The L3 Coaxial System

Application of Quality Control Requirements in the Manufacture of Components

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The application of quality control procedures, in addition to conventional maximum and minimum limits, is an important factor in the manufacture of components for the L3 carrier repeaters. In this application, control chart techniques are used for providing assurance that the average of each characteristic subject to control is held close to a desired value and that, collectively, individual units have a desired distribution about this average value. The three-cell method is frequently used under certain conditions encountered in the manufacture of these components when sampling procedures cannot be applied. This method consists of measuring each unit of product, classifying conforming units into one of three cells and the selection of groups of five units each to provide the desired distribution. Case histories of a number of factory applications of these methods are presented.

1.0 Introduction

1.1 GENERAL

Statistical quality control methods are well known and useful industrial tools for economically controlling quality during manufacture. These methods have as one of their goals the shipment of product meeting the end requirements for a particular quality characteristic. The application of such methods also makes possible the delivery of a product whose quality is statistically uniform as, for example, having a distribution whose average is maintained consistently close to the design center. Bell Telephone Laboratories engineers have made use of these principles in the development of the new L3 long distance carrier system which will employ hundreds of repeaters in tandem.

An important factor in the application of statistical quality control methods is the specification of distribution requirements in addition to conventional maximum and minimum limits for the characteristics of many of the components manufactured for the new repeaters. The introduction of distribution criteria where maximum and minimum are customarily specified requires a number of operations which are supplementary to normal procedures. The relatively simple act of identifying good product becomes complicated by the need of more extensive measurements, the recording of data, computations, plotting of charts and the active participation of technical personnel in the administration of the procedures.

The first step in the program was the development of practical statistical quality control techniques which would be applied under the special circumstances attending the design and manufacture of components of L3 carrier repeaters. This required careful study by Bell Telephone Laboratories and the Western Electric Company and resulted in the development of a general specification which provides procedures and criteria for maintaining the average value of a quality characteristic close to a nominal value and for obtaining as nearly as possible a random distribution of individual values around the nominal. The purpose of this paper is to discuss the procedures thus developed with emphasis on their relationship to manufacturing processes and to describe the problems encountered and solved in the course of application to the manufacture of components of L3 carrier repeaters. Detailed mathematical derivations and terms will be generally omitted since the theories underlying the principles involved are covered by another article.[1]

1.2 PARTICIPATION IN DEVELOPMENT

Normal practice in the creation of new product designs is for the development and construction of the first models to be handled by the design engineers. This work usually includes discussions with the manufacturing organization in order to minimize the costs and to utilize existing or most effective manufacturing facilities and various preferred or stocked materials. In the case of the critical components of the L3 carrier amplifiers, a design change in one component resulting from the transition from development to production requires especially close study and may require an adjustment in other components in order to compensate for the one being changed. Knowledge of the behavior of regular manufacturing facilities and methods used in the fabrication of preproduction units provides considerable assistance in establishing specification limits which are compatible with the product design and manufacturing process capabilities.

1.3 SEQUENCE OF MANUFACTURING OPERATIONS

The application of distribution requirements places added emphasis on the proper sequence of the various operations required for the fabrication of the product. Normally, any assembly or finishing operation following a process adjustment of a particular characteristic is designed to keep that characteristic within maximum and minimum limits in the final state. Such procedures often fail to satisfy the desired distribution and it is necessary to rearrange the sequence of operations. Once the proper sequence is established it must be rigidly maintained.

1.4 TESTING

As a result of refinements in design and in production methods employed for the critical components of the L3 amplifiers, the design engineer has in many instances been able to specify limits closer than ever before attained. The specification of such close limits may tax the precision of factory testing equipment and in many cases it has been necessary to develop and construct new electrical and mechanical inspection facilities. Measurement reproducibility as well as accuracy in terms of absolute values is important since the measuring instrument ordinarily indicates variations in repetitive readings, even though the product being measured remains constant. Once the characteristics of the measuring instrument are determined and used as a basis for the specification of limits, the measuring facility becomes an important part of the distribution control system and must be controlled the same as all other elements of the system. This means careful watch over the maintenance of factory inspection facilities so that these characteristics are controlled. Obviously, an adjustment made on the measuring instrument in the course of regular maintenance which introduces a significant bias or shift, even though well within accuracy limits, may have to be taken into consideration in the use of the instrument. One method of minimizing this problem is to employ stable fixed standards whose characteristics are numerically equal to or near the nominal value of the products being tested. Such standards can be used for either calibrating the instrument or as comparison standards in the actual measurement of the product. These auxiliary standards must still be periodically checked and extreme care taken to prevent any shift in their characteristics.

2.0 QUALITY CONTROL METHODS

2.1 CONVENTIONAL STATISTICAL QUALITY CONTROL METHODS

The concept of control as used here includes the use of data resulting from measurements made on product produced under the same essential conditions. The curve which can be used to represent the observed frequency distribution of data obtained under controlled conditions may, for most practical purposes, be illustrated by the shape shown in Fig. 1. The characteristics of this curve are mathematically represented by the average $\bar{X}$ (arithmetic mean) and the standard deviation σ (the root-mean-square deviation of individual values from their average $\bar{X}$).

