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16. ABSTRACT

I will discuss an approach to statistical controls being studied by the California Division of Highways. This is different from other approaches being proposed at this time.

While those of us doing research in this general area are trying various methods of applying the research findings, we do have a general area of agreement. Regardless of where the research in this field is being conducted, whether it has been by Miller-Warden Associates, the Bureau of Public Roads, or a State highway agency, the researchers have found that test results fall into some predictable pattern, usually a normal distribution as represented by a familiar bell-shaped curve. When only a few test results are plotted, the overall distribution often is not obvious but as more data is added, the characteristic distribution becomes apparent. This can be seen in Figure 1 where the histogram represents some 4600 penetration test results on paving grade asphalts. Even when the curve is skewed to one side the theory still can be applied without great difficulty.

All researchers working in this area also have observed considerable dispersion or spread in the test results. As can be seen in Figure 1 the curve tapers out slowly and a certain portion of the material falls outside the specification limits.

These studies have led to the conclusion that materials fall into a predictable pattern and that with present specifications we cannot expect 100 percent of the material to be within the limits even on well controlled projects. Figure 2 presents random test results for concrete aggregate passing the 3/4 inch sieve for one construction project. The represents an extreme case of noncompliance with specifications; however, we find the same general trend for almost every item studied.

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STATE OF CALIFORNIA
TRANSPORTATION AGENCY
DIVISION OF HIGHWAYS

Applications of Statistical Specifications For Highway Construction

Presented By

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Presented at the 1968 California Transportation and Public Works Conference, University of the Pacific - January 31 - February 3, 1968

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As a result of the variation in test results combined with rather restrictive specification limits, we find that we have a lot of red checks on our construction records even on our best projects. Statistical specifications may be one method of reducing these red checks. What we need to do is design our specifications to reflect good construction and provide our engineers with better methods of enforcement.

What must we do in order to implement statistical specifications? One thing we must do is to learn to think in terms of wider variations in test results. While I agree with other researchers that field engineers do not have to become statisticians, and in fact need to know very little on the subject, they still need to learn to think in terms of broad variations in test results.

Figures 3 and 4 illustrate this problem. Figure 3 is the histogram of test results of a random survey of a compacted embankment. We note that approximately 8 percent of the test results fall below the specification limit. While engineers do not find this particularly surprising many are concerned with Figure 4 where approximately 23 percent of the tests fall below the specification limit. These histograms are from randomly selected tests from embankment that were accepted by the Resident Engineer using normal construction control procedures.

Why the big difference between the two projects? The first project was constructed of very uniform, easily compacted material where a minimum of construction problems were encountered. The second project was constructed of extremely heterogeneous material varying from hard dry rock to soft wet clays and is typical of the soil which must be used in some areas of California. I should note that even though many construction difficulties were encountered, a higher average was achieved on the project shown in Figure 4. Once again I note that both of these jobs represent good acceptable construction.

04-80

On both of these projects the Resident Engineer's records differ somewhat from the random survey and it is in this area that we need to change our thinking. On the first project, where few construction difficulties were encountered, the random survey data and the Resident Engineer's acceptance data differed very little (see Figure 5). The curve noted as "final" is a plot of the Resident Engineer's test results used for accepting various areas of the embankment. When we look at the Engineer's records for the other project (Figure 6), where the material was extremely heterogeneous, we note that the curves differ sharply. If an engineer were presented with these two curves (Figure 6) without adequate explanation, he could conclude that something was wrong. One explanation for the marked difference in these curves is resampling. We should note that the final curve represents only the final accepted test and in many cases there were preceding tests which did not meet the specifications. Of course when a test result does not meet specifications, the contractor is asked to rework the area before a retest is made.

First, let us look at the theoretical effect of resampling as shown in Figure 7. The bell-shaped curve on the left represents an area of compacted embankment which the contractor has asked the Resident Engineer to accept. Let us assume that this area has been compacted to a point where 60 percent of all possible test results from this area would fail, and 40 percent would pass. We can see that on the first test there is a 40 percent probability of acceptance. But let us assume that the first test was from the 60 percent area and did not meet the specifications. It is further assumed that a resample was taken without rerolling so the 60-40 ratio still holds as shown by the second bell-shaped curve. We now find that the probability of acceptance has been increased by 24 percent for a total of 64 percent. The reason that resampling always works in favor of acceptance is because we only retest those areas which fail and do not retest those areas which met the specifications the first time. It is obvious that additional resampling would only increase the probability of acceptance.

But our Resident Engineers will tell you this does not represent their methods of control. They always reroll an area that does not meet specifications before they take another test. Figure 8 illustrates that the problem of resampling is still applicable. Again the bell-shaped curve on the left represents an area to be tested, compacted to the point where 40 percent of all test results would pass. In this case, let us assume that the contractor has rerolled the area before a second test is taken and that the compaction is improved until half of all possible test results from the area would pass. Instead of the 60-40 ratio we now have a 50-50 ratio but the theory remains the same. We have a total probability of acceptance of 70 percent.

It is obvious that if the rerolling and resampling process was carried through additional cycles that the probability of acceptance would continue to increase. It is therefore not surprising that the engineer's final acceptance factor differs sharply from a random survey of the accepted embankment.

How are we going to apply this information and come up with a realistic, enforceable specification that reflects good construction? First, we can carefully define the lot of material to be accepted or rejected; secondly, we can take five or six random samples from each lot and base our decision on the test results. But wait! Engineers want to know why they need to go to all this extra effort for control if they are doing a reasonably good job now. They know that in the final analysis, statistical control procedures must be judged on a cost-benefit ratio, so why greatly increase construction control costs when present methods appear reasonable? This is a good question and there are some of us who are working on this problem who believe that the answer lies in applying statistical specifications one step at a time and taking advantage of the more practical aspects to start with.

Our first attempt is to prepare specifications using a moving average as illustrated in Figure 9. The upper chart represents the plot of individual test results. The upper limit for the individual test is shown at 5. The lower chart is the moving average. Thus, the decision to accept or reject the material represented by Test No. 16 would not be based solely upon one single test result but on all the test results which are included in the shaded area in the upper plot. As the work progresses, the latest test result is added to the average and the oldest one is dropped off, thus the term "moving average". The primary reason for utilizing a moving average is to reduce the number of samples required. It also has the advantage of allowing the engineer to take an overall look at his project, thus allowing continuity in the control process. The area below 4 on the lower chart represents full control; the area between 4 and 4.75 is a caution area where the engineer may wish to increase sampling frequency; above 4.75 represents the area where materials are rejected. The moving average also allows us to give our field engineers a new degree of flexibility.

