximately $34.2 million), this represented only an increase of about five percent over the four-year period of the contract: this during a time when labor escalation generally rose at a considerably higher rate. It is, of course, difficult to assess the actual impact of the specification itself in this low-percentage wage escalation. Suffice it to say, however, that it was an effort to at least lessen the bidder's risk that, in my judgment, was supportive of the concept of minimizing the adversary relationship inherent in normal highway contract administration. When one considers the prevailing attitude of competitive bid for all work, with the contractor accepting all the risks associated with procuring and incorporating labor and materials in the finished product, such a willingness to share in major risk items manifests an intent toward mutual cooperation among the parties and a desire to complete the project on time and profitably as well.

In addition, the materials escalation (through July 1979) for each of the selected items is shown in Table 2. The total cost of materials was $1 330 161.94. Thus, including a common-carrier provision for escalation, which is normal for Colorado highway contracts, the total escalation costs as of July 1979, including labor and materials, amounted to approximately $3 049 990--this at a time when the rate of inflation was much higher in other highway contracts and in the economy in general. One can conclude that items of work carefully selected can have a slowing effect on costs associated with a particular project. In Figure 1 a comparison is given on escalation-controlled items versus general cost index.

ESCROW DOCUMENTS

The specification innovation most calculated to minimize the adversary relationship was the requirement for the contractor to deposit escrow documents as part of the bid. The pertinent provisions related to the escrow documents and the fixed-fee provision of the specification follow.

102.07 Escrow Documents Rev. 6-17-74

Each bidder shall submit with his proposal complete documentation clearly itemizing and separating costs for each contract item, except the contract item "fixed fee", contained in the proposal. Costs used to determine each unit price shall be separated and identified as costs of: labor, equipment, materials, fixed costs--on-project site, fixed costs--off-project site, and other costs included must be specifically identified.

(a) The documentation shall include copies of all quotes, memoranda, narratives or any other information used to arrive at the bid prices contained in the bid schedule and shall be clearly marked with the appropriate bid schedule item reference number. For purposes of identification, all such supporting documentation will be known as the escrow documents.

(b) The escrow documents shall be submitted in a sealed container along with the sealed envelope containing the proposal and will be clearly marked with the bidder's name, date of submittal, project number, and titled "escrow documents." The escrow documents shall be accompanied with an affidavit signed by the bidder, stating that he has personally examined the contents of the escrow document container and has found that the documents are in the container and are correct and complete. Escrow documents of the apparent successful bidder shall be examined in his presence for adequacy and accuracy prior to award. After award of the contract, the escrow documents of all other bidders will be returned unopened.

(c) The escrow documents of the successful bidder will be returned at such time that the contract is completed and final settlement has been achieved.

(d) Escrow documents shall be stored at a location and in a manner agreeable to the division (state highway agency) and the contractor.

Escrow documents may be examined any time deemed necessary by the chief engineer to determine the contractor's bid concept. This examination may be required for payment purposes for any and all contract items, subject to the following requirements:

Table 2. Increase in cost of materials.

Item	Escalation in Cost ($)	Unit	Pegged Price per Unit ($)	Last Price Paid per Unit ($)	Increase (%)
Structural steel	856 208.47	ton	660	709	7.42
Reinforcing steel	100 726.62	lb	0.16	0.173	8.28
Gasoline	26 970.87	gal	0.382	0.869	127.0
Diesel fuel	33 412.69	gal	0.33	0.48	45.0
Liquid petroleum gas	84 649.33	gal	0.30	0.414	38.0
Electrical power	228 195.96	-[a]	-[a]		

[a]See section 109.10(f).

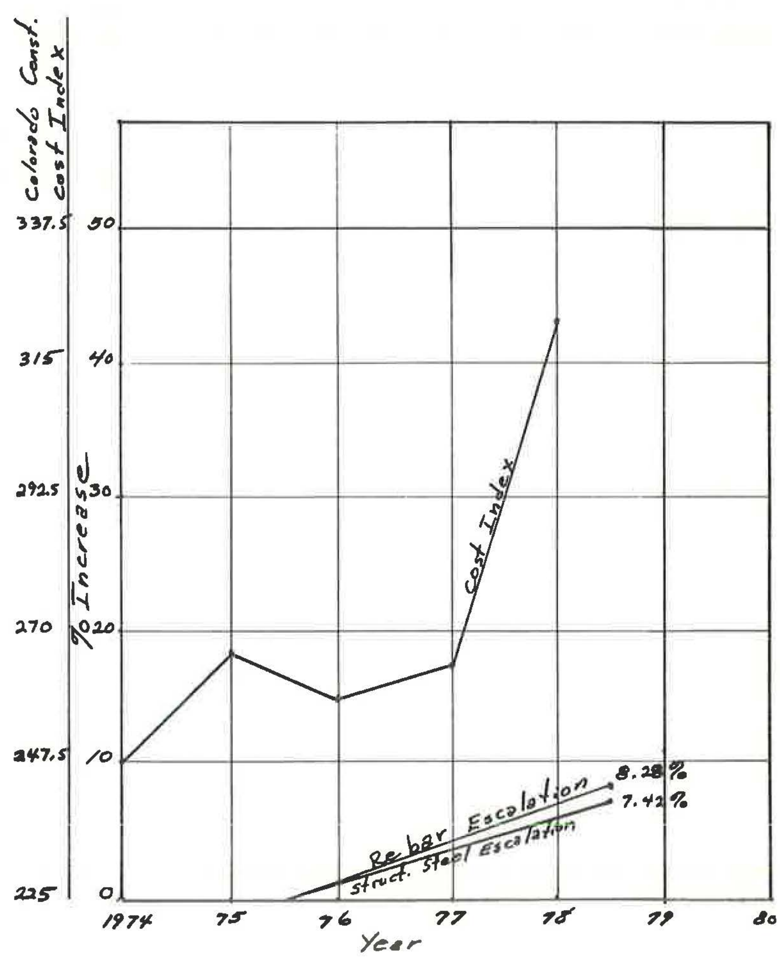

Figure 1. Comparison of escalation-controlled items versus general cost index.

1. Examination of documents shall be made by those specifically delegated by the chief engineer and a contractor representative.

2. These documents are considered proprietary and confidential in nature and shall be treated as such by those designated to review them. These documents, or any of the contents thereof, shall not be made available to any person or persons not herein designated without the specific consent of the contractor.

SECTION 699 Fixed Fee

699.01: Description

This section provides a contract item for profit earned by performance of work stipulated in the contract.

699.02: Basis of Payment

The amount bid for this contract item shall be adjusted only in the event of elimination of contract items under the provisions of subsection 109.05--eliminated items. If a contract item, or items, is eliminated, the amount of the "fixed fee" shall be reduced by a percentage equivalent to the percentage of reduction in contract work. This percentage of reduction in contract work shall be computed by dividing the sum of all contract item bid amounts, except the amount bid for contract item "fixed fee," into the sum of bid amounts for the contract items, or item, that are eliminated.

699.03 Profit, if any, for extra work shall be paid under the provisions of subsection 109.04--extra and force-account work.

699.04 Partial payments for fixed fee will be made once each month as the work progresses. These partial payments, as defined in subsection 109.06, will be made as follows:

(a) One percent of the bid price for "fixed fee" will be paid for each one percent of the original contract amount earned until 90 percent of "fixed fee" is paid.

(b) The remaining 10 percent of "fixed fee" will be included in the final payment.

(c) Payment will not be made for more than 100 percent of the amount bid for this item. Payment will be made under pay item--fixed fee; pay unit--lump sum.

The escrow documents, in effect, were the supporting documentation for the contractor's proposal for doing the work. The concept provided a mechanism for evaluation of the contractor's bid proposal, and later a control of costs associated with extra or otherwise directed work, through the requirement for a cost-accounting system that was related directly to pay items in the contract. The specification essentially provided for the contractor to prepare a proposal for each unit price bid on the basis of a bid item for a fixed fee separate from the anticipated costs for labor, equipment, materials, on-project fixed costs, and off-project fixed costs. The concept also provided a mechanism for price and time adjustment as a result of material procurement delays, adjustment of labor costs, and adjustment in material costs for certain defined materials (specification subsection 109.10).

Some concern was expressed that the requirement for a breakdown of the overhead cost items could lead to a tendency by the contractor to unbalanced bidding. Also, a faction believed that such unbalanced bidding by the contractor could result in the use of the escrow documents to the contractor's advantage by placing in the record higher bid items in those areas where a challenge might be anticipated to the specification during the work. Such actions by the contractor are possible; however, a contractor who is serious about submitting a proposal to perform work cannot risk major unbalancing of a bid unless, of course, the degree of certainty is high that he or she ultimately will profit from the unbalance. In a project that has a magnitude of $100 million, this possibility is remote; although, of course, some unbalancing of bids is inherent in the highway bidding process for any contract items related to an extent to the contractor's experience and equipment for prosecuting the particular type of work. The commitment to maintaining the proprietary and confidential aspect of these documents and the provision that the contractor have input into the decision as to when such documents will be used, I believe, is essential to the contractor's willingness to submit such documents in a fair and truthful manner.

The documents were most useful in establishing fair and equitable adjustments to the contract in several instances; specifically, a reduction in cost to the project due to an 87 percent underrun of a contract item, buttress berm grouting. The large percentage reduction qualified for a price change under the provisions of specification 104.02(d)3. The escrow documents were supportive of the contractor's request for change and provided recovery of costs for preparation for the drilling and grouting operations, timbering up for first-stage grouting, and other essentially fixed costs that are normally and reasonably spread against the total bid quantity of grout. Certainly an adjustment would have been provided under the normal specifications for a situation of this magnitude; nevertheless, the escrow documents facilitated the agreement and avoided the usual disparate opinions concerning the contractor's overhead and fixed-fee costs and the method of distribution of such costs to the particular change order.

The documents proved similarly useful in adjusting another contract bid item, item 29, pregrouting, which experienced a 96.6 percent underrun in contract bid quantities; also, a major underrun in contract bid item 43, sheet metal for panning. Each of these are items that are not amenable to precise engineering evaluation as to need during the preparation of the PS&E for a project. It is my judgment that the escrow documents tend to allay the fears of a contractor concerning the potential for wide deviation from plan quantity of these items and, assured with the knowledge that he or she will probably recover fixed costs based on certified and confidential documents, the contractor can and will devote more time and attention to the more substantive provisions of the bid; namely, how to drive through the mountain and at what cost. There is no doubt in my mind that in projects of large scope, protracted negotiations of contract price adjustments for changes and extra work that arises during advancement of the project are avoided. The result is a facilitation of just and reasonable payments to the contractor for justified work without an adversary relationship.

An important element in minimizing the adversary relationship that may have been overlooked somewhat as to its importance is the design, especially in the heavy-ground regions, which provided for the construction of a positive initial tunnel support system prior to excavation of the primary tunnel cross section. Although the design did not attempt to direct how the contractor should proceed with performance of the work, it clearly established an acceptable and safe sequencing of the work. The initial support system in this tunnel reach provided for a multidrift operation with crown and foundation drifts, in that order or simultaneously, to be completed prior to the excavation of sidewall and arch drifts, for a total of nine drifts in all. Considerable reluctance was expressed during the design phase of the first tunnel to a specification by the owner of such a support system.

The essential responsibility of the state and its engineers is to provide this type of basis on which the contractor can submit a bid proposal. Inherent with this, of course, is acceptance of the risk for the adequacy of the design and specifications. As a professional, this is a responsibility that the engineer must take. In addition, three other support systems, all of a horseshoe configuration, were provided. These were termed light, medium, and heavy tunnel support systems. Although the anticipated approximate stations for each of the four support systems were included in the plans as was a geologic summary of tunnel support types, these locations were not deemed to be fixed or unchanging, and throughout the construction process discussions with the contractor were considered as each support system was finally established. In my view, the proper role of the engineer as a designer and the contractor as a constructor was developed for this project. The design resulted in the contractor's confidence in the designer's understanding and knowledge about what was necessary to hold up the mountain and willingness to accept the risk of that design. Provision for alternate designs was not made but, in my judgment, the flexibility of set spacing and support system selection resulted in benefits equal to or better than what may have resulted from alternate design opportunities without the major problem of analysis of proposals by the contractor for comparability with the state's design. The design scheme for the construction of the support systems is available to the reader by contacting FHWA or the Colorado Department of Highways.

SUMMARY AND CONCLUSIONS

The innovations introduced into this project have the potential for continuing to improve or eliminate the adversarial relationship that is often thought must exist simply because the engineer and contractor have different perspectives on the purpose for their involvement in the project. This need not be the case. In fact, (a) their purpose for involvement in the project is more alike than dissimilar, (b) continued innovations are warranted to further improve the relationship, and (c) labor and materials escalation, bidder prequalification, affirmative design details, selective and proper use of escrow documents, and clear definition of dispute settlement procedures are a few of many possibilities for improving or eliminating an adversarial relationship that this paper has discussed. An overriding goal for underground construction should be the minimizing of adversarial relationships and, in its place, the development of a team concept between the engineer and contractor. For, after all, the mission of both is to produce works that are beneficial to the public and serve a useful societal need.

Management Strategies for Quality Assurance for Pittsburgh's South Busway

WALTER G. HEINTZLEMAN

The management strategies for quality assurance are examined for Pittsburgh's South Busway Program. Specific consideration is given to (a) management structure, (b) end-result specifications, (c) sharing areas of risk, (d) mutual respect, (e) open communications with bilateral resolution of issues, (f) process for feedback, and (g) monetary and nonmonetary rewards. The avoidance of adversarial relations between owner, engineer, and contractor was key to a successful quality program in an adversarial political environment.

This paper is the first of three to examine and evaluate management strategies for quality assurance used on Pittsburgh's South Busway Program from viewpoints of staff who represent the owner (Port Authority of Allegheny County), engineering manager, and a contractor. This evaluation is an outgrowth of the recognition of the interdependence of quality assurance and productivity and their dependence on management strategies.

These evaluations were initially stimulated as an outgrowth of ideas presented by Judson (1) in his paper at the American Society of Civil Engineers (ASCE) symposium on productivity in the construction industry. These ideas have been expanded in response to work being done by the Transportation Research Board.

BUSWAY DESCRIPTION

The port authority is engaged in a capital improvement program in excess of $0.5 billion. The first element constructed was the South Busway, a 6.4-km (4-mile), two-lane, two-direction, limited-access roadway. It begins at the Smithfield Bridge near downtown Pittsburgh and travels in a southerly direction through a 1.04-km (3400-ft) bus-trolley tunnel, through a trolley yard, across a new 520-m (1700-ft) bridge that crosses two major arteries, and then along a steep hillside that is parallel to the Norfolk and Western (N&W) railroad tracks for 2.5 km (1.5 miles). The busway then drops under a newly constructed N&W railroad bridge to merge again on a common right-of-way with trolleys for the last 1.6 km (1 mile) to its current terminus at the PA-88--PA-51 Glenbury intersection. The busway has 11 stops and three on-off ramps. All bus service is via existing bus routes, which now use the South

Busway to avoid the congested Liberty Tunnels and Bridge and approach arteries.