The control chart techniques as originally developed by Walter A. Shewhart[2] of Bell Telephone Laboratories provide economical methods for measuring and evaluating the characteristics of such distributions. In practice they are useful in obtaining an estimate of the capabilities of manufacturing processes, sometimes referred to as the "natural tolerances" of the process and in maintaining control at that quality level. In general, a process having a controlled distribution with an average $\bar{X}$

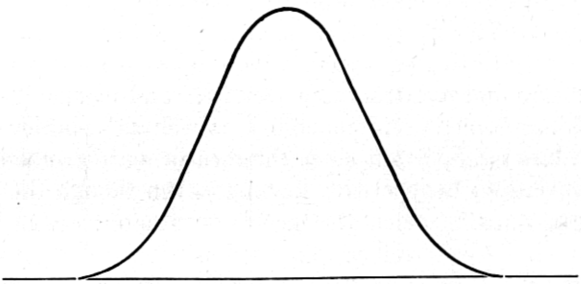


Fig. 1 — The ideal frequency distribution for observations obtained under controlled conditions.

and a standard deviation σ will result in practically all of the individual units of product falling within the band $\bar{X} \pm 3\sigma$.

Conventional quality control techniques are used by both the design and manufacturing engineers. The design engineer, in order to specify tolerances compatible with the design needs and the capabilities of economical commercial manufacture, applies the techniques to a reasonable number of preproduction models or possibly to a limited quantity of initial regular production. The manufacturing engineer in turn uses the techniques for determining the capabilities of existing or new manufacturing facilities in order to select the most effective facilities and methods. The techniques are also effective tools for locating and eliminating assignable causes of manufacturing variations, while their continued use as a regular part of the manufacturing process provides an excellent contribution to effective quality control. In these applications there usually exists a substantial margin between the $\pm 3\sigma$ variation around the nominal value and the specification limits. This is illustrated as specification limits, 1-1 in Fig. 2. The margin is attained either by improvement of the manufacturing processes or by widening the specification limits. This means that occasional out-of-control conditions can be indicated by the control chart without the factory being faced with a shut down in production, provided that corrective measures are taken before the magnitude of the deviations results in any significant quantity of the product failing to meet the specification limits.

The contrasting situation occurs where the spread between the maximum and minimum specification limits becomes equal to or less than the 6-sigma spread of the manufacturing process, as shown in Fig. 2. For specification limits 2-2, production must be stopped every time an out-of-control condition is indicated or 100 per cent inspection introduced until the cause of the condition is located and eliminated. In the case of specification limits 3-3 in Fig. 2, 100 per cent inspection must be continuously applied in order to eliminate non-conforming product as shown in the shaded portion under the distribution curve.

2.2 SPECIAL STATISTICAL QUALITY CONTROL METHODS

The special statistical quality control techniques developed for L3 carrier components present a special problem. Here they become an actual part of the product specification, rather than an aid in meeting it, although conventional methods may still be useful for process control. It was recognized that any attempt to express specification limits in terms of a $\pm 3\sigma$ variation around the nominal would have to include

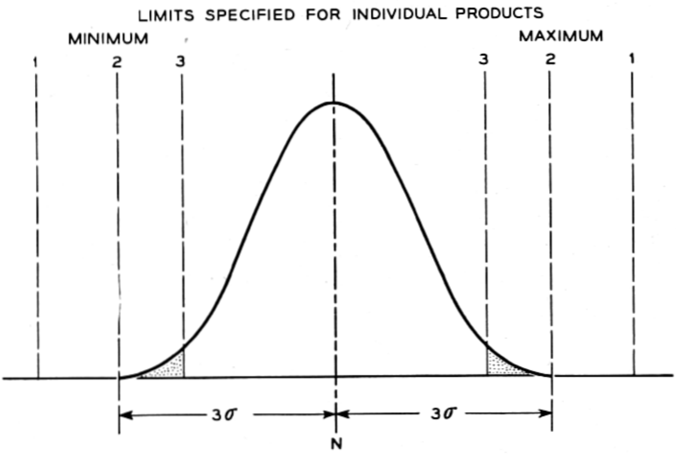


Fig. 2 — The relations between a frequency distribution of individual units of product and various specified maximum and minimum limits.

allowances for the process average to vary a reasonable amount around this nominal. The methods developed and included in the general specification allow the process average to vary within a band of $\pm\frac{1}{3}\sigma$ around the nominal which results in limits for individual units of product, designated as "A" limits in the specification, equal to nominal $(N) \pm 3\frac{1}{3}\ \sigma$. The value chosen represents a balance between the needs of the operating requirements of the product and the difficulties of maintaining closer controls in the factory.

In Fig. 3 the permissible variation of individual units of product is represented by a Normal distribution curve displaced $\pm\frac{1}{3}\sigma$ from the nominal N. Since the specification limits are represented by $\pm A$, the allowable variation in the process average is $\pm 0.1A$.

