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THE ECONOMIC FEASIBILITY OF THE APPLICATION OF STATISTICAL CONCEPTS AND METHODS TO THE CONTROL AND ACCEPTANCE OF HIGHWAY MATERIALS AND CONSTRUCTION

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I SUMMARY

This report represents the findings of an investigation made to evaluate the economic feasibility of placing responsibility for Quality Control on the Contractor and of the use of statistical procedures for acceptance of highway materials and construction. Since, unlike other large industries, statistical Quality Control is not generally practiced in the highway industry, the probable costs of such a system were estimated by projection of current costs of Contractors and Producers who are currently maintaining voluntary testing programs. Estimates based on data obtained from 49 concerns in 15 States indicate that the cost of an acceptable degree of Quality Control of highway materials or construction by the Contractor or Producer would average about 4 percent of contract price. Available information indicates that the current total engineering expenditures by State Agencies on Federal Aid projects is in the order of 10 percent of contract price. Comparisons of relative costs based on these numbers and on different proportions of Quality Control effort shared by the Contractor and the State Agency indicate that the optimum Quality Assurance System would be Quality Control by the Contractor with acceptance testing by the State Agency. The dollar cost of such a system is estimated to be about 20 percent less than that of current procedures. The economic benefits in terms of the degree of Quality Assurance obtained by this system as compared to the existing system are estimated to be even more favorable.

A related activity was a study of the relative size of Buyer's and Seller's risks using current acceptance procedures as compared to those which would be associated with a System of Coordinated Quality Control, revised specifications, and statistical sampling plans. This study indicated that the lowest risks for the same level of testing effort would be realized when a state of Statistical Control of production and construction processes was obtained.

II INTRODUCTION

The business of constructing highways differs from other large industries in the United States in at least one important respect, which is de facto assumption of responsibility for quality for the product by the purchasers. Today, practically all other large manufacturers of end-use items, or components, have accepted the philosophy that they have an inherent responsibility for quality and have installed Quality Control departments that assume an important role in management. In the case of suppliers to DOD or NASA, the establishment of an approved quality program to assure compliance with the requirements of the contract is mandatory on the Contractor and his sub-contractors. Many of the detailed requirements for the quality program and inspection system are given in two Military Specifications -- MIL-Q-9868A, and MIL-I-45208A.

The intent of these specifications is that the Producer so control manufacture that materials or products offered for acceptance will consistently maintain some agreed upon quality level. This level may be defined by some percentage of product that has measured values exceeding some limit, or product that does not contain more than a stated number of defects per 100 units. The purchaser specifies what is wanted, but does not inspect the manufacturing operation. The purchaser, however, may inspect the manufacturer's Quality Control system to make sure that it is adequate, and may perform acceptance sampling and testing on the completed product at the point of acceptance in accordance with well-defined procedures. There is no question as to the manufacturers' or Producers' responsibility for full compliance with the contract requirements.

Under current conditions, the assignment of responsibility for quality and satisfactory performance in the highway industry is not so sharply defined. The requirements of Subsection 104.01 of the AASHO Guide Specifications and similar requirements of State Agency highway construction contracts were interpreted by the Attorney General of Colorado(1)* as placing the responsibility for Quality Control on the Contractor. This responsibility applies not only to his own work and that performed by his subcontractors, but also for Quality Control of materials purchased from suppliers. However, to some extent, the State Agency usually directs the materials to be used, their proportions, the equipment and methods used in processing, and the equipment and methods of incorporating the final product into the pavement or structure. The end product or construction may then be tested to establish compliance with specification requirements that are often vaguely worded and subject to various interpretations. In case of non-compliance, the product or construction, in theory, is subject to removal and replacement without additional compensation to the Contractor. However, the representatives of the purchasing Agency who have been intimately involved in the production or construction may feel some moral responsibility for the end result and this may affect their acceptance decisions. Some current specifications contain requirements with which 100 percent compliance is highly improbable due to the normal variations of the measured characteristics, which results in acceptance tests made for record to be made on selected samples or on the basis of resampling. Highways built under these practices have generally given good performance; however, little reliable information is available that can be applied to improve future construction due to the incompleteness of project records with respect to the true average level and variability of measurements.

*Numbers in parentheses refers to number listed in Appendix D, References.

In recent years, designed experiments conducted in 38 States in cooperation with the Bureau of Public Roads have shown that measurements made on unbiased samples of highway materials and construction of satisfactory quality are highly variable.(2) Under these circumstances there will always be some percentage of test results that are outside of specification limits. A large part of the variation of measurements has been shown to be due to the methods of sampling and testing and it has become clear that the precision of a single test result applies only to the small amount of material or construction that was included in the test portion.

Statistics is that branch of mathematics that deals with variation. For this reason, statistical methods of controlling quality and determining the acceptability of product have been adopted by most large industries. If these statistical methods were made part of the assumption of Quality Control by the Producer or Contractor, they would serve two purposes. They would provide the Producer or Contractor with a means of detecting trends which could be quickly corrected before large amounts of unsatisfactory material or construction were produced or incorporated in the highway. They would also provide the purchasing Agency with assurance that the general level of quality was being maintained, together with an estimate of the expected variability of the measurements. This information would be of great value to the purchasing Agency in determining the amount of testing required to confirm and document the actual quality of the material and construction. It would also be of value in establishing realistic specification requirements that would make allowance for the normal variation of measurements made on samples of acceptable materials and construction.

Since the assumption of control of quality, making the required tests, and maintaining records by the Producer or Contractor would be a radical departure from current procedures, the economic effects of such a potential change are of importance. The purpose of the study herein reported was to estimate the economic changes due to the adoption of these Statistical Quality Control methods by the highway industry.

It was anticipated that the added costs of assumption of control would be offset by dollar benefits. However, it was found that although some industries associated with highway construction do practice a degree of Quality Control, very little information as to economic advantages was available. As in other industries(3), the justification for the current cost of voluntary testing was, in most cases, based on intangible benefits difficult to evaluate. Due to lack of experience in this area, the concerns contacted were unable to properly assess the economic advantages or disadvantages of assumption of Quality Control, more realistic specifications based on material variations, process capabilities, and more efficient acceptance procedures along with pre-defined reduced payment schedules. As a result, the cost-benefit relationships related to the adoption of coordinated Quality Control by the highway industry have necessarily been estimated on the basis of projections of current testing costs.

III OBJECTIVES

The overall objectives of the work reported herein were to evaluate the economic feasibility of the application of statistical concepts and methods to the control and acceptance of highway materials and construction.

The primary objectives were to ascertain and analyze the economic problems associated with the adaptation of statistical methods of control and acceptance by the highway industry. Particular areas of interest were manufactured products, Portland cement concrete construction, bituminous construction, and base and embankment construction.

Within these areas, the research effort was directed to determining testing costs at the current level of effort, both by State Agencies and by Producers and Contractors, and to estimating the effect of different degrees of transfer of responsibility for Quality Control from one group to the other. These effects included the end result in terms of a decrease or increase of the overall cost of the highway as well as intangible benefits which could accrue due to the construction industry by having a better understanding of the factors that affect the variability and level of specified characteristics. Effort was also directed towards determining the probable effect on the end product and economic advantages with respect to design performance relationships, and of having a better knowledge of as-built conditions.

A related objective was to estimate the risks of accepting poor material or construction and the risks of rejecting good material or construction under current acceptance procedures. These risks were to be compared with those encountered under a system of coordinated Quality Control, revised specifications and statistical sampling plans.

IV RESEARCH APPROACH

With minor exceptions, the information contained in this report, with respect to current Quality Control practices and costs, was obtained by direct interview. Preliminary investigation indicated that relatively few Contractors or Producers had their own testing organization so it was necessary to pre-select firms on the basis of information obtained from Trade Associations, Highway Agencies, and the Consultant's own organization.

In most cases, preliminary contact was made by letter explaining the objectives of the survey and requesting the privilege of an interview. Full advantage was taken of the personal contacts of various members of the Consultant's organization, and, in most cases, these persons participated in the interviews. Special interview outlines as shown in Appendix A, were prepared in advance and used as a guide in obtaining the information pertinent to the project.

In most cases, the interviews were granted on the condition that certain information was to be regarded as confidential and that the source not be identified. These conditions have been adhered to. Following the interview, a brief summary was prepared to document the information sources. This summary was mailed to the persons contacted with a request for approval, correction, or revision. Requested revisions and corrections were made and approval was assumed when the summary was not returned.

The sources of information obtained by interview are listed in Appendix B. They include concerns producing highway materials and items as shown in Table IV-1.

Table IV-1

CONCERNS AND PRODUCTS

No.	Product
19	Aggregate
23	Portland Cement Concrete
20	Bituminous Concrete
6	Prestressed Concrete Members
5	Concrete Pipe
1	Portland Cement
1	Liquid & Penetration Grade Asphalt

In addition to the above, one earth and concrete dam constructor, two concrete bridge constructors, and six large highway construction organizations were included in the study. Many of the Producers listed also had construction divisions. However, practically all information obtained by interview was furnished by personnel who were chiefly concerned with the materials or products shown, since pertinent data was not available from construction records.

The survey covered a geographical area of 15 States distributed in southern, northern, eastern, and western areas. The concerns contacted were given subjective size ratings of "1" small, "2" medium, and "3" large. Similar subjective ratings were assigned to the estimated level of current testing effort. The cost of this testing was not available in many instances. The estimates that were obtained are shown in other sections of this report.

Representatives of 10 State Highway Agencies interested in the practical application of statistical controls were interviewed to obtain opinion as to effect of placing the total Quality Control responsibility on the Contractor, and use of statistical acceptance plans. An attempt was also made to obtain estimates of current inspection and testing costs, and possible savings.

Eight Trade Associations representing the Producer's associated with highway construction were contacted. An attempt was made to obtain an opinion as to the attitude of their members with respect to a change of responsibility for Quality Control.

To compare the risks associated with the most generally used current control and acceptance procedures with the risks associated with procedures based on statistical concepts, various hypothetical acceptance situations were developed. These situations parallel those to be expected in actual practice and are based on the variability of measurements found by designed experiment whereby the entire range of values is determined by unbiased random sampling.(2)

V INTERVIEW FINDINGS

A. STATUS OF QUALITY CONTROL

Statistical Quality Control has been previously described as "A defined system of activities consisting of statistical random sampling, standardized test procedures, recording and analysis of test results, and established criteria for making decisions based on these results."

In this context, it is assumed that sampling frequency is sufficient to provide reasonably accurate estimates of the average level of measured characteristics and to enable the computation of normal variations by statistical methods.

If the above requirements are considered to be essential, the sampling of Producers and Contractors covered by this report indicates that Statistical Quality Control is not generally practiced in the highway industry.

Although several of the large concerns maintain "Quality Control" organizations, including several testing laboratories and a staff of 12 or more technicians at cost of up to $200,000 per year, the activities are most typically described as extensive spot checking, rather than Statistical Quality Control.

Practices vary widely, from the type of organization described above to the plant foreman or owner making an occasional test. In most cases, all testing is performed by the State Agency except for special projects where a private testing laboratory may be employed. The records are most frequently maintained in a ledger form with no attempt at statistical analysis, although in a few cases the data is fed to a computer and the record is in the form of a print-out with some statistical parameters. Sampling frequency on any one product at any one plant at any one location is sometimes once a day although there are exceptions where sampling and testing is stated to be practically continuous.

A few concerns have prepared sampling and testing manuals, but statistically random sampling is not the practice and samples may be biased. With very few exceptions, there is a total ignorance of statistical concepts and the available data is not fully utilized. The use of statistical control charts is almost completely unknown. There is a limited use of quality history charts where required or suggested by the State Agency. It was generally admitted that decisions were most often made on the basis of a single test result with no realization of the associated risks.

There appears to be an almost total lack of appreciation of the extent of variation due to the action of sampling and the reduction of samples. This was shown by frequent discussion by Producer or Contractor representatives of differences in results of tests on samples taken by the State Agency and by the Producer from the same stockpile, same truck, or same batch. Neither party was apparently cognizant of the fact that, due to normal sampling variation, both results were probably as nearly correct as could have been expected.

Except in the few cases where Quality Control engineers familiar with statistical control procedures had been employed, there was an almost total ignorance of the normal range of variability of test results. There was some interest and considerable surprise that such information was being developed and was published in Public Roads, A Journal of Highway Research.(2)

B. PRODUCER-CONTRACTOR COMMENTS

1. Problems and Obstacles to Statistical Quality Control

Most of the Producers and Contractors interviewed expressed skepticism that their Quality Control records would be recognized by the State Agency. Under current conditions, Producers who have equipped and staffed laboratories find that State Agency inspectors will not accept their test results. There was also skepticism that assumption of Quality Control will result in any overall economic benefit. A somewhat similar case was pointed out where the Contractor was required to perform layout and staking, but the State Agency duplicated work by checking with same number of personnel. Some Producers were concerned with the prospect of increased administrative responsibilities. Assumptions of Quality Control would require employment of technicians and some Contractors and Producers expressed doubts that they would be in a position to supervise them properly. Although some Contractors and Producers anticipated benefits from assumption of Quality Control, others believed that it would be an added burden and extra expense they would have to absorb. This was particularly the case where the State Agency is, in effect, presently providing free source inspection and certification of the Producer's output. Under such circumstances there is a lack of incentive to assume added responsibility.

Doubts as to the availability of a sufficient number of competent technicians were frequently expressed. However, many of the more progressive organizations are training their own people, on a rotating basis, by taking advantage of courses offered by Universities and Trade Associations.

Most of the representatives of the 49 concerns contacted were unfamiliar with the concept of realistic specifications based on statistical concepts and were uncertain of the effects of assuming responsibility for the quality of their product. As a result, they were reluctant to express an opinion as to the attitude of their concern on these matters. Those opinions that were obtained are listed in Table V-1.

Table V-1

OPINION SURVEY

	Yes	No
Would your concern be in favor of revised specifications?	6	6
Does your concern obtain tangible or intangible benefits from your current testing program?	22	3
Would your concern be in favor of assuming responsibility for Quality Control?	17	8

2. Anticipated Benefits

The greatest benefit foreseen of their assumption of responsibility for Quality Control by the Contractors and Producers interviewed was a reduction in shut-downs. In situations where specifications are strictly enforced, and an inspector shuts down an operation because of a single test result outside of the specified limits, the Contractor or Producer is subject to considerable loss. Payroll and equipment expenses pile up, the sequence of operations is disrupted, and administrative time must be devoted to rectifying the situation. Instances where the indicated non-compliance had been due to improper sampling were cited. The general opinion was that if sampling was performed by standard methods by Producer's technicians, monitored by State Agency representatives, much trouble and expense could be avoided.

Some Producers speculated that they could better control their product if their own personnel were doing the sampling and testing because of more reliable knowledge of actual conditions. Practices differ widely, but in some instances State Agency personnel will not make test results available to the Producer and merely issue instructions as to changes to be made. In other cases, only one or two tests are made daily and results vary so widely that the Producer is uncertain as to whether adjustments should be made based on the State Agency findings. These Producers expressed their desire to protect their reputation by shipping satisfactory material but were sometimes concerned by the fact that they had no latitude in the design or proportioning of mixtures.

Both Portland cement and bituminous concrete Producers expressed opinions that they could effect economies if they were permitted to design their own mixtures. Several central-mixed and truck-mixed concrete Producers with technical organizations have justified the cost of testing by significant savings in cement when supplying concrete on private work on a guaranteed strength basis. However, even with a specified cement content, they believe costs could be reduced if they were permitted more latitude in the selection of aggregates and if delays in getting test results were eliminated. In some cases, State Agency gradation requirements are restrictive and result in higher costs for concrete than that giving satisfactory performance on private work where restrictions do not apply.

Producers of asphalt paving mixtures believe they could effect economies if allowed to design their own mixtures. These savings would be derived from price differentials in certain types of aggregate, and from reduced use of commercial filler. However, one Producer stated that benefits from specifications based on statistical concepts would be negative due to provisions for reduction in price.

Current benefits accruing to concerns that have made a start on Quality Control are reported to be increased sales and better customer satisfaction. Testing personnel often act as troubleshooters and advise customers as to the proper materials and their use. In some cases, Producer's technicians monitor State Agency inspectors to make sure that materials are properly sampled, job-site tests properly made, and that test specimens are properly cared for.