The South Busway reduces normal travel time to downtown by as much as 15 min and, during times of heavy street congestion, by as much as 45 min. More importantly, the busway helps increase service reliability and reduces wait time for passengers from buses otherwise delayed in street traffic. The South Busway services approximately 21 000 patrons daily.

QUALITY-ASSURANCE OBJECTIVES

The objective of the busway construction program was to construct a busway that facilitates bus operations, has minimal maintenance, and also accomodates other concerned parties, at a cost that can be justified by the port authority and the funding bodies.

Quality-assurance objectives, from the owner's perspective, focused on the objectives of the busway construction program and, in turn, on the ultimate use of the busway from an operational and maintenance viewpoint.

The decisions of the authority's staff encouraged the engineer and contractor to follow these objectives as a guide.

ENVIRONMENT FOR QUALITY ASSURANCE

The owner, engineer, and contractor had to function within the political, social, and economic environment. In the early years of the project, the mayor of Pittsburgh vigorously opposed the project and publicly attacked construction contractors as the cause of the city's public works woes. It was popular and politically advantageous to use contractors as scapegoats and treat them in an adversarial manner.

Nonetheless, the staff for the owner, engineer, and legal counsel recognized that contractors must function cooperatively as important participants in the total effort and not be treated solely as advocates to the program.

MANAGEMENT STRATEGIES

Guided by the paper by Judson (1), seven strategies are presented that were effective in reaching quality-assurance objectives.

Management Structure

The authority tried to maximize private enterprise in design and construction. A small professional staff was employed to manage the program and the engineering management services of a general engineering consultant (GEC) were retained for engineering design and engineering management of construction. In turn, the GEC retained several subconsultants.

The actual construction was performed under contract to the authority, and contractors were selected through competitive bidding. Exceptions were track, signal, and communication work, which was handled mostly by force account.

Use of End-Result Specifications for Construction Contracts

Contract documents were based on the contractor's providing the end product, as configured in the specifications, to meet functional requirements within the time specified. Contractors were not told how to do the work, only what had to be done. The contractor guaranteed the work by bond for one year and, in some situations, up to five years. Inspectors were expected to anticipate problems and had to be problem solvers, not policemen. The authority expected the contractor to use quality-control standards to ensure that construction would meet those specifications that were designed around operational and maintenance requirements.

Management Risks

The owner and engineer made an effort to identify and deal with areas of potential risk in a timely manner. It is the policy of the port authority to identify known problems at the time of bidding and to share potential risk when feasible.

Mutual Respect

Perhaps the most important personal contribution in obtaining quality assurance was mutual respect. Mutual respect was important to develop trust and confidence in the performance of each entity in its area of authority. In this regard, it also was helpful to avoid second guessing, passing the buck, public criticism, and using other parties as scapegoats. Mutual respect also required understanding the role of others and the issues from their perspectives.

Open Communications and Bilateral Resolution of Issues

Mutual respect and willingness to identify and deal with risk generally led to open communications. An effort was made to avoid adversary relationships and to try to resolve issues with a cooperative approach within the framework of the contract documents. Open communications and bilateral resolution of issues provided the opportuntity for dozens of involved autonomous agencies and groups to participate in the process of identifying and resolving issues in a timely and relevant manner.

Process for Incorporating Learning into Future Actions

Four methods have been used to incorporate learning into future action:

1. Meetings, which provide opportunity for information and feedback;
2. Professional critiques;
3. Comparison of work done by contract with force account; and
4. Evaluation of finished work in light of alternate designs and management strategies.

Use of Monetary and Nonmonetary Rewards

Accurate, fair, and prompt payment for all work done in accordance with plans and specifications is, in itself, a form of reward.

Four methods of nonmonetary recognition also were used:

1. Personal expression of appreciation for work done well,
2. Letters of appreciation,
3. Professional recognition, and
4. Community recognition of work through the media.

CONCLUSION

These seven management strategies have been important in implementing the busway program. By comparison, these strategies could not be used effectively during the first few years of the busway program and productivity suffered. In the early 1970s, the program was delayed by political controversy, a year-long court suit, change in scope, and further studies. Openness and bilateral resolution of issues were not permitted by some municipal officials. This resulted in lack of information, lack of mutual respect and trust, subsequent delays in resolution of issues, redoing of work, and missed design opportunities.

Clearly, the management strategies found to be most effective in obtaining quality assurance while maintaining productivity were those that

1. Involved the parties in reaching mutually agreed-on objectives, and more important, agreeing on timely action;
2. Delineated areas of risk;
3. Avoided adversary relationships and encouraged mutual respect, with trust and confidence in the integrity of the involved parties;
4. Were based on open communications that allowed for bilateral resolution of issues;
5. Provided a process for feedback for future actions; and
6. Provided for monetary and nonmonetary rewards.

This list, although it is not exhaustive, has set the stage for effective action. The effectiveness of these strategies in obtaining quality assurance while maintaining construction productivity for the busway program can be further judged from the papers by Drosendahl and Mascaro in this Record, which provide viewpoints from the perspectives of an engineering manager for construction and a contractor.

REFERENCE

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Construction of Pittsburgh's South Busway: An Engineer's Viewpoint

JON W. DROSENDAHL

Contractual relationships play an important role in the success of a construction project and must be defined by contract. However, the participants in a project bring their own objectives, ideas, strengths, and resources to the effort. Because of the interrelationships of the participants, these individual characteristics must be understood and a cooperative attitude must be developed. The engineer, because of his or her unique understanding of the project, can play a leadership role in the development of the necessary cooperative attitudes. When the engineer is successful in this role, the project is a success and the objectives of the participants are achieved.

This paper is based on the role of Michael Baker, Jr., Inc., in the development of the busway system for the Port Authority of Allegheny County. As explained in a companion paper by Heintzleman in this Record, a busway is essentially a two-lane highway built for the exclusive use of buses. These busways bypass extremely congested areas of Pittsburgh, which permits rapid movement of the buses into or out of the downtown area during rush hours.

The firm of Michael Baker, Jr., Inc., was engaged as the consulting engineer by the port authority to perform the planning, design, and construction management tasks in conjunction with the development of the South Busway and East Busway. This overall engineering effort was managed by Baker's director of engineering, who supervised the various discipline managers.

As manager of construction inspection services, I reported directly to the director of engineering and was responsible for the management of the construction effort required for busway construction. The actual construction was performed by independent construction companies under contract to the port authority. The viewpoint of one of these contractors is also being presented as a companion paper by Mascaro in this Record.

The busway program is considered quite successful. The South Busway was opened three years ago, within the anticipated time and within the budget. Construction overruns were limited to less than 7 percent of the contractual cost of the project and, in half the cases, it was the result of changes in scope required by the funding agencies after the design phase had been completed. The East Busway, now under construction and scheduled to be in operation by early 1983, is on schedule and within budget.

CONTRACTUAL RELATIONSHIPS

As indicated in Figure 1, both Cameron Construction Company and Michael Baker, Jr., Inc., were under direct contract to the port authority. Cameron was contractually responsible for providing a product that met specifications. To ensure that these specifications were met, Cameron also provided a specified testing program through an independent laboratory.

Michael Baker, Jr., Inc. was contractually responsible for development of the specifications for the product and the specifications for the testing program. Michael Baker, Jr., Inc. was also required to monitor the testing program and conduct inspections to ensure that the product met specifications.

This, of course, is generally regarded as the traditional approach to construction and has been practiced both successfully and unsuccessfully for hundreds of years. However, there is more to quality assurance than is indicated in this sketch. Figure 2 indicates the relationship of the project team as developed for the busway construction. The owner, engineer, and contractor are all shown overlapping at the center of the project because

Figure 1. Contractual relations.

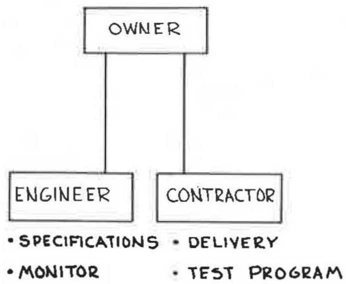
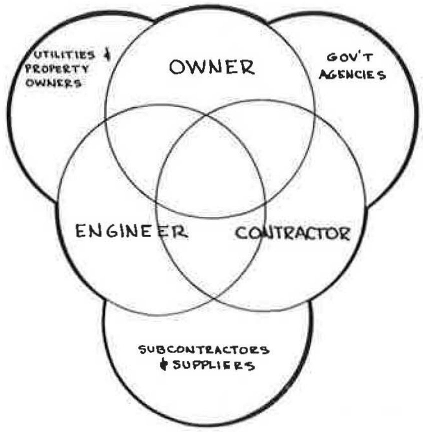


Figure 2. Project team.



each, at various times, is responsible for the success of the project and must interact with the others to fulfill this responsibility. It is within this area that the interrelationships become the most critical.

Each team member brings to the project his or her own goals, ideas, strengths, and resources. Because the engineer has participated in each stage of the project, he or she inherently knows and understands both the concepts and details of the project. This knowledge places the engineer in this center area as the project coordinator and provides the engineer with the opportunity to set the pace for the interactions of the team members.

The engineer coordinates the other team members in the spirit of cooperation, mutual trust, and overall common interest in the project. Through example and leadership, this cooperative spirit must be developed. Perhaps difficult questions must be asked, difficult positions taken, or team members must be reminded of their responsibility, but this cooperative spirit must be maintained.

Importance of Each Team Member

In order to emphasize the team-approach concept, the circles that represent the members in our sketch are of equal size. No matter how vast or narrow a portion of the project each member is responsible for, at some time that portion becomes the most important part. Each member, therefore, must be considered, coordinated, understood, and managed to ensure the fulfillment of his or her particular requirement or obligation to the project.

Interaction of Each Team Member

Again, as shown on our sketch, each member's circle overlaps that of the others. This overlap indicates the interrelationship and interdependence of all the team members. Interaction occurs among all the members at various times and with different intensities. This is the interaction that accomplishes the work, solves the problems, and determines either the success or failure of the project. Perhaps the interrelationship is required by contract or law, however, its existence must be accepted by each member as a prerequisite to the fair and successful pursuit of the project. The engineer may serve as the catalyst, moderator, or even go-between in some cases, but the major factor in the success or failure of an interaction is the attitudes of the interrelated members.

Attitude

The project is the sum total of the efforts of the team and all the members are bound firmly to it by their obligations and responsibilities. When properly presented, each member understands the implications of this agreement. At the risk of being redundant, the importance of the proper attitude of the members cannot be overemphasized. The rights as well as the responsibilities of others are understood and each member cooperates with the others, perhaps making sacrifices on occasion, in order to advance the project and obtain long-term objectives.

ILLUSTRATIONS OF THE TEAM APPROACH

These successful interrelationships can best be seen through the solution of a job problem that occurred during construction of the South Busway. The specifications as developed by the engineer required the contractor to coat an existing brick tunnel liner with a 5-cm (2-in) thick application of shot crete. Briefly, shot crete is a pneumatically applied mortar that contains pea gravel along with sand, cement, and water. This application was to provide a low-cost method for repointing the masonry as well as provide some additional structural strength.

To accomplish this task and also comply with a minority business enterprise, the contractor subcontracted the work to a small company more experienced in the application of gunite, a pneumatically applied mortar material that does not include the pea gravel contained in shot crete. The subcontractor made several attempts to apply the shot crete as specified but was unsuccessful. Meetings and discussions were held in an attempt to assist the subcontractor and to develop alternate coatings that could be applied more efficiently. Throughout the discussions, the engineer coordinated the objectives of all the participants. Also, he conducted all negotiations and secured all approvals to the general satisfaction of all the involved participants.

Agreement was reached to permit the subcontractor to substitute 2.5-cm (1-in) thick application of gunite instead of the shot crete in return for a credit to the owner. The gunite provided the required repointing of the masonry and, through careful examination of the existing brick surfaces, the additional structural strength required was reduced. The net result was threefold: The subcontractor could proceed efficiently with an application that he was experienced with, the construction could proceed in timely fashion, and the owner was provided with a satisfactory tunnel lining at a reduced price.

Another example of the successful management of the project team's interrelationship is demonstrated in the quality-assurance program developed for the concrete incorporated in the busway construction. The engineer recognized that concrete could be subject to problems attributable to the aggregate available in the Pittsburgh area. These aggregate, generally obtained by dredging the rivers or mining bank deposits, contain soft particles, coated pieces, or other troublesome materials.

In the design stage, the engineer selected concrete strengths to be specified that were within the experience record of the local concrete industry. Furthermore, a testing program was developed and incorporated into the specifications that would ensure that the aggregates used would be properly monitored in order to provide the necessary concrete strengths.

During the prebid stage, the engineer reviewed the specifications and required testing program with the local concrete suppliers and potential bidders. Discussions were held and the objectives behind these requirements were explained to the industry.

After the award of the contracts, the engineer met with the successful bidders, their appointed testing laboratories, and their concrete suppliers and assisted in the preparation of the quality-control manual for concrete. As concrete was supplied to the job, the results of the quality-control program were monitored and adjustments were made.

Throughout this procedure, the engineer assumed a leadership role, through the coordination of the efforts of the other team members. Through definition of objections, persuasion, and open discussions, the contractors and their suppliers were convinced that the program was to their advantage as well as to the advantage of the owner. The result of this effort is that the East Busway construction has proceeded without any concrete being removed because of insufficient strength.

CONCLUSION

Contractual relationships are an essential ingredient of the quality-assurance programs of all construction projects. Responsibilities and obligations must be clearly defined by contracts and the team members must undertake the fulfillment of these responsibilities. However, the success of the project is dependent on the team members' performance and interrelationships with the other team members. All the team members must function in this area, but the engineer, because of this understanding of the work, has the opportunity to develop the relationship necessary for success.

Contractor's Viewpoint and Case Study of Pittsburgh's $27 Million South Busway Program

JOHN C. MASCARO

Project participants on Pittsburgh's new South Busway worked hard to create a productive climate for the successful completion of their $27 million busway program. Throughout this project, quality assurance was of paramount importance. Quality construction and a productive climate were compatible through cooperation, goodwill, mutual trust, and teamwork among the owner, consulting engineer, contractor, and other parties. The project was completed on time and within budget through the owner's willingness to assume a fair share of risk. The principles and philosophies illustrated by this case study are not new and were used with a common-sense approach to the successful completion of this project.

