AN ABSTRACT OF THE THESIS OF

Roger B. Grinde for the degree of Master of Science in Industrial Engineering presented on June 2, 1986.

Title: Evaluation of the Limit Number Effects for Reduced Inspection in ANSI/ASQC Z1.4 using a Markov Model

Abstract approved: ____________________________  Edward D. McDowell

ANSI/ASQC Z1.4 is a widely used attributes acceptance sampling system. A necessary aspect of a scheme, from both a theoretical and psychological viewpoint, is the switching between normal, tightened, and reduced inspection as a function of quality history. In the latest revision of the standard the switching rules were altered to make use of the limit numbers for reduced inspection optional. Furthermore, a statement in the standard suggests that this action will have little effect on operating properties.

A Markov model was developed to analyze the effect of the limit numbers. The no limit number model was solved analytically. The resulting closed-form results eliminate the need for matrix inversion and show that the maximum average run length on normal inspection is only 12.7 lots.
The results show that use with the limit numbers significantly impacts many performance measures. Averaged across all 152 single sampling schemes and with quality at the AQL, the average run length on normal inspection increases 287% and the percent rejected increases 26% when limit numbers are used. Without limit numbers, the percent inspected on reduced increases 78%, the frequency of transitions between normal and reduced increases 108%, and the number of lots inspected before discontinuation increases 250%.

When quality is slightly worse than the AQL (1.25 AQL), the differences are even greater. The average run length on normal increases 452% and the percent rejected increases 36% with limit numbers. Reduced inspection is nearly eliminated when the limit numbers are used. Omission of the limit numbers increases the percent on reduced by 972%, the frequency of transitions between normal and reduced by 776%, and the number of lots inspected by 120%.

Contrary to the claim in ANSI/ASQC Z1.4, operating properties are significantly affected. Specifically, use of the limit numbers effectively controls random switching from normal to reduced, and makes reduced inspection truly a reward for exceptional quality rather than an expectation of marginal to poor quality.
Evaluation of the Limit Number Effects for Reduced Inspection in ANSI/ASQC Z1.4
Using a Markov Model

by

Roger B. Grinde

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# TABLE OF CONTENTS

**Chapter I** ................................................................. 1
  Introduction

**Chapter II** .............................................................. 2
  Analytical Formulas for the Evaluation of ANSI/ASQC Z1.4 Performance When Used Without Limit Numbers
    Introduction ..................................................... 3
    Mathematical Model Development ....................... 7
    Example Calculations .................................. 19
    Summary ....................................................... 26
    References ................................................... 28

**Chapter III** ............................................................ 29
  Analysis of ANSI/ASQC Z1.4 Scheme Performance When Used With and Without Limit Numbers
    Introduction ..................................................... 30
    Development of Mathematical Model .................... 37
    Analysis of Results .................................. 66
    Discussion of Results and Conclusions ............ 96
    References ................................................... 101

**Chapter IV** ............................................................. 103
  Summary of Results and Contributions

Bibliography .............................................................. 104

**Appendix A** ............................................................ 106
  Intermediate Calculations of Performance Measures

**Appendix B** ............................................................. 112
  Development of Reg-Normal ARL and Absorption Probabilities When R is the Starting State

**Appendix C** ............................................................. 114
  Computational Results

**Appendix D** ............................................................. 137
  Tabulated Results of Performance Measures
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>II.1</td>
<td>ANSI/ASQC Z1.4 Switching Rules</td>
<td>4</td>
</tr>
<tr>
<td>II.2</td>
<td>Transition Diagram of ANSI/ASQC Z1.4 Sampling Scheme</td>
<td>8</td>
</tr>
<tr>
<td>II.3</td>
<td>Average Run Lengths on Normal, Reduced, and Tightened Inspection</td>
<td>16</td>
</tr>
<tr>
<td>II.4</td>
<td>Single Sampling Results for Code Letter H, AQL = 1.5%</td>
<td>21</td>
</tr>
<tr>
<td>II.5</td>
<td>Double Sampling Results for Code Letter H, AQL = 1.5%</td>
<td>22</td>
</tr>
<tr>
<td>III.1</td>
<td>ANSI/ASQC Z1.4 Switching Rules</td>
<td>31</td>
</tr>
<tr>
<td>III.2</td>
<td>Transition Diagram of ANSI/ASQC Z1.4 Sampling Scheme</td>
<td>38</td>
</tr>
<tr>
<td>III.3</td>
<td>Super-Normal Transition Diagram for Code Letter H, AQL = 1.5% Scheme</td>
<td>43</td>
</tr>
<tr>
<td>III.4</td>
<td>Network Diagram for g(i,j) Calculation</td>
<td>47</td>
</tr>
<tr>
<td>III.5</td>
<td>Average Relative AOQL Values</td>
<td>69</td>
</tr>
<tr>
<td>III.6</td>
<td>Average Relative LQL Values</td>
<td>69</td>
</tr>
<tr>
<td>III.7</td>
<td>Maximum Percent Inspected On Normal</td>
<td>73</td>
</tr>
<tr>
<td>III.8</td>
<td>Maximum Normal Average Run Length</td>
<td>73</td>
</tr>
<tr>
<td>III.9</td>
<td>Normal Average Run Length</td>
<td>78</td>
</tr>
<tr>
<td>III.10</td>
<td>Transitions Per 1000 Lots</td>
<td>80</td>
</tr>
<tr>
<td>III.11</td>
<td>Percent Inspected on Normal</td>
<td>84</td>
</tr>
<tr>
<td>III.12</td>
<td>Percent Inspected on Tightened</td>
<td>85</td>
</tr>
<tr>
<td>III.13</td>
<td>Percent Inspected on Reduced</td>
<td>86</td>
</tr>
<tr>
<td>III.14</td>
<td>Percent Inspected on Each Plan</td>
<td>87</td>
</tr>
<tr>
<td>III.15</td>
<td>Lots Inspected Until Discontinuation</td>
<td>90</td>
</tr>
<tr>
<td>III.16</td>
<td>Overall Percent Rejected</td>
<td>92</td>
</tr>
<tr>
<td>C.1</td>
<td>FORTRAN Program Flowchart</td>
<td>115</td>
</tr>
<tr>
<td>C.2</td>
<td>Program Input File -- A=2 Case</td>
<td>118</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11.1</td>
<td>Tightened Inspection Analysis</td>
<td>14</td>
</tr>
<tr>
<td>11.2</td>
<td>Summary of Analytical Results</td>
<td>15</td>
</tr>
<tr>
<td>11.1.1</td>
<td>Summary of No Limit Number Results</td>
<td>40</td>
</tr>
<tr>
<td>11.2.1</td>
<td>Calculation of g(1,j)--Example Case</td>
<td>45</td>
</tr>
<tr>
<td>11.3</td>
<td>Selected g(1,j) Values--Example Case</td>
<td>50</td>
</tr>
<tr>
<td>11.4</td>
<td>Overall Averages of Performance Measures</td>
<td>94</td>
</tr>
<tr>
<td>11.5</td>
<td>Overall Percent Differences in Performance Measures</td>
<td>95</td>
</tr>
<tr>
<td>C.1</td>
<td>Normal Inspection Plans for Single Sampling Schemes</td>
<td>116</td>
</tr>
<tr>
<td>D.1</td>
<td>Relative Average Outgoing Quality Limit Values</td>
<td>138</td>
</tr>
<tr>
<td>D.2</td>
<td>Relative Limiting Quality Level Values</td>
<td>141</td>
</tr>
<tr>
<td>D.3</td>
<td>Maximum Percent Inspected on Normal</td>
<td>145</td>
</tr>
<tr>
<td>D.4</td>
<td>Maximum Normal Average Run Length</td>
<td>147</td>
</tr>
<tr>
<td>D.5</td>
<td>Normal Average Run Length</td>
<td>149</td>
</tr>
<tr>
<td>D.6</td>
<td>Transitions per 1000 Lots Between Normal and Reduced</td>
<td>153</td>
</tr>
<tr>
<td>D.7</td>
<td>Transitions per 1000 Lots Between Normal and Tightened</td>
<td>157</td>
</tr>
<tr>
<td>D.8</td>
<td>Transitions per 1000 Lots Between all Plans</td>
<td>161</td>
</tr>
<tr>
<td>D.9</td>
<td>Percent Inspected on Normal</td>
<td>165</td>
</tr>
<tr>
<td>D.10</td>
<td>Percent Inspected on Tightened</td>
<td>169</td>
</tr>
<tr>
<td>D.11</td>
<td>Percent Inspected on Reduced</td>
<td>173</td>
</tr>
<tr>
<td>D.12</td>
<td>Lots Inspected Until Discontinuation</td>
<td>177</td>
</tr>
<tr>
<td>D.13</td>
<td>Overall Percentage of Lots Rejected</td>
<td>181</td>
</tr>
</tbody>
</table>
The two papers presented in this thesis comprise a thorough analysis of ANSI/ASQC Z1.4 (1981) when used with and without limit numbers for reduced inspection.

Chapter II contains the first paper, which concerns the no limit number situation. A mathematical model of the sampling system is developed and solved analytically, providing closed-form equations for various operating properties. Thus, matrix inversion is not necessary with these results, since the calculation of the inverse is done analytically. These closed form results are the first with respect to the modeling of ANSI/ASQC Z1.4.

The second paper, contained in Chapter III, addresses the question of what effects the limit numbers have on various operating properties. The mathematical model of the first paper is expanded to include limit numbers. Results are then generated for the 152 single sampling cases with and without limit numbers. Analysis shows that there are indeed very significant differences in a scheme's operation if limit numbers are omitted, contrary to a statement made in the standard itself.
CHAPTER II

ANALYTICAL FORMULAS FOR THE EVALUATION OF ANSI/ASQC Z1.4 PERFORMANCE WHEN USED WITHOUT LIMIT NUMBERS
INTRODUCTION

ANSI/ASQC Z1.4 is one of the most widely used sampling systems in the world. It is a set of sampling plans and procedures for inspection by attributes. To encourage and reward high quality and discourage poor performance, the standard provides for three inspection plans—normal, tightened, and reduced. Switching between plans as a function of the quality history is an essential part of the system; it is designed to exert pressure on the supplier to take corrective action when quality falls below prescribed levels and to provide a reward for superior quality. Figure 11.1 summarizes the rules for switching between inspection plans. The limit number for reduced inspection is the maximum number of non-conforming units in the previous ten samples for which transition to reduced inspection is possible, assuming the previous ten lots have all been accepted on normal inspection.

The 1981 version of the standard made use of the limit number for reduced inspection optional. Thus, the primary requirement to switch from normal to reduced inspection is the acceptance of the last ten lots on normal inspection.

The objectives of the research reported in this paper are:
Figure 11.1  ANSI/ASQC Switching Rules
(Adapted from ANSI/ASQC Z1.4-1981)
1) To develop a mathematical model for evaluation of the performance of ANSI/ASQC Z1.4 without the limit number option (Paragraph 8.3.3b of the standard).

2) To solve the mathematical model analytically; i.e., to develop closed-form, analytical results for various quantities needed to calculate important performance measures such as:

   a) Average run length on normal inspection.
   b) Number of transitions between inspection plans per 1000 lots inspected.
   c) Percentage of lots inspected on normal, tightened, and reduced inspection.
   d) Expected number of lots inspected prior to discontinuation of sampling inspection.
   e) Overall probability of acceptance
   f) Average outgoing quality

State of the Art

Analysis of MIL-STD-105D began to appear shortly after the standard was published in 1963. Initially, Dodge (1965) used the formula for Continuous Sampling Plan (CSP-2) to derive the composite operating characteristic (OC) function and other characteristics. Hald and Thyregod (1966) used the theory of recurrent events to develop the composite OC function as well as the limiting probabilities. Neither of these studies considered the full implementation of the standard, in that they neglected reduced inspection.

Stephens and Larson (1967) were the first to use the theory of Markov Processes to analyze the standard. They included the full set of switching rules in their analysis, but omitted the criteria for termination of
inspection. Rather than terminating inspection after ten consecutive lots have been inspected under tightened inspection, they permitted inspection to continue indefinitely. Unfortunately, this introduces a significant error when process quality is poor. Moreover, this analysis used a discrete but infinite state space. Although theoretically correct, this approach requires the use of an approximation to obtain numerical results.

Brown and Rutemiller (1973) used different state definitions in order to obtain a finite state space Markov model which considered the full set of switching rules, including the termination of inspection. Because of the use of a finite state space, the Brown and Rutemiller model may be solved without approximation procedures. However, numerical inversion of all matrices was required for this model.

None of the above analyses have considered use of the standard without limit numbers, and none have provided analytical formulas for any results. There is a need for analytical results, because numerical solution of the mathematical model is computation-intensive. With closed-form results, measures of performance can quickly and easily be obtained with a simple micro-computer program.
MATHEMATICAL MODEL DEVELOPMENT

The ANSI/ASQC Z1.4 sampling system can be analyzed by means of a Markov Chain model. For the system without limit numbers, the system is divided into models for normal, tightened, and reduced inspection. In addition, an overall model is needed to analyze the transitions between inspection plans. The normal, reduced, and overall models are easiest to formulate and solve as finite state Markov chains. The tightened model can be analyzed as a Markov model; however, it is simpler to formulate and solve using standard probability theory.

Figure 11.2 is an overall transition diagram for the sampling system. The starting state is S, which is normal inspection. States 1A, 2A, ..., 9A represent one through nine consecutive acceptances on normal inspection. R, RA, RAA, and RAAA represent one rejection followed by 0, 1, 2, and 3 acceptances on normal. The state "Red" represents reduced inspection. State ST is the starting state for tightened inspection. Finally, states 1T, 2T, ..., 9T correspond to the number of lots inspected on tightened (whether accepted or rejected).
Figure 11.2 Transition Diagram of ANSI/ASQC Z1.4 Sampling Scheme
Overall Model

The overall model for the sampling system consists of four states, corresponding to normal, tightened, and reduced inspection, and the discontinuation of sampling inspection. Normal inspection is the starting state, and discontinuation of inspection is the sole absorbing state. Hence, the probability of eventually discontinuing sampling inspection is one. Note also that the only possible transition from reduced inspection is to normal, and that termination of inspection is only possible from tightened. The transition probabilities from state to state in this model are actually the absorption probabilities from the individual models for normal, tightened, and reduced inspection.

The overall transition matrix is shown below. The symbols D, N, T, and R represent discontinuation, normal, tightened, and reduced, respectively. Transition probabilities not equal to zero or one are denoted as $p_{NT}$, $p_{NR}$, $p_{TN}$, and $p_{TR}$, with the first letter of the subscript representing the origin state, and the second to the state transitioned to.

$$
\begin{bmatrix}
D & N & T & R \\
D & 1 & 0 & 0 & 0 \\
N & 0 & 0 & p_{NT} & p_{NR} \\
T & p_{TN} & p_{TR} & 0 & 0 \\
R & 0 & 1 & 0 & 0
\end{bmatrix}
$$
The matrix is arranged in the typical
\[
\begin{bmatrix}
I & 0 \\
-Q & R \\
\end{bmatrix}
\]
form, where I is an identity matrix, Q is a square matrix defining transitions among transient states, and R is a matrix defining transitions from transient states to absorbing states.

The matrix of special interest in this case is \((I-Q)^{-1}\), which gives the expected number of occurrences of normal, tightened, and reduced inspection prior to discontinuation. These are denoted \(V_N\), \(V_T\), and \(V_R\), respectively. Specifically, the first row of this matrix contains these quantities, given the process starts in normal inspection. Final results are given below, and the first row of the inverse is contained in Appendix A. Normal inspection is assumed for the starting state in the quantities below:

\[
\begin{align*}
V_N &= 1/(p_{NT}p_{TD}) \\
V_R &= p_{NR}/(p_{NT}p_{RD}) \\
V_T &= 1/p_{TD}
\end{align*}
\]

Note that \(V_N = V_R + V_T\), a result that is intuitive considering the operation and switching characteristics of the standard.

Normal Inspection Model

The normal inspection model is the largest one required, but is fairly straight-forward. Since ten
consecutive lots accepted is the criterion to switch to reduced, there are nine states corresponding to 1, 2, ..., 9 consecutive acceptances. Two rejections out of the last five lots requires a switch to tightened inspection. The states R, RA, RAA, and RAAA model the situations in which it is possible to transition to tightened on the next lot. For the no limit number case, there is only one possible starting state in normal inspection.

The transition matrix is shown in Appendix A. It is desired to obtain the expected number of lots inspected until a transition to either reduced or tightened (the average run length, or ARL\text{\textsubscript{w}}) and the absorption probabilities to reduced and tightened, p\text{\textsubscript{w}}, and p\text{\textsubscript{w}}, respectively. When the transition matrix is arranged in the usual form, these quantities are derived from \((1-Q)^{-1}\) and \((1-Q)^{-1}R\). Since there is only one possible starting state when limit numbers are not used, only the "START" rows of these matrices are needed.

Appendix A contains the first row of \((1-Q)^{-1}\), which corresponds to the starting state, and the first row of \((1-Q)^{-1}R\). Due to space limitations, all calculations of the inverse are not shown. Approximately 68 pivots are required to calculate the inverse of \((1-Q)\). To obtain the average run length on normal inspection, the elements in the first row of
\((I-Q)^{-1}\) are summed. This rather extensive algebraic calculation is given in Appendix A, and the final result is

\[
ARL_N = \frac{(2-p_N-2p_A^o+p_A^a)}{(1-p_N)(1-p_A^o+p_A^a)}
\]  

(4)

where \(p_N\) is the probability of acceptance of a lot on normal inspection. The calculations of absorption probabilities, given starting state "START," are also given in Appendix A. These results are:

\[
p_{N^R} = \frac{(2p_A^o-p_A^a)}{(1-p_A^o+p_A^a)}
\]  

(5)

\[
p_{N^T} = \frac{(1-p_A^o-p_A^a+p_A^a)}{(1-p_A^o+p_A^a)}
\]  

(6)

Note that \(p_{N^R} + p_{N^T} = 1\), as required, since reduced and tightened are the absorbing states.

Reduced Model

The reduced inspection model is extremely simple since there is only one transient state, "RED," and one absorbing state, "NORM." Let \(p_R\) represents the probability of accepting a lot and continuing on reduced inspection. The average run length on reduced inspection is easily found as

\[
ARL_R = (I-Q)^{-1} = (1-p_R)^{-1} = \frac{1}{(1-p_R)}
\]  

(7)

The probability of absorption to normal inspection is one.

Tightened Inspection Model

Although a standard Markov chain analysis can be used to model tightened inspection, standard
probability theory provides a simpler analysis. Recall that five consecutive acceptances on tightened are required to switch back to normal. The following events are defined to facilitate the formulation and solution:

\( A_k: \) Switch to normal immediately after \( k^{th} \) lot, \( k=1,2,...,10 \)
\( B_j: \) Switch to normal before or immediately after \( j^{th} \) lot, \( j=1,2,...,10 \)

Note that the events \( A_k, k=1,2,...,10 \) are mutually exclusive. Thus,

\[
P(B_j) = \sum_{k=1}^{j} A_k
\]

The probabilities of occurrence for the \( A_k \)'s are fairly intuitive. Since five consecutive acceptances are required to switch to normal inspection, \( P(A_k) = 0 \) for \( k=1,2,3,4 \). For \( A_5 \) to occur, all five lots have to be accepted. Hence, \( P(A_5) = p_T \), where \( p_T \) is the probability of acceptance of a lot on tightened inspection. The only way \( A_k, k=6,7,...,10 \) can occur is to reject the \( (k-5)^{th} \) lot and then accept the next five lots. Therefore, \( P(A_k) = q_T p_T, k=6,7,...,10 \), where \( q_T = 1-p_T \). These results are summarized and the \( P(B_k) \)'s are calculated in Table II.1.
Table 11.1: Tightened Inspection Analysis

To obtain absorption probabilities, note that $p_{TN} = P(T_{10})$ and $p_{TD} = 1 - P(B_{10})$. Hence,

$$P_{TN} = (1 + 5q_T)p_T = (1 + 5(1 - p_T))p_T = (6 - 5p_T)p_T$$  \hspace{1cm} (8)

and

$$P_{TD} = 1 - P_{TN} = 1 - p_T(6 - 5p_T)$$  \hspace{1cm} (9)

The average run length on tightened is just

$$ARLT = \sum_{k=1}^{10} kp(A_k) + 10p_{TD}$$

$$= 10 - 15p_T + 10p_T$$  \hspace{1cm} (10)

Each component of the standard has been modeled and essential results have been derived. These are summarized in Table 11.2.
Transition Probabilities Between Inspection Plans

\[ p_{MN} = \frac{2p^0 - p^4}{1 - p^0 + p^4} \]
\[ p_{NT} = \frac{1 - p_{MN}}{1 - p^0 + p^4} \]
\[ p_{TN} = p \theta (6 - 5p_T) \]
\[ p_{TD} = 1 - p_{TN} = 1 - p \theta (6 - 5p_T) \]

Average Run Lengths

\[ ARL_N = \frac{2 - 2p^0 + p^4}{(1 - p^0)(1 - p^4)} \]
\[ ARL_T = \frac{10 - 15p \theta + 10p^4}{1 - p^0} \]
\[ ARL_R = \frac{1}{1 - p_R} \]

Number of Visits Before Discontinuation

\[ V_N = \frac{1}{p_{NT} p_{TD}} \]
\[ V_T = \frac{1}{p_{TD}} \]
\[ V_R = p_{MN} / (p_{NT} p_{TD}) \]

Table 11.2 Summary of Analytical Results

It is useful to graph the average run length functions for normal, tightened, and reduced inspection against the probability of acceptance. These are shown in Figure 11.3. Since very general closed form results have been obtained, it is interesting to note that these graphs are applicable to all inspection schemes in ANSI Z1.4, including double- and multiple-sampling schemes. The only difference between schemes is that the same relative quality levels will correspond to different points on the curves. For example, consider single-sampling code letters H and M, and AQL's 4.0 and 0.40, respectively. Assuming that quality is at the AQL in both cases, the probabilities of acceptance (normal inspection) for H and M are 0.986 and 0.961, respectively. Hence, the average run lengths on normal inspection are 10.73 lots and 11.79,
Figure 11.3 Average Run Lengths on Normal, Reduced, and Tightened Inspection
respectively, for AQL quality.

The normal inspection average run length graph (Figure II.3a) is especially interesting. At very poor quality levels, a transition to tightened will occur after only two lots, and at exceptional qualities reduced inspection will be implemented after ten lots. However, at intermediate levels, the maximum ARL is approximately 12.7. This maximum occurs at about a 90% probability of acceptance. Not more than 12.7 lots can be expected to be inspected on normal before transition to another plan. It is certainly difficult to consider normal inspection as being "normal" in light of these results. The frequency of transitions when limit numbers are not used would appear to be high, and depending on how inspection is carried out, could be troublesome in practice. It is interesting to note that the limit numbers were originally introduced in the standard to control some of this random switching between inspection plans. Nevertheless, their use was made optional in the latest revision.

The reduced inspection average run length graph (Figure II.3b) is a reciprocal function. The ARL is very small up to approximately a 90% probability of acceptance, where it begins to rise rapidly.