Very few Producers could provide estimates of dollar benefits of their testing programs. However, three concrete Producers estimated savings of \$0.30 to \$0.40 per cubic yard of concrete and another reported savings of \$22,000 annually by adjusting cement content to meet required strength. One concern estimated that savings of 2.0 percent of the cost of pavement concrete could be realized if they were allowed to design mixtures so as to obtain correct yield. In another case, savings of \$0.01 per cubic yard of embankment totaling 150,000,000 cubic yards were reported as the result of the Contractor being allowed to use nuclear density meters. This eliminated delays so that the Contractor could keep moving.

The best documented estimates of savings were provided by a concern that manufactures prestressed concrete beams, concrete pipe, bituminous concrete, and ready-mixed concrete, with an annual volume of \$30,000,000. These materials were frequently tested by a team of 12 technicians at an annual cost of \$120,000 direct and \$80,000 indirect. These testing costs were about 0.67 percent of the product value. The total dollar benefits were estimated to be \$445,000 annually. This was broken down into the following items:

Prevented Losses	\$200,000
Reduced Rejections	200,000
Savings in Cost of Concrete	20,000
Reduced Shut-Down Time	75,000
Reduced Interest Costs Due to More Prompt Payment	50,000
	\$445,000

The cost-benefit derived from the testing program was about 123 percent of the cost of the testing. In addition, this concern reported that their testing program had resulted in increased customer satisfaction and increased sales. Test results have also been of value as legal evidence.

C. STATE AGENCIES

1. Anticipated Disadvantages and Benefits

Representatives of 10 State Highway Agencies interested in the practical application of statistical controls were contacted as to their attitude regarding specifications based on statistical concepts and transfer of Quality Control to the Contractor or Producer. All expressed some degree of interest but opinions differed widely as to practicality of total transfer of responsibility.

Some State officials stated since they are responsible for the utilization of public funds, the State would have to perform sufficient check testing to document that materials or construction were actually of specified quality. Also, suppliers would have to realize their responsibility when certifying materials and some enforcement of maintaining specified quality would have to be established. Even with a shift of responsibility, some plant and site inspection would have to be maintained to check quantities and to spot obviously defective materials or items that could occasionally be produced even under an effective Quality Control system. Currently, most Contractors and Producers do not have sufficient competent technical personnel, and an intensive educational program would be required. Some opinions were to the effect that personnel required to monitor the Contractor's or Producer's programs, plus those engaged in acceptance testing, would at least equal those presently employed for control under current procedures.

Other opinions were to the effect that some personnel would be shifted to the Producer's payroll so that overall personnel requirements would remain the same. For example, at a hot-mix plant the State personnel could be reduced from four technicians to one, but that an additional three technicians would have to be furnished by the Producer.

One State Agency reported savings estimated at up to $50,000 per year in the construction of cement stabilized base from the reduction in bid price of from the $0.10 per square yard following the adoption of statistically based acceptance procedures.

Several States are moving in the direction of reducing testing costs by accepting selected materials on certification, either with or without a random check sampling at point of delivery. One State reported estimated annual savings of $100,000 on cement testing, $50,000 on structural steel, and $10,000 to $15,000 on guard rail and H-pile by the adoption of acceptance by certification from manufacturers that provide proper Quality Control. It was also estimated that the bid price of hot-mix paving materials would be less under a soon-to-be implemented statistically based acceptance plan.

Other opinion was to the effect that bid prices would not be affected and that the format of statistically based specifications afforded a better definition of what was wanted.

The majority of State Highway personnel interviewed were of the opinion that adoption of statistical concepts for control and acceptance of highway materials and construction would be advantageous. Opinion was divided as to whether control should be entirely the function of the Contractor or Producer, one reason being the lack of competent technical personnel. One State is solving this problem by renting personnel and equipment to Contractors.

No firm estimates were obtained as to the number of State personnel required for a Coordinated System of Statistical Quality Control. The representative of one State Agency estimated that State personnel required for asphalt plant inspection could be reduced 25 percent. The representative of another State believed that the total number of personnel would remain constant but that State personnel would be reduced as the responsibility for control was gradually transferred to the Producers and Contractors.

D. CURRENT COST OF TESTING

1. Producers and Contractors

A total of 49 concerns were contacted in 15 States. Products and types of construction included Portland cement concrete, bituminous concrete, aggregates, concrete pipe, prestressed members, concrete and bituminous pavements, bridge construction, and earthwork.

Annual gross dollar volume as reported by 28 companies ranged from $300,000 to $59,000,000 with an average of about $11,000,000. The annual testing costs as reported by 19 companies ranged from $4,000 to $200,000 with an average of about $92,000.

On this basis, testing costs averaged about 0.8 percent of dollar volume. This is in fair agreement with the average of testing cost estimates reported on a percentage basis by 33 companies, which was about 1.0 percent of the dollar volume. The analyses of these costs are shown in Tables V-2 and V-3. Table V-2 shows the percent of product value expended on testing for various types of operations, i.e., bituminous concrete, Portland cement concrete, aggregates and combinations of materials and operations. This table indicates that, on the average, some Producers-Contractors are spending about one percent of their products' value on testing operations. Individual values range from a reported minimum of 0.1 percent to a maximum of 2.5 percent. Although the average percent of product value for various types of operation varies from a low of 0.50 percent to a high of 1.63 percent, there is no apparent correlation between the percent of expenditure for testing and the type of product or operation.

Table V-2

PERCENT OF PRODUCT VALUE EXPENDED BY PRODUCERS & CONTRACTORS ON TESTING BY TYPES OF OPERATION

	Aggregates	Bituminous Concrete	Portland Cement Concrete	Concrete Products	Aggregates & Bituminous Concrete	Aggregates & Portland Cement Concrete	Portland Cement Concrete & Concrete Products	Portland Cement Concrete & Highway Bridge Construction	Aggregates, Bituminous Concrete & Portland Cement Concrete
	0.06	2.00	0.01	0.40	2.00	0.01	0.67	0.02	1.00
	2.50	1.30	2.00	0.50	1.25	1.00	0.43	1.40	1.00
	0.10	1.00	2.00	0.70				0.25	1.00
		0.01	1.80						0.64
		0.25	1.00						0.70
									1.20
									0.68
									0.70
Number	3	5	5	3	2	2	2	3	8
Total	2.66	4.56	6.81	1.60	3.25	1.01	1.10	1.67	6.92
Average	0.89	0.91	1.36	0.53	1.63	0.50	0.55	0.56	0.86

GRAND AVERAGE: $\eta = 33$

$\bar{\bar{X}} = 0.896$

Table V-3

PERCENT OF PRODUCT VALUE EXPENDED ON TESTING

BY SIZE OF CONCERN AND LEVEL OF TESTING EFFORT

Level of Testing Effort	Size of Concern 1	Size of Concern 2	Size of Concern 3
1	0.25	0.06	0.01
	0.01	1.00	2.00
	0.10	0.50	0.25
	0.01		
	0.02		
2	2.50	1.00	2.00
	1.25	0.70	0.64
	2.00	1.40	2.00
	0.70	0.70	0.43
	1.30	0.68	
3	1.00	1.80	0.67
		1.20	1.00
			1.00
			1.20
			0.40
			3.00
Number	11	10	13
Total	9.14	9.04	14.60
Average	0.83	0.90	1.12
Std. Dev.	0.86	0.49	0.88
Range	0.01 - 2.50	0.06 - 1.80	0.01 - 3.00

Table V-3 and Figures V-1 through V-5 show the relation between the percent of product value expended on testing by the size of the Producer-Contractor and their level of testing effort. The ratings for size of concern are largely subjective and are based on number of plants and general scope of operations as well as reported value of annual production. This value was not available in many instances, in others the value of the product subject to tests was minor compared to the overall activities of the concern. From the data available, average product value of concerns of Size 1 was about $1.5 million annually, Size 2 was about $10 million, and Size 3 was $20 million plus. This interview data is shown graphically in Figure V-1.

Ratings for level of testing effort are also subjective. A rating of "1" typically indicates an ill-defined program that may only consist of spot checking by a company employee who has additional duties, a rating of "3" indicates operation of one or more well-equipped laboratories by trained technicians, while a rating of "2" is intermediate with respect to adequacy of personnel or equipment.

Comparing highway Contractors by size, as shown in Table V-3 and Figures V-2, V-3, and V-4, there is little difference in the average percent of product cost expended for Quality Control within each size operation. Larger Contractors do spend a slightly larger percent as expected. Essentially the same amount of the operating budget of each size firm is allocated for Quality Control. There is some variability among the three sizes of operation as denoted by the range and the standard deviation. The differences are not appreciable and are to be expected with the type of data available.