This paper presents a case study of the contractual relationships among owner, engineer, and contractor on Pittsburgh's South Busway Program and their effect on quality assurance. For the purposes of this paper, the following definitions are applicable:

1. Quality assurance is the total system that is used by management, their engineers, and their consultants to answer the general question, Are we doing the right things?
2. Quality control is that control that a person undertakes to check in a systematic manner, that the steps for implementation are correct and will enable the project to be constructed in the specified way.

The owner of the project was the Port Authority of Allegheny County, the engineer was Michael Baker, Jr., and the contractor was Cameron Construction Company, a Pittsburgh-based construction engineering and management firm.

Although traditional contractual relations among owner, engineer, and contractor were employed, a productive climate was created through cooperation, goodwill, mutual trust, and respect. More importantly, the project was completed on time, within budget, and with quality construction.

TRADITIONAL APPROACH TO THE CONSTRUCTION PROCESS

The owner's need to build usually results in a construction project. Owners are individuals, companies, or governments that must satisfy physical needs. Construction projects are physical needs and might be in the form of a home for a family, a large office building for a corporation's headquarters, or a new highway or dam for the federal government.

Once an owner decides to build, an engineer or architect is hired to evaluate the owner's needs. Throughout this paper, engineer, architect, and designer will be used interchangeably and synonymously. They shall represent a person, company, or group of partners that provides feasibility studies and conceptual designs based on the owner's scope parameters and budget. This is the first phase in the traditional construction approach and is called the decision phase. Once these initial items are completed, the owner then hires an architect or engineer to finalize the overall design and to make the drawings and specifications. This is the second phase, called the design phase, in which the architect or engineer develops a solution to meet the owner's requirements. These solutions are evidenced by plans and specifications and are referred to as the contract documents.

The third phase is the bid phase, which can follow two possible paths. If the owner intends to follow the competitive bid process, contract documents are issued to general contractors interested in bidding. The list of general contractors who bid can be a general list of qualified contractors or a select list of qualified contractors. The contractors then review the contract documents and submit their prices for the project to the owner for consideration. The owner then reviews the bids and makes the award of the contract. If the owner is a public agency, it is usually mandated to select the lowest responsible bidder; private owners may choose this or other criteria for selection.

The fourth phase is construction. Here the owner usually hires the architect or engineer to inspect and supervise the work performed by the general contractor and subcontractors. If during this phase the owner or architect or engineer decides to change the scope of work or the contract documents, they negotiate with the contractor to determine a fair price for the proposed changes. Figure 1 illustrates this traditional approach.

It is beyond the scope of this paper to discuss the advantages and disadvantages of the various contractual relations between the owner, architect, or engineer, and contractor. There are several other contractual relations that currently exist, such as design-build or turnkey contracts, construction-management contracts, owner as the construction manager with several prime contracts, engineer as the contractor and construction manager, plus other various combinations (1). Each one may have a different effect on quality assurance.

This traditional approach normally precipitates adversary roles among the owner, engineer, and contractor. The adversary relationship can and must be eliminated at all costs.

The South Busway was a $27 million project that was completed to everyone's satisfaction without litigation. The busway project did not have any special contractual relations with imaginative management and quality-assurance gimmicks. The owner, acting largely through the engineer, set out to foster a climate of cooperation. Foremost in the owner's mind was the main goal: to build the highest-quality project for the least cost.

BASIC ATTITUDE OF CONTRACTOR

The exact role of the contractor cannot be defined until the low bid is submitted and the owner and engineer have a chance to evaluate the contractor's attitude toward the project and quality assurance. The owner and engineer determine the projected course of action for the contractor. The contractor responds to the way he or she is treated. The Port Authority of Allegheny County and Michael Baker, Jr., Inc., created a productive construction environment in which the busway was to be built. Their attitude and construction values were analogous to ours. They were committed to a team-concept approach, where everyone worked together toward the same end product. Cameron Construction Company was not an adversary, and profit was not a dirty word. An open line of communication was immediately established between the Port Authority, Michael Baker, Jr., and Cameron Construction Company.

OWNER'S ROLE IN THE TOTAL SYSTEMS APPROACH

The total systems approach for quality assurance must use the team approach. At the beginning of any project, mutual trust, respect, and confidence must be established immediately among the team players. A thorough understanding of the main objectives and roles of each player is important to the success of the project. Adversary relations among the owner, engineer, and contractor must be eliminated and open communications among all parties will lead to resolution of issues with a cooperative approach within the framework of the contract documents. Communication was maintained via biweekly meetings held at the job site.

Another effect on quality assurance, besides the contractual relation among owner, engineer, and contractor, is the method of procurement for construction services. It should be analyzed and reevaluated. Lester Fettig, chief of the Office of Federal Procurement Policy, is strongly against the federal government's policy that "price is all". He asserted, "Taking the low bid is not a sensible way to buy anything, not even toothpaste". Sometimes the low bid is not always the cheapest for the owner. A contractor who has haphazardly prepared a low bid will be in trouble if he or she has not effectively considered all of the problems in a project. If a poor bid has been made, the contractor will realize, after construction is under way, that actual costs are substantially greater than estimated costs. If this disparity is large enough and the contractor cannot afford the loss, bankruptcy will result. Thus, completion of the project is delayed until another contractor can be solicited to complete the job. Delay costs everyone money.

Regardless of the method of procurement used by the owner, it is necessary that a productive management strategy be established that

1. Involves team players in reaching mutually agreed on goals and objectives,
2. Shares risk equitably, and
3. Encourages mutural respect, trust, and confidence among the owner, engineer, and contractor.

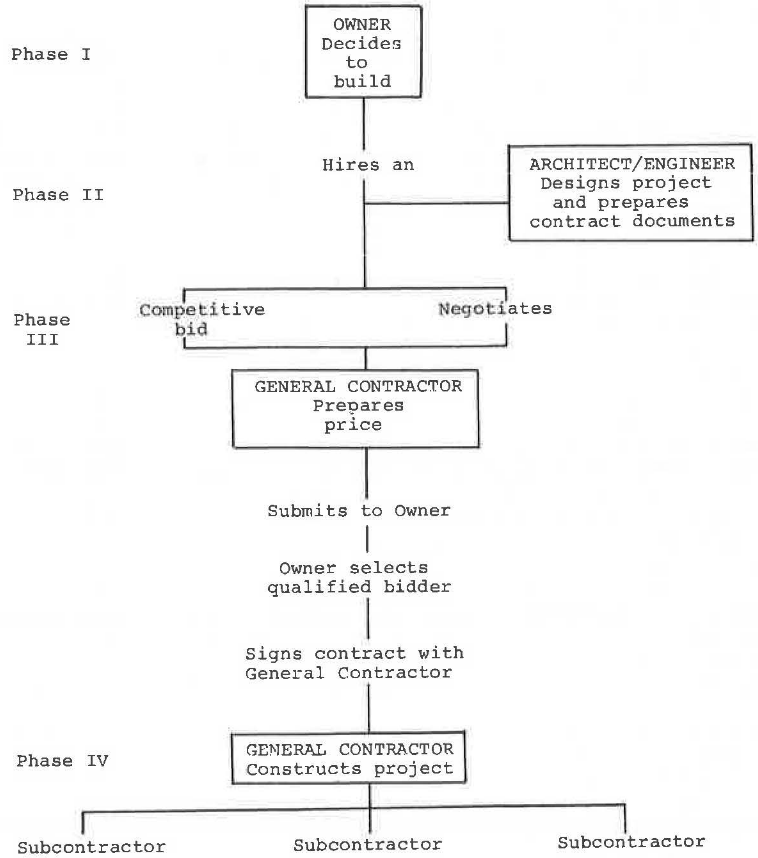
TOTAL SYSTEMS APPROACH

The exact role the engineer plays in the quality-assurance program is determined directly by the owner. The nature of contractual relations between the owner and engineer determines the involvement of the engineer during the construction phase. The owner may procure the engineer's services via competitive bidding or may negotiate with the engineer. If bidding for professional services is required, the engineer will be forced to use standard specifications and designs used previously on other projects to keep the cost down. Little time will be spent for the particular project. Inappropriate designs and specifications will lead to delays in the field and thus cause decreased productivity. If the engineer has the luxury of a negotiated contract with the owner, he or she can afford the time to guarantee that specifications are not obsolete and that the designs are economically constructible. Productivity begins long before the job starts and, once construction starts, the additional money spent in the initial stages of design will pay for itself many times over.

The majority of suggestions listed are based on the premises that (a) the contractor must bid competitively on the project; (b) the owner is public, not private, and does not do his or her own design; and (c) the engineer is a separate entity and has responsibility for design and inspection of construction but does not do the construction. Obviously there are many combinations of relations among the owner, engineer, and contractor. Some owners may want a design or build service from a firm where the contractor does the design and construction.

The traditional role for the owner, engineer, and contractor will be assumed. Resulting suggestions

Figure 1. Traditional approach to the construction process.



for improving quality assurance will be germane regardless of what type of construction method is employed.

The engineer's role in quality assurance will be analyzed in the following areas:

1. Working environment,
2. Specifications and design,
3. On-site inspection,
4. Risk sharing, and
5. Delays and changes.

Working Environment

Perhaps the most important role the engineer can play is that of team captain. The team consists of the owner, engineer, and contractor associated together in the construction of a project. The players are bound together by their contractual obligations and responsibilities, and the successful completion of the project is their ultimate goal. It is paramount that a constructive, working environment be established at the onset of the project. The engineer should share in the coordination and creation of a cooperative atmosphere. Everyone must recognize and respect the other's job and responsibilities. The success of the job depends on the cooperative attitude of the other participants. A good working environment will provide quality construction; a poor one creates confusion and disaster.

Specifications and Design

The plans and specifications are the framework within which the project is to be constructed. The language of the specifications has certain connotations that can create a good or bad working environment. Some examples of these contract provisions are given in Table 1 (2).

The tone and language of the specifications project the engineer's attitude about the project. Every specification has a price tag. The more devious is the language of the specification, the greater is the cost of the project to the owner. Language must be clear, firm, concise, and direct to ensure a quality product.

The specifications committee of the American Society of Civil Engineers (ASCE) conducted a survey to better understand the differences between the engineer and contractor regarding specifications. The results, published by Fisk, indicated that specifications are usually poorly written, ambiguous, obsolete, unclear, and irrelevant (3). Specifications are being prepared by writers who do not fully understand the complexity nor the importance of the document they prepare. Specification writers should be professionals who have field experience and can write with clarity and directness. Exculpatory clauses should be eliminated.

The apparent solution, according to Fisk, is to specify by objectives. "Specifying by objectives is little more than a new title for common-sense specifying." Under this concept, the specifications are written to meet only the specific needs of the project. This differs from the traditional approach only in that predetermined, arbitrary standards are avoided as long as the meaningful, true objectives can be reached successfully without them. In short, it means the following:

1. Determine the objectives (functional, quality);
2. Meet the objectives (allow reasonable tolerances);

Table 1. Evaluation of contract provisions.

Contract Provision	Good	Bad
Mobilization	Pay item for mobilization to compensate contractor for costs of mobilization and construction plant	No pay item for mobilization; contractor must unbalance bid or bank this cost until sufficient progress payments will cover them
Assignment of risk	Owner takes risk not controllable by the contractor, such as escalation, furnishing of long lead items, pay items for unknown but possible problems such as handling of ground water	Contractor takes all risks, including problems not under own control; as a consequence, must put contingency in bid that may be either unused or insufficient
Labor agreement	Area or project agreement negotiated in advance to set job rules, set up means of quickly settling disputes and means of arbitration	No agreement; contractors asked to take complete risk; negotiate job rules after award of contract
Right-of-way, contractor's work areas and permits	Owner obtains all right-of-way and work areas as well as all necessary permits in advance of construction	Contractor left to obtain right-of-way, work areas, and permits with insufficient time and no leverage
Schedule	Realistic schedule with time contingency included for expected delays and extension of time provisions to cover delays beyond contractor's control	Unrealistic schedule requiring shift work and extended workweek to complete on time with no provision for time extensions; contractor will consider these effects and add costs for these requirements

3. Do not exceed the requirements of the objectives.

Unrealistic or unnecessary constraints are costly. The owner must pay the bill.

The contractor's responses to the committee questionnaire on specifications have pointed out the need for improvement by many design professionals and have given birth to the concept of specification by objectives. If this concept is applied intelligently, by using properly qualified specifications engineers (not just specifications writers), it will be the first step in improving the turmoil that exists between the contractors and the specifiers. It seems a small wonder that the contractors' license board in California lists the failure to follow plans and specifications as the principal cause for the majority of contractor license suspensions.

On-Site Inspection

Too often the specifications are considered the bible and are blindly enforced by the on-site inspectors. Inspectors should use the specifications as a guideline only and good common sense should govern all decisions. The inspector should tell the contractor only what has to be done, not how to do it. Quality control and field testing should be placed on the contractor, not the engineer or owner. To safeguard the public's interest and ensure quality, a maintenance bond for a specified period can be provided by the contractor. This will guarantee end result and performance of the finished product. The contractor should have an independent testing laboratory to perform specified tests, in accordance with contract documents. The role of the inspector is elevated to that of a problem solver and not of a policeman or note taker. The inspector should have the authority to make decisions and not have to worry about being second guessed. The inspector should have the competence and knowledge to handle all job-related problems. If the engineer's inspection staff is multilayered, this layer of personnel will find it necessary to make their jobs important and have a tendency to cause delays in the field by questioning the contractor's operations to the nth degree.

In summary, if objective or performance specifications are used, the inspector only has to worry about the end product that is created by the contractor. The inspection staff should be small and well paid, use specifications as a guideline not a bible, and have the authority, competence, and experience to make all job decisions. Most important, the inspectors should have the right attitude and treat the contractor like a teammate not an adversary. Finally, profit should not be a dirty word in the inspector's vocabulary. Additional aspects concerning construction inspection not covered here are given in the ASCE task committee report on inspection (4).

Risk Sharing

Often too many exculpatory clauses are included in the contract documents. The engineer uses these clauses to cover for potential errors and omissions. Everyone should be willing to accept a share of the risk. There is no such thing as a get-something-for-nothing or at-no-additional-cost clause, such as incidental to construction, no payment for this item of work, or cost to be borne by the contractor. These are escape clauses in contract language that attempt to place all of the risk on the contractor. This type of language fools no one and the cost of every item of work will be somewhere in the contractor's proposal. These items of work will be priced and marked up accordingly--the higher the risk, the higher the profit, and thus the higher the cost to the owner. In the end, the owner pays for high-risk projects. Problem areas on jobs should be identified and, if the risk is so high that it will discourage competition of contractors, the owner and engineer should be willing to assume all or part of the risk by eliminating it from the bidding documents and negotiate it with the low bidder after the job is awarded. Reasonable risk sharing should result in lower costs with quality work.