This is a severe requirement, for in spite of the care employed in collecting data during the preproduction period for computing the "natural tolerance" of a manufacturing process, there is always the danger that all the variations which are an unavoidable part of regular production do not occur during the time data are collected. There could be periods after manufacture has started when the factory could not determine whether the out-of-control condition was one which should be promptly eliminated or whether some important characteristic of the process which had not occurred earlier had made its appearance. At this stage it is important to have available some method for sorting product already manufactured which will meet the desired distribution pattern

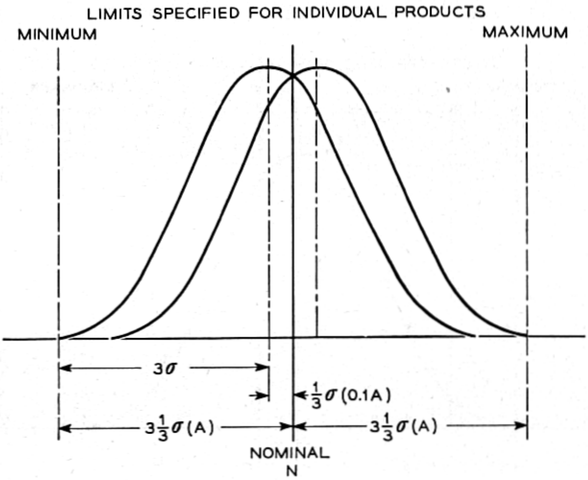


Fig. 3 — The relations between a frequency distribution of individual units of product and specified maximum and minimum limits when the average or nominal is allowed to vary $\pm\frac{1}{3}\sigma$.

so that large inventories will not accumulate in the factory and delivery commitments can be met. Such a method requires the measurement and classification of the product into groups or cells, followed by the selection of units from such cells in accordance with a required distribution. Although this method requires 100 per cent inspection instead of sampling inspection permitted by the use of control charts it was estimated that this method would be used extensively until new manufacturing processes were thoroughly proven and sufficient data collected to fully establish a process capability.

2.3 THE GENERAL SPECIFICATION

Anticipated application required consideration and development of methods for the wide variety of manufacturing conditions likely to be encountered in the production of such items as coils, condensers, resistors and vacuum tubes. These products may be manufactured at widely separated factories for assembly in equipment at still another location. In order to assist in the description of the factory applications, to be presented later, the methods developed which are referred to as "distribution requirements" in the general specifications are listed and briefly described below. With the exception of the Records method, distribution requirements are applied to only one characteristic of a product. If application to more than one characteristic is desirable a method suitable for use as a basis for shipment of the product is selected for the most important characteristic and the Records method is specified for the remaining characteristics.

1. Continuous production method.
2. Batch production method.
3. Three-cell method.
4. Records method.

2.31 *Continuous Production Method*

This method is for application where production comprises a reasonably steady succession of individual units or small groups of units of product from a common source so that individual units as produced may be kept in the order of their production. The criteria of this method apply to a series of units or groups of units of product arranged in the order of their production and are based on the use of control charts for averages and ranges for samples of 5 units each. Examples of typical control charts are shown in Figs. 4 and 5.

The inclusion of an allowance for the long time variation in the level of the process average results in the use of two sets of control limit lines for averages in place of the one used for conventional methods.[3] These consist of:

(1) A relatively narrow band equal to $N \pm 0.1A$ ($N \pm \frac{1}{3}\sigma$), designated in the general specification as "D" limits.

