B. E. King
COMMISSIONER OF HIGHWAYS

COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT, KENTUCKY 40601

November 25, 1970

H-2-36

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
DIVISION OF RESEARCH
533 SOUTH LIMESTONE STREET
LEXINGTON, KENTUCKY 40508
Telephone 606-254-4475

MEMORANDUM TO: A. O. Neiser
State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report, "Statistical Quality Control of Highway Construction Materials"; KYHPR-65-36; HPR-1(6), Part II

The substance of the report enclosed herewith is mostly informational; however, the inevitability of eventual recourse to statistical-type quality controls in some specification requirements is inferable from the information presented.

The austere, idealistic notions of assurances against defects in construction and materials or products must remain unchallenged and inviolable. Unfortunately, the most austere sampling and inspection plans may involve some risk or inability to detect one or more defects. If critical defects remain undiscovered, the consequences may impute the engineer. In contrast, imperfection connotes a tolerable type of defect, and so the criticalness of a defect becomes an admissive consideration. Quality assurance concepts, therefore, embrace a wide spectrum of certainty and uncertainty, tolerances, and physical attributes.

When each item of material or works is required to be inspected, measured or tested and thereupon accepted or rejected, statistics in no way guide the decisions; they may apply, however, to the accurancy of measuring and testing. If items are to be sampled, the question arises as to how many samples are needed to represent the whole -- that is, with some degree of assurance. There, full reliance must be vested in statistical probabilities.

Historical data banks provide helpful insights. Mean values and variabilities have been calculated. The data may be biased in some cases by sampling routines and by "check" sampling. Such data may indicate that some current specification limits need to be re-evaluated -- or that sampling frequencies could be reduced. Minimums or ranges in requirements may be continued in specifications by redefining them (revalued) as assured acceptance limits -- beyond which statistical criteria, described elsewhere, become applicable.

I may mention a requirement in the current specifications which I do not believe is providing sufficient quality assurance. The maximum limits for water in concrete mixtures (Maximum Free Water per sack of Cement, Table I, Article 403.3.1, **Standard Specificationss** ...) are the same as they were in the 1938 standards. Apparently, these requirements were set high so that there would always be an underrun of water. This past summer, an overrun occurred during the paving of the Audubon

Parkway, in Daviess County. Another instance involved Rockcastle Conglomerate sand in a laboratory evaluation. Inasmuch as the quality and strength of concrete depends so much, summarily, on the amount of water used, it seems proper to examine and refine these requirements from a quality assurance standpoint. Historical data will be compiled and submitted subsequently.

A companion study, KYHPR-63-29, "Changes in Certain Properties of Aggregate Materials, Used in Base Construction, Resulting from Construction", pertains largely to DGA and to degradation and segregation. The report has been delayed unduly because of difficulties encountered in analyzing the data. The difficulties have been resolved, and the report will soon be forthcoming.

A data bank of test results for reinforcing steel has been compiled but is not included in the report. There were cases where we were unable to identify the grade of steel specified and the grade supplied.

The issuance of this report formally concludes KYHPR-65-36. The original objectives have not been fully achieved. Future efforts should be more discretely channeled. A continuation or renewal plan would be prerequisite to future programming under HPR provisions. A general review of present status and a determination of new objectives are needed.

Respectfully submitted,

Jas. H. Havens

Jas. H. Havens
Director of Research

Attachment

cc's: Research Committee

Assistant State Highway Engineer, Research and Development
Assistant State Highway Engineer, Planning and Programming
Assistant State Highway Engineer, Pre-Construction
Assistant State Highway Engineer, Construction
Assistant State Highway Engineer, Operations
Assistant State Highway Engineer, Staff Services
Assistant Pre-Construction Engineer
Assistant Operations Engineer
Executive Director, Office of Computer Services
Executive Director, Office of Equipment and Properties
Director, Division of Bridges
Director, Division of Construction
Director, Division of Design
Director, Division of Maintenance
Director, Division of Materials
Director, Division of Photogrammetry
Director, Division of Planning

Director, Division of Research
Director, Division of Right of Way
Director, Division of Roadside Development
Director, Division of Rural Roads
Director, Division of Traffic
Division Engineer, Federal Highway Administration
Chairman, Department of Civil Engineering, University of Kentucky
Associate Dean for Continuing Education, College of Engineering, University of Kentucky
All District Engineers

JHH/cej

Research Report

295

STATISTICAL QUALITY CONTROL OF HIGHWAY CONSTRUCTION AND MATERIALS

KYHPR-65-36, HPR-1(6), Part II

by
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Former Assistant Research Engineer

Division of Research
DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

December 1970

ABSTRACT

The objective of this report is to review existing local practices used in establishing and enforcing highway specifications and construction processes and to compare these practices with procedures based on statistical quality control concepts. In order that statistical quality control concepts may be properly used where applicable, the first part of this report considers the general theory underlying the use of statistical control methods and the development of different types of acceptance plans which may be used in the highway construction industry. The second portion of the report is concerned with analyzing and comparing Kentucky's current specification requirements with typical quality control requirements established using basic statistical theory. Specifications used by some other agencies which are based on statistical principles are presented to illustrate the use being made of this type of acceptance plan. Historical data compiled for various contract items used in highway construction in Kentucky are also presented as background information useful for establishing statistically derived specifications in the future.

TABLE OF CONTENTS

INTRODUCTION

The ultimate objective of a set of highway construction and materials specifications is to define explicitly, completely, and enforceably all contract items. Current trends toward end-point specifications requires a review of present quality control methods to determine if the desired quality levels are adequately defined and can be maintained under the increasing pace set by the highway construction industry. The objective of this report is to review existing local practices used in establishing and enforcing highway specifications and construction processes and to compare these practices with procedures based on statistical quality control concepts. Where large variations appear to exist, a revision of practices may be in order, if practical.

A common misconception concerning statistical quality control should be emphasized. Many people consider statistical quality control as a method that will assure a superior product. This is not necessarily so; such control will only assure, within certain limits, that the product received is or is not that product which is specified or required. It is possible to receive products that conform to the required uniformity and statistical limits, yet are of an inferior quality. Only by using sound engineering principles and data in setting the control limits that will yield superior results can the tool known as "Statistics" actually assure that the products or results received are of a superior quality. The role of "Statistical Quality Control" begins only after the necessary engineering decisions have been made. It is also recognized that there is no immediate need to apply statistical control to every construction item. Study should therefore proceed first in those areas where statistical-type controls can be used to the greatest advantage. Since statistical quality control does not delineate what qualities or properties are best from an engineering viewpoint *(13)*, perhaps it is most fitting that such control be considered as a tool to be used in the conduct of business or the fulfillment of contract specifications.

Realizing that specification requirements do not govern variation, yet variation in materials and construction does govern the establishment of realistic specification limits, properly written statistical control specifications will allow for the natural or inherent variance in materials or construction and the sampling and testing procedures themselves. This is not to imply that full compliance with specification limits is always impossible or unnecessary but does emphasize that full compliance may require more effort than economically justifiable in many cases.

It is also important to distinguish between process or construction control and acceptance testing. Process control should be the means of providing concurrent checks during construction or production to maintain a given level of control with respect to both the mean and the variance (degree of uniformity). On the other hand, acceptance testing should provide the engineer with the means of accepting or rejecting the finished lot of material or construction on the basis of limited sampling. The trend in modern construction practice is to place the responsibility of process control more directly on the contractor rather than allowing the purchasing agency to assume the responsibility of both process control and acceptance testing. In keeping with this trend, this report is concerned primarily with acceptance testing; however, it is realized that ultimately the two must be equally emphasized for the most economical and satisfactory construction results.

In order that statistical quality control concepts may be properly used where applicable, the first part of this report will consider the general theory underlying the use of statistical control methods and the development of different types of acceptance plans which may be used in the highway construction industry. The second portion of the report will be concerned with analyzing and comparing Kentucky's current specification requirements with typical quality control requirements established using basic statistical theory. Specifications used by other agencies which are based on statistical principles will be presented to illustrate the use being made of this type of acceptance plan. Historical data compiled for various contract items used in highway construction in Kentucky will also be presented as background information useful for establishing statistically derived specifications in the future. The reliability of statistical methods, the economic compatibility of their use, and the necessary revisions in current sampling and testing procedures for employment of statistical control will all be considered before attempting to justify any adoption of statistical quality control methods.

DEVELOPMENT OF STATISTICAL ACCEPTANCE PLANS

SUITABILITY OF STATISTICAL METHODS

Lot-by-Lot Testing

Generally speaking, there are two purposes for making tests on highway construction. Firstly, the engineer must assure that unsatisfactory material or construction is not incorporated into the highway; and secondly, permanent records of the quality values received must be provided. In order to achieve the above results at a minimum of cost, statistically derived acceptance testing plans may, in many cases, be more efficient than the commonly used representative testing plans.

A statistically derived acceptance plan involves the concept of lot-by-lot testing, a lot being any well-defined quantity of material or construction produced by essentially the same process (e.g. the number of square yards of bituminous base placed in one day, or the number of cubic yards of concrete in a continuous placement). The lot is also the unit of material or construction accepted or rejected when an acceptance plan is used to determine compliance with specifications. One may therefore consider the construction of some highway facility as the production of a succession of lots -- these lots being presented to the engineer for acceptance or rejection.

Some of the advantages of lot-by-lot acceptance testing *(21)* are:

1. A better indication of acceptability is obtained.
2. Testing is not affected by variations in the rate of construction, thus allowing better utilization of inspection time.
3. The quantity of testing is directly related to the criticality of the construction or the materials involved.
4. Unsatisfactory lots are detected before a large quantity of unacceptable material or construction has been produced and at a time when corrective action is most likely to be feasible (i.e. the contractor knows where he stands from day to day and the engineer is protected from the possibility that a large quantity of defective work will be produced and from exigencies of the situation making adequate correction impractical).

Normal Distribution

The primary usefulness of statistics is in measuring the variation of individual measurements from their average. In order to do this, a distribution curve is fitted to the data. Such a curve that is most applicable for the type of data analyzed throughout most of the highway construction process is the "Normal Distribution Curve." This curve retains a characteristic bell shape, as shown in Figure 1, although the ratio of height to width of base may change radically.

Two parameters, the mean, $\bar{X}$, and the standard deviation, σ, completely define the shape and location of the normal distribution curve. By fitting a normal curve to the data to be analyzed, statistical inferences may be made and used in determining acceptance or rejection of the material or construction being studied. Regardless of its shape, a definite percentage of the total area beneath the curve is defined by vertical lines measured in standard deviation (sigma) units from its centerline or mean (see Figure 1). To convert data units, the following relationship is used:

$$Z = (X_i - \bar{X})/\sigma.$$

The value Z is a distance (in sigma units) measured along the base of the normal curve in either direction from the centerline; X_i is a particular value in data units; $\bar{X}$ is the mean of the data in data units; and σ is the standard

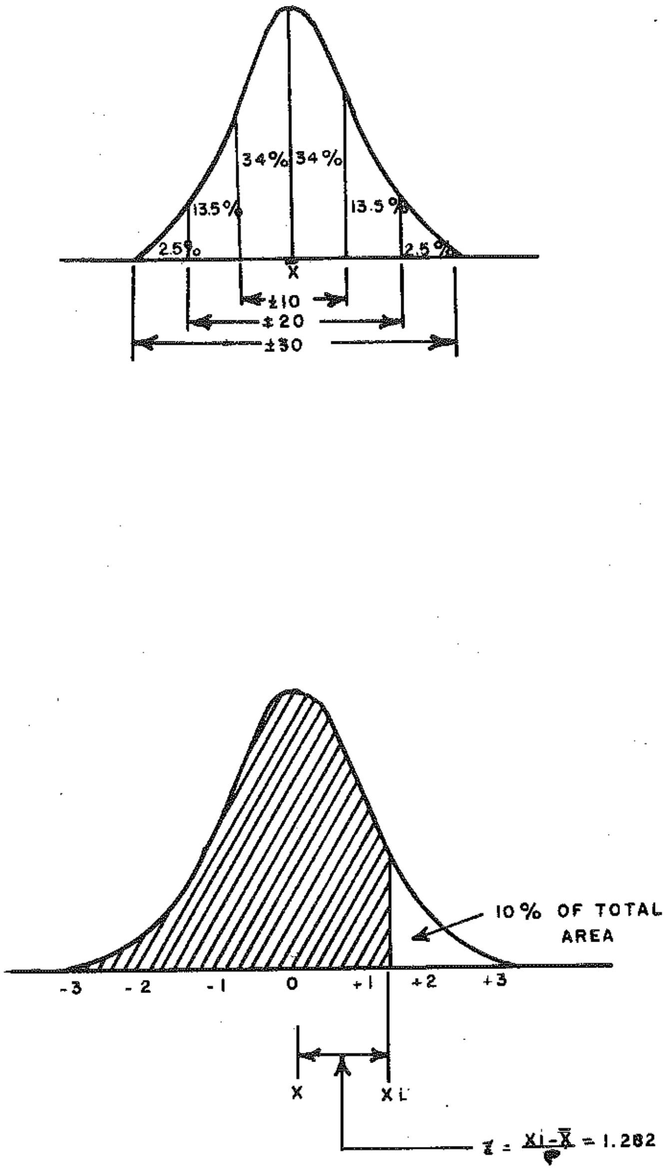

FIGURE 1. NORMAL DISTRIBUTION CURVE

deviation of the data in data units. Tables can be found in any statistics text or handbook for determining the percentage of area under the normal curve for a particular Z value.

Characteristics of the normal curve can be used as an aid in establishing realistic numerical acceptance limits whereby large risks of accepting poor material or construction or rejecting good material or construction can be avoided. If a specification, for example, had an upper limit (U) of $X_i = 36.4$, it is determined from Figure 1 that 90 per cent of the lot would be within this control limit. Although this is a rather elementary illustration of statistical evaluation, it should be remembered that, for practical purposes, the statistical analysis of data amenable to a normal curve type of fit is a simple procedure and not one requiring a vast knowledge of statistical theory.

A more useful application of the normal curve to acceptance sampling is to consider the average of n measurements when computing the Z statistic. In this case the standard deviation of the mean $\sigma_{\bar{X}}$ is given by $\sigma_{X} = \sigma/\sqrt{n}$. It follows that $Z = (\bar{X}-\bar{X}_g{}')/\sigma_{\bar{X}} = (\bar{X}-\bar{X}_g{}')/(\sigma/\sqrt{n})$, where $\bar{X}$ is the average of n measurements and $\bar{X}_g{}'$ is the desired average or the average of an acceptable lot. By using the average of n tests or samples for determining acceptance or rejection, a narrower distribution is obtained than by using the result of only one test. This in turn results in a better chance of accepting good material or construction and in a more reliable quality control procedure.

Decision Errors

Since acceptance or rejection of material or construction is to be made on the basis of sampling, there are possibilities of error. It would be very unlikely that the mean of the sample measurements, $\bar{X}$, would be the same as the true mean $\bar{X}'$ of the lot or that the sample standard deviation would be the same as the true standard deviation, σ'.

There are two types of errors of decision (see Table 1). The decision to reject a lot when the lot is actually satisfactory is a Type I or α error. This is the contractor's or seller's risk. On the other hand, a decision to accept a lot when the lot is actually unsatisfactory is a Type II or β error. This error is the engineer's risk or buyer's risk.

The basis of all statistical acceptance plans or specification limits lies in making decisions that will minimize the probability of making either Type I or Type II errors. Important relationships between these two types of errors in regard to acceptance plans or specification limits are *(21):*

1. The chances of rejecting a lot of poor quality are much greater than rejecting a lot of good quality.
2. The contractor's risk can be decreased by increasing either quality or uniformity, or both.
3. The buyer's or seller's risk, or both, can be decreased by increasing the number of measurements or by increasing the precision of measurements.

Random Sampling

By far the most important factor in obtaining information on which to establish realistic acceptance specifications and to enforce statistical control limits is the action of sampling. Obviously, precision of measurement and accuracy of computation are wasted efforts if the sample is taken improperly or, in the case of statistical control methods, in a non-random (biased) manner. It must be understood that methods of quality control using statistical concepts will yield reliable results only when random sampling (probability sampling) methods are employed. The terminology "random sample" does not imply a sample taken aimlessly, rather a sample taken without bias. The use of a table of random numbers is usually the best manner in which to assure randomness when employing statistical sampling and testing techniques.

Since the concept of randomness is of such importance in the sampling methodology, it seems worthy of further discussion and illustration. For a sample to be random, the lot must be sampled at some stage of the process when all parts of the lot are accessible. Consider a stockpile of aggregate. It is almost impossible to obtain a probability sample (random sample) from a stockpile of aggregate because increments cannot be taken from the

TABLE 1 - TWO TYPES OF DECISION ERRORS

Actual Conditions	Engineer's Decision Reject Material	 Accept Material
Material Acceptable	Type I Error (α) Engineer Incorrect (Contractor's Risk)	Engineer Correct
Material Unacceptable	Engineer Correct	Type II Error (β) Engineer Incorrect (State's Risk)

interior of the pile. To sample this material in a statistically valid manner, it should be passed over a belt, and increments taken from the stream at randomly determined intervals (i.e. determine the intervals of sampling by using a table of random numbers).

In addition to assuring an unbiased sample or test result, there is another important advantage in using random sampling procedures in lieu of "representative" procedures. When random sampling and testing techniques are used, the engineer or inspector is relieved of the responsibility of deciding what is a "representative" sample and of any charges of unfairness or favoritism to the contractor. Uniformity of specification enforcement is therefore greatly improved.

Analysis of Variance

Whenever the material or construction subject to statistical quality control is found to have a large standard deviation, a greater degree of uncertainty may exist concerning the true mean of the measured characteristic. Such circumstances may warrant an examination of the individual components contributing to the overall variance of the characteristic. The overall variance, σ^2, of the material or construction may be expressed as $\sigma^2 = \sigma_a^2 + \sigma_s^2 + \sigma_t^2$, where σ_a^2 is the actual or inherent variance in the material or construction, σ_s^2 is the variance due to sampling, and σ_t^2 is the variance within the test procedure.

A procedure for computing these components of the overall variance is presented in Reference 9. It should be remembered that the overall variance is the variance considered for acceptance sampling and testing. A breakdown of this variance into its components only serves to analyze what effect the sampling and testing procedures have on the overall variance, thus pointing out possible inadequacies in the procedures used.

CHOICE OF ACCEPTANCE PLANS

Prerequisites

There are certain prerequisites necessary for the design of any realistic and practical statistical acceptance plan. Some of the most important are *(10)*:

1. A direct correlation between the criticality of the specification requirement as defined by the engineer and the "measurement" risk.
2. An acceptance by both the engineer and the contractor of the risk associated with the sampling or testing plan corresponding to the criticality of the particular specification.
3. A particular number of samples or tests.
4. Reasonable and acceptable tolerance limits (reflecting successful past construction experience).
5. Simple and straightforward statistical procedures and mathematical computations.
6. An explicit interpretation to all parties involved.
7. A plan suitable for use throughout the highway industry.

Types of Acceptance Plans

1. Inspection by Attributes

Inspection-by-attributes plans are used to determine the percent defectives in a lot. Items inspected are classified as either acceptable or defective. The number of defectives found in a sample of n items is usually compared with some tabular value and acceptance or rejection of the lot is determined (see Plans 1 and 2). This type of plan is used when the significant characteristic of the material or construction cannot be measured and is not associated with a measurable property.

Obviously, certain risks must be taken if sampling inspection by attributes is to be used for acceptance decisions. A graph of these risks as a function of the incoming lot quality is known as an "Operating Characteristics" (OC) curve (see Figure 2). If the material or construction is of high quality (low percentage of defectives), the probability of acceptance should be high; conversely, if the quality is low, the probability of acceptance should be low. An ideal plan would accept all good lots and reject all bad lots, as illustrated in Figure 3. Unfortunately, no

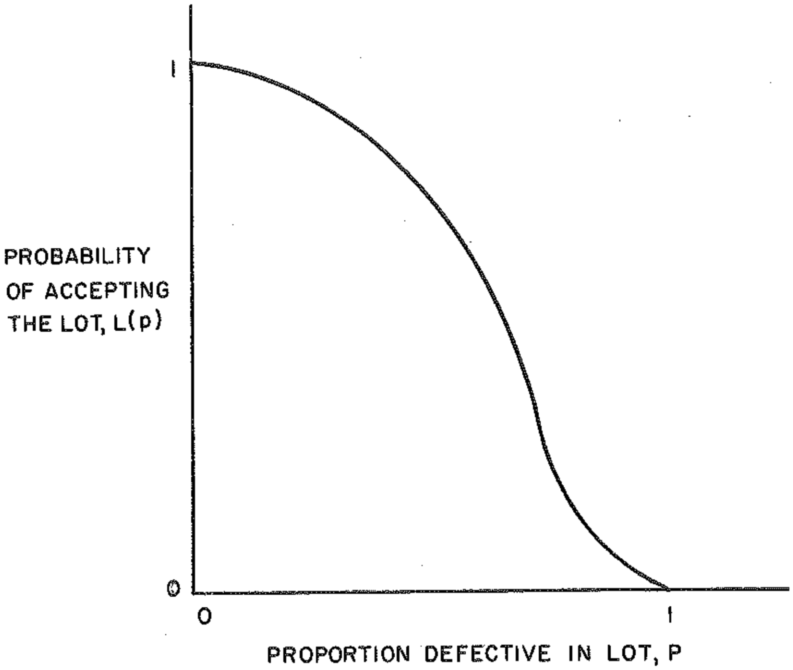

FIGURE 2. TYPICAL OPERATING CHARACTERISTICS (OC) CURVE FOR INSPECTION BY ATTRIBUTES

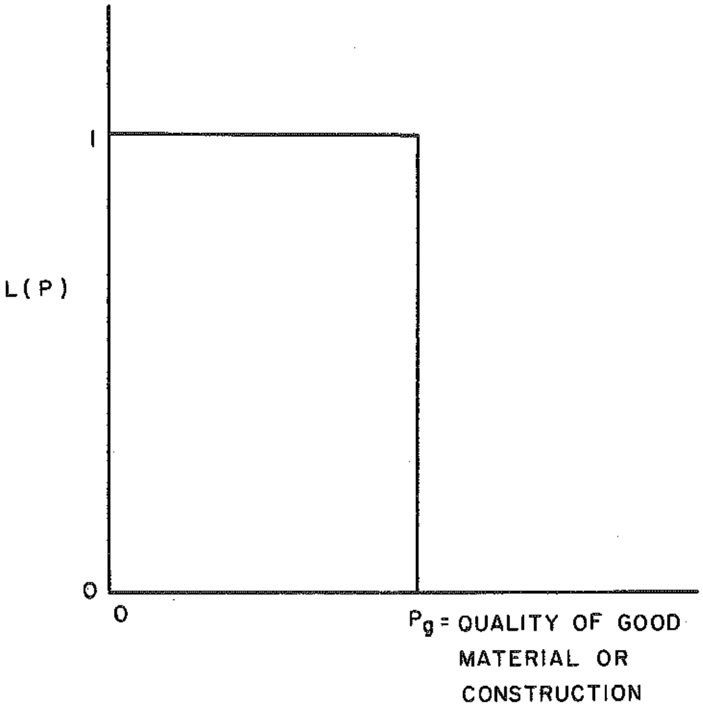

FIGURE 3. IDEAL OC CURVE

sampling plan can have such an ideal curve. The degree of approximation to this ideal curve is dependent on the size of the sample, n, and the allowable number of defectives, c. When c is held constant and n is increased, the slope of the OC curve becomes steeper (see Figure 4). Holding n constant and varying c will shift the curve to the right or left, as shown in Figure 4.

A further discussion of operating characteristics curves is presented in the section of this report on *Design* ι *Acceptance Plans.*

2. Inspection by Variables

Inspection procedures by variables are based upon the measurement of a variable quality characteristic; the decision to accept or reject a lot is a function of these measurements (as opposed to the number of defectives). Variables testing plans may be used when the format of the distribution is known and the testing of individual items requires that measurements be made. This type of plan makes greater use of the information concerning the lot than does inspection by attributes . Also, the variables plans require smaller sample sizes for the same protection.