The maximum number of lots which may be inspected on tightened inspection on any run is ten, and the minimum is five. A graph of the tightened inspection
ARL function is shown in Figure 11.3c.

From the average run lengths on and number of visits to each of normal, tightened, and reduced inspection, many important measures of performance can be calculated for various quality levels, such as:

- Number of lots inspected until discontinuation (LOTS)
- Percentage of lots inspected on normal, tightened, and reduced inspection (N%, T%, R%)
- Number of transitions between plans per 1000 lots (T_{NR}, T_{NT}, T)
- Overall probability of acceptance (P_a)
- Average outgoing quality (AOQ). This will often be referred to as the "relative AOQ," and will be expressed as a fraction or a percentage of the AQL.

Equations for the quantities of interest are given below, in terms of the ARL's and V's already developed, the probabilities of acceptance on normal, tightened, and inspection, p_N, p_T, and p_{R} (where p_{R} is the probability of acceptance on reduced, allowing for possible return to normal), respectively, and the fraction defective, p.

\[ \text{LOTS} = (\text{ARL}_N \times V_N) + (\text{ARL}_R \times V_R) + (\text{ARL}_T \times V_T) \]  
(11)

\[ \text{N\%} = \frac{(\text{ARL}_N \times V_N) \times 100}{\text{LOTS}} \]  
(12)

\[ \text{R\%} = \frac{(\text{ARL}_R \times V_R) \times 100}{\text{LOTS}} \]  
(13)

\[ \text{T\%} = \frac{(\text{ARL}_T \times V_T) \times 100}{\text{LOTS}} \]  
(14)

\[ T_{NR} = \frac{(2 \times V_R \times 1000)}{\text{LOTS}} \]  
(15)

\[ T_{NT} = \frac{(2 \times V_T \times 1000)}{\text{LOTS}} \]  
(16)

\[ T = T_{NR} + T_{NT} \]  
(17)

\[ P_a = (\text{N\%} \times p_N) + (\text{R\%} \times p_{R}) + (\text{T\%} \times p_T) \]  
(18)

\[ \text{AOQ} = p \times P_a \]  
(19)
EXAMPLE CALCULATIONS

Two particular sampling schemes of ANSI/ASQC Z1.4 will be analyzed without limit numbers. Consider the single- and double-sampling schemes defined by code letter H and AQL (Acceptable Quality Level) = 1.5%. The sample sizes and acceptance and rejection numbers are given below, where \( n \) = sample size, \( Ac \) = acceptance number, and \( Re \) = rejection number.

**Single-Sampling**

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th></th>
<th>Tightened</th>
<th></th>
<th>Reduced</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>Ac</td>
<td>Re</td>
<td>Ac</td>
<td>Re</td>
<td>Ac</td>
<td>Re</td>
</tr>
<tr>
<td>Single</td>
<td></td>
<td></td>
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<td>2</td>
<td>50</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Tightened</td>
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<td>2</td>
<td>50</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Reduced</td>
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<td>1</td>
<td>50</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

**Double-Sampling**

<table>
<thead>
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<th></th>
<th>Tightened</th>
<th></th>
<th>Reduced</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>Re</td>
<td>Ac</td>
<td>Re</td>
<td>Ac</td>
<td>Re</td>
</tr>
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<td>32</td>
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<td>3</td>
<td>32</td>
<td>1</td>
<td>13</td>
<td>0</td>
</tr>
</tbody>
</table>

For the single-sampling scheme at AQL quality, the probabilities of acceptance on the three plans are, using the binomial distribution, \( p_N = 0.9608 \), \( p_T = 0.8273 \), \( p_R = 0.9643 \), and \( p_d = 0.9968 \). From formulas summarized in Table 11.2, the following results can then be calculated:
Equations (11) through (19) yield the following values of performance measures:

\[
\begin{align*}
\text{LOTS} &= 2325 \\
\text{N\%} &= 30.61\% \\
\text{R\%} &= 68.25\% \\
\text{T\%} &= 1.14\% \\
\text{TWR} &= 48.79 \\
\text{TWT} &= 3.097 \\
\text{T} &= 51.89 \\
\text{P}_a &= 98.38\% \\
\text{AOQ} &= 98.38\% \text{ AQL}
\end{align*}
\]

It is interesting to study how these quantities vary as the incoming quality changes. Figures 11.4 and 11.5 contain graphs of the following operating properties plotted against incoming quality (as a percent of AQL) for single- and double-sampling, respectively.

a) ARL_w 

b) TW_R, TW_T, T 

c) N\%, T\%, R\% 

d) \ln(\text{LOTS}) 

e) P_a 

f) AOQ (Relative to AQL)

The maximum ARL_w for both schemes is 12.7 lots, occurring at 1.4 AQL for single-sampling and 1.7 AQL
Figure 11.4 Single Sampling Results for Code Letter H, AQL = 1.5%
Figure 2.5 Double Sampling Results for Code Letter H, AQL = 1.5%
for double-sampling. These graphs are essentially reverses of Figure II.3a, because II.3a is plotted against $P_r$ rather than percent defective, and these two quantities are inversely related.

The ARL_\text{N} affects the number of transitions made between inspection plans. Part (b) plots transitions per 1000 lots between normal and reduced, between normal and tightened, and cumulative for all plans. Without limit numbers, transitions occur quite often. For single-sampling at the AQL, 51.9 transitions per 1000 lots are made, or one every 19.3 lots. The corresponding double-sampling value is 119.5, or one transition every 8.4 lots! The maximum number of transitions between normal and reduced ($T_{NR}$) in the single-sampling case is 57.0 (one every 17.5 lots). Note that this maximum occurs at a quality worse than the AQL (130% AQL), where ideally, reduced inspection should never occur! Double-sampling results are even more startling, because the maximum $T_{NR}$ value is 117.3 (one transition every 8.5 lots), occurring at the AQL.

Results from Grinde (1986) show that use of limit numbers virtually eliminate $T_{NR}$ at qualities worse than the AQL for the single-sampling case. The limiting value of $T$ (total transitions/1000 lots) is 167 (2 every 12 lots) when the incoming quality is 100% defective. This occurs with one N$\rightarrow$T transition, and
one T→D transition, with 12 total lots inspected.

The quantities N%, T%, and R% are shown in part (c). Consider single-sampling (Figure II.4(c)). At qualities better than 1.35 AQL, reduced inspection is employed most often. Between 1.35 and 2.30 AQL, more lots are inspected on normal than either reduced or tightened. Tightened does not become the most predominant plan until quality becomes worse than 2.30 AQL.

It is interesting that normal is the plan most often used over a very small quality range (135% to 230% AQL), and that this range does not even include the AQL! The maximum value of N% is only about 55%. These surprising results occur because, without limit numbers, transition from normal to reduced is relatively easy. As quality worsens, N% and T% asymptotically approach $\frac{2}{12} = 16.67\%$ and $\frac{10}{12} = 83.33\%$, respectively. At 100% defective, transition to tightened will occur after two lots on normal, and discontinuation will occur ten lots later. Note that even though transitions to/from reduced are much more frequent with double-sampling, a greater percentage of lots are on normal. This suggests that the average run length on reduced is very small.

The natural logarithmic scale is needed in part (d) because at poor qualities, slightly above 12 lots are inspected, but as the percent defective approaches
zero, LOTS increases without bound. Ideally, above the AQL an infinite number of lots would be inspected, and below the AQL, 12. Hence, the slope of the LOTS curve at the AQL approaches negative infinity as the ideal situation is approached. For the single-sampling scheme, the slope of the LOTS curve (not the Ln(LOTS) curve) is approximately -237 (5800 at 0.9 AQL, 2330 at AQL, and 1060 at 1.1 AQL), which means that if quality worsens from the AQL to 1.01 AQL, approximately 237 fewer lots will be inspected prior to discontinuation.

Figures 11.4(e) and 11.5(e) are the overall OC curves (overall percent accepted) for the schemes. At the AQL, the P_a values are 98.38% and 98.36% for single- and double-sampling, respectively. The 50% P_a points occur at approximately 2.75 AQL and 2.80 AQL for single- and double-sampling. The OC curves are very similar, despite great differences in other operating properties.

The relative average outgoing quality curve is shown in part (f). In computing the AOQ, it is assumed that rejected lots are 100% screened, with defective items replaced by good ones. Also, any defectives found in samples are also replaced. As shown in the figures, the AOQL values are approximately 148% AQL and 155% AQL, occurring at about 2.0 AQL and 2.1 AQL, respectively for single- and double-sampling.
SUMMARY

Formulas for important performance measures of ANSI/ASQC Z1.4 when used without limit numbers have been derived in this paper. Closed-form expressions eliminate the need to invert a 14 x 14 matrix for normal inspection each time results are desired, greatly reducing computation time. A simple program can be written for a microcomputer or programmable calculator to perform the relatively simple calculations.

Single- and double-sampling examples were carried out to demonstrate important operating properties of the schemes. Particularly noteworthy is the small average run length on normal inspection, the frequency of transitions between sampling plans, and the proportion of lots inspected on each plan. A significant number of transitions occur between normal and reduced inspection, even when quality is worse than the AQL. The results raise questions about whether some of the basic philosophies of ANSI/ASQC Z1.4 are being violated when limit numbers are omitted. It seems that reduced inspection is relatively "normal" without limit numbers. Also, making transitions to another plan every ten or fewer lots (as in the double-sampling case) could certainly be as complex in
practice as applying the limit numbers.

The obvious extension of this research is to
develop corresponding formulas for the case when limit
numbers are used. Reduced and tightened inspection are
unchanged, but the limit number must be used in
modeling normal inspection. This case is much more
complicated, since it is possible to accept ten
consecutive lots on normal, but have the limit number
exceeded. This may be handled by including another
Markov Chain in the analysis, called "super-normal"
inspection. A transition to super-normal occurs when
ten consecutive lots on normal are accepted, but the
number of non-conforming units is greater than the
limit number. This chain has a variable number of
states depending on acceptance numbers and limit
numbers, and a stochastic starting state. This adds
considerable complexity to the model.
REFERENCES


CHAPTER III

ANALYSIS OF ANSI/ASQC Z1.4 SCHEME PERFORMANCE
WHEN USED WITH AND WITHOUT LIMIT NUMBERS
INTRODUCTION

ANSI/ASQC Z1.4 (1981) is one of the most widely used acceptance sampling standards. It is a set of procedures and plans for inspection by attributes. For each scheme, three inspection plans are used. These are termed normal, tightened, and reduced inspection. The application of switching rules in the standard results in transitions between plans based on the history of lot acceptances and rejections. Reduced inspection is intended as a reward for superior quality. Poor quality should result in a transition to tightened inspection, which puts pressure on a producer by lowering the probability of acceptance.

Between the two quality extremes, normal inspection is designed to be used, especially for quality levels near the acceptable quality level (AQL).

A schematic of the ANSI/ASQC Z1.4 system is shown in Figure III.1. The switching rules from normal to reduced inspection were altered in the latest revision of the standard. Specifically, use of the limit number in a transition from normal to reduced inspection was made optional. In reference to this change, Paragraph 8.5 of the standard states, "This action will have little effect on the operating properties of the scheme." However, "operating properties" is never
Preceding 10 Lots Accepted, with Total Nonconforming less than Limit Number (Optional), and Production Steady, and Approved by Responsible Authority

Lot not Accepted, or Lot Accepted but Nonconformities found lie between Ac and Re of Plan, or Production Irregular, or Other Conditions Warrant

START

2 out of 5 Consecutive Lots Not Accepted

5 Consecutive Lots Accepted

10 Consecutive Lots Remain on Tightened

Discontinue Inspection Under Z1.4

Figure III.1 ANSI/ASQC Z1.4 Switching Rules (Adapted from ANSI/ASQC Z1.4-1981)
defined, and "little effect" is never quantified. Furthermore, the basis on which this statement is made is the work of Schilling and Sheesley (1978a, 1978b). Their model neglected discontinuation of inspection, and only approximated the switching rules. Only nine sampling schemes were given as support of their conclusion that limit numbers have little effect, and the only performance measure used was the probability of acceptance ($P_\ast$). No mention of the effect limit numbers have on normal average run length ($\text{ARL}_n$), frequency of transitions, or lots inspected until termination is made. For these reasons, their conclusions are suspect.

One of the primary purposes of the limit numbers is to control superfluous switching between normal and reduced inspection (Hald, 1981). It is interesting to note that this issue is never mentioned either in the current version of the standard or in Schilling and Sheesley's previous work.

The purposes of the research reported in this paper are to i) evaluate various performance measures for all single sampling cases (152 in number), and ii) to quantify the differences in performance measures when the schemes are used with vs. without limit numbers.
State of the Art

Analysis of MIL-STD-105D (the military standard upon which ANSI/ASQC Z1.4 is based) began to appear shortly after its introduction in 1963. Dodge (1965) and Hald & Thyregod (1966) performed studies of the composite OC curve, but only for normal and tightened inspection.

Stephens and Larson (1967) employed a Markov Chain approach to analyze the standard. They included reduced inspection, but omitted the requirement for discontinuation of sampling if ten consecutive lots remain on tightened inspection. Thus, tightened inspection could be continued indefinitely, which introduces considerable error when quality is poor. They also used a discrete, but infinite, state space. This procedure requires a numerical approximation to obtain results.

Brown and Rutemiller (1973) employed the full set of switching rules in a finite state Markov model of MIL-STD-105D. This model was developed for an economic analysis of the system. Later work produced tables from which the cost per unit due to sampling can be determined (Brown & Rutemiller, 1974). Brown & Rutemiller (1975) also compared MIL-STD-105D to two other sampling systems. These two systems were both modifications of MIL-STD-105D, one by the MIL Study
Group of the Japanese Standards Association (Koyama, et. al., 1970) and one by the authors themselves. Neither modification proposed to simply discard the limit numbers for reduced inspection. In fact, the Japanese modification called for reduction of the limit numbers from normal to reduced inspection, since they felt too much switching occurred at the AQL. Note that this modification is the opposite of the change to make limit numbers optional.

The first attempt to tabulate various operating properties of the sampling schemes was undertaken by Schilling and Sheesley (1978a, 1978b). They used a model based on the one developed by Stephens and Larson (1967). Instead of modeling the limit number situation exactly, however, they chose to employ an approximation introduced by Burnett (1967). In lieu of an infinite state space, Burnett proposed use of the unconditional binomial probability \( p_r \) that the total number of non-conforming units in the ten samples is less than or equal to the limit number. If the tenth consecutive lot was accepted, then transition to reduced occurred with probability \( p_r \); otherwise, the tenth lot was simply dropped, and normal inspection was continued with nine consecutive accepted lots.

Schilling and Sheesley (1978a) modified this approximation as follows: if the tenth lot was
accepted, then transition to reduced occurred with probability $p_r$; otherwise normal inspection was continued (same as Burnett). However, if normal inspection was continued, the ten consecutive lots were discarded and the accumulation of consecutive lot acceptances was started over. The authors claim that this gives a conservative estimate of being on reduced inspection. However, if this is true, the approximation would also provide an underestimate of the true average outgoing quality (since inspection is not on reduced as often, which has a higher probability of acceptance). As in the Stephens and Larson case, discontinuation of sampling was ignored.

Randhawa, et. al. (1986) were the first to question the validity of the statement in ANSI/ASQC Z1.4 which claims that use without limit numbers has little effect on operating properties. A simulation model was used to compute measures of performance for selected sample size, acceptance number, and quality level combinations. A major conclusion of their work was that limit numbers effectively control superfluous switching between inspection plans by increasing the average run length on normal inspection when quality is near the AQL.

The true operating properties of ANSI/ASQC Z1.4 when used with and without limit numbers have not been evaluated and compared. Randhawa, et. al. (1986) have
addressed this question; however, results based on a mathematical model for all single sampling schemes are needed to compare fully the operation of the standard with vs. without limit numbers.
DEVELOPMENT OF MATHEMATICAL MODEL

A discrete state, discrete parameter Markov chain model is used to analyze ANSI/ASQC Z1.4. The no limit number case is the simpler, and is developed and solved analytically in Grinde (1986). Analysis of the standard when limit numbers are used requires another Markov chain for the modeling of the situation when ten consecutive lots have been accepted on normal inspection, but the limit number is exceeded. Without limit numbers, a transition to reduced inspection would be made at this point. This additional chain is termed "super-normal." It is possible to transition back to "regular-normal" from super-normal (with the rejection of a lot) or to reduced inspection (with consecutive acceptances resulting in the number of non-conforming units becoming less than or equal to the limit number). The majority of this section is devoted to the development of super-normal inspection theory.

A transition diagram of ANSI Z1.4 is shown in Figure III.2. The specific states of super-normal are not shown due to the generally high number of states and complex switching properties in super-normal. A diagram for super-normal is presented in a later section. In Figure III.2, states 1A, 2A, ..., 9A represent one through nine consecutive acceptances on
Figure 111.2 Transition Diagram of ANSI/ASQC Z1.4 Sampling Scheme
normal inspection. R, RA, RAA, and RAAA represent one rejection followed by 0, 1, 2, and 3 acceptances on normal. The state "Red" represents reduced inspection. States 1T, 2T, ..., 9T correspond to the number of lots inspected on tightened (whether accepted or rejected). Finally, states S and ST are the starting states on reg-normal and tightened, respectively. Discontinuation is the final absorbing state; hence, sampling inspection is eventually discontinued.

Figure III.2 is the general transition diagram when limit numbers are used. The no limit number case is obtained by deleting super-normal. Then, from state 9A, it is possible transition either to R (in reg-normal) or Red. For computational convenience, reg-normal, super-normal, reduced, and tightened were analyzed as finite state Markov chains with absorptions to the other chains. An overall Markov chain is used to analyze these absorptions to other chains, and eventually to discontinuation.

No Limit Number Model

As noted previously, analytical results for the no limit number case have been derived (Grinde, 1986). The results needed to calculate measures of performance are summarized in Table III.1.
Average Run Lengths

$$\text{ARL}_N = (2-p_A-2p^o+p^4)/(1-p_N)(1-p_A+p^o)$$

$$\text{ARL}_T = 10-15p_T/10p_T$$

$$\text{ARL}_R = 1/(1-p_R)$$

Transition Probabilities Between Inspection Plans

$$p_{NR} = (2p^o-p^4)/(1-p_A+p^o)$$

$$p_{NT} = 1-p_{NR} = (1-p_A-p^o+p^4)/(1-p_A+p^o)$$

$$p_{TR} = p_T(6-5p_T)$$

$$p_{TD} = 1-p_{TR} = 1-p_T(6-5p_T)$$

$$p_{RN} = 1$$

Number of Visits Before Discontinuation

$$V_N = 1/(p_{NT}p_{TD}) = (1-p_A+p^o)/[(1-p_A-p^o+p^4)(1-p_T(6-5p_T))]$$

$$V_T = 1/p_{TD} = 1/[1-p_T(6-5p_T)]$$

$$V_R = p_{NR}/(p_{NT}p_{TD}) = (2p^o-p^4)/[(1-p_A-p^o+p^4)(1-p_T(6-5p_T))]$$

Table III.1: Summary of No Limit Number Results

Notation in Table III.1 is fairly intuitive.

ARL$_N$, ARL$_T$, and ARL$_R$ represent the average run lengths on normal, tightened, and reduced inspection before absorption to another chain. The absorption probabilities are $p_{NR}$, $p_{NT}$, $p_{TR}$, and $p_{RN}$, with N, R, T, and D representing normal, reduced, tightened, and discontinuation, respectively. $V_N$, $V_T$, and $V_R$ are the number of visits to (occurrences of) normal, tightened, and reduced inspection prior to termination of inspection. Finally, $p_N$, $p_T$, and $p_R$ represent the probabilities of acceptance of a lot on normal, tightened, and reduced inspection, respectively. Note that $p_R$ is the probability of acceptance on reduced with a continuation of reduced inspection. In future
calculations, \( p_1 \) may be used, which represents the probability of acceptance on reduced with the allowance for possible return to normal inspection.

Limit Number Model

The mathematical model for the case with limit numbers incorporates everything from the no limit number model, but adds the super-normal Markov chain. As stated previously, this component of the model is applicable to the situation in which ten consecutive lots have been accepted on normal inspection, but the limit number is exceeded. States in super-normal are defined to be the total number of non-conforming units in the previous ten (accepted) lots. Since ten consecutive lots on normal have been accepted when on super-normal, the maximum number of non-conformities is \( 10A \), where \( A \) is the normal acceptance number. If, while on super-normal, the limit number criterion is met, reduced inspection is begun. Thus, the fewest number of non-conformities to consider in super-normal is \( L+1 \), where \( L \) is the limit number. Hence, the number of transient states in super-normal is \( 10A-L \).

Referring to the standard and ignoring the plans with \( A=0 \) for the time being (these schemes are actually generalizations of the no limit number situation, with 15-17 consecutive acceptances on normal required for a switch to reduced), the super-normal chain can have
between eight (A=1 and L=2) and 163 (A=44 and L=277) transient states. The two absorbing states are reg-normal and reduced.

Figure 111.3 is the super-normal transition diagram for the Code Letter H, AQL=1.5% scheme, with normal sample size of 50, A=2, and L=3. Transition probabilities are omitted; these quantities are calculated in the latter part of this section. Due to the differences between super-normal chains from scheme to scheme, it is clearer to study a specific transition diagram and envision the general case. From a given state, say k, the next state must be reg-normal (state R), reduced, or a super-normal state in the interval \([k-A,k+A]\). If \(k-A>L\), then absorption to reduced is impossible. The above interval may be compressed depending on the particular values of k, A, and L.

Recall that states are defined as the number of non-conforming units in the previous ten lots. When a new lot is inspected, it is either accepted or rejected. If it is rejected, absorption to reg-normal (state R) occurs. If the lot is accepted, either transition to another super-normal state or absorption to reduced occurs. To determine which state the transition is made to, the number of non-conformities in the "oldest" of the ten lots is subtracted, and the number of non-conformities in the current lot is added. The result is the new state. If this number is less
Figure III.3 Super-Normal Transition Diagram for Code Letter H, AQL = 1.5% Scheme
than \( L+1 \), absorption to reduced occurs.

The above explanation becomes clear with an example. Consider the specific case cited above, Code Letter H, AQL=1.5\%, A=2, and \( L=3 \). Assume that super-normal inspection is in effect. Suppose that the current state is \( k=5 \). A new lot is inspected and accepted. The number of non-conformities in this lot is \( d'=1 \). The oldest lot of the ten has \( d=2 \) non-conformities. Hence, the new state is \( k'=k-d+d' = 5-2+1 = 4 \). If \( d'=0 \), \( k'=3=L \), and absorption to reduced would occur. If the new lot was rejected, absorption to reg-normal would occur.

Since any of the transient states in the super-normal chain can be the starting state, it is necessary to find the starting probability vector. This is comprised of the probabilities of having \( L+1, L+2, \ldots, 10A \) total non-conformities in ten consecutive lots, given that i) the ten lots have been accepted on normal inspection, and ii) the limit number is not met. Also, the transition probabilities between states in super-normal must be calculated. Thirdly, the transition probabilities from reg-normal state 9A to reduced and super-normal must be found. These questions are answered by developing theory to calculate the probability of \( j \) total defectives \( (j=0,1,2,\ldots,10A) \), given that \( i \) lots \( (i=1,2,\ldots,10) \) have been inspected.
and accepted. The example cited previously will be extended to clarify the theoretical discussion.