Delays and Changes

Delays in the construction industry can occur at any time throughout the three main phases in the construction process: conception, design, and construction. Satisfaction of federal, state, and local regulations poses numerous and costly delays to owners and engineers. Regulations have increased the front-end costs of a project and the time required between project conception and start of project construction. This section will deal only with delays and changes in scope of work in the construction phase. Table 2 (5) lists contractors' responses to a questionnaire concerning major delay factors that affect their projects. A review of this chart will reveal some items over which the engineer has no control (i.e., weather, labor supply, and subcontractors). Other items, such as design changes, shop drawing and material approval, drawing and specification errors, site access, and utility relocation can be controlled by the engineer. De-

Table 2. Contractor responses to questionnaire based on percentage of replies received.

Delay Factor	Very Important	Important	Minor Importance	No Significance
Weather	59	31	9	2
Labor supply	48	32	16	5
Subcontractors	56	21	15	8
Design changes	36	34	24	5
Shop drawings	23	36	20	20
Foundation conditions	27	30	28	15
Material shortage	23	31	32	14
Manufactured items	19	32	31	18
Sample approvals	17	29	33	21
Jurisdictional disputes	17	27	27	29
Equipment failure	13	19	43	25
Contracts	13	18	30	39
Construction mistakes	10	17	39	33
Inspections	6	17	46	31
Finances	8	12	26	54
Permits	10	9	29	52
Building codes	2	8	27	63

Note: Rows may not total 100 due to rounding.

lays in the field, regardless of their nature, must be eliminated. If there are some delays in order to make use of technological advances, the owner must evaluate and compensate accordingly. The contractor's supervision, field offices, labor, and equipment, which cost thousands of dollars per day, are wasted while a design change is being considered.

The best way to avoid delays and minimize claims is for each actor to know his or her rights and protect them. The engineer should read the contract, plans, and specifications thoroughly and know what is expected before construction begins.

The engineer should conduct a thorough subsurface investigation to document soil conditions expected to be encountered. This should eliminate any delays due to differing site or concealed subsurface conditions. Drawings and specifications should be accurate and pertinent. Site access should be available and major utility relocation scheduled before construction begins. Design should be constructible by using reasonable techniques.

Regardless of the amount of time spent designing and scheduling, job problems and delays will occur. Problems should be identified early. The engineer should have a specific format to handle delays quickly and expeditiously and within a specified time frame so as to minimize the amount of additional cost to the contractor.

CONTRACTOR'S ROLE IN THE TOTAL SYSTEMS APPROACH

Once a low bid is submitted and the project is awarded, a construction team is selected from the available personnel. Our construction team consists of a project manager in the office and general superintendent, superintendent, craft foreman, and clerical staff in the field. This staff may vary depending on the size and complexity of the project.

Drawings and specifications are given to the field personnel so they can familiarize themselves with the project. The estimating team is available to the field personnel for consultation and advice in explaining the estimate, schedule, and tentative techniques to be employed. We will never start a project prematurely because we believe in the adage, "haste makes waste".

After the construction team is familiar with the project, a master schedule is made that incorporates the accountability of the owner, engineer, utilities, and others. This schedule should be as detailed as possible and incorporate every restraint and delay that can be envisioned. Critical path schedules and time grid schedules are used. We prefer the time grid, which uses a bar graph format and shows the interrelationship between various activities. The schedules are updated monthly. From the master schedule, separate schedules are made for the major subcontractors and distributed to them.

During the initial scheduling phase of the project, the project manager tends to the various administrative aspects of the contract, such as execution of contract, bonds, insurance, equal employment opportunity program, quality control program, and purchasing of subcontracts and all necessary materials.

Once construction starts, the management in the field has two basic goals:

1. Get the project completed within the original estimated budget and
2. Get the project completed within the original time frame estimated.

The project manager has these same goals, plus the elimination of delays and prevention of problems before they occur.

Throughout the job, proper and constant communication is vital between the team players. Biweekly meetings were held at the job site among the owner, engineer, contractor, major subcontractors, and utilities. Problems and job progress were discussed and deadlines were established. Everyone was held accountable to the deadlines established. Cameron Construction Company held weekly meetings with field personnel at the end of the day. The participants were the project manager, general superintendent, superintendent, and craft foreman. The following items were discussed at these meetings:

1. Costs,
2. Job progress and use of short-interval schedule (weekly),
3. Problems,
4. Problem-solving techniques (example of wall bulkhead), and
5. Method improvement techniques.

The main purpose of these meetings was to get field personnel involved and accountable. Costs were not hidden and job performance could be readily evaluated. Problems were discussed and analyzed. Our motto is that there is always a better way, a best way that is never truly achieved.

Motivation is maintained through bonus programs and other incentives.

In summary, the total systems approach produces a productive atmosphere for quality construction. The salient points of this approach are as follows:

1. Immediate establishment of professional trust and mutual respect among owner, engineer, and contractor;
2. Team concept--everyone works together toward the same common goal;
3. Profit is not a dirty word;
4. Owner and engineer are willing to share risks;
5. End-result specifications are to establish performance standards to be met;
6. Specifications tell what is required, not how to do it;
7. Quality control is the contractor's responsibility;
8. Qualified inspectors should understand construction; specifications should be used as a guideline, not a bible;
9. Elimination of delays in the field by anticipating them before they occur;

10. Decisions should be readily obtainable--management of owner and engineer should not be multilayered, no procrastination; and

11. Commitment by the utilities to cooperate with contractor.

CONCLUSION

There is no magic formula for success to a construction project. Common sense should govern all decisions. Among the secrets to improved contractual relationships and quality construction are creating a climate of respect and goodwill among the owner, engineer, and contractor; a willingness to adjust specifications to simplify construction while holding fast to end results; a willingness of the owner to assume risk for unforeseen conditions encountered and not let everything fall on the contractor's head.

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Analysis and Application of Correlated Compound Probabilities

RICHARD M. WEED

Many statistical applications require the calculation of compound probabilities and, frequently, the individual probabilities are not independent. The failure to recognize that correlation exists in cases such as these has resulted in numerous errors in the published literature. Although an exact analytical solution is not known, problems of this type can often be handled effectively by calculating lower and upper bounds for the desired compound probabilities. Bounds for both positively and negatively correlated cases are derived and then applied in the analysis of statistical acceptance procedures. The results of several computer simulation tests are presented to demonstrate the validity of the theoretically derived results.

The analysis of a variety of statistical acceptance procedures requires the calculation of compound probabilities. In many cases, the individual probabilities are correlated to some unknown degree, which precludes the direct calculation of the desired compound probability. However, lower and upper bounds for the desired probability can be calculated and, provided these bounds are not too far apart, this furnishes an interval estimate that is sufficiently precise for most practical purposes.

A previous paper (1) developed this approach for the case in which the individual probabilities are positively correlated. This paper repeats the derivation for positively correlated probabilities, develops the derivation for negatively correlated probabilities, applies these results to a simple sequential sampling scheme, and then derives the bounds for the probability of acceptance under a more complex acceptance procedure. This latter application is then checked by computer simulation.

BOUNDS FOR POSITIVELY CORRELATED PROBABILITIES

In accordance with a law of probability that is usually referred to as the general law of multiplication (2), the compound probability for the joint occurrence of event A and event B is given by Equation 1. Under this law, no assumption is made concerning the independence of these events, and they may be either positively or negatively correlated.

$$P(A \cap B) = P(A \mid B) \cdot P(B) = P(B \mid A) \cdot P(A) \tag{1}$$

When events A and B are correlated to some unknown degree, the values of $P(A|B)$ and $P(B|A)$ are not known and, consequently, $P(A \cap B)$ cannot be evaluated directly. However, when two events are positively correlated, the occurrence of one increases the likelihood of the occurrence of the other. This can be expressed in equation form as

$$P(A \mid B) \geqslant P(A) \tag{2}$$

which, when substituted into Equation 1, yields

$$P(A \cap B) \geqslant P(A) \cdot P(B) \tag{3}$$

as the lower bound for $P(A \cap B)$.

To obtain the upper bound, remember that any probability value is less than or equal to unity. Therefore, since $P(A|B)$ and $P(B|A)$ in Equation 1 both must be less than or equal to one,

$$P(A \cap B) \leqslant P(A) \tag{4}$$

$$P(A \cap B) \leqslant P(B) \tag{5}$$

and, from this,

$$P(A \cap B) \leqslant \mathrm{Min}\,[P(A), P(B)] \tag{6}$$

is derived as the upper bound.

Later on, it will be more convenient to designate these events numerically because the letters A and B will be used to refer to the first and second stages of a sequential sampling scheme. Equation 7 expresses both lower and upper bounds for the positively correlated case in this manner.

$$P_1 P_2 \leq P_{pos} \leq \mathrm{Min}(P_1, P_2) \qquad (7)$$

where

P_1 = probability of occurrence of first event,
P_2 = probability of occurrence of second event, and
P_{pos} = probability of the joint occurrence of the two positively correlated events.

BOUNDS FOR NEGATIVELY CORRELATED PROBABILITIES

For the negatively correlated case, another law of probability, the general law of addition (2), is useful. This is given in its basic form by Equation 8 and in a transposed form by Equation 9.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \qquad (8)$$

$$P(A \cap B) = P(A) + P(B) - P(A \cup B) \qquad (9)$$

Because the maximum value for the term $P(A \cup B)$ in Equation 9 is unity, this leads to the expression for the lower bound given by Equation 10. The maximum operator is required to ensure that the expression will not produce a value less than zero.

$$P(A \cap B) \geq \mathrm{Max}[0, P(A) + P(B) - 1] \qquad (10)$$

When events A and B are negatively correlated, the occurrence of one decreases the likelihood of the occurrence of the other. This can be expressed in equation form as

$$P(A \mid B) \leq P(A) \qquad (11)$$

which, when substituted into Equation 1, yields

$$P(A \cap B) \leq P(A) \cdot P(B) \qquad (12)$$

as the upper bound for $P(A \cap B)$.

As with the positively correlated case, it will be convenient to designate the events numerically. Equation 13 expresses both lower and upper bounds for the negatively correlated case in this manner:

$$\mathrm{Max}(0, P_1 + P_2 - 1) \leq P_{neg} \leq P_1 P_2 \qquad (13)$$

where

P_1 = probability of occurrence of first event,
P_2 = probability of occurrence of second event, and
P_{neg} = probability of the joint occurrence of the two negatively correlated events.

ANALYSIS OF A SEQUENTIAL ACCEPTANCE PROCEDURE

A fairly common sequential acceptance procedure requires that, when the tests on the initial sample indicate a deficiency, a second sample be taken and combined with the first to make the final assessment of compliance. Because the first sample is incorporated into the final sample, the probabilities of acceptance by the two stages of this procedure are not independent. For example, when a group of unusually low test values decreases the probability of acceptance by the first stage of the procedure, the presence of these same low values tends to reduce the probability of acceptance by the second stage of the procedure. Consequently, the two probabilities are positively correlated to some degree.

Although it might seem that this would be a likely application of the bounds for positively correlated probabilities, it will be seen that the bounds for negatively correlated probabilities are appropriate in this case. If A and B are defined as the events of passing the first and second stages of the sequential acceptance procedure, respectively, and if A' represents the complement of A (i.e., the event of not passing the first stage of the acceptance procedure), the probability of acceptance at either stage A or stage B is given by Equation 14.

$$P(\mathrm{Accept}) = P(A) + P(B \mid A') \cdot P(A') \qquad (14)$$

Because events A and B are not independent, the value of $P(B \mid A')$ is not known and the second term in the equation for P(Accept) cannot be evaluated directly. However, lower and upper bounds for this term can be calculated that, when added to P(A), will determine lower and upper bounds for P(Accept). To accomplish this, observe that, because A and B are positively correlated events, A' and B are negatively correlated. Therefore, by incorporating the bounds for negatively correlated probabilities from Equation 13 into Equation 14, Equation 15 can be derived.

$$P(A) + \mathrm{Max}[0, P(A') + P(B) - 1] \leq P(\mathrm{Accept}) \leq P(A) + P(B) \cdot P(A') \qquad (15)$$

Then, by noting that

$$P(A') = 1 - P(A) \qquad (16)$$

and by using slightly more convenient nomenclature, Equation 17 can be derived to give the bounds for the probability of acceptance under this type of sequential acceptance procedure.

$$\mathrm{Max}(P_A, P_B) \leq P \leq P_A + (1 - P_A)P_B \qquad (17)$$

where

P_A = probability of acceptance at stage A,
P_B = probability of acceptance at stage B, and
P = probability of acceptance at either stage A or stage B.

ANALYSIS OF A COMPLEX ACCEPTANCE PROCEDURE

The acceptance procedure used in this example is described in a recent National Cooperative Highway Research Program (NCHRP) report (3, p. 29) and was selected because it is sufficiently complex to require all of the theory developed in this paper. It is part of a specification for pavement thickness that uses both dual requirements and a sequential acceptance provision. The pavement thickness is considered acceptable if, based on five randomly selected cores, both of the following conditions are met:

1. The average length of the cores is equal to or greater than the specified thickness and
2. No more than 20 percent of the pavement (as estimated from the sample) has a thickness less than 85 percent of the specified thickness.

If either of these conditions is not met, an additional 10 randomly located cores are taken and combined with the original five cores. Then, in order for the pavement thickness to be judged acceptable, the same dual requirements must both be satisfied.

Although this may be an effective specification from the standpoint of accepting good workmanship and rejecting bad workmanship, it is somewhat of an analyst's nightmare to determine the operating characteristic (OC) curves for a plan of this type. Previously, because the various steps of this procedure are correlated in a complex manner, the only practical way to develop these curves would have been by computer simulation. However, by applying a combination of the techniques derived in this paper, it is possible to develop bounds for the probability of acceptance under this specification. Depending on the actual values used in the calculations, these bounds may be sufficiently close together to be of practical use. If not, it will be necessary to resort to computer simulation.

Since this is a sequential acceptance procedure, the bounds given by Equation 17 will be appropriate except that a further development is required. Whereas the probabilities P_A and P_B are fixed and known in Equation 17, they are not known in the case of the pavement thickness specification. In this case, P_A and P_B represent the probabilities of passing the dual requirements of stages A and B, respectively, of the sequential procedure. Since the dual requirements are always applied to the same sample, the probabilities of passing the dual requirements separately are positively correlated. Thus, the values P_A and P_B cannot be calculated directly but must themselves be defined by bounds in accordance with Equation 7.

What remains is to find a new minimum and a new maximum for the left and right sides, respectively, of Equation 17, both in terms of the bounds on P_A and P_B. The expression on the left will have its lowest value when P_A and P_B are at their minimums. When this expression is set equal to a new variable L and the appropriate bounds from Equation 7 are applied, the new lower bound is given by Equation 18.

$$L \geqslant \mathrm{Max}(P_{1A}P_{2A}, P_{1B}P_{2B}) \tag{18}$$

where

L = the value of the left side of Equation 17 when applied to the pavement thickness specification;

P_{1A}, P_{2A} = the probabilities of passing the first and second requirements, respectively, of stage A of the pavement thickness specification; and

P_{1B}, P_{2B} = the probabilities of passing the first and second requirements, respectively, of stage B of the pavement thickness specification.