For practical purposes, sampling by variables may be divided into three categories: known standard deviation plans, unknown standard deviation plans, and average range plans.

Known standard deviation plans are based upon the sample mean and the known standard deviation (see Plan 5). When the true standard deviation, σ', is known, both the buyer's and contractor's risks can be set at the desired level, fewer tests are necessary, and acceptance can be more simply stated. The true standard deviation may be assumed to be known when properly estimated from a sufficiently large number of measurements *(9)* (see Appendix B).

Unknown standard deviation plans are based upon the sample mean and the sample standard deviation (see Plan 4). The problem underlying this type of control is that only one risk can be fixed. It is generally most feasible to control the buyer's risk when this type of plan is used. Uniformity of material and construction should be the contractor's primary concern in order to avoid penalty or risk rejection of acceptable work. In keeping with the overally desire for construction and materials with both an acceptable average quality and a high degree of uniformity, this type of plan may be very useful when the situation of an unknown standard deviation governs.

Average range plans are based upon the sample mean and the average range in the subsamples (see Plan 3). Neither the buyer's nor the contractor's risks can be definitely fixed by this type of plan. One may therefore conclude that this type of acceptance plan is somewhat less desirable from the standpoint of overall quality control assurance.

Using any of the three variables plans, specifications limits (tolerances) may take three forms. There may be an upper limit, a lower limit, or both. In addition, the acceptance plan may be expressed in one of two ways. Firstly, the acceptance plan may specify a minimum percentage of material or construction having a certain measured value within the limit(s). Secondly, the value measured may be specified at some maximum or minimum.

Operating characteristics curves for inspection by variables are somewhat different from those presented for inspection by attributes. For inspection-by-variables plans, the risks involved are plotted as a function of the average value of the measured quality characteristic. Figure 5 shows a typical OC curve for this type of plan. the effect of sample size on the OC curve for variables sampling is shown in Figure 6. Holding the contractor's risk, α, constant, the state's risk, β, may be decreased by increasing the number of samples or tests. On the other hand, when the sample size is held constant, either the contractor's risk or the state's risk must increase as the other decreases (see Figure 7). This is a very fundamental rule governing all variables inspection plans and should be emphasized lest the reader be misled.

Criticality

Specified statistical sampling plans or control limits must consider the "criticality" of the measured property as it relates to the overall construction project or resulting product. Factors to be considered in assessing critically are:

1. Safety,
2. Serviceability, and
3. Cost (construction, control, maintenance).

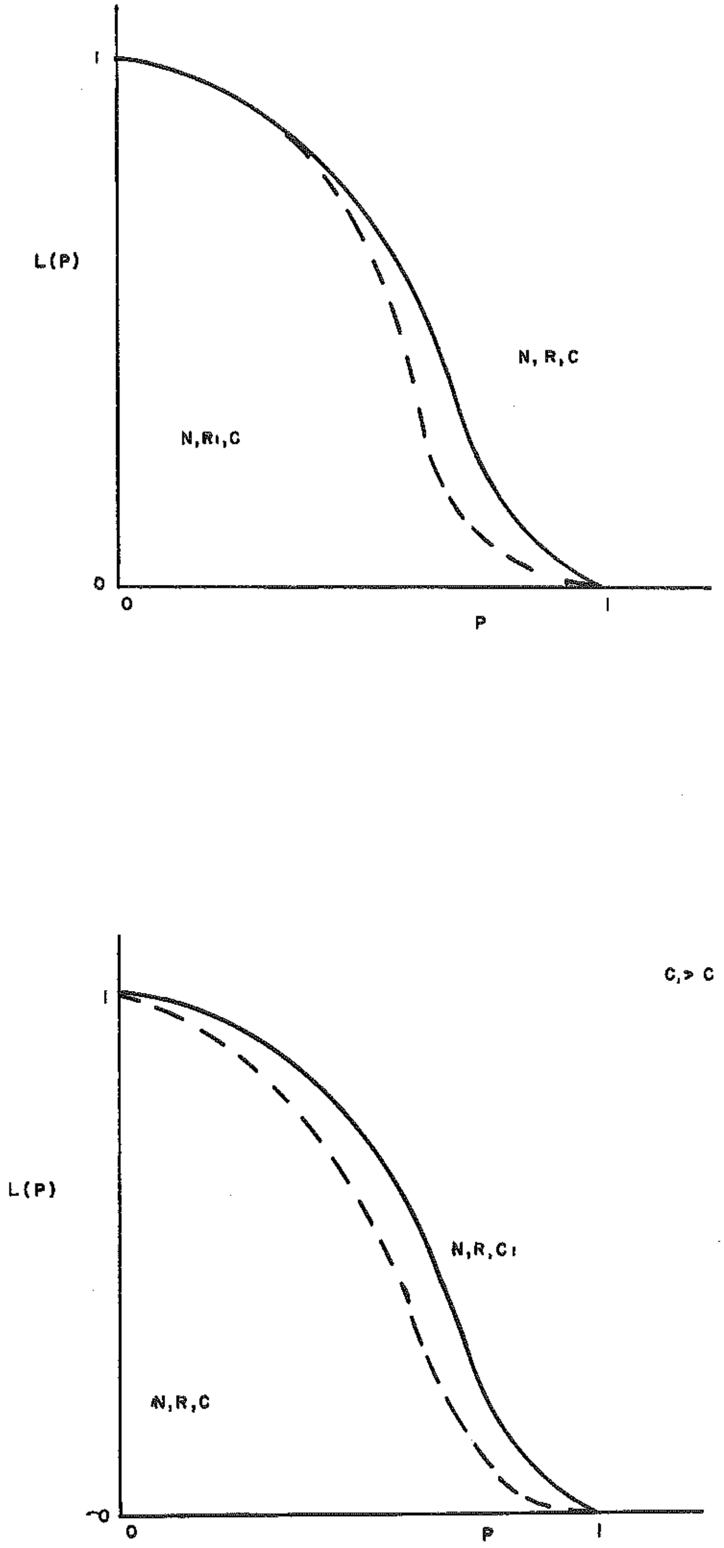

FIGURE 4. EFFECT OF VARYING THE SAMPLE SIZE, n, AND ALLOWABLE NUMBER OF DEFECTIVES, c, ON THE OC CURVE

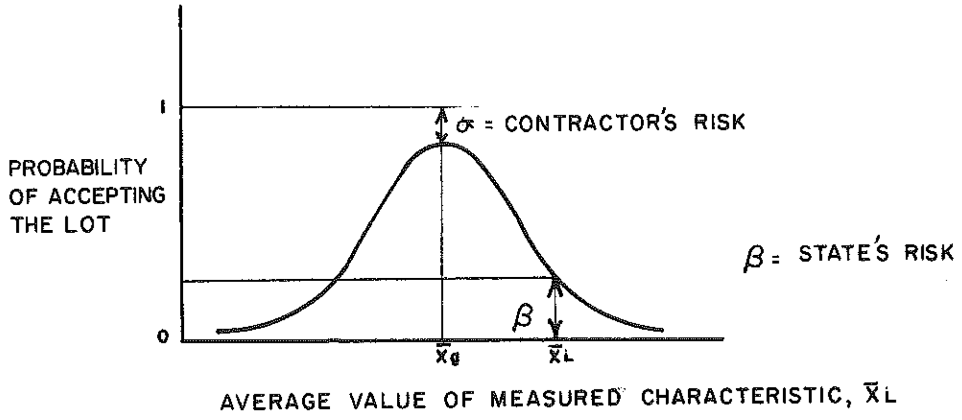

FIGURE 5. TYPICAL OC CURVE FOR INSPECTION BY VARIABLES

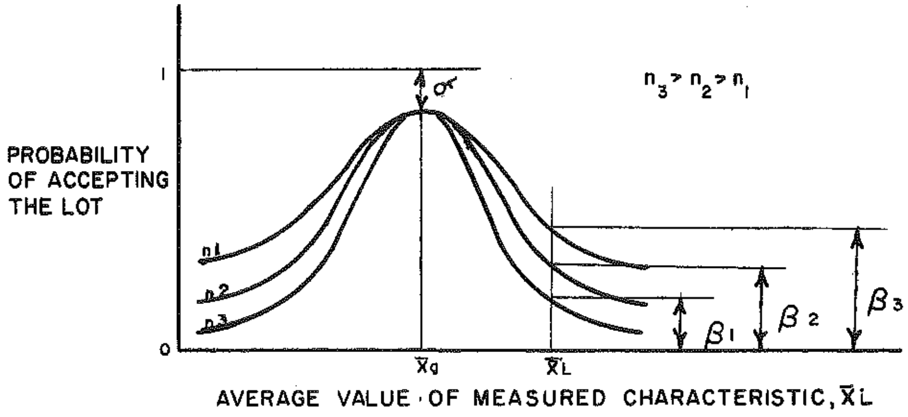

FIGURE 6. EFFECT ON OC CURVE OF VARYING SAMPLE SIZE WHILE HOLDING CONSTANT

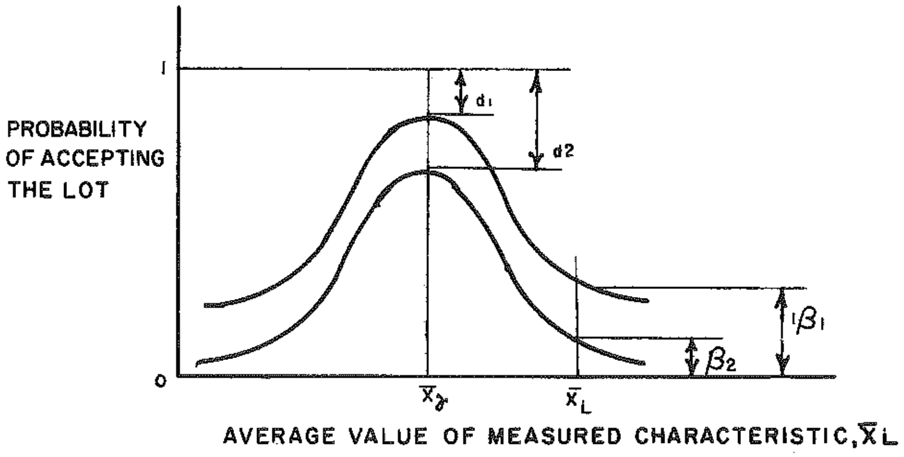

FIGURE 7. EFFECT ON OC CURVE OF VARYING WHILE HOLDING THE SAMPLE SIZE CONSTANT

For classification purposes, the following ratings of criticality have been suggested *(10):*

Critical - when the requirement is essential to preservation of life.

Major - when the requirement is necessary for the prevention of substanial economic loss.

Contractural - when the requirement is established to control uniformity and (or) provide a standard basis for bidding.

It is thought that the fewer and simpler the categories, the easier the use of such groupings for effectively rating the criticality of specification requirements. Also, it is important not to confuse the "major" category with that of "contractural" (the key difference lying in the phrase "of substantial economic loss"). An example of an item in the "critical" category is the tensile strength of the steel reinforcing strands in precast concrete bridge members. An item in the "contractural" category would be the 2.5-foot length of tie-bars for longitudinal joints in concrete pavement. Further categorical classifications are shown in Table 2 *(9)*.

Realistic Acceptance Limits

To establish realistic acceptance limits for use with statistical control methods, the following procedure has been suggested *(10)*

1. Determine the significant characteristics which are known to control the performance of the material or construction.
2. Determine the criticality of each chracteristic.
3. If a characteristic cannot be measured directly, determine correlatable properties which are amenable to measurement.
4. Select the method of test by which it is most practical to find the value of the measured characteristic. It is important to consider:
   a. the suitability of the method as a control test which will provide a quick indication of a deficiency at a time when remedial action is possible.
   b. equipment and manpower costs.
   c. the randomness of the measurement procedure.
   d. the accuracy of determination.
5. Using the selected test method, which will also be used for acceptance purposes, make a sufficient number of measurements to determine acceptable estimates of the true mean, $\bar{X}'$, and the true standard deviation, σ' (see Appendix B).
6. Repeat Step 5 a sufficient number of times (see Appendix B) to determine if the standard deviation:
   a. varies widely as a result of varying construction conditions, equipment, or materials with the average value, $\bar{X}$, of the characteristic also having a wide variation.
   b. varies widely, but the average value, $\bar{X}$, of the characteristic remains near the target value.
   c. is practically constant under usual construction conditions.
7. On the basis of the results in Step 6, determine the appropriate plan from *Design of Acceptance Plans* found in the next section of this report.
8. Compare the limits obtained from Step 7 with the existing specification limits and (or) engineering requirements, and examine the respective ranges and sources of variance for both.
9. Apply the statistically determined limits on a trial basis (not changing the current specification requirements) and evaluate the results.
10. Revise the current specifications or prepare new ones should the results in Step 9 indicate a necessary or expedient change.

TABLE 2

AREAS TO BE STUDIED FOR STATISTICAL QUALITY CONTROL AND TENTATIVE ASSIGNED CLASSIFICATIONS TO VARIOUS CHARACTERISTICS OF MATERIALS AND PROCESSES

By

The Task Force Group on Statistical Quality Control
Office of Research and Development
U. S. Bureau of Public Roads

Portland Cement Concrete Pavement

Item	Characteristics	Class
Pavement Slab	Thickness	Major
	Air content @ surface	Major
Plastic Concrete	Slump	Major
	Air content	Major
	Cylinder strength	Major
	Cement content	Major
Coarse aggregate	Grading	Major
	Durability	Major
	Passing #200	Major
	Deleterious materials	Minor
	Los Angeles loss	Minor
Fine Aggregate	Grading	Major
	Fineness Modulus	Major
	Passing #200	Major
	Sand Equivalent	Minor
Cement	Alkali content	Major
	Strength	Major
	Air Content	Minor
	Hot Mix Asphaltic Concrete	
Asphaltic Pavement	Density	Major
	Temperature at compaction	Major
	Thickness	Minor
	Surface tolerance	Minor
	Roughness	Minor
Asphaltic Base	Density	Major
	Thickness	Minor
Asphaltic Mix	Gradation of Aggregate	Major
	Dust Ratio	Major
	Asphalt content	Major
	Mixing temperature	Major
	Stability and flow	Minor
Asphalt Cement	Penetration or Viscosity	Major
	Retained penetration of thin residue	Major
	Thin film test lose	Minor
Aggregate	Los Angeles lose	Major
	Gradation	Major
	Liquid limit and Plastic index	Major
	Durability	Minor
	Deleterious material	Minor
	Flat and Elongated particles	Minor
	Base Course	
Soil Aggregate	Stability	Major
	Plasticity	Major
	Thickness	Minor
	Gradation	Minor
	Density	Minor
	Line and Grade	Minor
Stabilized Base	Stability	Major
	Additive quantity	Major
	Thickness	Minor
	Plasticity	Minor
	Gradation	Minor
	Soils	
Subgrade	Density	Major
	Stability	Minor
	Moisture content	Major
Embankment	Density	Minor
	Moisture	Minor

These tables are subject to additions and changes as the project develops.

Problems

It is to be expected that many problems will be encountered before statistical control methods can receive widespread adoption. The use of proper discretion in considering these problems may, however, alleviate much of the consternation associated with the use of statistical quality control techniques. The following discussions are concerned with problem areas that must be reconciled prior to the adoption of any type of statistical control procedures.

1. Technical Training

Engineers and inspectors who normally think in terms of representative testing and sampling will require some training to properly interpret random testing results. Figure 8 is illustrative of the type of results one might expect from random sampling as contrasted to representative sampling. Considering, however, that any approach to statistical control finally adopted must be subject to rather basic and simplified statistical concepts, the personnel training involved should be nominal, for the most part.

2. Engineering Judgment Decisions

Although statistical control procedures may be most useful in assuring the engineer or inspector when certain processes or materials are or are not within the tolerance limits specified, the indispensability of sound engineering judgment should not be slighted. All factors which contribute to the suitability of the finished product, obviously, cannot be measured statistically. Evident nonconformance to specification requirements must, as always, be corrected by the engineer regardless of test results.

3. Procurement of Data

Extensive information on the variability of the parameters that measure materials and construction quality will be necessary to establish the design parameters required for enforceable statistical acceptance plans. The procurement of the data may prove to be one of the largest physical hurdles to overcome in establishing realistic and completely enforceable statistically controlled specification tolerances. For certain manufactured items, suitable information may be available. If so, such information could be used for pilot specifications and employed on an experimental basis *(13)*.

4. Increases in Control Costs

Many engineers and administrators are concerned that the adoption of statistical control techniques may increase considerably the cost of quality control by increasing the necessary amount of sampling and testing required for acceptance. However, the introduction and implementation of quicker, more refined testing methods (e.g. nuclear gage determination of relative compaction) may significantly reduce the magnitude of this problem while also providing the engineer with more reliable test results. It may also be possible to establish systematic programs, where applicable, with manufacturers of construction items whereby periodic inspections of a plant's quality control procedures and records could be made. This may eliminate needless duplication of quality assurance sampling, while allowing audit sampling and inspections to be made on delivery to the job site as a means of verification of the plant's control and assurance that no damage or change has occurred during shipment. Another means of reducing control costs has been used by the California Division of Highways *(25,30)* and makes use of a "moving average" compliance specification to determine acceptance or rejection of construction and materials (see Plan 6).

5. Revision of Present Specifications

Generally speaking, current specifications and test procedures were not written with the intent of using any type of random or statistical approach to testing or acceptance. And, since statistical control procedures should not be used unless random sampling and testing is also incorporated into the testing procedure, the establishment of new specification limits and test methods will be required in many cases. This may very well prove to be a difficult hurdle in considering the adoption of statistical quality control procedures for the control of highway construction and materials.

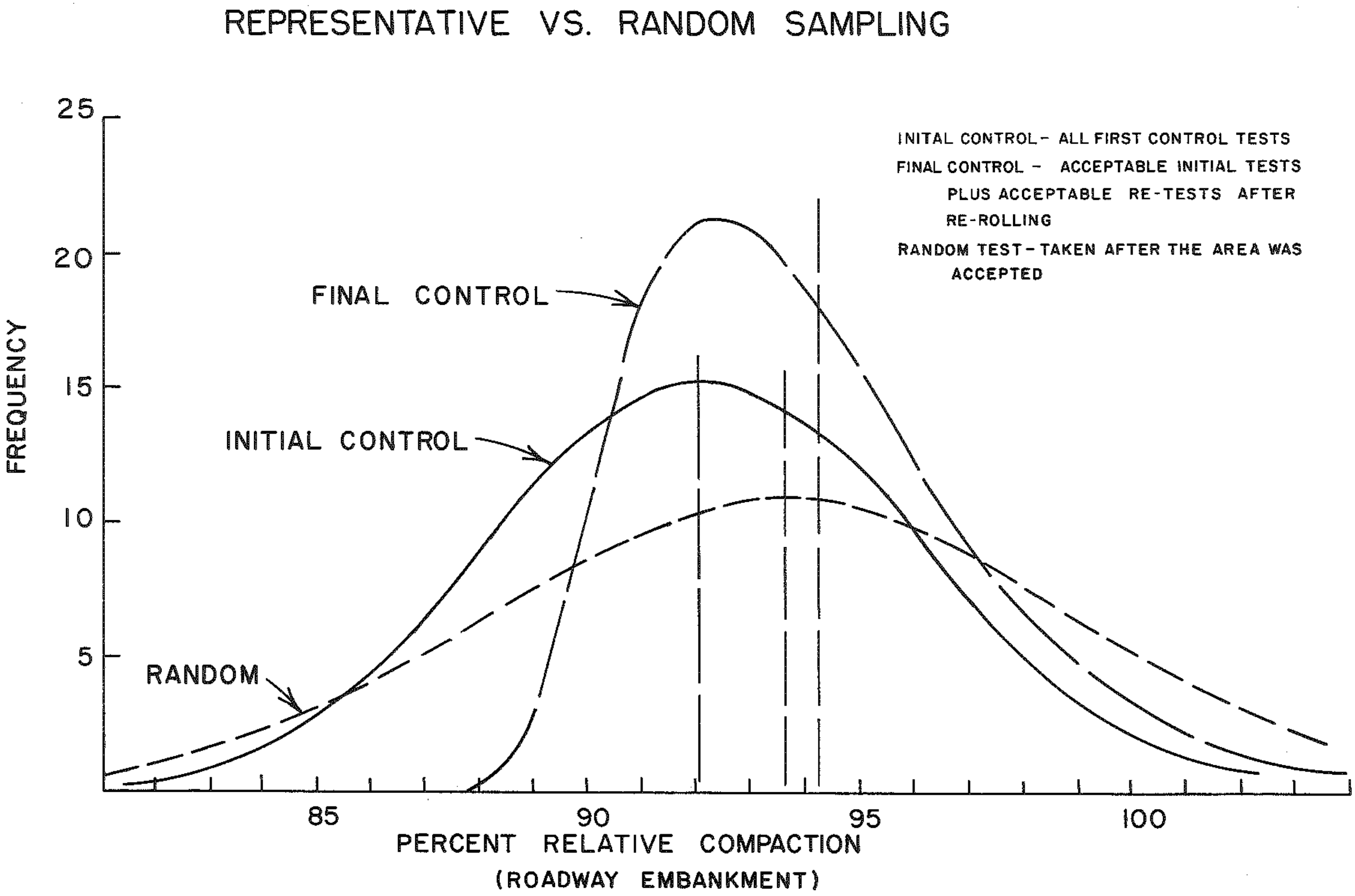

FIGURE 8. REPRESENTATIVE VS RANDOM SAMPLING

DESIGN OF ACCEPTANCE PLANS

Six types of statistical acceptance plans will be presented in this section. Discussion will concern the conditions under which each plan should be used, the advantages and disadvantages of each plan, and the design of each plan. Unit price adjustments and control charts will also be considered in conjunction with the use of these statistical acceptance plans.

Plan 1 - Protection Against Accepting Lots Containing an Excessive Number of Defective Items Using Single Sampling.

This type of plan is used when the significant characteristic of the materials or construction cannot be measured and is not associated with a measurable property. Acceptance or rejection is based entirely on the number of defectives in the sample (i.e. a "pass" or "fail", "go" or "no go" criteria). The choice of a single sampling plan is usually based on a specified "Acceptance Quality Level" (AQL), the quality of material or construction that will be accepted with a probability of $1\text{-}\alpha$, and (or) the "Lot Tolerance Percent Defective" (LTPD), the quality of material or construction that will be accepted with a probability of β (see Figure 9). Several standard sampling plans are available for acceptance by single-sampling. Two of these plans will be discussed and their basic design presented.

The first of these single-sampling plans, taken from Military Standard 105D tables, stresses the maintenance of a specified AQL and encourages the contractor to offer only high quality products to the consumer. There are three levels of inspection possible in conformance with different consumer (state's) risks. Inspection Level Two (normal level) is generally used. Level One requires smaller sample sizes while Level Three makes use of larger sample sizes. Also, three types of inspection -- normal, tightened, and reduced -- are performable, depending on the quality of previously sampled work. The type of inspection may be varied when the proportion of defectives for prior sampling indicates that the quality has been above or below the specified AQL. A Normal Inspection Plan (using a normal level of inspection and a normal type of inspection), which is applicable to most types of inspection by attributes necessary in the highway industry, is shown in Table 3.

The second plan is based on the Poisson distribution as an approximation to the binomial distribution. Using Table 4, the OC curve passing through the points $(p_1, 1\text{-}\alpha)$ and (p_2,β) is selected; and, accordingly, the acceptance number (allowable number of defectives) and the necessary number of samples are determined. Although apparently not as extensively used as the plans using Military Standards, this plan should be appropriate to use where reasonable estimates of α, β, AQL(p_1) and LTPD(p_2) can be obtained.

These plans are easy to design and use since acceptance is based simply on the number of defectives found in a sample of size n. These types of plans are not as efficient as using inspection by variables (see Plans 3,4,5, and 6) inasmuch as more samples or observations are necessary for the same risks.