Define \( g(i,j) \) to be the probability of a total of \( j \) non-conforming units, given that \( i \) consecutive lots have been inspected and accepted on normal inspection. Now \( g(1,j), j=0,1,\ldots,A \) is just the probability of \( j \) defective units in a sample, given that the lot is accepted. If \( P(X=k) \) is the unconditional probability of \( k \) defectives in a sample, and \( P_\ast = \frac{1}{\sum_{i=1}^A P(X=i)} \) is the probability of acceptance of a lot, then \( g(1,j) = \frac{P(X=j)}{P_\ast} \), for \( j=0,1,\ldots,A \). For \( j=A+1,\ldots,10A \), \( g(1,j)=0 \).

Recall the example with sample size \( n=50 \), acceptance number \( A=2 \), and \( AQL=1.5\% \). Assume incoming quality is at the AQL. Then, using the binomial distribution to calculate probabilities, \( g(1,j), j=0,1,2 \) is found in Table III.2.

<table>
<thead>
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<th>( P(X=j) )</th>
<th>( g(1,j) )</th>
</tr>
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<td>0.48888</td>
</tr>
<tr>
<td>1</td>
<td>0.35763</td>
<td>0.37224</td>
</tr>
<tr>
<td>2</td>
<td>0.13343</td>
<td>0.13888</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.96075</td>
</tr>
</tbody>
</table>

Table III.2 Calculation of \( g(1,j) \)--Example Case

In order to compute \( g(i,j) \) for \( i>1 \), only the vectors \( g(1) \) and \( g(i-1) \) are needed, where \( g(i) \) is the \((10A+1) \times 1\) vector of probabilities of \( 0,1,\ldots,10A \) defectives, given that \( i \) lots have been inspected and
accepted. This is because how \( g(i,j) \) is obtained is irrelevant, so it is not necessary to consider every possible path. Figure 11.4, which is a network diagram for the example, clarifies this. The \((i,j)\) pairs in each node represent \( i \) lots accepted with a total of \( j \) defectives in the samples. Each arc is labeled with the probability of a transition to the node at the end of the arc (given that the lot is accepted). For this example, only three branches emerge from each node, corresponding to 0,1, and 2 defectives in the sample. Obviously, for larger acceptance numbers, diagrams become extremely complex.

Consider node \((3,3)\). There are six distinct paths from \((0,0)\) to \((3,3)\). However, since the actual path is irrelevant, only three paths must be considered (from nodes \((2,1)\), \((2,2)\), and \((2,3)\)). The expression for \( g(3,3) \) can be written as

\[
g(3,3) = g(2,1)g(1,2) + g(2,2)g(1,1) + g(2,3)g(1,0)
\]

Note that it is not possible to transition from \((2,0)\) to \((3,3)\), since each accepted lot must only have 0, 1, or 2 non-conforming units.

Generalizing the above argument, the expression for the probability of \( j \) defectives in \( i \) samples from accepted lots is
Figure III.4 Network Diagram for $g(i,j)$ Calculation
\[ g(i, j) = \begin{cases} \sum_{k=\max(0, j-A)}^{j} g(i-1, k) * g(1, j-k) & i=2, 3, \ldots, 10 \\ 0 & i=1, 2, \ldots, 10 \\ j=i*A+1, \ldots, 10A \end{cases} \] (1)

The limits on the summation require explanation. Consider the lower limit on \( k, \max(0, j-A) \). This is the minimum number of defective units in \( i-1 \) samples from accepted lots for which it is possible to have \( j \) defective units if one more sample from an accepted lot is added. This new sample must have 0, 1, \ldots, or \( A \) defective units, so that in the \( i-1 \) samples, there must be at least \( j-A \) defectives. For \( j<A \), however, \( j-A \) is negative, hence the need for a lower bound of zero.

Just as the lower limit on the summation is the minimum number of defectives in \( i-1 \) samples, the upper limit on \( k, \) or \( j, \) is the maximum number of defective units in \( i-1 \) samples for which it is possible to obtain \( j \) defectives with the addition of another sample from an accepted lot.

The maximum difference between the upper and lower limits of the summation is \( A, \) when \( j>A \). This should be intuitive, since it is impossible to have more than \( A \) defectives in a sample if the lot is accepted.

Continuing the example of Code Letter H, AQL=1.5%, \( A=2, \) and quality at the AQL, \( g(2, j), j=0, 1, \ldots, 10*2 \) will be calculated. From equation (1) and Table III.2,
\[ g(2,0) = g(2-1,0) \cdot g(1,0-0) = (0.48888)(0.48888) = 0.2390 \]

\[ g(2,1) = g(2-1,0) \cdot g(1,1-0) + g(2-1,1) \cdot g(1,1-1) \\
= (0.48888)(0.37224) + (0.37224)(0.48888) = 0.3640 \]

\[ g(2,2) = g(2-1,0) \cdot g(1,2-0) + g(2-1,1) \cdot g(1,2-1) \\
+ g(2-1,2) \cdot g(1,2-2) \\
= (0.48888)(0.13888) + (0.37224)(0.37224) \\
+ (0.13888)(0.48888) = 0.2744 \]

\[ g(2,3) = g(2-1,1) \cdot g(1,3-1) + g(2-1,2) \cdot g(1,3-2) \\
+ g(2-1,3) \cdot g(1,3-3) \\
= (0.37224)(0.13888) + (0.13888)(0.37224) \\
+ (0.0)(0.48888) = 0.1034 \]

\[ g(2,4) = g(2-1,2) \cdot g(1,4-2) + g(2-1,3) \cdot g(1,4-3) \\
+ g(2-1,4) \cdot g(1,4-4) \\
= (0.13888)(0.13888) + (0.0)(0.37224) + (0.0)(0.48888) \\
= 0.0193 \]

\[ g(2,j) = 0, \ j=5,6,...,20 \]

Calculations are similar for \( i=3,4,...,10 \). Table 11.3 shows the \( g(i,j) \) probabilities for \( i=1,9, \) and 10. These results will be used in future calculations.
Table III.3 Selected $g(i,j)$ Values--Example Case

Transition Probabilities from Reg-Normal 9A

In the no limit number case, there are only two possible states which can be reached from normal state 9A. These states and transition probabilities are reduced and $R$ (one rejection), and $P_*$ and $1-P_*$, respectively, where $P_*$ is the probability of acceptance.

With limit numbers, however, absorption to super-normal is also a possibility. The transition probability from 9A to $R$ is still $1-P_*$, but the other two transition probabilities (which sum to $P_*$) become more complex. If the tenth lot is accepted, transition to reduced will occur if the total number of non-
conformities is less than or equal to the limit number \( L \). To calculate the transition probability from 9A to reduced, define event \( B_k \) as

\[ B_k : \text{event of accepting 10 consecutive lots and having a total of } k \text{ defectives in the samples.} \]

The probability of interest is

\[
P(B_k | 9 \text{ lots accepted}) = \frac{P(B_k \text{ and 9 lots accepted})}{P(9 \text{ lots accepted})} = \frac{P(B_k)}{P(9 \text{ lots accepted})}
\]

since if \( B_k \) occurs, 9 lots accepted had to occur. This probability can be simplified. Since

\[
P(B_k) = P(k \text{ defectives in 10 lots accept}) \times P(10 \text{ lots accept}) = g(10,k) \times P_{10}
\]

and \( P(9 \text{ lots accepted}) = P_9 \),

\[
P(B_k | 9 \text{ lots accepted}) = g(10,k) \times P_{10}.
\]

Thus, the transition probabilities from reg-normal state 9A to Red (reduced) and SN (super-normal) are

\[
P_{9A,R} = P_9 \sum_{k=0}^{L} g(10,k) \quad (2a)
\]

\[
P_{9A,SN} = P_9 \sum_{k=L+1}^{10} g(10,k) \quad (2b)
\]

Using results in Tables 111.2 and 111.3, and recalling that \( L=3 \), these probabilities are 0.0824 and 0.8784 for the example case. Note that without limit numbers, the transition probability from reg-normal state 9A to reduced is just \( P_9 = 0.9608 \), an increase of 1166%! Such an alarming increase in transition probability will greatly decrease the average run
length on normal inspection when limit numbers are omitted.

**Super-Normal Starting Probability Vector**

The starting state for super-normal is stochastic, and is calculated from the \( g(10) \) vector. Consider state \( k \) in super-normal inspection. Recall from the state definitions that this implies a total of \( k \) non-conforming units in the last ten samples from accepted lots. Then the probability of starting in state \( k \) of super-normal is

\[
\nu(k) = \frac{g(10,k)}{\sum_{j=L+1}^{10A} g(10,j)}, \quad k = L+1, L+2, \ldots, 10A
\]  

(3)

**Super-Normal Transition Probabilities**

The Markov chain for super-normal has a total of \( 10A-L+2 \) states, where \( A \) is the normal acceptance number and \( L \) is the limit number. Two of these states are absorbing states (Red (reduced) and RN (reg-normal)); the rest are transient, corresponding to \( L+1, L+2, \ldots, 10A \) total non-conformities in the previous ten samples. Transition probabilities must be derived in order to compute the average run length on super-normal (ARL_{SN}) and absorption probabilities to RED and RN (\( p_{SN,RED} \) and \( p_{SN,RN} \), respectively).

If a lot is rejected at any time while on super-normal, absorption to RN occurs immediately. This is because being on super-normal implies that ten
consecutive lots (at least) have been accepted on normal inspection. Therefore, from every transient state, the probability of transition to RN on the next lot is $1 - P_r$, the probability of rejection.

If a lot is accepted on super-normal, it is always possible to transition to another transient state. It is also possible to transition to RED from states numbered less than or equal to $L + A$. From state $L + A$, if a lot with $A$ defectives in its sample is dropped, and a lot with no defectives in its sample is added, the new total defectives is $(L + A) - A + O = L$, which meets the limit number criterion.

In general, if $J$ represents a transient state ($J \in \{L + 1, L + 2, \ldots, A\}$), then the next state can be

1) RN (reg-normal)
2) RED (reduced)
3) SN transient state in the interval $[\max(L + 1, J - A), \min(10A, J + A)]$

The max and min functions are needed because by definition, $J$ must be between $L + 1$ and $10A$. Also note that from state $J$, the maximum possible reduction in total number defective is $A$. Similarly, the maximum possible increase is $A$. This is true because both the dropped lot and the added lot have $0, 1, \ldots, A$ defectives in their samples, since they are both accepted lots.

To formulate the super-normal scenario mathematically, a lot is first "dropped" from the ten accepted lots, and then the current lot is "added."
Essentially three probability vectors are needed:

i) Unconditional probabilities of 0, 1, ..., A defectives in the sample (not assuming lot acceptance) (e.g., from Table III.2)

ii) \( g(9) \) vector (e.g., from Table III.3)

iii) \( g(10) \) vector (e.g., from Table III.3)

Several probabilistic events are defined to aid in the modeling. Let

\[ E_j : \text{ event that sample from dropped lot contains } j \text{ non-conformities, } j=0,1,...,A \]

\[ B_k : \text{ event that total defectives in ten samples from accepted lots (before dropping lot) is } k \]

\[ C_k : \text{ event that total defectives in nine samples from accepted lots (after dropping lot) is } k \]

The probabilities of the dropped lot having 0, 1, ..., A defectives, given that the ten lot total is \( k \) can now be found by use of Bayes' Theorem.

\[
P(E_0 | B_k) = \frac{P(B_k | E_0) g(1,0)}{P(B_k)} = \frac{P(C_k) g(1,0)}{P(B_k)}
\]

because \( P(B_k | E_0) = P(C_k) \) and \( g(1,0) \) is the previously developed probability of zero defectives, given lot acceptance. Similarly,

\[
P(E_1 | B_k) = \frac{P(B_k | E_1) g(1,1)}{P(B_k)} = \frac{P(C_k-1) g(1,1)}{P(B_k)}
\]

\[
\vdots
\]

\[
P(E_A | B_k) = \frac{P(B_k | E_A) g(1,A)}{P(B_k)} = \frac{P(C_k-A) g(1,A)}{P(B_k)}
\]

Generalizing for the dropped lot having \( m \) defectives, given that the total defectives in the ten samples is \( k \) yields
\[
P(E \mid B_k) = \frac{P(B_k \mid E_a)g(1,m)}{P(B_k)} = \frac{P(C_{k-1})g(1,m)}{P(B_k)}
\]

\[
= \frac{g(9,k-m)g(1,m)}{g(10,k)}
\]

(4)

Since the number of non-conformities in the dropped lot has nothing to do with the number of defectives in the lot to be added, dropping and adding are independent events. Hence, the probability of dropping \(m\) defectives and adding \(n\) is

\[
P(E \mid B_k)P(n) = \frac{P(C_{k-1})g(1,m) \cdot P(n)}{P(B_k)} = \frac{g(9,k-m)g(1,m) \cdot P(n)}{g(10,k)}
\]

(5)

where \(P(n)\) is the unconditional probability of \(n\) non-conformities in the sample (not assuming lot acceptance).

Recall the example case being studied. Assume that super-normal is in effect, and the current state is \(k=13\). The probability of dropping \(m=2\) defectives and adding \(n=1\), resulting in state \(13-2+1 = 12\), is

\[
P(E_2 \mid B_{13})P(1) = \frac{g(9,11)g(1,2)}{g(10,13)} \cdot P(1)
\]

\[
= (0.01232)(0.13888) \cdot (0.35763)
\]

\[
= (0.003823)
\]

\[
P(E_2 \mid B_{13})P(1) = 0.1601
\]

Note that this probability is not the transition probability from state 13 to 12, since it is also possible to reach 12 from 13 by, for example, dropping one defective and adding zero.

To calculate the probability of a transition from
J to J', it is necessary to determine all possible ways to start with J defectives, then drop a lot and add a lot, with the resulting number of defectives being J'. These probabilities, denoted as Q(J,J'), are computed below. For the time being, the possibility that J' < (L+1) is ignored, since the probability of transition from J to RED will be obtained by summing the transition probabilities from J to J' for J' < (L+1).

**J->J-A**: possible only if A defectives dropped, 0 added

\[ Q(J, J-A) = P(E_A; B_J) \cdot P(0) \]

**J->J-A+1**: possible if: A dropped, 1 added

\[ Q(J, J-A+1) = P(E_A; B_J) \cdot P(1) + P(E_A-1; B_J) \cdot P(0) \]

**J->J-1**: possible if: A dropped, A-1 added

\[ Q(J, J-1) = P(E_A; B_J) \cdot P(A-1) + P(E_{A-1}; B_J) \cdot P(A-2) + \ldots + P(E_1; B_J) \cdot P(0) \]

**J->J**: possible if number dropped = number added

\[ Q(J, J) = P(E_A; B_J) \cdot P(A) + P(E_{A-1}; B_J) \cdot P(A-1) + \ldots + P(E_0; B_J) \cdot P(0) \]
$J \rightarrow J+1$ : possible if: $A-1$ dropped, $A$ added  
$A-2$ dropped, $A-1$ added  
$\vdots$  
$0$ dropped, $1$ added  

$$Q(J,J) = P(E_{A-1};B_J)*P(A) + P(E_{A-2};B_J)*P(A-1) + \ldots + P(E_0;B_J)*P(1)$$  

$J \rightarrow J+A$ : possible if $0$ dropped, $A$ added  

$$Q(J,J+A) = P(E_0;B_J)*P(A)$$

To generalize these formulas, let $DJ$ (for "delta-J," or change in $J$) equal the change in the total number of defectives when an old lot is dropped and a new lot is added. Thus, $J' = J + DJ$, where $DJ$ is between $-A$ and $A$. Study of the preceding equations implies that the transition probability $Q(J,J+DJ)$ can be expressed as

$$Q(J,J+DJ) = P(E_{A-\max(0,DJ)};B_J)*P[A+\min(0,DJ)] + P(E_{A-\max(0,DJ)-1};B_J)*P[A+\min(0,DJ)-1] + \ldots + P(E_{A-\min(DJ)};B_J)*P[\max(0,DJ)]$$

(6)

Equation (6) is the basis from which super-normal transition probabilities are calculated. For $(J+DJ) > L$, equation (6) gives the probability of transition from state $J$ to state $J+DJ$, since no transition to reduced occurs. The probability of transition to reduced from transient state $J$ is

$$Q(J,\text{RED}) = \sum_{DJ \exists (J+DJ)<(L+1)} Q(J,J+DJ)$$

since, if $(J+DJ) < (L+1)$, the limit number has been met. As stated previously, transition to RN (reg-normal) occurs with probability $1-P_r$ from any transient state.
Several calculations will be performed from the example case. Suppose the current state is \( J=4 \), and the transition probability to RED is needed. Since \( A=2 \) and \( L=3 \) for this case, \( DJ \) may assume values \(-2,-1,0,1, \) and \( 2 \). Therefore, \( Q(4,4-2) \) and \( Q(4,4-1) \) must be summed to obtain the desired probability. From equations (5) and (6), and Tables III.2 and III.3,

\[
Q(4,2) = P(E_2:B_4)*P(0) \quad \text{(drop 2, add 0)} \\
= \frac{(g(9,2)\times g(1,2)\times P(0))}{g(10,4)} \\
= 0.0234
\]

\[
Q(4,3) = P(E_2:B_4)*P(1) + P(E_1:B_4)*P(0) \quad \text{(drop 2, add 1 or drop 1, add 0)} \\
= \frac{(g(9,2)\times g(1,2)\times P(1))}{g(10,4)} + \frac{(g(9,3)\times g(1,1)\times P(0))}{g(10,4)} \\
= 0.0178 + 0.14104 \\
= 0.1589
\]

Thus, the transition probability from state 4 to RED is \( 0.0234 + 0.1589 = 0.1823 \).

For a more typical transition probability calculation, consider state \( J=13 \) and next state \( J'=13 \).

This probability is computed as follows:

\[
Q(13,13) = P(E_2:B_{13})*P(2) + P(E_1:B_{13})*P(1) + P(E_0:B_{13})*P(0) \quad \text{(drop 2, add 2)} \\
+ \text{(drop 1, add 1)} \\
+ \text{(drop 0, add 0)} \\
= \frac{(g(9,11)\times g(1,2)\times P(2))}{g(10,13)} + \frac{(g(9,12)\times g(1,1)\times P(1))}{g(10,13)} + \frac{(g(9,13)\times g(1,0)\times P(0))}{g(10,13)} \\
= 0.059717 + 0.14495 + 0.069232 \\
= 0.274
\]

Finally, consider \( J=20 \) and \( J'=20+1=21 \). Note that \( J' \) is impossible to reach with ten accepted lots, since \( A=2 \) and \( 10A=20 \). The calculation of \( Q(20,21) \) supports
Q(20, 21) = P(E_1; B_{2,0}) * P(2) \quad \text{(drop 1, add 2)}
+ P(E_0; B_{2,0}) * P(1) \quad \text{(drop 0, add 1)}

= [g(9, 19) * g(1, 1) * P(2)] / g(10, 20)
+ [g(9, 20) * g(1, 0) * P(1)] / g(10, 20)

Q(20, 21) = 0 + 0 = 0

In this case J=20 and A=2. Therefore, all ten samples must have two defectives. Hence, it is impossible to drop a sample with 0 or 1 defective items.

All necessary theory for super-normal inspection have been developed. To compute the measures of performance for the limit number case, the following quantities are needed.

i) ARL_{SN}, the average run length on super-normal before absorption to RED or RN.

ii) P_{SN, RED} and P_{SN, RN}, the absorption probabilities to reduced and reg-normal, respectively.

iii) P_{RN, SN}, P_{RN, RED}, and P_{RN, RED}, the absorption probabilities from reg-normal to super-normal and to reduced, given the starting state is S (the original starting state).

iv) P_{RN, SN}, P_{RN, RED}, and P_{RN, TIR}, the absorption probabilities from reg-normal to super-normal, reduced, and tightened, given the starting state is R, the one rejection state (as on a return from super-normal).

v) ARL_{RN}, the average run length on reg-normal, given the starting state is R.

Quantities (i) and (ii) are calculated by arranging the super-normal transition matrix in standard
form, which is shown below, with individual elements omitted.

\[
\begin{bmatrix}
I & 0 \\
\vdots & \vdots \\
R & Q
\end{bmatrix}
\]

The summation of the elements in row \(j\) of the matrix \((I-Q)^{-1}\) is the expected number of lots until absorption, given that \(j\) is the starting state.

Letting \(M\) be the vector of these summations for \(j = L+1, L+2, \ldots, 10A\), and recalling that \(v\) is the super-normal starting probability vector,

\[ARLin = M \times v\]

Similarly, the absorption probabilities to RED and RN, given starting state \(j\), are the elements in the \(j^{th}\) row of \((I-Q)^{-1}R\). Thus, \(p_{AM,RED}\) and \(p_{AM,RN}\) are the elements in the 1x2 vector \(v((I-Q)^{-1}R)\).

To compute quantities (iii), results from Grinde (1986) are needed, in addition to transition probabilities from reg-normal state 9A to super-normal and reduced (equations 2a and 2b). Using these results, and letting \(p\) be the probability of acceptance on normal inspection for notational convenience,
\[
P_{\text{R N, S N I S}} = \frac{p^*+(p^9-p^1^0)}{(1-p^4+p^1^0)} \times \left[ p \sum_{k=L+1}^{10A} g(10,k) \right] \\
= \left[ \frac{(2p^1^0-p^4^t)}{1-p^4+p^1^0} \right] \times \sum_{k=L+1}^{10A} g(10,k) 
\] 
(7a)

Similarly,

\[
P_{\text{R N, R D I S}} = \left[ \frac{(2p^1^0-p^4^t)}{1-p^4+p^1^0} \right] \times \sum_{k=L+1}^{10A} g(10,k) 
\] 
(7b)

Quantities (iv) and (v) are also based on theory developed in Grinde (1986). The absorption probabilities and average run length on reg-normal, given the starting state is R, are needed for the limit number case because, upon return from super-normal, the reg-normal starting state is R (one rejection). These quantities are calculated in Appendix B, and are summarized here.

\[
P_{\text{R N, R H I R}} = \frac{p^1^0}{(1-p^4+p^1^0)} \times \sum_{k=L+1}^{10A} g(10,k) 
\] 
(8a)

\[
P_{\text{R N, R D I R}} = \frac{p^1^0}{(1-p^4+p^1^0)} \times \sum_{k=0}^{L} g(10,k) 
\] 
(8b)

\[
P_{\text{R N, T I R}} = \frac{(1-p^4)}{(1-p^4+p^1^0)} 
\] 
(8c)

\[
\text{ARL}_{\text{R H I R}} = \frac{(1-p^1^0)}{((1-p)(1-p^4+p^1^0))} 
\] 
(9)

Normal inspection is divided into reg-normal and super-normal to facilitate modeling of the limit number case. Theory for reg-normal was developed by Grinde (1986), while theory for super-normal has been developed in the preceding sections. It is now desirable to combine these developments to formulate
the average run length on normal inspection (reg-normal and super-normal combined) and absorption probabilities from normal to reduced and tightened. Quantities (i) through (v), calculated above, are used.