(2) The normal 3-sigma limits for averages of samples of 5 units

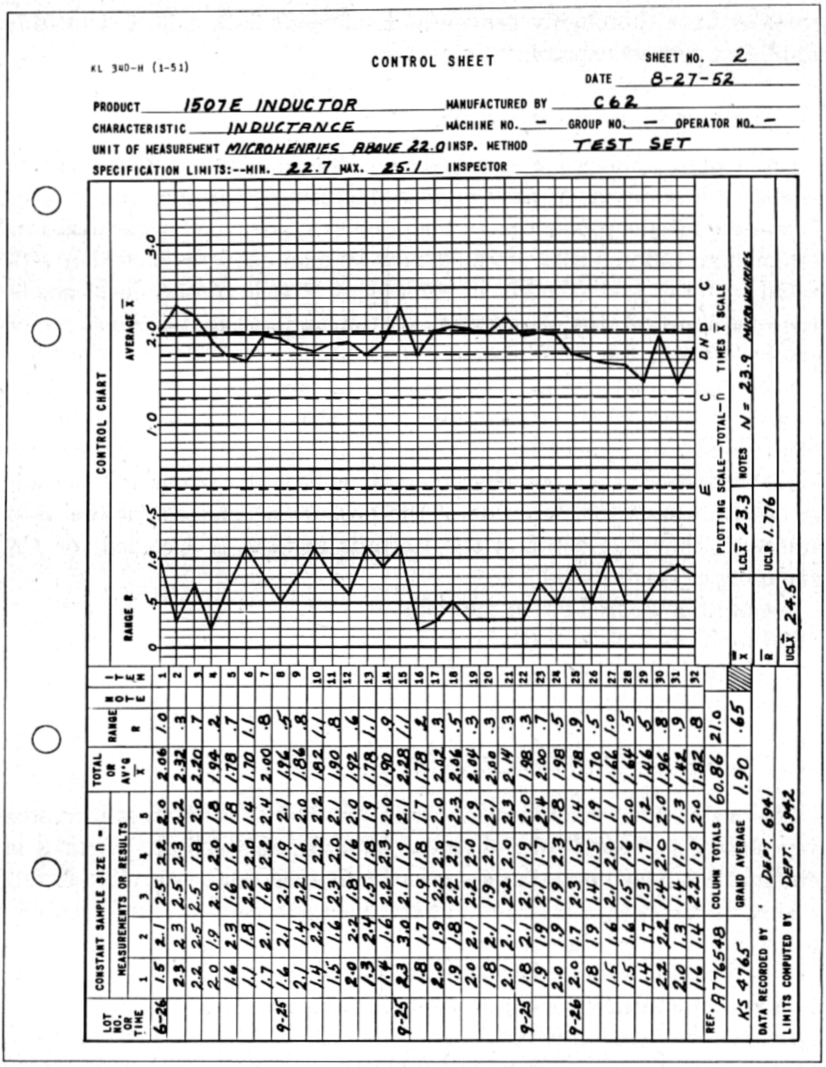


Fig. 4 — A typical control chart (1507E inductor).

placed outside the first band equal to $N \pm 0.5A$, designated in the general specification as "C" limits.

The control limit for ranges is the customary upper 3-sigma value computed by regular methods,[3] and equals $1.48A$. This is designated in the general specification as the "E" limit. The product specification requirements are expressed in the form $N \pm A$ so that the calculation of

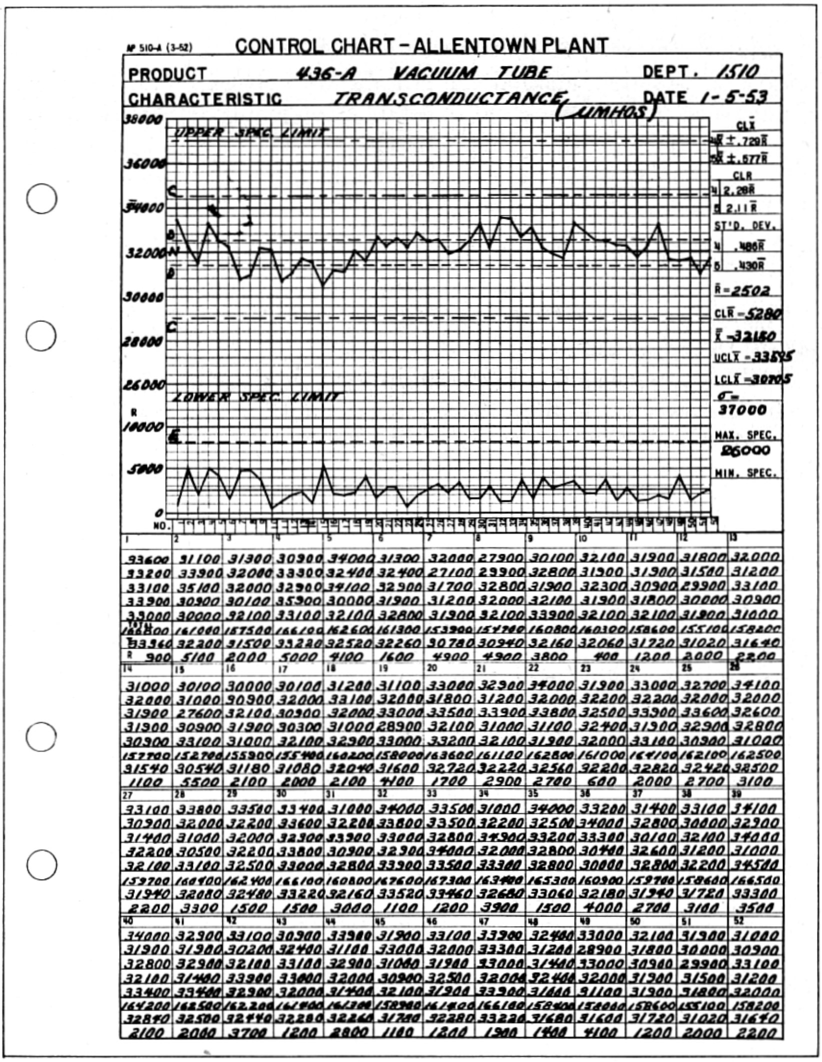


Fig. 5 — A typical control chart (436A vacuum tube).

the various control limits for factory use is a relatively simple operation. A typical example is the 1507A Inductor where the inductance requirement is expressed as 283.9 ± 20 microhenries.

Then the "C" limits = 283.9 ± 0.5 × 20, = 293.9 max., 273.9 min. microhenries, and the "E" limit = 1.48 × 20 = 29.6 microhenries.

Since the distribution requirements are a part of the specification, the product must meet rather exact criteria in terms of the limiting conditions previously described, even though they may appear complicated in terms of the usual manufacturing procedures. In the case of the Continuous production method the criteria are applied to the samples of 5 units each, in two steps, (1) to establish eligibility, either at the start of production or when eligibility is lost and (2) to maintain eligibility when once established. Prior to the establishment of eligibility or when eligibility is lost the three-cell method is applied.

Criterion 1

Eligibility is established as soon as 7 consecutive samples of 5 units satisfy the following:

(a) The averages, $\bar{X}$, all fall within the C limits.

