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<u>INFORMATION:</u> Engineering Brief No. 56
Development of Revised Acceptance Criteria
for Item P-401 and Item P-501

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Engineering Brief No. 56 discusses the revised acceptance criteria as contained in Change 10 to AC 150/5370-10A, issued March 11, 1998. The brief provides the engineering and statistical analysis used to revise the acceptable quality level, the rejectable quality level, and the specification tolerance limits. The brief provides information regarding the operating characteristics of the acceptance plans, including risk analysis.

Any comments you have concerning this brief will be appreciated.

ORIGINAL SIGNED BY
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Attachment

ENGINEERING BRIEF NO. 56 Development of Revised Acceptance Criteria for Item P-401 and Item P-501.

1. INTRODUCTION.

1.1 OBJECTIVE.

The purpose of this Engineering Brief is to present the revised acceptance criteria used for two specifications contained in Federal Aviation Administration (FAA) Advisory Circular (AC) 150/5370-10A, Standards for Specifying Construction of Airports, namely:

Item P-401 Plant Mix Bituminous Pavements.
Item P-501 Portland Cement Concrete Pavement.

The revised acceptance criteria presented herein were incorporated into the above specifications as Change 10 to AC 150/5370-10A, issued March 11, 1998. The major objectives of Change 10 were to:

1. Clarify what is meant by acceptable quality level (AQL), rejectable quality level (RQL), and by percentage within specification limits (PWL),

2. Adopt a uniform quality standard for acceptance of airport pavement surfaces,

3. Relate that standard to a revised pay adjustment schedules based on density and air voids for Item P-401, and based on strength and thickness for Item P-501, and

4. Revise the existing acceptance plans to add features that allow lot pay factors in excess of the contract unit price to offset the degree of uncertainty (risk) associated with acceptance plans when small fractions of material are used to evaluate a day's production.

1.2 BACKGROUND.

On several occasions, beginning in the 1970’s, the FAA has revised Items P-401 and P-501, to add and revise sliding scale pay adjustment schedules based on statistical concepts. The first efforts were conducted, in parallel, by the Washington Headquarters Office of Safety and Standards and the FAA Eastern Region Airports Division. The Headquarters Office developments, for both P-401 and P-501, were based on work (FAA Engineering Briefs No. 17 and 30) developed by Richard J. Worch, Civil Engineer, Headquarters Office of Safety and Standards, Engineering and Specifications Division.

The Region Office developments, specifically for the Eastern Region revisions to Item P-401, were based on work developed by William Degraff and Roy McQueen, Pavement Engineers, FAA Eastern Region Airports Division. The FAA Headquarters efforts also used acceptance methods developed by Brown, E.R., National Center For Asphalt Technology, Auburn, AL, in an unpublished letter report (circa 1977), requested by Worch.

The original approach used for both specifications provided sliding scale pay factors based on the range statistic for variability. Subsequent changes revised the pay adjustment schedules and acceptance criteria to use standard deviation for variability and added PWL concepts. These revisions were the result of successive research contracts that generated the following reports:

1. Burati, J.L., and Willenbrock, J.H., Acceptance Criteria for Bituminous Surface Course On Civil Airport Pavements, FAA-RD-79-89, 1979.

2. Burati, J.L. et.al., Field Validation of Statistically Based Acceptance Plan for Bituminous Airport Pavements, DOT/FAA/PM-84/12, 1984.

3. McQueen, R.D., Evaluation of Headquarters and Eastern Region P-401 Specifications, 1989.

4. Foster, J.E., and Majidzadeh, K., Development of Acceptance Plans for Airport Pavement Materials, DOT/FAA/RD-90/15, 1990.

5. McQueen, R.D., and Associates Ltd., Development of Statistically Based Acceptance and Quality Control Requirements for FAA Paving Items, 1992.

6. McQueen, R.D., and Associates, Ltd., Revisions to Item P-501 Payment Plans, 1993.

To summarize, this Engineering Brief draws heavily on the previous body of information reported under [1,2,3,4,5,6], with special dependence on [1,4] regarding quality concepts, the analytical explanation of probability and statistics, and the composition of tables and figures. Two other references [7,8] were used to help define basic terms relating to statistically-based acceptance plans and probability terms. The non-central t distribution values used in probability-based figures and tables were obtained from reference [9]. Reference [10], a set of add-on functions that work in Microsoft© Excel©, was used to simulate the acceptance plans.

7. Weed, R.M., Quality Assurance Software for the Personal Computer, FHWA Demonstration Project 89, Quality Management, FHWA-SA-96-026, 1996.

8. Burati, J.L., Jr., Hughes, C.S., Construction Quality Management for Managers (Demonstration Project 89), FHWA-SA-94-044, 1993.

9. Barros, R.T., The Theory and Computerized Design of Statistical Construction Specifications, FHWA/NJ-83/006, Software Version Dated 1989.

10. Crystal Ball©, Version 4.0c, Decisioneering, Inc., 1996.

2. QUALITY AND ACCEPTANCE CONSIDERATIONS.

2.1 BASIC CONCEPTS.

The FAA specifications for Items P-401 and P-501 incorporate provisions for contractor quality control and engineer acceptance. Contractor quality control is the responsibility of the contractor and is concerned with detecting changes in production, then taking the necessary steps to control the process to correct the change in production. Contractor quality control involves decisions based on the results of random samples of a small fraction of production material. Acceptance is the responsibility of the engineer and is concerned with monitoring product quality as the product is delivered in batches or lots. Acceptance involves the decision to accept or reject a lot based on random samples of a small fraction of material from the lot. The specifications require two random samples per day for selected process control parameters and four random samples, one per sublot per lot, for acceptance.

2.2 QUALITY LEVELS, SPECIFICATION TOLERANCES LIMITS, AND PERCENTAGE WITHIN SPECIFICATION LIMITS (PWL).

An essential part of developing a statistical acceptance plan is choosing the acceptable quality level (AQL) and the rejectable quality level (RQL). The AQL is the minimum quality level at which the work is considered acceptable at full pay. The RQL is the minimum quality level at which the work can be accepted at a reduced pay factor. When work fails to meet the RQL, there is usually an option to permit the work to be left in place at a 50 percent pay factor. The FAA bases the AQL and RQL on the desired percent of work required to be within specification tolerance limits.

The FAA accepts work on a lot basis and assumes an underlying normal distribution for pavement construction work, which means that acceptance parameters for a lot (the population parameters) are normally distributed about a mean (μ) according to a standard deviation (σ). This permits the standardized variable (Z) transformation to be performed and allows the acceptance parameters, along with the AQL and the RQL, to be related to the total area (or probability) under the standard normal distribution, which is equal to 1.0 or 100 percent.

The acceptance plans consider the average (mean, μ) value of the acceptance parameter, as well as the variability (standard deviation, σ) of the material and testing procedures. Acceptance is based on the percentage of work within specification tolerance limits (PWL), which is analogous to the area under a normal distribution above the lower specification tolerance limit (L), or below the upper specification tolerance limit (U). The area is determined after performing the standardized-variable Z transformation as follows:

For the lower tolerance limit, $Z = (\mu - L)/\sigma$.
For the upper tolerance limit, $Z = (U - \mu)/\sigma$.
Where, Z is expressed in terms of the number of standard deviations from the mean.

The area under the normal distribution at Z, which is analogous to the PWL, can be found using the standard normal probability table. For instance, at Z = 1.282, the area under the standard normal distribution is 0.90, which is analogous to 90 PWL. Stated in terms of the lower specification tolerance limit, when Z=1.282, there is a 90 percent probability that pavement construction work is greater than or equal to L. Stated in terms of the upper specification tolerance limit, when Z=1.282, there is a 90 percent probability that pavement construction work is less than or equal to U.

In order to determine the actual mean and standard deviation of the material in a lot, it would be necessary to test all of the material, which is not practical or possible. An alternate is to estimate the area under the normal distribution based on a random sampling plan. This method was first developed and reported in 1927 by the U.S. Department of Defense and published as Military Standard (MIL-STD) 414. It formed the basis for the method of estimating PWL.

This method determines a quality index (Q), which is similar to the Z value. The Q value is a function of sample size (n), sample average (X) and sample standard deviation (s). It is used to estimate the probable area under the a normal distribution at L and or U. The quality index (Q) at the upper and lower specification tolerance limits is computed as follows:

For the lower tolerance limit, Q = (X-L)/s.
For the upper tolerance limit, Q = (U-X)/s.
Where, Q is expressed in terms of the number of sample standard deviations from the sample mean.

Standard Q tables for different sample sizes have been developed to relate the Q value to an estimate of PWL. A portion of those tables, for sample sizes n=3 through n=8 are incorporated into FAA specifications. Note that, as the sample size increases, the Q value approaches the Z value.

2.3 ACCEPTANCE CRITERIA AND SPECIFICATION TOLERANCE LIMITS.

The FAA has adopted a uniform standard quality level for acceptance of airport pavement construction work consistent with FAA airport pavement design philosophy. The design parameters found in AC 150/5320-6, Airport Pavement Design and Evaluation, have been developed and revised, for the most part, assuming design parameters can vary one standard deviation (1σ) on either side of the mean (μ), and still meet the designer's intent. The area under a normal distribution, one standard deviation on either side of the mean, is 68.3 percent of the total area. The area is distributed equally with 34.1 percent on each side of the mean. The designer's assumptions are closely related to the AQL, which means the RQL can be expressed in terms of the AQL as follows:

AQL - area 1σ on either side μ = RQL
AQL - 34.1 percent = RQL

The FAA has adopted 90 PWL as the AQL, which implies the RQL can be adopted at (90-34.1)=55.9 PWL, say 55 PWL, and still meet the designer's intent

At the AQL, or when production quality is assumed to meet design (or model) parameters, 90 percent of the work is assumed to meet the design requirements and 10 percent of the work is considered defective. At the RQL, 55 percent of the work is assumed to meet the design (or model) requirements and 45 percent of the work is considered defective from a design viewpoint. RQL work is considered marginally acceptable at a reduced pay. Below the RQL, a large portion of the designer’s intent is likely not being met, and the work is rejectable.