The following steps are suggested in the design of single sampling plans:

a. Using Military Standard 105 D
   Step 1 - Determine the desired value of the AQL.
   Step 2 - Determine the lot or batch size.
   Step 3 - From Steps 1 and 2 and Table 3, determine the sample size n and the allowable number of defectives (acceptance and rejection numbers) for the sample of n.
   Step 4 - Specify the manner and frequency in which acceptance sampling and testing will be done and the methods of sampling and testing to be used.
   Step 5 - Specify the action to be taken if the number of defectives revealed is greater than or equal to the rejection number.

b. Using the Poisson approximation
   Step 1 - Determine the desired values of α, β, p_1 and p_2.
   Step 2 - From Step 1 and Table 4, determine the acceptance number, c, and the number of random samples, n, required.
   Steps 3 and 4 - Same as Steps 4 and 5 using Military Standard 105 D.

Plan 2 - Protection Against Accepting Lots Containing an Excessive Number of Defective Items Using Sequential Sampling

Such a plan, similar to Plan 1, may be used when the significant characteristic of material or construction

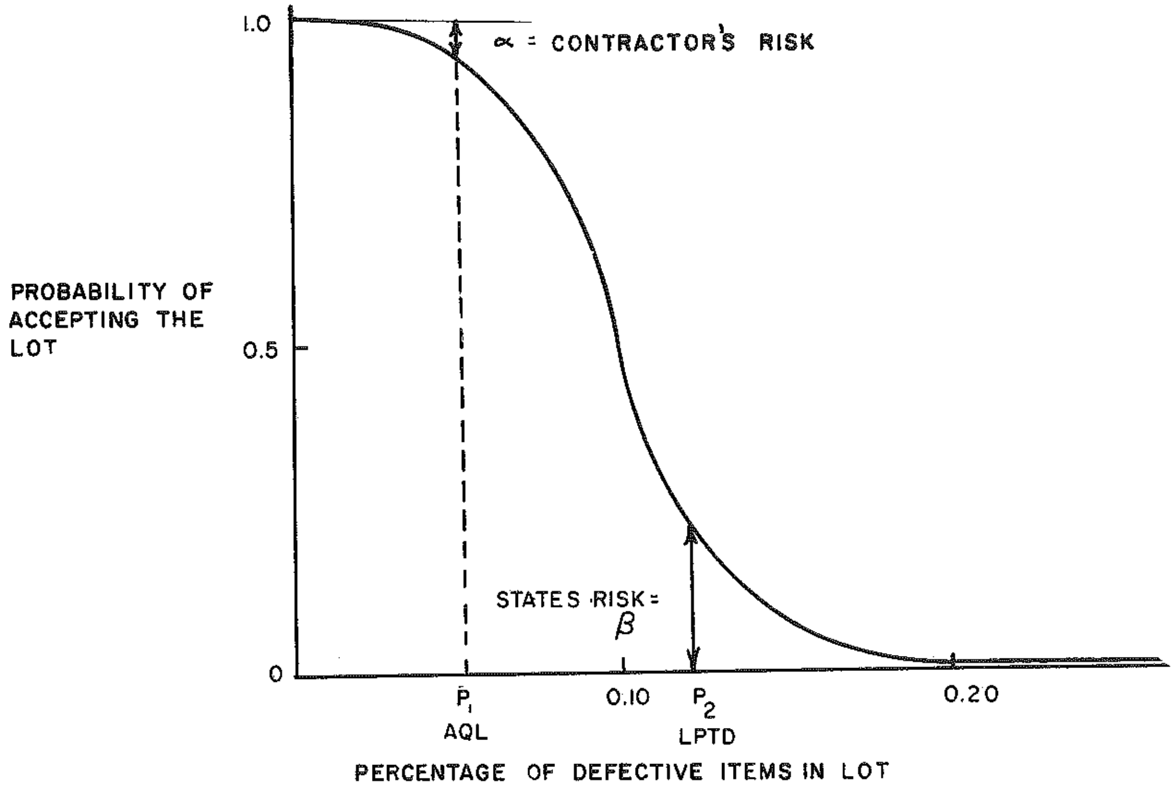

FIGURE 9. TYPICAL OC CURVE FOR INSPECTION BY ATTRIBUTES

TABLE 3 - SINGLE SAMPLING PLANS FOR NORMAL INSPECTION (21) (SEE MIL-STD-105 D FOR EXTENSIVE TABLES)

Lot or Batch Size	Sample Size (No.)	Acceptable Quality Levels[a,b] (Normal Inspection)																									
		0.010	0.015	0.025	0.040	0.065	0.10	0.15	0.25	0.40	0.65	1.0	1.5	2.5	4.0	6.5	10	15	25	40	65	100	150	250	400	650	1000
		AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE	AC RE
2 to 3	2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓		0 1	↓	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31
9 to 15	3	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45
16 to 25	5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲
26 to 50	8	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲	↑
51 to 90	13	↓	↓	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	30 31	44 45	▲	↑	↑
91 to 150	20	↓	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	▲	▲	↑	↑	↑
151 to 280	32	↓	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑
281 to 500	50	↓	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑
501 to 1200	80	↓	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑
1201 to 3200	125	↓	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑
3201 to 10000	200	↓	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
10001 to 35000	315	↓	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
35001 to 150000	500	↓	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
150001 to 500000	800	▼	0 1	▲	▼	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
500001 and over	1250	0 1	▲	↑	1 2	2 3	3 4	5 6	7 8	10 11	14 15	21 22	▲	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑

[a] ▼ = Use first sampling plan below arrow. If sample size equals or exceeds lot or batch size, do 100 percent inspection. ▲ = Use first sampling plan above arrow. Ac = Acceptance Number. Re = Rejection Number.

[b] The Acceptable Quality Level (AQL) is a nominal value expressed in terms of percent defective or defects per hundred units. The distinction between a defect and a defective is that a defective item may contain one or more defects. AQL's of 10.0 or less are expressed either in percent defective or in defects per hundred units only; those points over 10.0 are expressed in defects per hundred units only.

TABLE 4 - VALUES OF np'_1 AND c FOR CONSTRUCTING SINGLE SAMPLING PLANS WHOSE OC CURVE IS REQUIRED TO PASS THROUGH TWO POINTS (p'_1, 1-α) AND (p'_2,β) (6)

Here p'_1 is the fraction defective for which the risk of rejection is to be α, and p'_2 is the fraction defective for which the risk of acceptance is to be β. To construct the plan, find the tabular value of p'_2/p'_1 in the column for the given α and β which is equal to or just less than the value of the ratio. The sample size is found by dividing the np'_1 corresponding to the selected ratio by p'_1. The acceptance number* is the value of c corresponding to the selected value of the ratio.

	Values of p_2/p_1 for:					Values of p_2/p_1 for:			
c	α=0.05 β=0.10	α=0.05 β=0.05	α=0.05 β=0.01	np_1	c	α=0.01 β=0.10	α=0.01 β=0.05	α=0.01 β=0.01	np_1
0	44.890	58.404	89.781	0.052	0	229.105	298.073	458.210	0.010
1	10.946	13.349	18.681	0.355	1	26.184	31.933	44.686	0.149
2	6.509	7.699	10.280	0.818	2	12.206	14.439	19.278	0.436
3	4.890	5.675	7.352	1.366	3	8.115	9.418	12.202	0.823
4	4.057	4.646	5.890	1.970	4	6.249	7.156	9.072	1.279
5	3.549	4.023	5.017	2.613	5	5.195	5.889	7.343	1.785
6	3.206	3.604	4.435	3.286	6	4.520	5.082	6.253	2.330
7	2.957	3.303	4.019	3.981	7	4.050	4.524	5.506	2.906
8	2.768	3.074	3.707	4.695	8	3.705	4.115	4.962	3.507
9	2.618	2.895	3.462	5.426	9	3.440	3.803	4.548	4.130
10	2.497	2.750	3.265	6.169	10	3.229	3.555	4.222	4.771
11	2.397	2.630	3.104	6.924	11	3.058	3.354	3.959	5.428
12	2.312	2.528	2.968	7.690	12	2.915	3.188	3.742	6.099
13	2.240	2.442	2.852	8.464	13	2.795	3.047	3.559	6.782
14	2.177	2.367	2.752	9.246	14	2.692	2.927	3.403	7.477
15	2.122	2.302	2.665	10.035	15	2.603	2.823	3.269	8.181
16	2.073	2.244	2.588	10.831	16	2.524	2.732	3.151	8.895
17	2.029	2.192	2.520	11.633	17	2.455	2.652	3.048	9.616
18	1.990	2.145	2.458	12.442	18	2.393	2.580	2.956	10.346
19	1.954	2.103	2.403	13.254	19	2.337	2.516	2.874	11.082
20	1.922	2.065	2.352	14.072	20	2.287	2.458	2.799	11.825
21	1.892	2.030	2.307	14.894	21	2.241	2.405	2.733	12.574
22	1.865	1.999	2.265	15.719	22	2.200	2.357	2.671	13.329
23	1.840	1.969	2.226	16.548	23	2.162	2.313	2.615	14.088
24	1.817	1.942	2.191	17.382	24	2.126	2.272	2.564	14.853
25	1.795	1.917	2.158	18.218	25	2.094	2.235	2.516	15.623
26	1.775	1.893	2.127	19.058	26	2.064	2.200	2.472	16.397
27	1.757	1.871	2.098	19.900	27	2.035	2.168	2.431	17.175
28	1.739	1.850	2.071	20.746	28	2.009	2.138	2.393	17.957
29	1.723	1.831	2.046	21.594	29	1.985	2.110	2.358	18.742
30	1.707	1.813	2.023	22.444	30	1.962	2.083	2.324	19.532
31	1.692	1.796	2.001	23.298	31	1.940	2.059	2.293	20.324
32	1.679	1.780	1.980	24.152	32	1.920	2.035	2.264	21.120
33	1.665	1.764	1.960	25.010	33	1.900	2.013	2.236	21.919
34	1.653	1.750	1.941	25.870	34	1.882	1.992	2.210	22.721
35	1.641	1.736	1.923	26.731	35	1.865	1.973	2.185	23.525
36	1.630	1.723	1.906	27.594	36	1.848	1.954	2.162	24.333
37	1.619	1.710	1.890	28.460	37	1.833	1.936	2.139	25.143
38	1.609	1.698	1.875	29.327	38	1.818	1.920	2.118	25.955
39	1.599	1.687	1.860	30.196	39	1.804	1.903	2.098	26.770
40	1.590	1.676	1.846	31.066	40	1.790	1.887	2.079	27.587
41	1.581	1.666	1.833	31.938	41	1.777	1.873	2.060	28.406
42	1.572	1.656	1.820	32.812	42	1.765	1.859	2.043	29.228
43	1.564	1.646	1.807	33.686	43	1.753	1.845	2.026	30.051
44	1.556	1.637	1.796	34.563	44	1.742	1.832	2.010	30.877
45	1.548	1.628	1.784	35.441	45	1.731	1.820	1.994	31.704
46	1.541	1.619	1.773	36.320	46	1.720	1.808	1.980	32.534
47	1.534	1.611	1.763	37.200	47	1.710	1.796	1.965	33.365
48	1.527	1.603	1.752	38.082	48	1.701	1.785	1.952	34.198
49	1.521	1.596	1.743	38.965	49	1.691	1.775	1.938	35.032

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[1] From J. M. Cameron, "Tables for Constructing and Computing the Operating Characteristics of Single-Sampling Plans," Industrial Quality Control, July 1952, p. 39.

*The acceptance number equals the allowable number of defectives in a sample of size n.

cannot be measured and is not associated with a measurable property. However, this plan differs from Plan 1 in that the number of defectives found from a specified number of observations may be too low for rejection or too high for acceptance of the lot. When using this type of plan, continued sampling may be necessary in order to determine acceptance or rejection of the materials or construction being tested. A sequential sampling plan should, on the average, involve a smaller number of tests or samples than a single sampling plan, while providing the same degree of protection to both the purchaser and the contractor. The variability of the required number of observations may introduce difficulties in scheduling inspection time. Only when all of the lot is available for testing is this type of plan applicable or economical. For example, testing the proportions of some product as it is produced is not feasible using a sequential plan, since a continuous run of good products might lead to acceptance with only a small portion of the products having actually been produced. On the other hand, for stockpiled material or surface tolerance investigations of pavement components, a sequential type testing plan may prove to be very applicable. Also, entanglements may develop in deciding where testing must stop when the number of defectives remains in the "continue testing" region (see Figure 10).

The following procedure is suggested in designing a sequential sampling plan:

Step 1 - Determine the criticality category of the materials or construction to be observed.

Step 2 - From Step 1 and Table 5, determine the contractor's risk, α = the probability of rejecting the lot if the proportion defective is p_1, and the state's risk, β = the probability of accepting the lot if the proportion defective is p_2. It is desired that the plan accept the lot if the proportion defective is not greater than p_1 and reject the lot if any proportion defective is greater than p_2 (see Figure 9).

Step 3 - Specify the manner and frequency in which acceptance sampling and testing will be done (initially and sequentially), the methods of sampling and testing to be used, and the cutoff point or end point for testing that continues to fall in the "continue testing" region.

Step 4 - Specify the action to be taken if the number of defectives falls within the rejection region.

Step 5 - Calculations and acceptance decisions are to be made as follows:

a. Intermediate Calculations *(6)*

$$b = \ln[(1-\alpha)/\beta]$$
$$a = \ln[(1-\beta)/\alpha]$$
$$g_1 = \ln(p_2/p_1)$$
$$g_2 = \ln[(1-p_1)/(1-p_2)]$$
$$h_1 = b/(g_1 + g_2)$$
$$s = g_2/(g_1 + g_2)$$

b. Determine the rejection line from

$$r_m = h_2 + n\,s$$

c. Determine the acceptance line from

$$a_m = -h_1 + n\,s$$

d. The region between these two lines is the "Continue testing" region (see Figure 10). If the number of defectives revealed falls within this region, sampling or testing should continue until acceptance or rejection of the material or construction is determined or the cutoff point is reached.

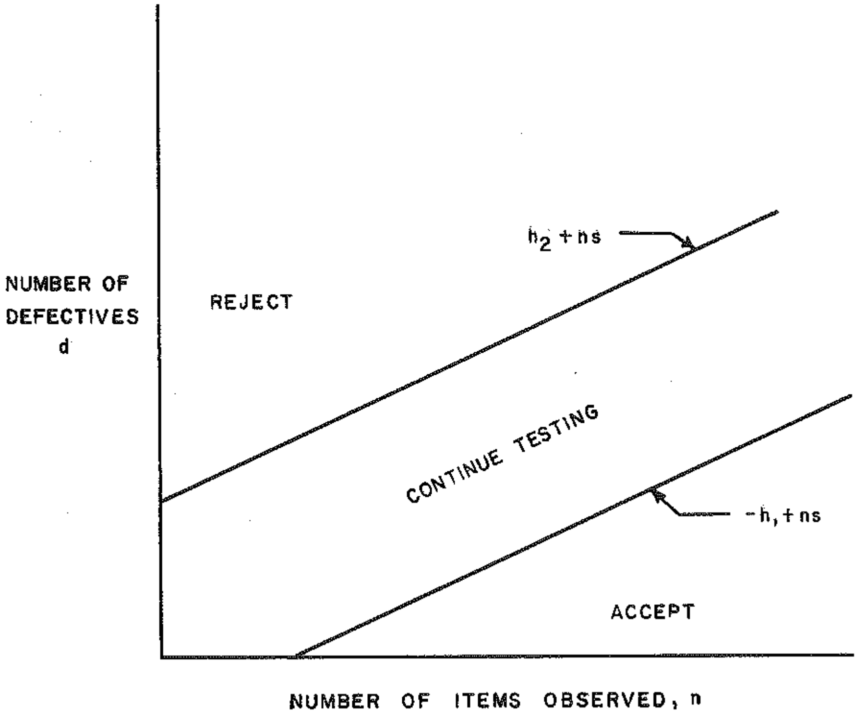

FIGURE 10. SEQUENTIAL TESTING PLAN

TABLE 5 - SUGGESTED BALANCE OF STATISTICAL PARAMETERS FOR PLAN 2

Criticality of Requirement	Probability of Rejecting Good Material	Probability of Accepting Poor Material
Critical	0.050	0.005
Major	0.010	0.050
Minor	0.005	0.100
Contractual	0.001	0.200

Plan 3 - Estimation of Percent within a Stated Tolerance; Mean $\bar{X}$ and Standard Deviation $\bar{\sigma}'$ unknown

This plan may be used when no information is available concerning the mean or standard deviation of a characteristic, or if these parameters are known to vary over a wide range. Such a plan is easy to design and use. It is difficult, however, to estimate the risks of making either Type I or Type II errors. Also, these risks (buyer's and contractor's) cannot be fixed.

The following is suggested in designing such an acceptance plan:

Step 1 - Specify the desired value of the characteristic to be measured.

Step 2 - Determine the criticality category of the characteristic.

Step 3 - From Step 2 and Table 6, determine the number of random measurements to be made on the lot.

Step 4 - Specify the manner and frequency in which acceptance sampling and testing will be done and the methods of sampling and testing to be used.

Step 5 - Specify the upper (U) and (or) lower (L) acceptance limit(s) and the percentage of material or construction that must fall within the limit(s).

Step 6 - Specify the action to be taken if the percentage of the lot within-tolerance material or construction is less than that specified in Step 5.

Step 7 - Calculations and acceptance decisions are to be made as follows:

a. Determine $\bar{X}$ from

$$\bar{X} = \Sigma X_i/n$$

b. If the sample size, n, is less than 10, determine the range, R, by subtracting the smallest value measured from the largest value measured.

c. If the sample size, n, is greater than or equal to 10, arrange the measurements in the order they were taken and divide into subgroups of five. Find R for each subgroup, add these values, and divide by the number of subgroups. This value is R.

d. Determine the Quality Indexes, Q_U and (or) Q_L, from

$$Q_U = (U - \bar{X})/R \text{ or } \bar{R}$$
$$Q_L = (\bar{X} - L)/R \text{ or } \bar{R}$$

e. From Table 7, determine the percentage of the lot within the upper (p_U) or lower (p_L) tolerance limit.

f. If both upper and lower tolerance limits are specified, determine the percentage of the lot within the tolerance limits from $p_{U,L} = p_U + p_L$.

Plan 4 - Fixed Protection Against Accepting Poor Material; Standard Deviation σ' Unknown

This plan is designed to provide a fixed probability of rejecting poor lots and to place on the contractor the responsibility of supplying construction or material of uniform acceptable quality. In order to use this plan, it is necessary to specify the mean value $\bar{X}_p'$ of unacceptable material or construction. Plan 4 makes maximum use of all available information. An increased variation in quality or a decrease in the level of quality will greatly increase the contractor's risk of rejection. The contractor's risk is hard to estimate unless a good estimate of the standard deviation can be obtained from measurements on probability samples taken from similar materials or construction.

Referring to Figures 11, 12, and 13, the following is suggested as a method of design for Plan 4:

Step 1 - Determine the value of $\bar{X}_p'$ the mean value of a lot which is unacceptable (i.e. the mean value of the least acceptable or borderline material or construction).

Step 2 - Determine the criticality category of the characteristic to be measured.

Step 3 - From Step 2 and Table 8, determine the number of random measurements to be made on the lot

TABLE 6 - SUGGESTED NUMBER OF MEASUREMENTS IN RELATION TO CRITICALITY FOR PLAN 3; STANDARD DEVIATION UNKNOWN (21)

Criticality of Characteristic	Number of Measurements
Critical	9
Major	7
Minor	5
Contractual	4

TABLE 7 - TABLE FOR ESTIMATING PERCENT OF LOT WITHIN TOLERANCE (21)
(RANGE METHOD)

P_U or P_L Percent Within Tolerance	Q_U or Q_L										
	n=4	n=5	n=7	n=10*	n=15*	n=25*	n=30*	n=35*	n=40*	n=50*	n=60*
99	0.66	0.66	0.65	0.82	0.88	0.93	0.94	0.95	0.95	0.97	0.97
98	0.64	0.65	0.61	0.76	0.80	0.83	0.84	0.85	0.85	0.86	0.86
97	0.63	0.62	0.58	0.71	0.74	0.77	0.78	0.78	0.78	0.79	0.79
96	0.62	0.60	0.55	0.68	0.68	0.72	0.73	0.73	0.73	0.74	0.74
95	0.60	0.58	0.53	0.64	0.66	0.68	0.68	0.69	0.69	0.70	0.70
94	0.59	0.57	0.51	0.62	0.63	0.64	0.65	0.65	0.66	0.66	0.66
93	0.58	0.55	0.49	0.59	0.61	0.61	0.62	0.62	0.62	0.62	0.62
92	0.56	0.53	0.47	0.57	0.58	0.59	0.59	0.59	0.59	0.60	0.60
91	0.55	0.51	0.46	0.54	0.55	0.56	0.57	0.57	0.57	0.57	0.57
90	0.54	0.50	0.44	0.52	0.53	0.54	0.54	0.54	0.54	0.55	0.55
89	0.52	0.48	0.43	0.50	0.51	0.52	0.52	0.52	0.52	0.52	0.52
88	0.51	0.46	0.41	0.48	0.49	0.50	0.50	0.50	0.50	0.50	0.50
87	0.50	0.45	0.40	0.47	0.47	0.47	0.48	0.48	0.48	0.48	0.48
86	0.48	0.44	0.38	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46
85	0.47	0.42	0.37	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.44
84	0.46	0.41	0.36	0.42	0.42	0.42	0.43	0.43	0.43	0.42	0.42
83	0.44	0.40	0.34	0.40	0.40	0.41	0.41	0.41	0.41	0.41	0.41
82	0.43	0.38	0.33	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
81	0.42	0.37	0.32	0.37	0.37	0.37	0.37	0.37	0.38	0.38	0.38
80	0.40	0.36	0.31	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
79	0.39	0.34	0.29	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.35
78	0.38	0.33	0.28	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
77	0.36	0.32	0.27	0.32	0.32	0.31	0.31	0.32	0.32	0.32	0.32
76	0.35	0.30	0.26	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
75	0.34	0.29	0.25	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
74	0.32	0.28	0.24	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
73	0.31	0.27	0.23	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.27
72	0.30	0.25	0.22	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
71	0.28	0.24	0.20	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
70	0.27	0.23	0.19	0.22	0.23	0.22	0.23	0.23	0.23	0.23	0.23
69	0.26	0.22	0.18	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
68	0.24	0.21	0.17	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
67	0.23	0.19	0.16	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
66	0.21	0.18	0.15	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
65	0.20	0.17	0.14	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
64	0.19	0.16	0.13	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.15
63	0.17	0.15	0.12	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
62	0.16	0.14	0.11	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
61	0.15	0.13	0.10	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
60	0.13	0.11	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

*When $n \geq 10$, the samples are arranged consecutively in subgroups of five, the range, R, of each subgroup is determined, and the average range, $\bar{R}$, of all subgroups is computed for use in finding Q_U or Q_L.