The following quote is from a proposed specification:

> "Generally, specifications will require both individual test results and moving average results to be within the specification limits. At the discretion of the engineer, an individual test result outside the specification limit may be waived providing the moving average is within limits. However, such a test result must be included in calculating the moving average. If the moving average exceeds the specification limit, the material does not meet the specifications."

When the Resident Engineer encounters a single test result which is out of specification, this clause allows him to use his judgment to accept or reject the material. Both field experience and research indicates that we can expect a percentage of test results to fall outside the specification limits even on well controlled projects. This degree of flexibility recognizes this fact and allows the engineer to act accordingly. If he has been encountering construction difficulties, or if the contractor has changed his materials source, he may conclude that it is best to reject the material, even though the moving average is within limits.

We have also developed control charts which indicate trends and can be understood by all concerned. Figure 10 is a photograph of a large wall chart proposed for use in construction control. While all the details cannot be seen in this reproduction it is possible to observe long-term trends in the moving averages. Figure 10 shows such details as the sieve size, fraction of material, overall specifications, and the job control formula for coarse aggregates. These control charts should indicate process control, and assist the engineer in making such decisions as sampling frequency and acceptance or rejection of materials.

Where do we stand today? The California Division of Highways currently has two projects under contract where this type of specification is being used for control of concrete aggregate. In addition, the control charts are being used on two other projects and soon will be used on a third to evaluate aggregate base, subbase, and cement treated base.

It is obvious that this approach to statistical control does not follow traditional statistical theory. We are not specifying frequency of sampling; we are not specifying random sampling; and we are not carefully defining the lot of material. We have not solved the resampling problem; however, we find that the use of control charts tends to reduce the resampling.

We do not take issue with the traditional statistical theory or with those who would use a different approach. I think that we need to proceed one step at a time and apply the more practical aspect as a starting point. We will need to collect more data and gain more experience to fully evaluate this approach.

In the long run perhaps more work will be done by the contractors and the materials producers. In this study we have worked closely with two aggregate producers and one producer is using the control chart that we have developed for this study.

Regardless of what direction this work takes, we will still be working toward the long-term goal of developing more enforceable specifications which reflect good construction.

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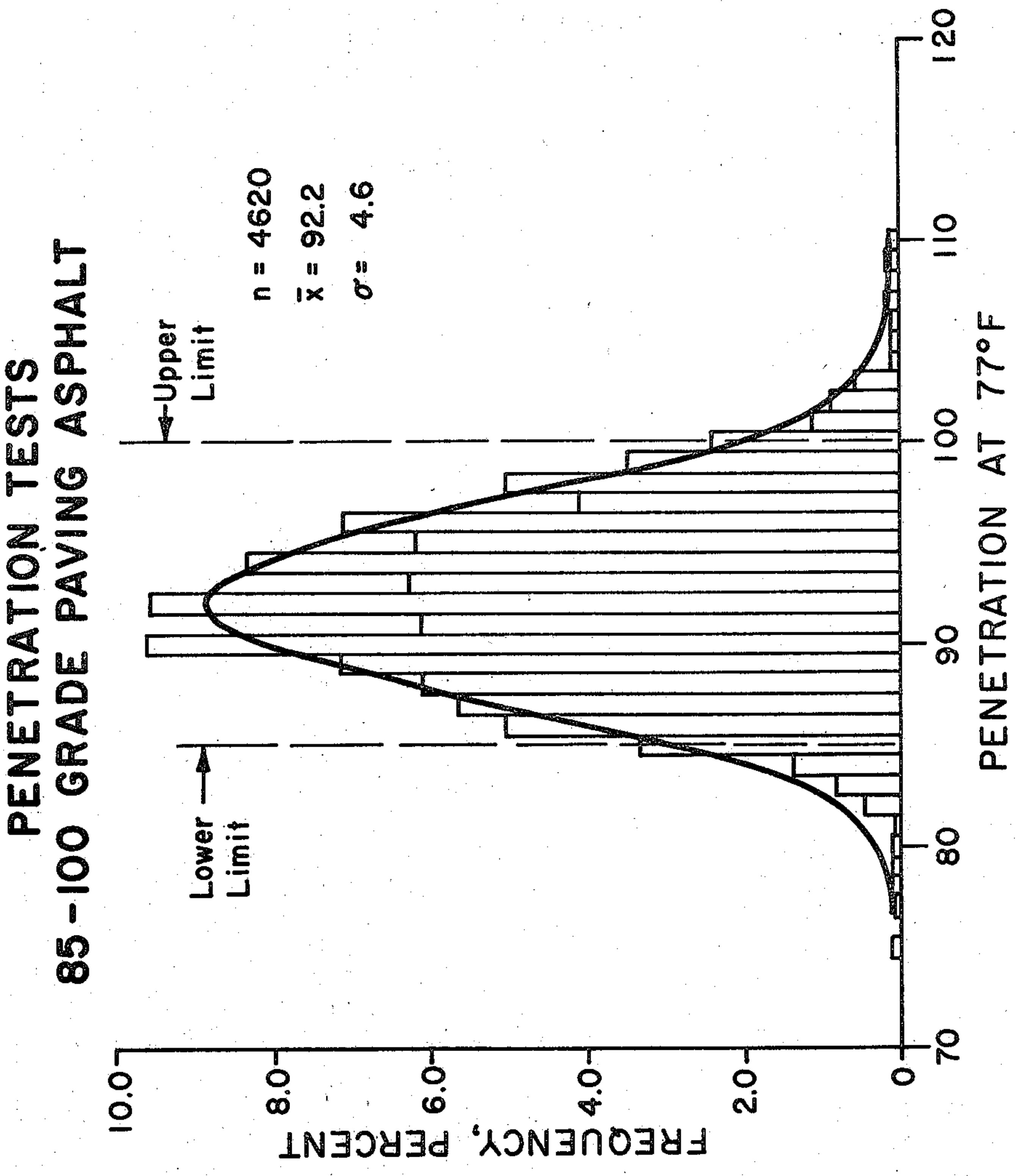
Figure I