The AQL for Item P-401 has been 90 PWL since incorporating PWL concepts into the specifications in the 1980's. For Item P-501, two different AQL values have been used. When the range-based acceptance method was allowed as an option in lieu of pass/fail criteria for acceptance, beginning in the late 1970's, the AQL was equivalent to approximately 60 PWL. When the PWL methods were incorporated with AC 150/5370-10A, Change 7 (5/20/94), 80 PWL was adopted as the AQL. The value of 80 PWL was consistent with the pass/fail acceptance criteria for strength that allowed not more than 20 percent of beam tests to fall below the design strength.

Prior to Change 10 (3/11/98), the FAA used 65 PWL as the RQL for Item P-401. The RQL under the range-based acceptance method for Item P-501 was equivalent to approximately 37 PWL, and was raised to 60 PWL with Change 7.

Pavement (lots) meeting the Item P-401 requirements have performed satisfactorily, even as operational requirements (traffic, grooving, rubber removal, etc.) have increased over the years. Just as important, contractors with airport construction experience have been able to consistently produce at a quality level that meets this evaluation requirement, on a lot by lot basis. Pavements meeting Item P-501 requirements, in effect since 1994, have not been evaluated; however, the 80 PWL requirement at the AQL is approximately 20 PWL higher than the range-based method of acceptance in effect prior to incorporating the PWL concepts with Change 7, and consequently, strengths have been higher.

With Change 10 (3/11/98), the same acceptable quality range has been adopted for Items P-401 and P-501. The revised specification tolerance limits related to the AQL of 90 PWL and the RQL of 55 PWL will be discussed.

For Item P-401, the mat density and air voids tolerance limits used with the AQL and RQL levels have evolved over time. They are based on successful performance of pavements that have met these limits, and in the case of the density criteria, they minimize the amount of pavement that is accepted below a density that provided unsatisfactory performance in the past. The FAA experienced problems when the specification used a pass/fail acceptance plan based on a maximum theoretical mat density of 94 percent. There were also problems associated with low density when the range-based density acceptance plan was used between the mid 1970's and the mid 1980's. The current mat density tolerance limit (L=96.3 percent) has been used since 1989. This lower tolerance limit is about 0.5 percent higher than the 90 PWL acceptable joint density, with joints historically being the poorest performing portion of pavements. Change 10 does not revise the tolerance limits for Item

P-401, but the allowable quality range between the AQL and RQL has been widened, which allows a slightly lower mat density to be included in the acceptable range. The revised acceptance criteria for Item P-401 are based on the same model parameters and allow acceptance when 90 percent of the material is within one standard deviation of the model parameters.

The tolerance limit for density, 96.3 percent of laboratory Marshall density, has been in use since 1989. Prior to 1989, the tolerance limit for density was 96.7 percent of laboratory Marshall density. The lower and upper tolerance limits for air voids, 2.0 percent and 5.0 percent, have been in use since 1992. Inspection of data from projects constructed using these limits indicates that construction meeting these limits has been consistently achieved by contractors. The AQL has remained the same for Item P-401, which implies that the same contractors will continue to meet the requirements.

As mentioned earlier, the FAA's adopted model parameters for mat density and air voids acceptance plans are based on past performance. Research data from [1,2,3] and subsequent data from requests by the FAA, indicate that construction superior to the model parameters has been attained on a lot by lot basis. The density model is based on a mean of 98 percent and a standard deviation of 1.3 percent. The air voids model is based on an allowable average between 2.8 and 4.2 percent and a standard deviation of 0.65 percent. The acceptance plan will be simulated using these model parameters in Section 4.

For Item P-501, revised strength and thickness tolerance limits at the AQL and RQL levels have been chosen to be consistent with the strength, thickness, loading, and traffic volume assumptions made during the development of the pavement design criteria.

The tolerance limit for thickness was established at 0.5 inches less than the design thickness based on a compromise between the grade tolerance allowed for base course material and the surface tolerance for concrete. Historically, deficient thickness has not been an issue. The FAA believes that mechanical controls to adjust thickness can readily achieve a variation of 3/8th inch or less, and in most cases, the contractor is furnishing a slightly thicker than required pavement. At the AQL, the revised criteria is slightly more demanding than the sliding scale thickness criteria in effect previous to Change 7, and approximately the same as the criteria developed for Change 7. Change 10 has provisions for a 106 percent lot pay factor for added thickness in excess of the AQL requirement.

The tolerance limit for concrete strength has been set at (0.93 x Design Strength). This value is based on the approximate value of the coefficient of variation from full-scale test pavements tested to failure in the 1970's. The strength of the pavements constructed for the tests was determined from beams made from fresh concrete and from beams sawed from hardened concrete. The quality control, expressed as the coefficient of variation for both types of tests, was between 6 and 8 percent, say 7 percent. The design curves in AC 150/5320-6 were generated from these full scale tests, which implies that the production strength should meet the average strength used to generate the design curves. This allows the lower tolerance limit for strength to be set at (0.93 x Design Strength), which is equivalent to one standard deviation from the average using 7 percent coefficient of variation as a baseline.

It may take additional effort for process control during construction to achieve the same level of control that was possible during the research work on the full-scale tests. However, in order to meet the designer's intent, it is reasonable and necessary to require a higher strength if production of higher variability is common or anticipated, as long as the excess is producible on a consistent basis. This has generally been the case when specifying mix design strength to meet design intent. Historically, the mix design strength has been specified to be at least equal to the specified design strength with not more than 20 percent of strength tests falling below the design strength. For a 650 psi. design strength, the specification has historically implied that the average (or 50 PWL) strength and the 80 PWL strength should exceed 650 psi.

A one standard deviation strength acceptance model was developed that requires at least 80 PWL (Z value for 80 PWL =0.8416) at the design strength coupled with a lower specification tolerance limit of (0.93 x Design Strength). Using a design strength of 650 psi. as a model parameter, and a lower specification tolerance limit of 604.5 psi., the model standard deviation that provides an 80 PWL strength of 650 psi. is 55 psi. This was determined as follows:

$Z=(\mu-L)/\sigma$, which implies $\sigma=(\mu-L)/Z$

Where: $Z=0.8416$ (at 80 PWL

$L=604.5$ (at 650 psi design strength)

$\mu=650$ psi. (average desired at 80 PWL)

$\sigma=(650-604.5)/0.8416$, $\sigma=54.1$ psi, say 55 psi.

This model is compared to previous revisions to the specification in Table 2.1. Table 2.1 summarizes the AQL, RQL, tolerance limits, and strength requirements, assuming a model standard deviation of 55 psi., for the three recent revisions to the Item P 501 acceptance criteria for strength.

TABLE 2.1 SUMMARY OF STRENGTH REQUIREMENTS FOR ITEM P-501 ACCEPTANCE CRITERIA ASSUMING 55 psi STANDARD DEVIATION.

				Strength Required to Meet PWL			
Specification Revision	AQL PWL	RQL PWL	L psi.	AQL Strength	RQL Strength	80 PWL Strength	50 PWL Strength
Range-Based (converted to PWL)	60	37	650	664 psi	632 psi	696 psi	650 psi
Change 7	80	60	650	696 psi	664 psi	696 psi	650 psi
Change 10	90	55	604.5	675 psi	611 psi	651 psi	604.5 psi

Where: AQL = Acceptable quality level
RQL = Rejectable quality level
L = Lower specification tolerance limit
PWL = Percentage within specification limits

The range-based specification and Change 7 required the strength at 50 PWL to be at least 650 psi., which satisfies the designer's intent to have the average strength at least equal to the design strength. The range-based specification and Change 7 required the production strength to be higher than the design strength at the AQL, to meet the designer's intent to have not more than 20 percent fall below the design strength. Both specifications used the design strength as the lower limit, with Change 7 being consistent with the designer's assumptions. Both specifications had a narrow 32 psi. band between the AQL and the RQL (assuming a 55 psi standard deviation). Both specifications met the designer's intent. Under Change 7, the contractor could achieve a 106 percent lot pay factor, which helped offset the added strength requirement to meet an AQL of 80 PWL (696 psi.) versus the AQL of 60 PWL (664 psi.) contained in the range-based specification.

The revised acceptance criteria issued in Change 10 provides balance. The designer's intent for at least 80 percent of the concrete to have a strength of at least 650 psi. is achieved (at 55 psi. standard deviation). The contractor's desire to minimize the excess strength required to meet the specification is still reasonable, includes provisions to achieve a 106 percent lot pay factor, and the narrow strength band between the AQL and RQL has been increased without sacrificing the designer's intent. The limited amount of data from projects that were constructed under Change 7 suggest that contractors are striving to achieve a 106 percent lot pay factor by providing added strength. The FAA believes this practice will continue under the revised criteria, so the risk associated with accepting a strength at the RQL that is less than the design strength, is reduced.

Table 2.2 shows the strength requirements and model standard deviations applied to design strengths ranging from 600-750 psi. Table 2.3 summarizes the AQL, RQL, and upper and lower specification limits for Items P-401 and P-501.

TABLE 2.2 FAA STRENGTH REQUIREMENTS FOR 600, 650, 700, and 750 psi. DESIGN STRENGTHS.

Design Strength (psi.)	Lower Spec. Limit (L)	Model Standard Deviation	RQL (55 PWL)	80 PWL	AQL (90 PWL)
600	558.0	51	564	601	623
650	604.5	55	611	651	675
700	651.0	59	658	701	727
750	697.5	63	705	751	778

TABLE 2.3 ACCEPTANCE CRITERIA, ITEM P-401 ITEM P-501.

	QUALITY LEVELS		TOLERANCE LIMITS	
Item P-401	AQL	RQL	L	U
Mat Density	90 PWL	55 PWL	96.3 percent	-
Air Voids	90 PWL	55 PWL	2 percent	5 percent
Item P-501	AQL	RQL	L	
Strength	90 PWL	55 PWL	0.93 X Design	
Thickness	90 PWL	55 PWL	Plan - 0.50 in.	

Where: AQL = Acceptable quality level
RQL = Rejectable quality level
L = Lower specification tolerance limit
U = Upper specification tolerance limit

2.4 REVISED PAY ADJUSTMENT SCHEDULE.

The pay adjustment schedule in Change 10, was designed to add features that allow lot pay factors in excess of the contract unit price to offset the degree of uncertainty (risk) associated with acceptance plans when small fractions (sample size n=4 sublots) of material are used to evaluate a day's production. The goals were to minimize risk at the AQL, accept a reasonable risk at the RQL, and revise the pay adjustment schedule to reflect full pay when the estimated PWL was the same as the AQL and to reflect the minimum pay factor when the estimated PWL was the same as the RQL. The risk analysis will be discussed later in this section and in Section 4.