Figure V-1

REPORTED VALUE OF TESTED PRODUCT RELATED TO SIZE OF CONCERN

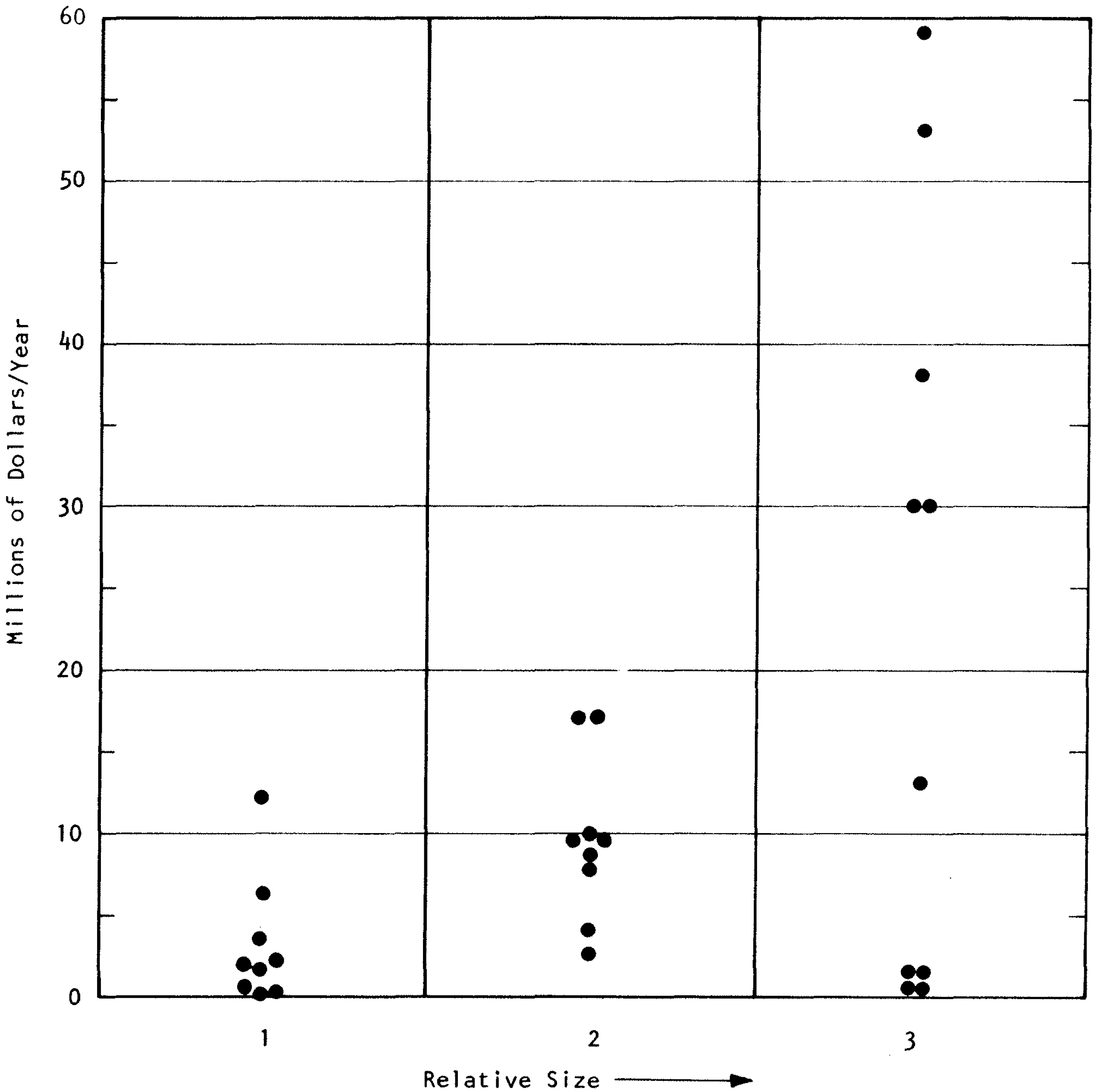


Figure V-2

RELATIVE SIZE RELATED TO REPORTED ANNUAL TESTING COSTS

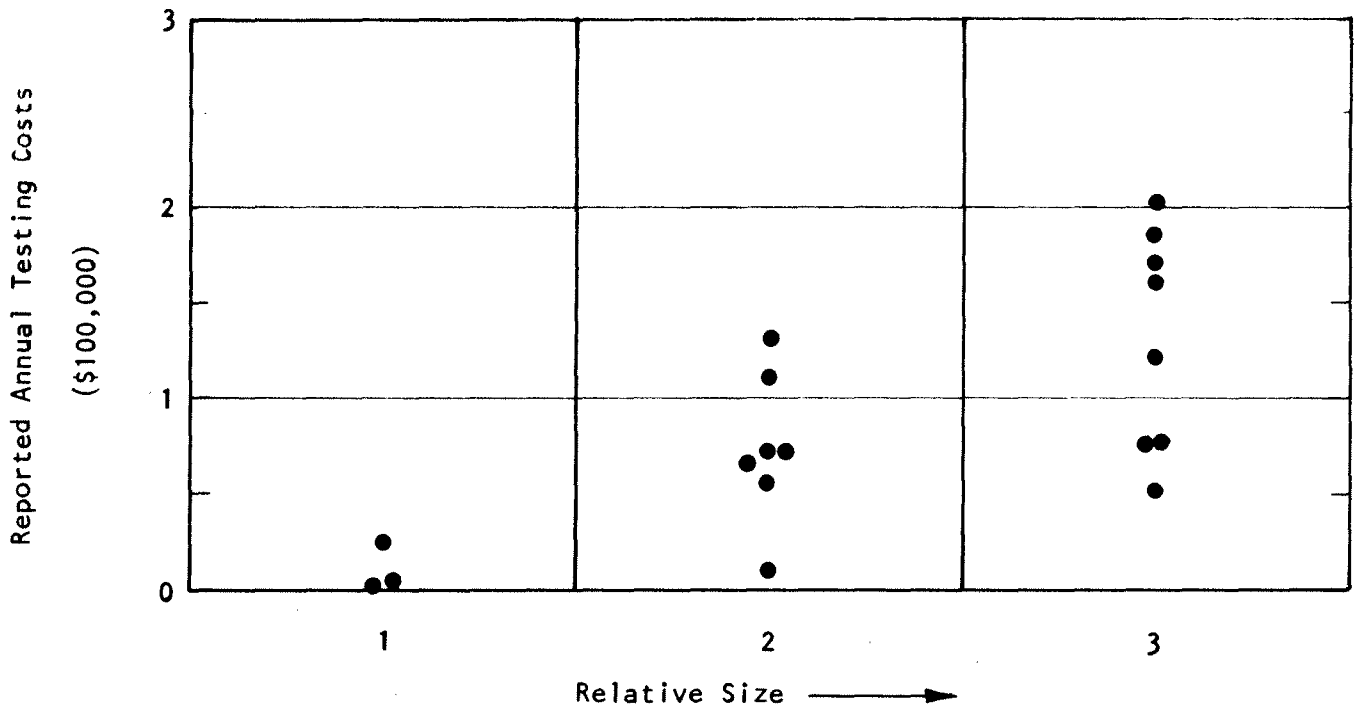


Figure V-3

CURRENT TESTING COSTS RELATED TO SIZE OF CONCERN

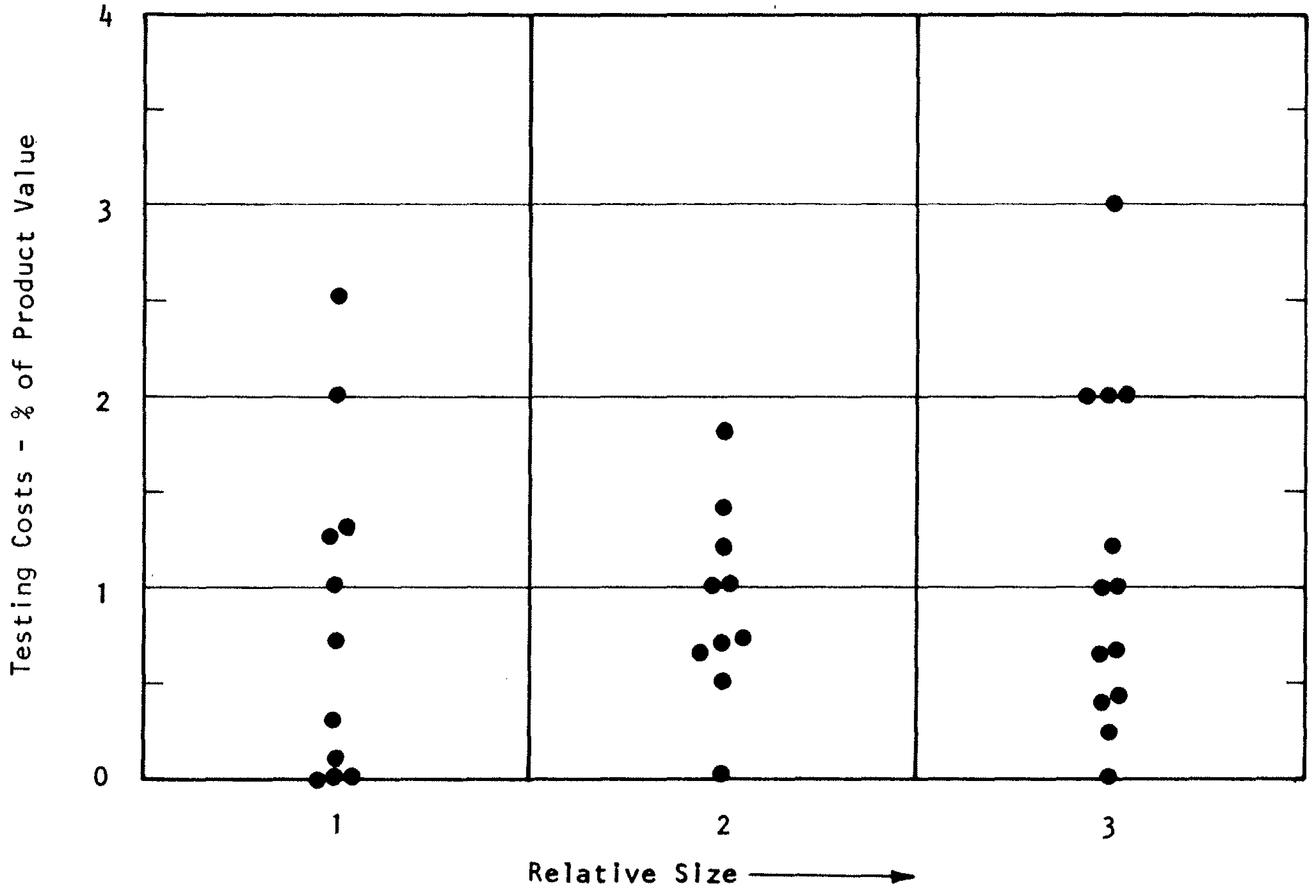
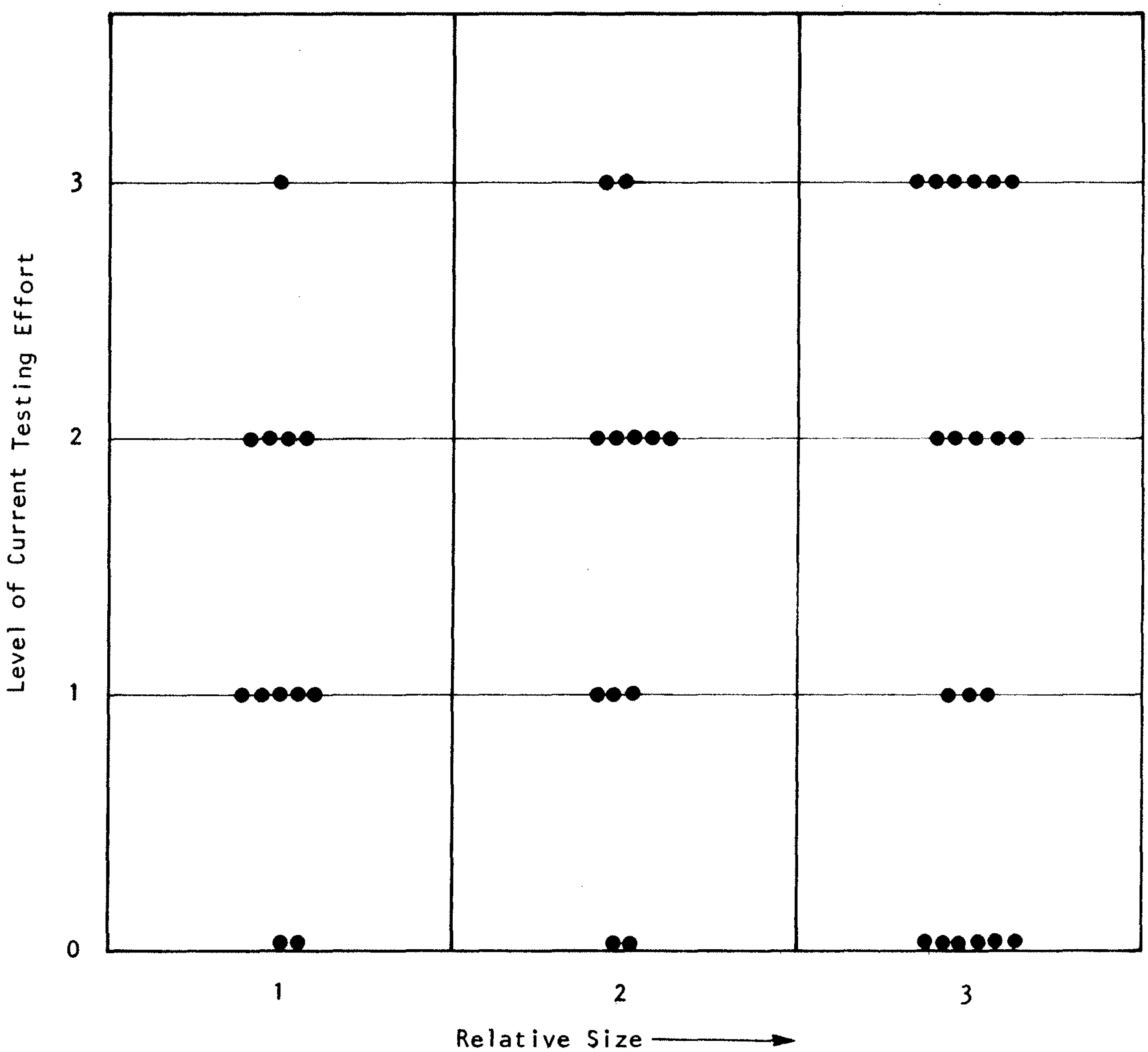


Figure V-4

CURRENT TESTING EFFORT RELATED TO SIZE OF CONCERN



The fact that the percents are the same, of course, means that the actual expenditures in dollars differ by size of operation. To compare these differences, information is needed on the actual operating expenses of the firms, information the concerns would not divulge.

The costs considered in computing the above percentages are for the most part very approximate. They do not all include the cost of equipment, physical facilities, and perhaps for training personnel for Quality Control work. Facilities and equipment would cost approximately the same for the large as for the small concerns with some advantage to large concerns conducting multiple operations within a small geographical area.

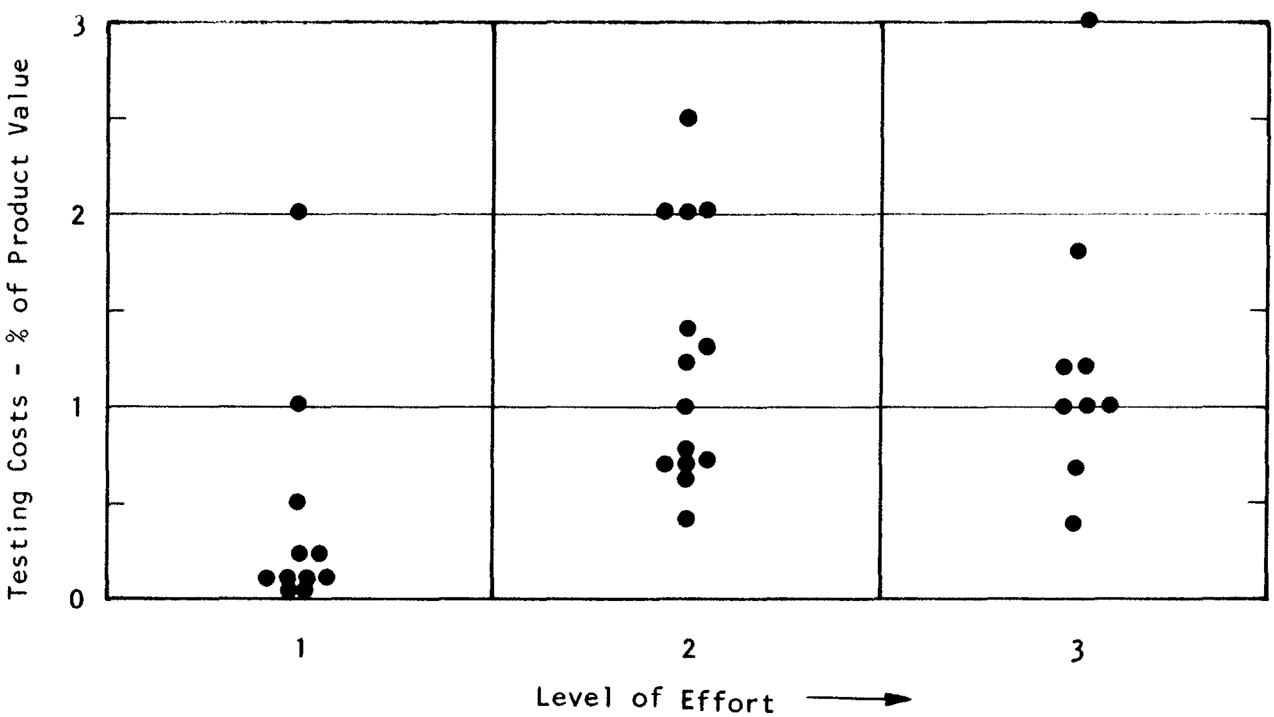
The current testing costs (percent of product value) of the Producers and Contractors as related to their level of testing effort is presented in Table V-3 and shown graphically in Figure V-5. As would be expected, the level of testing costs increases with an increase in the level of testing effort. However, there is little difference in testing costs, about one percent of product value, for level of efforts of "2" and "3".

2. State Agencies

Only two estimates of engineering costs were obtained as the result of interviews with representatives of 10 State Agencies responsible for the quality of highway construction. In one case, this was a firm estimate of 13 percent of construction costs, in the other that these costs probably exceeded 10 percent of construction costs. It was not possible to obtain an estimate of the proportion of these funds expended directly for overall Quality Control and acceptance testing. In the absence of this information, the total costs have been used in this report as estimates of the maximum costs of activities currently conducted by State Agencies, but which could probably be performed by Contractors and producers more economically.

Figure V-5

CURRENT TESTING COSTS RELATED TO LEVEL OF QC EFFORT



VI RISKS ASSOCIATED WITH SPECIFICATIONS AND ACCEPTANCE PROCEDURES

A. BUYER'S AND SELLER'S RISK

A related objective of this investigation was to estimate the alpha (α) and beta (β) risks associated with current specifications and acceptance procedures for selected products and construction. Corresponding risks were to be estimated under the same conditions on an assumed system of coordinated Quality Control, revised specifications, and statistical sampling plans.

In general, both the α or Seller's risk and the β or Buyer's risk depend on the variability of the specified characteristics as expressed in standard deviation units, the number of tests that are averaged, and the specifications limit, or limits, as related to the normal capability of the process. This process includes the production of the material or construction, the selection of samples or test locations, and the actual measurement of the characteristic. To eliminate some of these variables for the purpose of defining risks, hypothetical acceptance situations have been assumed using numerical values of the same order of magnitude as would be expected in practice.

The comparison of the size of the Buyer's risk of accepting material that would not meet the specification requirements, and the size of the Seller's risk of having acceptable material rejected, has been made by the use of tables. One table shows the risks associated with current acceptance procedures for different degrees of variation and for the number of test results on which a decision is based. The other table shows the corresponding risks when a statistical acceptance plan is used. These comparative tables are discussed in the following sections.

B. DENSITY OF CONSTRUCTED BASES AND EMBANKMENTS

The required density of compacted soil and aggregate mixtures is commonly specified in terms of the percent of some standard of dry density indicated by measurements of the in-place dry density. Since these materials, with the possible exception of blended mixtures from a pug-mill, are not homogenous, the measurements are quite variable and the amount of variation is not constant.

Regardless of the method used to measure the percent of the standard density that has been obtained, available data indicate that the standard deviation of the results is usually in the range of 3 to 8 percentage points. Since in a particular situation, the standard deviation is not known, the risks of accepting insufficiently compacted material or requiring additional compaction of highly compacted material can be quite large, depending on the actual material variation and the number of individual tests that are averaged.

Table VI-1 illustrates the size of these risks. To construct this table, it was assumed that 100 percent was an entirely acceptable average degree of compaction ($\overline{X}_g'$), that the 90 percent average compaction was not acceptable ($\overline{X}_p'$) and that compacted material would be accepted if the test result, or average of test results, indicated 96 percent compaction (L). Figure VI-1 graphically presents this acceptance situation and shows the relationship between $\overline{X}_p'$, L, $\overline{X}_g'$, and the risks.

In Table VI-1 the α risk is that of requiring additional compaction when the true average degree of compaction is 100 percent. The β risk is that of accepting material that has, in fact, been compacted to an average of only 90 percent of the standard or reference density.

The acceptance rule is "Accept if $\overline{X}_n \geq 96$ percent".

Table VI-1 shows that, when current acceptance procedures are used, that the Buyer's risk (β) of accepting insufficiently compacted material may be from

Figure VI-1

ACCEPTANCE SITUATION DENSITY OF BASE COURSE

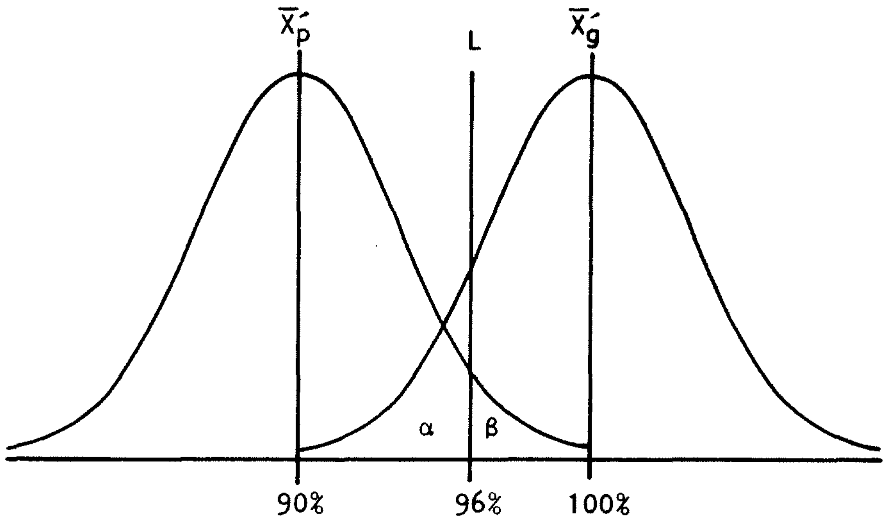


Table VI-1

RISKS ASSOCIATED WITH DENSITY ACCEPTANCE PLAN BASED ON $\overline{X}_n$

$\overline{X}_p' = 90\ \%$ $L = 96\%$ $\overline{X}_g' = 100\%$

Standard Deviation (σ)

σ	3		4		5		6		7		8	
n	α	β	α	β	α	β	α	β	α	β	α	β
1	9	2	16	7	21	12	25	16	28	20	31	23
2	3	0	8	2	9	4	18	8	21	11	24	14
3	1	0	4	0	8	2	12	4	16	7	19	10
4	0	0	2	0	6	1	9	2	13	4	16	7
5	0	0	1	0	4	0	7	1	10	3	13	5
6	0	0	1	0	2	0	5	1	8	2	11	3

2 percent to 23 percent when acceptance is based on a single density test result. The corresponding Seller's risk (α) of having to recompact sufficiently compacted material is from 9 percent to 31 percent over the assumed range of values of standard deviation. Since the actual standard deviation is unknown the values of the risks within these ranges are not known. As the number of test results (n), on which the acceptance decision is based, is increased, both the Buyer's and Seller's risks are decreased. It would be necessary to average at least three test results to reduce the Buyer's risk to an acceptable value of 10 percent assuming that the standard deviation did not exceed 8 percent. The corresponding Seller's risk with three measurements would be 19 percent.