PENETRATION TESTS
85-100 GRADE PAVING ASPHALT
n = 4620
x̄ = 92.2
σ = 4.6
Upper Limit
Lower Limit
FREQUENCY, PERCENT
10.0
8.0
6.0
4.0
2.0
0
70
80
90
100
110
120
PENETRATION AT 77°F

Figure 2

CONCRETE AGGREGATE GRADATION

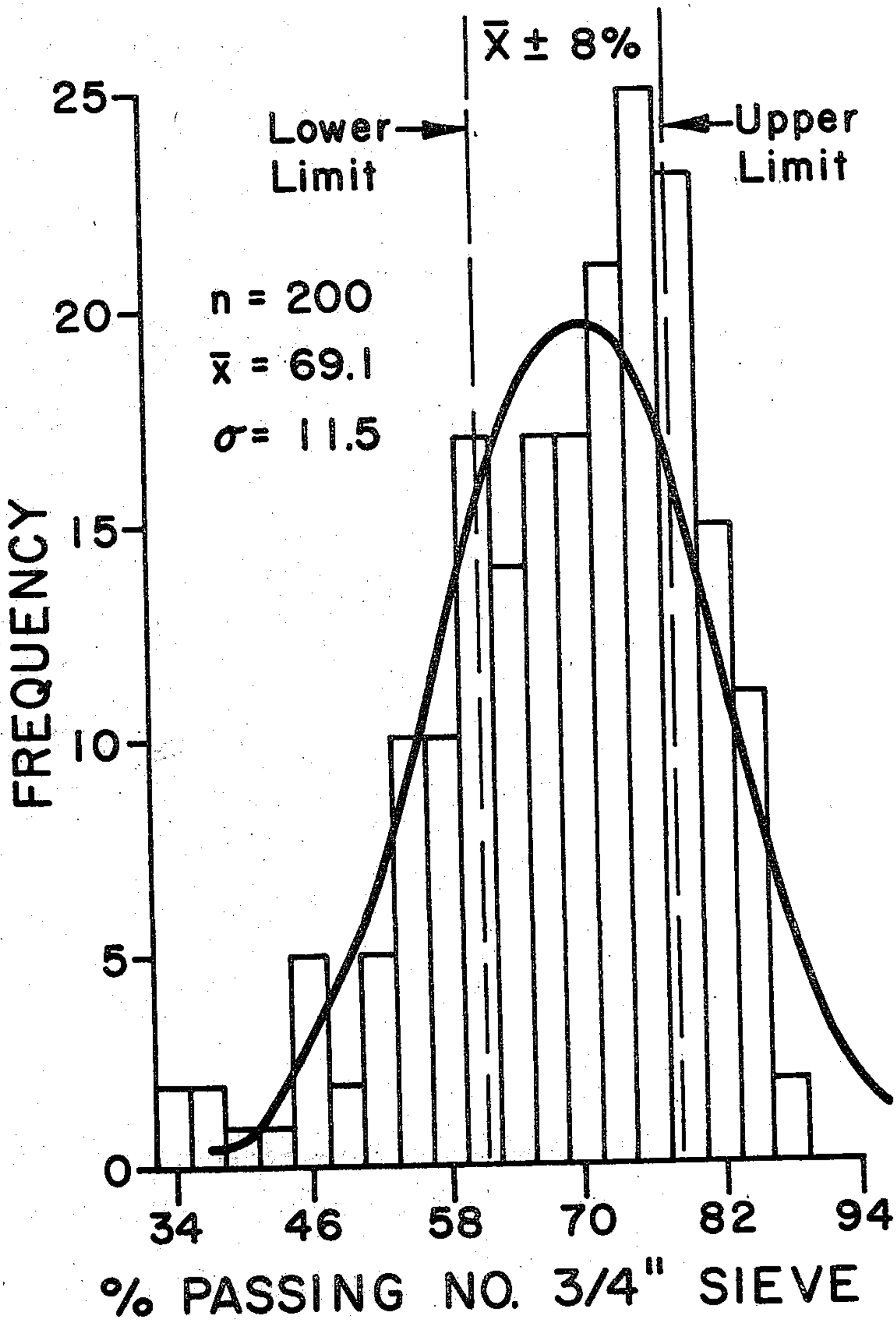
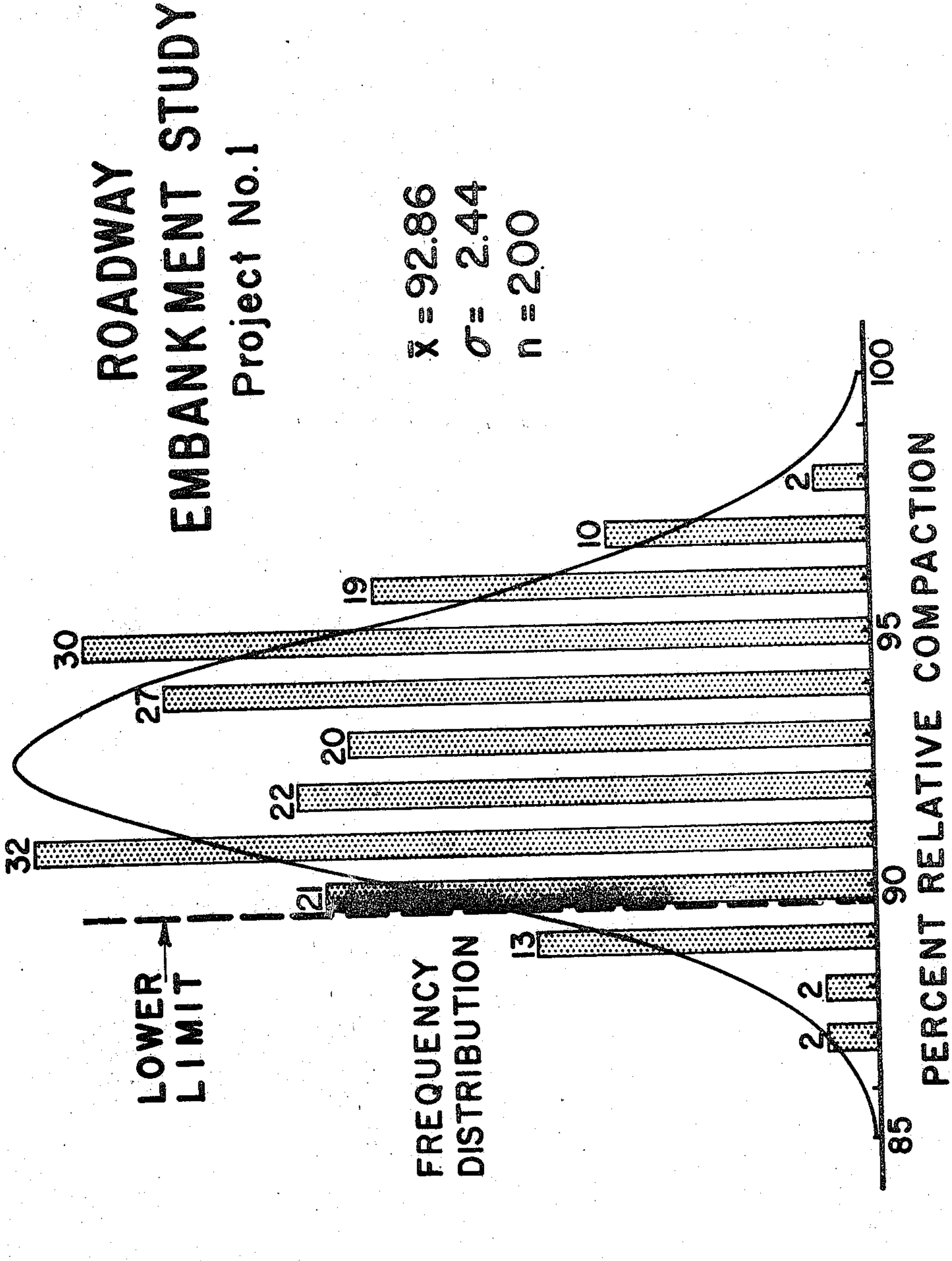