The existing Item P-401 pay adjustment schedule was revised to accomplish these goals and to incorporate the new RQL of 55 PWL. The 65 percent pay factor at the RQL was maintained. The existing pay adjustment schedule was incorporated into Item P-501 using the previously described revisions to the specification tolerance limits for strength and thickness. This accomplished the goal of adopting a uniform quality standard for acceptance of airport pavement surfaces.

The first step in the revision accommodated the new lower RQL. The existing pay curve from Item P-401 had two slopes, 0.5 between 80-90 PWL, and 2.0 between 65-80 PWL. It was decided to keep two slopes between the AQL and the RQL, and to keep the 0.5 slope in the higher quality region. The next step distributed the added quality range (65-55 = 10 PWL) equally, 5 PWL to the upper quality region (75-90 PWL), and 5 PWL to the lower quality region (55-74 PWL). The next step derived the new slope for the lower quality region using 65 percent pay at 55 PWL. This resulted in a slope of 1.4 between 55-74 PWL.

The final step was an iterative process to minimize the contractor's risk and provide full pay at the AQL. This required an incentive pay factor for quality above the AQL. The combination that successfully accomplished this resulted in a third slope, of 1.0 between 90 PWL and 96 PWL, and a pay factor range increasing linearly to 106 percent at 96 PWL, was added. The 106 percent lot pay factor is consistent with the incentive allowed in Item P-501 and with pay adjustment schedules recommended [3,5] for Item P-401.

Figure 2.1 summarizes the steps described above, and the lot pay factor adjustment schedule is shown in Table 2.4.

FIGURE 2.1 SUMMARY OF STEPS USED TO REVISE PAY FACTOR SCHEDULE.

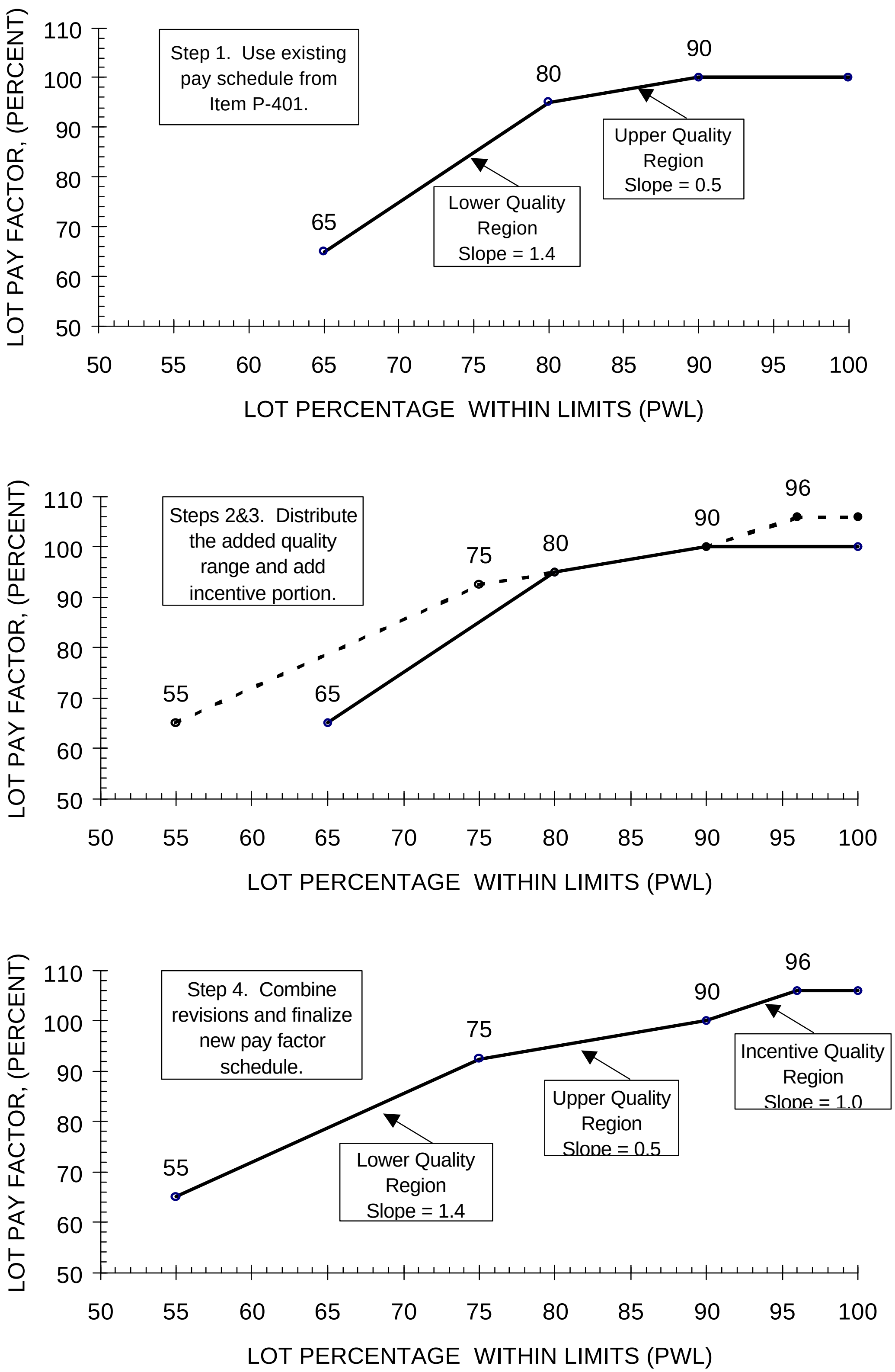


TABLE 2.4 PAY FACTOR ADJUSTMENT SCHEDULE.

PWL	Lot Pay Factor
96 and above	106
90 to 96	PWL +10
75 to 90	0.5 PWL +55
55 to 74	1.4 PWL -12
below 55 PWL	Reject (at 50 % pay)

PWL = Percentage within specification limits

Note: There is an option to allow the lot to remain in place at 50 percent pay when the pay factor is less than 65 percent.

The revised lot pay factor schedule applies to the density and air voids acceptance plans for Item P-401, and to the strength and thickness acceptance plans for Item P-501. It has been integrated with the specification tolerance limits contained in each specification.

The acceptance plans have additional features, explained in the individual specifications, that allow a measure of added quality furnished for one acceptance parameter to offset a measure of reduced quality furnished for the other acceptance parameter, on a lot-by-lot basis. For example, under certain conditions, Item P-401 lot pay factors in excess of 100 percent for density can offset air void pay factor reductions for the same lot, or, lot pay factors in excess of 100 percent for air voids can offset density pay factor reductions for the same lot. This also applies to the Item P-501 lot pay factors. For example, under certain conditions, Item P-501 lot pay factors in excess of 100 percent for thickness can offset strength pay factor reductions for the same lot, or, lot pay factors in excess of 100 percent for strength can offset thickness pay factor reductions for the same lot.

The relationship between design assumptions, the lot pay factor schedule, and the specification tolerance limits will be demonstrated for Item P-501 acceptance parameters. To demonstrate this relationship for the revised thickness tolerance, assume a Boeing B-767 aircraft is the design aircraft and conduct a design example using the following assumptions:

Flexural Strength	650 psi.
Modulus of Subgrade Reaction	300 pci.
Aircraft Gross Weight	325,000 lbs.
Number of Annual Departures	25,000

The design thickness derived using these assumptions is 15 inches. Now, assume the contractor standard deviation is 0.38 inches. This implies that 90 PWL requires 15.0 inches of pavement. This implies that 55 PWL requires 14.55 inches of pavement. According to the lot pay factor schedule, the contractor receives 65 percent pay at the RWL. Referring to the same design parameters, back-calculating the number of departures at 14.55 inches is less than 15,000 annual departures. This is less than 60 percent of the designer's intent.

The same design example is used to show how the lot pay factor schedule integrates with the revised tolerance limit. The RQL is (0.93 X design strength) for flexural strength. Now, assume the contractor's standard deviation is 55 psi. This implies that 90 PWL requires 675 psi., 80 PWL requires 651 psi., and 55 PWL requires 611 psi. The designer's intent is exceeded at the AQL and the strength required at 80 PWL is the design strength. At the RQL, the number of departures is between 6,000 and 15,000, again less than 60 percent (actually less than 50 percent of the designer's intent).

In both cases, material produced at the AQL meets the designer's intent, and material produced below the RQL does not meet the designer's intent.

3. OPERATING CHARACTERISICS, EXPECTED LOT PAY FACTORS, AND RISK ANALYSIS.

3.1 OPERATING CHARACTERISTICS (OC).

The FAA has adopted a sample size of n=4 sublots per lot, and has integrated a sliding scale pay adjustment schedule into the PWL acceptance plans applicable to Items P-401 and P-501. The AQL and RQL have been established at 90 PWL and 55 PWL respectively, so the probability of acceptance at any quality level, using a sample size of n=4 can be calculated. When plotted, these probability curves are called the operating characteristics (OC) of the acceptance plan, which is defined as the probability that a lot being produced at a given PWL (population statistics) will be accepted at a given lot pay factor based on the estimated PWL from sample statistics. The OC at various PWL values is shown in Table 3.1.

The probabilities were derived from software [9] that supplements and elaborates on the acceptance procedures presented in

MIL-STD 414, and calculates the probabilities based on the non-central-t and symmetrical beta probability distributions. The probabilities were derived by rounding the estimated PWL values to the next higher PWL value, a feature required in the specifications. For instance, at 90 PWL, the probability that the estimated PWL is 89.01 PWL or higher was the probability used to obtain the OC at 90 PWL. The values chosen for Table 3.1 can be arbitrary, since an OC can be determined for each PWL.

The values chosen for Table 3.1 correspond to the probability of estimating a lot at or above PWL'S of 96, 90, 80, 73, 66, 59, and 55 percent, which correspond to lot pay adjustment factors of 106, 100, 95, 90.2, 80.4, 70.6, and 65 percent, respectively. In all cases, 50 percent pay was assumed at PWL values below the RQL (55 PWL).