To compute the average run length on normal inspection (ARL_n) with limit numbers, let:

\[
P_1 = \text{P}_{\text{RN, SNIS}} \\
P_2 = \text{P}_{\text{RN, SNIR}} \\
P_3 = \text{P}_{\text{SN, RN}} \\
L_1 = \text{ARL}_{\text{RNIS}} \\
L_2 = \text{ARL}_{\text{RNIR}} \\
L_3 = \text{ARL}_{\text{RN}}
\]

Then \[\text{ARL}_n = L_1 + p_1 L_3 + p_1 p_3 L_2 + p_1 p_3 p_2 L_3 + \ldots\]

because normal inspection is continued as long as either reg-normal or super-normal is in effect. This reduces to

\[
\text{ARL}_n = L_1 + p_1 L_3 (1 + p_2 p_3 + p_3^2 + \ldots) + p_1 p_3 L_2 (1 + p_2 p_3 + p_3^2 + \ldots) = L_1 + \left[ p_1 \times \left( L_3 + p_3 L_2 \right) / (1 - p_2 p_3) \right]
\]

In original notation, this is

\[
\text{ARL}_n = \text{ARL}_{\text{RNIS}} + \left( \text{P}_{\text{RN, SNIS}} / [1 - \left( \text{P}_{\text{RN, SNIR}} \right) \left( \text{P}_{\text{SN, RN}} \right)] \right) * \left[ \text{ARL}_{\text{RN}} + \left( \text{P}_{\text{SN, RN}} \right) \left( \text{ARL}_{\text{RNIR}} \right) \right]
\]

(10)

Absorption probabilities to reduced and tightened from normal can similarly be calculated. The following notation is used in the development.
P₁ = PR₈, RED₁₈
P₂ = PR₈, SN₁₈
P₃ = PR₈, T₁₈ = 1 - p₁ - p₂
P₄ = PR₈, RED
P₅ = PR₈, R₄₈ = 1 - p₄
P₆ = PR₈, REDIR
P₇ = PR₈, SN₈
P₈ = PR₈, TIR = 1 - p₆ - p₇

ₚ₈₉ = Probability of absorption from normal to reduced
ₚ₈₇ = Probability of absorption from normal to tightened

Then \( p₈₉ = p₁ + p₂ p₄ + p₂ p₃ p₆ + p₂ p₃ p₇ p₄ + \ldots \)

\[ = p₁ + p₂ \left( \frac{p₄ + p₅ p₆}{1 - p₅ p₇} \right) \]

In original notation,

\[ p₈₉ = \frac{PR₈, RED₁₈ + PR₈, SN₁₈\left(PS₈, R₄₈ + PR₈, R₈₁₈ \right)}{1 - \left(PR₈, R₄₈ \right)\left(PR₈, R₈₁₈ \right)} \]

Equation (11a)

Similarly,

\[ p₈₇ = p₃ + p₃ p₄ + p₃ p₅ p₆ + p₃ p₅ p₆ p₇ + \ldots \]

This reduces to

\[ p₈₇ = p₃ + \left[ p₂ p₃ p₆ \left/ \left(1 - p₅ p₇ \right) \right. \right] \]

or, original notation,

\[ p₈₇ = \frac{PR₈, T₁₈ + \left(PR₈, SN₁₈\right)\left(PR₈, R₄₈\right)\left(PR₈, T₁₈\right)}{1 - \left(PR₈, R₄₈\right)\left(PR₈, SN₁₈\right)} \]

Equation (11b)

Development of theory for the limit number case is complete. Equations (10), (11a), and (11b) are the corresponding results to the formulas in Table III.1, for the no limit number case. There is no difference between reduced and tightened operation when using limit numbers or not. Note that, since analytical results have been developed for the no limit number case, and since these results also apply to the limit number case, only the super-normal Markov chain
requires a matrix inversion. Analytical results, besides being conceptually attractive, yield great computational savings.

**Measures of Performance**

Several performance measures were calculated to analyze scheme operating properties. These are divided into two groups: i) Values for specific quality levels, and ii) Single quantity measures. The results of the Markov model used to calculate these, and the performance measures calculated, are listed below:

**Results of Markov Model**

- **p**: incoming percent non-conforming
- **p_w**, **p_r**, and **p_t**: probabilities of acceptance on normal, reduced, and tightened inspection. **p_R** is the probability of acceptance on reduced and continuation of reduced inspection. Also used is **p_A**, which is the probability of acceptance on reduced, allowing for a possible return to normal inspection on the next lot.
- **ARL_w**, **ARL_R**, and **ARL_T**: average run lengths until transition on normal, reduced and tightened inspection
- **V_w**, **V_R**, and **V_T**: number of visits to normal, reduced, and tightened inspection before discontinuation
Values for Specific Quality Levels

1) ARL$_N$ : Average run length on normal inspection. Result of Markov model.

2) T$_{NR}$, T$_{NT}$, and T : Transitions between normal and reduced, normal and tightened, and total, per 1000 lots inspected

\[
T_{NR} = (2V_N/LOTS) \times 1000
\]
\[
T_{NT} = (2V_T/LOTS) \times 1000
\]
\[
T = T_{NR} + T_{NT}
\]

3) N%, R%, and T% : Percentage of lots inspected on normal, reduced, and tightened inspection.

\[
N\% = \frac{V_N ARL_N}{LOTS}
\]
\[
R\% = \frac{V_R ARL_R}{LOTS}
\]
\[
T\% = \frac{V_T ARL_T}{LOTS}
\]

4) LOTS : Lots inspected until discontinuation of sampling inspection.

\[
LOTS = V_N ARL_N + V_R ARL_R + V_T ARL_T
\]

5) P$_r$ : Probability of rejection (or overall percent rejected)

\[
P_r = 1 - [(N\%)p + (R\%)p + (T\%)p]
\]

Single Quantity Measures

1) AOQL : Maximum Average Outgoing Quality, where

\[
AOQ = (1-P_r)p
\]

2) LQL(10%) and LQL(5%) : Relative quality levels (fractions or percentages of the AQL) for which 1-P$_r$ = P$_r$ = 10% and 5%.

3) Maximum ARL$_N$ : Maximum value of the normal average run length

4) Maximum N% : Maximum percentage of lots inspected on normal inspection

The following section analyzes the effects of the limit numbers for reduced inspection.
ANALYSIS OF RESULTS

A FORTRAN computer program based on the mathematical model of the ANSI/ASQC Z1.4 single sampling case was written to generate numerical results. This program is discussed and listed in Appendix C. Also contained in this appendix is a table showing the normal inspection plans of the 152 schemes studied.

Analysis of the limit number effects is divided into two sections: i) single quantity measures, i.e., measures which have one value for each sampling scheme, such as AOQL; and ii) values of performance measures at selected quality levels. Area (i) is attractive since a single value for each inspection scheme is generated. However, a complete analysis requires investigation of the performance measures at specific quality levels.

Single Quantity Measures

The measures obtained which are characterized by a single value per scheme were listed previously. The relative quality levels at which they occur were found in addition to the values themselves.

AOQL

The AOQL is a measure of the worst possible outgoing quality when a particular scheme is employed.
Computation of the AOQ assumes that rejected lots are 100% screened, with defective items being replaced with acceptable ones. This replacement is also made for defective items in each sample, whether the lot is accepted or not. The AOQL for the sampling schemes of ANSI Z1.4 is usually referred to with no mention of the quality at which it occurs. This is unfortunate, since knowing the quality level at which a scheme reaches its AOQL may be just as important as the AOQL itself.

Table D.1 (a,b) contains the relative AOQL values and relative quality levels at which the AOQL's occur. The term "relative" means that the values are given as either fractions or percentages of the AQL. This permits comparison of schemes which have different AQL's. The format of the tables is the same as the tables in ANSI Z1.4, being indexed by code letter and AQL. For a given scheme, there are two values, one for use without limit numbers, and the other with limit numbers. For example, the scheme with code letter H, AQL=1.5% has AOQL’s without and with limit numbers of 151% AQL (occurring at 238% AQL) and 146% AQL (occurring at 244% AQL), where values in parentheses are the relative quality levels at which the AOQL’s occur.

Note the consistency of the AOQL’s and quality levels for common normal acceptance numbers. Diagonal
elements (from upper right to lower left) correspond to the same acceptance numbers. This trend is clearly evident for all measures of performance studied. Acceptance numbers provide a better general characterization of sampling schemes of ANSI Z1.4 than either code letters or AQL's. For this reason, averages were computed for common normal acceptance numbers. These averages are listed in the tables. Ranges and standard deviations are also stated, to demonstrate the consistency of values for particular acceptance numbers.

Figure III.5 (a,b) contains graphs of the average relative AOQL values and corresponding quality levels. Part (a) shows that, as the acceptance number (A) increases, the AOQL tends toward the AQL. This is not surprising, since schemes with larger A values should control outgoing quality more strictly. Schemes with A=0 have an average AOQL of about 205% AQL with and without limit numbers. Part (b) of the figure shows a similar trend with corresponding quality levels, where schemes with larger A's reach the AOQL near the AQL.

Outgoing quality when limit numbers are not used is slightly, but consistently, worse than when using limit numbers. This result is logical because without limit numbers, it is easier to transition to reduced inspection. Hence, more lots will be inspected on reduced when limit numbers are not used. Since the
Figure III.5 Average Relative AOQL Values

Figure III.6 Average Relative LQL Values
probability of acceptance on reduced is greater than that for either normal or tightened, more lots with poor quality will be accepted when limit numbers are not used.

ANSI Z1.4 tabulates the AOQL's for use with limit numbers only. However, these values were obtained from a model which only approximated the switching rules, and which ignored the discontinuation of inspection (Schilling & Sheesley, 1978a). Table D.1c lists the percent differences between the ANSI values and the actual values obtained with the model described in this paper. Note that for \( A=2 \) the average difference is 10.4%, which implies that the true AOQL's for this acceptance number are actually higher on average (quality is worse) than those tabled in the standard. Table D.1 should be included in the next revision of the standard, not only to correct it, but to provide values both with and without limit numbers.

LQL VALUES

The LQL is the quality level for which the probability of acceptance of a lot is a specific quantity. Thus, \( LQL (10\%) \) and \( LQL (5\%) \) are the quality levels for which \( P_* = 10\% \) and 5\%, respectively. The LQL is useful when concerned with controlling the consumer's risk of accepting a poor-quality lot. If the LQL is high relative to the AQL, then there is a
significant probability of accepting a bad lot. However, if the LQL is only slightly above the AQL, there is little chance of accepting a poor lot. LQL values for 10% and 5% are listed in Tables D.2a and D.2b. Figure 111.6 is the graphical representation of averages for common acceptance numbers. The graphs are very similar in shape, and the primary difference is that the LQL (5%) values are slightly larger. Discrimination of poor lots improves as acceptance numbers increase, since LQL values approach the AQL. For A=0, however, the incoming quality must be about 15.5 times the AQL for P. to reach 0.05. This result implies that the consumer assumes a high risk of accepting a poor lot when A=0. As in the AOQL case, differences with and without limit numbers are fairly minimal.

ANSI Z1.4 tables LQL values for 10% and 5%, with limit numbers. Tables D.2c and D.2d show that, especially for smaller acceptance numbers and P*=10%, that the ANSI value is actually understating the LQL by up to 12.3% (A=5 case). Hence, the schemes do not control consumer's risk as well as the standard implies. Tables D.2a and D.2b should replace the ANSI Z1.4 LQL tables.

MAXIMUM PERCENT INSPECTED ON NORMAL

The tables listing the maximum percentage of lots
inspected on normal (and associated quality levels) are D.3a and D.3b. In the former, note how small the standard deviations of averages are. Results are very consistent for common acceptance numbers. For intermediate A's, it is possible that nearly all lots (up to 94%, when A=7 or 10) will be inspected on normal when limit numbers are used. Without limit numbers, however, the maximum percent on normal is 68%, when A=1.

Averages of the values in Table D.3 are graphically shown in Figure III.7. It is noteworthy that, without limit numbers, relatively few lots are inspected on normal (part a). Further, the maximum percent on normal without limit numbers usually occurs at about 150% of the AQL (part b). At the AQL, one would expect most lots to be inspected on normal. However, when limit numbers omitted, this could hardly be the case, since the maximum possible percent on normal is only 50-68 percent. The range with limit numbers is 57-94 percent. It is difficult to think of normal inspection as being "normal" when limit numbers are not used.

MAXIMUM NORMAL AVERAGE RUN LENGTH

Results for the maximum average run length on normal inspection show even greater differences with vs. without limit numbers. Table D.4 (a,b) presents
Figure III.7 Maximum Percent Inspected on Normal

Figure III.8 Maximum Normal Average Run Lengths
This information. The average maximum ARL\textsubscript{w} without limit numbers never rises above 12.7 lots, while the corresponding values with limit numbers range from 21.9 (with A=0) to 125.0 (with A=7).

Figure III.8 contains two graphs displaying these results. These graphs dramatically show the differences with vs. without limit numbers. Even for A=0, the difference is nearly two-fold and at A=7, the average maximum ARL\textsubscript{w} with limit numbers is almost ten times the no limit number value! With only 11.5 to 12.7 lots inspected on normal between transitions without limit numbers, normal inspection will certainly not seem "normal." Further, this maximum usually occurs above the AQL, so that when AQL quality is submitted, ARL\textsubscript{w} will be even smaller. A shorter ARL\textsubscript{w} will affect the frequency of transitions made between normal, tightened, and reduced inspection.

Analysis for Selected Quality Levels

The limit number effects have been discussed in reference to single quantity measures. Analyzing single quantity measures provides a fairly brief glimpse of some of the effects use without limit numbers causes. It is desired to select specific quality levels and determine the effects use of a sampling scheme without limit numbers causes. The maximum differences in performance measures, and the
quality at which they occur were calculated. It was noted that the maximum differences usually occur near the AQL, between 75% AQL and 150% AQL. Therefore, four quality levels were selected (relative to the AQL) for analysis: 75%, 100%, 125%, and 150% AQL. Selection of these levels allows analysis if quality is good (75%), acceptable (100%), and poor (125% and 150%).

In the study, it was noted that with quality better than 75% AQL, very few differences with vs. without limit numbers were notable. This is because, with extremely good quality, the limit number criterion is met almost as often as ten consecutive lots are accepted. Thus, in this case, the limit number plays a small role. Differences were also minimal for extremely poor quality. Since the probability of acceptance is small at poor qualities, ten consecutive lots are rarely accepted. Thus, the limit number also plays a small role in this case. It is at qualities near the AQL that the limit number is effective. At these qualities (which are neither extremely good nor bad), it is relatively easy to accept ten consecutive lots on normal, but is is much more difficult to do this in addition to meeting the limit number. Consider a simplified case of Code Letter H (sample size = 50), A=2, L=3, and quality at the AQL=1.5%. The probability of acceptance of a single lot is, using the binomial
distribution, 0.9608. Hence the probability of accepting ten consecutive lots is 0.9608 raised to the power of ten, or 0.6701. Now consider the unconditional probability of meeting the limit number (ignoring the requirement of accepting ten consecutive lots, which would lessen the probability). This is the probability of obtaining $L=3$ or fewer defectives in a sample of $10 \times 50 = 500$ units, or 0.0578. There is over an eleven times greater chance of accepting ten consecutive lots than unconditionally meeting the limit number! This indicates that extremely significant differences may occur near the AQL.

The performance measures analyzed in this section were listed at the conclusion of the theory section. In the discussion and figures which follow, the general shapes of the graphs are nearly as interesting as the differences with vs. without limit numbers. With the normal acceptance numbers plotted on the horizontal axis and the performance measure values along the vertical, graphs can change dramatically from one quality to the next.

**AVERAGE RUN LENGTH ON NORMAL INSPECTION**

$\text{ARL}_n$ results for the four quality levels are listed in Table D.5 (parts a, b, c, and d). As in previous tables, results for common normal acceptance numbers are very consistent. Averages for each accept
number are shown. Also shown are overall averages (for all schemes) and overall percent differences when limit numbers are omitted.

For all acceptance numbers and quality levels, use with vs. without limit numbers causes dramatic changes in ARLₙ. Results are shown graphically in Figure III.9. When quality is good (75% AQL), differences are most significant for small and medium acceptance numbers. In these cases the ARLₙ with limit numbers is roughly twice that without limit numbers.

Limit numbers have virtually no effect with 75% AQL quality and A=21, 30, and 44. This is because these schemes are good discriminators of good and bad quality, and with quality at 75% AQL, transition to reduced is made quickly. The overall ARLₙ's at this quality with and without limit numbers are 16.5 and 10.5, respectively, so that omission of limit numbers results in an average 34.8 decrease in normal average run length.

The largest differences in ARLₙ occur at 100% and 125% AQL. With AQL quality, ARLₙ is decreased from an overall average of 43.7 lots to 11.3 lots when limit numbers are omitted. Differences are greatest for A>1. When quality is slightly above the AQL (125%), use of limit numbers increases the ARLₙ by ten times for A=5, 7, and 10. For other accept numbers the differences are not as dramatic, but are certainly noteworthy. The
Figure 11.9 Normal Average Run Length
overall average increase when limit numbers are used is from 12.2 lots to 67.4 lots, an increase of 450%! With poor quality (150%), differences are moderate for small A, large for medium A, and small for large A. Use without limit numbers decreases the ARLw by an average of 55.7%, from 24.7 lots to 10.9 lots.

TRANSITIONS BETWEEN INSPECTION PLANS

The ARLw affects several other performance measures. The one most directly influenced is the frequency with which transitions between inspection plans occur.

These results are listed in Tables D.6 through D.8. Total transitions are separated into transitions between normal and reduced, and between normal, tightened, and discontinuation. The switching rules guarantee that every transition from normal to reduced must be followed by a transition from reduced to normal. Similarly, every time a transition from normal to tightened occurs, a transition from tightened to either normal or discontinuation becomes imminent. To obtain a measure of the frequency of transitions, transitions per 1000 lots inspected is used. It can be seen in Figure 111.10 that use of the limit numbers controls the amount of switching effectively when quality is near the AQL. One of the criticisms of ANSI Z1.4 is that, even with limit numbers, switching occurs
Figure III.10 Transitions per 1000 Lots
too frequently with quality near the AQL (Koyama, et. al., 1970). However, without limit numbers, switching is even more frequent. Note especially transitions between normal and reduced at qualities 125% and 150% AQL. With 125% quality an overall average of 57.9 transitions per 1000 lots occur without limit numbers. This corresponds to one transition from normal to reduced or vice versa for every 17.3 lots inspected. However, use of limit numbers lowers the transition rate to 6.6 per thousand, or one every 152 lots. Since quality is poor, no transitions should be made to reduced (ideal case).

When quality is 1.5 AQL, the problem of "random switching" is even more pronounced. With limit numbers, an overall average 2.4 transitions per 1000 lots occur between normal and reduced (one every 417 lots). This seems reasonable at this quality level. However, if limit numbers are omitted, the average is 41.4 per thousand, or one every 24 lots!

Transitions between normal and tightened inspection are also affected when limit numbers are dropped. Differences as dramatic as the normal-reduced situation are not present. At all quality levels and acceptance numbers, however, the use of limit numbers increases the number of transitions made. This is due to the fact that use of the limit numbers makes
transition to reduced more difficult. Since more lots will be inspected on normal, this increases the transition rate between normal and tightened. Above the AQL, this is the desired case, since, theoretically, tightened inspection should be employed frequently when quality is poor. Below the AQL, however, tightened inspection should occur infrequently, and use of limit numbers does not violate the ideal too seriously (an average of 4.0 transitions per 1000 lots with .75AQL quality; corresponding no limit number quantity is 3.0).

It is also important to consider the total number of transitions made between all inspection plans. This quantity is represented as the overall height of the bars in Figure III.10. The issue of transitions is not merely a theoretical and philosophical question, but an imminently practical one. Depending on the particular situation, making a transition from one inspection plan to another could be costly. Hence, it is undesirable to transition unless it is truly warranted (quality actually is superior) or necessary (quality may be poor).

Use of the limit numbers controls the amount of switching very effectively. Above the AQL, normal-reduced transitions are nearly eliminated with limit numbers. However, if limit numbers are not used the N-R transition rate actually increases from AQL quality.
(46.8 per 1000) to 125% quality (57.9 per 1000).

Similarly, more transitions are made between normal and tightened inspection above the AQL when limit numbers are used, which helps to protect the consumer against poor quality.

PERCENT ON NORMAL, TIGHTENED, AND REDUCED INSPECTION

The great differences in ARLw and transition frequency with vs. without limit numbers cause the lots to be distributed differently between normal, tightened, and reduced inspection. Since use without limit numbers eases the requirements to switch to reduced, more lots are inspected on reduced. Further, since reduced inspection is more common without limit numbers, and tightened inspection can only be reached directly from normal, fewer lots will be inspected on tightened without limit numbers.

Results for N%, T%, and R% are listed in Tables D.9 through D.11. Graphical displays are shown in Figures III.11 through III.14. The line graphs are included to provide a better visual impression of the differences with vs. without, and to show the relationship between percentages and acceptance numbers more clearly. Bar graphs clearly show the relative contribution of each sampling plan with and without limit numbers.
Figure III.11 Percent Inspected on Normal
Figure III.12 Percent Inspected on Tightened
Figure III.13 Percent Inspected on Reduced
Figure III.14 Percent Inspected on Each Plan
As shown in Figure III.14(a), differences are relatively small at 75% AQL. Overall, at this quality, 20.1% of the lots are on normal without limit numbers, and 27.8% with. Most of this difference is accounted for in reduced inspection. The general shape of the normal inspection curve (Figure III.11a) deserves mention. At small acceptance numbers, between 30 and 50 percent of the lots are inspected on normal. As A increases, however, the proportion of lots inspected on normal approaches zero (both with and without limit numbers). Schemes with large acceptance numbers typically discriminate between good and bad quality very effectively. Since the quality is 0.75 AQL, almost all lots will be inspected on reduced for large values of A.

The largest differences occur at the three higher quality levels. With AQL quality, almost twice as many lots are inspected on normal with limit numbers. The graph shows that most of this difference goes to reduced inspection. At 125% and 150% AQL qualities, very few lots are inspected on reduced when limit numbers are employed. However, there is still a significant portion on reduced without limit numbers.

At qualities near the AQL, reduced inspection is very frequent if limit numbers are omitted. In fact, the overall average percent on reduced without limit numbers is 66% at the AQL, 43% at 1.25 AQL, and 19% at
1.5 AQL. Results such as these do not support the general philosophy that only exceptional quality be rewarded with reduced inspection.

LOTS INSPECTED PRIOR TO DISCONTINUATION

Since there are differences in the percentage of lots on normal, tightened, and reduced, and since discontinuation is only possible from tightened, more lots will be inspected, on the average, when limit numbers are omitted.

The LOTS results are listed in Table D.12. Note that for quality levels 75% AQL and 100% AQL, both averages and the natural logarithms of the averages are listed. A transformation is needed to construct an effective graph. Schemes with small accept numbers tend to inspect a relatively small number of lots, while more lots are inspected with a larger acceptance number. Note that for AQL quality and acceptance numbers 0 and 1, very few lots are inspected, on the average, prior to termination. With limit numbers the LOTS values are 164 and 200, respectively, for A=0 and A=1. When limit numbers are omitted, both of these values increase to 221. For these schemes, quality must be extremely good in order to continue sampling for a large number of lots. A normal scale is used for 125% and 150% AQL.