In order to determine the maximum of the expression on the right side of Equation 17, it will be convenient to set this expression equal to a new variable R and then recombine terms as shown in Equation 19:

$$R = P_A + (1 - P_A)P_B = P_B + (1 - P_B)P_A \tag{19}$$

Although it is possible to derive the maximum of R more formally by using calculus, it can be deduced quite readily by inspection of Equation 19. In the first arrangement of terms, R is at its maximum for any given value of P_A when P_B is at its maximum. Similarly, in the second arrangement of terms, R is at its maximum value for any given value of P_B when P_A is at its maximum. Therefore, R is at its maximum when P_A and P_B are both at their maximum values. By substituting the upper bounds for P_A and P_B given by Equation 7 into Equation 19, the upper bound for this expression becomes

$$R \leqslant \mathrm{Min}(P_{1A}, P_{2A}) + [1 - \mathrm{Min}(P_{1A}, P_{2A})] \cdot \mathrm{Min}(P_{1B}, P_{2B}) \tag{20}$$

Finally, Equations 18 and 20 are combined and rearranged slightly to yield

$$\mathrm{Max}(P_{1A}P_{2A}, P_{1B}P_{2B}) \leqslant P \leqslant \mathrm{Min}(P_{1A}, P_{2A}) + \mathrm{Min}(P_{1B}, P_{2B}) - \mathrm{Min}(P_{1A}, P_{2A}) \cdot \mathrm{Min}(P_{1B}, P_{2B}) \tag{21}$$

where P is the overall probability of acceptance under the pavement thickness specification. Note that Equation 21 was developed in a general way and is appliable for any acceptance procedure of the same form as the pavement thickness specification.

COMPUTER SIMULATION TESTS

In order to check the theoretical bounds given by Equation 21, several tests were made by using computer simulation. To simplify the presentation, the specific thickness units have not been identified. In this example, the standard deviation is 2.5 percent of the specified thickness, which is typical for concrete pavement. Each simulation result is the average of a minimum of 2000 replications of the sampling procedure. The theoretical bounds are calculated by using conventional normal distribution theory for the first of the dual requirements and the noncentral-t distribution (4,5) for the second requirement. [The first reference on noncentral-t is more instructive; the second provides more complete tables. As an alternate method, slightly less precise results can be obtained by interpolating between the OC curves of Military Standard 414 (6).] The results of these tests are listed in Table 1 and plotted in Figure 1. Note that, in every case, the simulation results fall within the theoretically predicted bounds.

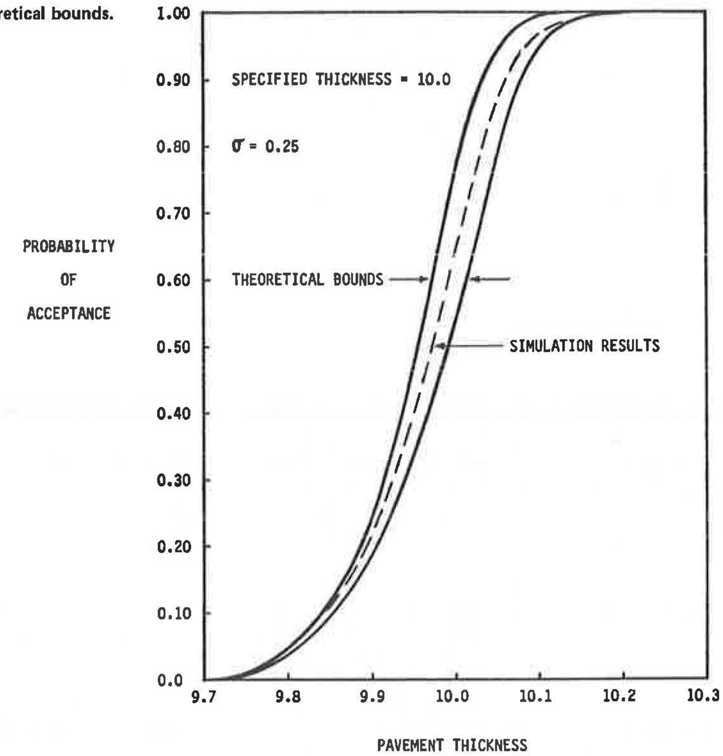
Although the interval estimates for the probability of acceptance provided by the theoretical bounds are not precise for some values of pavement thickness, they may still be useful, particularly if computer simulation is not readily available to provide better estimates. For example, the upper OC curve in Figure 1 indicates that, if the mean of the pavement thickness population is 9.85, the maximum probability of acceptance is 10.0 percent. This may be sufficient to convince the developers of this acceptance procedure that it will provide ample protection against accepting pavement that is deficient in thickness. Similarly, if a minimum probability of acceptance of 95.0 percent is desired, the lower OC curve indicates that a population mean of at least 10.11 must be obtained. This information would be extremely helpful to a contractor during both the bidding and construction stages of a project governed by this acceptance procedure.

Table 1. Computer simulation tests.

Population Mean	Estimated Probability of Acceptance	95.0% Confidence Interval	Theoretical Bounds for Probability of Acceptance
9.7	0.00	0.00-0.00	0.00-0.00
9.8	0.04	0.03-0.04	0.04-0.04
9.9	0.22	0.20-0.24	0.19-0.24
10.0	0.63	0.60-0.65	0.50-0.75
10.1	0.96	0.95-0.97	0.94-0.99
10.2	1.00	1.00-1.00	1.00-1.00

Note: Specified thickness = 10.0; σ = 0.25.

Figure 1. Comparison of simulation results with theoretical bounds.



SUMMARY AND CLOSING REMARKS

Many errors in the literature have resulted from the failure to recognize the existence of correlation in a variety of applications of compound probabilities. Although exact analytical solutions are not known, lower and upper bounds for the desired compound probabilities can be readily calculated. Bounds for both positively and negatively correlated cases were derived and applied to a complex acceptance procedure. Although the interval estimates provided by these bounds were not always precise, they can still be of considerable practical value, both to the specification writer in developing the acceptance procedure and to the contractor in determining the appropriate target value to meet it. Finally, several tests were made by computer simulation, all of which produced results that fell within the theoretically predicted bounds.

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Method to Exclude the Effect of Testing Error When Estimating the Percentage Defective of a Continuous Normal Population

RICHARD M. WEED AND WILLIAM E. STRAWDERMAN

The quality of a product is often characterized by the percentage of the population that falls outside specific limits. Although established methods for estimating this percentage defective are accurate as far as the overall distribution of test results is concerned, part of the variability of this distribution is due to the presence of testing error that causes the percentage defective of the product itself to be overestimated. A method is developed to overcome this problem and computer simulation is used to demonstrate that it is effective for situations in which the testing error is no larger than about one-half of the variability associated with the product. The results of several unsuccessful attempts to improve on this technique are also presented and described briefly.

Engineers and specification writers have found the concept of percentage defective (percentage of the total population outside specification limits) to be a particularly effective way to describe the quality of a variety of construction materials and products. The overall proportion within specification limits is believed to be strongly related to a product's performance, service life, or a combination of these qualities.

To implement a specification that uses this concept, an acceptable quality level (AQL), an acceptable level of percentage defective, is defined along with a sampling procedure and a means for estimating the percentage defective for prescribed quantities of product. A graduated pay schedule is usually employed to establish the appropriate reduction in payment when the production lot is found to be of less than AQL.

Established procedures for estimating percentage defective are effective in that they provide unbiased estimates of the quality of the populations to which they are applied. However, because any test result is affected by both product and testing variablity, the population to which the estimation procedure is applied is somewhat more dispersed and, consequently, its apparent percentage defective is somewhat larger than the true product percentage defective. This is illustrated in Figure 1.

In some cases, this effect is of little concern. If specification writers have defined an AQL that is based on historical data that included testing error, and the present testing error has not changed appreciably, there is no real need to modify the acceptance procedure. It will continue to accept product of the same quality considered acceptable in the past. Also, if the testing error is relatively small in comparison to product variability, or if the sampling procedure is such that the effect of the testing error is reduced by averaging several replicate tests together, then the estimate of percentage defective will be virtually unaffected. However, in other cases a method may be desired to estimate the true product percentage defective exclusive of the effects of testing error. It is toward this end that the efforts of this paper are directed.

DEVELOPMENT OF THE METHOD

In the discussion that follows, the total sample from any given quantity of product that is to be evaluated consists of N random samples, each of size n. This assumes that the samples are taken from N different portions of product and that, within each portion, the n individual tests are subject only to testing error. A test result is defined as the mean of n tests and, therefore, the estimate of the percentage defective is based on N test.results.

The standard deviation method of Military Standard 414 (1) is generally recognized as the best method for estimating the percentage defective of a normal population. A quality index (Q) is calculated by Equation 1 and special tables are consulted to convert this to a percentage defective estimate. Although the number of samples (N) does not enter into the computation of Q, it is accounted for when entering the percentage defective tables. A typical table is shown in Figure 2.

$$Q = (\bar{X} - L)/S \tag{1}$$

where

- Q = quality index (for lower limit in this example),
- L = lower limit,
- $\bar{X}$ = sample mean (more specifically, an unbiased estimate of the population mean), and
- S = sample standard deviation (more specifically, the square root of the unbiased estimate of the population variance).

A careful look at the definitions of $\bar{X}$ and S in Equation 1 makes it possible to deduce what is required to obtain an estimate of the true product percentage defective. First, in place of $\bar{X}$, an unbiased estimate of the mean of the product distribution will be required. This is an easy matter since, assuming there is no testing bias, the sample mean is also an unbiased estimate of the product mean. Therefore, this term will remain unchanged in the method to be developed.

Second, an unbiased estimate of the variance of the product distribution is required. By using the well-known theorem that independent variances are additive and then transposing, Equation 2 can be written:

$$\sigma_P^2 = \sigma_N^2 - (\sigma_n^2/n) \tag{2}$$

where

- σ_P^2 = variance of the product population,
- σ_N^2 = variance of the population of sample means (so designated because there are N sample means per lot),
- σ_n^2 = variance associated with the n replicate tests for each of the N samples (i.e., the testing error), and
- n = number of replicate tests (i.e., size of each of the N samples).

For each of the N samples, n replicate tests are made. If the variance is calculated for each set of n values, this furnishes N independent unbiased estimates of σ_n^2. These are pooled to give a single un-

Figure 1. Illustration of effect of testing error on percentage defective.

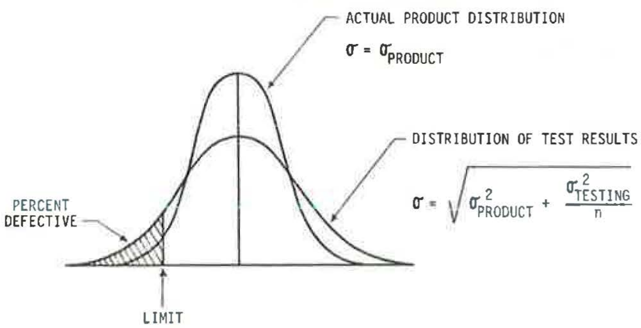

Table 1. Sample calculations required for the modified method.

	Test			Sample Statistics	
Sample	1	2	3	Mean	SD
1	103	100	103	102.0	1.732
2	101	103	106	103.3	2.517
3	102	98	99	99.7	2.082
4	105	107	104	105.3	1.528
5	106	105	109	106.7	2.082
6	103	100	98	100.3	2.517
7	105	103	106	103.7	1.528

Note: $\bar{X}$ of the means = 103.0, S_N of the means = 2.541, and pooled S_n for the standard deviations = 2.036.

Figure 2. Typical table used to estimate the percentage defective of a normal population: standard deviation method (N = 7).

Q	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	50.00	49.63	49.25	48.88	48.50	48.13	47.75	47.38	47.01	46.63
0.1	46.26	45.89	45.51	45.14	44.77	44.40	44.03	43.65	43.28	42.91
0.2	42.54	42.17	41.80	41.44	41.07	40.70	40.33	39.97	39.60	39.23
0.3	38.87	38.50	38.14	37.78	37.42	37.06	36.69	36.33	35.98	35.62
0.4	35.26	34.90	34.55	34.19	33.84	33.49	33.13	32.78	32.43	32.08
0.5	31.74	31.39	31.04	30.70	30.36	30.01	29.67	29.33	28.99	28.66
0.6	28.32	27.98	27.65	27.32	26.99	26.66	26.33	26.00	25.68	25.35
0.7	25.03	24.71	24.39	24.07	23.75	23.44	23.12	22.81	22.50	22.19
0.8	21.88	21.58	21.27	20.97	20.67	20.37	20.07	19.78	19.48	19.19
0.9	18.90	18.61	18.33	18.04	17.76	17.48	17.20	16.92	16.65	16.37
1.0	16.10	15.83	15.56	15.30	15.03	14.77	14.51	14.26	14.00	13.75
1.1	13.49	13.25	13.00	12.75	12.51	12.27	12.03	11.80	11.56	11.33
1.2	11.10	10.87	10.65	10.42	10.20	9.98	9.77	9.55	9.34	9.13
1.3	8.93	8.72	8.52	8.32	8.12	7.93	7.73	7.54	7.35	7.17
1.4	6.98	6.80	6.62	6.45	6.27	6.10	5.93	5.77	5.60	5.44
1.5	5.28	5.13	4.97	4.82	4.67	4.52	4.38	4.24	4.10	3.96
1.6	3.83	3.70	3.57	3.44	3.31	3.19	3.07	2.96	2.84	2.73
1.7	2.62	2.51	2.41	2.30	2.20	2.11	2.01	1.92	1.83	1.74
1.8	1.66	1.57	1.49	1.41	1.34	1.26	1.19	1.12	1.06	0.99
1.9	0.93	0.87	0.81	0.76	0.70	0.65	0.61	0.56	0.51	0.47
2.0	0.43	0.39	0.36	0.32	0.29	0.26	0.23	0.21	0.18	0.16
2.1	0.14	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.02
2.2	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.0	0.0	0.0

biased estimate, which will be designated S_n^2. Equation 3 can then be written in terms of sample standard deviations to obtain the value being sought, the standard deviation of the product distribution, which is the square root of the unbiased estimate of the product variance.

$$S_P = \sqrt{S_N^2 - (S_n^2/n)} \quad (3)$$

where

- S_P = estimated standard deviation of the product population,
- S_N = computed standard deviation of the N sample means,
- S_n = pooled estimate of testing error, and
- n = size of each of the N samples.