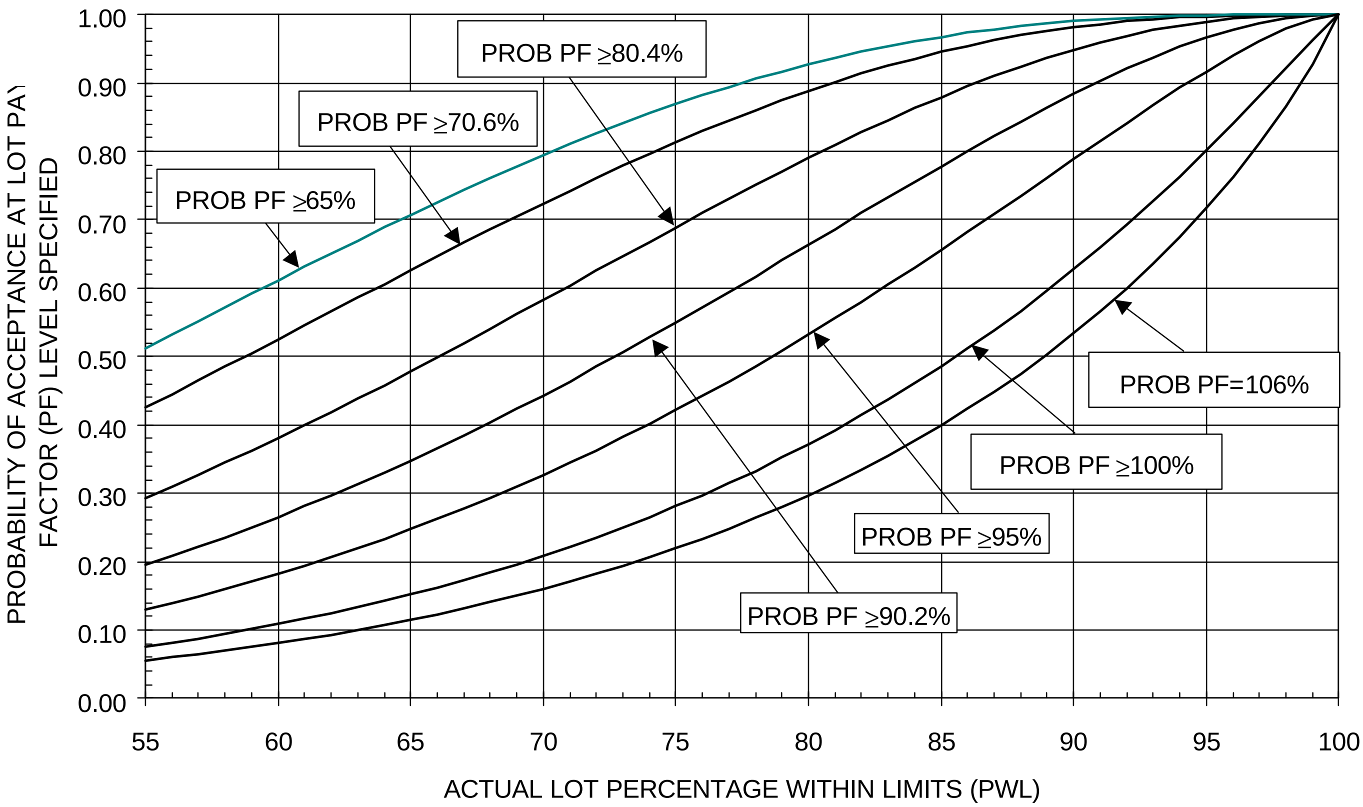
TABLE 3.1 OPERATING CHARACTERISTICS AT VARIOUS PWL LEVELS USING A SAMPLE SIZE n=4.

	PROBABILITY THAT THE LOT PAY FACTOR WILL BE:						
Lot PWL	106% or ≥ 96PWL	≥100% or ≥ 90PWL	≥95% or ≥ 80PWL	≥90.2% or ≥ 73PWL	≥80.4% or ≥ 66PWL	≥70.6% or ≥ 59PWL	≥65% or ≥ 55PWL
96	0.7624	0.8401	0.9397	0.9778	0.9939	0.9987	0.9995
90	0.5334	0.6270	0.7882	0.8839	0.9486	0.9814	0.9901
80	0.2973	0.3717	0.5320	0.6632	0.7900	0.8885	0.9271
73	0.1940	0.2497	0.3819	0.5061	0.6464	0.7791	0.8411
66	0.1231	0.1622	0.2620	0.3660	0.4990	0.6463	0.7257
59	0.0751	0.1010	0.1708	0.2501	0.3625	0.5047	0.5916
55	0.0554	0.0752	0.1303	0.1956	0.2931	0.4253	0.5116

PWL = Percentage within specification limits

Figure 3.1 graphically depicts the values in the table. This figure can be used to establish target production levels necessary to achieve a desired probability of acceptance, which will be explained in Section 4.

FIGURE 3.1 SET OF OPERATING CHARACTERISTICS CURVES FOR THE FAA ACCEPTANCE PLAN, SAMPLE SIZE n=4 SUBLOTS, AC 150/5370-10A, CHANGE 10 ITEMS P-401 AND P-501



3.2 EXPECTED LOT PAY FACTORS.

The expected lot pay factor is the AVERAGE fraction of full pay a contractor receives for a series of many lots produced at a given PWL. It is not the same as contract pay, as detailed in Section 4. Expected lot pay factors can be determined from the probability values in Table 3.1. The expected lot pay factor is determined at each quality level by choosing probability intervals between the AQL and the RQL, multiplying the interval probability by the average pay factor for the interval, then summing the pay factors for all the intervals between the AQL and the RQL. For example, assume the lot quality is 90 PWL, and the interval probability of interest is between 80-90 PWL. The average pay factor for a series of lots produced between 80-90 PWL is computed as follows:

(pay at 80PWL + pay at 90PWL)/2 or
(95 + 100)/2 = 97.5 percent

Also, the probability of evaluating a series of lots--being produced at 90 PWL--between the interval of 80-90 PWL is the difference between the probability of estimating the lot quality at 80 PWL or more and the probability of estimating the lot quality 90 PWL or more. The probability between the 80-90 PWL interval is determined, using Table 3.1, as follows:

(prob. at ≥80PWL) - (prob. at ≥90PWL) or
(0.7882 - 0.6270) = 0.1612

The contribution to the expected lot pay factor--at 90 PWL--for the probability between the 80-90 PWL is determined as follows:

(prob.) x (avg. pay factor) or
0.1612 x 97.5 percent = 15.72 percent

Interval probabilities for the PWL levels given in Table 3.1 are presented in Table 3.1A.

TABLE 3.1A OPERATING CHARACTERISICS AT VARIOUS PWL LEVELS USING A SAMPLE SIZE n=4.

PROBABILITY THAT THE LOT PAY FACTOR WILL BE:								
Lot PWL	106% or ≥ 96PWL	≥100% or ≥ 90PWL	≥95% or ≥ 80PWL	≥90.2% or ≥ 73PWL	≥80.4% or ≥ 66PWL	≥70.6% or ≥ 59PWL	≥65% or ≥ 55PWL	50% or < 55PWL
96	0.7624	0.0777	0.0996	0.0381	0.0161	0.0048	0.0008	0.0005
90	0.5335	0.0936	0.1612	0.0957	0.0646	0.0327	0.0087	0.0099
80	0.2973	0.0744	0.1603	0.1312	0.1268	0.0985	0.0386	0.0729
73	0.1940	0.0557	0.1322	0.1242	0.1403	0.1327	0.0620	0.1589
66	0.1231	0.0391	0.0998	0.1040	0.1330	0.1473	0.0794	0.2743
59	0.0751	0.0259	0.0698	0.0793	0.1124	0.1422	0.0869	0.4084
55	0.0554	0.0198	0.0551	0.0653	0.0975	0.1322	0.0863	0.4884

PWL = Percentage within specification limits
Note: Assumes 50% pay when pay factor is less than 65%

The expected lot pay factors (that is, the summation of the above interval multiplied by the average pay between the intervals) corresponding to the PWL levels given in Tables 3.1 and 3.1A, are presented in Table 3.2 for the acceptance plan when n=4 sublots.

The expected lot pay factor at a given PWL is analogous to the operating characteristics when pay adjustment schedules are part of the acceptance plan, and can be used to analyze risk.

TABLE 3.2 EXPECTED LOT PAY FACTORS FOR FAA ACCEPTANCE PLAN.

SAMPLE SIZE n=4 SUBLOTS.

Lot Quality (PWL)	Expected Lot Pay Factor
96	103.87%
90	99.84%
80	91.47%
73	84.83%
66	78.00%
59	71.41%
55	67.90%

PWL = Percentage within specification limits

Note: Assumes 50% pay when pay factor is less than 65%

3.3 RISK ANALYSIS AND EXPECTED LOT PAY FACTOR.

There are two types of risk associated with the acceptance plan. The contractor’s risk is the risk that material of acceptable quality will be rejected and the owner’s risk is the risk that material of rejectable quality will be accepted. The goal of Change 10 was to use the probabilities associated with a sample size n=4 sublots, an AQL of 90 PWL and a RQL of 55 PWL, in combination with a new pay adjustment schedule to essentially eliminate the contractor’s risk at the AQL and minimize the owner’s risk at the RQL.

The expected lot pay factor at any PWL can be analyzed for risk by using the lot pay factor schedule as the baseline. The contractor’s risk and the owner's risk can be expressed as the difference between the pay determined from the lot pay factor schedule and the pay determined from the expected pay factor curve. If the expected pay factor is less than the lot pay factor schedule value, the contractor has risk. If the expected pay factor is more than the lot pay factor schedule value, the owner has risk. Table 3.3 shows the contractor’s and owner’s risk at the quality levels used in Tables 3.1, 3.1A, and 3.2.

TABLE 3.3 CONTRACTOR'S AND OWNER'S RISK AT VARIOUS QUALITY LEVELS.

Lot Quality (PWL)	Col B Lot Pay Factor Schedule	Col C Expected Lot Pay Factor	Contractor Risk (B - C)	Owner Risk (C - B)
96	106%	103.87%	2.13%	-
90	100%	99.84%	0.16%	-
80	95%	91.47%	3.53%	-
73	90.2%	84.83%	5.37%	-
66	80.4%	78.00%	1.60%	-
59	70.6%	71.41%	-	0.81%
55	65%	67.90%	-	2.90%

PWL = Percentage within specification limits

Note: Assumes 50% pay when pay factor is less than 65%

Note: Risks above the AQL and below the RQL are analyzed in Section 4.