The graphs are shown in Figure 111.15.
Figure III.15 Lots Inspected Until Discontinuation

(a) Normal Accept Number

(b) Normal Accept Number

(c) Normal Accept Number

(d) Normal Accept Number
Differences are actually more than they appear for 0.75AQL and 1.0AQL. Quality levels 100%, 125%, and 150% of the AQL produce the largest percent increases in lots until termination when limit numbers are omitted. Taking overall averages, these increases are 250%, 120%, and 32%, respectively. These results are significant because, if quality is poor, sampling inspection should be discontinued as early as possible. Using the standard without limit numbers increases the number of lots inspected. Thus, the termination of sampling is delayed. Recall also that over 42% of the lots are inspected on reduced with 125% AQL quality and no limit numbers. There is a false sense of good quality and a delayed sign of poor quality if limit numbers are omitted.

OVERALL PERCENT REJECTED

With a greater portion of lots being inspected on reduced without limit numbers, fewer lots will be rejected. Table D.13 and Figure 111.16 represent the results. Note the general shape of these curves, especially for 125% AQL. High acceptance numbers are representative of discriminating schemes. Hence, P should be relatively high in these cases. Schemes with small acceptance numbers tend to be more strict in the sense that P is usually higher for qualities near the AQL. In between, the schemes are neither extremely
Figure III.16 Overall Percent Rejected
strict nor are excellent discriminators. These observations help explain the concave upward shape of this graph.

The differences with vs. without limit numbers are not as great for \( P \) as for other measures. Even so, \( P \) is reduced by 21.5\% and 26.2\% at the AQL and 1.25 AQL with the omission of limit numbers. The concern should be for significant reductions at poor quality levels. Maximum differences occur at 125\% AQL. Although an argument can be made that use without limit numbers causes acceptance of more good lots above the AQL, which is true, this must be weighed against the fact that more poor lots are accepted below the AQL.

**Summary of Analysis**

Contrary to the statement in ANSI/ASQC Z1.4 to the effect that use without limit numbers will cause small differences in operating properties, the effects are, in general, very large. More importantly, the largest differences occur close to the AQL (usually at it or slightly above it).

A summary of overall averages of performance measures and percent differences is given in Tables III.4 and III.5. These tables give, at a glance, the average values for all schemes at a particular quality level. Most significant are the values for \( R \% \), LOTS, \( T_{WR} \), and \( T \). The percent differences when limit numbers are
omitted are the values of the second table.

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<th>125</th>
<th>150</th>
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<td>N%</td>
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<td>31.5</td>
<td>48.5</td>
<td>53.8</td>
</tr>
<tr>
<td></td>
<td>27.8</td>
<td>59.4</td>
<td>83.2</td>
<td>67.3</td>
</tr>
<tr>
<td>R%</td>
<td>78.8</td>
<td>65.8</td>
<td>42.6</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>70.9</td>
<td>37.0</td>
<td>4.0</td>
<td>1.1</td>
</tr>
<tr>
<td>T%</td>
<td>1.0</td>
<td>2.7</td>
<td>9.0</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>3.6</td>
<td>12.8</td>
<td>31.6</td>
</tr>
<tr>
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<td>11.3</td>
<td>12.2</td>
<td>10.9</td>
</tr>
<tr>
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<td>16.5</td>
<td>43.7</td>
<td>67.4</td>
<td>24.7</td>
</tr>
<tr>
<td>Pr</td>
<td>1.3</td>
<td>2.7</td>
<td>7.3</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3.4</td>
<td>9.9</td>
<td>23.6</td>
</tr>
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</tr>
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<td>9.4E04</td>
<td>280.</td>
<td>55.</td>
</tr>
<tr>
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<td>32.2</td>
<td>46.8</td>
<td>57.9</td>
<td>41.4</td>
</tr>
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<td></td>
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<td>22.5</td>
<td>6.6</td>
<td>2.4</td>
</tr>
<tr>
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<tr>
<td>T</td>
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<td>38.1</td>
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</table>

Without Limit Numbers value on top

Table III.4: Overall Averages for Performance Measures, Without and With Limit Numbers
Table 111.5: Overall Percent Differences in Performance Measures, Without vs. With Limit Numbers

Briefly, the limit number effects can be explained as follows: Use without limit numbers eases the requirements to switch from normal to reduced. Hence, the average run length on normal decreases. This implies that the frequency of transition from normal to reduced increases, and thus, more lots will be inspected on reduced, and fewer on tightened. Since the percent rejected is lower at all quality levels on reduced, the overall percent rejected will be lower when limit numbers are omitted. Also, since fewer lots are on tightened without limit numbers, more lots will be inspected prior to discontinuation of inspection.
DISCUSSION OF RESULTS AND CONCLUSIONS

A Markov model which captures the operation of the switching rules exactly has been developed in this paper. Part of the model was developed by Grinde (1986), and closed form equations are used for measures of performance, eliminating matrix inversions for the reg-normal Markov Chain. The portion of the model developed in this paper is for super-normal inspection, which requires a matrix inversion for analysis.

In terms of analysis of the effects on performance measures with the omission of limit numbers, almost all where changed significantly. Maximum differences tend to occur at or slightly above the AQL. This is the quality level for which transition to reduced is very likely without limit numbers, but very improbable with limit numbers. The standard switches between inspection plans (especially between normal and reduced) much too frequently at these quality levels when limit numbers are not used. In terms of total transitions per 1000 lots, use without limit numbers increases the transition rate 25.8%, 67.6%, 109.2%, and 41.5% at qualities 0.75, 1.0, 1.25, and 1.5 of the AQL, respectively. For AQL quality, transitions increase from 32.2 per thousand (one every 31 lots) to 54.0 per thousand (one every 18.5 lots). At 125% quality, the
increase is from 38.1 per thousand (one every 26 lots) to 79.8 per thousand (one every 12.5 lots).

It has been claimed that the limit numbers add unnecessary complexity to the standard and make it difficult to use (Schilling & Sheesley, 1978a). However, the drastic increase in frequency of transitions, especially to and from reduced when quality does not warrant it, adds much complexity to the operation of the sampling scheme. Also, the false impression of excellent quality is potentially dangerous. Since reduced inspection is so frequent, workers may feel that they can let up a bit on quality, when in actuality the AQL is being exceeded!

Even above the AQL, a very significant proportion of lots are inspected on reduced when limit numbers are not used. As Table III.5 shows, 42.6% of the lots are inspected on reduced without limit numbers. This compares to 4.0% on reduced when limit numbers are used. It is difficult to consider reduced inspection as a reward for superior quality when it is being employed so often at a poor quality level. The psychological reward of being on reduced inspection should not be taken seriously if limit numbers are not used. In fact, reduced inspection seems to be more "normal" when limit numbers are not used. Use of limit numbers controls unnecessary switching between
inspection plans, and minimizes the proportion of lots on reduced at qualities above the AQL.

A review of the graphs of the operating properties points out an interesting feature of them, especially for 1.25 AQL and 1.50 AQL. Many of these graphs are "U-shaped" (or inverted U). Note in particular graphs for ARL, transitions, T%, LOTS, and P. T\% and P. are strikingly similar in shape. This is logical, since tightened plans are stricter than either reduced or normal plans. Thus, when more lots are inspected on tightened, more lots will be rejected. These graphs (especially above the AQL) have definite U-shapes. Schemes with small acceptance numbers are typically fairly strict, hence they will have high P, s. Also, large acceptance number schemes are excellent discriminators of good and bad quality. Therefore, P. will be high above the AQL. At intermediate acceptance numbers, the schemes are neither extremely strict nor are excellent discriminators. Thus, P. is U-shaped. By the preceding logic, then, T% is also U-shaped. Now, at small A's (acceptance numbers), many lots are on tightened. Thus, since discontinuation can only occur from tightened, relatively few lots will be inspected prior to termination of inspection. Similar arguments apply to medium and large acceptance numbers.

The average run length on normal and transitions
graphs are unique, because the shapes with vs. without limit numbers are quite different. In general, the "U" shapes are more pronounced with limit numbers. For the ARL, this makes sense, since the maximum value without limit numbers is only about 12.7 lots. ARL and transition frequency are negatively correlated. That is, when ARL is low, transition frequency will be high, and vice versa. Considering 1.25 AQL and 1.50 AQL qualities, the shape of the ARL curves can be explained using the Pr logic. Since small acceptance number schemes are strict, transitions will generally be made quickly, (often to tightened, as the transition graph shows). Hence, these schemes have small ARL values. Large A schemes also have small normal average run lengths, because they are good discriminators. In between, transitions (at least without limit numbers) are infrequent; hence, these schemes have large normal average run lengths.

The results presented in this paper suggest that the statement in ANSI/ASQC Z1.4 claiming that limit numbers make little difference is in error. Limit number effects should be explained and tabled in the next revision.

Results presented in this paper also enable more informed decisions to be made as to the selection of a sampling scheme and whether to employ limit numbers or
Several criteria should enter into this decision; cost of sampling inspection, cost of switching from one plan to another, the AOQ, and the producer's & consumer's risks are some possible factors to consider.

Several opportunities for future research exist. The mathematical model for super-normal inspection could possibly be reformulated to allow for an analytical solution, as in the reg-normal case (Grinde, 1986). Instead of inverting a large matrix for each different case (which consumes considerable computer time), closed form results could be obtained by inverting the matrix manually once, or by a specially designed computer program.

Research could also be performed to build a multi-criteria decision model designed to select the best sampling scheme and the operating policy (with vs. without limit numbers). This would link the mathematical analyses to decision makers, who could then understand the choices available and the implications of each one.
REFERENCES


CHAPTER IV
SUMMARY OF RESULTS AND CONTRIBUTIONS

Two major contributions have been made with the research reported in this thesis. The first one is the development of closed form results for the no limit number situation. These results have not been developed until now.

Detailed analysis of limit number effects on scheme operating properties is the second major contribution. Although ANSI/ASQC Z1.4 states that limit numbers have little effect, this simply is not the case. Tables appropriate for inclusion in the next revision of the standard have been developed. Finally, and perhaps most important to quality managers, it is now possible to be informed of the implications of using any single sampling scheme with vs. without limit numbers.
BIBLIOGRAPHY


APPENDICES
APPENDIX A
INTERMEDIATE CALCULATIONS OF PERFORMANCE MEASURES

This appendix outlines the calculations of the inverses of the matrices for the overall system and for normal inspection. Gaussian Elimination is used to find the inverses.

Overall Markov Chain

The states of the overall chain are D (Discontinue inspection), N (Normal inspection), T (Tightened inspection), and R (Reduced inspection). After arranging the transition matrix in the standard

\[
\begin{bmatrix}
1 & 0 \\
R & Q
\end{bmatrix}
\]

form, the needed inverse is \((I-Q)^{-1}\). This matrix will yield the expected number of times normal, tightened, and reduced inspection are visited prior to discontinuation of sampling inspection. A general outline of the calculations is shown below:

1. Overall Transition Matrix

\[
\begin{bmatrix}
D & N & T & R \\
D & 1 & 0 & 0 & 0 \\
N & 0 & 0 & 1-p_{N,N} & p_{N,R} \\
T & 1-p_{T,R} & p_{T,N} & 0 & 0 \\
R & 0 & 1 & 0 & 0
\end{bmatrix}
\]
2. Calculate \((1 - Q)\):

\[
N \begin{bmatrix}
1 & -1 + p_{WR} & -p_{WR} \\
-p_{TN} & 1 & 0 \\
-1 & 0 & 1
\end{bmatrix}
\]

3. Calculate inverse of \(1 - Q\). Specifically, calculate the first row of this matrix, since the starting state is normal inspection.

a. Set up for Gaussian Elimination procedure.

\[
\begin{bmatrix}
1 & p_{WR} - 1 & -p_{WR} & 1 & 0 & 0 \\
-p_{TN} & 1 & 0 & 0 & 1 & 0 \\
-1 & 0 & 1 & 0 & 0 & 1
\end{bmatrix}
\]

b. Calculate inverse. Elements of the first row are given below.

\begin{align*}
(1 - Q)^{-1}_{1,1} &= \frac{p_{WR}}{(1 - p_{WR})(1 - p_{TN})(1 - p_{TN} + p_{WR}p_{TN})} \\
&\quad + \frac{1}{1 - p_{TN} + p_{WR}p_{TN}} \\
(1 - Q)^{-1}_{1,2} &= \frac{p_{WR}}{(1 - p_{TN})(1 - p_{TR} + p_{WR}p_{TN})} \\
&\quad + \frac{1 - p_{WR}}{(1 - p_{TN} + p_{WR}p_{TN})} \\
(1 - Q)^{-1}_{1,3} &= \frac{p_{WR}}{(1 - p_{WR})(1 - p_{TN})}
\end{align*}

c. Reduce inverse elements to a simpler form.

\begin{align*}
(1 - Q)^{-1}_{1,1} &= \frac{1}{(1 - p_{WR})(1 - p_{TN})} = \frac{1}{p_{TR}p_{RD}} \\
(1 - Q)^{-1}_{1,2} &= \frac{1}{1 - p_{TN}} = \frac{1}{p_{TR}} \\
(1 - Q)^{-1}_{1,3} &= \frac{p_{WR}}{(1 - p_{WR})(1 - p_{TN})} = \frac{p_{WR}}{p_{TR}p_{RD}}
\end{align*}

4. Summarize results for overall Markov Chain, given a start in Normal Inspection.

\[
\begin{align*}
V_n &= \text{Visits to Normal} = \frac{1}{p_{TR}p_{RD}} \\
V_t &= \text{Visits to Tightened} = \frac{1}{p_{TR}} \\
V_r &= \text{Visits to Reduced} = \frac{p_{WR}}{p_{TR}p_{RD}}
\end{align*}
\]

Normal inspection Markov Chain

The Markov Chain for normal inspection consists of
9 states for 1, 2, ..., 9 consecutive acceptances, and the states R, RA, RAA, and RAAA, corresponding to a rejection followed by 0, 1, 2, or 3 acceptances. In addition to these transient states, the two absorbing states are tightened inspection and reduced inspection.

It is desired to obtain the expected number of lots inspected on normal inspection before absorption. In addition, the absorption probabilities are also needed. Hence, both the \((I-Q)^{-1}\) and the \((I-Q)^{-1}R\) matrices are needed, assuming the transition matrix is in the form. The normal inspection transition matrix is shown below. For notational simplicity, "p" represents the probability of acceptance on normal, and "q" represents the probability of rejection, or 1-\(p\).

\[
\begin{bmatrix}
1 & 0 \\
\vdots & \vdots \\
R & Q
\end{bmatrix}
\]

The normal inspection transition matrix is shown below. For notational simplicity, "p" represents the probability of acceptance on normal, and "q" represents the probability of rejection, or 1-\(p\).

\[
T \quad Rd \quad S \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad R \quad RA \quad RAA \quad RAAA
\]

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & p & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & p & 0 & 0 & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & q & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q
\end{bmatrix}
\]
From the normal transition matrix, \((I-Q)^{-1}\) is computed. This procedure requires about 68 pivots using Gaussian Elimination. The only possible starting state in normal inspection without limit numbers is the "S" state. Thus, this row is the only one which is necessary. The elements of this row are summarized below.

Note: In the formulas below, \(d = 1/(p^1 \cdot p^4 + 1)\)

\[
\begin{align*}
(I-Q)_{s1} &= 1 \\
(I-Q)_{s1} &= p \\
(I-Q)_{s2} &= p^2 \\
(I-Q)_{s3} &= p^3 \\
(I-Q)_{s4} &= p^4 + (p^4 - p^1) \cdot d \\
(I-Q)_{s5} &= p^5 + (p^5 - p^1) \cdot d \\
(I-Q)_{s6} &= p^6 + (p^6 - p^1) \cdot d \\
(I-Q)_{s7} &= p^7 + (p^7 - p^1) \cdot d \\
(I-Q)_{s8} &= p^8 + (p^8 - p^1) \cdot d \\
(I-Q)_{s9} &= p^9 + (p^9 - p^1) \cdot d \\
(I-Q)_{s10} &= (p^{10} - p^{10} - p^1 + p^2) \cdot d \\
(I-Q)_{s11} &= (p^1 - p^{11} + p^1 + p^2) \cdot d \\
(I-Q)_{s12} &= (p^{12} - p^{12} + p^1 + p^2) \cdot d \\
(I-Q)_{s13} &= (p^3 - p^3) \cdot d
\end{align*}
\]

The formulas above give the expected number of times a given state will be visited before absorption, assuming that "S" is the starting state. To find the average run length on normal inspection, these values
are summed. This calculation is shown below.

$$ARL_N = \frac{(2+2p+2p^2+p^3+p^4+p^5+p^7+p^9 - p^{10} - p^{11} - p^{12} - p^{13})/(1-p^4+p^{10})}{1}$$

Since $$\sum_{j=0}^{K} p^j = (1-p^{k+1})/(1-p)$$, the following result is obtained:

$$ARL_N = \frac{(1-p^{10}+p^4)(1-p^{14})...[(1-p^{10})(1-p^{14})]}{(1-p^{10})}$$

$$ARL_N = \frac{(2p^4-2p^{10}+p^{14})}{[(1-p)(1-p^4+p^{10})]}$$

It is also desired to obtain the absorption probabilities to reduced and tightened inspection. These values are obtained by multiplying the $$(I-Q)^{-1}$$ matrix by the R matrix. In this case the calculations are fairly simple, since the R matrix has only a few non-zero entries. Also, since there is only one possible starting state in normal inspection, only the row corresponding to this state needs to be multiplied by R. These calculations are detailed below.

$$p_{NR} = \frac{(p^{10}+(p^{10}-p^{14}d)p = p^{10} + (p^{10}-p^{20})d}{1-p^4+p^{10}}$$

$$p_{NR} = \frac{(p^{10}-p^{14}+p^{20}+p^{10}-p^{20})/(1-p^4+p^{10})}{1-p^4+p^{10}}$$

$$p_{NR} = \frac{(2p^{10}-p^{14})}{1-p^4+p^{10}}$$
\[ P_{NT} = (1-p)[(1-p^1) + (p-p^1) + (p^2-p^1) + (p^3-p^1-p^4 + p^2) + p^3-p^1-p^2+p^1+p^2+p^3-p^1^3) d] \]


\[ = (1-p^3-p^1+p^1^3) + (p^3-p^7-p^1+p^1^7+p^2+p^2) d \]

\[ = [(1-p^4+p^1)(1-p^3-p^1+p^1^3) + (p^3-p^7-p^1+p^1^7+p^2+p^2+p^2) d] /

\[ = (1-p^4+p^1^4) / (1-p^4+p^1^0) \]

It is easily verified that \( p_{NT} + p_{NT} = 1 \), as required.
Grinde (1986) has derived formulas for measures of performance for the no limit number case. In this situation, the starting state on reg-Normal is always the same, S. When using ANSI Z1.4 with limit numbers, however, there are two possible starting states. S is the initial starting state, and R is the starting state upon returns from tightened and reduced inspection. Upon a return from super-normal, however, the starting state is R (one rejection). To model operation with limit numbers, then, the average run length and absorption probabilities must be computed for reg-norm, given R as the starting state.

The row of $(1-Q)^{-1}$ for reg-norm with starting state R is given below, where $p$ is the probability of acceptance on normal, and $d=1-p^i+p^o$. For a more detailed discussion of reg-normal, see Grinde (1986).

\begin{align*}
(1-Q)_{R;1A} &= 0 \\
(1-Q)_{R;2A} &= 0 \\
(1-Q)_{R;3A} &= 0 \\
(1-Q)_{R;4A} &= p^i d \\
(1-Q)_{R;5A} &= p^o d \\
(1-Q)_{R;6A} &= p^o d \\
(1-Q)_{R;7A} &= p^i d
\end{align*}
\[(I-Q)_{1\rightarrow 0}^{A} = p^{a}d\]
\[(I-Q)_{1\rightarrow 1}^{A} = p^{b}d\]
\[(I-Q)_{2\rightarrow 1}^{A} = 1 + (p^{4} - p^{16})d\]
\[(I-Q)_{3\rightarrow 1}^{A} = p + (p^{5} - p^{12})d\]
\[(I-Q)_{4\rightarrow 1}^{A} = p^{2} + (p^{6} - p^{12})d\]
\[(I-Q)_{5\rightarrow 1}^{A} = p^{3}d\]

The sum of these elements is

\[AR_{LRN} = (1-p^{10})/[(1-p)(1-p^{4}+p^{16})]\]

To compute \(RN_{SNIR}, RN_{REDIR},\) and \(RN_{TIR},\) the entries of the \(R\) row of the reg-normal \((I-Q)^{-1}\) matrix are multiplied by the reg-normal matrix of transition probabilities from transient states to absorption states. Thus,

\[RN_{SNIR} = \left[p^{10}/(1-p^{4}+p^{16})\right] \sum_{k=L+1}^{10A} g(10, k)\]

\[RN_{REDIR} = \left[p^{10}/(1-p^{4}+p^{16})\right] \sum_{k=0}^{L} g(10, k)\]

\[RN_{TIR} = (1+p+p^{2}) \left[\frac{(p^{3} + p^{4} + p^{5} + p^{6} - p^{16} - p^{12})}{1-p^{4}+p^{16}}\right] \frac{(1-p)}{(1-p^{4}+p^{16})}\]

\[= (1-p^{4})/(1-p^{4}+p^{16})\]

It is easily verified that the sum of the absorption probabilities is one.
APPENDIX C
COMPUTATIONAL RESULTS

This appendix contains a brief description of the FORTRAN computer program written to evaluate operating properties. Also included is a table of schemes studied, and a description of an approximation procedure used. The program listing is also given.

Generation of Results

A flowchart of the program is shown in figure C.1. The program was developed using FORTRAN 77 on the IBM Personal Computer. For smaller cases execution times on the microcomputer are acceptable. However, for cases with 30x30 or larger matrices, a faster system is needed if multiple cases are to be analyzed. Therefore, the program was transferred to the Oregon State University CDC Cyber 720. For the largest case (super-normal matrix size of 163x163), approximately 8.5 CPU minutes were needed to perform calculations for seven quality levels on the mainframe computer.

Scope of Problem

Table C.1 is the ANSI Z1.4 table of normal inspection sample sizes and acceptance numbers (single sampling). Measures of performance were computed for all 152 cases at 7-15 different quality levels.
Figure C.1 FORTRAN Program Flowchart
Table C.1  
Normal Inspection Plans for Single Sampling Schemes  
(Adapted from ANSI/ASQC Z1.4-1981)
Appendix D contains complete tables of the results with and without limit number in a format similar to tables present in ANSI/ASQC Z1.4. In accordance with the general procedure of ANSI Z1.4, the binomial distribution was used for cases with AQL ≤ 10%, and the Poisson for cases with AQL > 10%.

The computer program was run eleven times, with each run calculating measures of performance for all schemes with a specific normal acceptance number. Acceptance numbers and the number of schemes for each one are listed below.

<table>
<thead>
<tr>
<th>Accept #</th>
<th># Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

Execution was organized by acceptance number (as opposed to sample size or AQL) because processing time is highly dependent upon acceptance number. Recall that the number of transient states in the super-normal matrix is 10A-L, where A is the normal acceptance number and L is the limit number.