Table VI-2

ALPHA RISKS ASSOCIATED WITH STATISTICAL DENSITY ACCEPTANCE PLAN
WHEN β = 10 PERCENT

Sample Standard Deviation s ≈ σ

	3		4		5		6		7		8	
n	L	α	L	α	L	α	L	α	L	α	L	α
2	96	10	99	33	101	38	103	47	105	53	107	58
3	93	0	94	5	95	9	97	18	98	27	99	34
4	92	0	93	1	94	2	95	7	96	13	97	20
5	92	0	93	0	93	0	94	3	95	7	95	12
6	92	0	92	0	93	0	94	1	94	3	95	7

When a statistically derived sampling plan is used, the Buyer's risk does not depend on the size of the standard deviation, but is fixed at some acceptable value. In this case, for the purposes of comparison, the β risk has been fixed at 10 percent as shown in Table VI-2. The acceptance limit (L) and the Seller's risk (α) increase as the standard deviation increases, and both decrease as the number of measurements on which the decision is based increases.

The decision rule is "Accept if $\overline{X}$ - 90 > FR".

Where:

$\overline{X}$ = average of test results

90 = the acceptance limit (L)

F = a factor computed for the particular acceptance plan

R = the difference between the largest and smallest values in the group of test results.

Comparing the risks in the two tables show that, under the conditions previously assumed, the same β risk of 10 percent and the nearly same α risk of 20 percent would be present when the statistical plan was based on four density measurements as compared with three density measurements if the standard deviation was known to be 8 percent.

This analysis indicates that, under the assumed conditions, both the Buyer's (β), and the Seller's (α) risks are so large as to be unacceptable under current acceptance procedures when decisions as to adequate density are based on a single measurement. If an estimate of the standard deviation of the measurements was available, from two to three measurements would reduce the risks to an acceptable level. However, when there is no prior information as to the normal variability of the measurements under site conditions, a statistically derived acceptance plan based on four measurements should be used.

C. ASPHALT CONTENT OF HOT-MIXED BITUMINOUS PAVING MIXTURES

The asphalt content of paving mixtures is usually specified as a target value called the job mix formula (JMF) to which some plus and minus tolerance is applied. The acceptance rule usually applied is that the result of a test for asphalt content or the average of two or more of such tests must fall within the tolerance limits.

To investigate the risks associated with this acceptance procedure, it is assumed that mixtures having an asphalt content equal to the target value are entirely satisfactory, mixtures having an asphalt content of 0.6 percent more or less than the target value are not satisfactory and that, under current procedures, mixtures having an indicated asphalt content within plus or minus 0.4 percent of the target value are acceptable. This acceptance situation is illustrated in Figure VI-2. With this model the Buyer's risk (β) and Seller's risk (α) have the values shown in Table VI-3.

The acceptance rule is "Accept if the test result or the average of n tests results is within 0.4 percent of the JMF value".

In Table VI-3, the alpha (α) risk is that of rejecting material having an average asphalt content equal to the JMF value while the beta (β) risk is that of accepting material having an average asphalt content differing by 0.6 percent plus or minus from the JMF value.

Table VI-3

RISKS ASSOCIATED WITH FIXED ACCEPTANCE LEVEL FOR ASPHALT CONTENT

Standard Deviation (σ)

σ	0.2		0.3		0.4		0.5		0.6	
n	α	β	α	β	α	β	α	β	α	β
1	2	16	9	25	16	31	21	34	25	38
2	0	8	3	17	8	24	13	28	17	32
3	0	4	1	13	4	19	8	25	13	28
4	0	2	0	9	2	16	6	21	9	26
5	0	1	0	7	1	13	4	19	7	23
6	0	1	0	5	1	11	2	16	5	21

Figure VI-2

ACCEPTANCE SITUATION ASPHALT CONTENT OF BITUMINOUS PAVING MIXTURE

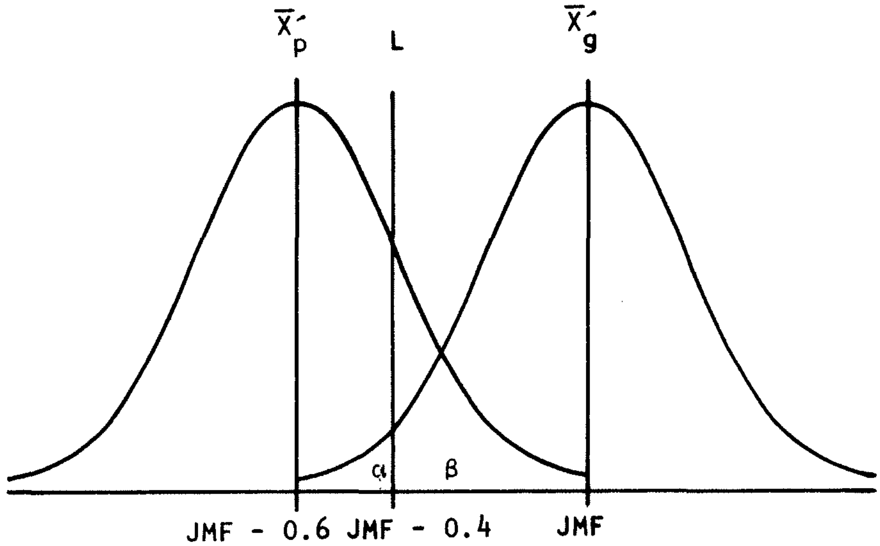
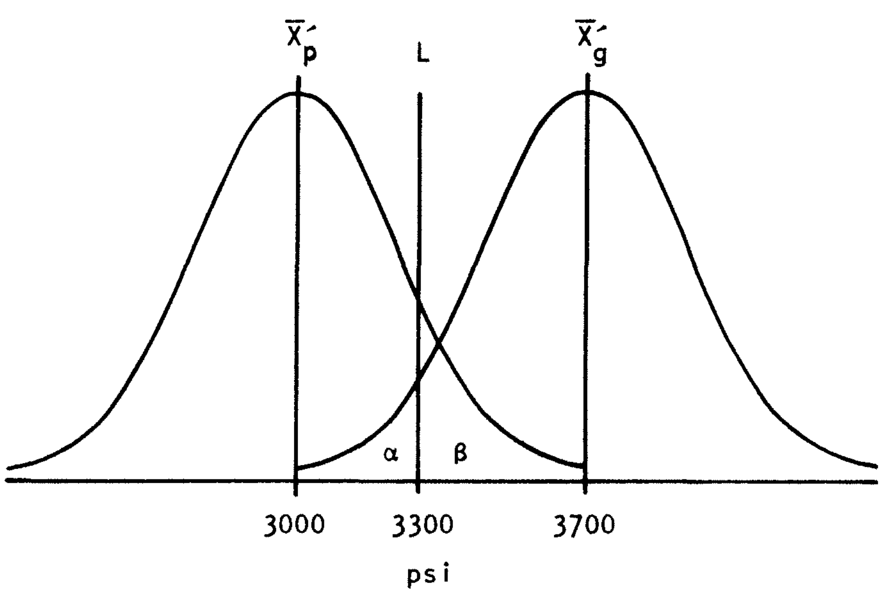


Figure VI-3

ACCEPTANCE SITUATION STRUCTURAL CONCRETE



With this procedure, the Buyer's risk (β), under the assumed conditions, is between 16 and 38 percent when an acceptance decision is based on a single test result. The Seller's risk is less when the standard deviation of the test results is small but becomes unacceptable when the standard deviation exceeds about 0.3 percent. Also, when the standard deviation is more than 0.3 percent, four or more test results would have to be averaged to reduce the Buyer's risk to an acceptable value.

A statistically derived acceptance plan that would be independent of the variation of asphalt content would fix the Buyer's risk of accepting material having an average asphalt content differing by 0.6 from the JMF at β = 10 percent. The associated Seller's risk (α) is shown in Table VI-4.

Table VI-4

SELLER'S RISK (α) ASSOCIATED WITH FIXED BUYER'S RISK (β) OF 10 PERCENT

Sample Standard Deviation $s \approx \sigma$

n	0.2	0.3	0.4	0.5	0.6
2	19	38	51	60	65
3	1	9	24	37	47
4	0	2	11	23	34
5	0	0	5	14	24
6	0	0	2	9	17

With this plan, the Buyer's risk (β) and Seller's risk (α) are approximately equal when acceptance is based on the average of three tests and the sample standard deviation (s) is 0.3.

In this case, the acceptance rule would be "Accept if $\left|\overline{X}_4 - JMF\right| < 0.6 - 0.37R$".

Where:

$\overline{X}_4$ = average of four tests for asphalt content

JMF = Job Mix Formula or target value for asphalt content

0.6 = maximum allowable difference of asphalt content from JMF value

R = difference between largest and smallest result of test for asphalt content

0.37 = a statistically derived factor used to fix (β) at 10 percent.

D. STRUCTURAL CONCRETE

Strength requirements, overdesign factors and required average strengths for various classes of concrete are shown in Table 1 of the current ASTM Specification, Ready-Mixed Concrete, (ASTM Designation C 94-69). These average strengths are computed by use of the equation

$$f_{cr} = \frac{f_c'}{(1 - tV)} \qquad \text{Equation (1)}$$

Where:

f_{cr} = required average strength

f_c' = design strength specified (psi)

t = a constant depending on the proportion of tests that may fall below f_c' and the number of tests involved. For $n > 30$, $t = 1.282$.

V = the coefficient of variation expressed as a decimal.

For acceptance purposes, the ASTM Specification requires that, for Class 1 concrete, no more than 10 percent of the strength tests shall have values less than the specified strength f_c', and the average of any three consecutive strength tests shall be equal to or greater than the specified strength. For groups of six tests, or less, factors are given for computing the required average strength of the group. These factors appear in ACI 214-65 and are applicable when the coefficient of variation is 15 percent. Equation (2) has been derived for the computation of equivalent factors (F) for other values of the coefficient of variation.

$$F = \frac{f_{cr}\sqrt{n} - f_{cr}V(2.055)}{f_c'\sqrt{n}} \qquad \text{Equation (2)}$$

The Seller's risk (α) of rejection of concrete having an actual average strength f_{cr} is fixed at 2 percent when the factors (F) from ASTM C 94 or computed from Equation (2) are used to compute the lowest acceptable average strength of a group of tests, providing that the actual average strength ($\overline{X}$) is the same as computed by Equation (1) and that the actual coefficient of variation (V) is the value used in the computation. There is another Seller's risk involved due to the requirement that the moving average of three test results must be equal to, or greater than, the specified strength. The size of this risk cannot be stated exactly since it depends on the number of consecutive tests as well as other factors. Since a percentage of test results lower than f_c' is allowed, there is a probability that, by chance, some of these test results will be consecutive, and this probability increases with the number of times the moving average is applied. However, simulation techniques indicate that this risk is not large providing that the proper average of f_{cr} is maintained.

To estimate the Buyer's risk (β) associated with this procedure for the acceptance of Class 1 concrete having $f_c' = 3000$ psi, it is assumed that the concrete has been designed by the use of Equation (1) for different values of (V) resulting in the values of f_{cr} shown in Table VI-5.

It is also assumed that the acceptance of the concrete having these values of f_{cr} will be based on the acceptance limits (L) which are derived by multiplying the average ($\overline{X}$) of the number (n) of the test results by a factor (F) obtained from ASTM C 94 or by the use of Equation (2). These limits are shown in the columns of Table VI-5 for values of n from 1 to 6.

Table VI-5

BUYER'S RISK (β) ASSOCIATED WITH ASTM DESIGNATION C 94-69

Seller's Risk (α) = 2 Percent f'_c = 3000

	V	5	10	15	20	25
	f_{cr}	3210	3440	3720	4030	4220
β (%)	n	Acceptance Limit (L) for $\overline{X}_n$				
78	1	2880	2730	2570	2380	2150
60	2	2970	2940	2900	2860	2810
44	3	3020	3030	3050	3080	3110
31	4	3040	3090	3140	3210	3280
21	5	3060	3130	3200	3290	3400
14	6	3070	3150	3250	3360	3490

The Buyer's risk (β) associated with this acceptance procedure under the assumed conditions is shown on the left-hand column of Table VI-5. It can be seen that the Buyer's risk (β) is so large as to be unacceptable when the number of tests (n) is less than five.

In actual practice, the Buyer's risk (β) and Seller's risk (α) associated with this acceptance procedure are largely indeterminate due to the basic assumption that the coefficient of variation (V) is known and remains constant.

A more equitable and reliable acceptance plan for LOT-by-LOT acceptance can be designed by not assuming that the coefficient of variation (V) or the sample standard deviation (s) is known. The Buyer's risk (β) can be fixed and the Seller's risk (α) can be estimated for computations based on t and non-central t. Such a plan for concrete having a specified design strength of f_c = 3000 psi, roughly comparable to the previous example, can be designed by fixing the Buyer's risk (β) at 20 percent and making the same assumptions. This acceptance situation is shown in Figure VI-3 and the Seller's risks (α) are shown in Table VI-6.

Table VI-6

SELLER'S RISK (α) ASSOCIATED WITH STATISTICAL ACCEPTANCE PLAN

Buyer's Risk (β) 20 Percent

	V	5	10	15	20	25
	σ	160	344	557	807	1104
	f_{cr}	3210	3440	3720	4030	4220
α (%)	n	Acceptance Limit (L) for $\overline{X}_n$				
28	2	3160	3340	3540	3790	4070
13	3	3100	3210	3340	3490	3680
6	4	3080	3170	3270	3390	3540
3	5	3070	3150	3230	3340	3470
2	6	3060	3130	3210	3300	3420

The values for acceptance limits in Table VI-6 are estimates based on the assumption that the coefficient of variation (V) of the concrete under test is as stated and are to be used only for purposes of comparison with those in Table VI-5. In practice, the acceptance limit would be computed for each individual LOT, and would depend on the sample standard deviation, or the range, of the tests made on the LOT. Because of ease of computation, the range is preferred and the acceptance rule would be "Accept if $\overline{X} - f_c' > FR$".

Where:

$\overline{X}$ = average of group of tests

f_c' = design strength specified

R = difference between largest and smallest test value in group

F = value shown in Table VI-7.

This acceptance rule is independent of any assumptions made as to the standard deviation or coefficient of variation of concrete strengths. Values of F for different Buyer's risks (β) of accepting concrete having an average strength f_c' are shown in Table VI-7. The associated Seller's risk (α) will depend on the actual average strength and variability of the concrete in the LOT.

Table VI-7

FACTORS (F) FOR ASSOCIATED BUYER'S RISKS (β)

n	Buyer's Risks (β)			
	5%	10%	15%	20%
3	0.88	0.57	0.42	0.32
4	0.53	0.37	0.28	0.22
5	0.39	0.28	0.22	0.17
7	0.26	0.19	0.15	0.12

E. THICKNESS OF CONCRETE PAVEMENT

The 1968 AASHO Construction Guide Specification for thickness of concrete pavement (Paragraph 501.23) states, in effect, that one core shall be taken at random in each 1000 feet of pavement. If this core is deficient by more than 0.2 inch from plan thickness, two additional cores shall be taken. If the average of the three cores is deficient by more than 0.2 inch, a reduction in price will be enforced.

The effect of applying this acceptance plan depends on two probabilities.
(1) The probability of the first core being short by more than 0.2 inch, and
(2) The probability that the average of three cores being deficient in length

by more than 0.2 inch. Because of correlation effects, the overall probability is difficult to estimate, but if the true average thickness was exactly equal to the plan thickness (9.0 inches) and the standard deviation of the thickness measurements was 0.3 inch, the probability of acceptance would be about 92 percent. One-half of the pavement area could be less than 9.0 inches in thickness and about 5 percent could be only 8.4 inches thick. If the standard deviation was more than 0.3 inch still thinner areas of pavement could be present in the accepted areas. The probability of acceptance for pavement of different average thicknesses and having a standard deviation of thickness of 0.3 inch is shown in Figure VI-4.

A statistically derived plan that would insure only about a 5 percent risk of accepting pavement having a thickness of less than plan thickness (T) minus 0.2 inch and which would be independent of the variability of thickness would be: Take four cores at random locations in each 1000 foot section, "Accept if ($\overline{X}_4$ - 0.53R) > Plan T - 0.2 inch".

Where: Plan T = specified plan thickness

$\overline{X}_4$ = average length of 4 cores

R = difference in length between longest and shortest cores

0.53 = a statistically derived factor used to fix β at 5 percent.