(b) The ranges, R, all fall below the E limit.

(c) Seven consecutive averages, $\bar{X}$, are not all outside the same D limit (not all above the upper D limit or all below the lower D limit.)

Criterion 2

Eligibility is maintained as long as each current sample of 5 units satisfies the following:

(a) The average, $\bar{X}$, either

1. falls within the C limits or

2. falls outside the C limits but at the same time all of the 6 preceding consecutive averages fall within the C limits.

(b) The range R either

1. falls within the E limit or

2. falls outside the E limit but at the same time all of the 6 preceding consecutive ranges fall within the E limit.

(c) Seven consecutive averages $\bar{X}$ (the current sample and the six preceding samples) do not fall outside the same D limit.

2.32 *Batch Production Method*

This method is for application where production consists of intermittent batches of 50 or more units, all of which have been made under the same essential conditions with respect to materials, parts, workmanship and processing. The criteria of this method apply to a series of batches or lots of product arranged in the order of their production and are based on the use of control charts for averages and standard deviations for samples of 50 units each.

The control limits for averages are for 50 units of product and also include an allowance for the long time variation in the level of the process average. They are represented by a band $N \pm 0.23A$ which is equal to the customary[3] 3-sigma control limits for averages of 50 units placed outside a band corresponding to $N \pm 0.1A$ ($N \pm \frac{1}{3}\sigma$) and are designated in the general specification as "C" limits. In this method the "E" limit in the specification is the control limit for the standard deviation (σ) of a sample of 50 units and equals $0.41A$.

For this method a batch, represented by the sample, is considered conforming if the sample meets the following criterion.

(a) The average $\bar{X}$, falls within the C limits.

(b) The standard deviation, σ, either:

1. falls within the E limit; or
2. falls outside the E limit but at the same time all of the 6 preceding consecutive standard deviations fall within the E limit.

2.33 *Three-Cell Method*

This method is for application whenever the product fails to meet the criteria of the first two methods or where the manufacturing conditions dictate its use. When maximum and minimum limits are specified the method consists of testing or measuring each unit of product and classifying conforming units in one of three cells: Lower, Middle or Upper.

The distribution is shown graphically in Fig. 6. Groups of 5 units of product are selected from this classification so as to meet one of the two distributions given in Table I and maintained as such for shipment.

In order to provide a graphic record of whether or not the manufacturing process is in statistical control, this method includes procedures for obtaining control chart data based on samples of product taken from regular production before classification.

2.34 *Records Method:*

This method is for application when it is not practicable to impose the requirements of the other methods but it is still desirable to systematically maintain a graphic history of the measurements made on a quality characteristic. Action required to maintain the distribution of the product within the limits implied by the control charts is left to the initiative of personnel administering the application of the method.

The records are based on measurements on samples of 5 units each selected at random prior to the regular inspection of individual units for conformance. The number of such samples should be adequate to provide a control chart record of the quality of the product.

In all of the methods described except the one requiring records only, the final product is packaged in groups of 5 units for shipment. When an order calls for a quantity other than an integral multiple of 5, the fractional part of the group shall consist of units randomly selected from a group which has been previously packaged.

3.0 Factory Application

3.1 GENERAL

The Distribution Requirements are being applied to 91 components consisting of 31 different codes of product used in the L3 carrier repeaters. In addition, Record methods are applied to 66 characteristics of the line and office amplifiers.

The components involved are identified in Table II.

These products require the maintenance of over 100 control charts in the factory in a form suitable for reproduction since engineering review of the results is necessary for adjustment of limits. Many of the charts are prepared and handled by factory personnel who required and received training in order to provide assurance of accurate results. Comprehensive instructions were prepared in order to assist in this training.

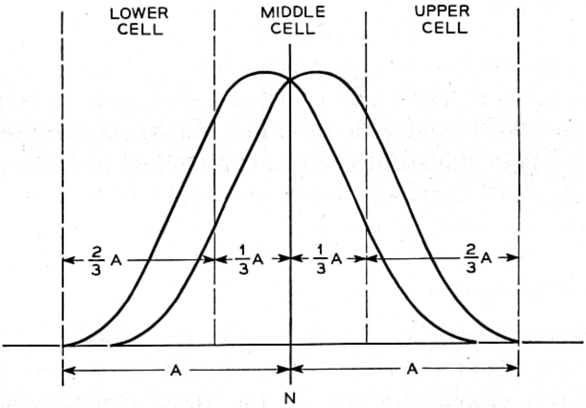


Fig. 6 — A three-cell pattern superimposed on a frequency distribution of individual units of product when the average is allowed to vary $\pm\frac{1}{3}\sigma$.

TABLE I

Distribution	Number of Units		
	Lower Cell	Middle Cell	Upper Cell
1	1	3	1
2	0	5	0

A number of special forms were developed to facilitate the preparation of control charts, two of which are shown in Fig. 4 and Fig. 5. Since these control charts are directly related to the manufacture of the product, the cost of their preparation is included in the cost of the product, either by having the operation handled by production personnel or by the application of appropriate cost factors. This required in many cases the preparation of specific instructions to factory personnel in the form of manufacturing layouts which are also used as a basis for computing manufacturing costs and wage incentive rates.