Figure C.2 is a portion of an input file for the computer program. This particular file is for the A=2 cases. Note that it is conceivable that 15 quality levels will be examined. Program logic was structured so as to guarantee execution at least through the 200% AQL quality, and to terminate execution when the overall probability of acceptance dropped below 1.0% (with and without limit numbers). This insures that an
accurate approximation to the LQL values will be calculated.

A2N1  |  A2N2  |  A2N3  |  ---- Output files  
A2N4  |  A2N5  |  A2N6  |  15
  0250 |  0500  |  0750  |  1000  |  ---- Quality levels (Relative to AQL)
  0    |  0    |  0    |  0    |
  30000 |  01000 |  00500 |  P, values for LQL Calculations  
A--AQL = 40.0%  |  Description  
  2   2  |  Normal Sample Size, Acc #  
  2   2  2 |  Reduced  "  "  "  "  
  2   1  |  Tightened  "  "  "  "  
  4   4000000 |  Limit Number, AQL (Formatted)
  0    |  0    |
H--AQL = 1.5%  
  50  2  
  20  1  2  
  50  1  
  3   0150000  
  0    |
R--AQL = 0.040%  
  2000  2  
  800  1  2  
  2000  1  
  4   0004000  

Program automatically terminates when EOF is reached  

Figure C.2 Program input File--A=2 Cases  

Approximation Procedure for Single Quantity Measures  

An approximation procedure was used to find the maxima of the functions for i) AOQ, ii) percent on
normal, and iii) normal ARL. A similar approximation was used to find LQL values. Three points on the functions were saved, each corresponding to a specific quality level examined. These points (and quality levels) correspond to the maximum calculated value (for the AOQ, for example), and the two points to each side of this value. A quadratic function was then fit through these three points and the maximum found (in addition to the abscissa, the quality level). This maximum is the tabled AOQL value, for example. LQL values were also found by applying this technique, except in this case the ordinate is known (P. = 0.10, for example), and the problem is to determine the abscissa. Since quality levels considered are relatively close together (... , 75%, 100%, 125%, 150%, ... of AQL), these approximations to the true values are very good. A logical search routine (built into the program) to find exact values would have been computationally prohibitive, since many more quality levels would have to be examined.

The FORTRAN listing of the computer program written to evaluate measures of performance of ANSI/ASQC Z1.4 follows.
PROGRAM ANZ14(INPUT, TAPE5=INPUT, TAPE6, TAPE7, TAPE8, 
& TAPE9, TAPE10, TAPE11)
C*** THIS PROGRAM USES A MARKOV MODEL TO COMPUTE MEASURES OF 
C*** PERFORMANCE OF ANSI/ASQC Z1.4 WHEN USED WITH AND WITHOUT 
C*** LIMIT NUMBERS FOR REDUCED INSPECTION
C
C*** DECLARATION OF VARIABLES & COMMON BLOCK
REAL PQ, PA(3), UPA(102), RNARL(2), SNARL, 
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3), 
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18), 
& LNLQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER
INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2), 
& LQLFLAG(2), OFN(6), IFN, ARLFLAG(2), PNMFLAG(2), AOQFLAG(2), 
& KLOTS, ARN
COMMON /MIL1/ NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2), 
& LQLFLAG(2), OFN(6), IFN, ARLFLAG(2), PNMFLAG(2), AOQFLAG(2), 
& KLOTS, ARN
C
C*** VARIABLES SPECIFIC TO MAIN PROGRAM ANZ14
REAL QUALLEV(100)
INTEGER NUMLEV
CHARACTER INFILE*15, OUTFILE(6)*15, DESCRIPTOR*20
C
IFN = 5
C*** OPEN OUTPUT FILES
DO 5 11 = 1, 6
OFN(11) = 11 + 5
READ(IFN, 802) OUTFILE(11)
OPEN(OFN(11), FILE=OUTFILE(11), STATUS=NEW)
5 CONTINUE
C
C*** INITIALIZE VARIABLES
MAXA = 102
TOLER = 1.0E-05
JJCASE = 0
C
C*** READ QUALITY LEVELS
READ(IFN, 804) NUMLEV
WRITE(OFN(1), 806)
DO 10 1 = 1, NUMLEV
READ(IFN, 805) QUALLEV(I)
WRITE(OFN(1), 805) QUALLEV(I)
10 CONTINUE
C
READ(IFN, 807) LQLLEV(1), LQLLEV(2)
WRITE(OFN(1), 807) LQLLEV(1), LQLLEV(2)
LQLLEV(1) = LQLLEV(1) * 100.
LQLLEV(2) = LQLLEV(2) * 100.
C
C*** COMPUTE MEASURES OF PERFORMANCE FOR ALL QUALITY LEVELS
C
C*** INITIALIZE FLAGS & OTHER VARIABLES
100 DO 115 J = 1, 2
NLQFLAG(J) = 0
LQLFLAG(J) = 0
ARLFLAG(J) = 0
AOQFLAG(J) = 0
PNMFLAG(J) = 0
DO 105 I = 1, 18
MAXDIFF(J, I, 1) = 0.
MAXDIFF(J, I, 2) = 0.
MAXDIFF(J, I, 3) = 0.
105 CONTINUE
DO 110 I = 1, 3
DO 108 K=1,2
   A0Q(J,K,I)=0.
   LNLQL(J,K,I)=0.
   NLNLQL(J,K,I)=0.
   ARL(J,K,I)=0.
   PNRM(J,K,I)=0.
108  CONTINUE
110  CONTINUE
115  CONTINUE
   DO 117 JJ=1,MAXA
      UPA(JJ) = 0.
117  CONTINUE
C*** READ CASE DATA & VERIFY--WHEN DONE SKIP TO 200
   READ(IFN,817,END=200) DESCRP
   READ(IFN,809) NN,AN
   READ(IFN,809) NR,AR,ARN
   READ(IFN,809) NT,AT
   READ(IFN,810) LN,AQL
   DO 120 KK=1,6
      WRITE(IFN(KK),811) DESCRP
      WRITE(IFN(KK),812) 'NORMAL',NN,AN
      WRITE(IFN(KK),812) 'REDUCED',NR,AR,ARN
      WRITE(IFN(KK),812) 'TIGHTENED',NT,AT
      WRITE(IFN(KK),813) LN
      WRITE(IFN(KK),814) 100.*AQL
120  CONTINUE
IF(AN .EQ. 0) THEN
   READ(IFN,809) KLOTS
   WRITE(OFN(1),816) KLOTS
ENDIF
WRITE(OFN(1),815)
WRITE(OFN(1),818)
WRITE(OFN(2),819)
WRITE(OFN(2),820)
WRITE(OFN(3),821)
WRITE(OFN(3),822)
WRITE(OFN(4),823)
WRITE(OFN(4),824)
WRITE(OFN(5),825)
WRITE(OFN(5),826)
JJCASE = JJCASE+1
C*** LOOP TO COVER ALL QUALITY LEVELS
   DO 150 I=1,NUMLEV
      WRITE(*,*)'CASE ',JJCASE,' RUN ',I,",DESCRP"
      PQ = QUALLEV(I)*AQL
      CALL REDUCED
      CALL TIGHT
      CALL REGNORM
      IF(AN .EQ. 0) THEN
         CALL NORMAZ
      ELSE
         CALL SUPNORM
      ENDIF
      CALL NLNSUM
      IF(AN .EQ. 0) THEN
         CALL NAZSUM
      ELSE
         CALL LNSUM
      ENDIF
      CALL MIDIFF
      CALL GETTHRE
      DO 145 KKK=1,5
         CALL PNTMEAS(KKK)
      IF(MEASPER(1,6) .GT. 99.) .AND. (MEASPER(2,6) .GT. 99.) .AND. 
      (PQ*100./AQL .GE. 200.) GO TO 160
145  CONTINUE
C*** COMPUTE AND PRINT OVERALL MEASURES
   DO 150 KKK=1,5
      CALL PNTMEAS(KKK)
   IF(MEASPER(1,6) .GT. 99.) .AND. (MEASPER(2,6) .GT. 99.) .AND. 
   (PQ*100./AQL .GE. 200.) GO TO 160
150  CONTINUE
CALL PNTMXDF
GO TO 100
C*** WHEN DONE SKIP TO LABEL 200
200 CLOSE(IFN)
DO 210 KK=1,6
210 CLOSE(OFN(KK))
STOP
C
C*** FORMATS FOR MAIN PROGRAM
801 FORMAT(' INPUT FILE?')
802 FORMAT(A15)
803 FORMAT(' OUTPUT FILE?')
804 FORMAT(I3)
805 FORMAT(F6.3)
806 FORMAT(' ANSI/ASQC Z1.4 ANALYSIS'//'QUALITY LEVELS RELATIVE ',
& ' TO AQL')
807 FORMAT(2F6.3)
808 FORMAT(' LQL LEVELS',2F8.3)
809 FORMAT(16,214)
810 FORMAT(14,F12.7)
811 FORMAT(' STATEMENT OF PROBLEM ',A20/15X,' S SIZE',10X,
& ' ACC */')
812 FORMAT(A10,15,13X,13,3X,13)
813 FORMAT(' LIMIT NUMBER = ',14)
814 FORMAT(' AQL%(%) = ',F10.4)
815 FORMAT(' 1/2X,QUALITY%(%)',3X,'% AQL',6X,'PERCENT NORMAL',5X,
& ' PERCENT REDUCED',4X,'PERCENT TIGHTENED',7X,'NORMAL ARL')
816 FORMAT(' SPECIAL CASEAaad ',13,' CONSECUTIVE ACCEPTANCES FOR ',
& ' SWITCH TO REDUCED')
817 FORMAT(A20)
818 FORMAT(24X,3(' WITHOUT WITH',5X), ' WITHOUT WITH')
819 FORMAT(1/2X,'QUALITY%(%)',3X,'% AQL',12X,'A0Q (%)',18X,
& ' P(REJECT)',13X,'LOTS TILL TERMINATION',8X,
& ' TRANSITIONS N-->R')
820 FORMAT(24X,' WITHOUT WITH',8X,' WITHOUT',9X,'WITH',8X,
& ' WITHOUT WITH',11X,'WITH')
821 FORMAT(1/2X,'QUALITY%(%)',3X,'% AQL',6X,'TRANSITIONS N-->T',
& 8X,'ABSORB PROB(N-R)',14X,'ABSORB PROB(N-T)')
822 FORMAT(24X,' WITHOUT WITH',8X,' WITHOUT',9X,'WITH',
& 10X,' WITHOUT',9X,' WITH')
823 FORMAT(1/2X,'QUALITY%(%)',3X,'% AQL',10X,'ABSORB PROB(T-N)',
& 14X,'ABSORB PROB(T-D)',10X,'REduced ARL')
824 FORMAT(24X,2(' WITHOUT WITH',9X,'WITH',10X),' WITHOUT',9X,' WITH')
825 FORMAT(1/2X,'QUALITY%(%)',3X,'% AQL',10X,'TIGHTENED ARL',9X,
& ' VISITS TO NORMAL',14X,' VISITS TO REDUCED',12X,
& ' VISITS TO TIGHTENED')
826 FORMAT(24X,' WITHOUT WITH',7X,3(' WITHOUT',9X,'WITH',10X))
C
END
C
C*******************************************************************
C
SUBROUTINE REDUCED
C
Cm COMPUTES AVERAGE RUN LENGTH ON REDUCED
C
REAL PQ, PA(3), UPA(102), RNARL(2), SNARL, 
& RNAPLN(2,3), SNAP(2), AQL, AQ0(2,2,3), 
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18), 
& LNLQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER 
C
INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRNS, NLQLFLAG(2), 
& LQFLAG(2), OFN(6), IFN, ARFLAG(2), NNLFLAG(2), AQ0FLAG(2), 
& KLOTS, ARN 
C
COMMON /MIL1/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL, 
& RNAPLN, SNAP, AQL, MAXA, LN, NTRNS, 
& AQ0, LQLLEV, NLQLFLAG, LQFLAG, MEASPER, NLNLQL, LNLQL, 
& MAXDIFF, OFN, IFN, ARL, PNORM, ARFLAG, NNLFLAG, TOLER, 
& KLOTS, ARN, AQ0FLAG
WRITE(*,*)' REDUCED'

C*** COMPUTE PROBABILITY OF ACCEPTANCE, PA(2)
C*** USE POISSON DISTRIBUTION WHEN AQL > 0.10
IF (AQL.GT.0.10) THEN
   CALL POISN(NR,AR,PQ,UPA,PA(2),MAXA)
   ELSE
   CALL BINOM(NR,AR,PQ,UPA,PA(2),MAXA)
ENDIF
C*** COMPUTE AVERAGE RUN LENGTH
MEASPER(1,14) = 1./(1.-PA(2))
MEASPER(2,14) = MEASPER(1,14)

RETURN
END

C******************11***********i**********************11**************
C SUBROUTINE TIGHT
C*** CALCULATES AVERAGE RUN LENGTH ON TIGHTENED AND ABSORPTION PRODS
C
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
 & RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
 & LNLNLQL(2,2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
 & LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
INTEGER NN,NR,NT,AN,AR,AT,MAXA,LN,NTRNS,NLQFLAG(2),
 & LQLFLAG(2),OFN(6),IFN,ARLFLAG(2),PMFLAG(2),AOQFLG(2),
 & KLOTS,ARN
COMMON /MIL1/ NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
 & RNAPLN,SNAP,AQL,MAXA,NN,NTRNS,
 & AOQ,LQLLEV,LNLQL,LNLQ,MEASPER,LNLNLQL,LNLQ,
 & MAXDIFF,OFN,IFN,ARL,PNORM,ARLFLAG,PMFLAG,TOLER,
 & KLOTS,ARN,ÃOQFLG
WRITE(*,*)' TIGHT'

RETURN
END

C SUBROUTINE REGNORM
C*** CALCULATES ARL-NORM WHEN STARTING IN START AND REJECT.
C*** CALCULATES ABSORPTION PROBS FOR POSSIBLE STARTING STATES
C
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
 & RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
 & LNLNLQL(2,2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
 & LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
INTEGER NN,NR,NT,AN,AR,AT,MAXA,LN,NTRNS,NLQFLAG(2),
 & LQLFLAG(2),OFN(6),IFN,ARLFLAG(2),PMFLAG(2),AOQFLG(2),
 & KLOTS,ARN
COMMON /MIL1/ NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
 & RNAPLN,SNAP,AQL,MAXA,NN,NTRNS,
 & AOQ,LQLLEV,LNLQL,LNLQ,MEASPER,LNLNLQL,LNLQ,
 & MAXDIFF,OFN,IFN,ARL,PNORM,ARLFLAG,PMFLAG,TOLER,
 & KLOTS,ARN,ÃOQFLG
WRITE(*,*)' TIGHT'

RETURN
END
* *** VARIABLES LOCAL TO REGNORM
  REAL CD
  WRITE(*,*)' REGNORM'

* COMPUTE PROBABILITY OF ACCEPTANCE AND PROBABILITIES OF J DEFECTIVES PER SAMPLE, J=0,1,...,AN
  IF (AQL .GT. 0.10) THEN
    CALL POISN(NN,AN,PQ,UPA,PA(1),MAXA)
  ELSE
    CALL BINOM(NN,AN,PQ,UPA,PA(1),MAXA)
  ENDIF

* COMPUTE COMMON DENOMINATOR FOR CALCULATIONS
  CD = 1. - (PA(1)**4) + (PA(1)**10)

* ARL--START IN START
  RNARL(1) = (2.-(PA(1)**4)-(2.*(PA(1)**10))+(PA(1)**14))/CD

* ARL--START IN IREJECT
  RNARL(2) = (1.-(PA(1)**10))/((1.-PA(1))*CD)

* P(ABSORB REDUCED ACCEPTABLE)--NO LIMIT NUMBERS
  MEASPER(1,10) = (12.*(PA(1)**10))-(PA(1)**14))/CD

* P(ABSORB TIGHT ACCEPTABLE)--LIMIT NUMBERS
  RNAPLN(1,1) = MEASPER(1,11)

* FACTORS FOR ABSORB REDUCED & SUPNORM, START IN START, LN
  RNAPLN(1,2) = ((2.*(PA(1)**9))-(PA(1)**13))/CD

* FACTORS FOR ABSORB TIGHT & SUPNORM, START IN 1 REJECT, LN
  RNAPLN(2,1) = (1.-(PA(I)**4))/CD

* FACTORS FOR ABSORB TIGHT & SUPNORM, START IN 1 REJECT, LN
  RNAPLN(2,2) = (PA(1)**9)/CD

* RETURN

* *******************************************************

* SUBROUTINE SUPNORM

* REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
  & RNAPLN(2,3),SNAP(2,3),AQL,AQD(2,3),
  & LNQD(2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
  & NQD(2,3),ARL(2,3,3),PNORM(2,3,3),TOLER

* INTEGER NN,NR,NT,AN,AR,AT,MIXA,LTNTRNS,NLQDFLAG(2),
  & LQDFLAG(2),OFN(6),IFN,ARLFLAG(2),PNMFLAG(2),AQDFLAG(2),
  & KLOTS,ARN

* COMMON /SN1/ G(10,446),SNSTRT(165),Q(165,165),
  & QINV(165,165),R(165,2),SNAPMAT(165,2),
  & NTPROB(3),SUM1

* INTEGER MAXTRNS,MAXG

* COMMON /MIL1/ NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
  & RNAPLN,SNAP,AQL,MIXA,LTNTRNS,
  & AQL,LQLLEV,NLQDFLAG,QLDFLAG,MEASPER,NLQD,LQD,
  & MAXDIFF,OFN,IFN,ARL,PNORM,ARLFLAG,PNMFLAG,TOLER,
  & KLOTS,ARN,AQDFLAG
WRITE(*,*),' MXDIFF'

DO 100 I=1,18
  IF( I .EQ. 12 .OR. I .EQ. 13 .OR. I .EQ. 14 .OR. I .EQ. 15
  & .OR. I .EQ. 18) GO TO 100
  RAWDF = MEASPER(1,I)-MEASPER(2,1)
  PERCDF = (RAWDF/MEASPER(2,1))*100.
  IF(ABS(RAWDF) .GT. ABS(MAXDIFF(1,1,1)))THEN
    MAXDIFF(1,1,1) = RAWDF
    MAXDIFF(1,2,1) = PERCDF
    MAXDIFF(1,3,1) = PQ*100.
  ENDIF
  IF(ABS(PERCDF) .GT. ABS(MAXDIFF(2,2,I)))THEN
    MAXDIFF(2,1,I) = RAWDF
    MAXDIFF(2,2,I) = PERCDF
    MAXDIFF(2,3,I) = PQ*100.
  ENDIF
100 CONTINUE
RETURN
END
WRITE(OFN(6),802)
DO 50 I=1,18
  WRITE(*,*,*)MEASAM(I),MAXDIFF(J,1,1),MAXDIFF(J,2,1),
  MAXDIFF(J,3,1)
  WRITE(OFN(6),803)MEASAM(I),(MAXDIFF(J,K,1),K=1,3),
  MAXDIFF(J,3,1)/AQL
50 CONTINUE
100 CONTINUE
RETURN
C
801 FORMAT(1X,' MAXIMUM RAW DIFFERENCES WITHS WITHOUT,',
  * QUALITY LEVELS*/),
802 FORMAT(19X,'RAW DIFF',8X,'% DIFF',8X,'RAW QUAL(%)',6X,'REL QUAL'),
803 FORMAT(1X,A15,4(3X,G12.6)),
804 FORMAT(/' MAXIMUM PERCENT DIFFERENCES WITH VS WITHOUT,',
  * QUALITY LEVELS*/),
END

C
SUBROUTINE CLCAOQL
C
C*** CALCULATES AND PRINTS AOQL BY FITTING A QUADRATIC FUNCTION TO
C*** THE THREE LARGEST AOQ VALUES
C
C REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
  & RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
  & LNQLQ(2,2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
  & LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
INTEGER NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
  & RNAPLN,SNAP,AQL,MAXA,LNARLSNLQNLQ(2),
  & LQLFLAG,OFN(6),IFN,ARLFLAG(2),PNMFLAG(2),AOQFLAG(2),
  & KLOTS,ARN
COMMON /MIL1/ NN,NR,NT,AN,AR,AT,MAMAXA,LNTRNSNLQNLQFLG(2),
  & LQLFLAG,OFN(6),IFN,ARLFLAG(2),PNMFLAG(2),AOQFLAG(2),
  & KLOTS,ARN
C
C*** VARIABLES LOCAL TO CLCAOQL
REAL AOQL(2),AA,BB,CC,XAOQL(2),DIFAOQL(2)
WRITE(*,**,*)' CLCAOQL'
C
WRITE(OFN(6),**) 'NLNAOQ'
C
WRITE(OFN(6),0) AOQ(1,1,1),AOQ(1,1,2),AOQ(1,1,3)
C
WRITE(OFN(6),0) AOQ(2,1,1),AOQ(2,1,2),AOQ(2,1,3)
C
WRITE(OFN(6),0) AOQ(1,1,1),AOQ(1,1,2),AOQ(1,1,3),AA,CC
C
WRITE(OFN(6),0) AA,BB,CC,XAOQL(2),DIFAOQL(2)
WRITE(*,**,*)' CLCAOQL'
C
WRITE(OFN(6),**) 'NLNAOQ'
C
WRITE(OFN(6),**) 'AOQ(1,1,1),AOQ(1,1,2),AOQ(1,1,3)
C
WRITE(OFN(6),**) 'AOQ(1,1,1),AOQ(1,1,2),AOQ(1,1,3)
C
WRITE(OFN(6),**) 'AA,CC'
C
WRITE(OFN(6),**) 'XAOQL(1) = -BB/(2.**AA)
C
WRITE(OFN(6),**) 'AOQL(1) = (AA*XAOQL(1)**2)+(BB*XAOQL(1))+CC
C
WRITE(OFN(6),**) 'XAOQL(1) = XAOQL(1)*100.
100 CONTINUE
C
C*** CALCULATE DIFFERENCE (ABSOLUTE AND RELATIVE) BETWEEN AOQL'S
DIFAOQL(1) = AOQL(1) - AOQL(2)
DIFAOQL(2) = DIFAOQL(1)*100./AOQL(2)
C
WRITE(OFN(6),801)
WRITE(OFN(6),802)* AOQL('%'),AOQL(1),AOQL(2)
WRITE(OFN(6),802)* QUALITY('%'),XAOQL(1),XAOQL(2)
WRITE(OFN(6),803)* RAW DIFF',DIFAOQL(1),'% DIFF',DIFAOQL(2)
RETURN
SUBROUTINE CLCPNRM
C*** CALCULATE AND PRINTS MAXIMUM PERCENT INSPECTED ON NORMAL
C
REAL PNRM(2),AA,BB,CC,XPNRM(2),DIFPNRM(2)
WRITE(*,*)' CLCPNRM'
WRITE(OFN(6), *)'NLNPNORM'
WRITE(OFN(6),OPNORM(1,1,1),PNORM(1,1,2),PNORM(1,1,3)
WRITE(OFN(6),OPNORM(2,1,1),PNORM(2,1,2),PNORM(2,1,3)
WRITE(OFN(6), *)'LNPNORM'
WRITE(OFN(6),OPNORM(2,2,1),PNORM(2,2,2),PNORM(2,2,3)
C*** FIT A QUADRATIC TO THE 3 HIGHEST PNORM VALUES
DO 100 I=1,2
CALL QUADFIT(PNORM(1,2,1),PNORM(1,1,1),PNORM(1,2,2),PNORM(I,1,2)
& PNORM(1,2,3),PNORM(I,1,3),AA,BB,CC)
C*** CALCULATE QUALITY LEVEL AT WHICH PNRM OCCURS
XPNRM(I) = -BB /(2.*AA)
C*** CALCULATE PNRM
PNRM(I) = (AA*(XPNRM(1)**2))+(BBCONRM(1))+CC
XPNRM(I) = XPNRM(I)*100.
CONTINUE
C * ** CALCULATE DIFFERENCE (ABSOLUTE AND RELATIVE) BETWEEN PNRMS'S
DIFPNRM(1) = PNRM(1)
DIFPNRM(2) = DIFPNRM(1)*100./PNRM(2)
RETURN
C*** VARIABLES LOCAL TO CACLPNRM
REAL PNRM(2),AA,BB,CC,XPNRM(2),DIFPNRM(2)
WRITE(*,*)' CLCPNRM'
WRITE(OFN(6),*)'NLNPNORM'
WRITE(OFN(6),OPNORM(1,1,1),PNORM(1,1,2),PNORM(1,1,3)
WRITE(OFN(6),OPNORM(2,1,1),PNORM(2,1,2),PNORM(2,1,3)
WRITE(OFN(6),OPNORM(2,2,1),PNORM(2,2,2),PNORM(2,2,3)
C
SUBROUTINE CALCARL
C*** CALCULATES AND PRINTS THE LARGEST NORMAL ARL
C
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
& RNLQL(2,2,3),SNARL(2,2,3),LNLQL(2,2,3),MEASPER(2,18),MAXDIFF(2,3,18),
& LNQLLEV(2),RNARL(2),SNARL(2),LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3)
& TOLER(2,2,3)
INTEGER NN,NR,NT,AN,AR,AT,MAXA,LNLNLQL(2,2,3),LQLLEV(2)
& AOQ(2,2,3),PNMFLAG(2),ARLFLEG(2),PNMFLAG(2),
& AQL(2,2,3),PNMFLAG(2),AOQFLAG(2),
& KLOTS,ARN
COMMON /MIL1/ NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
& RNAPLN,SNAP,AQL,MASK,MAXA,LNLNLQL,NNRNLQL,MAXDIFF,OFN,IFN,ARLFLAG(2),PNMFLAG(2),
& KLOTS,ARN,AQLFLAG
C
WRITE(OFN(6),801)
WRITE(OFN(6),802)' PNRW,PNRM(1),PNRM(2)
WRITE(OFN(6),802)' QUALITY(%),XPNRM(1),XPNRM(2)
WRITE(OFN(6),803)' RAW DIFF',DIFPNRM(1),' % DIFF',DIFPNRM(2)
RETURN
801 FORMAT(1/20X,'AOQL TABLE'/18X,'WITHOUT',11X,'WITH')
802 FORMAT(A12,2(3X,G15.6))
803 FORMAT(2(1/20X,'AOQL TABLE'/18X,'WITHOUT',11X,'WITH'))
* Variables local to CALCARL