Figure 3


ROADWAY
EMBANKMENT STUDY
Project No. 1
x̄ = 92.86
σ = 2.44
n = 200
LOWER LIMIT
FREQUENCY DISTRIBUTION
2
2
13
21
32
22
20
27
30
19
10
2
85
90
95
100
PERCENT RELATIVE COMPACTION

ROADWAY EMBANKMENT STUDY

Project No. 3

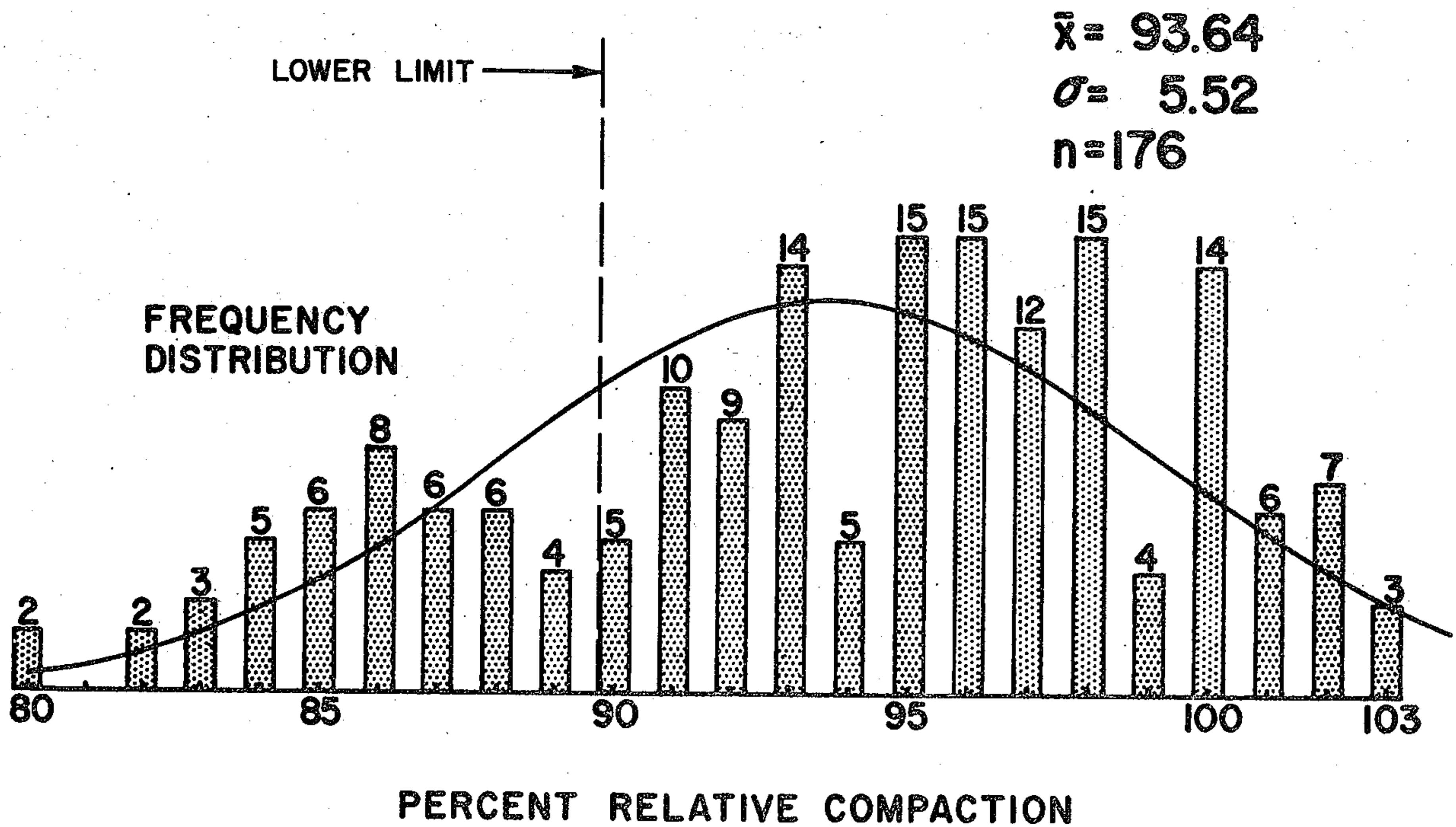


Figure 4

Figure 5

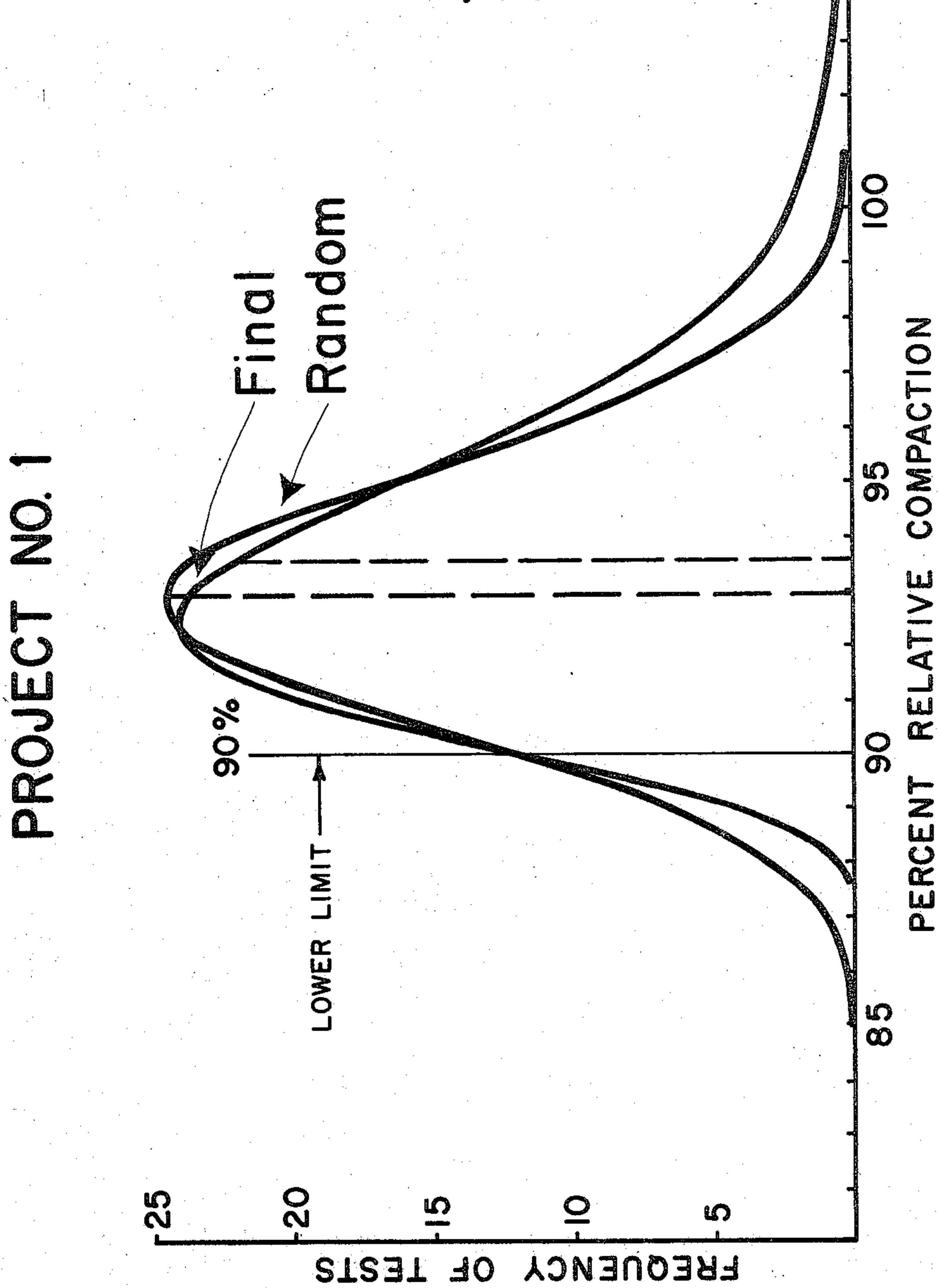

PROJECT NO. 1
Final
Random
90%
LOWER LIMIT