One of the most serious problems in the application of these methods is the accumulation of large inventories of product when the manufacturing processes fail to meet the distribution requirements. In the case of regular maximum and minimum limits, procedures for the disposal of non-conforming product are direct and well known. In the case of distribution requirements however, there may be substantial quantities of product which meet the "*A*" limits but fail to meet the required distribution. Product which originally cannot be packaged must be put aside with the hope that product subsequently manufactured will result in combinations which will meet the required distribution. The discussion of applications to the products listed in Table II will show that a great measure of success has been realized in the solution of this problem.

TABLE II

Description	Number of Different Codes	Number of Different Repeater Components
Controlled pitch single layer coils (AWA, 302, 320, 1500, 1507 type)	18	18
Mica capacitors (500 type)	4	21
Quartz disc capacitors (505 type)	3	3
Carbon deposited resistors (200 type)	2	45
Quartz input-output transformer (2504 type)	1	1
Vacuum tubes	3	3
Total	31	91

3.2 APPLICATION TO COILS

3.21 *Single Layer Type Inductors*

The problems encountered in the application of quality control techniques to the various codes of the single layer type coils follow a similar pattern so that a discussion of any one code covers many of the conditions common to the entire group. The early application of distribution requirements to L3 carrier coil characteristics was associated with the development of the 1500-type inductor commonly referred to as the "Splitting Coil". This coil derives its name from its primary circuit function of separating or splitting the transformer winding capacitance from the input capacitance of the amplifier vacuum tube. The circuit in which this coil is used permits an estimated variation in inductance from a desired value of approximately ±¼ per cent, which includes manufacturing deviation, aging and temperature effects. A coil of this type having such close tolerances could not be produced economically with normal manufacturing methods. At this point the use of control chart methods played an important part in the development of tolerances and measuring techniques. The control chart techniques combined with the simultaneous development of manufacturing methods and sources of critical raw material have permitted the widening of limits of coils under the general distribution specification using "A" limits of ±1 per cent in place of the originally estimated limits of ±¼ per cent without a controlled distribution.

The splitting coil consists of a single layer winding wound on a ceramic form under a tension of 50 to 75 per cent of the wire breaking strength. The winding is terminated in lead wires which have been secured in holes located in the ceramic core transverse to the axis of the coil. The use of the ceramic core on this coil has reduced the temperature and aging effects to the point of becoming negligible, due to the nature of the core material and winding conditions. Major factors affecting the inductance variation are as follows:

a. Diameter of wire — standard commercial tolerances on wire of the sizes used, equalling ±0.0003″ will produce a variation in coil inductance of approximately ±0.15 per cent.

b. Diameter of core — a variation of core diameter of 0.0005″ will produce a variation of approximately ±0.5 per cent in the coil inductance.

c. Length of winding — a variation in the nominal length of winding of ±0.001″ will result in a variation in inductance of about ±0.13 per cent.

During the initial period of manufacture of these inductors, it was found that the seriousness of the variations in inductance, contributed by the wire diameter tolerance, could be minimized by selection of the wire stock. Experience has indicated that because of the small amount of wire used per coil, this procedure can be followed without undue losses.

The variations contributed by the core diameter tolerance have been minimized by the introduction of a ground core having a diameter tolerance of $\pm 0.0002''$. By virtue of the manufacturing methods introduced by the core manufacturer to meet this close diameter tolerance, a fairly normal distribution of the core diameter was obtained.

In addition to the variables due to the material used for these coils there were substantial variations in inductance inherent in the winding machines and operator winding techniques particularly in the attachment of the wire to the terminals. Early control charts showed an erratic

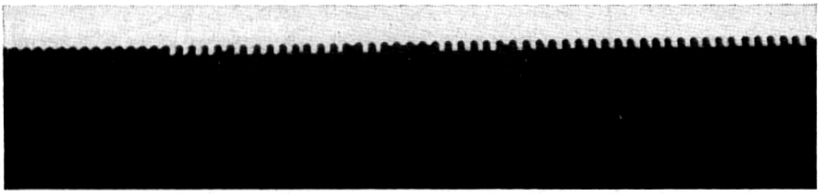


Fig. 7 — A shadowgraph of a coil winding showing irregularities in the wire spacing due to non-uniformity in pitch control of winding machine.

variation of inductance which was traced chiefly to backlash in the winding machine.

Fig. 7 is a shadowgraph of the coil winding showing the irregularities in the wire spacing due to non-uniformity in the pitch control of the winding machine. In addition to this variation, trouble was experienced in maintaining pitch control at the end of the winding due to the necessity of sanding the lead before splicing to the terminal. This latter variation was brought under control by the introduction of a type of wire which can be soldered to the terminal without mechanically removing the insulation, thus avoiding the loss of the winding machine accuracy of spacing and tension. After numerous machine modifications, satisfactory control of the winding pitch has been obtained so that with normal variations, the inductance of the coils is within the distribution requirements of the specification. This uniformity of winding is illustrated in the shadowgraph in Fig. 8, which is a typical example of current product. The type of machine modifications required to produce this improvement in product control included the following:

1. Eliminate slack in gear train by introduction of loaded gear drive.
2. Provide a constant force spring load on the worm drive so that the distributor exactly follows the cam motion.
3. Miniaturize wire guide assembly so that wire as placed on winding core will more closely follow the distributor motion.
4. Improve spindle bearings and distributor alignment.
5. Provide improved shut-off counter so that machine will give exact winding turns without overrun.