Acceptance under this plan would insure that a minimum of about 90 percent of the area of concrete in the 1000 foot section exceeded plan thickness minus 0.2 inch. The required average thickness would depend on the overall standard deviation of the measurements as shown in Table VI-8.

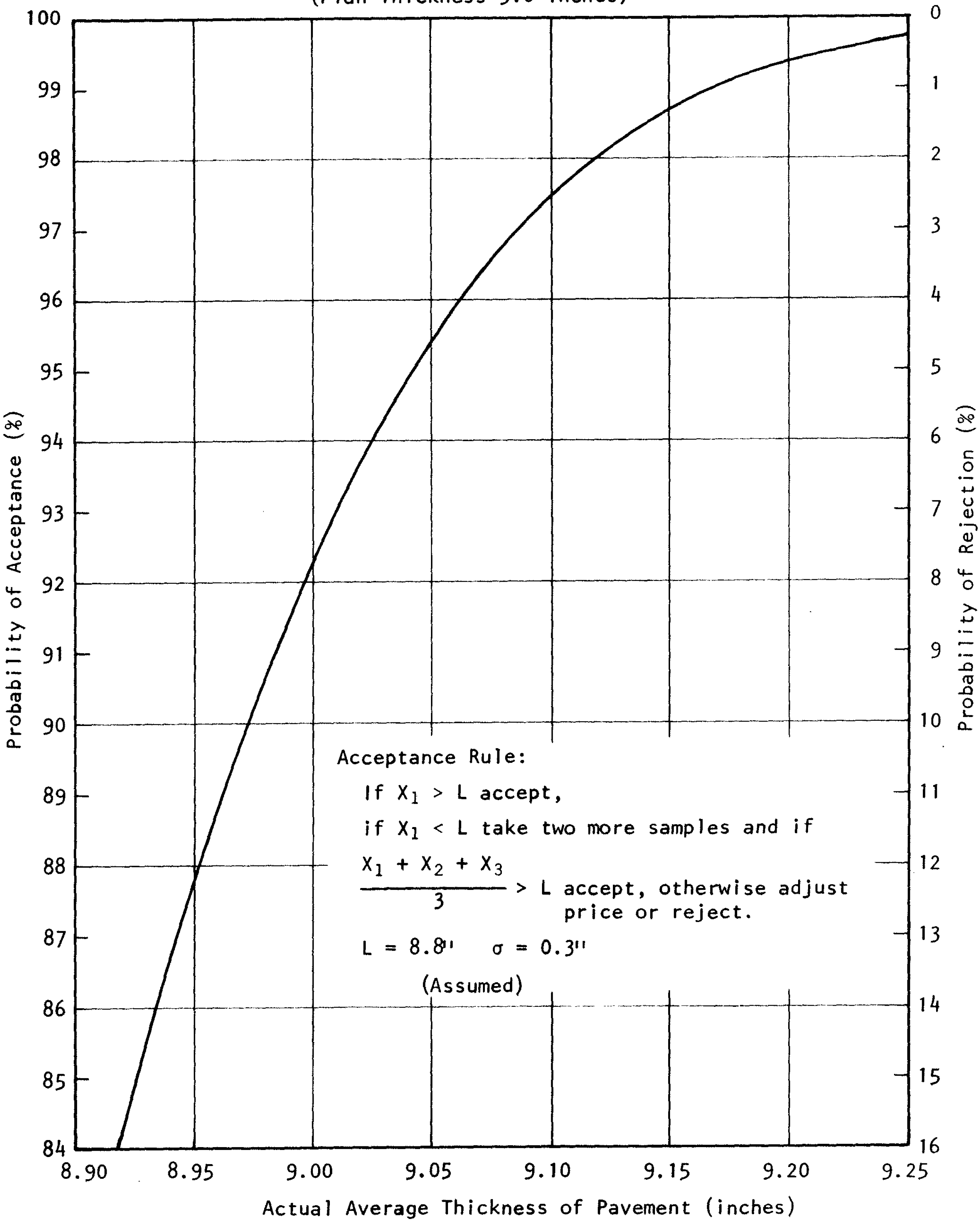
If the actual standard deviation was 0.3 inches, the α risk of rejecting pavement 9.4 inches thick would be about 10 percent.

A variation of this plan has the advantage of providing a rational basis for assessing reductions in price for non-conforming construction. Since the

Figure VI-4

OPERATING CHARACTERISTICS CURVE FOR ACCEPTANCE PROCEDURES
OF PARAGRAPH 501.23 OF 1968 AASHO GUIDE SPECIFICATIONS

(Plan Thickness 9.0 Inches)



performance of concrete pavement is a function of the uniformity of thickness as well as the average thickness, the percent within tolerance (PWT) serves as a measure of the combination of these parameters.

Table VI-8

REQUIRED AVERAGE THICKNESS OF PAVEMENT

FOR 90 PERCENT WITHIN TOLERANCE OF PLAN THICKNESS MINUS 0.2 INCH

Buyer's Risk (β) 5 Percent

σ	$\overline{X}$
0.1	Plan T + 0.0
0.2	Plan T + 0.0
0.3	Plan T + 0.2
0.4	Plan T + 0.5
0.5	Plan T + 0.6

To use this approach, the acceptance rule would be: Take 4 cores at random locations in each 1000 foot section. Subtract plan thickness minus 0.2 inch from the average of the measured length of the cores. Divide the result by the difference between the longest and shortest core measurements. If the result is 0.53 or larger, the payment will be accepted and paid for at the contract price. If the result is less than 0.53, the pavement will be accepted at a reduced price as shown in Table VI-9.

Table VI-9

PAYMENT SCHEDULE

$\frac{\overline{X}_4 - (T - 0.2)}{R_4}$	Percent of Pavement Within (T - 0.2)	Proportional Part of Contract Price Allowed
0.53	90	100%
0.52 - 0.34	75	80%
0.33 - 0.24	68	70%
0.23 - 0.07	55	60%
< 0.07	-55	50%

VII EFFECT OF STATISTICAL QUALITY CONTROL AND ASSURANCE

A. STATISTICAL QUALITY ASSURANCE

Statistical Quality Control, as required of the Contractor, is usually considered to be "A defined system of activities consisting of statistical random sampling, standardized test procedures, record and analysis of test results, and established criteria for making decisions based on these results." Its purpose is to make sure that the average level and the variability of some measured characteristic of the output of a process is remaining within acceptable limits, rather than to insure that the small individual samples of the output meet certain standards. To accomplish this purpose requires a defined system of activities consisting of statistical random sampling, standardized test procedures, recording and analysis of test results, and established criteria for making decisions based on these analyses.

Acceptance procedures of a State Agency under a System of Coordinated Quality Control will include the acceptance of certain manufactured materials or products on the basis of certification by the manufacture that they have been produced under an adequate system of Quality Control and are in conformance with specified requirements. The State Agency will monitor the Contractors or manufacturers Quality Control system to insure that it is adequate, properly staffed and will provide reliable information. These acceptance procedures also include the enforcement by the State Agency of realistic specifications with numerical limits and tolerances sufficiently large to allow for the inherent variation of measurements of the characteristics of acceptable materials and construction. The specifications should include a definite acceptance plan to be used for each material, product or item of construction. This plan will specify, as shown in Table VII-1, the point of acceptance sampling, method of sampling, size of LOT, number of tests on which acceptance or rejection will be based, and the test procedures to be used. The plan will also state the method of determining compliance or non-compliance with the specified limits on the basis of the results of the tests. Finally, the plan will state the action to be taken in the case of non-compliance and the portion of the contract price to be paid for acceptable but partially non-conforming materials, products or items of construction.

Statistical Quality Assurance is obtained under a System of Coordinated Quality Control whereby the Quality Control effort of the Contractor is documented by the acceptance procedures of the State Agency.

In practice, the degree of responsibility placed on the Contractor and the amount of acceptance sampling and testing performed by the State Agency will probably vary in proportion in different States and for different types of materials and construction. The economic effects of five possible combinations of Contractor Quality Control effort and State Agency acceptance procedures are compared in the following section.

B. COMPARISON OF FIVE SYSTEMS OF QUALITY ASSURANCE

The economic effect of assumption of responsibility for Quality Control by the Contractor will depend upon the degree of control relinquished by State Agencies. Five Quality Assurance Systems are described for purposes of comparison and evaluation.

1. The Existing System (System No. 1)

Under the existing system, State Agencies exercise, in general, process control of the Contractor's materials and construction. The State Agencies further perform testing for acceptance of materials and construction except

Table VII-1

ESSENTIALS OF COMPLETE SPECIFICATION ACCEPTANCE PLAN
(Based on Statistical Concepts)

1. Size of LOT.
2. Point of Random Sampling.
3. Method of Sampling.
4. Size of Sample (number of measurements or test portion).
5. Method of Test or Measurement.
6. Target (desired) Value of Measured Characteristic.
7. Realistic Tolerance(s) on Target Value.
8. Required Percentage Within Tolerance(s).
9. Method of Computing Percentage Within Tolerance Limits (PWL).
10. Action to be Taken in Case of Substantial Compliance or Non-Compliance with Requirements.
    (a) Reduction in Price.
    (b) Rejection (non-acceptance) or Removal and Replacement.

for a few materials which may be accepted by Producer's or manufacturer's certification. The existing system, with very few minor exceptions, has none of the attributes associated with the system of Statistical Quality Assurance previously described. The total engineering cost has been estimated by two State Agencies to be about 10 percent of the cost of construction financed under the Federal Aid system. In the absence of other information this figure of 10 percent has been used as an estimate of cost to State Agencies for combined functions of process control and acceptance testing.

2. Quality Assurance by Contractor and Monitoring by State Agency (System No.2)

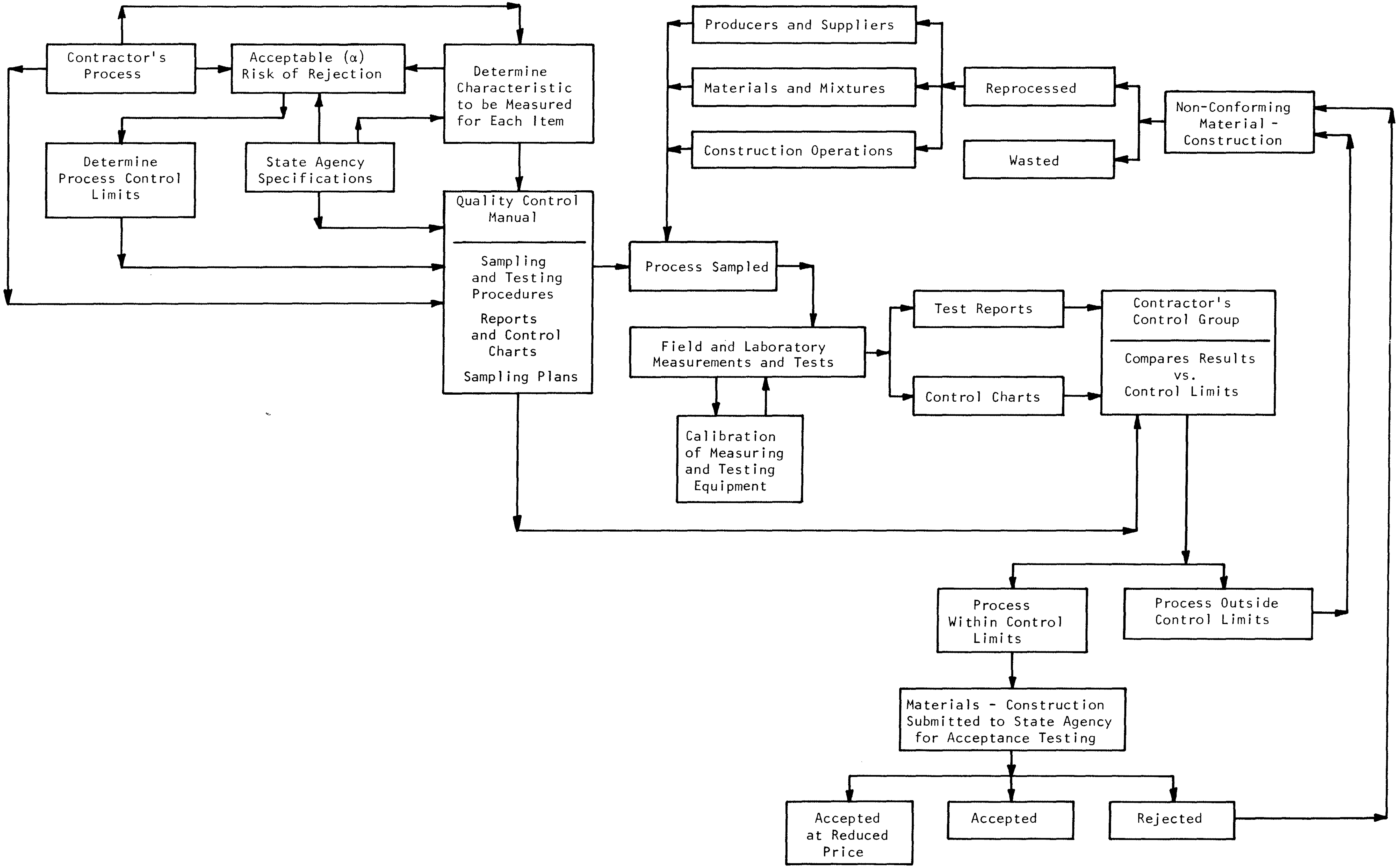
This system of Quality Assurance by the Contractor with monitoring by the State Agency would conform to the Quality Assurance requirements outlined above in Section VII-A of this report. In this system, the Contractor would establish a Quality Control organization staffed with trained and qualified technicians. The State Agency would prescribe the minimum Quality Control activities of the Contractor and monitor the Quality Control procedures but would, in effect, accept practically all materials and construction on certification. Certification would be documented by the Contractor's test reports and control charts. Typical Contractor's Quality Control requirements, as defined in the specifications, are shown in Appendix C. One form of a Contractor's Process Quality Control System is shown schematically in Figure VII-1. This flow chart presents the major elements essential to a process control system.

Properly administered, this procedure should result in a possible reduction of Quality Assurance costs by up to an estimated 4 percent of construction costs as discussed in Section VII-F of this report.

In some cases, the Contractor's and his supplier's Quality Control procedures at source would be more or less continuously under the surveillance

Figure VII-1

CONTRACTOR'S PROCESS QUALITY CONTROL



of a representative of the State Agency. The advantage of this arrangement would be that the State Agency representative could certify as to outgoing quality and provide the supplier protection from possible Contractor claims that materials were not satisfactory.

3. Quality Assurance by Contractor and Acceptance Testing by State Agency (System No. 3)

This system of Quality Assurance is essentially the same as described for System No. 2, but, in addition to monitoring the system, the State Agency would, in most cases, only accept materials on the basis of their acceptance tests. The Contractor would have complete responsibility for producing material and construction of specified quality. He would maintain an approved Quality Control system that would provide assurance that all materials and construction offered for acceptance meet contract requirements. The State Agency would check the adequacy of the Quality Control system and perform acceptance testing as required. Savings in Quality Assurance costs up to 2 percent of construction costs are estimated to be possible under this system.

4. Quality Assurance by State Agency (System No. 4)

Some State Agencies may prefer to assume responsibility for all process control and acceptance procedures using statistically derived Quality Control methods, specifications, and acceptance plans. Since this would probably involve some increase in testing frequency over current levels, this procedure could result in an estimated 2 percent increase in cost of the existing system.

This system of process control of the Contractor's operations by the State, followed by conditional acceptance of the material or construction has all the problems and difficulties (legal, moral, and technical) associated with the existing system. However, use of specifications and acceptance plans based on statistical concepts, as previously described, would be more realistic and legally defensible than the current specifications.

The end result of this system would be a better knowledge of as-built quality, but this approach would not accomplish the purpose of properly placing responsibility on the Producer, Supplier, or Contractor.

5. Quality Assurance Performed by Both Contractor and State Agency

This system would be similar to System No. 2 where the Contractor was required to have a Quality Control system, but the State Agency conducted an independent testing program, and in effect, duplicated the Quality Control work. This would double the testing effort required and could result in an estimated six percent increase in cost over the current system. However, as discussed later, this system's effectiveness or its relative Quality Assurance is the greatest of all the systems discussed due to the increased testing effort.