25
20
15
10
5
85
90
95
100
PERCENT RELATIVE COMPACTION
FREQUENCY OF TESTS

Figure 6

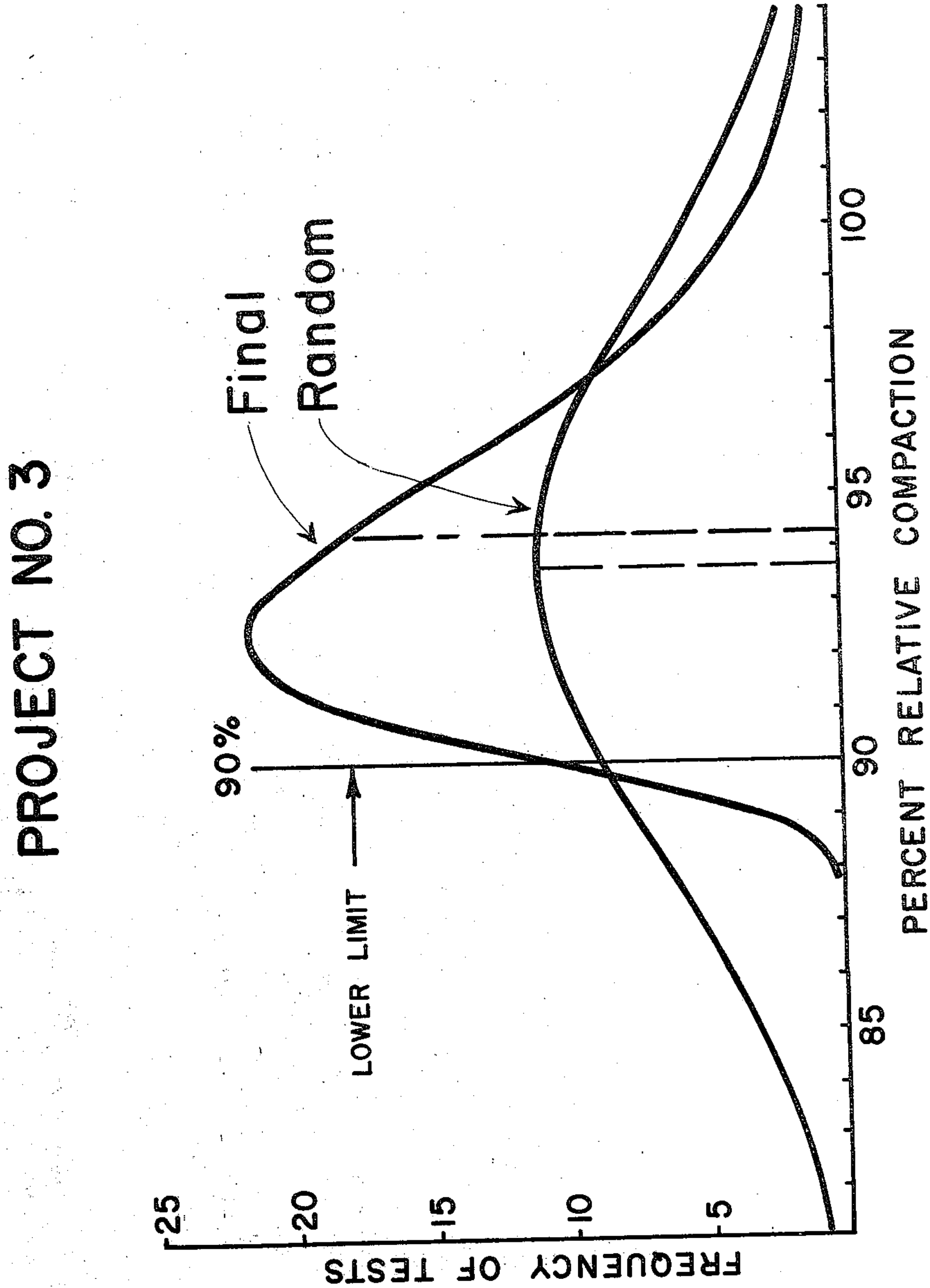

PROJECT NO. 3
Final
Random
90%
LOWER LIMIT
PERCENT RELATIVE COMPACTION