Although it might appear from the above discussion that winding coils on a controlled pitch basis will automatically result in the product having a normal distribution around a specified nominal inductance, the desired result can only be attained by continued vigilance, as many unpredictable variations will creep into the process from time to time. Gradual changes in control are readily observed from the charts, and in

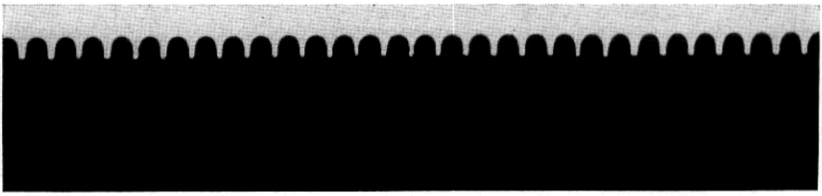


Fig. 8 — A shadowgraph of a coil winding showing uniformity of winding necessary to meet distribution requirements for inductance.

many cases, are enough indication to show need of replacement or repair of worn winding-machine members which control the winding pitch of the coil.

The 320-type retardation coil used in the cosine equalizer of the L3 system, requires all of the control vigilance of the splitting coil and, in addition, has introduced the necessity for even further winding precautions. Although this coil has the same per cent tolerance as some of the other coils manufactured under this specification, it is more difficult to control, since it has only about one-tenth as many turns in the winding as most of the other coils. The major inductance variations in this coil, therefore, are controlled by the variation in the end turn location and the winder checks the inductance by a continuous sampling of the product during the winding procedure. It is thus possible to promptly make necessary modifications in the location of the final turn to maintain the inductance distribution within requirements. Experience has shown that normal variations from operator to operator can run as high as ½ per cent on coils having a tolerance of 1 per cent, until the operator becomes sufficiently skilled in the terminating methods. Thus, in order to obtain a product having normal distribution, close control of the winding operation must be maintained.

In addition to the above-mentioned single layer type coils, there is another general family of coils wherein distribution controls are useful during the initial period of development. The 1507 type, referred to as L-R inductors, are precise low-Q single-layer inductors wound with resistance wire on closely-controlled, low temperature-coefficient core tubes. These inductors are used in the input feedback network and as plate-feed inductors in the L3 amplifier, and are units which combine resistance and inductance in a single product. The stability of these coils is obtained by winding on a ceramic core form, similar to that used in the "splitting" coil, and using a low temperature-coefficient resistance wire in the winding. Simultaneous control of the resistance and inductance of this coil is obtained by the calibration of the winding machine setup to fit the resistivity of the wire used on the coil. Once the required turns and pitch have been determined for a given spool of wire, experience has shown that the resistance control will remain valid until the wire from the spool is exhausted.

The problem of making an accurate electrical measurement of a low Q inductor is a difficult one to resolve and it is here that an accurate control of testing methods by means of statistical analysis was employed. When an inductance (L_0) and a resistance (R) occur as series elements and the combination is shunted by the residual capacitance (C) across the bridge terminals, the resulting measured inductance is equal to that of the original inductance minus the product of the capacitance and the square of the resistance.

$$\text{Measured inductance} = L_0 - CR^2$$

The above equation is generally true in the case of coils where the inductive reactance is small compared to the resistance. If standard test procedures were followed to make the measurement of inductance, using the familiar Maxwell Bridges,[4] an error would be introduced due to residual bridge and test jig capacitance. This would make the measured value considerably different from the coil inductance and would be dependent upon this residual capacitance and the coil resistance which could not be controlled with any degree of uniformity. Parallel resonating capacitance techniques are inadequate for the accuracies required, since the shunt equivalent of a very low-Q inductance is equal to that inductance divided by Q^2. Determination of inductance by this method, while better than the Maxwell Bridge method, is subject to errors due to the inadequate readability of the capacitance standard of available test facilities.

Since the theoretical values of resistance and inductance are specified by design, the following methods of determining actual design parameters are used:

A. Determine mathematically, or by experiment, the number of turns of a given resistance wire wound on the core tube to produce the required resistance.

B. Wind high Q inductors using copper wire of the same diameter as the resistance wire and having the same number of turns as determined in Step A, varying the winding pitch to produce the required inductance.

C. Wind low Q inductors with the wire and number of turns of Step A and the pitch as determined in Step B.

D. Make Maxwell Bridge inductance measurements for the two groups of low and high Q inductors. The two sets of readings are then subjected to a statistical analysis to insure that the processes are in control so that the data may be used in selecting a nominal coil from the low Q group to use as as a reference standard. While it is true that the apparent value of the resistance-wound inductors will be appreciably less than those of the copper wire variety, due to the CR^2 correction, the nominal intrinsic inductances of the two groups of coils will be the same, due to their identical physical geometry.