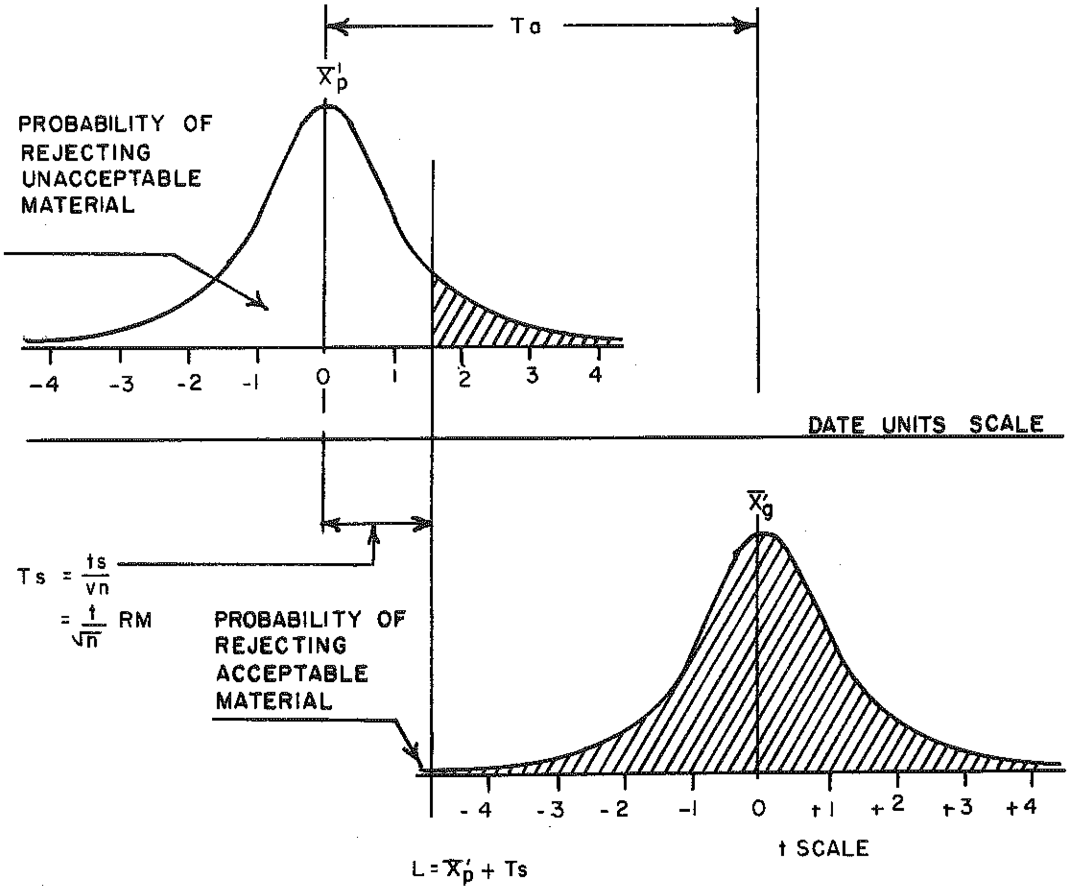

FIGURE 11. PLAN 4, LOWER ACCEPTANCE LIMIT ONLY

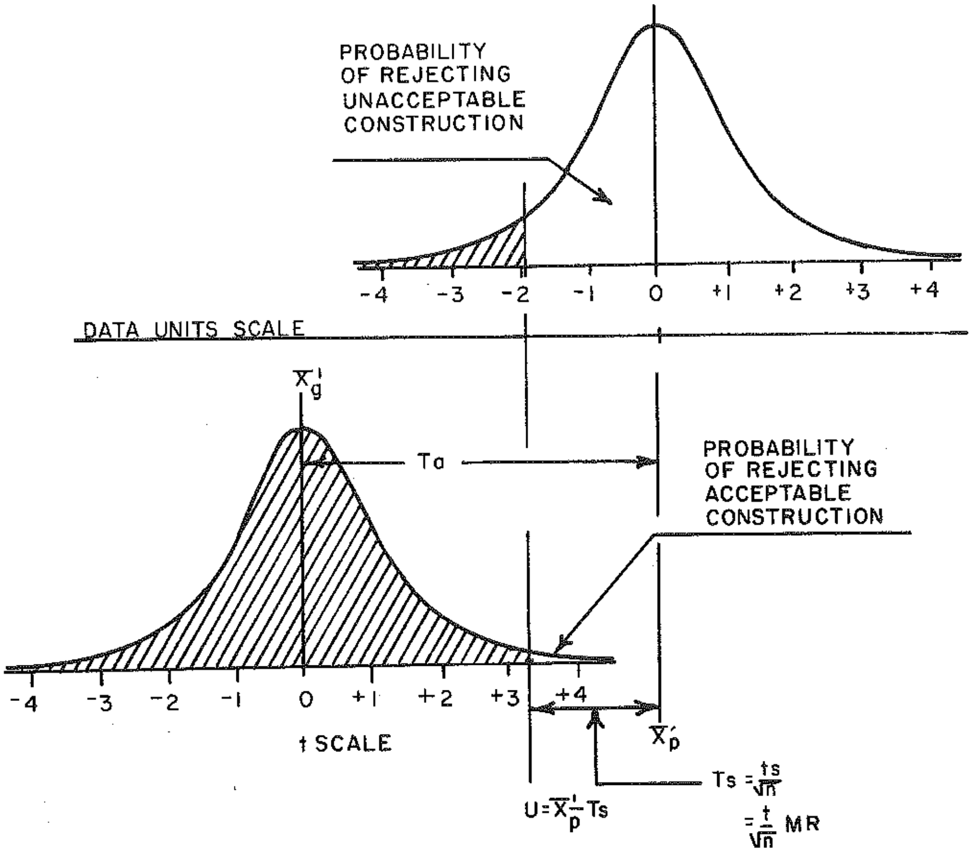

FIGURE 12. PLAN 4, UPPER ACCEPTANCE LIMIT ONLY

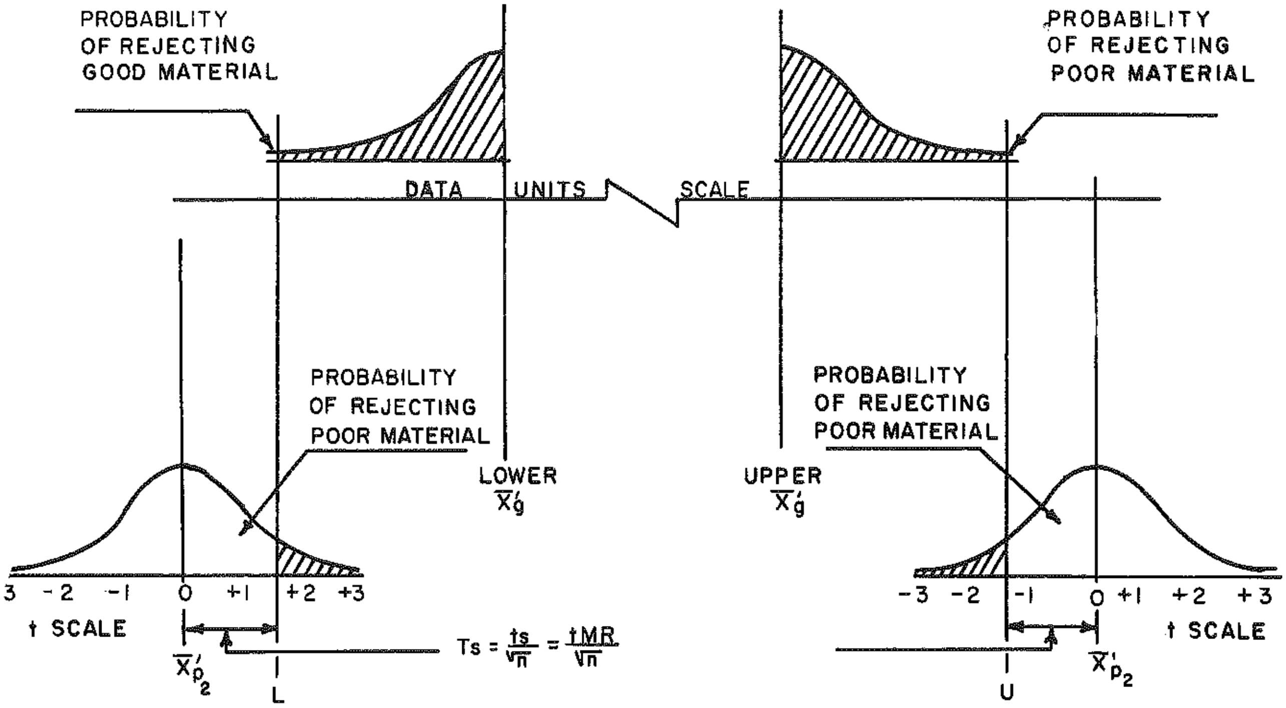

FIGURE 13. PLAN 4, UPPER AND LOWER ACCEPTANCE LIMITS

TABLE 8 - SUGGESTED BALANCE OF ACCEPTANCE SPECIFICATION FACTORS FOR PLAN 4; STANDARD DEVIATION UNKNOWN (21)

Criticality of Requirement	Probability[a] of Rejection of Good Material, $P_g = \alpha$	Probability of Rejection of Poor Material, $P_p = 1-\beta$	t^b	Number of Measurements, n	Difference Between Means, $T_a{}^c$	Acceptance Limits[d]
Critical	0.0640	0.995	3.355	9	$\pm 1.75\sigma$	$\bar{x}_p'$ ± 0.376 R
Major	0.0085	0.950	1.943	7	$\pm 1.75\sigma$	$\bar{x}_p'$ ± 0.271 R
Minor	0.0043	0.900	1.533	5	$\pm 2.00\sigma$	$\bar{x}_p'$ ± 0.295 R
Contractual	0.0005	0.800	0.978	4	$\pm 2.25\sigma$	$\bar{x}_p'$ ± 0.237 R

[a] Probabilities for single limit specification. When specification has both an upper and a lower limit, the probability of rejecting acceptable material may theoretically be doubled.

[b] Since the true standard deviation is unknown, a t distribution is used (5).

[c] The difference between means ($Ta = \bar{x}_g' - \bar{x}_p'$) is approximately equal to the estimated value of σ multiplied by the tabulated factors.

[d] $\bar{x}_p' \pm T_s$; $T_s = \frac{ts}{\sqrt{n}} = \frac{t}{\sqrt{n}} MR$; M = 0.486, p.430, 0.370, 0.337, respectively for n = 4, 5, 7 and 9

and the acceptance limit(s).

Step 4 - Specify the manner and frequency in which acceptance sampling and testing will be done and the methods of sampling and testing to be used.

Step 5 - Specify the action to be taken if the mean, $\bar{X}$, of the material or construction measured is outside the limit(s) specified in Step 3.

Step 6 - Calculations and acceptance decisions are to be made as follows:

a. Determine X_p' from reasonable engineering requirements or the characteristics of acceptable materials or construction.

b. Determine $\bar{X}$ from $\bar{X} = \Sigma X'/n$.

c. Determine R from the difference between the largest and smallest values measured from n tests.

d. If the material or construction has a lower limit (L) only, the acceptance limit is found from $L = \bar{X}_p' + AR$, where A is the multiplier from Table 8. The acceptance rule would read: If the average, $\bar{X}$, of the measurements on n samples is less than L, reject the lot. If the average, $\bar{X}$, is greater than or equal to L, accept the lot.

e. If the material or construction has an upper limit (U) only, the acceptance limit is found from $U = X_p' - AR$, where A is the multiplier from Table 8. The acceptance rule would read: If the average, X, of the measurements on n samples is greater than U, reject the lot.

f. If the material or construction has both an upper limit (U) and a lower limit (L), the acceptance limits are found from $L = X_p' + AR$ and $U = X_p' - AR$, where X_{p_1}' and X_{p_2}' are the mean values of an unacceptable material or construction for the lower and upper specification requirements, respectively, and A is the multiplier from Table 8. The acceptance rule would read: If the average, X, of the measurement on n samples is less than L or greater than U, reject the lot.

Plan 5 - Fixed Protection Against Accepting Poor Material or Rejecting Good Material; Standard Deviation σ' Known

This plan is designed to provide a fixed probability of rejecting both poor and good lots of material or construction. Best use of this plan is made when either acceptable or unacceptable material or construction can be defined in terms of the mean value of some significant characteristic or measurable property, and the true standard deviation, σ', is believed to be known and unchanging. Plan 5 enables the designer to fix both the buyer's and contractor's risks. Also, a fewer number of measurements are required than in Plans 3 or 4. However, an accurate estimation of the true standard deviation, σ', may be very difficult and costly to obtain, if possible at all, for many materials used in the highway construction industry.

Referring to Figures 14, 15, and 16, the following method is suggested in designing acceptance plans:

Step 1 - Same as Plan 4. In Plan 5, $\bar{X}_p'$ may be determined from $X_g' \pm T_a$, where T_a is the difference between the desired mean, $\bar{X}_g'$, and the mean of unacceptable material or construction, $\bar{X}_p'$. Plan 4, however, does not permit this type of relationship to be used for design purposes since the standard deviation, σ', is unknown.

Step 2 - Same as Plan 4.

Step 3 - From Step 2 and Table 9, determine the number of random measurements to be made on the lot and the acceptance limit(s).

Step 4 - Same as Plan 4.

Step 5 - Same as Plan 4.

Step 6 - Calculations and acceptance decisions are to be made as follows:

a. Same as Plan 4.

b. Determine the value of the true standard deviation, σ', from historical data collected from

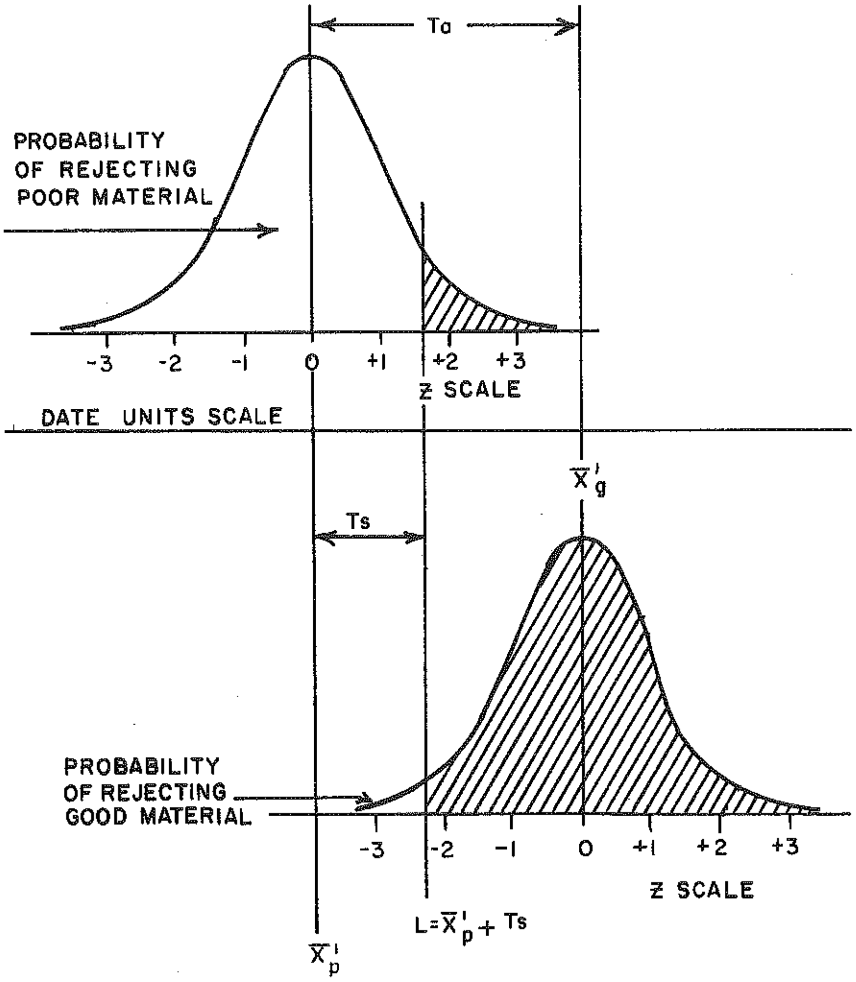

FIGURE 14. PLAN 5, LOWER ACCEPTANCE LIMIT ONLY

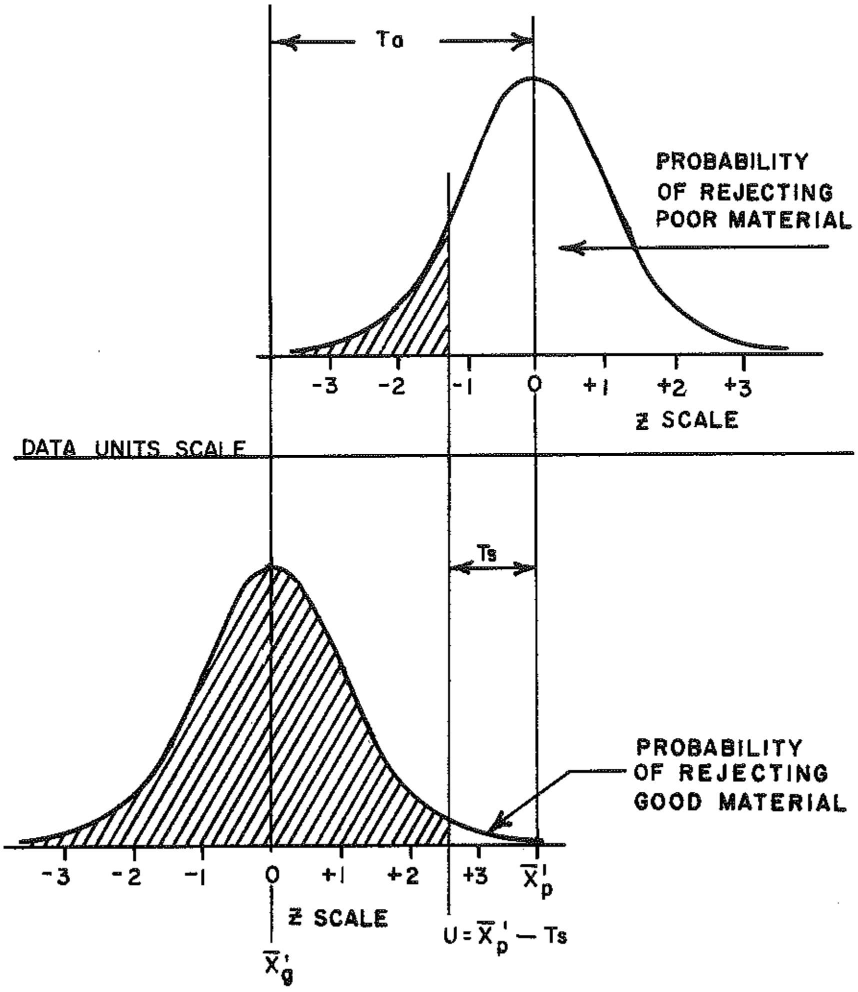

FIGURE 15. PLAN 5, UPPER ACCEPTANCE LIMIT ONLY

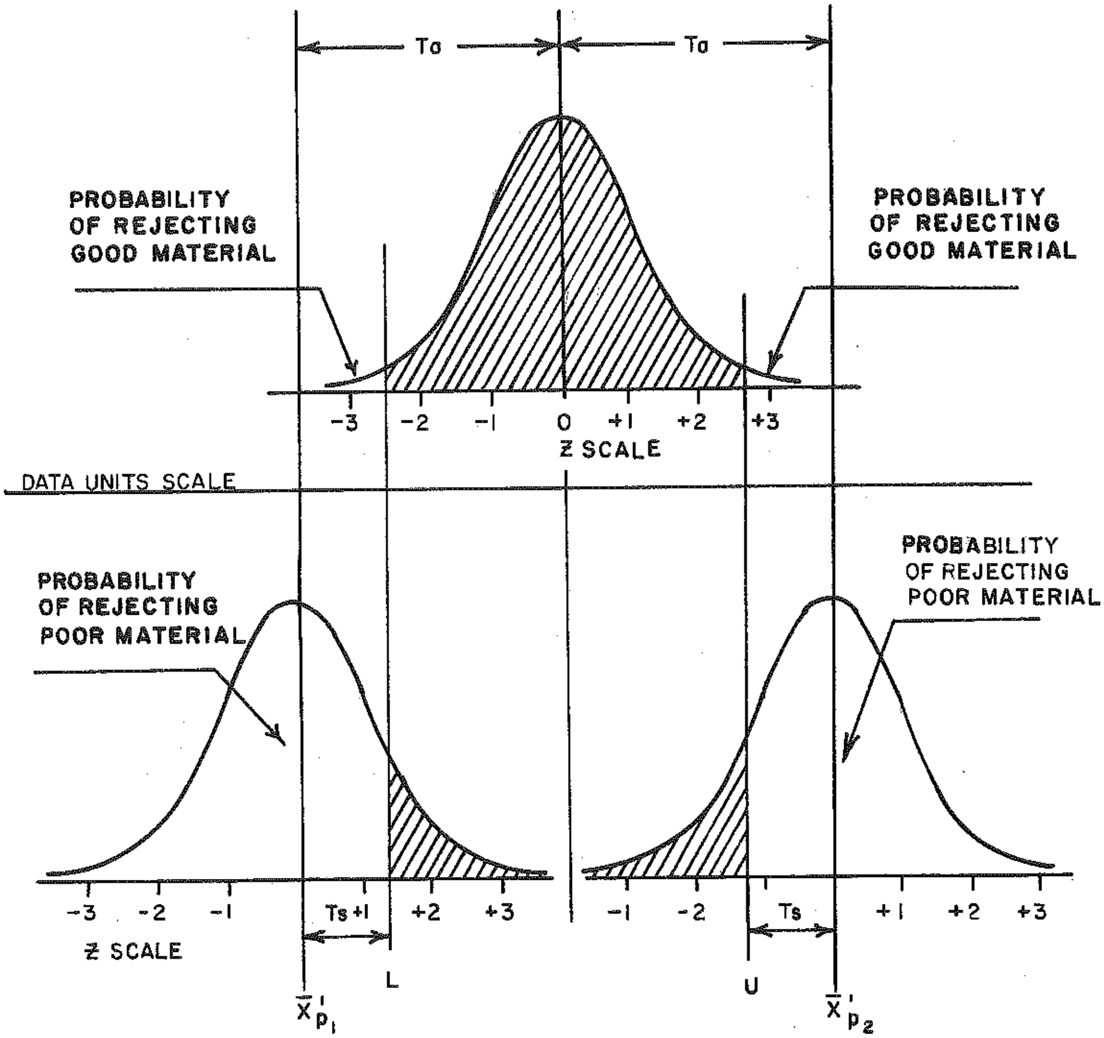

FIGURE 16. PLAN 5, UPPER AND LOWER ACCEPTANCE LIMITS

TABLE 9 - SUGGESTED BALANCE OF ACCEPTANCE SPECIFICATION FACTORS FOR PLAN 5; STANDARD DEVIATION KNOWN (10)

Criticality of Requirement	Probability[a] of Rejection of Good Material, $P_g = \alpha$	Probability of Rejection of Poor Material, $P_p = 1-\beta$	Number of Measurements, n	Difference Between Means, T_a	Acceptance Limits[b]
Critical	0.050	0.995	6	$\pm 1.72\sigma'$	$\bar{x}_p' \quad \pm 1.051\sigma'$
Major	0.010	0.950	5	$\pm 1.78\sigma'$	$\bar{x}_p' \quad \pm 0.736\sigma'$
Minor	0.005	0.900	4	$\pm 1.93\sigma'$	$\bar{x}_p' \quad \pm 0.642\sigma'$
Contractual	0.001	0.800	3	$\pm 2.27\sigma'$	$\bar{x}_p' \quad \pm 0.486\sigma'$

[a] Probability for single limit specification; when specification has both an upper and a lower limit, the probability of rejecting acceptable material may theoretically be doubled.

[b] $\bar{x}_p' \pm T_s$; $T_s = \frac{Z\sigma'}{\sqrt{n}}$

acceptable material and construction or from the procedure discussed in Appendix B.

c. If the material or construction has a lower limit (L) only, the acceptance limit is found from $L = X_p' + A\sigma'$, where A is the multiplier from Table 9. The acceptance rule would read: If the average, $\bar{X}$, of the measurements on n samples is less than L, reject the lot. If the average, $\bar{X}$, is greater than or equal to L, accept the lot.

d. If the material or construction has an upper limit (U) only, the acceptance limit is found from $U = X_p' - A\sigma'$, where A is the multiplier from Table 9. The acceptance rule would read: If the average, $\bar{X}$, of the measurements on n samples is greater than U, reject the lot.

e. If the material or construction has both an upper limit (U) and a lower limit (L), the acceptance limits are found from $L = \bar{\bar{X}}_{p_1}' + A\sigma'$ or $(\bar{\bar{X}}_g' - T_a) + A\sigma'$ and $U = \bar{\bar{X}}_{p_2}' - A\sigma'$ or $(\bar{\bar{X}}_g' + T_a) - A\sigma'$, where A is the multiplier from Table 9. The acceptance rule would read: If the average, X, of the measurements of n samples is less than L or greater than U, reject the lot.

Plan 6 - Modified Statistical Determination of Specification Compliance Using Moving Averages

This plan, although somewhat modified and less rigorous statistically, may be useful when it can be assumed that the material or construction is produced by some process which results in reasonably uniform results with comparitively low variance over a period of time *(25,30)*. Plan 6 requires a fewer number of measurements than some of the other plans and may, therefore, be more economical to use when the process being controlled is amenable to this type of analysis. The precision of the control can still be maintained at the desired level by specifying the number of tests to be used in figuring the moving or running average. If this plan is used for controlling processes in which the material or construction is subject to large, sudden, non-random variation, unsatisfactory lots may not be detected at a time when corrective action is most feasible.