REAL MARL(2), AA, BB, CC, XARL(2), DIFMARL(2)

WRITE(*,*) 'CALCARL'

WRITE(OFN(6),*) 'NLNARL'

WRITE(OFN(6),OAARL(1,1,1),ARL(1,1,2),ARL(1,1,3))

WRITE(OFN(6),OAARL(2,1,1),ARL(2,1,2),ARL(2,1,3))

WRITE(OFN(6),OAARL(2,2,1),ARL(2,2,2),ARL(2,2,3))

C*** Fit a quadratic to the three highest ARL values
DO 100 I = 1, 2
CALL QUADFIT(ARL(1,2,1), ARL(1,1,1), ARL(1,2,2), ARL(I,1,2),
& ARL(1,2,3), ARL(1,1,3), AA, BB, CC)
C*** Calculate quality level at which MARL occurs
XARL(I) = -BB/(2.*AA)
C*** Calculate MARL
MARL(I) = (AA*(XARL(I)**2))*(BB*XARL(I)) + CC
XARL(I) = XARL(I)*100.
100 CONTINUE

C*** Calculate difference (absolute and relative) between MARL's
DIFMARL(1) = MARL(1) - MARL(2)
DIFMARL(2) = DIFMARL(1)*100./MARL(2)

WRITE(OFN(6),801)
WRITE(OFN(6),802)' MAX NORM ARL', MARL(1), MARL(2)
WRITE(OFN(6),802)' QUALITY(%)', XARL(1), XARL(2)
WRITE(OFN(6),803)' RAW DIFF', DIFMARL(1), ' % DIFF', DIFMARL(2)

RETURN

C**** Subroutine CALCLQL

C*** Calculates and prints LQL values for 2 probabilities of acceptance
C
REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG

C***************************************************************
C SUBROUTINE CALCLQL
C***************************************************************

REAL PQ, PA(3), UPA(102), RNARL(2), SNARL,
& RNAPLN(2,3), SNAP(2), AQL, AOQ(2,2,3),
& NLNLQL(2,2,3), LQLLEV(2), MEASPER(2,18), MAXDIFF(2,3,18),
& LNQL(2,2,3), ARL(2,2,3), PNORM(2,2,3), TOLER

INTEGER NN, NR, NT, AN, AR, AT, MAXA, LN, NTRANS, NLQFLAG(2),
& LQLFLAG(2), QFN(6), IFN, ARLFLAG(2), PNFLAG(2), AQFLAG(2),
& KLOTS, ARN

COMMON /MIL/ NN, NR, NT, AN, AR, AT, PQ, PA, UPA, RNARL, SNARL,
& RNAPLN, SNAP, AQL, MAXA, LN, NTRANS,
& AOQ, LQLLEV, NLQFLAG, LQLFLAG, MEASPER, NLNLQL, LNQL,
& MAXDIFF, QFN, IFN, ARL, PNORM, ARLFLAG, PNFLAG, TOLER,
& KLOTS, ARN, AQFLAG
**VARIABLES LOCAL TO CALCLQL**

REAL XLQL(2,2), DIFLQL(2,2), AA, BB, CC

**CALCULATE LQL AT 2 POINTS, LQLLEV(1) AND LQLLEV(2)**

DO 100 1 = 1, 2
   CALL QUADFIT(NNLQL(1,2,1), NLNLQL(1,1,1), NLNLQL(1,2,2),
               NLNLQL(1,1,2), NLNLQL(1,2,3), NLNLQL(1,1,3), AA, BB, CC)
   XLQL(1,1) = (-BB - SQRT((BB**2) - (4.*AA*(CC - LQLLEV(I))))/(2.*AA)
   XLQL(1,1) = 100.*XLQL(1,1)
100 CONTINUE

**DO THE SAME WITH LIMIT NUMBERS**

DO 200 1 = 1, 2
   CALL QUADFIT(LNLQL(1,2,1), LNLQL(1,1,1), LNLQL(1,2,2),
               LNLQL(1,1,2), LNLQL(1,2,3), LNLQL(1,1,3), AA, BB, CC)
   XLQL(2,1) = (-BB - SQRT((BB**2) - (4.*AA*(CC - LQLLEV(I)))))/(2.*AA)
   XLQL(2,1) = 100.*XLQL(2,1)
200 CONTINUE

**CALCULATE DIFFERENCES**

DO 300 1 = 1, 2
   DIFLQL(1,1) = XLQL(1,1) - XLQL(2,1)
   DIFLQL(1,2) = DIFLQL(1,1) * 100./XLQL(2,1)
300 CONTINUE

**PRINT RESULTS**

DO 400 1 = 1, 2
   WRITE(OFN(6), 801) LQLLEV(1)
   WRITE(OFN(6), 802) 'LQL(%)', XLQL(1,1), XLQL(2,1)
   WRITE(OFN(6), 803) 'RAW DIFF', DIFLQL(1,1), '% DIFF', DIFLQL(1,2)
400 CONTINUE

RETURN

**POISN(NNN, AA, PPQ, UUPA, PPA, MAXA)**

**COMPUTES POISSON PROBABILITIES**

REAL AA, PPQ, UUPA(MAXA), PPA
INTEGER NNN, AA, MAXA

A = REAL(NNN)*PPQ
UUPA(1) = EXP(-A)
PPA = UUPA(1)
DO 10 I = 2, AA+1
   UUPA(I) = A*UUPA(I-1)/REAL(I-1)
   PPA = PPA + UUPA(I)
10 CONTINUE
SUBROUTINE BINOM(NNN, AA, PPQ, UUPA, PPA, MAXA)
C*** COMPUTES BINOMIAL PROBABILITIES
C
REAL A, PPQ, UUPA(MAXA), PPA
INTEGER NNN, AA, MAXA
C
WRITE(*, *)' BINOM'
PPPP=1-PPQ
WRITE(*,*)'1-PQ',PPPP
C
C*** THIS SUBROUTINE INVERTS A MATRIX USING LU DECOMPOSITION
C
UUPA(1) = (1-PPQ)**NNN
A = PPQ/(1.-PPQ)
PPA = UUPA(1)
DO 10 I=2,AA+1
   UUPA(I) = MUUPA(1-1)*REAL(NNN-1+2)/REAL(I-1)
10    PPA = PPA + UUPA(I)
RETURN
END

SUBROUTINE INVERT(MAT, MATINV, MAXN, N)
C*** THIS SUBROUTINE INVERTS A MATRIX USING LU DECOMPOSITION
C
REAL MAT(MAXN,MAXN), MATINV(MAXN,MAXN), B(165), X(165)
INTEGER ORDER(165), ERR, N, MAXN
C
WRITE 01, +)' INVERT',N
C
C*** DECOMPOSE THE INPUT MATRIX
C
C*** FIND MATRIX INVERSE
C
C*** CHECK IF NEAR SINGULAR MATRIX--ISSUE WARNING IF APPLICABLE
IF (KERR .EQ. 1) WRITE(6,800)
DO 100 I=1,N
   DO 50 1=1,N
      B(J) = 0.0
      IF (J .EQ. I)B(J)=1.0
50 ,N
   MAT(1,KCOL) = MAT(1,KCOL)/MAT(1,1)
20 CONTINUE
C*** COMPLETE THE COMPUTING OF L AND U ELEMENTS. THE GENERAL PLAN
C*** IS TO COMPUTE A COLUMN OF L'S, THEN CALL APVT TO INTERCHANGE ROWS,
C*** AND THEN GET A ROW OF U'S.
NM1=N-1
DO 80 JCOL=2,NM1
   C*** FIRST COMPUTE A COLUMN OF L'S
   JM1=JCOL-1
   DO 50 IROW=JCOL,N
      SUM=0.0
      DO 40 KCOL=1,JM1
         SUM=SUM+MAT(IROW,KCOL)*MAT(KCOL,JCOL)
40    CONTINUE
      MAT(IROW,JCOL)=MAT(IROW,JCOL)-SUM
50 CONTINUE
C*** INTERCHANGE ROWS IF NECESSARY, THEN TEST FOR TOO SMALL PIVOT
CALL APVT(MAT, MAXN, N, ORDER, JCOL)
IF(ABS(MAT(JCOL,JCOL)) .LT. 1.0E-05)KERR=1
C
C*** GET A ROW OF U'S
JP1=JCOL+1
DO 70 KCOL=JP1,N
   SUM=0.0
   DO 60 IROW=1, JM1
      SUM=SUM+MAT(JCOL, IROW)*MAT(IROW, KCOL)
60    CONTINUE

CALL LUDCMP(MAT, MAXN, N, ORDER, KERR)
\[
\text{MAT}(J, K) = \frac{(\text{MAT}(J, K) - \text{SUM})}{\text{MAT}(J, J)}
\]

**CONTINUE**

**CONTINUE**

**GET LAST ELEMENT IN L MATRIX**

\[
\text{SUM} = 0.0
\]

**DO** 90 **KCOL** = 1, NM1

\[
\text{SUM} = \text{SUM} + \text{MAT}(N, KCOL) \times \text{MAT}(KCOL, N)
\]

**CONTINUE**

\[
\text{MAT}(N, N) = \text{MAT}(N, N) - \text{SUM}
\]

**RETURN**

**END**

---

**SUBROUTINE APVT(MAT, MAXN, N, ORDER, JCOL)**

**THIS SUBROUTINE FINDS THE LARGEST ELEMENT FOR PIVOT IN JCOL**

**AND MAKES NECESSARY INTERCHANGES TO PRESERVE AS MUCH ACCURACY AS POSSIBLE**

**REAL MAT(MAXN, MAXN), SAVE**

**INTEGER ORDER(MAXN), ISAVE, N, MAXN**

**WRITE(*,*)' APVT', N**

**FIND PIVOT ROW, CONSIDERING ONLY THE ELEMENTS ON AND BELOW THE DIAGONAL**

\[
\text{PVT} = \text{JCOL}
\]

\[
\text{BIG} = \text{ABS(MAT}(J, J))
\]

\[
\text{JP1} = JCOL + 1
\]

**DO** 10 **IROW** = JP1, N

\[
\text{ANEXT} = \text{ABS(MAT}(I, J)\)
\]

**IF** (ANEXT .GT. BIG) **THEN**

\[
\text{IPVT} = IROW
\]

\[
\text{BIG} = \text{ANEXT}
\]

**ENDIF**

**CONTINUE**

**INTERCHANGE ROW ELEMENTS IN THE ROW WHOSE NUMBER EQUALS JCOL WITH THE PIVOT ROW, UNLESS PIVOT ROW IS JCOL**

\[
\text{IF}(\text{IPVT} .NE. \text{JCOL}) \text{THEN}
\]

**DO** 20 **KCOL** = 1, N

\[
\text{SAVE} = \text{MAT}(J, K)
\]

\[
\text{MAT}(J, K) = \text{MAT}(\text{IPVT}, K)
\]

\[
\text{MAT}(\text{IPVT}, K) = \text{SAVE}
\]

**CONTINUE**

**SWITCH ELEMENTS IN THE ORDER VECTOR**

\[
\text{ISAVE} = \text{ORDER}(J)
\]

\[
\text{ORDER}(J) = \text{ORDER}(\text{IPVT})
\]

\[
\text{ORDER}(\text{IPVT}) = \text{ISAVE}
\]

**END**

**RETURN**

**END**

---

**SUBROUTINE SOLVLU(MAT, B, X, MAXN, N, ORDER)**

**THIS SUBROUTINE SOLVES THE SYSTEM OF EQUATION MAT(X) = B, WHERE MAT HAS ALREADY BEEN DECOMPOSED**

**REAL MAT(MAXN, MAXN), B(MAXN), X(MAXN), SUM**

**INTEGER ORDER(MAXN), N, MAXN**

**WRITE(*,*)' SOLVLU', N**

**REARRANGE THE ELEMENTS OF THE B VECTOR. X IS USED TO HOLD THEM**

**DO** 10 **I** = 1, N

\[
\text{J} = \text{ORDER}(I)
\]

\[
\text{X}(I) = B(J)
\]

**CONTINUE**

**COMPUTE B', BY FORWARD SUBSTITUTION OF LB' = B, STORING BACK IN X.**

\[
\text{X}(1) = X(1)/\text{MAT}(1, 1)
\]
DO 50 IROW=2,N
  IM1=IROW-1
  SUM=0.0
  DO 40 JCOL=1,IM1
    SUM=SUM+MAT(IROW,JCOL)*X(JCOL)
  40 CONTINUE
  X(IROW)=(X(IROW)-SUM)/MAT(IROW,IROW)
50 CONTINUE

C***GET THE SOLUTION VECTOR X. NOTE THAT X(N)=X(N) ALREADY.
DO 70 IROW=2,N
  NVBL=N-IROW+1
  SUM=0.0
  NP1=NVBL+1
  DO 60 JCOL=NVBL,NP1
    SUM=SUM+MAT(NVBL,JCOL)*X(JCOL)
  60 CONTINUE
  X(NVBL)=X(NVBL)-SUM
70 CONTINUE
RETURN
END

C*******************************************************************
C*******************************************************************
C
SUBROUTINE ACMPTE(MAT,MAXN,N)
REAL MAT(MAXN,MAXN)
INTEGER MAXN,N
WRITE(*,*)'ACMPTE',N
  DO 100 I=1,N
    DO 50 J=1,N
      MAT(I,J) = -MAT(I,J)
      IF(I .EQ. J)MAT(I,J)=1.0 + MAT(I,J)
    50 CONTINUE
100 CONTINUE

RETURN
END

C*******************************************************************
C*******************************************************************
C
SUBROUTINE MATMULT(MATA,MATB,MATC,RA,CA,RB,CB,RC,CC,RAU,CAU,CBU)
REAL MATA(RA,CA),MATB(RB,CB),MATC(RC,CC)
INTEGER RA,CA,RB,CB,RC,CC,RAU,CAU,CBU
WRITE(*,*)'MATMULT'
  DO 200 I=1,RAU
    DO 180 J=1,CBU
      MATC(I,J) = 0.0
      DO 170 K=1,CAU
        NATC(1,J) = MATC(I,J) + (MATA(1,K)*MATB(K,J))
      170 CONTINUE
180 CONTINUE
200 CONTINUE

RETURN
END

C*******************************************************************
C*******************************************************************
C
SUBROUTINE QUADFIT(X1,Y1,X2,Y2,X3,Y3,AAA,BBB,CCC)
C*** FITS A QUADRATIC FUNCTION TO THREE POINTS
C
REAL X1,Y1,X2,Y2,X3,Y3,AAA,BBB,CCC,D1,D2,D3,XXX(3,3)
WRITE(*,*)'QUADFIT'
  XXX(1,2) = X1-X2
  XXX(1,3) = X1-X3
  XXX(2,1) = -XXX(1,2)
  XXX(2,3) = X2-X3
  XXX(3,1) = -XXX(1,3)
  XXX(3,2) = -XXX(2,3)
C
D1 = XXX(1,2)*XXX(1,3)
D2 = XXX(2,1)*XXX(2,3)
D3 = XXX(3,1)*XXX(3,2)
C
AAA = (Y1/D1) + (Y2/D2) + (Y3/D3)
BBB = -(((X2+X3)*Y1)/D1)(((X1+X2)*Y3)/D3)
CCC = ((X2*X3*Y1)/D1) + ((XIIX3 *Y2) /D2) + ((XIIX2IY3) /D3)
C
WRITE(11,*)'AAA,BBB,CCC',AAA,BBB,CCC
RETURN
END
C
SUBROUTINE FNDTHRE(ARRY,FLAG,TARG1,TARG2,PPQ,MEAS1,MEAS2)
C
C*** FINDS THREE CLOSEST VALUES TO THE TARGET, TARG
C*** VARIABLES
REAL ARRY(2,2,3),TARG(2),PPQ,MEAS(2),TARG1,TARG2,MEAS1,MEAS2
INTEGER FLAG(2)
C
TARG(1)=TARG1
TARG(2)=TARG2
MEAS(1)=MEAS1
MEAS(2)=MEAS2
C
DO 100 I=1,2
IF(MEAS(I) .GE. TARG(I)) THEN
ARRY(I,1,1) = ARRY(I,1,2)
ARRY(I,2,1) = ARRY(I,2,2)
ARRY(I,1,2) = ARRY(I,1,3)
ARRY(I,2,2) = ARRY(I,2,3)
ARRY(I,1,3) = MEASI1)
ARRY(I,2,3) = PPQ
ELSE
IF(FLAG(I) .EQ. 0) THEN
ARRY(I,1,1) = ARRY(I,1,2)
ARRY(I,2,1) = ARRY(I,2,2)
ARRY(I,1,2) = ARRY(I,1,3)
ARRY(I,2,2) = ARRY(I,2,3)
ARRY(I,1,3) = MEAS(1)
ARRY(I,2,3) = PPQ
FLAG(I) = 1
ENDIF
ENDIF
100 CONTINUE
RETURN
END
C
SUBROUTINE GETTHRE
C
C*** SAVE 3 CLOSEST VALUES OF MEASURES OF PERFORMANCE TO SOME
C*** TARGET VALUE
C*** TARGET
C
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
& RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
& NLNLQL(2,2,3),LQUEV(2),MEASPER(2,18),MAXDIFF(2,3,113),
& LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
INTEGER NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
& RNAPLN,SNAP,AQL,AOQ(2,2,3),
& NLNLQL(2,2,3),LQUEV(2),MEASPER(2,18),MAXDIFF(2,3,113),
& LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
C
COMMON /MIL1/ NN,NR,NT,AN,AR,AT,MAXA,LN,NTRNS,NLQFLAG(2),
& LQLFLAG(2),OFN(6),IFN,ARLFLAG(2),PNMFLAG(2),AOQFLAG(2),
& KLTS,ARN
C
COMMON /SN2/ Q
COMMON /SN3/ QINV
    WRITE(*,*) 'SUPNORM'
MAXG = 446
MAXTRNS = 165

C*** COMPUTE CONDITIONAL PROBS, STARTING PROBABILITY VECTOR, AND
C*** SUPER-NORMAL TRANSITION PROBABILITIES
NTRNS = 10*AN-LN
CALL GCMPUTE
CALL SNSPROB
CALL SNTRANS

WRITE(*,*) 'NTRNS = ', NTRNS
CALL GCMPUTE
CALL SNSPROB
CALL SNTRANS

WRITE(*,*) 'RETURNED FROM SNTRANS'
WRITE(*,*) 'Q(1,1) = ', Q(1,1)
WRITE(*,*) 'R(1,1) = ', R(1,1)
WRITE(OFN(1),*) 'G PROBABILITIES'
CALL MATPRNT(G,10,MAXG,10,10*AN+1,OFN(1),4)
WRITE(OFN(1),*) 'STARTING PROBABILITY VECTOR'
DO 5 JJ=1,10*AN-LN
WRITE(OFN(1),*) 'SNSTRT(JJ)
CONTINUE
WRITE(OFN(1),*) 'SUPERNORMAL TRANSITION MATRIX (Q)'
CALL MATPRNT(Q,MAXTRNS,MAXTRNS,NTRNS,NTRNS,OFN(1),4)
WRITE(OFN(1),*) 'SUPERNORMAL R MATRIX'
CALL MATPRNT(R,MAXTRNS,2,NTRNS,2,OFN(1),4)
WRITE(*,*) 'COMPUTING ROW SUMS'
DO 10 II=1,NTRNS
    SUM1 = 0
    WRITE(*,*) 'COMPUTING TRANSITION MATRIX ROW SUMS'
    DO 7 JJ=1,NTRNS
        SUM1 = SUM1 + Q(1,II)
    CONTINUE
    SUM1 = SUM1 + R(1,II) + R(II,2)
    IF(ABS(SUM1-1.) .GT. TOLER) WRITE(OFN(1),*) 'ERROR@ADD ROW ', II, '=' , SUM1
10 CONTINUE