The next step is to substitute these results into Equation 1 to develop a modified Q-statistic for use in estimating the percentage defective of the product distribution only. This modified value, designated Q' to distinguish it from the standard Q value, is given by Equation 4.

$$Q' = (\bar{X} - L)/S_p = (\bar{X} - L)/\sqrt{S_N^2 - (S_n^2/n)} \quad (4)$$

Sample Calculation

For this example, there are N = 7 samples, each of size n = 3, and the lower limit is 100.0. The test results and calculations given in Table 1 are substituted into the appropriate equations to give the following results.

By using Equation 3 and the results from Table 1,

$$S_P = \sqrt{2.541^2 - (2.036^2/3)} = 2.253.$$

By using Equation 4 and the results from Table 1,

$$Q' = (103.0 - 100.0)/2.253 = 1.33.$$

From Figure 2, the estimated percentage defective by the modified method = 8.32.

By using Equation 1,

$$Q = (103.0 - 100.0)/2.541 \doteq 1.18.$$

From Figure 2, the estimated percentage defective by the standard method = 11.56.

Although the difference in the results obtained by the two methods is not great in this example, there are situations in which this difference may be important. If the AQL were defined to be 10 percent, the modified method would produce a clearly acceptable result, but the standard approach would not. If a graduated pay schedule were in effect, a difference of a few percent might correspond to a substantial reduction in payment.

A Minor Problem

A problem that occasionally turns up in analysis of variance applications may occur with this procedure. When a variance component is estimated from the difference between two other estimates, on rare occasions this difference will be negative. This occurs because the two estimates are independent random variables and it is possible for two extreme values to combine to produce a negative result. If this should occur in the expression for S_P in Equation 3, the appropriate remedy is to set S_P equal to zero. This produces a zero denominator in the Q'-statistic in Equation 4, which is handled in the same manner as it is for a conventional Q-statistic. If the sample mean is greater than or equal to the lower limit, the percentage defective is considered to be zero. If the sample mean is less than the lower limit, the percentage defective is estimated to be 100 percent.

Computer Simulation Tests

In order to demonstrate the effectiveness of the modified Q-statistic given by Equation 4, a computer simulation program was written that permitted the testing of this approach with various combinations of product and testing variability, sample size, and percentage defective. Each simulation run involved 5000 replications of the sampling and testing procedure with a lower limit of L = 3000.0. The other values of interest are presented along with the simulation results in Table 2.

It can be seen from the results in this table

Table 2. Typical results of computer simulation tests.

Samples	Sample Size	Product SD	Testing SD	Product Mean	Product Percentage Defective	Average Estimated Percentage Defective: Standard Method	Average Estimated Percentage Defective: Modified Method
3	4	400.0	0.0	3658.08	5.0	5.06	5.06
3	4	400.0	0.0	3512.69	10.0	10.12	10.12
3	4	400.0	0.0	3336.58	20.0	20.06	20.06
3	4	400.0	0.0	3101.17	40.0	39.96	39.96
3	4	400.0	200.0	3658.08	5.0	5.59	5.29
3	4	400.0	200.0	3512.69	10.0	11.12	10.61
3	4	400.0	200.0	3336.58	20.0	20.60	19.79
3	4	400.0	200.0	3101.17	40.0	40.86	40.44
5	3	400.0	100.0	3658.08	5.0	5.35	5.21
5	3	400.0	100.0	3512.69	10.0	10.52	10.31
5	3	400.0	100.0	3336.58	20.0	20.07	19.79
5	3	400.0	100.0	3101.17	40.0	39.80	39.64
5	3	400.0	300.0	3658.08	5.0	6.38	5.29
5	3	400.0	300.0	3512.69	10.0	12.24	10.40
5	3	400.0	300.0	3336.58	20.0	22.35	20.00
5	3	400.0	300.0	3101.17	40.0	40.71	39.39
7	2	400.0	200.0	3658.08	5.0	5.95	5.11
7	2	400.0	200.0	3512.69	10.0	11.40	10.12
7	2	400.0	200.0	3336.58	20.0	21.04	19.38
7	2	400.0	200.0	3101.17	40.0	40.71	39.88
7	2	400.0	400.0	3658.08	5.0	8.81	5.83
7	2	400.0	400.0	3512.69	10.0	14.69	10.48
7	2	400.0	400.0	3336.58	20.0	24.24	18.71
7	2	400.0	400.0	3101.17	40.0	42.02	39.55

Note: The lower limit = 3000.0 and there were 5000 replications per run.

that, when the testing error is zero (or relatively small compared to product variability), the two methods both produce very accurate estimates of the product percentage defective. As the testing error becomes larger, the standard method begins to overestimate the product percentage defective; however, the modified method continues to be accurâte within the degree of precision expected of the simulation experiment.

Limitations of the Modified Method

Although it would be very unusual in actual practice for the testing standard deviation to equal or exceed the product standard deviation, additional simulation tests were made to determine whether the modified method would produce accurate estimates under such extreme conditions. The results of these tests are presented in Table 3.

The tables used for estimating percentage defective do not exist for fewer than N = 3 samples and the modified approach requires a minimum sample size of n = 2 so that testing error can be distinguished from product variability. Therefore, the first group of results in Table 3 represents the smallest total sample and the most severe test of the modified method. Within this group, the results appear to be quite satisfactory up to and including a testing error equal to about one-half of the product standard deviation. As the testing error increases above this level, even the modified method begins to overestimate the product percentage defective, apparently the result of the occurrence of too many negative variance estimates.

The second group of tests in Table 3 demonstrates the mitigating effect of an increased sample size. This reduces the frequency of occurrence of negative variance estimates and lessens the tendency to overestimate the product percentage defective. In this case, the modified method may remain accurate for testing errors somewhat greater than one-half of the product standard deviation.

The inability of the modified method to remain unbiased for extremely large values of testing error is not considered to be a serious drawback. For most practical applications, the component of variability due to testing will be substantially less than the variability associated with the product, a condition under which the modified method is accurate. Furthermore, for those rare cases in which the modified method may exhibit some bias, it is still considerably less biased than the standard method.

In addition to accuracy (lack of bias), another important characteristic of any statistical estimator is its degree of precision (repeatability). Several tests were made that indicated that the precision of the modified method is essentially the same as that of the standard method.

Attempts to Improve the Modified Method

Several attempts were made to improve the modified method. Although none of these proved to be fruitful, each will be discussed briefly in the belief that this may be of some use to other researchers.

Table 4 presents typical results obtained when a total of six methods were applied with increasing levels of testing standard deviation. The first method (Standard Q) refers to the standard method based on Equation 1 and the second method (Q, S_p) is the modified method based on the estimate of the product standard deviation (S_p) from Equation 3 and the modified Q-statistic in Equation 4.

The third method (Q, S_p, EQUIV N) is based on the well-known facts that the variance of a sample drawn from a normal population is a χ^2-distributed variable and that the difference between two χ^2-distributed variables is not distributed as χ^2. Therefore, the value of S_p^2 derived in this paper is not distributed as χ^2 and, consequently, the modified Q-statistic given by Equation 4 must be distributed somewhat differently from the standard Q-statistic in Equation 1. However, if S_p^2 can be assumed to be approximately χ^2 distributed, it is possible to derive an expression that gives the equivalent degrees of freedom in much the same way that this is done for the approximate F-test (2, p. 247). Then, if we assume that the equivalent sample size ($\hat{N}$) is one more than the degrees of freedom, Equation 5 can be written. The estimate of percent-

Table 3. Tests that demonstrate the limitations of the modified method.

Samples	Sample Size	Testing SD	Average Estimated Percentage Defective: Standard Method	Average Estimated Percentage Defective: Modified Method	Relative Frequency of Negative Variance Estimates
3	2	100.0	10.38	10.12	0.029
3	2	200.0	11.29	10.36	0.106
3	2	300.0	13.25	11.29	0.178
3	2	400.0	14.87	11.96	0.259
3	2	500.0	16.37	12.55	0.319
3	2	600.0	19.12	14.67	0.369
3	2	700.0	20.70	15.36	0.405
3	2	800.0	22.99	17.71	0.424
3	4	100.0	10.12	9.85	0.012
3	4	200.0	10.38	9.86	0.054
3	4	300.0	11.48	10.24	0.117
3	4	400.0	12.33	10.57	0.180
3	4	500.0	13.89	11.20	0.236
3	4	600.0	15.00	11.47	0.287
3	4	700.0	17.00	12.61	0.358
3	4	800.0	17.86	13.13	0.371

Note: Lower limit = 3000.0; product mean = 3512.69; product SD = 400.0; product percentage defective = 10.0; replications per run = 5000.

Table 4. Results of attempts to improve the modified method.

Method	Testing SD	Estimated Percentage Defective: Mean	Min/Max	SD	Relative Frequency of Negative Variance Estimates
Standard Q	0.0	10.04	0.0/ 57.5	9.3	0.0
Q, S_P	0.0	10.04	0.0/ 57.5	9.3	0.0
Q, S_P, EQUIV N	0.0	10.04	0.0/ 57.5	9.3	0.0
Q, S_P, NEG VAR	0.0	10.04	0.0/ 57.5	9.3	0.0
STD NML, $S_{P,N-1}$	0.0	10.60	0.0/ 58.0	8.5	0.0
STD NML, $S_{P,N}$	0.0	9.27	0.0/ 58.6	8.2	0.0
Standard Q	100.0	10.38	0.0/ 57.8	9.4	0.0
Q, S_P	100.0	10.04	0.0/ 57.9	9.4	0.0
Q, S_P, EQUIV N	100.0	9.93	0.0/ 57.9	9.5	0.0
Q, S_P, NEG VAR	100.0	10.04	0.0/ 57.9	9.4	0.0
STD NML, $S_{P,N-1}$	100.0	10.60	0.0/ 58.4	8.6	0.0
STD NML, $S_{P,N}$	100.0	9.41	0.0/ 59.0	8.3	0.0
Standard Q	200.0	11.49	0.0/ 56.0	9.9	0.0
Q, S_P	200.0	10.22	0.0/ 56.1	9.9	0.008
Q, S_P, EQUIV N	200.0	9.73	-11.7/ 56.1	10.4	0.008
Q, S_P, NEG VAR	200.0	10.22	-0.1/ 56.1	9.9	0.008
STD NML, $S_{P,N-1}$	200.0	10.72	0.0/ 56.5	9.2	0.008
STD NML, $S_{P,N}$	200.0	9.91	0.0/ 57.0	8.8	0.002
Standard Q	300.0	12.93	0.0/ 53.1	10.4	0.0
Q, S_P	300.0	10.28	0.0/ 54.1	10.4	0.042
Q, S_P, EQUIV N	300.0	9.25	-15.7/ 52.4	11.6	0.042
Q, S_P, NEG VAR	300.0	10.25	-34.1/ 54.1	10.5	0.042
STD NML, $S_{P,N-1}$	300.0	10.69	0.0/ 54.4	9.7	0.042
STD NML, $S_{P,N}$	300.0	10.47	0.0/ 54.1	9.4	0.009
Standard Q	400.0	14.83	0.0/ 65.4	11.1	0.0
Q, S_P	400.0	10.55	0.0/100.0	11.2	0.101
Q, S_P, EQUIV N	400.0	9.14	-18.6/100.0	13.1	0.101
Q, S_P, NEG VAR	400.0	10.30	-39.8/138.5	11.8	0.101
STD NML, $S_{P,N-1}$	400.0	10.86	0.0/100.0	10.7	0.101
STD NML, $S_{P,N}$	400.0	11.31	0.0/ 68.9	10.3	0.031

Note: Number of samples = 7; sample size = 2; lower limit = 3000.0; product SD = 400.0; product percentage defective = 10.0; replications per run = 5000.

age defective can then be obtained by using $\hat{N}$ to interpolate between appropriate tables of the type shown in Figure 2.

$$N = [S_N^2 - (S_n^2/n)]^2/\{[S_N^4/(N-1)] + [S_n^4/n^2(n-1)]\} + 1 \quad (5)$$

Bounds for $\hat{N}$ can readily be derived and are given by Equation 6. Because $\hat{N}$ can take on values as low as one, but the tables for estimating percentage defective do not exist for N less than three, it is sometimes necessary to extrapolate to obtain the estimate of percentage defective. Unfortunately, this often produces negative values of percentage defective, as can be observed from the results in Table 4.

$$1 \leq \hat{N} \leq \mathrm{Max}(N, n) \quad (6)$$

Although the concept of a negative value of percentage defective has no physical interpretation, it conceivably could have practical value if the distribution from which it came provided an unbiased estimate of the true percentage defective of the population being sampled. However, as can be seen in Table 4, this appears not to be the case. For this particular series of tests, the method of using an equivalent value of N is negatively biased to a slightly greater degree than the positive bias of the original modified method.

The fourth method (Q, S_P, NEG VAR) was planned to occasionally produce estimates of percentage defective outside the normal range of 0-100 percent. This procedure did not set negative variance estimates equal to 0 as was done with the previous methods. In this case, S_P was calculated as the square root of the absolute value of the variance. Then, if the variance was negative, a minus sign was attached to the estimate of percentage defective. It was clear that this approach would tend to reduce the positive bias, but to what extent was not known. As seen from the results in Table 4, the reduction was too slight to be of value.

Two additional methods were included, both of which involved the use of the standard normal distribution. For the fifth method (STD NML, $S_{P,N-1}$), a Z-score was computed by using the value of S_P obtained from Equation 3. The final method (STD NML, $S_{P,N}$) was identical except that all standard deviations were computed by using N instead of N-1 in the denominator under the radical. For both procedures, the percentage defective estimate was the area under the standard normal distribution that corresponds to the computed Z-score. As can be observed from the results in Table 4, these two methods were no more successful than the others.

Although the distributions of percentage defective estimates are extremely skewed for all of these methods, the standard deviations have been included in Table 4 as an indicator of precision. Since the standard deviations for all methods are about the same and the original modified method (Q, S_P) exhibits less bias while producing no percentage defective estimates outside the range of 0-100 percent, it is judged to be the best of the methods that were tested.

SUMMARY AND CLOSING REMARKS

The standard method for estimating the percentage defective is unbiased, but the population to which it is applied includes the component of variability due to the testing process and this causes the percentage defective of the actual product to be overestimated. For those situations in which it is deemed desirable to overcome this inaccuracy, a method based on analysis of variance techniques is presented that makes it possible to estimate the actual percentage defective of a continuous normal population exclusive of testing error.

An extensive series of computer simulation tests was conducted to demonstrate that the method is effective, provided the testing error does not exceed about one-half the product standard deviation--a condition that is easily met in most practical situations. Even for those cases in which the testing error is larger than this, the modified method is still considerably less biased than is the standard method.