Plan 6 is identical to Plans 3, 4, and 5 with the following exception: the average to be determined in Plan 6 is the moving average, $\bar{X}_m$ which is equal to the average of the n-1 most recent test results representing accepted material or construction plus the test results from the material or construction being considered for acceptance. When the moving average is outside of the specification limits and corrective action has been taken, the next measurement made is used to start a new moving average series.

Unit Price Adjustments

Having experienced great difficulty in rejecting completed work and having realized that the removal or replacement of inferior materials or construction is not always practical, some agencies have attempted to implement a system of price adjustments based on the quality and uniformity of the finished product or construction. Such price adjustments may allow acceptance of marginal material or construction on a formal contract basis while also curbing criticism from other bidders and reviewing authorities. In addition, the specification remains fully enforceable -- the reduced price graduated to conform to the possible loss of serviceability. This is not meant to imply that material or construction should be accepted where safety criteria may be involved. Such a series of price adjustments may, however, be desirable where durability or serviceability is the determinant.

An example of a price adjustment specification currently in Kentucky's Standard Specifications for Road and Bridge Construction is found in Paragraph 307.5.2. This specification allows for a proportional payment of the contract price for concrete pavement thickness deficiencies not greater than one inch. A pavement deficient in thickness by more than one inch is required to be removed. This is a prime example of the nature of price adjustment specifications that are many times necessary where a loss in serviceability or durability may be permissable up to a certain point. However, it should be noted that as the design thickness of the pavement varies, the criticality of any thickness deficiency should also vary. Possibly, this has not been taken into consideration when detailing these specification requirements.

To advocate the use of price adjustment factors in all cases involving marginal quality materials or construction is absurd; yet the use of such factors where the economic implications warrant some action short of complete removal of the work should be given due consideration. Statistical acceptance testing may provide a more precise evaluation of the out-of-tolerance production and therefore be very valuable to the engineer in determining the degree of flexibility he can justify in the acceptance of marginal or borderline results. Perhaps the largest hurdle to overcome in this type of analysis is in correlating serviceability or durability to some measurable characteristic.

Control Charts

In order that trends in the quality and uniformity of materials or construction may be observed and the desired quality be maintained with a minimum of disruption, delay, or expense to either the purchaser or the contractor, the use of control charts may be very helpful for many construction processes. These charts show the sample test average, $\bar{X}$, compared to the desired average for good material or construction, X_g'; the individual test results, X_i, as compared to the desired average, X_g';and the variability of the material or construction compared to the desired standard deviation, σ', or range, R (see Figure 17). Charts that provide assurance that only uniformity of a process is being maintained are called "No Standards Given" control charts. This type of chart is used when the true standard deviation of the measured characteristic is unknown. The control limits presented in Table 10 are used in conjunction with a "Standards Given" control chart. The "Standards Given" chart, in contrast to the "No Standards Given" chart, provides regulations for both process uniformity and specification tolerances. Control charts for attributes sampling may also be developed, but will not be considered in this presentation.

It should also be noted that control charts may be more advantageous to the contractor than to the purchaser, since their primary usefulness is in showing trends that may be developing in the process schedule. Should undesirable trends be observed, the contractor may oftentimes take corrective action prior to rejection of the material or construction. These, obviously, are the primary objectives in the use of control charts -- to observe trends in the uniformity of the process and to avoid costly remedial action by taking corrective action prior to the loss of process control.

USE OF STATISTICAL ACCEPTANCE PLANS

The first section of this report dealt with the theoretical concepts from which basic statistical acceptance testing methods are formulated, and statistical acceptance plans that may be useful in the highway construction industry are developed. This section will be concerned with analyzing and comparing Kentucky's current construction specification requirements with typical requirements developed using statistical acceptance testing concepts.

In order that these discussions may be more meaningful, specifications now being used by other agencies, which employ to some degree the statistical concepts previously studied, will first be presented. This presentation is not meant to imply that these specifications represent the ultimate development in statistical quality control of construction and construction materials; nor is any criticism intended where comments are made. Nevertheless, these agencies are certainly forerunners in the field of statistical quality control in the highway industry, and every effort should be made to scrutinize their work, realizing that eventually Kentucky and other states will most likely be required to incorporate some form of statistically derived acceptance testing plans into their construction specifications.

Historical data compiled for various contract items used in highway construction in Kentucky are also presented as background information which may be useful for establishing statistically derived acceptance specification requirements. Although the statistical usefulness of this data may be questioned, this data may be helpful in developing some feeling for the range of values of the various parameters that must be considered for each item. It is still necessary to consider the reliability of certain statistical methods, the economic compatibility of their use, and the necessary revisions in current sampling and testing procedures for statistical acceptance testing before attempting to justify the adoption of statistical quality control methods to Kentucky's Standard Specifications for Road and Bridge Construction.

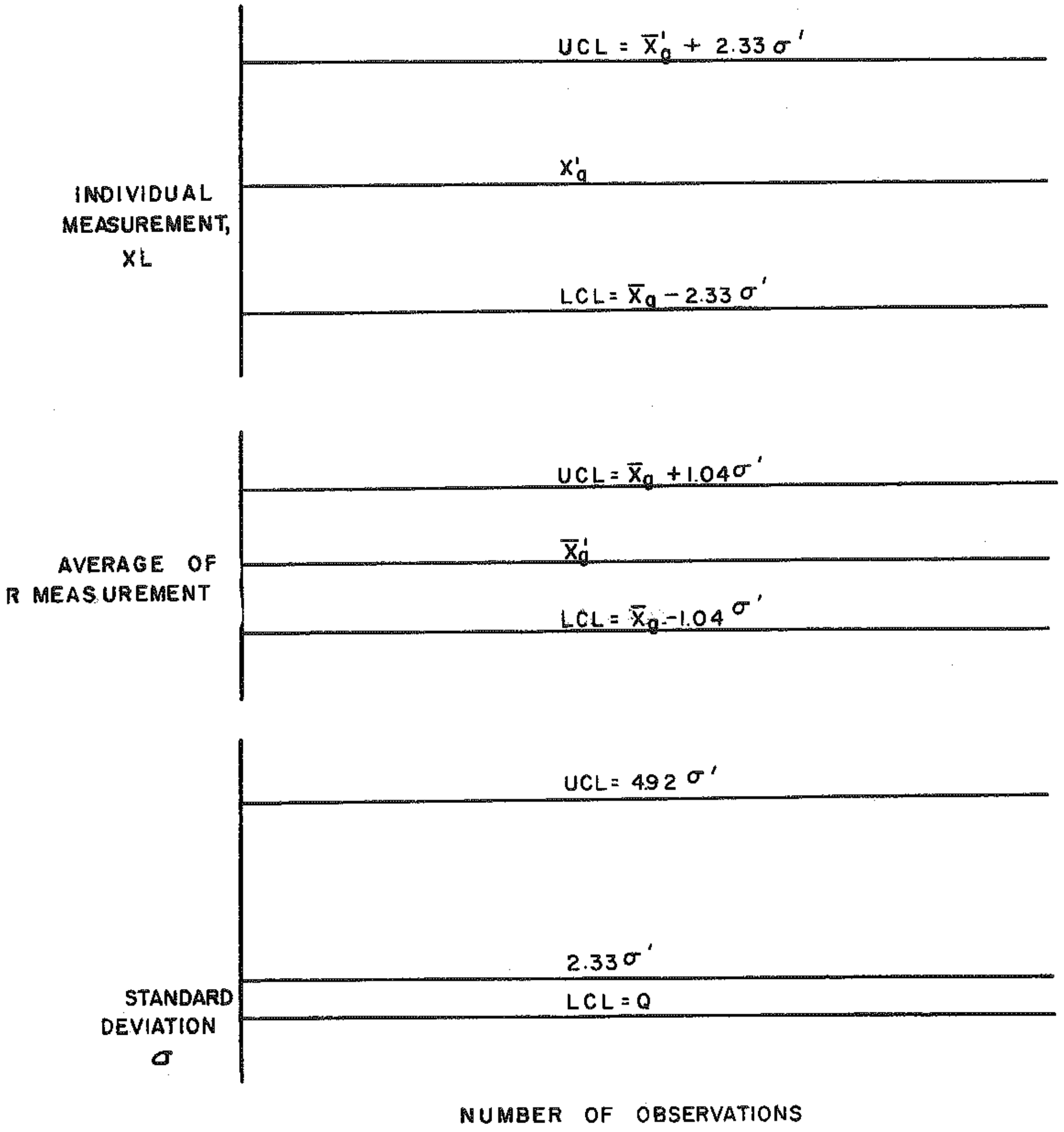

FIGURE 17. EXAMPLE OF CONTROL CHART FOR PLAN 5

TABLE 10 - CONTROL LIMITS FOR A "STANDARDS GIVEN" CONTROL CHART[a]

Criticality of Requirement	Type of Chart	Central Line	Upper Limit[b]	Lower Limit	Sample Size
Critical	Individual	$\bar{x}_g'$	$\bar{x}_g' + 1.64\sigma'$	$\bar{x}_g' - 1.64\sigma'$	1
	Average	$\bar{x}_g'$	$\bar{x}_g' + 0.67\sigma'$	$\bar{x}_g' - 0.67\sigma'$	6
	Range	$2.53\sigma'$	$5.08\sigma'$	0	
Major	Individual	$\bar{x}_g'$	$\bar{x}_g' + 2.33\sigma'$	$\bar{x}_g' - 2.33\sigma'$	1
	Average	$\bar{x}_g'$	$\bar{x}_g' + 1.04\sigma'$	$\bar{x}_g' - 1.04\sigma'$	5
	Range	$2.33\sigma'$	$4.92\sigma'$	0	
Minor	Individual	$\bar{x}_g'$	$\bar{x}_g' + 2.58\sigma'$	$\bar{x}_g' - 2.58\sigma'$	1
	Average	$\bar{x}_g'$	$\bar{x}_g' + 1.29\sigma'$	$\bar{x}_g' - 1.29\sigma'$	4
	Range	$2.06\sigma'$	$4.70\sigma'$	0	
Contractual	Individual	$\bar{x}_g'$	$\bar{x}_g' + 3.08\sigma'$	$\bar{x}_g' - 3.08\sigma'$	1
	Average	$\bar{x}_g'$	$\bar{x}_g' + 1.78\sigma'$	$\bar{x}_g' - 1.78\sigma'$	3
	Range	$1.69\sigma'$	$4.36\sigma'$	0	

[a] This type of chart would be used for Plan 5 (Known Standard Deviation Plan).

[b] The limits for Individual and Average Values given in this chart are expressed in Terms of $\bar{x}_g'$ and σ'. They are identical to those in Table 11 when the difference between the means, T_a, is taken from Table 11. Limits for Range Values are taken from ASTM Manual on Quality Control of Materials, STP 15-C, January 1951.

SPECIFICATIONS USED BY OTHER AGENCIES

Virginia's Control Strip for Density

In an effort to minimize many of the problems of compaction control of granular base materials, the Virginia Department of Highways has developed a control strip approach to determine density requirements. This is not a new concept, yet the use of nuclear testing devices and a modified form of statistical decision theory makes it worthy of consideration. Although the statistical validity in using 98 percent and 95 percent of the control strip mean in the decision criteria may be questionable, the general procedure outlined in this "Special Provision" *(1)* is exemplary of the type of specification that may alleviate, in some areas, many problems concerned with acceptance sampling of base courses:

VIRGINIA DEPARTMENT OF HIGHWAYS
SPECIAL PROVISIONS FOR
NUCLEAR FIELD DENSITY TESTING OF
AGGREGATE BASE AND SURFACE COURSES

February 23, 1965
Rev. 20-19-66

Section 308 of the 1966 edition of the Road and Bridge Specifications is amended in this contract to require the construction of density control strips for the purpose of using the nuclear field density testing device. The revisions are as follows:

At the beginning of the work the Contractor shall build a control strip of the material on an approved and stable subgrade for the purpose of the Engineer's determining density requirements for the project. This control strip will be at least 400 square yards in area and of the same material and depth to be used in the remainder of the work. Compaction will be carried out with conventional rollers approved by the Engineer until no appreciable increase in density is accomplished or until in the opinion of the Engineer no appreciable increase in density will be obtained by additional rolling. Upon completion of the rolling, the density of the strip will be determined by use of a portable nuclear test device.

The compaction of the remainder of the aggregate base course material shall be governed by the density of the control strip. The material shall be tested by sections of approximately 2800 square yards each. The mean density of 5 randomly selected sites from the test section shall be at least 98 percent of the mean density of 10 tests taken from the approved control strip. Placing, compacting and individual testing may be done in subsections of approximately 280 square yards each. When the mean of the test section is less than 98 percent of the control strip mean, the Contractor may be required to rework the entire section. Also, each individual test value shall be at least 95 percent of the mean value of the control strip. When an individual test value is less than 95 percent of the control strip mean, the Contractor shall be required to rework the area represented by that test.

Each test section shall be tested for thickness and any deficiency outside the allowable tolerance shall be corrected by scarifying, placing additional material, remixing, reshaping and recompacting to the specified density.

A new control strip may be requested when:

(1) a change in the source of the material is made, or
(2) a change in the material from the same source is observed, or
(3) ten (10) test sections have been approved without the construction of additional control strips.

Louisiana's Special Provisions for Bituminous Pavements

The Louisiana Department of Highway is experimenting in several areas with statistical type acceptance testing plans. In determining approval of the job-mix formula, four trucks are sampled at random and the average of the four samples taken are required to meet certain requirements for Marshall stability and flow. Also, the contractor is given the responsibility for process control. The contractor is required to furnish a certified asphaltic concrete technician capable of designing asphalt mixes at the plant and to take random samples from each day's run. The results of each run are to be plotted on control charts for individuals and averages. The upper and lower control limits for individual tests and averages shall be set from the job-mix formula values in the following table *(17)*.

U. S. Sieve	Control Limits (17)	
	Individual	Average of 2 Tests
3/4 inch & larger	± 9	± 8
1/2 inch	± 12	± 9
3/8 inch	± 10	± 7
No. 4	± 10	± 7
No. 10	± 9	± 6
No. 40	± 7	± 5
No. 80	± 5	± 4
No. 200	± 3	± 2
% Bitumen	± 6	± 4
Temp. of Mix F*	± 40	± 25

* As based on the approved mixing temperature measured after discharge.

Compaction of mixtures for Marshall stability and flow determination are conducted by the Engineer's personnel at the plant. Four random tests are required and their average must be within the acceptance limits specified in the table below. When less than four tests are run due to unfavorable circumstances, then the acceptance limits shown in this table are based on a lesser number of tests. Adjustments in the unit price are made for mixes outside the limits specified.

Type of Mix	Acceptance Limits for Marshall Stability Average of: (Samples)				Control Limits for Flow Average of: (Samples)			
	4	3	2	1	4	3	2	1
Type 1, 2 & 4								
AC-3, BC & WC	1200 Min	1150 Min	1050 Min	900 Min	15 Max	15 Max	15 Max	18 Max
AC-5, BC & WC	1100 Min	1050 Min	1000 Min	800 Min	15 Max	15 Max	15 Max	18 Max
Type 3								
AC-3, Base	1200 Min	1150 Min	1050 Min	900 Min	15 Max	15 Max	15 Max	18 Max
AC-3, Binder	1450 Min	1400 Min	1300 Min	1100 Min	15 Max	15 Max	15 Max	18 Max
AC-3, Wearing	1800 Min	1700 Min	1600 Min	1350 Min	15 Max	15 Max	15 Max	18 Max
Shoulder	1100 Min	1050 Min	1000 Min	800 Min	15 Max	15 Max	15 Max	18 Max

Surface tolerance acceptance decisions are also made by using statistical sampling plans. The sample, representing one lot, consists of one path of a 10-foot rolling straight edge, 500 feet in length, selected using random sampling procedures for the longitudinal and transverse locations. A lot generally is one day's production of bituminous mix. For lots that result in less than 500 linear feet of roadway, the entire lot is tested. Two surface tolerance settings *(17)* as shown in the table below, are used for the evaluation of a sample. Whenever sections of pavement do not meet the requirements for surface tolerance, the unit price paid per lot is adjusted according to the following table.

Type of Mix	Surface Tolerance Settings
Types 1, 2 and 4 Mixes and Shoulders:	1/8 inch and 3/16 inch
Type 3 Mix:	
Asphaltic Concrete Base Course	3/8 inch and 1/2 inch
Asphaltic Concrete Binder Course	1/4 inch and 1/2 inch
Asphaltic Concrete Wearing Course	1/8 inch and 3/16 inch

ADJUSTMENT IN BID PRICE PER TON
FOR SURFACE TOLERANCE (17)

Linear Percent of Sample Exceeding Surface Tolerance		Percent of Contract Price Per Ton of Aggregate Per Lot
Lower Tolerance Setting	Upper Tolerance Setting	
1% or less	None	105% Payment
1 to 2%	0.5% or Less	100% Payment
More than 2%	0.5 to 0.75%	95% Payment
More than 2%	0.75% to 1.5%	80% Payment
More than 2%	More than 1.5%	50% or remove

The Louisiana Department of Highways seemingly has indicated that realistic tolerances may be established using basic statistical concepts. The schedule of price adjustments also points out the economic or direct dollar motivation for contractors, materials suppliers, and producers to control the uniformity of their products. Another significant point illustrated in these special provisions is that the contractor is being given the responsibility for process control, while the highway department handles only acceptance testing.

New York's Job-Mix Formula Tolerances

Statewide research has been conducted by the New York Department of Public Works to determine the uniformity of asphaltic concrete surface course mixes. The pooled results from this research have been used in establishing job-mix formula tolerances, set at two standard deviations; therefore, only five percent of the samples should fall outside these limits if production is in accordance with the job-mix formula. The pooled standard deviations for the typical plant in New York were compared to AASHO Road Test standard deviations and found to be in fairly close conformance *(24)*. From this comparison, it was reasoned that the tolerances observed were apparently representative of good quality control practice.

The acceptance testing procedure used is somewhat sequential in nature. A uniformity test is run for every 100 batches, and a hot bin analysis is performed after every four uniformity tests. However, a complete hot bin analysis is run whenever a uniformity test result indicates non-uniformity and (or) gradation outside the job-mix tolerances. Results of the hot bin analysis that are not within the stated tolerances are not acceptable. If the specified mix gradation includes material below the No. 80 and No. 200 sieves, one extraction test is performed each day *(24)*. The uniformity test consists of determining the percentage of primary size material in the No. 1 (1/2" - 1/4") and No. 1A (1/4" - 1/8") bins.

Mississippi's Density Control for Bases and Subbases

Mississippi has used a statistically based specification for the past five construction seasons for acceptance testing of density in base and subbase construction. First, a target value, defined as a Specified Value (SV), is assigned for each material. Test values are assumed to be normally distributed, and the base of the normal curve is divided into 20 equal parts, defined as Units of Deviation (UD). For density requirements, one UD is equal to one percent of the SV. The following criteria are then used for acceptance determination *(22)*:

1. the average of six lots must fall within ± 3 UD,
2. each lot must fall within ± 5 UD, and
3. any test must fall within 10 UD.

These criteria are incorporated into a moving average type control plan with increased testing required when compliance is not first met. The following excerpt from Mississippi's Standard Specifications is presented for illustration *(22)*:

Section 700

DESIGNATED CONDITIONS

No lot shall be considered to be within reasonably close conformity if any test result deviates more than ten (10) controlling UD from the SV. In addition, certain of the following numbered conditions shall be applicable to the determination of reasonably close conformity in designated lots as set out hereinbelow.

Condition 1. Two (2) tests will be performed in the lot. The deviation of the test value for the lot shall not be more than three (3) UD from the SV.

Condition 2. One (1) verification test shall be performed for each one of the two (2) initial tests. The new test value (the average of the results of the two (2) verification tests together with the two (2) initial tests) shall deviate no more than three (3) UD from the SV.

Condition 3. Two (2) additional tests shall be performed in a similar manner as the two (2) initial tests and the new test value (the average of the six (6) test results thus obtained) shall be no more than three (3) UD from the SV.

Condition 4. Two (2) tests will be performed in the lot. The test value (the average value of the two (2) test results) shall be no more than five (5) UD from the SV and such test value together with test values used to determine conformity in all of the previous adjacent lot(s), shall deviate no more than three (3) UD from the SV.

Condition 5. One (1) test will be performed in each lot. The deviation of this test result shall be not more than five (5) UD from the SV and such deviation, when averaged with the deviation of all test values used to determine conformity in the five (5) previous adjacent lots shall be no more than (3) UD from the SV.

Condition 6. One (1) additional test shall be taken in a similar manner as the initial test in the lot. The test value of the two (2) test results shall be subject to the requirements set out for the initial test result in the lot.

CONFORMITY DETERMINATION

Lot No. 1. Lot No. 1 in each frame (or any other lot(s) designated as provided herein to be evaluated for compliance in the same manner as for the first lot) is intended to be a test lot to appraise in some detail the quality of the material or the effort, as the case may be, before acceptance or rejection. Such lot shall be subject to

Condition 1; failing compliance with Condition 1 shall then be subject to Condition 2, and failing to comply with Condition 2 shall be subject to Condition 3. In the event this lot does not comply after the application of all three (3) conditions, it shall not be acceptable as being in reasonably close conformity.

Lot Nos. 2, 3, 4, and 5. Lot Nos. 2, 3, 4, and 5 each shall comply with Condition No. 4, otherwise shall not be acceptable as being in reasonably close conformity.

Lot No. 6 and Remaining Lots. Lot No. 6 and all remaining lots shall be subject to Condition No. 5; failing to comply with Condition No. 5, shall be subject to Condition No. 6, and failing to comply with Condition No. 6, shall not be acceptable as being in reasonably close conformity.

Any Lot. When conditions arise justifying the interruption of the continuity of evaluation, such as variation in materials from the same or different sources, variations in type of equipment or in construction methods, indications of borderline products, or other factors that effect the need for closer control to assure the desired results, the Engineer may revert to the initial procedure for determining compliance, beginning again as for the first and succeeding lots as set forth herein.

A system to study variances and percent compliance is being considered to analyze the data collected from the random testing procedures. This is an excellent example of how a statistically based acceptance criteria can be incorporated into construction specifications while valuable data banks are being simultaneously established to enable a more rigorous acceptance criteria eventually to be formulated. Also, the concept of moving-average control, where the contractor's efforts are rewarded by less interruption for testing purposes, is exemplified by this specification.

COMMENTS ON CONVENTIONAL SPECIFICATIONS

The following discussion will consider certain portions of Kentucky's present specification requirements as compared to statistically derived acceptance sampling and testing plans. Any criticism of these specifications is not meant to imply that the tolerances now being used are inadequate or illogical, but is presented to illustrate the statistical type acceptance sampling plans now being considered in keeping with modern construction trends and advancing technology. Particular attention will be given to "Job Control Requirements" for:

1. Soil Embankment and Subgrade Construction
2. Dense-Graded Aggregate Base Construction
3. Bituminous Concrete Construction
4. Structural and Incidental Cement Concrete Construction.

Soil Embankment and Subgrade Construction

Kentucky's present specification requirements *(15)* for Extra Compaction for embankment construction stipulate: "*. . . embankment shall be compacted to a density of not less than 95 percent of maximum density as determined by . . . AASHO designation . . . Tests will be made at such frequency as deemed necessary by the Engineer . . .*"

Kentucky's Manual of Field Sampling and Testing Practices further recommends that a minimum of one test be run for each three feet in elevation per 1000 lineal feet. This type of specification requirement bases acceptance almost entirely on the judgment of the engineer and is rather ambiguous as regards the actual testing or sampling requirements themselves.

A similar specification requirement using statistical acceptance Plan 4 would require the average, $\bar{X}$, of five random tests per lot to be greater than or equal to $X_p' + 0.295R$. For purpose of illustration X_p' might be taken as 95 percent of the maximum density as determined by AASHO Designation T99.