As shown in the table, the risks are well balanced in the acceptable quality range. The contractor can expect to average full pay in the long run for consistent production at the AQL, and the owner only has a 3 percent risk of accepting work if consistently produced at the RQL. These are theoretical risks and the contractor's risk appears to be slightly conservative when compared to simulations as will be shown. A more complete analysis of risk above the AQL and below the RQL is presented in Section 4.

4. SIMULATION OF ACCEPTANCE PLANS.

The acceptance plans were simulated [10] for each of the acceptance parameters for Items P-401 and P-501. For Item P-401, simulations were conducted for density and air voids. For Item P-501, simulations were conducted for strength and thickness.

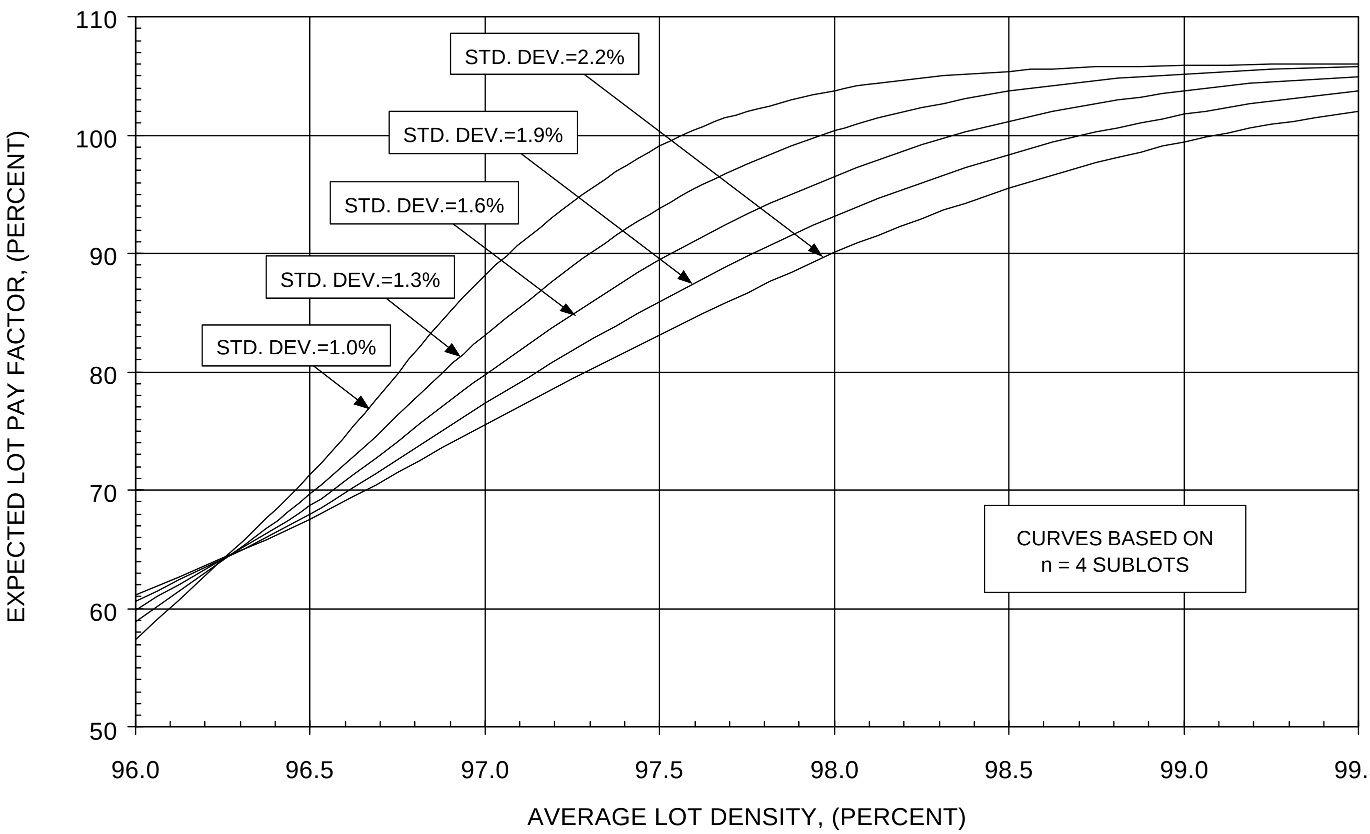
4.1 ITEM P-401 MAT DENSITY ACCEPTANCE PLAN.

The acceptance plan for mat was simulated by randomly generating lot data, with 4 sublots per lot, using a normal distribution with:

- L=96.3 percent.
- Standard deviation = 1.0, 1.3, 1.6, 1.9, and 2.2 percent.
- Average density values of: 96.0, 96.5 97.0, 97.5, 98.0, 98.5, 99.0, and 99.5 percent density.
- Outlier check at 5 percent significance, with outliers excluded from the evaluation and a revised n=3 used to calculate the estimated PWL).
- All lots that fall below 55 PWL allowed to remain in place at 50 percent pay.

10,000 lots, each with 4 random sublot values, were generated for each average and standard deviation combination. Each lot result was evaluated according to the method of estimating PWL, and pay factors were calculated using the lot pay factor schedule. The average lot pay factor for 10,000 lots, at each density was considered the expected lot pay factor at that density. The results are shown in Figure 4.1.

FIGURE 4.1 EXPECTED LOT PAY FACTORS FOR DENSITY ACCEPTANCE PLAN,
ITEM P-410 WITH OUTLIER CHECK AT 5% SIGNIFICANCE



The expected lot pay factor for density depends on the variability (standard deviation) as well as the average (mean) density. The expected lot pay factor corresponding to a specific density and variability combination is defined as the AVERAGE lot pay factor a contractor receives for a series of many lots produced at the specific density and standard deviation combination and sampled at the indicated number of sublots per lot. For example, if hot mix is produced at 98.0 percent density with a standard deviation of 1.3 percent, the AVERAGE lot pay factor a contractor would receive for a series of lots, sampled at n=4 sublots per lot, would be slightly higher than 100 percent of full pay.

Production (population) density is defined as the average density that would result if all of the hot mix in a lot were random sampled and tested for density. Production (population) variability is defined as the standard deviation from all density tests in a lot if all of the material in a lot were tested. The expected lot pay factors are calculated using the sample average and sample standard deviations using the sample required in the specifications, size n=4 sublots.

Figure 4.1 shows the expected lot pay factor for density for various standard deviations when the lower specification limit is 96.3 percent. Using 1.3 percent as the contractor's standard deviation, for example, the average production density must equal or exceed 98.0 percent to expect a lot pay factor of 100 percent or more when using n=4 sublots. If the contractor's standard deviation is 1.6 percent, then the average density must equal or exceed 98.4 percent to expect a lot pay factor of 100 percent or more. The figure shows the impact that process control has on expected lot pay factors. For example, if the production density is 98.0 percent. the expected lot pay factor at a standard deviation of 1.3 percent is 100.3 percent. The expected lot pay factor drops to 90 percent at 98.0 percent density, at a standard deviation of 2.2 percent.

4.2 ITEM P-401 AIR VOID ACCEPTANCE PLAN.

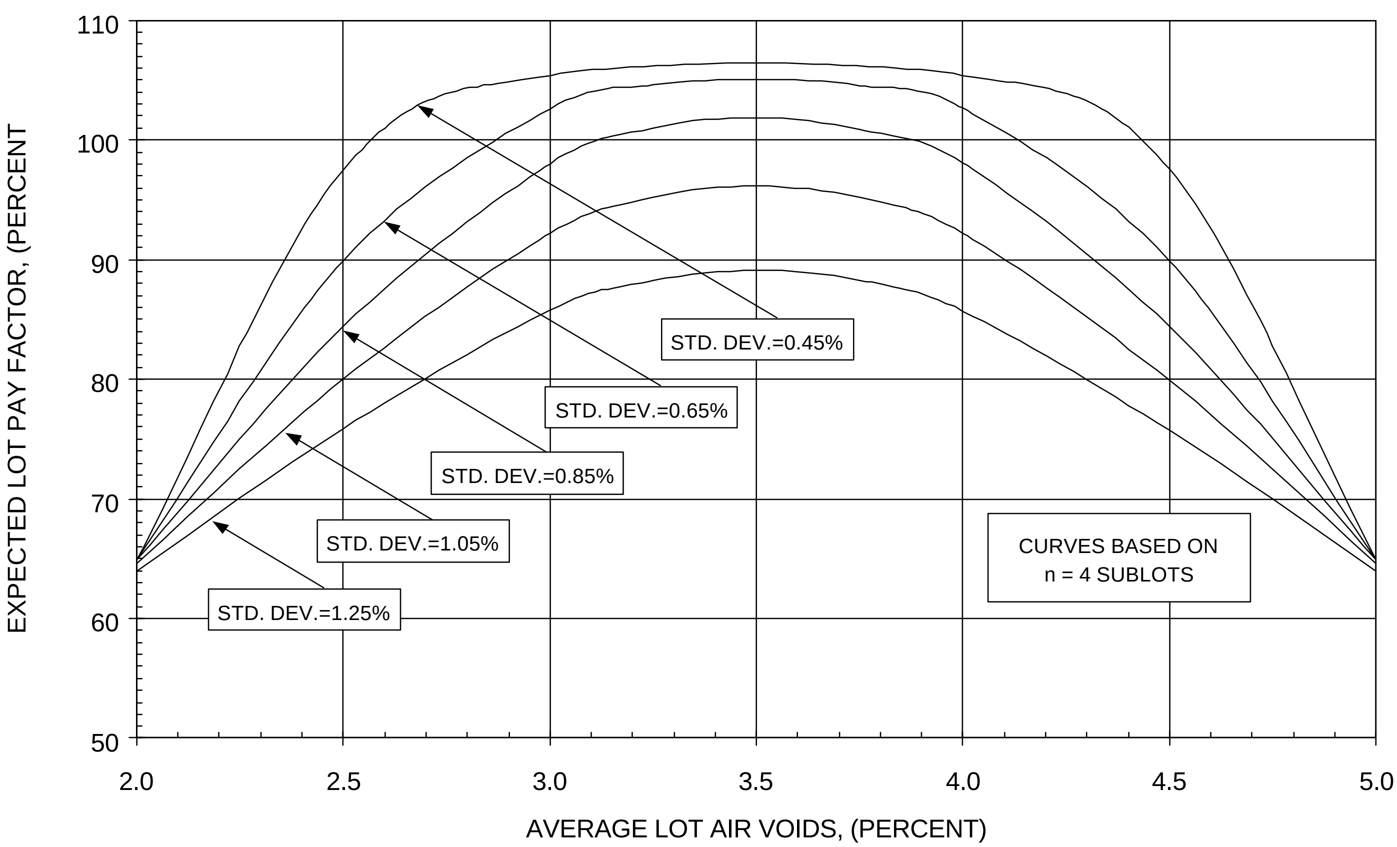
The air void acceptance plan was simulated by randomly generating lot data, with 4 sublots per lot, using a normal distribution with:

- L=2.0 percent.
- U=5.0 percent.
- Standard deviation = 0.45, 0.65, 0.85, 1.05. and 1.25 percent.
- Average air voids of: 2.0, 2.5, 3.0, 3.25, 2.5, 3.75, 4.0, 4.5, and 5.0 percent.