85
90
95
100
FREQUENCY OF TESTS
5
10
15
20
25

Figure 7

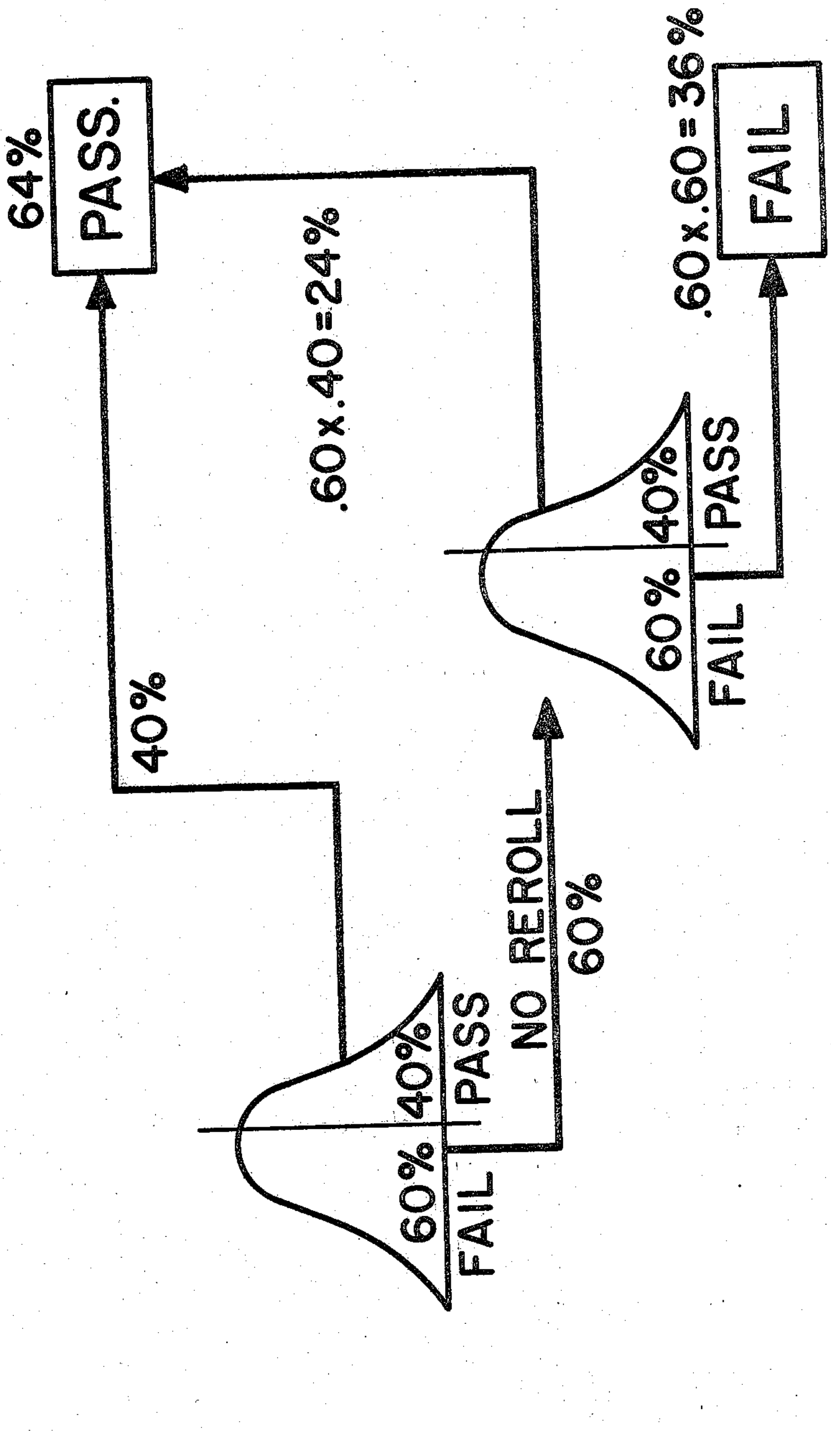
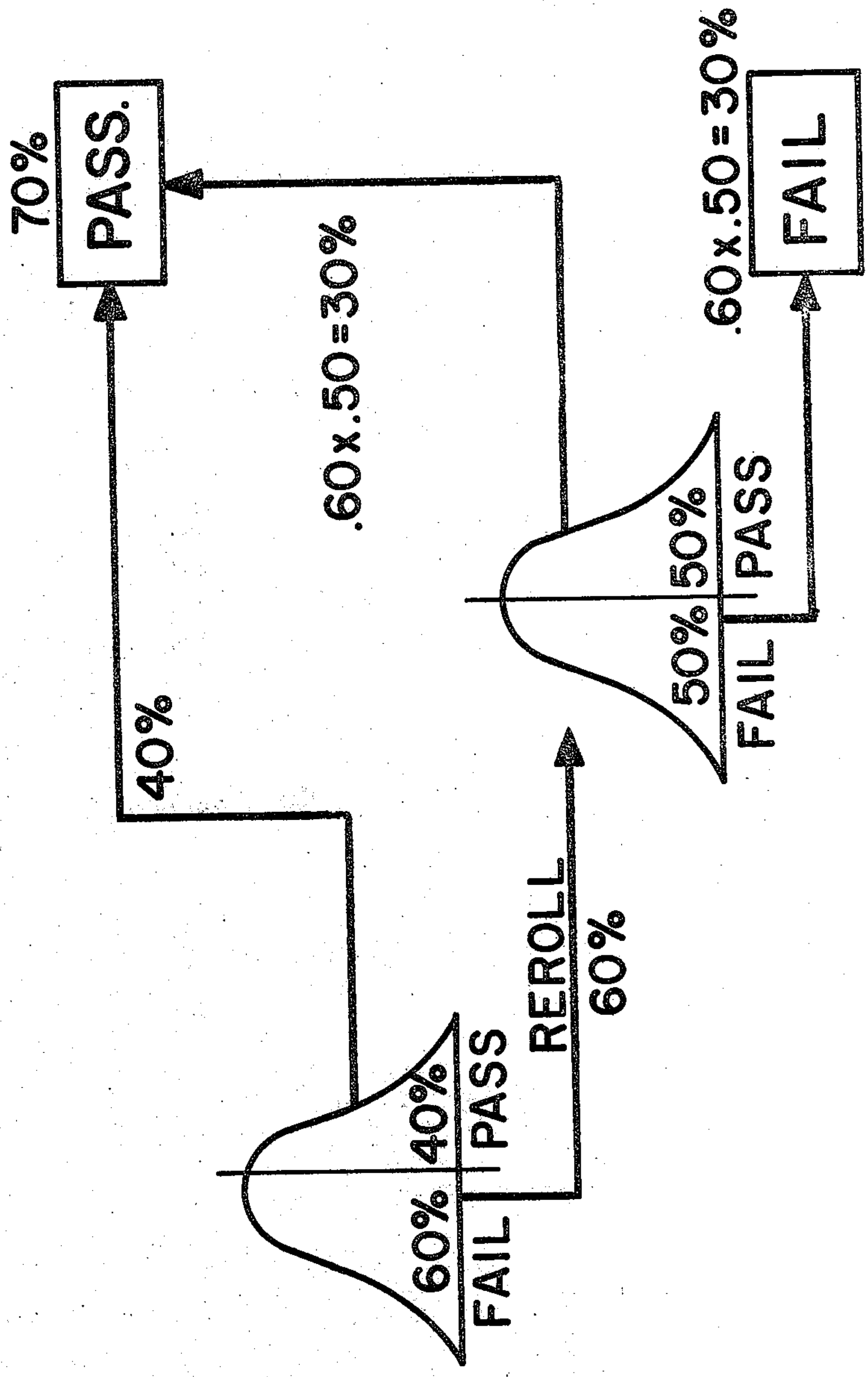
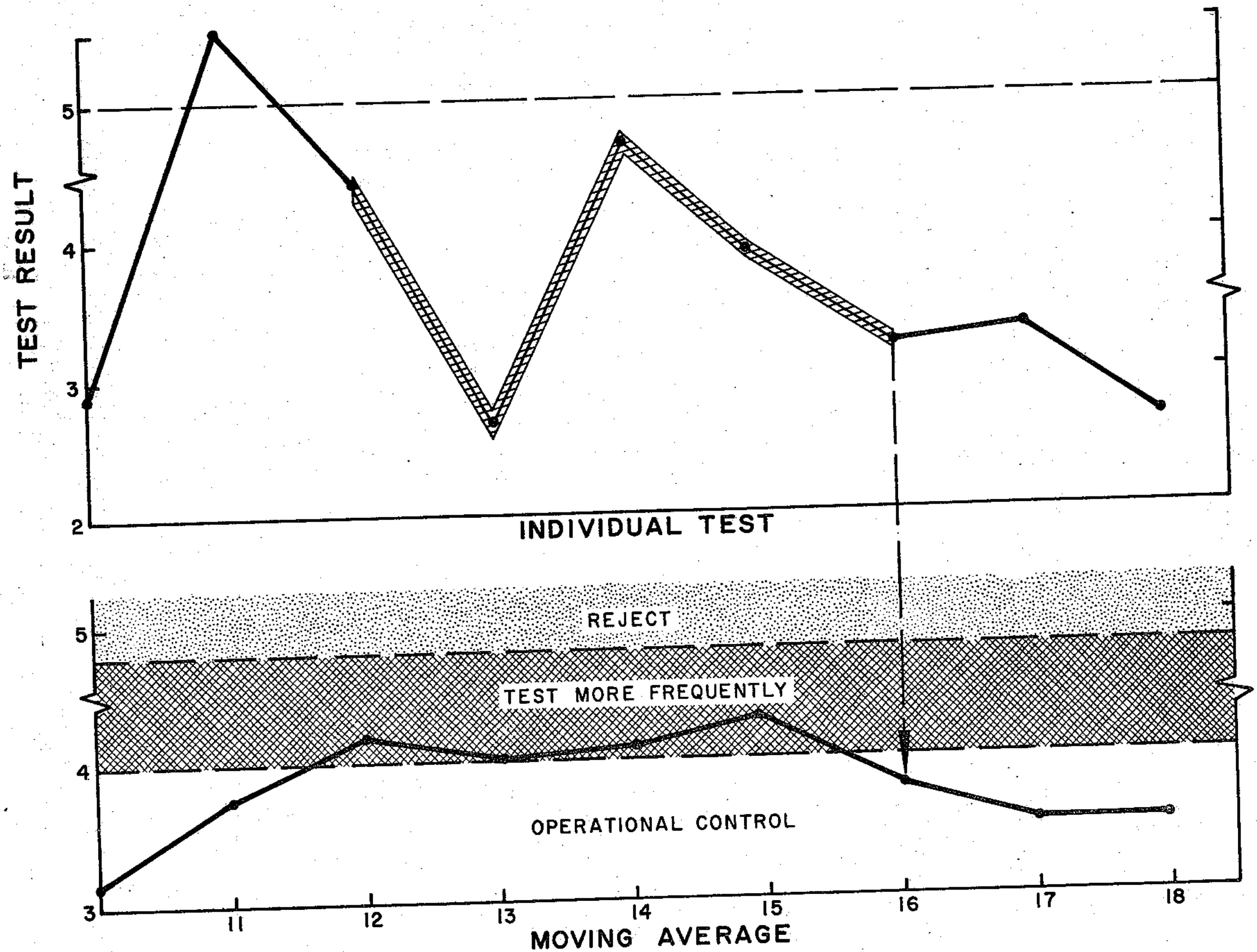