Although this more rigorous statistical specification may define more completely and explicitly the acceptance criteria, it is not presented without realizing the possible disadvantages concerning its use. Firstly, a larger number of tests would be required unless the lot size were appreciably increased from that now recommended as three feet in elevation per 1000 lineal feet. Secondly, the determination of 95 percent of maximum density would require a statistically significant sample size in order to resolve the correct value of X_p' for a particular material. Even if this type of control were established, engineering judgment would always be necessary in determining the acceptance or rejection of unsatisfactory areas where test results could not possibly point out the inadequacy.

It is also worthy to note the other types of statistical acceptance plans that might be considered for this type of construction material. Should a value for the true standard deviation of the embankment material be known, Plan 5 would be much more satisfactory. Considering the usual variability of this type of material, determining a substantiated value for σ' does, however, seem rather unlikely. Plan 3, which is less definite in assigning the buyer's and contractor's risks, might also be useful for embankment and subgrade construction due to the usual variability of the materials involved.

Dense-Graded Aggregate Base Construction

The Department requires a minimum of two gradation tests daily if the daily quantity of material run is 250 tons or greater. If the quantity is less than 250 tons, a minimum of one test daily is required. Assuming that a good estimate of the allowable range for each sieve size is known or could be determined by methods presented in Bureau of Public Roads *Research Guides for Statistical Quality Control (9)*, Plan 5 could be used for acceptance determinations of the gratation of the material. From Tables 2 and 9, it can be determined that five gradation tests would be required for each normal day's run. Requirements for low tonnage days could be made in accordance with statistical principles. Although the number of tests required is consequently increased, the reliability of the test results based on an average of five gradation analyses would seem to warrant the extra effort and (or) expense involved.

Field density requirements for dense-graded aggregate base construction call for a minimum of one test per compacted thickness, per 1000 lineal feet, per roadway *(14)*. This specification might be revised for use under a statistical acceptance criteria by requiring five random tests per compacted thickness per day using Plan 5. For short tonnage days, this plan could be adjusted statistically. Under Plan 5, acceptance would be met when the average, $\bar{X}$, of five random tests was greater than or equal to $\bar{X}_p' + 0.736\,\sigma'$. In this specification, $\bar{X}_p'$ might be taken as equal to 84 percent of the solid volume. Whether or not this particular plan would be adaptable for acceptance testing of dense-graded aggregate density requirements depends on the reliability of the necessary determination of σ' and $\bar{X}_p'$ or $\bar{X}_g'$ for this type of material. Again engineering judgment is required to determine if this statistical tool is or is not advantageous to use.

Plan 6, which makes use of the concept of a moving average control criteria, might also be worthy of consideration for this type of construction. With this plan, a lesser number of tests is required and the contractor is subject to less interruption, as long as test results prove satisfactory. If there is a great deal of variability in t' materials or construction involved, this type of plan may not be very desirable.

Bituminous Concrete Pavement Construction

In order to avoid redundant discussion of statistical acceptance plans as previously analyzed in the section dealing with specifications used by other agencies for statistical quality control, only a few terse remarks will be added here. By making a detailed analysis and a sufficiently large sample survey, the necessary statistical parameters can be determined for generating statistical type acceptance specifications for bituminous pavement construction *(9, 17, 25, 26)*. Either attributes inspection plan presented in this report (Plans 1 or 2) may be used for determining realistic surface or thickness tolerances acceptance criteria based on the desired risks established by engineering judgment. The extent to which this type of control, in lieu of 100 percent inspection, may be desirable will depend on the allowable risks that are determined and the degree of conformance to existing specification requirements that is found using conventional construction methods. With the continuing development of more uniform bituminous pavement placement systems, the necessity for 100 percent inspection may eventually become undesirable from the standpoint of overall efficiency of the inspection team.

Structural and Incidental Concrete Construction

Analogous to other statistical acceptance testing plans, the problems encountered when entertaining statistically-based specification requirements are the determination of the mean of acceptable or unacceptable material or construction and the necessary lot size. Where incidental work is involved, these problems may not be too difficult to resolve. Yet, in major structural concrete construction, these problems may become of paramount importance. Plan 5 would be the most useful statistical acceptance plan for work of this nature. For compressive strength cylinder tests, conservative estimates of X_p' might be taken from Table 1 of Section 403.3.1 of Kentucky's specifications *(15)*. Reliable estimates of the standard deviation, σ, may be secured from scheduled sampling programs as outlined in BPR research guides *(9)*.

The Department's field sampling manual *(14)* requires a minimum of one set of two compression test cylinders per day for each 50 cubic yards of concrete poured. Using a statistical acceptance testing plan, the number of cylinders required per lot would be increased to five or six. Although this is a significant increase in the number of cylinders required, unless large pours are made each day, the resulting inferences that might be drawn concerning the quality of the concrete placed may justify the additional effort. On days where only a small amount of concrete is poured, a modified type of analysis would obviously have to be incorporated into the statistical acceptance criteria. For these small pours, the conventional one set of two cylinders could be used and the acceptance criteria altered accordingly.

Gradation sampling requirements might also be revised in a manner similar to that already discussed under DGA construction. Air content and slump determinations may also be subjected to statistical analysis after having determined realistic values for the parameters involved.

Data Bank

Test data have been compiled over the course of this study from historical records of materials used for highway construction in Kentucky. These data are presented in Tables 11 through 17. Although these data more than likely represent biased sampling techniques, they are of significance in showing to some degree the variability that may be expected from each contract item studied. Perhaps it would be best to consider these efforts in tabulating pertinent statistical parameters as a first step in collecting useful statistical information on which more refined statistical acceptance testing plans may eventually be supported. It should be remembered, however, that before more refined statistical acceptance testing plans can be incorporated into construction specifications, the necessary statistical parameters must be determined by random sampling procedures.

SUMMARY

Perhaps it should be reemphasized when comparing statistical control concepts to conventional practices that the outcome is possibly a more accurate determination of the quality of the material or construction being used, but the product itself is not necessarily superior. For example, even the most accurate testing and sampling methodology for compressive strength of concrete will not yield results at a time when remedial action short of removal of the in-place concrete can be taken. The issue to be studied is whether or not a more reliable appraisal of the quality of the in-place concrete is necessary prior to acceptance of the contractor's work.

Giving due consideration to the ever increasing speed of modern highway construction, it is reasonable to surmise that eventually the State of Kentucky, as well as other states, will have to incorporate within their construction specifications certain statistical methods of acceptance sampling and testing. It seems, therefore, that even though the Department may not be ready to initiate this process, certain considerations should be made at this time. Firstly, the basic concepts of statistical quality control must be understood by Department personnel before any successful statistical control specifications can be initiated. With this thought in mind, a series of workshops introducing these basic principles and how they may apply to the highway construction industry should be set up

TABLE 11 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR ASPHALT CEMENTS

GRADE	SUPPLIER	SOURCE	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION																	
			Specific Gravity			Solubility in CCl_4			Thin Film Loss			Flash Point			Penetration			% of Original Penetration		
PAC-3	0	2	13	1.0212	.0032	1	0.00	.00	3	.180	.089	13	580	21	13	68.7	3.9	3	59.6	4.8
		15	12	1.0236	.0041	2	99.95	.00	4	.067	.035	15	592	22	15	67.5	1.8	4	61.6	4.3
	1	1	10	1.0304	.0047	4	99.80	.19	5	.084	.053	10	547	6	10	64.4	3.0	5	61.0	1.5
		2	12	1.0320	.0033	5	99.95	.03	5	.092	.059	12	567	18	12	65.6	2.9	5	68.1	4.0
		3	6	1.0359	.0026	0	0.00	.00	0	.000	.000	6	548	16	6	67.5	2.1	0	0.0	0.0
	7	2	15	1.0197	.0045	4	99.95	.03	0	.000	.000	16	534	17	16	65.2	2.6	5	62.3	10.1
	Total		68	1.0258	.0068	16	99.91	.11	17	.099	.066	72	563	28	72	66.5	3.1	22	62.8	6.1
PAC-5	0	2	33	1.0195	.0039	6	99.95	.03	12	.105	.038	33	581	23	33	93.4	6.8	12	59.2	5.0
		15	89	1.0205	.0039	11	99.94	.08	13	.118	.075	97	592	17	101	94.9	3.1	13	57.7	4.6
	1	1	11	1.0243	.0079	5	99.93	.06	5	.230	.249	12	550	31	12	90.4	6.3	5	57.2	6.7
		2	32	1.0248	.0052	9	99.90	.06	11	.092	.083	31	560	14	32	93.1	3.1	12	61.9	4.7
		3	24	1.0336	.0015	0	0.00	.00	0	.000	.000	24	541	50	24	96.7	3.3	0	0.0	0.0
	3	2	67	1.0067	.0041	25	99.93	.06	32	.072	.052	68	580	27	68	92.9	4.8	33	64.5	6.7
	5	6	12	1.0105	.0034	11	99.95	.03	11	.313	.196	11	542	27	12	97.6	11.3	11	54.3	5.2
		9	28	1.0258	.0057	3	99.86	.10	0	.000	.000	28	641	12	28	91.3	2.7	5	64.9	9.4
	6	10	37	1.0214	.0059	12	99.83	.13	0	.000	.000	37	542	24	37	94.3	5.5	13	58.8	6.8
	7	2	11	1.0148	.0029	3	99.86	.13	0	.000	.000	11	520	13	11	89.9	3.2	3	58.5	7.2
		11	21	1.0149	.0035	4	99.88	.02	0	.000	.000	21	535	18	21	96.3	7.0	6	63.5	5.4
		12	58	1.0147	.0047	8	99.86	.15	9	.179	.128	61	542	20	61	93.3	3.2	9	64.3	3.5
	9	14	9	1.0256	.0074	2	99.77	.00	2	.065	.000	9	576	25	9	91.3	3.5	2	55.9	0.0
	Total		462	1.0188	.0086	106	99.90	.10	96	.130	.130	473	574	36	479	93.8	4.8	131	61.0	6.6
PAC-7	0	2	23	1.0160	.0045	2	99.91	.00	4	.107	.017	23	570	33	23	134.1	7.5	4	57.3	7.2
		15	43	1.0156	.0043	2	99.92	.00	3	.080	.079	43	583	16	43	132.1	15.5	3	50.6	3.1
	1	1	12	1.0205	.0055	4	99.77	.15	5	.262	.203	12	530	28	12	131.7	6.1	5	53.6	6.7
		2	22	1.0261	.0049	7	99.90	.09	10	.660	.255	22	503	41	22	138.2	7.0	10	52.5	6.7
	3	2	56	1.0041	.0054	15	99.90	.07	13	.188	.208	56	576	35	56	133.6	8.4	17	60.8	4.5
	5	9	3	1.0265	.0010	1	0.00	.00	0	.000	.000	3	623	6	3	135.3	2.9	1	0.0	0.0
	6	10	8	1.0189	.0031	0	0.00	.00	0	.000	.000	8	536	28	8	138.6	3.0	2	52.6	0.0
	7	2	20	1.0111	.0032	3	99.95	.04	0	.000	.000	20	526	18	20	125.8	6.9	4	66.3	4.5
		11	17	1.0108	.0041	3	99.75	.08	1	.000	.000	14	554	28	17	136.6	9.2	3	63.4	7.4
		12	68	1.0118	.0037	14	99.92	.08	9	.174	.064	73	537	20	73	136.8	5.8	11	64.0	6.0
	Total		272	1.0130	.0076	51	99.89	.09	45	.323	.165	274	553	37	277	134.3	9.4	60	59.0	7.4
PAC-9	0	2	2	1.0140	.0000	0	0.00	.00	2	2,010	.000	2	483	00	3	307.3	76.6	1	0.0	0.0
	1	1	7	1.0195	.0053	2	99.93	.00	3	.820	.544	7	485	37	7	230.3	20.6	3	46.0	5.5
		2	15	1.0237	.0065	1	0.00	.00	4	1.067	.684	14	484	62	15	232.1	19.7	3	43.8	1.2
	3	2	34	1.0002	.0064	2	99.94	.00	2	.750	.000	34	569	24	34	254.6	28.3	2	51.8	0.0
	5	9	18	1.0158	.0030	3	99.91	.02	0	.000	.000	18	619	6	18	250.4	8.6	4	57.5	9.0
	6	10	16	1.0110	.0029	4	99.81	.13	0	.000	.000	16	541	28	16	252.6	29.5	6	51.3	6.5
	7	2	6	1.0077	.0094	0	0.00	.00	0	.000	.000	6	520	15	6	252.0	32.2	0	0.0	0.0
		11	7	1.0067	.0037	1	0.00	.00	0	.000	.000	8	528	24	8	274.3	41.5	2	53.5	0.0
		12	9	1.0026	.0038	5	99.90	.06	2	.165	.000	12	533	16	12	274.0	26.8	2	60.4	0.0
	Total		114	1.0097	.0099	18	99.89	.08	13	.864	.830	117	547	52	119	253.9	31.0	23	51.2	7.6

NOTE: Lines showing "Total" include values for which the supplier and source were unknown.

TABLE 12 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR CUT-BACK ASPHALTS

GRADE	SUPPLIER	SOURCE	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION																										
			Specific Gravity			Solubility in CCl4			Flash Point			Penetration			Residue at Spec. Pen.			Viscosity			Distillation								
																					Up to 437°F.			Up to 500°F.			Up to 600°F.		
Primer L	1	1	7	.9341	.0030	2	99.95	.00	0	0	0	7	99	20	7	54	6	7	73	9	0	0	0	0	0	0	0	0	0
		2	18	.9325	.0057	4	99.87	.11	0	0	0	18	94	9	18	55	2	18	76	20	0	0	0	0	0	0	0	0	0
	Total		25	.9330	.0051	6	99.89	.10	0	0	0	25	96	13	25	55	3	25	75	18	0	0	0	0	0	0	0	0	0
RC-1	3	2	14	.9261	.0029	0	0.00	.00	10	100	11	14	101	6	14	71	2	9	118	44	14	79.2	3.2	14	89.5	1.2	14	96.2	0.8
	Total		14	.9261	.0029	0	0.00	.00	10	100	11	14	101	6	14	71	2	9	118	44	14	79.2	3.2	14	89.5	1.2	14	96.2	0.8
RC-2	1	1	2	.9613	.0000	2	99.96	.00	2	85	0	2	116	0	2	74	0	2	164	0	2	71.4	0.0	2	82.5	0.0	2	92.9	0.0
	3	2	14	.9464	.0027	0	0.00	.00	13	94	13	14	100	5	14	77	1	14	171	17	14	74.1	2.5	14	85.8	1.9	14	94.8	0.7
	6	10	19	.9645	.0041	10	99.88	.12	19	95	11	19	90	4	19	79	1	19	165	18	19	66.0	2.7	19	82.8	0.9	19	94.5	1.0
	7	12	2	.9554	.0000	0	0.00	.00	2	85	0	2	101	0	2	75	0	2	153	0	2	74.3	0.0	2	86.9	0.0	2	96.0	0.0
	Total		37	.9570	.0093	12	99.89	.11	36	93	11	37	96	8	37	78	2	37	166	17	37	69.8	4.7	37	84.2	2.1	37	94.6	1.0
RC-3	0	2	29	.9747	.0043	11	99.89	.07	29	106	15	29	112	9	29	82	1	29	383	44	29	47.9	8.6	29	72.5	4.8	29	90.6	2.0
		15	31	.9754	.0033	6	99.90	.09	31	105	19	31	109	17	31	82	1	31	375	45	31	43.7	3.9	31	70.2	2.0	31	90.6	1.8
	1	1	25	.9826	.0040	4	99.85	.11	23	112	24	25	103	11	25	81	2	25	393	56	25	60.0	4.2	25	78.2	1.7	25	91.7	1.2
		2	26	.9828	.0038	9	99.95	.02	26	102	15	26	98	9	26	79	1	26	398	40	26	64.3	5.0	26	79.6	3.3	26	91.1	2.6
		3	24	.9882	.0024	6	99.94	.04	18	95	8	24	94	6	24	79	1	24	430	27	24	67.4	2.8	24	80.3	1.3	24	90.9	1.2
	3	2	70	.9591	.0057	19	99.93	.04	70	101	12	70	106	9	69	80	2	70	356	67	70	63.5	6.7	70	80.7	3.5	70	92.7	1.5
	5	7	17	.9833	.0032	3	99.88	.09	17	101	9	17	113	10	17	81	1	17	340	51	17	54.2	3.7	17	77.8	2.1	17	92.8	1.2
	6	10	47	.9819	.0070	26	99.91	.09	47	127	41	47	130	67	47	84	1	47	372	62	38	53.6	13.1	47	63.0	26.9	47	87.5	9.0
	7	2	21	.9658	.0045	8	99.95	.04	21	98	9	21	104	5	20	80	2	21	426	80	21	62.9	3.2	21	80.0	2.0	21	92.0	1.2
		12	2	.9626	.0000	0	0.00	.00	2	93	0	2	92	0	2	79	0	2	375	0	2	68.4	0.0	2	83.6	0.0	2	93.0	0.0
	9	2	9	.9627	.0028	7	99.94	.04	9	114	15	9	110	6	9	79	1	9	391	28	9	52.6	4.3	9	75.2	2.5	9	91.0	1.5
		14	18	.9672	.0032	4	99.92	.08	16	97	9	17	100	9	17	81	3	18	368	27	17	54.7	2.4	17	76.6	1.5	17	91.7	1.0
	Total		324	.9735	.0112	108	99.92	.07	314	106	23	323	109	29	321	81	2	324	380	59	314	57.3	10.1	323	75.3	12.2	323	91.0	4.1
RC-4	1	1	2	.9864	.0000	0	0.00	.00	2	178	0	2	99	0	2	84	0	2	178	0	2	62.6	0.0	2	77.6	0.0	2	90.3	0.0
	3	2	36	.9644	.0038	5	99.93	.04	34	108	22	36	101	6	36	85	2	36	207	29	36	61.9	7.2	36	79.7	3,7	36	92.5	1.9
	Total		38	.9655	.0063	5	99.93	.04	36	112	27	38	101	6	38	85	2	38	206	29	38	61.9	7.1	38	79.6	3.7	38	92.4	2.0
MC-3	0	2	17	.9711	.0023	7	99.90	.08	17	187	10	17	264	20	17	84	1	17	370	39	4	3.9	1.0	17	24.7	5.3	17	77.9	2.5
		15	10	.9713	.0004	1	0.00	.00	4	188	17	10	259	27	10	84	1	10	379	24	1	0.0	0.0	10	18.5	4.8	10	75.0	3.0
	1	1	14	.9826	.0019	4	99.94	.05	14	182	24	14	185	37	14	80	2	14	403	45	2	3.5	0.0	14	14.1	4.4	14	71.6	2.7
		2	21	.9847	.0014	7	99.95	.05	21	189	12	21	164	14	21	80	1	21	400	40	1	0.0	0.0	21	20.5	2.8	21	73.4	3.4
	3	2	56	.9624	.0113	12	99.91	.07	51	186	12	55	174	36	13	76	8	56	355	67	20	23.6	7.6	15	75.6	12.6	18	80.4	1.4
	5	7	7	.9855	.0025	1	0.00	.00	7	186	8	7	197	22	7	84	1	7	452	63	0	0.0	0.0	7	19.6	7.5	7	73.9	1.9
		8	6	.9804	.0006	6	99.95	.06	6	182	16	6	159	8	6	82	0	6	355	8	5	3.8	1.0	6	27.6	2.3	6	77.6	1.4
	6	10	9	.9754	.0063	1	0.00	.00	9	195	10	9	233	34	9	86	3	9	292	77	0	0.0	0.0	9	12.0	4.6	9	69.3	6.4
	7	2	22	.9708	.0102	6	99.88	.19	21	166	48	22	140	41	18	80	2	18	401	31	0	0.0	0.0	18	19.2	2.9	18	73.6	4.0
		11	7	.9677	.0015	0	0.00	.00	7	174	34	7	155	8	7	80	1	7	436	60	0	0.0	0.0	7	21.3	2.7	7	76.5	2.4
		12	13	.9660	.0011	1	0.00	.00	13	192	13	13	171	27	13	80	1	13	353	24	2	1.8	0.0	13	18.8	4.2	13	74.4	1.5
	9	2	6	.9706	.0020	3	99.93	.04	6	183	12	6	190	31	6	81	1	6	398	117	0	0.0	0.0	6	21.2	4.8	6	75.1	1.5
	Total		192	.9712	.0109	53	99.92	.08	180	184	22	191	187	48	145	81	4	188	376	62	38	15.2	11.7	147	26.2	19.1	150	75.2	4.2
MC-4	1	1	12	.9902	.0027	2	99.95	.00	12	194	21	12	185	18	12	86	1	12	210	27	0	0.0	0.0	11	7.8	5.0	12	64.3	4.1
		2	11	.9904	.0050	3	99.95	.04	11	199	15	11	167	14	11	82	1	11	192	13	0	0.0	0.0	11	13.8	2.3	11	66.6	2.2
	Total		23	.9903	.0039	5	99.95	.04	23	197	18	23	176	18	23	84	2	23	202	23	0	0.0	0.0	22	10.8	4.9	23	65.4	3.4

Note: Lines showing "Total" include values for which the supplier and source were unknown.