- Outlier check at 5 percent significance, with outliers excluded from the evaluation and a revised n=3 used to calculate the estimated PWL.
- All lots that fall below 55 PWL allowed to remain in place at 50 percent pay.

10,000 lots, each with 4 random sublot values, were generated for each average and standard deviation combination. Each lot result was evaluated according to the method of estimating PWL, and lot pay factors were calculated using the lot pay factor schedule. The average lot pay factor for 10,000 lots, at each air void content was considered the expected lot pay factor at that air void content. The results are shown in Figure 4.2.

FIGURE 4.2 EXPECTED LOT PAY FACTORS FOR AIR VOID ACCEPTANCE PLAN, ITEM P-410 WITH OUTLIER CHECK AT 5% SIGNIFICANCE



The expected lot pay factor for air voids depends on the variability (standard deviation) as well as the average (mean) air voids. The expected lot pay factor corresponding to a specific air void and standard deviation combination is defined as the AVERAGE lot pay factor a contractor receives for a series of many lots produced at the specific air void and standard deviation combination and sampled at the indicated number of sublots per lot. For example, if hot mix is produced at 2.8 percent air voids with a standard deviation of 0.65 percent, the AVERAGE lot pay factor a contractor would receive for a series of lots, sampled at n=4 sublots per lot, would be 100 percent of full pay.

Production (population) air voids are defined as the average air voids that would result if all of the hot mix in a lot were random sampled and tested for air voids. Production (population) variability is defined as the standard deviation from all air voids tests in a lot if all of the material in a lot were tested. The expected lot pay factors are calculated using the sample average and sample standard deviations using the sample required in the specifications, size n=4 sublots.

Figure 4.2 shows the expected lot pay factor for air voids for various standard deviations when the lower specification limit is 2.0 percent and the upper specification limit is 5.0 percent. Using 0.65 percent as the contractor's standard deviation, for example, the average production air voids must be between 2.8 - and 4.2 percent to expect lot pay factors of 100 percent or more when using n=4 sublots. If the contractor's standard deviation is 1.05 percent, then the average air voids must be between 3.4 - 3.8 percent to expect lot pay factors of 100 percent or more. The figure shows the impact that process control has on expected lot pay factors. For example, if the production air voids are 2.8 percent or 4.2 percent, the expected lot pay factor at a standard deviation of 0.65 percent is 100 percent. The expected lot pay factor drops to 90 percent at 2.8 percent or 4.2 percent air voids, at a standard deviation of 1.05 percent.

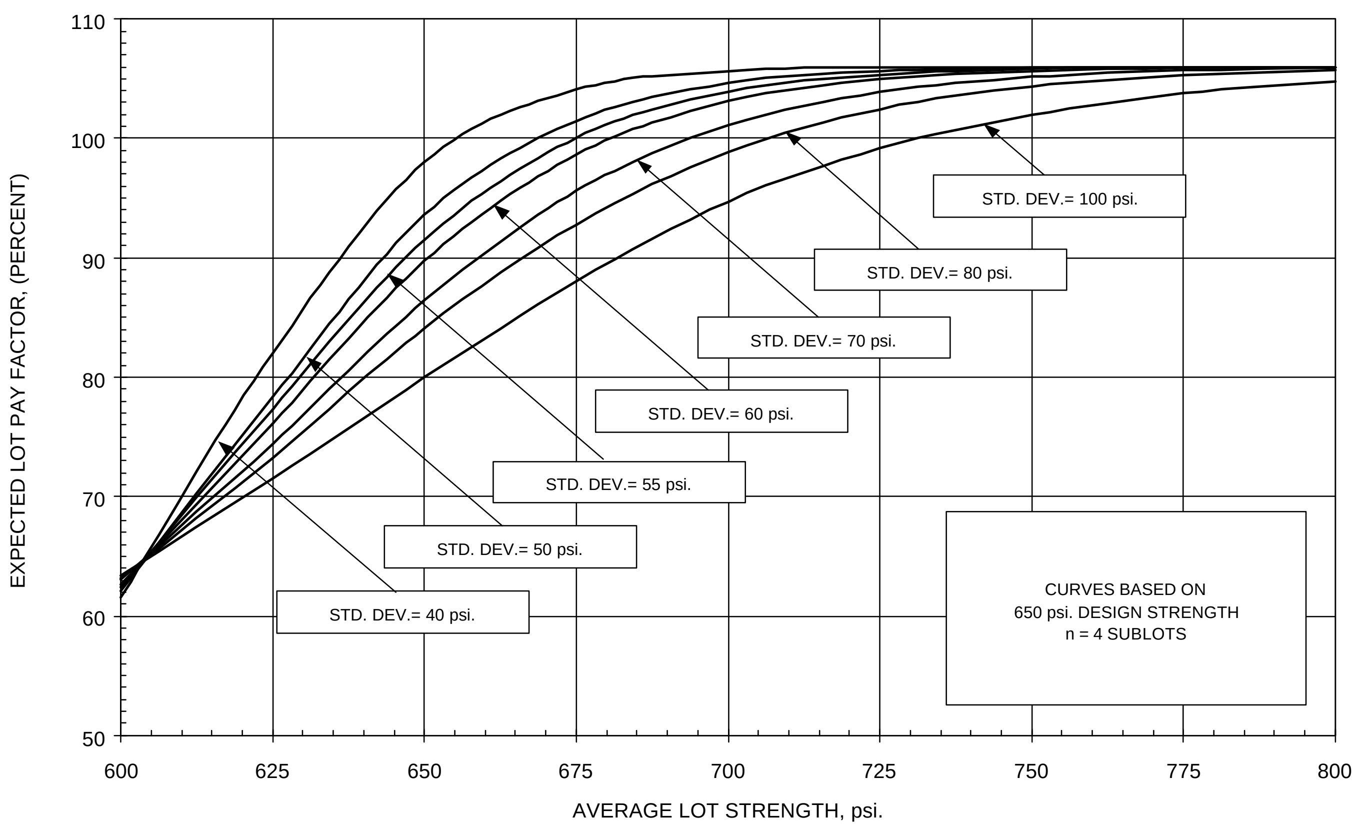
4.3 ITEM P-501 STRENGTH ACCEPTANCE PLAN.

The strength acceptance plan was simulated by randomly generating lot data, with 4 sublots per lot, using a normal distribution with:

- L=604.5 psi (650 psi. Design Strength).
- Standard deviation values of: 40, 50, 55, 60, 70, 80, and 100 psi.
- Average flexural strength values of: 600, 625, 650, 675, 700, 725, 750, 775, and 800 psi.
- Outlier check at 5 percent significance, with outliers excluded from the evaluation and a revised n=3 used to calculate the estimated PWL).
- All lots that fall below 55 PWL allowed to remain in place at 50 percent pay.

10,000 lots, each with 4 random sublot values, were generated for each average and standard deviation combination. Each lot result was evaluated according to the method of estimating PWL, and lot pay factors were calculated using the lot pay factor schedule. The average lot pay factor for 10,000 lots, at each flexural strength was considered the expected lot pay factor at that flexural strength. The results are shown in Figure 4.3.

FIGURE 4.3 EXPECTED LOT PAY FACTORS FOR STRENGTH ACCEPTANCE PLAN, 650 psi DESIGN STRENGTH, WITH OUTLIER CHECK AT 5% SIGNIFICANCE



The expected lot pay factor for strength depends on the variability (standard deviation) as well as the average (mean) strength. The expected lot pay factor corresponding to a specific strength and variability combination is defined as the AVERAGE lot pay factor a contractor receives for a series of many lots produced at the specific strength and variability combination and sampled at the indicated number of sublots per lot. For example, if concrete is produced at 675 psi. with a standard deviation of 55 psi, the AVERAGE lot pay factor a contractor would receive for a series of lots, sampled at n=4 sublots per lot, would be 100 percent of full pay.

Production (population) strength is defined as the average strength that would result if all of the concrete in a lot were random sampled and tested for strength. Production (population) variability is defined as the standard deviation that would result from all strength tests in a lot if all of the material in a lot were tested. The expected lot pay factors are calculated using the sample average and sample standard deviations using the sample required in the specifications, size n=4 sublots.