64%
PASS.
.60x.40=24%
.60x.60=36%
FAIL
40%
60%
40%
PASS
60%
FAIL
NO REROLL
60%
40%
PASS
60%
FAIL

Figure 8



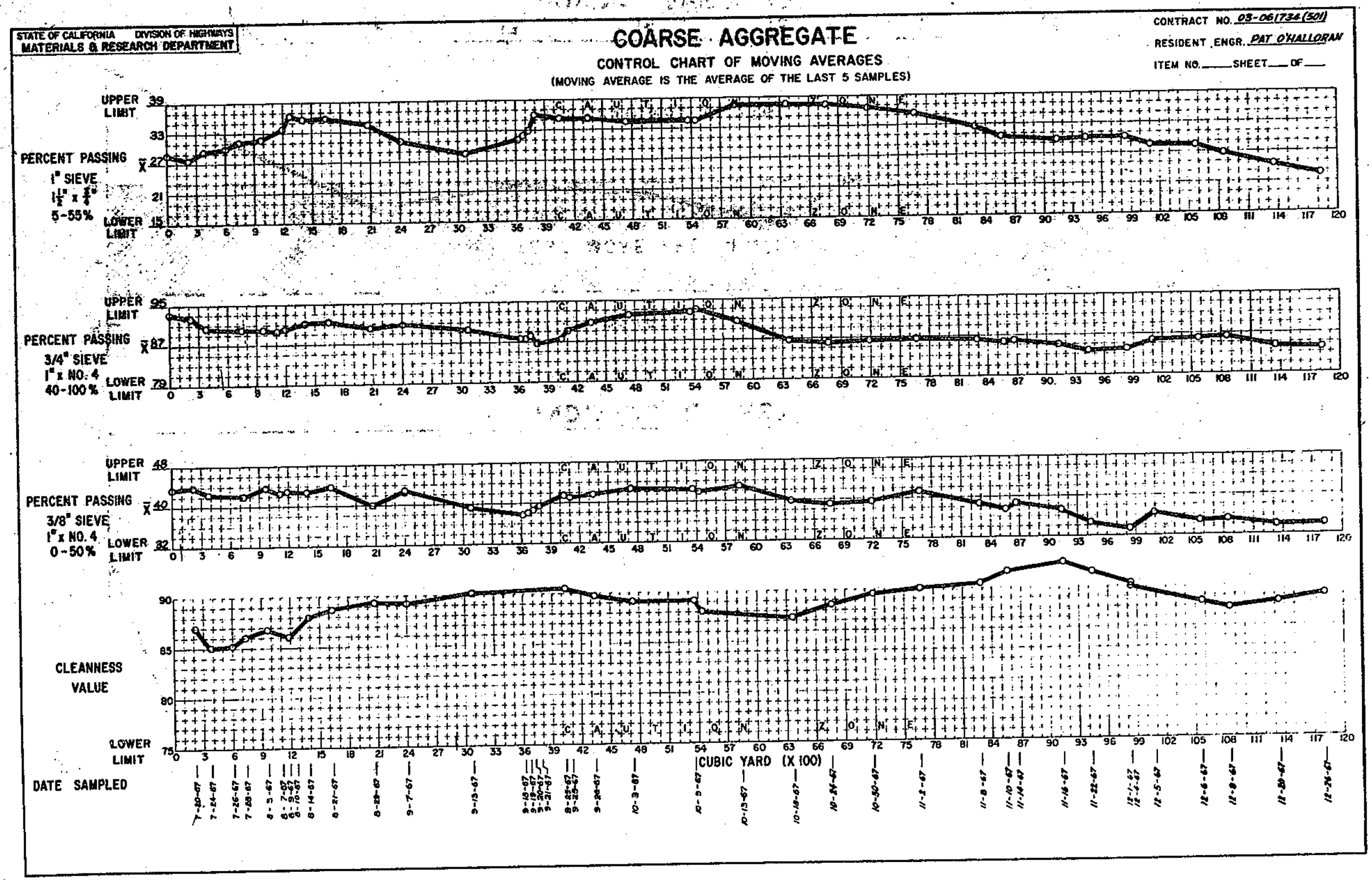
FAIL
60%
40%
PASS
REROLL
60%
40%
FAIL
50%
50%
PASS
.60x.50=30%
70%
PASS.
.60x.50=30%
FAIL

Figure 9



The decision to accept lot 16 is based on the average of test results 12 through 16. For lot 17 the average of 13 through 17 would be used, etc.

Figure 10



STATE OF CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPARTMENT
COARSE AGGREGATE
CONTROL CHART OF MOVING AVERAGES
(MOVING AVERAGE IS THE AVERAGE OF THE LAST 5 SAMPLES)
CONTRACT NO. 03-06(734(501)
RESIDENT ENGR. PAT O'HALLORAN
ITEM NO.____SHEET____OF____
UPPER LIMIT 39
PERCENT PASSING
1" SIEVE
1½" x ¾"
5-55%
LOWER LIMIT 15
UPPER LIMIT 95
PERCENT PASSING
3/4" SIEVE
1" x NO. 4
40-100%
LOWER LIMIT 79
UPPER LIMIT 48
PERCENT PASSING
3/8" SIEVE
1" x NO. 4
0-50%
LOWER LIMIT 32
CLEANNESS VALUE
LOWER LIMIT 75
CAUTION ZONE
CUBIC YARD (X 100)
DATE SAMPLED