TABLE 13 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR EMULSIFIED ASPHALTS

GRADE	SUPPLIER	SOURCE	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION																							
			Specific Gravity			Solubility in CCl_4			Penetration			Sieve Test			Settlement (5 Days)			Residue of Spec. Pen.			Viscosity			Demulsibility		
RS-1	1	1	9	1.0163	.0041	3	99.77	.10	9	156	11	3	.11	.09	5	1.98	0.69	8	57.9	1.9	9	37	9	9	83.2	14.4
		2	19	1.0157	.0038	6	99.65	.23	19	156	17	11	.12	.06	8	1.27	0.83	19	59.2	1.7	19	35	9	19	75.8	11.6
	3	2	7	1.0003	.0040	0	0.00	.00	7	162	12	6	.13	.05	1	0.00	0.00	7	63.6	4.4	7	73	16	7	73.5	13.9
	5	6	4	1.0138	.0067	1	0.00	.00	3	158	31	2	.15	.00	2	0.95	0.00	4	63.8	2.6	4	41	8	4	79.2	17.2
		7	6	1.0070	.0055	1	0.00	.00	6	150	23	6	.40	.32	3	0.60	0.87	6	64.9	2.7	6	55	23	6	76.2	11.4
	7	2	9	1.0047	.0020	2	99.82	.00	9	135	12	5	.18	.13	4	0.37	0.34	9	61.4	2.6	9	23	3	9	73.8	11.3
		11	13	1.0071	.0025	2	99.77	.00	12	131	8	6	.12	.04	5	0.40	0.45	13	60.4	2.4	13	31	5	13	71.7	15.7
	Total		67	1.0101	.0067	15	99.62	.35	65	149	19	39	.17	.16	28	0.98	0.86	66	60.8	3.3	67	39	17	67	75.7	13.3
RS-2	1	1	22	1.0126	.0044	5	99.79	.22	21	162	10	22	.35	.25	7	0.40	0.42	22	65.7	1.4	23	202	82	22	90.2	8.7
		2	20	1.0120	.0052	5	99.66	.15	20	160	16	19	.43	.25	6	1.50	2.43	20	65.6	1.2	20	213	93	19	86.0	9.2
	2	4	5	1.0006	.0023	0	0.00	.00	2	116	00	5	.42	.50	0	0.00	0.00	4	67.9	1.1	5	259	29	4	50.7	9.9
	3	2	24	0.9982	.0056	3	99.69	.27	24	173	9	19	.35	.17	9	0.91	0.61	24	68.1	1.6	24	220	95	24	86.4	8.1
	5	6	24	1.0079	.0048	3	99.25	.45	23	149	13	22	.18	.09	7	0.69	0.85	24	65.6	1.4	24	157	52	24	73.5	10.2
		7	10	1.0078	.0041	0	0.00	.00	8	148	20	10	.57	.31	4	0.12	0.05	9	65.5	1.8	10	138	75	9	77.8	15.3
	7	2	14	1.0044	.0030	2	99.89	.00	13	161	14	11	.20	.10	2	0.85	0.00	13	66.5	1.3	14	108	54	12	77.1	8.8
		11	24	1.0045	.0025	2	99.87	.00	24	168	14	22	.25	.13	8	0.36	0.14	24	65.1	1.2	24	164	59	24	78.0	12.3
	8	2	40	1.0081	.0046	4	99.82	.18	38	146	18	30	.41	.57	17	0.53	0.53	38	66.4	1.9	39	140	48	28	69.6	9.7
	Total		264	1.0075	.0056	34	99.74	.26	239	158	17	239	.32	.30	91	0.65	0.91	248	66.3	1.8	267	157	83	232	78.4	12.0
MS-2	1	2	2	1.0235	.0000	1	00.00	.00	2	138	00	2	.15	.00	1	0.00	0.00	2	64.3	0.0	2	93	0	0	0.0	0.0
	Total		2	1.0235	.0000	1	00.00	.00	2	138	00	2	.15	.00	1	0.00	0.00	2	64.3	0.0	2	93	0	0	0.0	0.0
SS-1	3	2	2	1.0055	.0000	0	00.00	.00	2	173	00	0	.00	.00	0	0.00	0.00	2	63.8	0.0	2	76	0	0	0.0	0.0
	5	6	1	0.0000	.0000	0	0.00	.00	1	0	00	0	.00	.00	0	0.00	0.00	1	0.0	0.0	1	0	0	0	0.0	0.0
		7	4	1.0165	.0033	0	0.00	.00	3	173	42	0	.00	.00	0	0.00	0.00	3	66.5	0.5	4	41	6	0	0.0	0.0
	Total		7	1.0123	.0059	0	0.00	.00	6	175	27	0	.00	.00	0	0.00	0.00	6	65.2	2.0	7	48	20	0	0.0	0.0
SS-1h	1	1	13	1.0217	.0052	0	0.00	.00	12	81	12	0	.00	.00	0	0.00	0.00	13	58.3	0.7	13	39	7	0	0.0	0.0
		2	10	1.0227	.0027	0	0.00	.00	10	78	13	0	.00	.00	0	0.00	0.00	10	58.8	1.0	10	37	7	0	0.0	0.0
	5	6	1	0.0000	.0000	0	0.00	.00	1	00	00	0	.00	.00	0	0.00	0.00	1	0.0	0.0	1	0	0	0	0.0	0.0
	Total		32	1.0209	.0051	0	0.00	.00	31	81	11	0	.00	.00	0	0.00	0.00	32	58.9	1.3	32	35	9	0	0.0	0.0
MS-3	1	1	1	0.0000	.0000	1	0.00	.00	0	0	0	1	.00	.00	0	0.00	0.00	0	0.0	0.0	1	0	0	0	0.0	0.0
		2	7	1.0201	.0115	4	99.68	.19	0	0	0	3	.23	.15	0	0.00	0.00	7	68.7	1.6	7	157	27	0	0.0	0.0
	Total		8	1.0211	.0110	5	99.71	.18	0	0	0	4	.25	.13	0	0.00	0.00	8	69.2	2.0	8	158	25	0	0.0	0.0
RS-2C	1	1	5	1.0186	.0064	1	0.00	.00	5	193	14	4	.27	.10	3	0.77	0.68	5	66.5	1.4	5	167	60	0	0.0	0.0
		2	16	1.0173	.0047	1	0.00	.00	16	182	20	15	.23	.21	13	1.58	0.85	16	66.5	1.8	16	174	41	0	0.0	0.0
	5	6	1	0.000	.0000	0	0.00	.00	1	0	0	0	.00	.00	1	0.00	0.00	1	0.0	0.0	1	0	0	0	0.0	0.0
	Total		22	1.0051	.0051	2	0.00	.00	22	182	22	19	.24	.19	17	1.40	0.82	22	66.5	1.6	22	172	44	0	0.0	0.0

Note: Lines showing "Total" include values for which the supplier and source were unknown.

TABLE 14 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR TARS

GRADE	SUPPLIER	SOURCE	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION																							
			Specific Gravity			Solubility in CCL_4			Distillation															Viscosity		
									Up to 170°			170° - 235°			235° - 270°			270° - 300°			Residue @ 300°					
RT-2	4	5	21	1.1741	0.0074	7	92.50	2.10	0	0.0	0.0	0	0.0	0.0	21	22.4	3.8	21	35.6	2.1	0	0.0	0.0	21	99	7
	7	2	12	1.1625	0.0081	0	0.0	0.0	6	0.3	0.4	0	0.0	0.0	12	27.6	2.0	12	37.4	1.6	0	0.0	0.0	12	92	6
		11	6	1.1460	0.0159	0	0.0	0.0	2	1.3	0.0	0	0.0	0.0	5	24.9	1.9	5	34.2	3.6	0	0.0	0.0	6	116	33
		13	40	1.1557	0.0046	6	93.02	0.48	19	1.1	0.5	0	0.0	0.0	26	24.7	2.1	26	34.6	1.9	0	0.0	0.0	40	94	8
	Total		117	1.1516	0.0194	22	93.67	1.72	63	1.5	1.0	0	0.0	0.0	102	24.9	3.0	64	35.4	2.3	38	32.0	2.5	117	100	16

Note: Line showing "Total" includes values for which the supplier and source were unknown.

TABLE 15 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR DENSE-GRADED AGGREGATE

Specific Gravity	Solid Density	Project	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION								
			Field Density			% Moisture			% Solid Density		
2.28	142.30	5	23	125.0	3.9	23	6.1	1.9	23	87.8	2.7
2.62	163.50	9	8	139.7	1.7	8	3.3	0.3	8	85.5	1.0
		10	42	141.3	2.5	42	3.4	0.6	42	86.3	1.4
		Total	50	141.0	2.4	50	3.3	0.5	50	86.2	1.4
2.63	164.11	15	6	144.5	3.0	6	4.9	0.4	6	88.0	1.9
2.65	165.35	1	5	141.7	1.3	5	4.1	0.7	5	85.6	0.7
		8	218	142.7	4.0	218	2.3	0.6	218	86.2	2.5
		18	245	144.0	3.7	245	3.1	0.9	245	86.5	2.3
		19	136	143.2	3.8	136	2.8	0.9	136	86.5	2.3
		21	47	141.3	2.5	47	2.9	0.9	47	85.5	1.5
		Total	651	143.2	3.8	651	2.8	0.9	651	86.4	2.3
2.66	165.98	14	30	143.3	5.7	30	3.9	1.0	30	84.7	7.2
		22	2	146.7	-	2	2.0	-	2	88.4	-
		Total	32	143.5	5.7	32	3.8	1.1	32	84.9	7.1
2.67	166.60	7	4	144.8	2.4	4	2.9	0.6	4	86.9	1.4
		10	19	140.9	3.0	19	3.4	0.6	19	84.7	1.8
		13	4	143.4	8.6	4	4.2	1.6	4	86.3	5.2
		17	2	146.9	-	2	5.9	-	2	88.4	-
		21	34	142.4	3.3	34	3.3	0.8	34	85.5	2.0
		22	37	141.1	3.7	37	2.7	1.0	37	84.7	2.2
		Total	100	141.9	3.7	100	3.2	1.0	100	85.2	2.3
2.68	167.23	3	12	142.9	1.9	12	3.1	0.5	12	85.4	1.1
		8	15	142.7	1.5	15	4.9	1.5	15	85.3	0.9
		11	44	138.8	6.4	44	3.6	1.2	44	82.9	3.9
		Total	71	140.3	5.5	71	3.7	1.3	71	83.9	3.3
2.69	167.86	2	34	142.7	4.1	34	2.2	0.5	34	85.0	2.5
		12	20	141.7	6.3	20	2.5	0.7	20	84.3	3.8
		16	10	146.1	2.5	10	2.4	0.5	10	87.0	1.5
		22	3	148.2	3.8	3	2.5	0.1	3	88.3	2.2
		23	18	146.3	2.8	18	3.0	0.8	18	87.1	1.7
		26	13	145.8	3.4	13	3.1	0.6	13	86.9	2.1
		Total	98	144.1	4.6	98	2.6	0.7	98	85.8	2.8
2.70	168.48	8	96	144.4	3.2	96	3.0	1.1	96	85.7	3.7
		22	10	145.4	2.4	10	2.5	0.7	10	86.3	1.4
		24	2	141.6	-	2	3.5	-	2	84.1	-
		25	4	142.2	0.4	4	2.9	0.2	4	84.4	0.3
		Total	112	144.3	3.7	112	2.9	1.0	112	85.7	3.5
2.71	169.40	20	4	144.5	1.4	4	3.4	0.6	4	85.3	0.9
2.72	169.73	4	33	143.7	3.5	33	2.8	0.7	33	84.7	2.1

TABLE 16 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR SUBGRADE DENSITIES AND MOISTURE CONTENTS

NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION

Project Code No.	Proctor Density			Proctor Moisture			Field Density			Field Moisture		
1	117	107.4	2.0	117	17.5	1.0	117	103.8	2.4	117	16.2	4.2
2	153	105.1	5.3	153	20.1	2.9	153	108.2	8.1	153	17.2	4.0
3	102	102.9	5.8	102	20.8	2.7	102	106.4	8.0	102	19.1	5.1
4	5	99.8	0.0	5	21.0	0.0	5	97.8	1.5	5	19.9	1.3
5	26	114.1	2.1	26	21.1	-	26	110.5	7.4	26	7.9	2.7
6	2	114.4	0.0	2	8.6	0.0	2	117.4	0.0	2	2.3	0.0
7	146	109.4	5.4	146	16.9	2.1	146	106.4	5.0	146	15.6	3.4
8	19	95.9	5.8	19	27.6	5.0	19	95.1	6.1	19	25.0	4.4
9	98	105.4	1.9	98	19.9	0.4	98	105.1	4.7	98	18.3	3.0
10	145	119.8	3.5	145	11.9	1.6	145	117.9	5.4	145	11.0	2.6
11	83	106.7	2.3	83	18.3	2.5	83	105.1	4.7	83	17.6	3.4
12	596	110.7	1.4	596	15.6	3.4	596	111.3	7.3	596	13.1	4.8
13	420	107.0	1.9	420	18.4	2.9	420	104.5	6.6	420	17.6	5.3
14	21	114.4	4.2	21	7.0	1.8	21	110.7	3.4	21	6.3	2.8
15	26	109.6	4.0	26	18.2	2.4	26	107.3	4.7	26	14.7	3.5
16	6	111.8	8.8	6	18.7	3.8	6	104.7	16.8	6	10.4	2.1
17	39	114.3	1.6	39	13.4	2.3	39	119.4	4.3	39	7.3	1.2
18	6	110.2	1.5	6	18.6	1.0	6	113.0	4.5	6	11.7	2.6
19	53	110.0	1.5	53	17.2	1.2	53	108.5	8.4	53	7.3	1.5
20	110	110.0	3.0	110	16.2	1.9	110	107.6	3.7	110	13.9	2.1
21	71	102.5	2.2	71	20.3	2.0	71	97.4	17.1	71	13.4	2.2
22	22	101.0	4.5	22	20.9	1.5	22	101.6	6.9	22	11.6	2.6
23	128	106.5	5.1	128	20.0	2.6	128	108.0	7.5	128	12.7	3.4
24	58	103.0	3.3	58	20.2	1.4	58	96.6	6.7	58	17.1	2.4
25	50	102.6	3.5	50	21.4	2.6	50	101.0	4.7	50	20.7	2.7
26	3	104.2	0.0	3	19.5	0.0	3	101.6	1.7	3	12.9	2.7
27	201	106.2	4.0	201	18.9	2.0	201	106.5	4.9	201	15.0	3.5
28	74	108.7	3.0	74	17.3	1.5	74	108.9	3.8	74	13.0	2.7
29	1	-	-	1	-	-	1	-	-	1	-	-
30	145	106.9	3.6	145	18.2	2.2	145	102.0	6.5	145	16.4	4.7
31	550	104.3	4.4	550	19.8	2.9	550	102.5	5.2	550	18.9	3.3
32	893	104.5	4.4	893	19.5	2.7	893	104.6	6.0	893	18.5	4.0
33	98	105.5	3.2	98	19.0	2.2	98	104.4	4.7	98	18.6	2.9
34	162	107.9	4.8	162	16.9	3.1	162	109.0	6.9	162	15.2	3.7
35	53	105.5	2.8	53	20.3	2.7	53	106.1	3.7	53	17.7	2.5
36	88	105.0	6.0	88	20.2	4.6	88	105.6	8.3	88	15.6	4.1
37	44	104.9	3.9	44	20.9	3.4	44	106.8	4.3	44	16.3	3.5

TABLE 17 - ARITHMETIC MEANS AND STANDARD DEVIATIONS FOR CORRUGATED PIPE

GAUGE	SUPPLIER	SOURCE	NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION																													
			WEIGHT IN OZ/FT^2			% OFF GAUGE NO.			SPELTER WT. (OZ/FT^2)			CARBON*			MANGANESE			PHOSPHOROUS			SULFUR			SILICON			SUM OF COMPONENTS			COPPER		
8	1	1	2	112.6	0.0	2	+0.1	0.0	2	2.3	0.0	2	.066	.000	2	.339	.000	2	.008	.000	2	.022	.000	2	0.0	0.0	2	.435	.000	2	.264	.000
		ST†	2	112.6	0.0	2	+0.1	0.0	2	2.3	0.0	2	.066	.000	2	.339	.000	2	.008	.000	2	.022	.000	2	0.0	0.0	2	.435	.000	2	.264	.000
	3	3	12	112.4	2.3	12	-0.1	2.1	12	2.6	0.2	12	.071	.005	12	.372	.080	12	.015	.017	12	.022	.005	12	0.0	0.0	12	.479	.083	12	.263	.035
		15	1	112.2	0.0	1	-0.3	0.0	1	2.3	0.0	1	.068	.000	1	.418	.000	1	.004	.000	1	.020	.000	1	0.0	0.0	1	.510	.000	1	.214	.000
		ST	13	112.4	2.2	13	-0.1	2.0	13	2.6	0.2	13	.070	.005	13	.376	.078	13	.014	.016	13	.021	.005	13	0.0	0.0	13	.482	.080	13	.259	.036
	4	5	4	111.2	2.4	4	-1.1	2.1	4	2.3	0.2	4	.073	.002	4	.349	.081	4	.018	.020	4	.027	.004	4	0.0	0.0	4	.468	.104	4	.280	.035
		ST	4	111.2	2.4	4	-1.1	2.1	4	2.3	0.2	4	.073	.002	4	.349	.081	4	.018	.020	4	.027	.004	4	0.0	0.0	4	.468	.104	4	.280	.035
	5	6	1	115.4	0.0	1	+2.6	0.0	1	2.7	0.0	1	.068	.000	1	.322	.000	1	.003	.000	1	.035	.000	1	0.0	0.0	1	.428	.000	1	.304	.000
		ST	1	115.4	0.0	1	+2.6	0.0	1	2.7	0.0	1	.068	.000	1	.322	.000	1	.003	.000	1	.035	.000	1	0.0	0.0	1	.428	.000	1	.304	.000
	8	9	3	109.1	3.2	3	-3.0	2.9	3	2.5	0.7	3	.076	.007	3	.341	.149	3	.009	.011	3	.023	.003	3	0.0	0.0	3	.449	.145	3	.241	.010
		10	5	109.8	2.2	5	-2.4	2.0	5	2.3	0.2	5	.073	.002	5	.305	.057	5	.006	.001	5	.022	.006	5	0.0	0.0	5	.406	.052	5	.271	.041
		11	3	112.0	1.3	3	-0.5	1.2	3	2.4	0.2	3	.070	.006	3	.320	.024	3	.007	.004	3	.022	.002	3	0.0	0.0	3	.419	.019	3	.253	.049
		ST	11	110.2	2.4	11	-2.0	2.1	11	2.4	0.4	11	.073	.005	11	.319	.078	11	.007	.006	11	.022	.004	11	0.0	0.0	11	.421	.076	11	.258	.037
	12	17	3	112.2	1.0	3	-0.3	0.9	3	2.4	0.2	3	.073	.002	3	.242	.038	3	.018	.010	3	.023	.006	3	0.0	0.0	3	.356	.038	3	.255	.038
		ST	3	112.2	1.0	3	-0.3	0.9	3	2.4	0.2	3	.073	.002	3	.242	.038	3	.018	.010	3	.023	.006	3	0.0	0.0	3	.356	.038	3	.255	.038
	TOTAL		34	111.6	2.4	34	-0.8	2.1	34	2.5	0.3	34	.071	.005	34	.339	.079	34	.012	.013	34	.023	.005	34	0.0	0.0	34	.445	.082	34	.252	.035
10	1	1	1	89.0	0.0	1	-3.8	0.0	1	2.4	0.0	1	.076	.000	1	.294	.000	1	.008	.000	1	.024	.000	1	0.0	0.0	1	.402	.000	1	.220	.000
		ST	1	89.0	0.0	1	-3.8	0.0	1	2.4	0.0	1	.076	.000	1	.294	.000	1	.008	.000	1	.024	.000	1	0.0	0.0	1	.402	.000	1	.220	.000
	2	2	21	91.6	1.5	21	-0.9	1.6	21	2.4	0.2	21	.071	.004	21	.333	.055	21	.007	.003	21	.021	.007	21	0.0	0.0	21	.433	.059	21	.247	.029
		ST	21	91.6	1.5	21	-0.9	1.6	21	2.4	0.2	21	.071	.004	21	.333	.055	21	.007	.003	21	.021	.007	21	0.0	0.0	21	.433	.059	21	.247	.029
	3	3	25	93.1	1.7	25	+0.6	1.8	25	2.4	0.2	25	.076	.003	25	.352	.074	25	.012	.009	25	.019	.006	25	0.0	0.0	25	.460	.073	25	.263	.033
		15	3	92.6	1.8	3	+0.1	2.0	3	2.5	0.3	3	.073	.001	3	.320	.065	3	.004	.002	3	.021	.008	3	0.0	0.0	3	.418	.056	3	.226	.030
		ST	28	93.0	1.7	28	+0.5	1.8	28	2.4	0.3	28	.076	.003	28	.349	.073	28	.011	.009	28	.020	.006	28	0.0	0.0	28	.456	.071	28	.259	.034
	4	5	7	92.6	2.0	7	+0.1	2.1	7	2.5	0.3	7	.071	.005	7	.357	.064	7	.010	.010	7	.030	.005	7	0.0	0.0	7	.468	.067	7	.290	.007
		ST	7	92.6	2.0	7	+0.1	2.1	7	2.5	0.3	7	.071	.005	7	.357	.064	7	.010	.010	7	.030	.005	7	0.0	0.0	7	.468	.067	7	.290	.007
	5	6	2	92.1	0.0	2	-0.4	0.0	2	2.3	0.0	2	.068	.000	2	.399	.000	2	.013	.000	2	.022	.000	2	0.0	0.0	2	.503	.000	2	.218	.000
		ST	2	92.1	0.0	2	-0.4	0.0	2	2.3	0.0	2	.068	.000	2	.399	.000	2	.013	.000	2	.022	.000	2	0.0	0.0	2	.503	.000	2	.218	.000
	6	7	1	88.5	0.0	1	-4.3	0.0	1	4.3	0.0	1	.072	.000	1	.320	.000	1	.015	.000	1	.013	.000	1	0.0	0.0	1	.420	.000	1	.288	.000
		ST	1	88.5	0.0	1	-4.3	0.0	1	4.3	0.0	1	.072	.000	1	.320	.000	1	.015	.000	1	.013	.000	1	0.0	0.0	1	.420	.000	1	.288	.000
	7	12	2	92.3	0.0	2	-0.3	0.0	2	2.8	0.0	2	.073	.000	2	.355	.000	2	.003	.000	2	.016	.000	2	0.0	0.0	2	.448	.000	2	.236	.000
		ST	2	92.3	0.0	2	-0.3	0.0	2	2.8	0.0	2	.073	.000	2	.355	.000	2	.003	.000	2	.000	.000	2	0.0	0.0	2	.448	.000	2	.236	.000
	8	9	10	91.5	1.0	10	-1.0	1.1	10	2.7	0.4	10	.072	.004	10	.198	.044	10	.008	.003	10	.021	.007	10	0.0	0.0	10	.300	.043	10	.251	.016
		10	22	91.0	1.5	22	-1.6	1.6	22	2.6	0.4	22	.073	.003	22	.267	.071	22	.009	.006	22	.026	.008	22	0.0	0.0	22	.376	.075	22	.263	.033
		11	9	91.5	2.0	9	-1.1	2.2	9	2.7	0.3	9	.074	.002	9	.246	.068	9	.007	.004	9	.021	.005	9	0.0	0.0	9	.348	.069	9	.264	.042
		ST	41	91.2	1.5	41	-1.4	1.6	41	2.7	0.4	41	.073	.004	41	.246	.070	41	.008	.005	41	.024	.007	41	0.0	0.0	41	.351	.073	41	.260	.032
	9	13	2	92.2	0.0	2	-0.3	0.0	2	2.3	0.0	2	.056	.000	2	.330	.000	2	.004	.000	2	.013	.000	2	0.0	0.0	2	.403	.000	2	.201	.000
		ST	2	92.2	0.0	2	-0.3	0.0	2	2.3	0.0	2	.056	.000	2	.330	.000	2	.004	.000	2	.013	.000	2	0.0	0.0	2	.403	.000	2	.201	.000
	10	14	1	91.0	0.0	1	-1.5	0.0	1	2.2	0.0	1	.074	.000	1	.375	.000	1	.031	.000	1	.028	.000	1	0.0	0.0	1	.508	.000	1	.268	.000
		ST	1	91.0	0.0	1	-1.6	0.0	1	2.2	0.0	1	.074	.000	1	.375	.000	1	.031	.000	1	.028	.000	1	0.0	0.0	1	.508	.000	1	.268	.000
	11	16	3	91.0	0.7	3	-1.7	0.8	3	2.8	0.3	3	.069	.002	3	.282	.035	3	.012	.007	3	.023	.004	3	0.0	0.0	3	.385	.036	3	.274	.039
		ST	3	91.0	0.7	3	-1.7	0.8	3	2.8	0.3	3	.069	.002	3	.282	.035	3	.012	.007	3	.023	.004	3	0.0	0.0	3	.385	.036	3	.274	.039
	12	17	3	90.5	0.5	3	-2.1	0.6	3	2.3	0.2	3	.074	.004	3	.207	.031	3	.018	.012	3	.028	.005	3	0.0	0.0	3	.327	.038	3	.254	.016
		ST	3	90.5	0.5	3	-2.1	0.6	3	2.3	0.2	3	.074	.004	3	.207	.031	3	.018	.012	3	.028	.005	3	0.0	0.0	3	.327	.038	3	.254	.016
	TOTAL		112	91.8	1.7	112	-0.7	1.8	112	2.5	0.4	112	.073	.005	112	.303	.081	112	.009	.007	112	.022	.007	112	0.0	0.0	112	.408	.082	112	.257	.033
12	1	1	2	71.3	0.0	2	-1.5	0.0	2	2.6	0.0	2	.077	.000	2	.370	.000	2	.011	.000	2	.029	.000	2	0.0	0.0	2	.486	.000	2	.248	.000
		ST	2	71.3	0.0	2	-1.5	0.0	2	2.6	0.0	2	.077	.000	2	.370	.000	2	.011	.000	2	.029	.000	2	0.0	0.0	2	.486	.000	2	.248	.000
	2	2	66	72.3	1.6	66	-0.2	2.2	66	2.5	0.4	66	.072	.004	66	.346	.058	66	.009	.006	66	.020	.007	66	0.0	0.0	66	.447	.058	66	.241	.031
		ST	66	72.3	1.6	66	-0.2	2.2	66	2.5	0.4	66	.072	.004	66	.346	.058	66	.009	.006	66	.020	.007	66	0.0	0.0	66	.447	.058	66	.241	.031
	3	3	35	72.4	1.6	35	-0.1	2.2	35	2.4	0.2	35	.073	.012	35	.371	.104	35	.032	.016	35	.022	.009	35	0.0	0.0	35	.498	.106	35	.261	.042
		15	2	72.3	0.0	2	-0.3	0.0	2	2.3	0.0	2	.073	.000	2	.246	.000	2	.006	.000	2	.023	.000	2	0.0	0.0	2	.348	.000	2	.236	.000
		ST	37	72.4	1.6	37	-0.1	2.2	37	2.4	0.2	37	.073	.012	37	.365	.105	37	.031	.017	37	.022	.009	37	0.0	0.0	37	.490	.109	37	.259	.041
	4	5	22	72.5	1.5	22	+0.1	2.0	22	2.6	0.4	22	.072	.003	22	.359	.079	22	.010	.008	22	.029	.006	22	0.0	0.0	22	.469	.077	22	.268	.033
		ST	22	72.5	1.5	22	+0.1	2.0	22	2.6	0.4	22	.072	.003	22	.359	.079	22	.010	.008	22	.029	.006	22	0.0	0.0	22	.469	.077	22	.268	.033
	5	6	6	71.9	1.5	6	-0.9	2.1	6	3.0	0.5	6	.069	.004	6	.335	.037	6	.009	.008	6	.023	.006	6	0.0	0.0	6	.436	.035	6	.275	.039
		ST	6	71.9	1.5	6	-0.9	2.1	6	3.0	0.5	6	.069	.004	6	.335	.037	6	.009	.008	6	.023	.006	6	0.0	0.0	6	.436	.035	6	.275	.039
	7	12	1	75.3	0.0	1	+3.9	0.0	1	3.1	0.0	1	.072	.000	1	.346	.000	1	.006	.000	1	.022	.000	1	0.0	0.0	1	.446	.000	1	.238	.000
		ST	1	75.3	0.0	1	+3.9	0.0	1	3.1	0.0	1	.072	.000	1	.346	.000	1	.006	.000	1	.022	.000	1	0.0	0.0	1	.446	.000	1	.238	.000
	8	9	20	72.3	1.3	20	-0.3	1.8	20	2.6	0.4	20	.072	.003	20	.219	.055	20	.017	.019	20	.024	.006	20	0.0	0.0	20	.333	.053	20	.260	.032
		10	24	72.2	1.5	24	-0.4	2.1	24	2.8	0.3	24	.074	.004	24	.243	.057	24	.011	.014	24	.023	.006	24	0.0	0.0	24	.357	.057	24	.243	.054
		11	14	72.1	1.4	14	-0.6	1.9	14	2.6	0.3	14	.074	.002	14	.257	.051	14	.010	.006	14	.024	.011	14	0.0	0.0	14	.364	.055	14	.254	.036
		ST	58	72.2	1.4	58	-0.4	1.9	58	2.7	0.4	58	.073	.003	58	.240	.056	58	.013	.015	58	.024	.007	58	0.0	0.0	58	.350	.056	58	.251	.043
	10	14	1	70.0	0.0	1	-3.4	0.0	1	2.5	0.0	1	.076	.000	1	.268	.000	1	.014	.000	1	.023	.000	1	0.0	0.0	1	.381	.000	1	.256	.000
		ST	1	70.0	0.0	1	-3.4	0.0	1	2.5	0.0	1	.076	.000	1	.268	.000	1	.014	.000	1	.023	.000	1	0.0	0.0	1	.381	.000	1	.256	.000
	11	16	8	71.3	1.5	8	-1.6	2.1	8	2.4	0.2	8	.069	.004	8	.335	.030	8	.011	.010	8	.033	.008	8	0.0	0.0	8	.448	.029	8	.267	.020
		ST	8	71.3	1.5	8	-1.6	2.1	8	2.4	0.2	8	.069	.004	8	.335	.030	8	.011	.010	8	.033	.008	8	0.0	0.0	8	.448	.029	8	.267	.020
	12	17	7	71.2	1.3	7	-1.7	1.8	7	2.5	0.3	7	.072	.003	7	.293	.055	7	.012	.009	7	.022	.006	7	0.0	0.0	7	.399	.055	7	.274	.043
		ST	7	71.2	1.3	7	-1.7	1.8	7	2.5	0.3	7	.072	.003	7	.293	.055	7	.012	.009	7	.022	.006	7	0.0	0.0	7	.399	.055	7	.274	.043
	TOTAL		208	72.2	1.5	208	-0.3	2.1	208	2.6	0.4	208	.072	.006	208	.319	.085	208	.014	.014	208	.023	.008	208	0.0	0.0	208	.428	.087	208	.253	.038