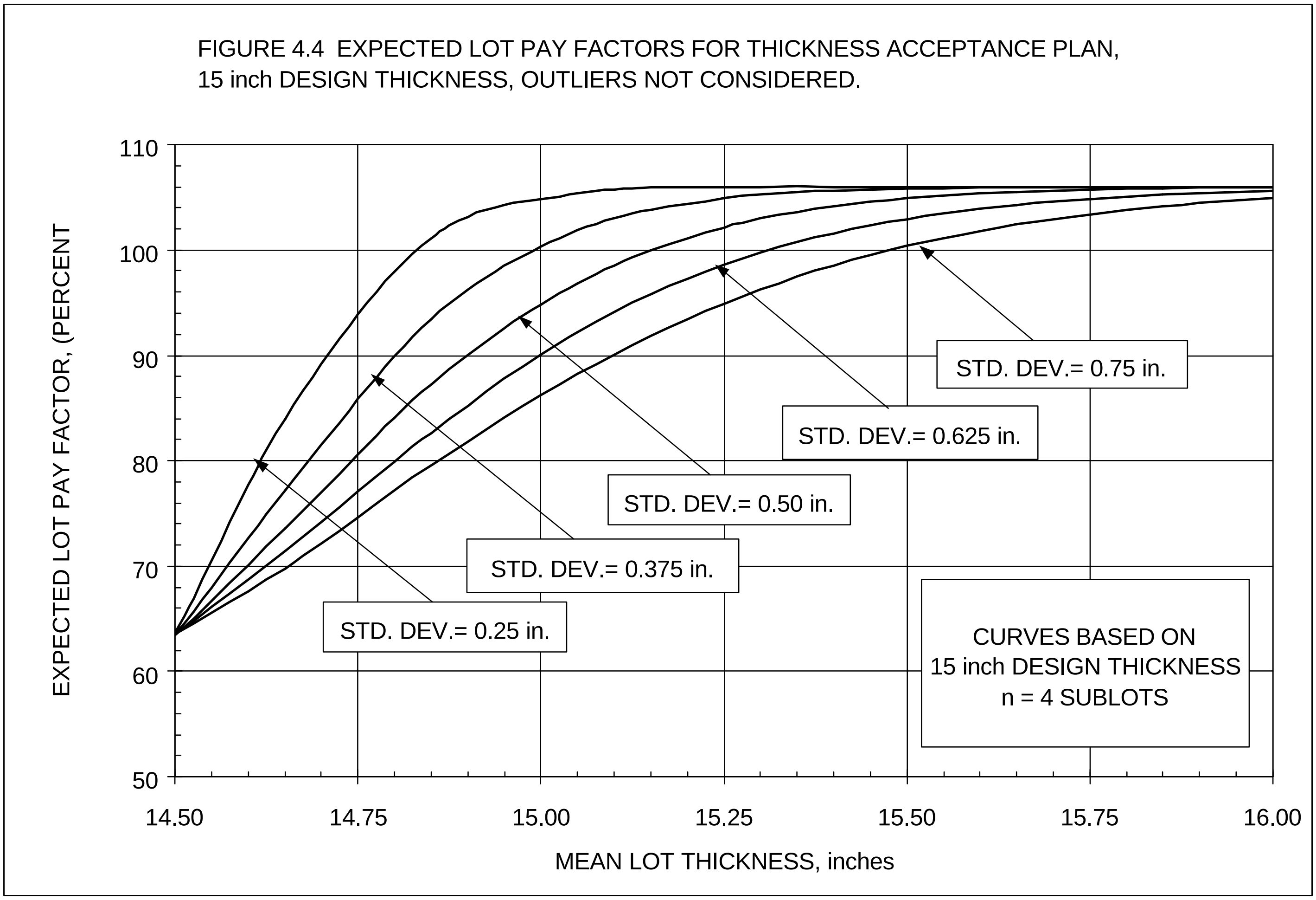
Figure 4.3 shows the expected lot pay factor for strength for various standard deviations when the lower specification limit is 604.5 psi (design strength is 650 psi.) Using 55 psi. as the contractor's standard deviation, for example, the average production strength must equal or exceed 675 psi. to expect lot pay factors of 100 percent or more when using n=4 sublots. If the contractor's standard deviation is 70 psi., then the average strength must equal or exceed 695 psi. to expect lot pay factors of 100 percent or more. The table shows the impact that process control has on expected lot pay factors. For example, if the production strength is 675 psi., the expected lot pay factor at a standard deviation of 55 psi. is 100 percent. The expected lot pay factor drops to 95.6 percent at a standard deviation of 70 psi.

4.4 ITEM P-501 THICKNESS ACCEPTANCE PLAN.

The thickness acceptance plan was simulated by randomly generating lot data, with 4 sublots per lot, using a normal distribution with:

- L=14.5 in. (15 inch Design Thickness).
- Standard deviation values of: 0.25, 0.375, 0.50, 0.625, and 0.75 in.
- Average thickness values of: 14.5, 14.75, 15.0, 15.25, 15.5, 15.75, and 16.0 in.
- There is no outlier provision for thickness.
- All lots that fall below 55 PWL allowed to remain in place at 50 percent pay.

10,000 lots, each with 4 random sublot values, were generated for each average and standard deviation combination. Each lot result was evaluated according to the method of estimating PWL, and lot pay factors were calculated using the lot pay factor schedule. The average lot pay factor for 10,000 lots, at each thickness was considered the expected lot pay factor at that thickness. The results are shown in Figure 4.4.



The expected lot pay factor for thickness depends on the variability (standard deviation) as well as the average (mean) thickness. The expected lot pay factor corresponding to a specific thickness and variability combination is defined as the AVERAGE lot pay factor a contractor receives for a series of many lots produced at the specific thickness and variability combination and sampled at the indicated number of sublots per lot. For example, if concrete is produced at 15.0 inches with a standard deviation of 0.375 in., the AVERAGE lot pay factor a contractor would receive for a series of lots, sampled at n=4 sublots per lot, would be 100 percent of full pay.

Production (population) thickness is defined as the average thickness that would result if all of the concrete in a lot were sampled and tested for thickness. Production (population) variability is defined as the standard deviation that would result from all thickness tests in a lot if all of the material in a lot were tested. The expected lot pay factors are calculated using the sample average and sample standard deviations using the sample required in the specifications, size n=4 sublots.

Figure 4.4 shows the expected lot pay factor for thickness for various standard deviations when the design thickness is 15 inches. Using 0.375 in. as the contractor's standard deviation (population), for example, the average (mean) production thickness must equal or exceed 15 inches to expect lot pay factors of 100 percent or more when using n=4 sublots. If the contractor's standard deviation is 0.50 in., then the average thickness must equal or exceed 15.15 in., to expect lot pay factors of 100 percent or more. The table shows the impact that process control has on expected lot pay factors. For example, if the production thickness is 15.0 in., the expected lot pay factor at a standard deviation of 0.375 in. is 100 percent. The expected lot pay factor drops to 90 percent at a standard deviation of 0.625 in.

4.5 RISKS DETERMINED FROM SIMULATIONS OF ACCEPTANCE PLANS.

As mentioned earlier, the contractor's risk calculated from the probability tables appears to be conservative when compared to the simulations. Table 4.1 shows the risks calculated from the simulations with an outlier check at 5 percent significance. Table 4.2 shows the risks calculated when no outlier provision is included. In both cases, the contractor essentially achieves a lot pay factor of 100 percent in the long run when production is consistently at the AQL, and the owner has about 4 percent risk at the RQL. Below the RQL, the owner assumes a much higher risk, about 17-18 percent, if material is accepted. Since it is highly unlikely that a contractor would purposely produce below the RQL, this higher risk is acceptable. The owner relies on the resident project engineer to use engineering judgement before agreeing to allow material evaluated below the RQL to remain in place at 50 percent pay. The maximum contractor's risk using the acceptance plans, indicated at about 75 PWL, is less than 5.5 percent. The contractor's risk when producing higher than the AQL is generally less than the contractor's risk when production is lower than the AQL. Production higher than the AQL will be discussed later.

The contractor’s risk and the owner's risk can be calculated at any PWL. Risk is expressed as the difference between the lot pay factor schedule value and the expected pay factor value at the same PWL. If the expected pay factor is less than the lot pay factor schedule value, the contractor has risk. If the expected pay factor is more than the lot pay factor schedule value, the owner has risk. Table 4.1 and Table 4.2 show the contractor’s and owner’s risk at various PWL levels, and Figure 4.5 graphically depicts the expected lot pay factors.

TABLE 4.1 CONTRACTOR'S AND OWNER'S RISK AT VARIOUS QUALITY LEVELS FROM SIMULATION (Outlier Check), VALID FOR DENSITY, AIR VOIDS, AND STRENGTH ACCEPTANCE PLANS.

Lot Quality (PWL)	Col B Lot Pay Factor Schedule	Col C Expected Lot Pay Factor	Contractor Risk (B - C)	Owner Risk (C - B)
99	106%	105.59%	0.41%	-
98	106%	105.11%	0.89%	-
97	106%	104.57%	1.43%	-
96	106%	104.02%	1.98%	-
95	105%	103.43%	1.57%	-
94	104%	102.82%	1.18%	-
93	103%	102.20%	0.80%	-
92	102%	101.53%	0.47%	-
91	101%	100.83%	0.17%	-
90	100%	100.12%	-	0.12%
85	97.5%	96.21%	1.29%	-
80	95.0%	91.90%	3.10%	-
75	92.5%	87.15%	5.35%	-
70	86.0%	82.46%	3.54%	-
65	79.0%	77.74%	1.26%	-
60	72.0%	73.06%	-	1.06%
55	65.0%	68.83%	-	3.83%
54	50.0%	67.95%	-	17.95%
50	50.0%	64.67%	-	14.67%

PWL = Percentage within specification limits
Note: Assumes all lots allowed to remain in place at 50% pay when the lot pay factor is less than 65%