C. COST EFFECTS OF QUALITY CONTROL BY PRODUCERS AND CONTRACTORS

1. Cost of Coordinated Quality Control for Bituminous Hot-Mixed Plant

Upon the initial assumption of Quality Control by Producers and Contractors, no reliable Quality Control records would be available and acceptance by the State Agency would be based on discovery sampling. Combined Contractor and State Agency personnel would be high during this period but would decrease as quality history was accumulated.

As a specific example, assume a bituminous hot-mix plant, without automatic print-out, in continuous production of binder and surface mixtures with an average daily volume of 800 tons having a value of $5.50 FOB plant.

Producer's Quality Control, as specified by State Agency, would require a sampling frequency of one stability test per 200 tons, 3-bin uniformity tests per day, one combined aggregate analysis per day, two asphalt extraction tests per day, maintain X, $\overline{X}_5$, and R control charts and ledger.

It is assumed that the stability and Bulk specific gravity (B.s.g.) tests would be the primary means of process control and that any significant changes in their values would be cause for immediate corrective action.

Plant costs to Producer

2 Technicians @ $30 per day		$60
Equipment & Supplies		15
	Total	$75 per day

$0.094 per ton or approximately 1.7 percent of product value.

During initial operations, two State Agency technicians would be required to document quality by discovery sampling and to perform independent tests. In addition, one checker would be required to monitor plant operations and document quantities.

Daily plant costs to State Agency

Checker and 2 Technicians @ $25		$75
Transportation		15
Supervision		6
	Total	$96

$0.12 per ton or approximately 2.2 percent of product value.

Total initial cost of Quality Assurance would be $0.21 per ton or 3.9 percent of value of product FOB plant.

After a period of initial operation, establishing control charts and certification of technicians, State Agency personnel would be reduced to one checker and a monitoring of one test series per day by State Agency technician. The State Agency would accept last moving average of five test results including monitored test, as test result for record. State Agency cost would be \$35 per day and total Quality Assurance cost would be about \$0.14 per ton (\$0.094 Producer + \$0.044 State Agency) or 2.5 percent of value of product FOB plant.

In the case of an automatic plant with automatic print-out accepted as documentation of quantity, the State Agency checker could be eliminated. The overall cost of Quality Assurance would then be about \$0.10 per ton or 1.8 percent of value of product.

2. <u>Effect on Bid Prices</u>

Very few of the representatives of the concerns contacted would give an estimate of the effect of assumption of responsibility on bid price. General opinion was that bid prices would probably be increased initially by large and intermediate size Producers. This would be more as a protection against reduced payment schedules and unknown contingencies than for the purpose of recovering testing costs. Small Producers believed that they would have to raise prices and might be forced out of the bidding on projects requiring Quality Control.

The estimates that were obtained are probably not very realistic due to unfamiliarity on the part of the persons interviewed with the actual cost of Quality Control at the required level of effort. These estimates were \$0.01 to \$0.20 per ton for hot-mix, \$0.10 to \$0.50 per cubic yard for ready-mixed concrete. No estimate could be obtained for earthwork or base construction.

To obtain more definite cost figures, the following hypothetical situations have been used as the basis for independent estimates of the cost of Quality Control to suppliers of various highway materials and products. Sampling frequencies have been estimated on the basis of available information and the variability of the measurements.

Hot-Mix Asphaltic Paving Mixtures

The plant cost of Quality Control to the Producer have been previously estimated to be $75 per day. Field control would require one technician to supervise compaction, check surface smoothness, take five density specimens each day, test at plant laboratory, and maintain control chart on percent pavement voids.

Cost to the Contractor

1 Technician @ $30 per day	$30
Equipment & Transportation	15
Total	$45

$0.056 per ton = approximately 1.01 percent of value of product.

The total cost of plant and field Quality Control to the hot-mix Producer would be approximately $120 per production day or about 2.7 percent of product value.

Construction Aggregates

Assume production of 2000 tons coarse aggregate per day at $2.80 per ton and 500 tons fine aggregate per day at $2.80 per ton. Testing frequency would require one gradation test per 200 tons of coarse aggregate and one gradation test per 500 tons of fine aggregate plus percent minus No. 200.

Plant costs to Producer

2 Technicians @ $30	$60
Equipment, Supplies, Transportation	20
Total	$80

$0.03 per ton = approximately 1.1 percent of product value.

Ready-Mix Concrete

Assume 800 cubic yards per day at $15 per cubic yard. Sampling frequency is one test (3 cylinders, percent air, slump) per 100 cubic yards plus tests of yield, aggregate gradation, and fine aggregate moisture. Cylinders are capped and tested at plant laboratory.

It is assumed that early test (1 cylinder per 100 cubic yards of each class of concrete) would be the primary means of process control with verification by 28-day tests. Laboratory equipment amortized over 10 years.

Plant costs to Producer

4 Technicians @ $30	$120
Equipment, Supplies, Transportation	60
Total	$180

$0.225 per cubic yard or 1.5 percent of value of product.

The above are net cost estimates and do not include overhead, profit, added insurance costs, or allowances for dead time when plant is not producing material for which Quality Control is required. It is estimated that these factors would double the Producer's actual costs for Quality Control. The possible increase in bid price would probably be about one to two percent of bid price. However, it is quite probable that the Producer's Quality Control system would be self-liquidating in several years and an increase in bid prices would no longer be required to support the Quality Control system. There is evidence as previously discussed, that an efficiently managed, technically competent Quality Control system will not only pay its own way but will save money due to reduced shut-downs, reduced wastage, and sales benefits on private work. Even if the potential savings, due to the Producer's Quality Control does not materialize, the possible increase in bid prices would be offset by a reduction in personnel of the State Agency.

3. Effect of Coordinated Quality Control on Costs of Acceptance Sampling

The Buyer's (β) and Seller's (α) risks of making acceptance decisions based on the sampling practices in general use in the Existing System are compared in Section VI with the risks connected with acceptance plans based on statistical concepts. These tables show, in general, that the risks associated with making an acceptance decision based on the result of a single test of commonly used materials or types of construction are so large as to be unacceptable. They also show that even when decisions are based on the average of a few tests, the risks may be unacceptable when the unknown standard deviation is larger than an assumed or estimated value. These Buyer's and Seller's risks can be controlled by the use of statistically derived sampling plans and specifications.

Statistical sampling plans to determine compliance with the specified limits of measured characteristics of materials or construction may be either of two types. In one case, variability is assumed to be known, in the other, the variability is unknown.

When the variability of the output of a process as measured by the standard deviation of results of tests on the product is unknown, the sampling plan must be of the type illustrated by Table VI-1 where the standard deviation is estimated from differences among a number of tests on independent samples obtained by discovery sampling. Plans of this type require a minimum of four or more tests on which to base a decision with acceptable Buyer's (β) and Seller's (α) risks. This amount of testing may be considered to be impractical due to costs or time and personnel requirements.

When the standard deviation of test results is known, acceptance decisions can be based on the average of a group of test results that is smaller in number than when both the average and the variability must be estimated from the group. The saving in the number of tests required is shown by comparing the number of tests associated with the same risks in Tables VI-1 and VI-2. In general, at least one less test is required when the standard deviation is known and the same degree of risks maintained. Also, the assumption of known variability infers a stable process which is justification for increasing LOT size so that fewer groups of measurements are required for a given quantity of material or construction. Still another advantage of having a reliable estimate of the standard deviation is that the acceptance plan is based on the average of a small group of independent samples rather than on the average and the differences among the group of independent samples as is the case when the standard deviation is unknown. This means that, in many situations, the samples can be averaged by compositing and the acceptance decision can be based on a single test on the composite sample.

The assumption of known variability can only be made when continuous records of the standard deviation of the results of tests on the output of a process show that the variability of the test results remain constant over a period of time. One of the essential requirements of a Coordinated Quality Control System should be that the Contractor or Producer maintain control charts for each measured characteristic. These control charts would serve as the basis for an estimate of the standard deviation as well as providing the State Agency with assurance that the general level of quality was within the specified limits. This assurance would be confirmed by acceptance testing, using sampling plans based on the standard deviation indicated by the control charts. The amount of this acceptance testing would be a minimum consistent with acceptable risks and purposes of record.

Another possible benefit associated with the use of control charts by Producers and Contractors is that the size of the standard deviation currently associated with results of tests on the output of processes producing some materials and items of construction might be greatly reduced. As the interpretation of these charts becomes familiar to the users, it is probable that many currently existing assignable causes of variation can be identified and removed. If the standard deviation associated with a process could be cut in half, it would have a significant effect on the amount of acceptance testing required for the same degree of risk. This is shown in Table VI-3, where four measurements are required to reduce the α (Seller's) risk to 9 percent and the β (Buyer's) risk to 25 percent when the standard deviation of the measurements is 0.6. If the standard deviation could be reduced to 0.3, only one test would be required on which to base an acceptance decision with these same risks.

In theory, the most economical amount of testing is given by the decision function Equation (4)

$$n = 0.54 \left(\frac{\ell\sigma}{c}\right)^{\frac{2}{3}}$$

ℓ = the loss, in dollars, resulting from a unit deviation from the desired value.

σ = the standard deviation of individual measurements

n = the number of measurements made on the LOT

c = the cost of each measurement

If (ℓ) and (c) remain constant or (K), the number of tests (n) would be

$$n = \sigma^{\frac{2}{3}}(K)$$

A reduction in the size of σ from 8 to about 5.2 would result in the reduction in the required number of measurements from $n = 4$ to $n = 3$, a saving of 25 percent in the amount of testing required by this approach.

D. EFFECT ON PERSONNEL REQUIREMENTS OF A COORDINATED SYSTEM OF QUALITY CONTROL

A System for Coordinated Quality Control of highway materials and construction would require personnel at several levels of training and competency. A

Quality Control Engineer will be required at State Agency administrative level to check and analyze data immediately on receipt. This engineer would have the responsibility of keeping all data records updated and making sure that all project records were complete with respect to reliable information that could be used for future reference. An appropriate computer program would be of value for this purpose.

Under the Quality Control Engineer would be a number of engineers or senior technicians who were expert in sampling and testing procedures and were also versed in the basic statistical methods used in Quality Control work. Each of these engineers or technicians would audit field personnel with respect to random sampling and testing procedures, analyses of data, record keeping, and the establishing and maintenance of control charts. They would be responsible for the prompt transmission of data to the Quality Control Engineer.

Below this level, technicians would be required at material plants and at the construction site to sample and test materials and construction. Currently employed inspection and testing personnel might serve in this capacity, but would need special training in the principles of random sampling and indoctrination in the objectives of Quality Control. Whether these personnel were employed by the State Agency or by a Producer or Contractor would depend upon the degree to which responsibility for Quality Control was relinquished by the State Agency. Representatives of some States have expressed the opinion that, although they are in favor of adopting Quality Control principles and procedures, they would prefer to handle the work with their own forces. On the other hand, several of the large Producers and Contractors interviewed believed that they could handle the work more efficiently with employees on their own payroll. If they were required to assume total responsibility, they would establish a central laboratory and a small nucleus of trained technicians under a Quality Control Engineer. This task force, with some assistance from plant and site personnel would handle the Quality Control work at several plants and construction sites, replacing the total number of State Agency personnel currently stationed at each location. This would result in a considerable reduction in overall cost.

The assumption of responsibility for Quality Control would, to some degree, work a hardship on the small Producer or Contractor. Some of those interviewed expressed the opinion that it would put them out of business. Since their operations are not sufficiently extensive or continuous to justify permanent employment of technicians, they would be forced to hire technicians from private testing laboratories. This would be expensive and would place them in an unfavorable bidding position. However, several Producers with moderate size operations believed that they could train some of their permanent employees to handle the Quality Control work and some were currently taking advantage of available training programs by sending their employees to these classes on a rotating basis.

During the initial transfer of responsibility, it is probable that the State Agency would maintain their customary plant inspection and discovery sampling or spot checking. This would lead to a temporary excess of personnel and duplication of effort which would be eliminated when Producer or Contractor technical personnel were judged competent and reliable.

In cases where the State Agency conducted the Quality Control work there would probably be no change in personnel providing that efficiency was up-graded to compensate for the sampling frequency required for effective Quality Control. For some types of tests, this increase in efficiency could result from the use of equipment currently available or under development that provides quick test results.

In general, it is the opinion of the Research Agency that adoption of a Coordinated System of Quality Control and the total transfer of responsibility to Producers and Contractors would result in a reduction of overall personnel requirements. Intermediate degrees of relinquishment of control by State Agencies would result in about the same number of total personnel or in a temporary increase.

A temporary shortage of trained personnel is anticipated by both industry and State Agency representatives, particularly in the area of statistical methods of sampling and analysis of data. This condition could be ameliorated by the generation of suitable training material.

E. PROBABLE EFFECTS ON END PRODUCT

The information obtained by interview in the course of this study and theoretical considerations indicate that the effects of assumption of Quality Control by Producers and Contractors would result in better highways with lower maintenance costs due to more uniform quality. Although the average level of quality of good construction is generally considered satisfactory under current acceptance procedures, maintenance costs for relatively small areas may be incurred due to variations in quality that are not detected by the present inspection system. The maintenance of control charts by the Producer or Contractor would not only provide a measure of average quality but would also record the amount of variability which could be related to future maintenance requirements.

Control charts, properly established and maintained by unbiased sampling and testing, would also provide a better basis for evaluating design-performance relationships than do the current construction control records. These as-built records could, in some instances, indicate areas where specification requirements could be relaxed with more efficient use of available materials and with resulting economic benefits.

F. TOTAL COST OF QUALITY ASSURANCE SYSTEMS

Estimates of comparative costs for the previously described Quality Assurance systems are shown in Table VII-2. Total engineering costs including the cost of the Quality Control and acceptance testing by State Agencies has been estimated to be 10 percent of contract price. This estimate is based on information secured from two State Agencies. A literature search has indicated that this percentage of cost of product for Quality Assurance has been approximated in some industries.[5][6]

The cost to the Contractor and his suppliers of maintaining an adequate Quality Control program, including all testing, inspection, and administration has been estimated at 4 percent. This figure is based on an actual testing cost of 2 percent projected from current testing costs of Contractors and Producers at the present level of effort. This direct cost has been increased by 100 percent to cover overhead costs such as administration, insurance, taxes, fringe benefits, profit, and periods of unproductive time for technical personnel. This last cost is difficult to estimate since it would largely depend on the continuity of contract work for which Quality Control was required.

Costs for systems where Quality Assurance is obtained by coordinated effort of the Contractor and the State Agency are estimated from the two base costs modified by estimates of the proportional Contractor-Agency effort.

Estimates of comparative dollar costs for different Quality Assurance systems are shown in Table VII-3. These estimates were derived by multiplying the total quantities and weighted prices of major bid items reported by the Bureau of Public Roads in Highway Statistics, 1968, by the estimated Quality Control percentage costs shown in Table VII-2. The figures shown in Table VII-3 are estimates but they are relevant for comparison purposes.

Table VII-3 indicates that Quality Assurance System No. 2 has the lowest cost followed closely by System No. 3 and then in increasing order of cost

Table VII-2

ESTIMATES OF COMPARATIVE COST

OF FIVE DIFFERENT QUALITY CONTROL SYSTEMS:

COST EXPRESSED IN PERCENTS OF CONTRACT PRICE

System Number	Type of System	Contractors	State	Total
1	Existing System	0	10	10
2	Quality Control by Contractor and Monitoring by State Agency	4	2	6
3	Quality Control by Contractor and Acceptance Testing by State Agency	4	4	8
4	Quality Control by State Agency	0	12	12
5	Quality Control Performed by Both Contractor and State Agency	4	12	16

Table VII-3

COMPARISON OF RELATIVE COSTS OF FIVE QUALITY CONTROL SYSTEMS[a]
FOR MAJOR ITEMS OF HIGHWAY CONSTRUCTION

		Contractor		State		Total		Total Cost Changes	
System Number	Type of System	Percent (b)	Dollars (thousands)	Percent (b)	Dollars (thousands)	Percent (b)	Dollars (thousands)	Change (c)	Percent Change (c)
1	Existing System	0	- - - -	10	212,741	10	212,741	- - - -	- - -
2	Quality Control by Contractor and Monitoring by State Agency	4	85,096	2	42,548	6	127,644	-85,097	-40.0
3	Quality Control by Contractor and Acceptance Testing by State Agency	4	85,096	4	85,096	8	170,192	-42,549	-20.0
4	Quality Control by State Agency	0	0,000	12	255,289	12	255,289	+42,548	+20.0
5	Quality Control Performed by Both Contractor and State Agency	4	85,096	12	255,289	16	340,385	+127,644	+60.0

Notes: (a) Source: Highway Statistics, 1968, Bureau of Public Roads, Table PT-3.