* CHEMICAL COMPONENTS ARE IN % OF WEIGHT OF THE ALLOY

† SUBTOTAL

TABLE 17 — (Continued)

NUMBER OF SAMPLES, ARITHMETIC MEAN, AND STANDARD DEVIATION

GAUGE	SUPPLIER	SOURCE	WEIGHT IN OZ/FT^2			% OFF GAUGE NO.			SPELTER WT. (OZ/FT^2)			CARBON[a]			MANGANESE			PHOSPHOROUS			SULFUR			SILICON			SUM OF COMPONENTS			COPPER		
14	1	1	2	52.9	0.0	2	+0.9	0.0	2	2.5	0.0	2	.072	.000	2	.436	.000	2	.014	.000	2	.027	.000	2	0.0	0.0	2	.549	.000	2	.272	.000
		ST†	2	52.9	0.0	2	+0.9	0.0	2	2.5	0.0	2	.072	.000	2	.436	.000	2	.014	.000	2	.027	.000	2	0.0	0.0	2	.549	.000	2	.272	.000
	2	2	73	52.2	1.5	73	-0.6	2.9	73	2.5	0.3	73	.073	.003	73	.337	.068	73	.008	.005	73	.020	.007	73	0.0	0.0	73	.446	.090	73	.234	.028
		ST	73	52.2	1.5	73	-0.6	2.9	73	2.5	0.3	73	.073	.003	73	.337	.068	73	.008	.005	73	.020	.007	73	0.0	0.0	73	.446	.090	73	.234	.028
	3	3	51	53.2	1.6	51	+1.2	3.1	51	2.5	0.3	51	.072	.010	51	.405	.058	51	.042	.015	51	.021	.006	51	0.0	0.0	51	.540	.059	51	.259	.042
		15	2	50.6	0.0	2	-3.5	0.0	2	2.4	0.0	2	.070	.000	2	.341	.000	2	.003	.000	2	.024	.000	2	0.0	0.0	2	.440	.000	2	.215	.000
		ST	53	53.1	1.6	53	+1.1	3.1	53	2.5	0.3	53	.072	.009	53	.402	.059	53	.041	.016	53	.021	.006	53	0.0	0.0	53	.536	.061	53	.258	.047
	4	5	23	53.0	3.8	23	+0.7	7.3	23	2.5	0.3	23	.073	.003	23	.349	.063	23	.009	.007	23	.025	.006	23	0.0	0.0	23	.455	.062	23	.264	.036
		ST	23	53.0	3.8	23	+0.7	7.3	23	2.5	0.3	23	.073	.003	23	.349	.063	23	.009	.007	23	.025	.006	23	0.0	0.0	23	.455	.062	23	.264	.036
	5	6	3	51.1	1.1	3	-2.6	2.1	3	2.8	0.7	3	.073	.005	3	.312	.041	3	.015	.011	3	.038	.011	3	0.0	0.0	3	.438	.015	3	.279	.005
		ST	3	51.1	1.1	3	-2.6	2.1	3	2.8	0.7	3	.073	.005	3	.312	.041	3	.015	.011	3	.038	.011	3	0.0	0.0	3	.438	.015	3	.279	.005
	7	12	1	51.5	0.0	1	-1.9	0.0	1	3.0	0.0	1	.072	.000	1	.270	.000	1	.006	.000	1	.032	.000	1	0.0	0.0	1	.380	.000	1	.282	.000
		ST	1	51.5	0.0	1	-1.9	0.0	1	3.0	0.0	1	.072	.000	1	.270	.000	1	.006	.000	1	.032	.000	1	0.0	0.0	1	.380	.000	1	.282	.000
	8	9	25	52.0	1.0	25	-1.0	1.9	25	2.7	0.3	25	.073	.003	25	.197	.093	25	.023	.054	25	.023	.007	25	0.0	0.0	25	.317	.072	25	.251	.029
		10	31	52.2	1.2	31	-0.6	2.3	31	2.8	0.5	31	.072	.003	31	.276	.082	31	.007	.004	31	.025	.006	31	0.0	0.0	31	.378	.084	31	.250	.039
		11	26	52.2	1.4	26	-0.6	2.7	26	2.7	0.3	26	.072	.004	26	.341	.083	26	.010	.005	26	.024	.010	26	0.0	0.0	26	.447	.085	26	.255	.028
		ST	82	52.1	1.2	82	-0.7	2.3	82	2.8	0.4	82	.072	.004	82	.273	.102	82	.013	.030	82	.024	.008	82	0.0	0.0	82	.381	.095	82	.252	.033
	6	7	1	52.8	0.0	1	+0.6	0.0	1	2.3	0.0	1	.072	.000	1	.509	.000	1	.002	.000	1	.022	.000	1	0.0	0.0	1	.605	.000	1	.244	.000
		ST	1	52.8	0.0	1	+0.6	0.0	1	2.3	0.0	1	.072	.000	1	.509	.000	1	.002	.000	1	.022	.000	1	0.0	0.0	1	.605	.000	1	.244	.000
	9	13	2	53.1	0.0	2	+1.0	0.0	2	2.3	0.0	2	.059	.000	2	.297	.000	2	.004	.000	2	.012	.000	2	0.0	0.0	2	.372	.000	2	.232	.000
		ST	2	53.1	0.0	2	+1.0	0.0	2	2.3	0.0	2	.059	.000	2	.297	.000	2	.004	.000	2	.012	.000	2	0.0	0.0	2	.372	.000	2	.232	.000
	11	16	6	52.4	1.5	6	-0.2	2.8	6	2.6	0.3	6	.070	.004	6	.298	.064	6	.007	.009	6	.033	.011	6	0.0	0.0	6	.408	.073	6	.288	.020
		ST	6	52.4	1.5	6	-0.2	2.8	6	2.6	0.3	6	.070	.004	6	.298	.064	6	.007	.009	6	.033	.011	6	0.0	0.0	6	.408	.073	6	.288	.020
	12	17	8	51.7	1.4	8	-1.4	2.7	8	2.5	0.4	8	.072	.003	8	.269	.053	8	.016	.006	8	.022	.004	8	0.0	0.0	8	.379	.053	8	.276	.019
		ST	8	51.7	1.4	8	-1.4	2.7	8	2.5	0.4	8	.072	.003	8	.269	.053	8	.016	.006	8	.022	.004	8	0.0	0.0	8	.379	.053	8	.276	.019
	TOTAL		254	52.4	1.8	254	-0.2	3.4	254	2.6	0.4	254	.072	.005	254	.328	.092	254	.017	.023	254	.023	.008	254	0.0	0.0	254	.442	.100	254	.251	.035
16	1	1	10	42.2	1.2	10	-0.8	2.8	10	2.3	0.2	10	.073	.005	10	.318	.065	10	.007	.004	10	.026	.010	10	0.0	0.0	10	.424	.065	10	.237	.018
		ST	10	42.2	1.2	10	-0.8	2.8	10	2.3	0.2	10	.073	.005	10	.318	.065	10	.007	.004	10	.026	.010	10	0.0	0.0	10	.424	.065	10	.237	.018
	2	2	212	42.2	0.9	212	-0.6	2.1	212	2.5	0.3	212	.073	.004	212	.336	.071	212	.008	.006	212	.021	.007	212	0.0	0.0	212	.438	.073	212	.243	.036
		ST	212	42.2	0.9	212	-0.6	2.1	212	2.5	0.3	212	.073	.004	212	.334	.071	212	.008	.006	212	.021	.007	212	0.0	0.0	212	.438	.073	212	.243	.036
	3	3	130	43.1	1.5	130	+1.4	3.2	130	2.4	0.2	130	.074	.003	130	.379	.069	130	.034	.019	130	.022	.007	130	0.0	0.0	130	.509	.074	130	.269	.056
		4	1	43.3	0.0	1	+1.9	0.0	1	2.5	0.0	1	.078	.000	1	.348	.000	1	.001	.000	1	.015	.000	1	0.0	0.0	1	.442	.000	1	.285	.000
	3	15	2	41.8	0.0	2	-1.5	0.0	2	2.3	0.0	2	.073	.000	2	.369	.000	2	.003	.000	2	.022	.000	2	0.0	0.0	2	.466	.000	2	.220	.000
		ST	133	43.1	1.5	133	+1.4	3.2	133	2.4	0.2	133	.074	.003	133	.378	.069	133	.034	.019	133	.022	.007	133	0.0	0.0	133	.508	.074	133	.269	.056
	4	5	25	42.1	0.8	25	-0.7	2.0	25	2.5	0.3	25	.072	.003	25	.350	.064	25	.008	.005	25	.029	.007	25	0.0	0.0	25	.459	.061	25	.274	.035
		ST	25	42.1	0.8	25	-0.7	2.0	25	2.5	0.3	25	.072	.003	25	.350	.064	25	.008	.005	25	.029	.007	25	0.0	0.0	25	.459	.061	25	.274	.035
	5	6	3	42.6	1.1	3	+0.1	2.6	3	3.3	0.2	3	.071	.005	3	.312	.062	3	.015	.003	3	.032	.013	3	0.0	0.0	3	.430	.054	3	.240	.039
		ST	3	42.6	1.1	3	+0.1	2.6	3	3.3	0.2	3	.071	.005	3	.312	.062	3	.015	.003	3	.032	.013	3	0.0	0.0	3	.430	.054	3	.240	.039
	6	7	3	41.6	0.9	3	-2.0	2.3	3	2.4	0.1	3	.073	.001	3	.429	.054	3	.004	.001	3	.020	.003	3	0.0	0.0	3	.525	.056	3	.269	.018
		ST	3	41.6	0.9	3	-2.0	2.3	3	2.4	0.1	3	.073	.001	3	.429	.054	3	.004	.001	3	.020	.003	3	0.0	0.0	3	.525	.056	3	.269	.018
	7	8	7	42.3	0.3	7	-0.6	0.7	7	2.5	0.2	7	.072	.002	7	.324	.011	7	.008	.003	7	.023	.011	7	0.0	0.0	7	.427	.022	7	.287	.041
		12	3	43.1	2.3	3	+1.4	5.5	3	2.7	0.1	3	.073	.003	3	.311	.016	3	.004	.002	3	.027	.008	3	0.0	0.0	3	.415	.022	3	.256	.031
		ST	10	42.5	1.2	10	0.0	2.8	10	2.5	0.2	10	.072	.002	10	.320	.013	10	.007	.003	10	.024	.010	10	0.0	0.0	10	.423	.021	10	.278	.040
	8	9	39	42.5	0.9	39	-0.3	2.1	39	2.7	0.4	39	.073	.004	39	.252	.086	39	.008	.005	39	.026	.009	39	0.0	0.0	39	.359	.084	39	.248	.036
		10	58	42.2	1.0	58	-0.6	2.5	58	2.7	0.3	58	.072	.003	58	.284	.083	58	.008	.006	58	.023	.007	58	0.0	0.0	58	.387	.082	58	.259	.031
		11	33	41.6	0.8	33	-2.1	1.8	33	2.6	0.3	33	.073	.003	33	.268	.067	33	.007	.005	33	.021	.006	33	0.0	0.0	33	.370	.065	33	.270	.042
		ST	130	42.1	1.0	130	-0.9	2.3	130	2.7	0.4	130	.073	.003	130	.270	.081	130	.008	.005	130	.023	.008	130	0.0	0.0	130	.374	.079	130	.259	.036
	9	13	7	42.4	1.0	7	-0.2	2.2	7	2.7	0.4	7	.067	.011	7	.335	.018	7	.009	.002	7	.021	.009	7	0.0	0.0	7	.431	.026	7	.284	.049
		ST	7	42.4	1.0	7	-0.2	2.2	7	2.7	0.4	7	.067	.011	7	.335	.018	7	.009	.002	7	.021	.009	7	0.0	0.0	7	.431	.026	7	.284	.049
	10	14	5	41.4	0.9	5	-2.5	2.1	5	2.6	0.4	5	.074	.003	5	.285	.111	5	.012	.002	5	.024	.008	5	0.0	0.0	5	.396	.118	5	.264	.032
		ST	5	41.4	0.9	5	-2.5	2.1	5	2.6	0.4	5	.074	.003	5	.285	.111	5	.012	.002	5	.024	.008	6	0.0	0.0	5	.396	.118	5	.264	.032
	11	16	7	42.4	0.9	7	-0.1	2.2	7	2.3	0.2	7	.072	.003	7	.300	.052	7	.012	.012	7	.031	.007	7	0.0	0.0	7	.416	.060	7	.251	.028
		ST	7	42.4	0.9	7	-0.1	2.2	7	2.3	0.2	7	.072	.003	7	.300	.052	7	.012	.012	7	.031	.007	7	0.0	0.0	7	.416	.060	7	.251	.028
	12	17	17	44.3	7.4	17	0.0	2.5	17	2.4	0.2	17	.073	.003	17	.276	.046	17	.008	.007	17	.026	.008	17	0.0	0.0	17	.383	.048	17	.270	.040
		ST	17	44.3	7.4	17	0.0	2.5	17	2.4	0.2	17	.073	.003	17	.276	.046	17	.008	.007	17	.026	.008	17	0.0	0.0	17	.383	.048	17	.270	.040
	TOTAL		562	42.5	1.7	562	-0.2	2.6	562	2.5	0.3	562	.073	.004	562	.328	.081	562	.014	.015	562	.023	.008	562	0.0	0.0	562	.438	.087	562	.256	.043
18	1	1	4	34.4	0.9	4	-0.3	2.7	4	2.2	0.3	4	.072	.004	4	.315	.038	4	.006	.003	4	.030	.000	4	0.0	0.0	4	.423	.034	4	.259	.056
		ST	4	34.4	0.9	4	-0.3	2.7	4	2.2	0.3	4	.072	.004	4	.315	.038	4	.006	.003	4	.030	.000	4	0.0	0.0	4	.423	.034	4	.259	.056
	3	3	11	34.7	0.7	11	+0.6	1.9	11	2.3	0.3	11	.074	.004	11	.378	.087	11	.008	.006	11	.025	.019	11	0.0	0.0	11	.485	.084	11	.237	.035
		ST	11	34.7	0.7	11	+0.6	1.9	11	2.3	0.3	11	.074	.004	11	.378	.087	11	.008	.006	11	.025	.019	11	0.0	0.0	11	.485	.084	11	.237	.036
	10	14	2	32.6	0.0	2	-5.5	0.0	2	2.1	0.0	2	.077	.000	2	.334	.000	2	.014	.000	2	.038	.000	2	0.0	0.0	2	.462	.000	2	.231	.009
		ST	2	32.6	0.0	2	-5.5	0.0	2	2.1	0.0	2	.077	.000	2	.334	.000	2	.014	.000	2	.038	.000	2	0.0	0.0	2	.462	.000	2	.231	.000
	TOTAL		17	34.4	1.0	17	-0.3	2.8	17	2.3	0.2	17	.074	.004	17	.358	.077	17	.008	.006	17	.028	.016	17	0.0	0.0	17	.468	.074	17	.242	.040

[a] CHEMICAL COMPONENTS ARE IN % OF WEIGHT OF THE ALLOY

† SUBTOTAL

for division directors, district engineers, and others involved at the policy making level. Later these workshops could be presented for construction and materials personnel directly involved in the testing and sampling process. Secondly, the introduction of random sampling techniques in lieu of representative sampling techniques should be made and established now as a requirement for sampling and testing programs. If random sampling methods are already in use, the transition to statistical type quality control specifications should be smooth and with little loss in efficiency or compliance. If random sampling methods are in use and if all test results are reported by field personnel (not just the test results that eventually pass), the historical data that can be accumulated from construction and materials records will be most valuable in setting reliable statistical quality control specification tolerances. Should these recommendations be followed, BPR research guides *(9)* could then be used for outlining the sampling programs necessary to establish realistic estimates of σ', $\bar{X}_g'$, and $\bar{X}_p'$ for various materials and processes used in the highway industry. Then, tentative specification tolerances could be developed based on the statistical analyses and tested under Special Provisions on selected projects. The success of this type of acceptance criteria could then be evaluated by both the Department and the contracting agencies to determine whether or not the tolerances specified actually resulted in more explicit, complete, and enforceable specification requirements.

The reliability of using basic statistical techniques for acceptance sampling apparently has been substantiated by industrial concerns. It now remains to ascertain the economic compatibility of their use in the highway industry by employing statistical acceptance methods on a trial basis.

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APPENDIX A

STATISTICAL NOTATION

α = contractor's (producer's) risk or the probability of rejecting a lot of quality p_1.

β = State's (consumer's) risk or the probability of accepting a lot of quality p_2.

c = allowable number of defectives in the sample.

d = observed number of defectives in the sample.

$k_p = (X_g' - X_p')/\sigma$ the number of standard deviation units between the mean values of acceptable and unacceptable material or construction.

L = lower specification limit.

M = a factor used to convert the sample standard deviation, s, to the range, R; s = MR.

N = lot size.

n = number of random samples or tests on which acceptance is based.

P_g = probability of rejecting good material or construction.

P_L = percentage of the lot within the lower specification limit, L.

P_p = probability of rejecting poor material or construction.

P_U = percentage of the lot within the upper specification limit, U.

$P_{U,L} = P_U + P_L - 100$, percentage of the lot within the upper and lower specification limits.

p_1 = quality of material or construction that will be accepted with a probability of 1-x.

p_2 = quality of material or construction that will be accepted with a probability of β.

$Q_L = (\bar{X}-L)/R$ or $\bar{R}$, the quality index used to determine P_L.

$Q_U = (U-\bar{X})\ R$ or $\bar{R}$, the quality index used to determine P_U.

L(p) = probability of accepting a lot with percentage of defectives equal to p.

R = range of the measured values, equal to the difference between the largest number and the smallest number in a set of numbers.

$\bar{R}$ = average of a number of ranges.

s = standard deviation of a limited number of samples (i.e. an estimate σ').

$\sigma = [\Sigma(X_i - \bar{X})^2]/(n - 1)$, overall deviation.

σ' = true value of the standard deviation.

$\sigma_{\bar{X}} = \sigma / \sqrt{n}$, standard deviation of the mean, X.

$\bar{\sigma}$ = average of a number of standard deviations.

σ_a^2 = inherent or actual variance of a lot.

σ_s^2 = variance due to sampling.

σ_t^2 = variance due to testing error.

$T_a = \bar{X}_g' - \bar{X}_p'$, difference between the desired mean, X_g', and the mean of unacceptable material or construction, X_p'.

T_i = allowable difference of individual measurements from the specified mean.

T_s = specification tolerance, equals to the difference between X_p' and the specification limit.

t = a distribution slightly more scattered than a normal distribution. The distribution may be used when σ' is unknown.

U = upper specification limit.

X_i = value of an individual measurement.

$\bar{X} = \Sigma X_i / n$, average of n measurements.

$\bar{\bar{X}}$ = grand average or average of averages.

$\bar{X}_m$ = moving average, the average of the n-1 most recent test results representing acceptable material or construction plus the test result from the material or construction being considered for acceptance.

$\bar{X}'$ = desired average or target value of the measured characteristic.

$\bar{X}_g'$ = desired average or the mean of a distribution of good, acceptable material or construction.

$\bar{X}_p'$ = average value of poor, unacceptable material or construction.

Z = distance in standard deviation units from the centerline to a point on the base of the normal distribution curve.

APPENDIX B

SUGGESTED METHOD FOR ESTIMATING THE TRUE STANDARD DEVIATIONS *(10)*

Step 1* - Design a plan that will insure randomness of sampling.

Step 2 - Apply the sampling plan to the material or item of construction produced under acceptable, routine conditions and usual job control. Take at least 50 samples in duplicate from each of three locations (there will be 300 samples).

Step 3 - Divide each sample into two portions which are as nearly alike as possible (there will be 600 portions).

Step 4 - Obtain data relating to the selected characteristics by making measurements on each portion by routine methods which will be used in acceptance testing.

Step 5 - For each characteristic, compute the average level, the overall variance, and the components of the overall variance.

*Note: BPR research guides *(9)* describe detailed sampling plans that may be used for various materials and construction processes.