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Stratified Random Sampling from a Discrete Population

RICHARD M. WEED

In the development of statistical acceptance procedures for products whose quantity is measured on a continuous scale by using units such as length, area, volume, or weight, quality-assurance engineers usually specify stratified random sampling plans to ensure a more uniform coverage of the product than is often achieved by pure random sampling. Stratified plans divide the total quantity of the product into an appropriate number of equal-sized sublots and require that a single random sample be taken from each. Not only is it desirable to develop an equivalent procedure for products that are measured in discrete units, but in many cases, such a procedure will prove to be more convenient for continuous products that are produced or delivered in discrete units such as batches or truckloads. However, the development of such a procedure is not as straightforward as might be expected. Weaknesses of some of the more obvious approaches are discussed and then a method is presented that achieves the desired result.

With pure random sampling, all possible sample combinations are equally probable. Although the theory associated with most statistical acceptance procedures is based on the concept of pure random sampling, this approach has the disadvantage that, on occasion, the samples may tend to be clustered within a small segment of the population. In the development of acceptance procedures for products whose quantity is measured in continuous units such as length, area, volume, or weight, it has become common practice to avoid this drawback by specifying stratified random sampling plans. These plans divide the total quantity of the product into an appropriate number of equal-sized sublots and require that a single random sample be taken from each.

Some construction products are measured only in discrete units such as pieces, and others that are measured in continuous units are produced or delivered in discrete units such as batches or truckloads. For both of these cases, it will be desirable to develop a stratified sampling procedure suitable for discrete populations. However, the stratification method described in the preceding paragraph cannot be applied directly unless the sample size happens to be an exact divisor of the lot size. Since this occurs only rarely, a modification of this procedure is required that will spread the samples throughout the entire population in a manner that produces the same degree of randomness as that provided by continuous stratified plans.

Whereas all possible combinations of individual samples may occur with pure random sampling, this obviously is not the case with stratified sampling since only one portion of the population is selected from each subgroup. However, computation of the probability of any particular portion being included in the sample is not difficult, and it can be shown that this probability is equal for all portions. It follows that the degree of randomness achieved by stratified random sampling is such that each item of the population has an equal chance of appearing in the sample.

This is a necessary but insufficient condition for pure random sampling and emphasizes that stratified random sampling produces a more restricted degree of randomness. Since the theory associated with statistical acceptance procedures is based primarily on pure random sampling, one might wonder about the extent to which the validity of these procedures is compromised by stratified sampling. By their silence on this subject, most authors have implied that there is no serious problem. Based on a few brief tests with computer simulation, this appears to be a correct assumption, although this is an area that might warrant further study. For purposes of this paper, however, assume that stratified sampling is a valid and practical approach, and attention will now be directed toward the development of a method for selecting stratified random samples from discrete populations.

UNSATISFACTORY METHODS

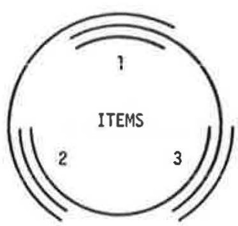
The objectives of the method to be developed are to guarantee that the samples will be distributed throughout the entire population and to do this in a manner that produces the same degree of randomness as that provided by continuous stratified plans. It is a simple matter to accomplish the first objective, but care must be exercised to ensure that the second objective is achieved. In several of the more obvious approaches, the probability of being included in the sample is not equal for all items of the population.

One method that produces an imperfect result consists of stratification by quantity, selection of the sample location by quantity, determination of the discrete batch or load within which this random location occurs, and then random sampling from that batch or load. For example, if a construction material is normally measured in tons, a lot could be defined as 1000 tons, each lot could be divided into five sublots of 200 tons each, and specific tonnage values would designate the random sampling locations within each sublot. The discrete sampling locations would then be the particular trucks within which these random tonnage values occur. Although this method works reasonably well when the total number of trucks represented by each sublot is large, it has a minor flaw that can become pronounced when the number of trucks is small. If the random sampling locations for two successive sublots both fall close to the boundary between these two sublots, they may both occur within the same truckload. When this happens, the theoretically correct approach is to take two samples from the same truck. However, from a practical standpoint, it is usually considered to be

Figure 1. A possible stratified sampling scheme.

TRUCK:	1 2 3	4 5 6 7	8 9 10 11	12 13 14	15 16 17 18
SUBGROUPING:					
SUBGROUP SIZE:	3	4	4	3	4

Figure 2. Possible subgroup arrangements when circular array concept is used.



more useful to sample two successive trucks or to make some other similar adjustment. Either way, this distorts the randomness because not all trucks in the population are equally likely to experience this effect. This distortion increases as the number of trucks within each subgroup decreases and, in some cases, can become quite severe.

The method to be described next includes a useful procedure for stratifying a discrete population but, because of the steps that follow, the desired degree of randomness is not achieved. Since the sample size usually will not be an exact divisor of the population size, the best that can be done is to divide the population into subgroups of two sizes that differ by one unit. This is accomplished by the following equations:

$$S_1 = [N_P/N_S] \quad (1)$$

$$S_2 = S_1 + 1 \quad (2)$$

$$N_1 = N_S S_2 - N_P \quad (3)$$

$$N_2 = N_S - N_1 \quad (4)$$

where

- N_P = population size,
- N_S = sample size,
- S_1 = size of smaller subgroup,
- S_2 = size of larger subgroup,
- N_1 = number of smaller subgroups,
- N_2 = number of larger subgroups, and
- $[X]$ = largest integer in X.

Once these computations have been made, Equation 5 can be used to check that they have been performed properly:

$$N_1 S_1 + N_2 S_2 = N_P \quad (5)$$

For example, suppose the population consists of $N_P = 18$ trucks of which $N_S = 5$ are to be sampled. Equations 1-5 can be used to develop a stratification plan as follows:

$$S_1 = [N_P/N_S] = [18/5] = [3.6] = 3 \quad (6)$$

$$S_2 = S_1 + 1 = 3 + 1 = 4 \quad (7)$$

$$N_1 = N_S S_2 - N_P = (5)(4) - 18 = 2 \quad (8)$$

$$N_2 = N_S - N_1 = 5 - 2 = 3 \quad (9)$$

$$N_1 S_1 + N_2 S_2 = (2)(3) + (3)(4) = 18 = N_P \quad (10)$$

Once the numbers (N_1, N_2) and sizes (S_1, S_2) of the subgroups have been determined, the subgroups are arranged in random order. Then, to determine the items to be sampled, a random selection within each subgroup is made. For the case in which $N_P = 18$ and $N_S = 5$, one possible outcome of this procedure is shown in the schematic diagram in Figure 1, in which the horizontal lines define the separate subgroups and the circled numbers are the trucks that have been randomly selected for sampling.

To demonstrate that this is a satisfactory approach, it would be necessary to prove that, for any combination of values of N_P and N_S, each item in the population has an equal chance of being included in the sample. Conversely, to disprove this method, it is only necessary to show by counterexample that some particular combination of N_P and N_S produces an unsatisfactory result. This is a problem in combinatorial analysis that leads to very complex calculations except for those cases in which the sample size is only slightly smaller than the population size. Consequently, the following two cases have been selected to demonstrate that not all of the items in the population have an equal chance of being included in the sample:

Item	Probability: Case 1, $N_P = 7$, $N_S = 6$	Probability: Case 2, $N_P = 8$, $N_S = 6$
1	0.917	0.833
2	0.833	0.700
3	0.833	0.734
4	0.833	0.734
5	0.833	0.734
6	0.833	0.734
7	0.917	0.700
8		0.833
Total	5.999	6.002

Several interesting observations can be made from these computations. First, the sum of the probabilities equals the sample size, which is the mathematical expectation of this procedure. Second, there is a distinct departure from equal probability and an apparent tendency for the first and last items of the population to have a greater likelihood of being included in the sample. Finally, the departure from equal probability increases as the population size (N_P) increases from seven to eight, which suggests that this is a problem that will not diminish rapidly for larger populations. Subsequent tests by computer simulation indicate that this tendency persists even for much larger population sizes.

It should be emphasized that this problem is not the result of the stratification method given by Equations 1-4 but, rather, was caused by the manner in which the subgroups were randomly distributed throughout the population. The next section shows that this problem can be overcome by a simple refinement of this procedure.

DEVELOPMENT OF A SATISFACTORY METHOD

Although the subgroups were arranged in random order in the method that was just discussed, this produces different conditions for items in different positions in the population. This is best illustrated by a simple example for which $N_P = 3$ and $N_S = 2$, as shown in the following schematic diagram:

Items: 1 2 3
Possible subgroup arrangements:

In this trivial example, only two possible subgroup arrangements exist; both are equally likely (P = 0.5) because they are selected at random. If an item happens to fall in the subgroup of size n = 1, it is certain that it will be selected as the sample from that subgroup and the probability of this event is P = 1.0. Similarly, if the item happens to fall in the subgroup of size n = 2, its probability of being selected is P = 0.5. By using routine probability theory, each item's probability of being included in the sample can be calculated as follows:

$$P_1 = (0.5)(1.0) + (0.5)(0.5) = 0.75 \quad (11)$$

$$P_2 = (0.0)(1.0) + (1.0)(0.5) = 0.50 \quad (12)$$

$$P_3 = (0.5)(1.0) + (0.5)(0.5) = 0.75 \quad (13)$$

Total 2.00

As before, the sum of the probabilities is equal to the sample size. The second item has a lower probability of being selected than does the first or third item because it can occur only in a subgroup of size n = 2. Similar results occur with larger populations and samples although the probability computations become much more complex.

Only a very slight conceptual change is required to correct this condition. If the items are thought of as being arranged in a circular array, the end effects are avoided and the individual probabilities will be equal. This is demonstrated by the diagram in Figure 2.

Now there are three possible arrangements of subgroups, and each item occurs once in a subgroup of size n = 1 and twice in a subgroup of size n = 2. The probabilities are equal and compute to be

$$P_1 = P_2 = P_3 = (0.333)(1.0) + (0.667)(0.5) = 0.667 \quad (14)$$

and, as a check, it is seen once again that their sum is equal to the sample size.

Figure 3. Sampling scheme resulting from the circular array concept.

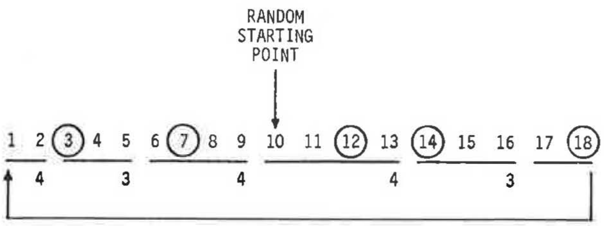


Figure 4. Typical work sheet outlining steps of discrete random selection procedure.

STRATIFICATION PROCEDURE

POPULATION SIZE = N = 23 (MAXIMUM 50)

SAMPLE SIZE = 6 (SAMPLE SIZE = N WHEN N < 6)

SIZE OF SMALLER SUBGROUP = $S_1 = \left[\frac{N}{6}\right] = \left[\frac{23}{6}\right] = 3$ (DISCARDING FRACTIONAL REMAINDER)

SIZE OF LARGER SUBGROUP = $S_2 = S_1 + 1 = 4$

NUMBER OF SMALLER SUBGROUPS = $N_1 = (6)(S_2) - N = (6)(4) - 23 = 1$

NUMBER OF LARGER SUBGROUPS = $N_2 = 6 - N_1 = 5$

CHECK THAT $(N_1)(S_1) + (N_2)(S_2) = N$: $(1)(3) + (5)(4) = 23$

ARRANGE SUBGROUPS IN ANY ORDER: 3, 4, 4, 4, 4, 4.

RANDOM STARTING POINT (TABLE R1) = 11

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 ~~24 25~~
4 4 4 3 4 4
~~26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50~~

RANDOM SELECTION PROCEDURE

LIST OF ITEMS IN SUBGROUP	RANDOM SELECTION (TABLE R2)	ITEM NUMBER
11, 12, 13	2	12
14, 15, 16, 17	3	16
18, 19, 20, 21	2	19
22, 23, 1, 2	4	2
3, 4, 5, 6	2	4
7, 8, 9, 10	3	9

ORDERED LIST OF ITEMS TO BE SAMPLED: 2, 4, 9, 12, 16, 19.

Figure 5. Special random number tables for use with discrete random selection procedure.

TABLE R1

21	47	18	47	37	10	44	6	37	21	29	25	15	20	37	6	18	43	10	6	1	31	37	47	37	43	25	46	35	21
11	46	10	35	9	24	50	13	10	9	3	14	2	15	43	45	2	31	11	44	30	43	2	46	16	5	15	28	15	6
12	20	49	7	6	20	42	34	11	42	39	32	32	21	27	47	3	27	2	12	20	50	37	45	34	33	36	14	36	35
8	49	2	9	48	25	14	33	48	15	22	7	18	25	41	13	7	35	15	34	43	32	5	49	18	39	2	46	45	3
45	38	7	28	39	5	34	5	6	38	19	12	22	43	9	33	40	10	37	2	50	40	36	8	43	32	42	32	26	1
40	27	33	45	15	4	31	29	48	38	26	30	3	1	41	41	33	31	6	20	30	44	23	4	20	42	43	40	47	9
41	14	33	30	16	35	42	16	5	5	3	11	9	29	17	48	37	4	23	25	44	24	17	32	38	37	42	46	46	21
39	23	34	22	44	19	5	9	4	15	50	15	2	28	8	24	36	32	2	8	7	46	45	1	10	12	38	3	27	8
13	49	20	43	49	14	26	28	17	44	26	7	14	47	19	36	42	26	26	49	29	15	50	30	49	20	7	6	11	3
27	19	14	1	17	39	45	27	34	13	32	23	42	11	26	50	5	46	6	14	11	26	10	48	41	22	13	4	19	33
9	48	41	16	23	8	23	40	36	13	18	24	33	9	17	47	11	24	16	28	5	47	18	20	10	12	37	17	10	13
25	13	35	16	25	47	11	48	23	46	21	28	48	19	22	18	7	48	22	4	41	41	35	1	18	49	22	35	36	37
50	43	33	15	24	4	23	25	23	19	1	31	30	35	1	34	35	8	34	16	40	49	30	17	44	31	30	50	50	2
41	23	19	4	7	40	36	11	28	26	5	29	25	49	35	38	29	29	38	4	27	28	24	44	38	1	44	9	39	12
36	13	40	42	19	8	21	4	35	44	1	29	41	3	40	17	27	1	14	36	17	45	6	23	15	13	39	48	19	46
8	2	34	41	41	6	30	34	3	9	1	45	12	7	10	31	5	22	42	28	22	40	24	26	13	44	38	40	27	16
22	42	11	20	42	26	18	12	8	5	37	27	18	9	48	3	28	25	17	45	12	12	31	44	6	28	43	25	32	50
46	4	27	24	16	29	18	30	32	16	2	38	10	27	39	33	29	17	21	19	19	21	46	39	20	47	36	23	39	40
3	8	13	22	29	22	32	24	34	20	38	45	21	34	12	29	33	17	14	30	39	30	24	31	14	49	25	8	43	31
12	50	18	14	7	28	7	10	24	32	38	11	21	36	26	48	47	21	49	39	33	4	16	50	47	3	16	31	45	31