(b) For Percents, see Table VII-2.

(c) All changes are computed relative to the Existing System. A negative sign indicates a reduction; a positive sign indicates an increase.

System Nos. 1, 4, and 5. Comparison figures for the five systems, using System No. 1 Existing System as a base, are shown in the last two columns of the Table. The cost of System Nos. 2 and 3 are 40 percent and 20 percent respectively less than the cost of the Existing System. System Nos. 3 and 4 are comparatively estimated to cost 20 percent and 60 percent more than the Existing System, however, the degree of Quality Assurance obtained by the different systems is not related to cost alone as discussed below.

Estimates of comparative dollar cost on a State basis for the five different Quality Assurance systems are shown in Table VII-4. In this table, costs for the five Quality Assurance systems are estimated for the relatively largest State in terms of Interstate highway expenditures, for the relatively smallest State and for a ficticious State that would be median in Interstate highway construction. Since the same cost multipliers were used, the relative savings in Quality Assurance costs among the five systems are the same as in Table VII-3.

1. <u>Cost-Effectiveness Analysis</u>

A cost-effectiveness study was made to compare the different systems of Quality Control in terms of relative value received with the potential estimated cost. The result of the analysis is shown in Table VII-5.

The probability of obtaining the specified quality (P) used in the analysis is based primarily on the amount of testing performed under the different systems but weighted by such factors as Contractor or Producer motivation and incentive and the potential maximum utilization of the Quality Control findings. The relative cost of the Quality Assurance program was determined for the cost of major items of highway construction and the median expenditure for Interstate construction as shown in Tables VII-3 and VII-4, respectively.

Table VII-4

COMPARISON OF RELATIVE COSTS OF FIVE QUALITY CONTROL SYSTEMS[a]
FOR MAJOR ITEMS OF HIGHWAY CONSTRUCTION BY SELECTED STATES

System Number	Type of System	Contractor		State		Total		Total Cost Changes	
		Percent	Dollars (thousands) (b)	Percent	Dollars (thousands) (b)	Percent	Dollars (thousands) (b)	Change (c)	Percent Change (c)
		0	0,000	10	23,497	10	23,497		
1	Existing System				3,549		3,549		
					439		439		
2	Quality Control by Contractor and Monitoring by State Agency	4	9,399	2	4,699	6	14,098	-9,399	-40.0
			1,419		710		2,129	-1,420	
			176		88		264	- 175	
3	Quality Control by Contractor and Acceptance Testing by State Agency	4	9,399	4	9,399	8	18,798	-4,699	-20.0
			1,419		1,419		2,838	- 711	
			176		176		352	- 87	
		0	0,000	12	28,196	12	28,196	+4,699	+20.0
4	Quality Control by State Agency				4,259		4,259	+ 710	
					527		527	+ 88	
5	Quality Control Performed by Both Contractor and State Agency	4	9,399	12	28,196	16	37,595	+14,098	+60.0
			1,419		4,259		5,678	+ 2,129	
			176		527		703	+ 264	

Notes: (a) Source: Highway Statistics, 1968; Bureau of Public Roads, Table FA-41, (65.3 Percent of Total Expenditures per Note 1, Table PT-3).

(b) The first figure is for the state with highest expenditures (California). The second figure represents median expenditures. The third figure is for the state with lowest expenditures (Delaware).

(c) All changes are computed relative to the Existing System. A negative sign indicates a reduction; a positive sign indicates an increase.

Table VII-5

COMPARISON OF RELATIVE COST EFFECTIVENESS OF FIVE QUALITY CONTROL SYSTEMS

System Number	Type of System	Probability of Obtaining Specified Quality (P)	Major Items of Highway Construction[a]: Total Cost Dollars (thousands)	Major Items of Highway Construction[a]: Relative Cost Quality Control (c)	Interstate Highway Construction[b]: Total Cost Dollars (thousands)	Interstate Highway Construction[b]: Relative Cost Quality Control (c)
1	Existing System	0.70	213,000	63,900	3,500	1,050
2	Quality Control by Contractor and Monitoring by State Agency	0.90	128,000	12,800	2,100	210
3	Quality Control by Contractor and Acceptance Testing by State Agency	0.93	170,000	11,900	2,800	196
4	Quality Control by State Agency	0.85	255,000	38,250	4,300	645
5	Quality Control Performed by Both Contractor and State Agency	0.95	340,000	17,000	5,700	285

Notes: (a) Relative total cost (rounded) from Table VII-3.

(b) Relative total costs (rounded) from Table VII-4, median expenditure.

(c) Relative cost in dollars (thousands) = total cost x (1.00 - P).

This analysis indicates that the effort of the Contractor or Producer in primary control of the construction or product, coordinated with the effect of the State Agency in verifying quality levels by acceptance testing (System No. 3) would be most nearly optimum. However, since this analysis is partly subjective, use of this system as opposed to Contractor Quality Control with monitoring by the State Agency (System No. 2) is not definitely indicated, and the use of either system would probably depend on the type of product or construction. The interrelationships between the Contractor and the State Agency for the optimum Quality Assurance system are shown in Table VII-2. The details of the Contractor's Quality Control system are shown in Figure VII-2. A comparison of the other systems is shown in Table VII-7 in which the systems are ranked in terms of cost-effectiveness by ascending relative cost. It is of interest to note that although Quality Assurance System No. 5 has the highest estimated comparative cost, it is ranked third in cost-effectiveness. Quality Assurance by the State Agency (System No. 4) is the least desirable of the systems utilizing statistical control procedures. The Existing System has the highest relative cost and is ranked last.

A Sensitivity Test made by substituting the relative dollar values from Tables VII-3 and VII-4 and scale values of the Probability of Obtaining Specified Quality (P) indicate that the order of ranking of the cost-effectiveness of the five systems is not affected by these factors.

Figure VII-2

OPTIMUM QUALITY ASSURANCE SYSTEM

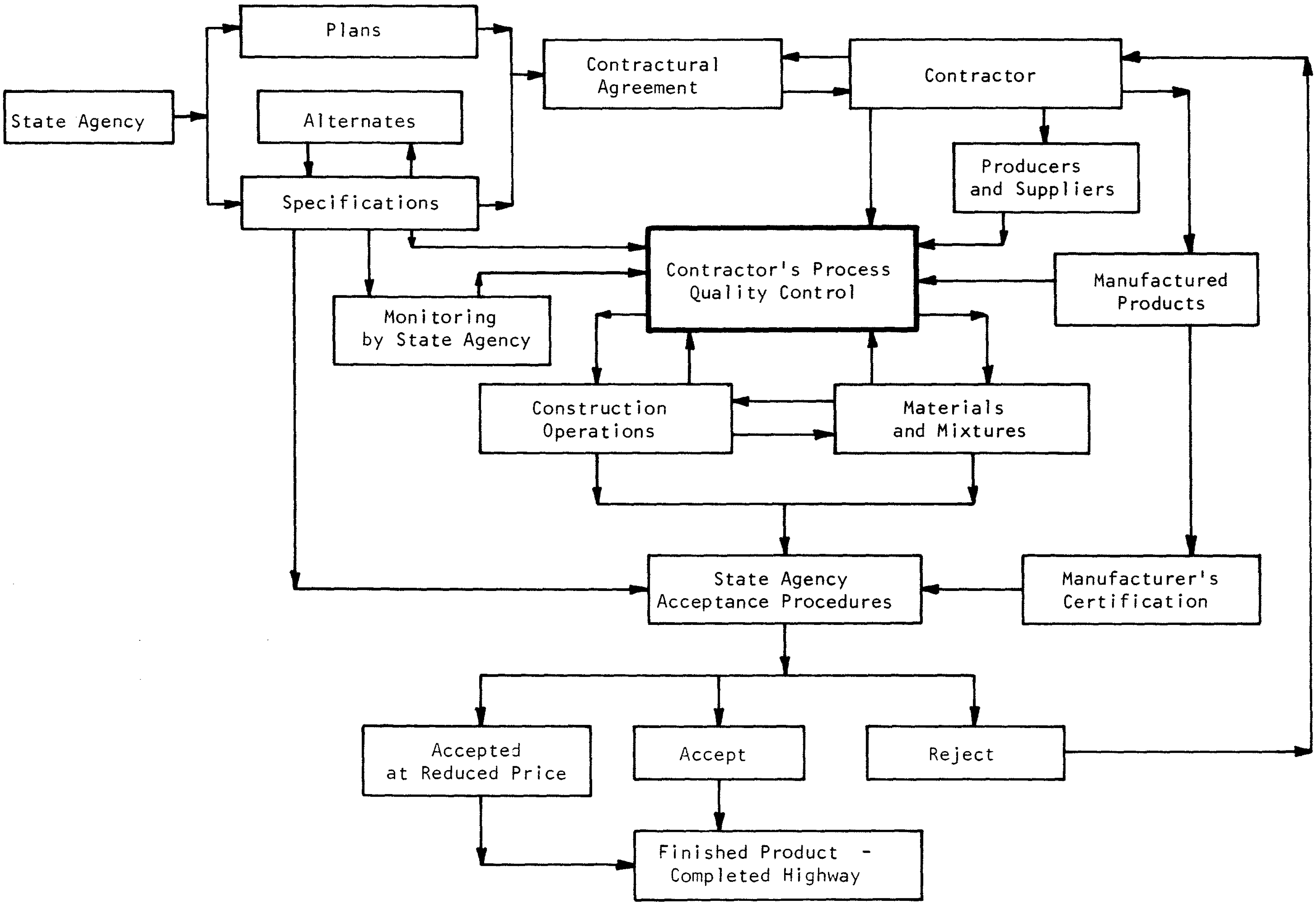


Table VII-7

COST-EFFECTIVENESS RANKING

OF FIVE QUALITY CONTROL SYSTEMS

Relative Cost Rank	Type of System	System Number
1	Quality Control by Contractor and Acceptance Testing by State Agency	3
2	Quality Control by Contractor and Monitoring by State Agency	2
3	Quality Control Performed by Both Contractor and State Agency	5
4	Quality Control by State Agency	4
5	Existing System	1

VIII CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The investigations and analyses of data made in connection with the accomplishment of the objectives of this research indicate that:

1. The adoption of a Coordinated System of Quality Assurance by the highway industry is economically feasible;
2. The system providing the most cost-effective benefits would be Statistical Quality Control by the Contractor with acceptance testing by the State Agency;
3. Placing responsibility for maintaining Statistical Quality Control on the Contractor would probably result in an initial small increase in bid price and in overall Quality Assurance costs. The increase in bid price would be minimized and dollar benefits obtained when Contractor and State Agency efforts are fully coordinated;
4. A Coordinated Quality Control System would require an increase in technical personnel indoctrinated in Statistical Quality Control principles. Total personnel, Contractor plus State Agency should be less, and will not exceed present levels;
5. Properly maintained Contractor Quality Control records will provide reliable information with respect to as-built conditions. This information will also be of value in establishing realistic specification limits, and determining optimum

LOT size and acceptance testing frequency compatible with desired Buyer's and Seller's risks;

6. Efficient operation of Quality Control systems should result in the elimination of assignable causes of large variations of measurements. The increase in uniformity should make possible more accurate design-performance relationships;

7. Elimination of assignable causes and attaining a state of Statistical Control in Contractor and Producer processes will result in a reduction of acceptance testing frequency and costs, while maintaining acceptable levels of Buyer's and Seller's risks; and

8. General acceptance of the concepts of Contractor Quality Control and statistical acceptance procedures by the highway industry will require intensive educational effort. This effort must be comprehensive with respect to all levels of industry and State Agency personnel.

B. RECOMMENDATIONS

1. To avoid hardship on the part of small contracting or producing concerns, Quality Control requirements should initially apply to large contracts only.

2. Resistance to the adoption of statistical acceptance procedures should be minimized by initially suspending enforcement of provisions for reduction in price for material or construction not in full compliance with specification requirements.

3. Prior to requiring transfer of responsibility for Quality Control to Contractors and Producers, they should be made fully aware of the advantages and disadvantages of the change of responsibility by an indoctrination program.

Suggested methods of indoctrination include:

a. Articles in trade publications including simple illustrations of statistical concepts to highway construction situations;

b. Packaged lectures to be given before meetings of local groups of Contractors and Producers;

c. Papers to be presented before national meetings of Trade Associations; and

d. A task-oriented statistical manual available for use by lower echelon Contractor and State Agency personnel.

4. To hasten the adoption of Statistical Quality Control procedures the use of rapid test methods now available and under development should be encouraged in construction research projects.

APPENDIX A

INTERVIEW OUTLINE

APPENDIX A

MATERIAL PRODUCERS CURRENTLY
USING PROCESS CONTROL

INTERVIEW OUTLINE
BPR'S CONTRACT NO. FH-11-7272
ECONOMIC FEASIBILITY OF QUALITY CONTROL

BY ______________________ DATE ______________

COMPANY ______________________________________

ADDRESS ______________________________________

______________________ PHONE ______________

PERSON CONTACTED ______________ TITLE ______________

NO. PERSONNEL ______________________________________

TYPE OF TESTS ______________________________________

TESTING FREQUENCY ______________________________________

SAMPLING PLAN ______________________________________

Written Instruction or QC Manual ______________________

RECORDS

Time Covered ______________________________________

Ledger ______________________________________

QC Charts ______________________________________

USE OF DATA

Corrective Action ______________________________

Quality History ______________________________

ANNUAL DOLLAR VOLUME OF PRODUCT(s) ______________________________

ANNUAL COST OF QC

Direct ______________________________

Indirect ______________________________

Total ______________________________

BENEFITS OF QC

Dollar Benefits ______________________________

Production Cost Savings ______________________________

Reduced Rejections ______________________________

Reduced Shut-Down Time ______________________________

More Prompt Payment (Interest Costs) ______________________________

Bonding Costs ______________________________

Total Estimated Dollar Benefits ______________________________

INTANGIBLE BENEFITS

Customer Satisfaction ______________________________

Increased Sales ______________________________

Legal Evidence ______________________________

Other ______________________________

PROBLEMS

Initial ______________________________

Current ______________________________

PERMISSION TO IDENTIFY DATA ______________________________

COMMENTS:

APPENDIX A

CONSTRUCTION CONTRACTORS

INTERVIEW OUTLINE

BPR CONTRACT NO. FH-11-7272

ECONOMIC FEASIBILITY OF QUALITY CONTROL

BY ______________________ DATE ______________________

NAME OF COMPANY AND ADDRESS ______________________ PHONE ______________________

PERSON INTERVIEWED ______________________ TITLE ______________________

TYPE OF CONSTRUCTION ______________________

CURRENT SPECIFICATION ______________________

ACCEPTANCE PROCEDURE

Type of Tests ______________________

Sampling Procedure

Systematic ______________________

Random ______________________

Judgment ______________________

Reference Standard

Tests By ______________________

Acceptance By ______________________

Quantity of Construction Accepted or Rejected ______________________

Action Taken on Failing Tests ______________________

Procedure Satisfactory ______________________

Disadvantages ______________________

HYPOTHETICAL SITUATION UNDER CONTRACTOR PROCESS CONTROL

REALISTIC SPECIFICATION LIMITS BASED ON RANDOM SAMPLING OF SATISFACTORY CONSTRUCTION

REALISTIC REFERENCE STANDARDS SUCH AS CONTROL STRIP FOR COMPACTION

USE OF RANDOM SAMPLING

SUFFICIENT NUMBER OF TESTS TO MINIMIZE BUYER'S AND SELLER'S RISKS

LOT-by-LOT Acceptance ____________________

DOLLAR COSTS (FIXED)

Laboratory ____________________

Test Equipment ____________________

DOLLAR COSTS (ANNUAL)