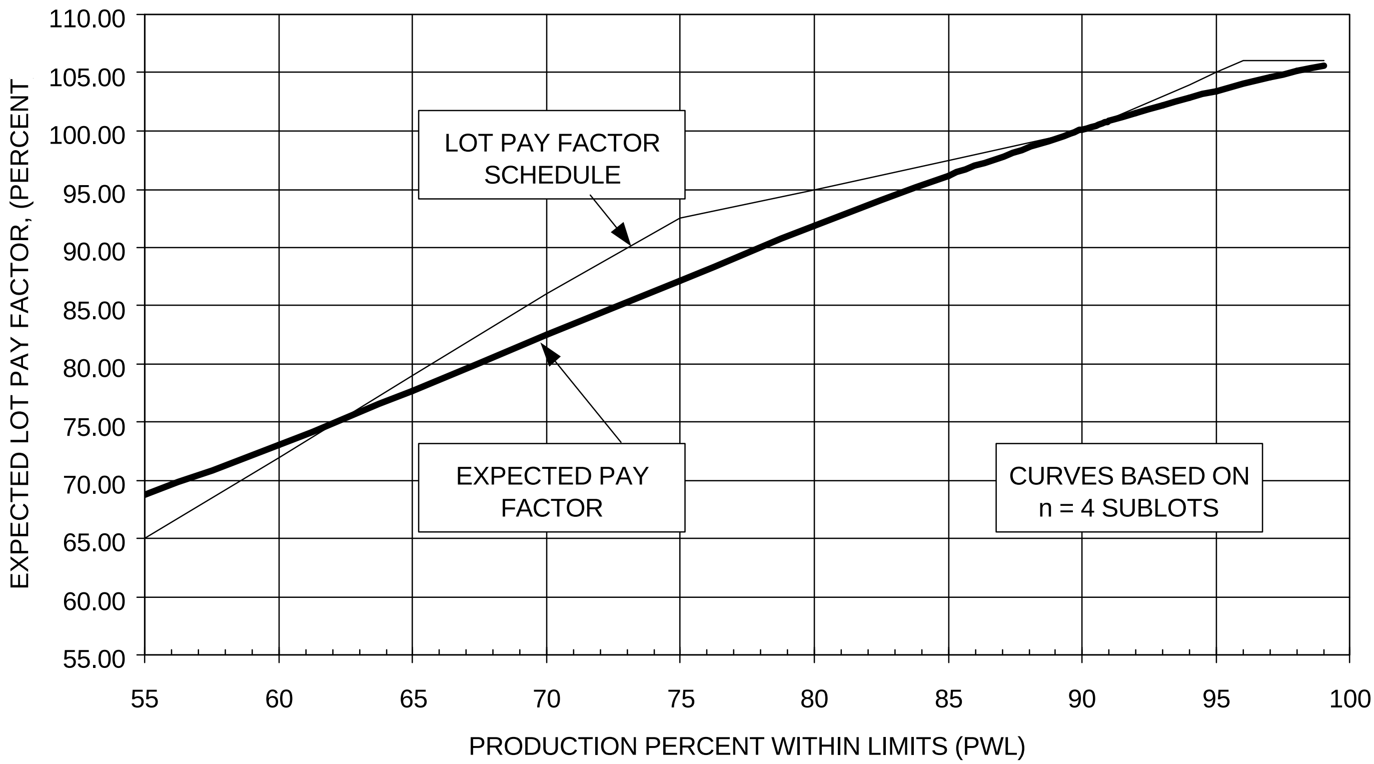
TABLE 4.2 CONTRACTOR'S AND OWNER'S RISK AT VARIOUS QUALITY LEVELS FROM SIMULATION (No Outlier Check), VALID FOR THICKNESS ACCEPTANCE PLAN.

Lot Quality (PWL)	Col B Lot Pay Factor Schedule	Col C Expected Lot Pay Factor	Contractor Risk (B - C)	Owner Risk (C - B)
99	106%	105.56%	0.44%	-
98	106%	105.05%	0.95%	-
97	106%	104.47%	1.53%	-
96	106%	103.89%	2.11%	-
95	105%	103.26%	1.74%	-
94	104%	102.59%	1.41%	-
93	103%	101.92%	1.08%	-
92	102%	101.24%	0.76%	-
91	101%	100.51%	0.49%	-
90	100%	99.75%	0.25%	-
85	97.5%	95.69%	1.81%	-
80	95.0%	91.23%	3.77%	-
75	92.5%	86.36%	6.14%	-
70	86.0%	81.48%	4.52%	-
65	79.0%	76.58%	2.42%	-
60	72.0%	71.86%	0.14%	-
55	65.0%	68.83%	-	3.83%
54	50.0%	66.67%	-	16.67%
50	50.0%	63.42%	-	13.42%

PWL = Percentage within specification limits

Note: Assumes all lots allowed to remain in place at 50% pay when the lot pay factor is less than 65%

FIGURE 4.5 EXPECTED LOT PAY FACTORS FOR FAA ACCEPTANCE PLAN, ITEMS P-410 and P-501, WITH OUTLIER CHECK AT 5% SIGNIFICANCE AND LOT PAY FACTOR SCHEDULE



4.6 EXPECTED PAY AND CONTRACT PAY--NOT THE SAME.

The above analyses of risk and expected pay factors are based on theoretical considerations and theoretically valid simulations using many lots (10,000 lots) of material produced consistently at specific PWL levels. The analyses show that the acceptance plan is capable of identifying the pavement quality levels desired with risk levels that are acceptable. The results should not be construed to mean that contract pay and expected pay are the same--they are not. The contractor must assess his or her equipment, personnel, and process control capabilities, using the production average (μ) and production standard deviation (σ), in order to establish production targets that are compatible with capabilities. Project size, expressed as the number of lots in a project, effects the ability of the incentive portion of the pay factor schedule to offset reduced quality.

Regardless of project size, the contract's pay factor is based on evaluating material, on a lot by lot basis, according to the specifications. This means it is prudent to establish production targets at some level higher than the AQL, which increases the probability of acceptance. The incentive portion of the pay factor schedule, whether administered as an actual pay, or as a crediting provision to offset lots that do not meet requirements, has been incorporated to offset the contractor's risk and has the effect of offsetting a portion of the added cost when establishing production targets higher than the AQL.

A contractor can use Figure 3.1 to help establish production targets to have an increased probability of getting a given pay factor. For example, assume a contractor would like to have a high probability, say about 85 percent, of evaluating at full pay. Referring to the figure and table, the contractor could achieve this goal by setting production quality level at slightly higher than 96 PWL. Using Figure 3.1, the intersection of 0.85 probability and 100 percent pay is desired. This occurs at about 96 PWL. From Table 3.1, the probability of achieving a 100 percent pay factor at 96 PWL is slightly higher than 84 percent, and the probability of achieving a 106 percent pay factor is about 76 percent. The expected pay factor at 96 PWL is about 104 percent.

Table 4.3 shows the increasing probability of achieving specific lot pay factors, corresponding to the probability of evaluating at 75, 80, 85, 90, and 96 PWL, when production targets are set at quality levels higher than the AQL. The table can be used to help establish production targets to have an increased probability of achieving a given pay factor.

Table 4.3 PROBABILITY OF ACHIEVING LOT PAY FACTORS WHEN PRODUCTION PWL EXCEEDS THE AQL.

USING A SAMPLE SIZE OF n=4.

	Probability of Achieving a Lot Pay Factor of:				
Production PWL	106% or ≥96 PWL	≥100% or ≥90 PWL	≥97.5% or ≥85 PWL	≥95% or ≥80 PWL	≥92.5% or ≥75 PWL
99	0.9275	0.9634	0.9824	0.9930	0.9977
98	0.8663	0.9219	0.9562	0.9788	0.9914
97	0.8118	0.8805	0.9268	0.9606	0.9818
96	0.7624	0.8401	0.8960	0.9397	0.9695
95	0.7170	0.8011	0.8644	0.9168	0.9550
94	0.6750	0.7634	0.8327	0.8925	0.9385
93	0.6360	0.7272	0.8011	0.8672	0.9205
92	0.5995	0.6924	0.7697	0.8413	0.9011
91	0.5654	0.6590	0.7389	0.8149	0.8807
90	0.5334	0.6270	0.7086	0.7882	0.8593

Where: AQL = Acceptable quality level = 90 PWL
PWL = Percentage within specification limits

The production PWL is calculated using population statistics,

μ = production average
σ = production standard deviation

Table 4.4 PRODUCTION VALUES REQUIRED TO EVALUATE AT QUALITY LEVELS IN EXCESS OF THE AQL. ITEM P-401 and P-501 EXAMPLES USING A SAMPLE SIZE OF n=4.

	Probability of Achieving a Lot Pay Factor of:					Production Values Needed to Achieve Quality Level, Using FAA Model Assumptions			
						Item P-401		Item P-501	
Production PWL	106%	≥100%	≥97.5%	≥95%	≥92.5%	Density μ =98.0% σ =1.3% L=96.3%	Air Voids μ =3.5% σ =0.65% L=2%, U=5%	Strength μ =675 psi. σ =55 psi. L=604.5 psi.	Thickness μ =15.0 in. σ =0.38 in. L=14.5 in.
99	0.93	0.96	0.98	0.99	1.00	99.32	3.49 - 3.51	732	15.38
98	0.87	0.92	0.96	0.98	0.99	98.97	3.33 - 3.67	717	15.28
97	0.81	0.88	0.93	0.96	0.98	98.75	3.22 - 3.78	708	15.21
96	0.76	0.84	0.90	0.94	0.97	98.58	3.14 - 3.86	701	15.17
95	0.72	0.80	0.86	0.92	0.96	98.44	3.07 - 3.93	695	15.13
94	0.68	0.76	0.83	0.89	0.94	98.32	3.01 - 3.99	690	15.09
93	0.64	0.73	0.80	0.87	0.92	98.22	2.96 - 4.04	686	15.06
92	0.60	0.69	0.77	0.84	0.90	98.13	2.91 - 4.09	682	15.03
91	0.57	0.66	0.74	0.81	0.88	98.04	2.87 - 4.13	678	15.01
90	0.53	0.63	0.71	0.79	0.86	97.97	2.83 - 4.17	675	14.99

AQL = Acceptable quality level = 90 PWL
PWL = Percentage within specification limits = area under the standard distribution at Z.
For L, the production PWL is the area under the standard normal distribution at $Z = (\mu - L)/\sigma$
For U, the production PWL is the area under the standard normal distribution at $Z = (U - \mu)/\sigma$
where μ = production average; L = lower specification tolerance limit
σ = production standard deviation; U = upper specification tolerance limit
Z = number of standard deviations from the average using the standard normal curve

Table 4.4 summarizes the production quality needed to achieve the probability values listed in Table 4.3. The table relates the increasing probability of achieving specific lot pay factors for Items P-401 and P-501, assuming model production parameters. Similar tables can be constructed for any combination of μ, σ, L, and U. The values for L and/or U are provided in the specifications. The contractor must assign values to μ and σ, based on knowledge of his or her equipment, personnel, and process control capabilities. The production values listed in Table 4.4 for Item P-501 are based on a design strength of 650 psi. and a design thickness of 15 inches. Table 4.5 lists Z values from standard normal probability tables at corresponding PWL values between 90-99 PWL.

Table 4.5. Z VALUES AT CORRESPONDING PWL.

PWL	Z VALUE
99	2.326
98	2.054
97	1.881
96	1.751
95	1.645
94	1.555
93	1.476
92	1.405
91	1.341
90	1.282

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