TABLE R2

7	8	3	7	8	3	6	9	6	2	4	5	8	3	8	9	1	2	4	1	4	1	3	7	1	8	5	4	3	2	7	4	9	7	5	7	7	1	2	9	6	3	1	9	1
8	8	4	8	9	4	2	5	2	9	8	9	2	2	5	9	4	3	6	8	1	9	7	8	7	8	8	1	9	2	8	6	9	7	3	2	3	5	8	7	9	8	6	4	5
5	4	9	9	4	3	8	5	4	6	5	9	8	2	3	9	8	3	4	6	2	2	1	7	6	1	6	4	2	9	4	1	7	9	9	2	2	7	6	2	7	9	8	6	1
6	8	5	2	6	1	2	1	4	5	6	1	1	6	5	3	3	5	8	7	3	1	9	8	6	7	7	9	7	4	2	4	6	7	7	5	6	1	2	7	3	3	2	3	4
5	7	4	1	6	8	3	6	2	7	6	9	3	6	6	9	2	5	1	4	7	7	1	9	2	6	7	1	6	9	4	5	8	2	1	9	9	4	9	7	6	3	7	4	2
2	6	8	9	7	3	8	8	3	5	3	6	6	9	4	9	9	1	1	6	1	1	6	8	8	4	6	8	1	3	1	1	7	4	8	5	9	4	5	7	2	3	2	1	4
7	4	6	8	1	5	7	6	5	1	5	8	3	9	4	4	8	5	3	2	4	1	2	6	7	7	3	6	9	2	3	6	9	2	8	3	9	9	2	3	7	9	4	8	7
2	8	5	7	4	3	9	8	7	2	3	7	5	8	7	8	8	2	3	3	4	3	8	4	2	9	8	9	5	2	5	4	6	6	6	8	9	2	7	3	9	6	9	4	4
2	7	9	6	1	6	5	6	5	2	3	8	5	8	7	5	1	5	8	1	4	8	1	7	4	3	1	4	8	8	6	8	1	1	5	1	4	3	1	2	6	4	2	9	7
4	3	6	2	9	3	9	5	1	7	1	8	3	7	6	5	6	3	7	9	7	2	2	3	5	4	6	7	6	4	9	7	3	7	8	6	1	4	7	3	6	6	2	9	9
8	5	9	6	3	4	8	9	1	1	5	4	1	8	7	9	3	6	9	6	6	4	9	3	7	7	9	7	2	2	3	8	3	7	5	4	1	7	5	3	3	5	9	2	6
5	8	8	2	6	4	9	1	4	8	9	5	2	2	6	9	2	3	2	1	4	7	8	2	4	1	4	5	5	2	4	5	6	9	5	8	2	7	9	9	2	5	7	5	4
9	1	2	1	7	4	1	6	4	4	7	6	3	4	5	3	9	1	7	5	1	7	2	6	4	8	9	1	6	6	1	4	7	6	2	7	6	2	4	8	9	1	5	9	8
1	3	7	7	7	2	5	2	6	1	4	8	2	2	2	3	3	2	4	7	4	8	2	8	2	6	1	2	9	4	3	1	4	5	3	6	3	2	8	6	8	3	5	4	7
7	3	6	5	4	5	2	9	6	5	7	3	6	1	4	1	9	9	8	7	1	7	9	3	3	5	5	1	5	8	7	3	9	6	6	7	1	7	5	9	6	9	3	1	7
9	3	3	6	6	7	4	5	6	7	9	4	4	8	8	1	9	2	4	8	8	2	1	9	5	9	1	3	2	3	7	8	3	8	5	1	3	4	1	6	8	2	6	7	1
3	3	2	3	6	5	9	2	2	2	7	4	1	8	4	4	8	8	9	2	9	9	2	8	1	8	9	2	6	1	3	4	3	7	3	1	7	3	5	6	5	6	7	8	1
1	5	3	7	7	4	1	8	4	6	2	7	2	9	6	3	7	9	8	9	4	5	8	1	4	2	2	4	5	2	1	5	1	3	5	1	3	3	4	9	3	6	6	1	4
6	5	3	6	4	8	3	7	5	2	8	8	8	9	9	2	6	2	9	3	8	5	4	3	8	8	4	8	2	4	9	9	6	9	5	5	5	4	8	7	7	4	2	9	2
8	8	9	1	1	8	6	8	8	4	2	5	5	9	6	9	5	1	3	9	1	7	3	8	8	9	4	9	1	9	9	2	3	4	6	3	1	3	8	2	8	3	7	1	5
5	9	5	5	8	9	4	8	3	5	3	4	3	6	6	6	7	5	1	2	3	8	5	6	8	4	2	2	3	4	6	3	5	7	5	5	3	3	1	5	3	7	3	9	6
9	4	6	3	7	9	8	9	4	8	5	3	2	4	8	2	2	5	5	1	5	9	1	4	8	3	2	4	1	5	2	2	5	6	8	5	2	8	6	5	1	2	9	9	3
2	2	2	4	7	4	4	6	7	7	1	7	7	7	3	2	2	7	2	4	1	7	2	4	3	6	9	1	7	3	7	3	3	7	5	4	1	8	4	5	8	5	3	5	8
5	6	7	5	6	6	7	1	6	1	9	3	6	8	7	7	6	2	6	3	5	5	9	8	2	3	2	7	7	9	4	2	6	7	6	9	3	1	2	5	8	9	9	2	8
7	5	8	8	1	9	1	3	1	4	2	2	3	5	7	3	5	7	5	4	3	3	1	2	2	4	7	4	1	1	7	1	2	5	7	8	3	2	4	4	8	7	3	7	1
5	6	7	6	5	8	8	7	5	8	1	9	1	4	4	8	6	5	3	5	2	7	6	8	1	4	9	7	3	6	8	6	5	1	5	8	5	5	8	2	8	7	1	9	7
4	8	5	7	1	6	7	9	6	9	3	3	5	7	9	3	7	2	9	2	3	5	1	4	6	6	5	8	3	3	8	5	3	5	3	1	1	5	4	7	5	4	2	7	7
5	2	4	1	7	1	6	4	9	4	2	8	5	7	6	9	4	7	4	7	9	6	8	7	6	8	7	6	9	9	3	9	1	1	1	7	9	5	6	5	2	3	5	1	9
7	3	3	4	5	8	1	7	6	2	7	3	2	6	6	4	3	6	8	2	8	3	3	1	3	2	1	2	4	4	6	4	2	1	8	2	4	8	9	1	8	6	4	2	9
3	4	8	3	6	4	8	8	5	2	7	2	3	9	1	1	9	9	4	8	6	8	3	6	4	5	7	6	8	2	5	7	5	4	3	7	9	6	3	5	1	1	5	5	5
4	6	1	9	5	6	6	9	3	5	9	4	2	3	8	8	7	2	7	4	1	5	1	5	2	2	1	5	6	5	4	5	5	2	1	8	2	2	4	8	1	8	4	6	3
9	1	4	6	2	5	5	8	2	3	6	7	6	7	4	7	2	9	1	2	7	4	8	4	5	4	6	2	1	9	1	4	9	3	6	8	5	1	2	8	5	3	9	4	3
1	1	6	9	2	4	7	2	9	3	8	5	5	9	2	1	6	2	1	5	4	4	5	3	4	6	4	7	6	7	4	6	9	8	6	7	7	8	3	8	9	3	6	6	1
6	4	9	4	8	7	6	3	5	9	3	6	5	4	6	8	6	7	1	9	4	6	5	2	2	4	6	7	8	4	8	5	9	1	9	7	6	2	3	1	9	9	1	7	1
8	8	9	1	5	9	6	3	1	8	9	8	5	6	9	4	9	2	4	3	4	1	3	8	6	7	8	6	4	4	4	7	2	4	5	1	8	5	6	9	8	9	5	8	3
7	7	5	2	1	7	7	5	7	8	5	4	8	8	2	3	6	6	8	2	6	5	9	8	2	4	5	1	5	6	1	2	5	9	2	6	9	8	6	9	5	1	5	2	4
9	6	3	9	8	9	3	6	1	6	2	5	4	7	1	9	2	7	3	4	2	6	5	1	2	3	2	1	3	6	3	2	4	1	8	7	8	8	7	4	7	1	7	2	7
7	6	4	9	9	9	3	7	6	7	1	8	2	1	6	2	9	4	3	8	6	9	7	3	4	1	9	4	7	6	4	4	2	2	6	6	9	8	4	2	4	6	2	1	1
1	6	7	6	8	9	9	2	6	9	5	5	9	3	4	5	3	2	3	7	3	4	2	3	4	3	9	1	6	3	3	7	8	1	8	1	5	2	1	7	9	6	9	3	1
4	2	7	6	2	9	5	1	4	2	5	3	7	6	8	2	2	9	5	9	2	4	8	2	3	3	9	6	6	4	5	4	1	6	5	3	1	4	6	6	1	7	9	1	1
3	4	1	2	1	1	2	3	9	8	5	4	3	5	4	1	4	1	9	2	4	1	9	5	8	1	3	5	1	6	9	9	8	3	7	8	4	9	1	4	1	7	3	3	2
4	4	1	8	2	3	8	7	4	6	8	5	6	1	8	7	3	8	7	3	1	9	7	6	4	2	4	8	5	3	1	5	7	2	6	6	5	9	5	4	3	4	2	4	5
2	5	1	9	8	7	9	1	7	7	7	9	1	8	6	7	8	7	1	7	2	9	3	8	4	9	5	5	3	1	4	1	6	4	3	2	3	8	5	8	1	9	4	8	3
5	6	1	9	5	9	2	6	1	9	5	7	3	3	7	3	1	5	1	4	1	7	4	3	2	1	2	8	2	3	7	3	4	5	8	3	3	6	1	2	5	4	9	1	8
9	7	9	8	4	6	5	6	2	7	6	7	7	2	7	1	4	4	1	7	4	2	9	3	9	4	7	9	5	3	5	2	1	8	6	5	3	5	5	7	9	3	2	3	8
7	2	3	9	1	7	9	5	5	7	5	6	8	5	5	5	7	3	1	2	4	3	8	5	8	6	6	2	3	9	7	8	7	5	8	8	1	8	9	5	2	1	5	2	5
1	6	2	9	3	2	2	5	8	6	9	7	1	7	4	5	2	9	5	6	4	6	8	1	2	6	1	3	6	3	6	1	8	7	8	8	3	8	5	4	9	7	9	6	2

A somewhat simpler procedure can be devised that will produce the same result and be much easier to implement. As long as the array is considered to be circular, any arbitrary arrangement of the subgroups will be satisfactory provided that the starting point is selected at random. To see that this is so, consider the earlier example of selecting 5 out of 18 trucks. Since the concept of the circular array simply allows a subgroup to extend from the tail end to the front end of the array, it will be more convenient to list the array in the usual linear fashion and arrange the subgroups accordingly. Suppose the $N_1 = 2$ subgroups of size $S_1 = 3$ and the $N_2 = 3$ subgroups of size $S_2 = 4$ have been arbitrarily arranged in the order 4, 3, 4, 3, 4 and that item 10 has been determined to be the random starting point. The diagram in Figure 3 illustrates a sampling scheme that might result when the circular array concept is used.

To show that this procedure produces the desired degree of randomness, it is necessary to prove that every item in the population has an equal probability of being included in the sample. Although the particular random selections within the subgroups have not yet been made at the time the random starting point is chosen, it is known that five such selections will be made. Regardless of the actual combination that is ultimately chosen, only 5 of the 18 possible starting points will result in any particular item being included in the sample. For example, with the selections shown in Figure 3, random starting points of 1, 4, 8, 10, and 15 result in item 12 being included in the sample; however, all other starting points exclude it. Since all 18 starting points are equally likely, the probability that item 12 will be included in the sample is 5/18. Similarly, this same probability holds for all other items in the population, and this result can be generalized to apply to any size of population and sample.

This result greatly simplifies the implementation of this procedure, since only a single random starting point is required in place of a random arrangement of several subgroups. It is still necessary to make a random selection within each subgroup but, with the aid of special random number tables, this method is extremely easy to apply. Figure 4 illustrates a typical work sheet that was used to select a stratified random sample of size $N_S = 6$ from a population size of $N_P = 23$; Figure 5 shows the special random number tables used with this procedure. The user obtains the starting point for the stratification arrangement by entering Table R1 at a random location and then moving in any predetermined direction until a number less than or equal to the population size is obtained. After underlining the subgroups on the work sheet, the user then enters Table R2 and, again moving in any predetermined direction, obtains a total of $N_S = 6$ numbers that are less than or equal to the respective subgroup sizes. The process is completed by converting these to actual item numbers as shown at the bottom of the work sheet. For convenience, the outline of the procedure and the special random number tables can be printed back to back on single sheets of paper. In this way, the documentation for the random selection process for each lot will be contained on a single piece of paper.

GENERATION OF SPECIAL RANDOM NUMBER TABLES

Although standard random number tables can be used for the sampling procedure just described, it is preferable to generate special tables such as those shown in Figure 5. For this particular application, in which the maximum population size is $N_P = 50$ and the sample size is specified to be $N_S = 6$, the largest numbers required in Tables R1 and R2 are 50 and 9, respectively. To generate tables of this type by computer, a one-dimensional array is first filled with equal quantities of all numbers from one up to the largest number that is to appear in the table. These values are then shuffled into random order by using a uniform random number generator (1,2) and a suitable shuffling algorithm (3, p. 125). Because each number appears with equal frequency but in random order, the table can be used repeatedly without the introduction of bias. This is not necessarily true for all random number tables that have been published although, for practical purposes, any bias of this type that might occur is so small that it would be of little consequence.

One other consideration regarding the use of these tables should be mentioned. For the selections to be strictly independent, a new random entering point should be chosen for each selection that is to be made. However, in the example illustrated in Figure 5, it will be observed that six selections were made from Table R2 by using only one random entry point. This is a practical expedient and is justified by the large size of this table. Since each digit appears a total of 235 times in Table R2, the selection of any particular digit has almost no effect on the probability of obtaining the same digit again on a subsequent selection. Table R1 has been designed to be smaller because only one selection at a time is required from this table.

SUMMARY AND CLOSING REMARKS

Stratified random sampling has gained wide acceptance as a practical method for sampling products whose quantity is measured in continuous units of various types. This approach can be equally useful for products that are measured in discrete units as well as for continuous products that are produced or delivered in discrete units. It was demonstrated that some of the potential methods for applying stratified sampling to discrete populations do not produce the desired degree of randomness, but this problem can be overcome with a minor refinement. A satisfactory method was then developed that, with the aid of a work sheet and special random number tables, is extremely easy to apply.

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