C*** TRANSITION MATRIX AND R MATRIX ARE COMPUTED. NOW, COMPUTE
C*** INVERSE OF (I-Q) SO THAT EXPECTED VALUES AND ABSORPTION
C*** PROBABILITIES CAN BE OBTAINED
WRITE(*,*) 'CALLING ACMPTE'
CALL ACMPTE(Q,MAXTRNS,NTRNS)
WRITE(*,*) '(I-Q) MATRIX'
CALL MATPRNT(Q,MAXTRNS,MAXTRNS,NTRNS,NTRNS,OFN(1),4)
WRITE(*,*) 'CALLING INVERT'
CALL INVERT(Q,QINV,MAXTRNS,NTRNS)
WRITE(OFN(1),*) 'INVERSE OF (I-Q) MATRIX'
CALL MATPRNT(QINV,MAXTRNS,MAXTRNS,NTRNS,NTRNS,OFN(1),4)
WRITE(*,*) 'CALLING MATMULT'
CALL MATMULT(QINV,R,SNAPMAT,MAXTRNS,MAXTRNS,MAXTRNS,2, & MAXTRNS,2,NTRNS,NTRNS,2)
WRITE(OFN(1),*) 'ABSORPTION PROBABILITY MATRIX--SUPERNORMAL'
CALL MATPRNT(SNAPMAT,MAXTRNS,2,NTRNS,2,OFN(1),4)

SNARL = 0
SNAP(1) = 0
SNAP(2) = 0
DO 100 II=1,NTRNS
    SNARL = SNARL + SNSTRT(II)*QINV(II,II)
    SNAP(1) = SNAP(1) + SNSTRT(II)*SNAPMAT(II,1)
    SNAP(2) = SNAP(2) + SNSTRT(II)*SNAPMAT(II,2)
100 CONTINUE
WRITE(OFN(1),*) 'SNARL = ', SNARL
WRITE(OFN(1),*) 'SNAP = ', SNAP(1),SNAP(2)
RETURN
END

C*******************************************************************
C*** SUBROUTINE PNTMEAS(FN)
C**** PRINTS A LINE OF OUTPUT CONTAINING MEASURES OF PERFORMANCE
C
C*** DECLARATION OF VARIABLES & COMMON BLOCK
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
& RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
& NLNLQL(2,2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
& LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
C
INTEGER NN,NR,NT,AN,AR,AT,MAXA,LN,NTRNS
& NLQFLAG(2),LQLFLAG(2),OFN(6),IFN,ARLFLAG(2),PNMFLAG(2),AOQFLAG(2),
& KLOTS,ARN
C
COMMON /MILS/ NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
& RNAPLN,SNAP,AQL,MAXA,LN,NTRNS,
& AOQ,LQLLEV,NLQFLAG,LQLFLAG,MEASPER,NLNLQL,LNLQL,
& MAXDIFF,OFN,IFN,ARL,PNORM,ARLFLAG,PNMFLAG,TOLER,
& KLOTS,ARN,AOQFLAG
C
C*** VARIABLES LOCAL TO PNTMEAS
REAL QL,RQL
INTEGER FN
WRITE(*,*)' PNTMEAS',FN
QL = PQ*100.
RQL = QL/AQL
IF(FN .EQ. 1)
  WRITE(OFN(FN),801)QL,RQL,((MEASPER(I,J),1=1,2),J=1,4)
IF(FN .EQ. 2)
  WRITE(OFN(FN),802)QL,RQL,((MEASPER(I,J),1=1,2),J=5,8)
IF(FN .EQ. 3)
  WRITE(OFN(FN),803)QL,RQL,((MEASPER(I,J),1=1,2),J=9,11)
IF(FN .EQ. 4)
  WRITE(OFN(FN),804)QL,RQL,((MEASPER(I,J),1=1,2),J=12,14)
IF(FN .EQ. 5)
  WRITE(OFN(FN),805)QL,RQL,((MEASPER(I,J),1=1,2),J=15,18)
C
801 FORMAT(G12.6,3X,F6.1,3X,6(F7.3,3X),2(F8.3,3X))
802 FORMAT(G12.6,3X,F6.1,3X,2(G12.6,3X),2(F8.4,3X),2(G14.8,3X),
& 2(F7.3,3X))
803 FORMAT(G12.6,3X,F6.1,3X,2(F7.3,3X),4(G12.6,3X))
804 FORMAT(G12.6,3X,F6.1,3X,6(G12.6,3X))
805 FORMAT(G12.6,3X,F6.1,3X,2(F5.3,3X),6(G12.6,3X))
C
RETURN
END
C
C******************************************************************************
C
C*** CALCULATES THE MAXIMUM ABSOLUTE AND MAXIMUM RELATIVE DIFFERENCES
C*** BETWEEN NLNL AND LN FOR THE MEASURES OF PERFORMANCE
C
REAL PQ,PA(3),UPA(102),RNARL(2),SNARL,
& RNAPLN(2,3),SNAP(2),AQL,AOQ(2,2,3),
& NLNLQL(2,2,3),LQLLEV(2),MEASPER(2,18),MAXDIFF(2,3,18),
& LNLQL(2,2,3),ARL(2,2,3),PNORM(2,2,3),TOLER
C
INTEGER NN,NR,NT,AN,AR,AT,PQ,PA,UPA,RNARL,SNARL,
& RNAPLN,SNAP,AQL,MAXA,LN,NTRNS,
& AOQ,LQLLEV,NLQFLAG,LQLFLAG,MEASPER,NLNLQL,LNLQL,
& MAXDIFF,OFN,IFN,ARL,PNORM,ARLFLAG,PNMFLAG,TOLER,
& KLOTS,ARN,AOQFLAG
C
C*** VARIABLES LOCAL TO MXDIFF
REAL RAWDF,PERCDF
& KLOTS, ARN, AOQFLAG

C*** VARIABLES LOCAL TO GETTHRE
REAL PAC
WRITE(*,*) 'GETTHRE'

CALL FNOFORM(ARL,ARLFLAG,ARL(1,1,3),ARL(2,1,3),PQ,
& MEASPER(1,4), MEASPER(2,4))
CALL FNOFORM(AOQ, AOQFLAG, AOQ(1,1,3),AOQ(2,1,3),PQ,
& MEASPER(1,5), MEASPER(2,5))
CALL FNOFORM(PNORM,PNMFLAG,PNORM(1,1,3),PNORM(2,1,3),PQ,
& MEASPER(1,1), MEASPER(2,1))
PAC = 100. - MEASPER(1,6)
CALL FNOFORM(NLNLQL,NLQFLAG,NLQLLEV(1),NLQLLEV(2),PQ,
& PAC,PAC)
PAC = 100. - MEASPER(2,6)
CALL FNOFORM(NLNLQL,NLQFLAG,NLQLLEV(1),NLQLLEV(2),PQ,
& PAC,PAC)

RETURN
END
APPENDIX D
TABULATED RESULTS OF PERFORMANCE MEASURES

This appendix contains tables of the performance measures discussed. They are formatted similarly to the present tables in ANSI/ASQC Z1.4, indexed by sample size and AQL. Values with and without limit numbers occur together, for ease of comparison.
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1 WITH LH

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| Avg Wkth   | 2.5 | 2.7 | 2.9 | 3.1 | 3.3 | 3.5 | 3.7 | 3.9 | 4.1 | 4.3 | 4.5 | 4.7 | 4.9 | 5.1 | 5.3 | 5.5 | 5.7 | 5.9 | 6.1 |

Table D.1(a) Relative Average Outgoing Quality Limit Values
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<th>G</th>
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Table D.2(b) Relative Limiting Quality Level Values
## Table D.2(c) Relative Limiting Quality Level Values

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### Notes
- The table provides relative limiting quality level values for various codes.
- Each code is assigned a set of quality levels corresponding to different performance criteria.
### Table D.2(d) Relative Limiting Quality Level Values

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#### Note
- **Accept No:** Acceptable quality level number
- **Average:** Average value
- **Range:** Range value
- **Std Dev:** Standard deviation
- **Z-score:** Z-score value
- **Minima:** Minimum value
- **Maxima:** Maximum value
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Table D.3(a) Maximum Percent Inspected on Normal
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Legend: **X** Without AUE; **+** With AUE

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Table D.3(b) Maximum Percent Inspected on Normal
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Table D.4(b) Maximum Normal Average Run Length

Code: [A] 0.015 0.025 0.04 0.06 0.1 0.15 0.2 0.25 0.3 0.4 0.5 0.6 0.8 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0

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Table D.5(a) Normal Average Run Length
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**Legend:**

- **Without AQL:**
- **With AQL**

**Table D.5(b) Normal Average Run Length**
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|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| A    | 11.4 | 12.2 | 12.6 | 12.7 | 11.9 | 11.7 | 12.2 | 12.7 | 12.6 | 12.1 | 15.4 | 11.3 | 31.4 | 40.9 | 100.0 | 150.0 | 183.9 | 30.1 | 30.8 | 23.8 |
| B    | 11.9 | 12.6 | 12.5 | 12.5 | 11.9 | 11.7 | 11.4 | 12.3 | 12.2 | 12.5 | 17.9 | 27.2 | 52.0 | 84.9 | 127.2 | 156.1 | 209.5 | 357.5 | 114.3 | 25.4 |
| C    | 11.9 | 12.4 | 12.6 | 12.6 | 11.9 | 12.3 | 12.2 | 12.3 | 12.6 | 12.1 | 16.0 | 22.0 | 52.0 | 51.1 | 50.0 | 67.4 | 103.9 | 255.5 | 64.2 | 23.0 | 9.0 |
| G    | 12.0 | 12.1 | 12.5 | 11.9 | 12.2 | 12.5 | 12.7 | 12.2 | 12.1 | 9.1 | 17.0 | 50.5 | 54.9 | 103.0 | 201.1 | 73.6 | 52.1 | 114.3 | 23.0 | 10.0 |
| E    | 11.7 | 12.1 | 12.7 | 12.8 | 12.3 | 12.5 | 12.6 | 12.5 | 8.1 | 16.4 | 19.3 | 41.6 | 62.7 | 127.2 | 187.4 | 73.0 | 30.6 | 30.9 | 33.4 | 9.0 |
| F    | 11.7 | 12.3 | 12.6 | 12.6 | 11.6 | 11.7 | 12.2 | 12.7 | 12.6 | 18.5 | 19.4 | 42.4 | 48.6 | 109.6 | 155.1 | 503.9 | 52.1 | 30.8 |
| G    | 11.9 | 12.4 | 12.6 | 12.6 | 11.9 | 11.9 | 12.7 | 12.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 |
| H    | 11.9 | 12.2 | 12.5 | 12.5 | 11.7 | 12.1 | 12.3 | 12.3 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 |
| J    | 12.0 | 12.0 | 12.6 | 12.4 | 11.8 | 12.3 | 12.5 | 12.5 | 12.2 | 17.5 | 18.6 | 39.3 | 57.4 | 112.6 | 191.9 | 52.0 | 70.9 | 114.3 |
| K    | 11.9 | 12.2 | 12.7 | 12.6 | 11.5 | 11.9 | 12.1 | 12.7 | 12.4 | 17.0 | 19.3 | 40.2 | 52.5 | 103.4 | 121.7 | 222.2 | 53.0 | 93.0 |
| L    | 11.7 | 12.2 | 12.6 | 12.6 | 11.9 | 11.7 | 12.2 | 12.6 | 12.7 | 25.1 | 40.7 | 46.7 | 127.8 | 159.5 | 144.0 | 52.1 | 47.1 |
| M    | 11.8 | 12.4 | 12.6 | 12.6 | 12.0 | 12.0 | 11.7 | 12.6 | 12.6 | 15.9 | 25.3 | 39.2 | 53.7 | 112.6 | 161.6 | 300.0 | 66.1 | 64.9 |
| N    | 11.9 | 12.2 | 12.5 | 12.5 | 11.0 | 12.8 | 12.3 | 12.2 | 12.6 | 17.0 | 19.3 | 53.0 | 61.5 | 106.9 | 180.0 | 33.7 | 103.6 | 43.3 | 33.7 |
| P    | 12.0 | 12.6 | 12.5 | 11.9 | 12.6 | 12.5 | 12.6 | 12.7 | 12.2 | 17.5 | 18.5 | 30.4 | 50.2 | 100.0 | 150.0 | 274.7 | 54.5 | 53.5 | 121.1 |
| Q    | 11.9 | 12.2 | 12.7 | 12.6 | 11.5 | 12.0 | 12.2 | 12.7 | 12.6 | 17.0 | 19.3 | 39.7 | 51.2 | 104.9 | 110.8 | 105.6 | 61.2 | 66.1 |
| R    | 12.2 | 12.6 | 12.7 | 11.9 | 11.7 | 12.2 | 12.7 | 12.6 | 19.3 | 36.4 | 41.0 | 102.4 | 157.2 | 244.9 | 52.6 | 62.9 | 91.4 |

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Avg. 2.0

| Accept No 0 1 2 3 5 7 10 14 21 30 44
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| Letter | 0.01% | 0.05% | 0.1% | 0.2% | 0.3% | 0.4% | 0.5% | 1% | 2% | 4% | 6% | 10% | 15% | 20% | 25% | 40% | 50% | 100 |
|--------|-------|-------|------|------|------|------|------|----|----|----|----|-----|-----|-----|-----|-----|-----|
| A      | 54.4  | 63.3  | 67.2 | 54.7 | 28.0 | 21.1 | 23.9 | 29.0 | 24.4 | 23.5 | 34.4 | 27.9 | 23.1 | 26.3 | 13.9 | 25.4 | 16.4 | 15.7 |
| B      | 51.8  | 29.0  | 62.5 | 59.6 | 20.1 | 21.2 | 23.9 | 24.5 | 25.6 | 15.7 | 22.4 | 23.0 | 26.4 | 24.3 | 16.7 | 14.6 | 15.6 | 17.7 |
| C      | 42.4  | 23.5  | 29.5 | 26.0 | 28.7 | 25.1 | 19.1 | 14.4 | 12.9 | 10.6 | 22.4 | 21.1 | 21.3 | 23.9 | 29.1 | 24.3 | 23.3 |
| D      | 41.5  | 76.9  | 41.1 | 77.8 | 50.0 | 49.2 | 25.5 | 21.0 | 12.5 | 11.4 | 20.8 | 32.8 | 21.8 | 29.5 | 27.3 | 23.5 | 18.4 | 14.7 |
| E      | 41.4  | 75.0  | 49.8 | 60.7 | 56.2 | 53.6 | 29.0 | 30.1 | 23.8 | 19.5 | 17.0 | 21.4 | 33.4 | 21.3 | 25.3 | 27.0 | 17.4 | 16.5 | 16.2 | 15.6 | 12.6 |
| F      | 42.0  | 52.0  | 50.3 | 64.1 | 64.2 | 55.6 | 20.1 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 23.9 | 2.2  | 29.2 | 23.9 |
| G      | 42.6  | 52.0  | 47.5 | 58.9 | 58.9 | 58.9 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 | 81.5 |
| H      | 42.6  | 52.9  | 53.1 | 53.1 | 53.1 | 53.1 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 | 37.8 |
| J      | 43.0  | 74.7  | 52.1 | 62.9 | 62.9 | 50.0 | 30.4 | 29.7 | 18.8 | 23.6 | 23.6 | 23.6 | 23.6 | 23.6 | 23.6 | 23.6 | 23.6 |
| K      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| L      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| M      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| N      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| P      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| Q      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |
| R      | 42.6  | 77.5  | 52.9 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 | 63.4 |

Table D.6(b) Transitions per 1000 Lots Between Normal and Reduced
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Table D.6(c) Transitions per 1000 Lots Between Normal and Reduced
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Legend:
- At least one lot
- At least two lots
- At least three lots
- At least four lots
- At least five lots

Table D.6(d) Transitions per 1000 Lots Between Normal and Reduced
| Code | Code | Letter | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| A    | 27.0 | 7.8 | 0.8 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| B    | 19.2 | 9.3 | 1.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| C    | 16.1 | 9.4 | 0.5 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| D    | 13.9 | 11.6 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| E    | 17.0 | 12.3 | 0.7 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| F    | 17.3 | 13.0 | 0.6 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| G    | 15.7 | 11.5 | 0.5 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| H    | 21.1 | 13.2 | 0.8 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| J    | 15.7 | 11.6 | 0.9 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| L    | 27.3 | 11.7 | 0.8 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| M    | 25.1 | 13.5 | 1.3 | 1.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| N    | 15.7 | 11.7 | 0.5 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| P    | 14.1 | 13.3 | 0.6 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Q    | 15.7 | 11.7 | 0.5 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| R    | 13.7 | 11.7 | 0.8 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Legend: With LN | Without LN

Table D.7(a) Transitions per 1000 Lots Between Normal and Tightened
Table D.7(b) Transitions per 1000 Lots Between Normal and Tightened
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Table D.7(c) Transitions per 1000 Lots Between Normal and Tightened
Table D.7(d)  Transitions per 1000 Lots Between Normal and Tightened

| Legend | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
|        |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| Acceptable Quality Level | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|                   | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 |
|                   | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 |
|                   | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 |
|                   | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 | 69.6 | 51.8 | 31.4 | 77.6 | 51.8 | 31.4 |
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*Note: The table continues with similar data entries.*
### Table D.8(a) Transitions per 1000 Lots Between all Plans

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Legend:
- **No threat**
- **High threat**
- **Extreme threat**
Table D.8(b) Transitions per 1000 Lots Between all Plans
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**Table D.8(c) Transitions per 1000 Lots Between all Plans**
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|------|--------|-------|-------|------|------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| A    | 103.1  | 95.5  | 96.4  | 96.9 | 93.0 | 91.2 | 112.3 | 121.9 | 137.5 | 54.2 |
| B    | 102.1  | 111.0 | 103.1 | 95.7 | 90.1 | 84.2 | 96.5  | 101.9 | 100.8 | 139.8 |
| C    | 94.9   | 70.9  | 67.4  | 80.6 | 29.1 | 34.5 | 31.7  | 74.5  | 87.5  | 130.5 |
| D    | 93.2   | 54.3  | 38.3  | 52.7 | 61.7 | 74.5  | 85.1  | 137.5 | 129.6 |
| E    | 95.6   | 113.0 | 85.1  | 102.0 | 95.2 | 93.0  | 117.5 | 130.4 | 131.8 | 155.6 |
| F    | 92.9   | 60.5  | 52.1  | 52.7 | 73.9  | 130.9 | 139.6 |
| G    | 95.6   | 109.4 | 86.3  | 103.9 | 95.7 | 93.9  | 109.2 | 117.6 | 156.6 |
| H    | 93.9   | 109.5 | 81.4  | 103.1 | 93.5 | 95.3  | 80.9  | 94.3  | 112.0 |
| J    | 91.9   | 89.4  | 65.4  | 102.3 | 94.0 | 96.1  | 91.7  | 102.2 | 122.0 |
| K    | 93.8   | 109.5 | 87.7  | 103.2 | 90.7 | 94.0  | 86.3  | 100.4 | 103.7 |
| L    | 96.0   | 109.7 | 86.7  | 104.2 | 94.4 | 91.5  | 87.5  | 106.1 | 139.7 |
| M    | 94.2   | 109.8 | 85.3  | 103.2 | 95.1 | 94.5  | 77.4  | 103.0 | 112.6 |
| N    | 95.8   | 107.5 | 82.3  | 103.3 | 94.5 | 97.1  | 86.5  | 111.3 | 114.5 |
| P    | 91.6   | 100.3 | 65.2  | 101.9 | 93.6 | 95.3  | 94.2  | 106.7 | 101.7 |
| Q    | 82.1   | 88.1  | 65.6  | 48.6  | 31.1 | 48.5  | 32.4  | 82.8  | 122.0 |
| R    | 93.7   | 109.3 | 80.0  | 103.3 | 91.2 | 94.8  | 89.9  | 108.5 | 111.9 |
| S    | 94.2   | 86.1  | 92.4  | 23.0  | 32.2 | 61.4  | 81.7  | 102.3 |
| T    | 103.7 | 96.9  | 84.2  | 94.6  | 92.0 | 89.0  | 107.5 | 123.7 |
| U    | 85.3  | 95.6  | 61.6  | 33.2  | 34.3 | 61.5  | 96.9  | 116.2 |

Legend:  
- Without LN:  
- With LN:  

**Table D.8(d)** Transitions per 1000 Lots Between all Plans
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Legend:  
- **A** with **L**  
- **M** with **L**

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- Reg & Tbl # 10.4 17.7 26.1 19.9 13.6 9.9 6.0 3.0 1.0 0.0 0.0 0.0 0.0 0.0
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- Reg & Tbl # 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3 3.3

Table D.9(b) Percent Inspected on Normal
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Legend:
- **Without LN**:
- **With LN**:

### Table D.9(c) Percent Inspected on Normal

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Legend: [AQL] [Acceptable Quality Level]

Table D.10(a) Percent Inspected on Tightened
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**Legend:**
- **AQL:** Acceptable Quality Level
- **Without LN:**
- **With LN:**

Table D.10(b) Percent Inspected on Tightened
| Code | Letter | .005 | .025 | .04 | .06 | .10 | .15 | .25 | .40 | .65 | 1.0 | 1.5 | 2.5 | 4.0 | 6.0 | 7.5 | 10 | 15 | 25 | 50 | 100 | 200 | 500 | 1000 |
|------|--------|------|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| R    | A      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|      | B      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|      | C      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|      | D      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|      | E      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|      | F      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | G      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | H      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | J      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | K      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | L      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | M      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | N      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | O      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | P      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | Q      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
|    | R      | 0.0  | 0.0  | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |

Legend:  
1: Good  
2: Fair

Table D.10(c) Percent Inspected on Tightened
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Legend: L = Lotter LN  = 16th LN  = 26.3

Table D.10(d) Percent Inspected on Tightened
### Table D.11(a) Percent Inspected on Reduced

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Legend: Uathout 116

Table D.11(a) Percent Inspected on Reduced
Table D.11(b) Percent Inspected on Reduced
| Table D.11(c) Percent Inspected on Reduced |

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Legend: 14th Lab US | 16th Lab US
PERCENT ON REDUCED -- 150% OF AQL

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Legend: 
- 1% Looked On
- 1% Looked On

Table D.11(d) Percent Inspected on Reduced
Table D.12(a)  
Lots Inspected Until Discontinuation
| A    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| B    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| C    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| D    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| E    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| F    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| G    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| H    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| I    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| J    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| K    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| L    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| M    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| N    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| O    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| P    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Q    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| R    | 0.05    | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

**Legend**
- **Acceptable Lot:** The lot is acceptable if the inspection results are within the acceptable quality levels.
- **Reject Lot:** The lot is rejected if the inspection results exceed the acceptable quality levels.

Table D.12(b) Lots Inspected Until Discontinuation
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**Legend:**
- **A:** All lots inspected
- **B:** All lots inspected

Table D.12(c) Lots Inspected Until Discontinuation
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Table D.12(d) Lots Inspected Until Discontinuation
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Legend: | L | LH | U |
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Table D.13(a) Overall Percentage of Lots Rejected
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Table D.13(b) Overall Percentage of Lots Rejected
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*Legend: 14th Week: L1, 14th Week: L2*
### Percent Rejected — 15% of AQL

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Legend:
- **11th Lot**: Overall Percentage of Lots Rejected

Table D.13(d) Overall Percentage of Lots Rejected