Personnel ____________________

Records

Ledger ____________________

Charts ____________________

ASSUMPTION OF RESPONSIBILITY

Design and Control of Mixtures ____________________

Choice of Equipment ____________________

ADVANTAGES

Early Acceptance or Rejection of Relatively Small Quantities of Construction

Opportunity to Take Early Corrective Action ______

Less Risk of Withholding of Payment

Reduced Interest ______

Funds Not Tied Up ______

Handling Costs ______

Freedom of Action ______

DISADVANTAGES

Cost of Process Control ______

Increased Responsibility ______

Unknown Factors ______

ANNUAL DOLLAR VOLUME OF CONSTRUCTION ______

POTENTIAL INCREASED COST ______

POTENTIAL SAVINGS ______

EFFECT ON BID PRICE ______

PERMISSION TO IDENTIFY ______

APPENDIX B

CONTRACTORS AND PRODUCERS CONTACTED

APPENDIX B

CONTRACTORS AND PRODUCERS CONTACTED

Name	Location
Hilltop Concrete Corporation	Ohio
Hi-Way Paving, Inc.	Ohio
Nello L. Teer Company	North Carolina
Ohio River Sand & Gravel Company	West Virginia
Graniterock	California
Teichart Aggregates	California
Pacific Cement & Aggregates	California
Tri-County Asphalt	New Jersey
H. T. Campbell Corporation	Maryland
Vulcan Materials Company	Virginia
Vulcan Materials Company	Alabama
Houdaille Construction Materials, Inc.	New Jersey
Arundel Corporation	Maryland
Trap Rock Industries Inc., & Affiliates	New Jersey
Criss Concrete Company	West Virginia
Southern Materials, Inc.	Virginia
Criss & Shaver, Inc.	West Virginia
Anderson Concrete Corporation	Ohio
Denton Construction Company	Michigan
Clawson Concrete Company	Michigan
Kuhlman Builders Supply & Brick Company	Ohio
Highway Materials, Inc.	Pennsylvania
Black Rock Contracting	West Virginia
Thompson Arthur Paving	Virginia
Marvin V. Templeton & Sons	Virginia
Columbia Bituminous Concrete Company	Ohio
Freeman-Sondgroth Construction Company	California
Sloan Construction Company	South Carolina

CONTRACTORS AND PRODUCERS CONTACTED
(Continued)

Name	Location
T. L. James & Company	Louisiana
Harbert Construction Company	Alabama
Jutton-Kelly Company	Michigan
Gordon H. Ball, Inc. Northern Division	California
Schuykill Products, Inc.	Pennsylvania
New Enterprise Stone & Lime Company, Inc.	Pennsylvania
Prestressed Concrete Products Company	Louisiana
Centurial Products Corporation	West Virginia
Reliance Universal, Inc.	Ohio
Spartanburg Concrete Company, Inc.	South Carolina
Lehigh Cement Company	Pennsylvania
Chevron Asphalt	Maryland
Ballenger Corporation	South Carolina
Wright Contracting Company	Georgia
Bituminous Surface Treating Company	Minnesota
The General Crushed Stone Company	Pennsylvania
Industrial Asphalt	California
H. L. Baughman Transit-Mix Corporation	New York
Buffalo Slag Company, Inc.	New York
Manitou Construction Company, Inc.	New York
Pine Hill Concrete Mix Corporation	New York

STATE HIGHWAY AGENCIES CONTACTED

Name	Location
California Division of Highways	California
Louisiana Department of Highways	Louisiana
Mississippi State Highway Department	Mississippi
North Carolina State Highway Commission	North Carolina
Pennsylvania Department of Highways	Pennsylvania
Ohio Department of Highways	Ohio
Virginia Department of Highways	Virginia
South Carolina State Highway Department	South Carolina
West Virginia Department of Highways	West Virginia
New York Department of Transportation	New York

TRADE ASSOCIATIONS CONTACTED

The Asphalt Institute	Maryland
Louisiana Asphalt Pavement Association	Louisiana
National Asphalt Pavement Association	Texas
National Crushed Stone Association	Washington, D. C.
National Slag Association	Virginia
National Sand & Gravel Association & National Ready-Mixed Concrete Association	Maryland
The Ohio Sand & Gravel Association	Ohio

RESEARCH AGENCIES CONTACTED

Virginia Council of Highway Research & Investigation	Virginia

APPENDIX C

CONTRACTOR'S QUALITY CONTROL REQUIREMENTS

A. SCOPE

The Contractor shall provide and maintain a Quality Control system that will provide reasonable assurance that all materials, products, and items of construction submitted to the Agency for acceptance conform to the contract requirements whether manufactured or processed by the Contractor or procured from suppliers or subcontractors. The Contractor shall perform or have performed the inspection and tests required to substantiate product conformance to contract requirements, and shall also perform or have performed all inspections and tests otherwise required by the contract. The Contractor's Quality Control inspections and tests shall be documented and shall be available for review by the Agency throughout the life of the contract.

B. DOCUMENTATION

The Contractor shall maintain adequate records of all inspections and tests. The records shall indicate the nature and number of measurements made, the number and type of deficiencies found, the quantities approved and rejected, and the nature of the corrective action taken as appropriate. The Contractor's documentation procedures will be subject to the review and approval of the Agency prior to the start of the work and to compliance checks during the progress of the work.

1. <u>Charts and Forms</u>

All conforming and non-conforming inspections and test results shall be promptly recorded on approved forms and charts which shall be kept complete and shall be available at all times to the Agency during the performance of the work. Process control procedures and inspection shall be an integral part of the Contractor's inspection system. In addition to the above requirements, the Contractor's Quality Control system shall be documented. Test data for materials or products resulting from continuous processes, such as Portland cement concrete, bituminous concrete or graded aggregates or aggregate mixtures shall be plotted on control charts. The type and format of the chart shall be approved by the Agency. (Details on how to construct one type of a control chart are shown in Table C-1.)

C. CORRECTIVE ACTION

The Contractor shall take prompt action to correct conditions which have resulted, or could result, in the submission to the Agency of materials and products which do not conform to the quality required by the contract.

D. MEASURING AND TESTING EQUIPMENT

The Contractor shall provide and maintain measuring and testing apparatus necessary to assure that the materials and products conform to the contract requirements. In order to assure continued accuracy, the apparatus shall be inspected and calibrated at established intervals against certified standards.

When required, the Contractor's measuring and testing apparatus shall be made available for use by the Agency representative to determine conformance of materials and products with contract requirements. In addition, the Contractor's personnel shall be made available for obtaining and processing samples for operation of such apparatus, and for verification of their accuracy and condition.

E. SAMPLING AND TESTING

The Contractor shall employ only competent and qualified personnel to make all samplings and perform all tests. All sampling, testing and recording activities shall be under the direction and authority of a qualified (certified) Quality Control Technician.

Sampling and testing methods and procedures used by the Contractor to determine quality conformance of the materials and products shall, in general, parallel those used by the Agency for acceptance testing. Alternative sampling methods and procedures and inspection equipment may be used by the Contractor when such procedures and equipment provide, as a minimum, the quality assurance required by the specifications. Prior to applying such alternative inspection procedures, the Contractor shall describe them in a written proposal and shall demonstrate for the approval of the Agency that their effectiveness is equal to, or better than, the contract requirements. In case of dispute as to whether certain procedures of the Contractor's inspection system provide equal assurance, the procedures stipulated by the specifications shall apply.

F. NON-CONFORMING MATERIAL

The Contractor shall establish and maintain an effective and positive system for controlling non-conforming material, including procedures for its identification, isolation, and disposition. Reclaiming or reworking on non-conforming materials or construction shall be in accordance with procedures acceptable to the Agency.

All non-conforming materials and products shall be positively identified to prevent use, shipment, and intermingling with conforming materials and products. Holding areas, mutually agreeable to the Agency and the Contractor shall be provided by the Contractor.

G. AGENCY INSPECTION AT SUBCONTRACTOR'S OR SUPPLIER'S FACILITIES

The Agency reserves the right to inspect materials not manufactured within the Contractor's facility. Agency inspection shall not constitute acceptance nor shall it in any way replace the Contractor's inspection, or otherwise relieve the Contractor of his responsibility to furnish an acceptable material or product. When inspection of a subcontractor's or supplier's product is performed by the

Agency, such inspection shall not be used by the Contractor as evidence of effective inspection or such subcontractor's or supplier's product.

Subcontracted or purchased materials shall be subjected to inspection by the Contractor when received, as necessary, to assure conformance to contract requirements. The Contractor shall report to the Agency any non-conformance found on Agency source-inspected material, and shall require his supplier to take necessary corrective action.

Table C-1

CONTROL CHART FOR INDIVIDUALS AND MOVING RANGE

To start this type of a control chart, plot the value of each measurement* against its sequence identification number, using any convenient scale.

1. As soon as the second measurement becomes available, find the range (R), which is the difference between the two measurements. When the third measurement is available, find another value of R, which is the difference between the second and third measurements. Continue to find R values by computing the difference between each measurement and the one before it.

2. Add each value (X) to the sum of the previous values and divide this accumulated total by the number of values (X's) to get a moving average ($\overline{X}$). This moving average ($\overline{X}$) is the center line for the control chart for individual X's.

3. Add each range (R) to the sum of the previous values and divide this accumulated total by the number of R's to get a moving average range ($\overline{R}$). This moving average range is the center line for the control chart for the moving range (R).

4. Compute the 95% warning limits for individuals (X's) by multiplying each value of $\overline{R}$ by 1.77 and then add and subtract this value from the corresponding value of $\overline{X}$ to get the upper and lower limits.

5. Multiply each value of $\overline{R}$ by 2.51 to get the upper limit of the moving range (R). (Lower limit is 0).

6. Continue to compute $\overline{X}$ and $\overline{R}$ until a sufficient number of measurements (usually about 30) have been accumulated and these values have become stable. Control limits based on these stable values may then be used, without further computation, until some process change takes place.

*A single measurement or the average of two or more companion measurements.

NOTES:

The construction of the control chart, as described above is examplified by the computations shown in Table C-2 and the graphs of Figure C-1. The numbers of successive tests of Bulk specific gravity of Marshall specimens is shown in Col. (1) of Table C-2. The corresponding measurement values are shown in Col. (2).

The first range (R) is the difference between the results of Test Nos. 1 and 2 and is shown in Col. (3). The range (R) between Test Nos. 2 and 3 and the successive ranges fill out the remainder of Col. (3).

The accumulated sum of the test results is shown in Col. (6). Each sum is divided by the number of measurements summed to obtain the moving average ($\overline{X}$) shown in Col. (7). These values are plotted in Figure C-1 to locate the center line on the control chart for individuals.

The accumulated sum of the ranges is shown in Col. (4). Each sum is divided by the number of ranges summed to obtain the moving range ($\overline{R}$). These values are used to locate the center line for the control chart for ranges in Figure C-1.

The values of $\overline{R}$ in Col. (5) are multiplied by 1.77 and the results are added to and subtracted from the corresponding $\overline{X}$. These values are shown in Cols. (8) and (9) and are used to locate the upper and lower 95 percent warning lines on the control chart for individuals. As long as the process is in statistical control, not more than one point in twenty should fall outside these lines.

The values of $\overline{R}$ shown in Col. (5) are multiplied by 2.51 to obtain the values shown in Col. (10). These values are used to locate the upper 95 percent warning line on the control chart for ranges.

If there is no change in sampling and testing procedures $\overline{R}$ should stabilize at a constant value (R') at this point the control chart for ranges may be discontinued. The 95 percent warning lines for the control chart for individuals are now fixed at $\overline{X} \pm 1.77\overline{R}'$.

Table C-2

DATA FOR CONTROL CHARTS

INDIVIDUALS AND MOVING RANGE

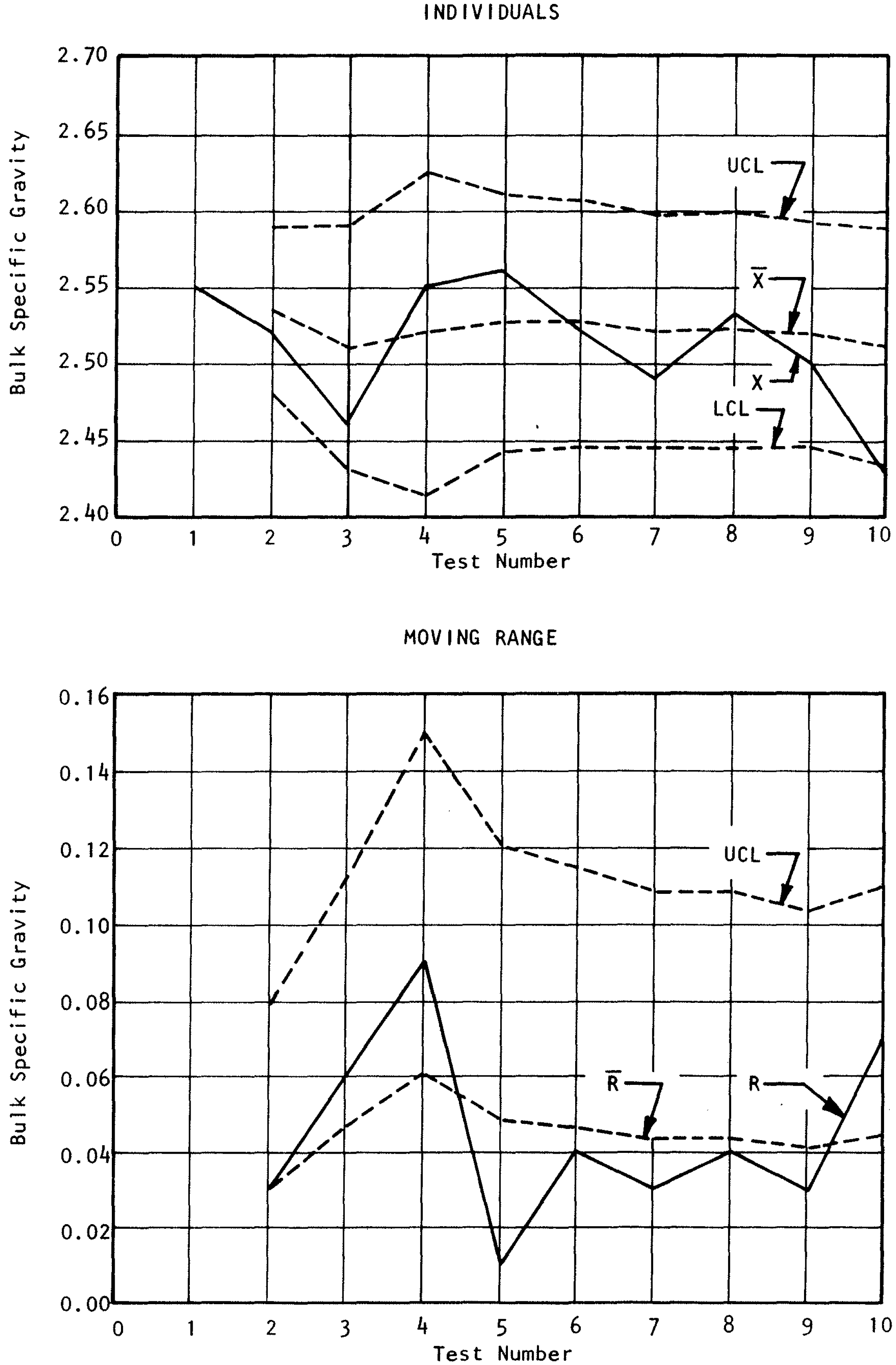
Bulk Specific Gravity of Marshall Specimens

(1) Test Number	(2) X	(3) R	(4) ΣR	(5) $\overline{R} = \frac{\Sigma R}{n_R}$	(6) ΣX	(7) $\overline{X} = \frac{\Sigma X}{n_X}$	(8) $UCL_X = \overline{X} + \overline{R}(1.77)$	(9) $LCL_X = \overline{X} - \overline{R}(1.77)$	(10) $UCL_R = \overline{R}(2.51)$
1	2.55								
		0.03	0.03	0.030	5.07	2.535	2.588	2.482	0.075
2	2.52								
		0.06	0.09	0.045	7.53	2.510	2.590	2.430	0.113
3	2.46								
		0.09	0.18	0.060	10.08	2.520	2.626	2.414	0.151
4	2.55								
		0.01	0.19	0.048	12.64	2.528	2.613	2.443	0.120
5	2.56								
		0.04	0.23	0.046	15.16	2.527	2.608	2.446	0.115
6	2.52								
		0.03	0.26	0.043	17.65	2.521	2.597	2.445	0.108
7	2.49								
		0.04	0.30	0.043	20.18	2.522	2.598	2.446	0.108
8	2.53								
		0.03	0.33	0.041	22.68	2.520	2.593	2.447	0.103
9	2.50								
		0.07	0.40	0.044	25.11	2.511	2.589	2.433	0.110
10	2.43								

Figure C-1

CONTROL CHART FOR INDIVIDUALS AND MOVING RANGE

Bulk Specific Gravity of Marshall Specimens



APPENDIX D

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3. SPINDLER, JAMES R. R., *Justifying Future Q. C. Expenses*, ASQC Annual Technical Conference Transactions, 1970, pp. 117.

4. MACE, Arthur E., *Sample Size Determination*, Reinhold Publishing Corp., New York, 1964.

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