Thus, by a method of comparison of two sets of readings, each of which is within process control, it is possible to select coils which can be used as reference standards. Any measurement which is made on a bridge set up from this reference standard will require correction of the inductance reading to compensate for the resistance variation. Self-compensating bridge methods have been developed which make it possible to read with good accuracy, directly on the bridge, the low Q coils covered by this family of inductors.

During the initial production of the 1507-type inductors, it was found expedient, for easier maintenance of control of the resistance and inductance variations, to use a nine-cell post-office method (three-cell by three-cell) which permits selection of product in any one of five ways using diametral axes, yet still maintaining the specification distribution covered by the three-cell method. The nine-cell method has gradually become less important, as experience has been gained with the use of the winding machines and control of winding operator variations.

Table III gives the over-all results of production of single-layer inductors and retardation coils, over a period of approximately one year. It can be seen that the design and production facilities are such that it is possible to manufacture a product within the requirements imposed by

TABLE III — YIELD OF COILS PRODUCED UNDER THE DISTRIBUTION REQUIREMENTS

Code	Nominal Values L—Microhenries R—Ohms	Tolerance Per cent ±	Total Production	Accumulated Unpackaged Product
AWA21 retard	L—191.61	1.0	514	90
AWA22 retard	L—166.2	2.0	342	6
302AW retard	L—1.58	10.0	545	0
302AY retard	L—3.70	5.0	410	47
302BA retard	L—1.425	1.3	702	140
302E retard	L—3.52	1.1	514	35
320F retard	L—26.11	1.7	702	130
320G retard	L—19.62	10.0	653	1
320M retard	L—1.428	1.0	307	53
320N retard	L—18.0	2.0	54	0
320P retard	L—0.874	1.0	10122	41
1500A inductor	L—43.53	1.0	1883	121
1500B inductor	L—40.44	1.0	738	12
1507A inductor	L—283.9 R—260.8	7.0 7.0	560	10
1507C inductor	L—78.2 R—2025	4.0 2.0	685	71
1507D inductor	L—6.5 R—166.6	2.0 5.0	881	230
1507E inductor	L—23.9 R—1655	5.0 5.0	828	88

NOTE: Production includes product manufactured which did not fall within the "A" Limits.

the distribution specification. In the case of the 302BA and 320F retards, the lower yield of these coils was found to be due to machine variations which have been corrected. In the case of the 1507D inductors, an additional limitation is caused by the lack of fine enough machine pitch control to permit proper manufacture of this coil. A new winding machine having adequate control is being provided to eliminate this condition.

It has become apparent, as production has progressed, that the manufacture of coils, such as are given in Table III, is going to remain a small lot business. Therefore, in all probability, the great majority of the production will be shipped by the three-cell method, with only a few cases of enough production to warrant the use of the Batch or Continuous methods where advantage can be taken of the sampling procedures.

3.3 APPLICATION TO CAPACITORS

3.31 *500-Type Molded Mica Capacitors*

The 500-type molded mica capacitors have been one of the most difficult products to control within the requirements of the distribution specification. This condition is inherent in the design and methods of manufacture of this type of product, as the process consists of an integrated group of manually-controlled operations. The following brief summary of these operations will give a better appreciation of the difficulties encountered in the control of a product of this type:

3.311 *Mica cut to size and silver coated*

A. Inspected for visual and mechanical dimensional defects.
B. Laminations silver coated by silk screen process and fired.

3.312 *Assembly*

A. Laminations stacked by count and interleaved with lead foil. In this state, the stack consists of laminations having multiple silvered areas.

B. Dip-sealed in Bi-Wax to hold pileup firmly together for subsequent operations and excess wax pressed out of pileup.

3.313 *Sectioning*

A. Section the multiple stack of laminations by punch and die to provide individual capacitor pileups.

3.314 *Preliminary stacking to capacitance range*

A. Rough adjust the individual capacitor pileups by adding or removing single laminations to meet a broad capacitance range which is capable of adjustment. Terminals are then attached by crimping.

3.315 *Adjusting*

A. Adjust by scraping silver from outer layer of mica until capacitance is within ± 0.2 mmf of specified value.

3.316 *Molding — Stabilizing*

A. Mold in mica-filled molding compound.
B. Stabilize by temperature cycling.

In a process of this type a number of individual operations combine to determine the final product capabilities. Control of distribution is difficult since many of these operations tend to substantially modify the distribution obtained in previous steps of the process. Figs. 9 and 10 show the conditions encountered on two types of these capacitors which have different capacitance tolerances. Studies indicate that the percentage of the product falling within the cell limits at the present time will vary from 40 to 80 per cent depending on the capacitance value and tolerance. Thus an expected merchandise loss of 20 to 60 per cent falling outside of allowable tolerance exists which, in addition to the units classified but not eligible to ship due to poor distribution of product among cells, creates a condition resulting in increased cost of the product. It is expected, based on current methods and design, that the yield of the capacitors shipped within the requirements of the distribution specification will be between 20 and 70 per cent of the product manufactured. This represents a situation in which the specification tolerances, the product design, and the manufacturing process capabilities are not compatible, but because of the design needs it is still necessary to meet the distribution requirements. The use of the three-cell method makes this possible by the acceptance of relatively large shrinkages until improved manufacturing methods and materials now under investigation are introduced.

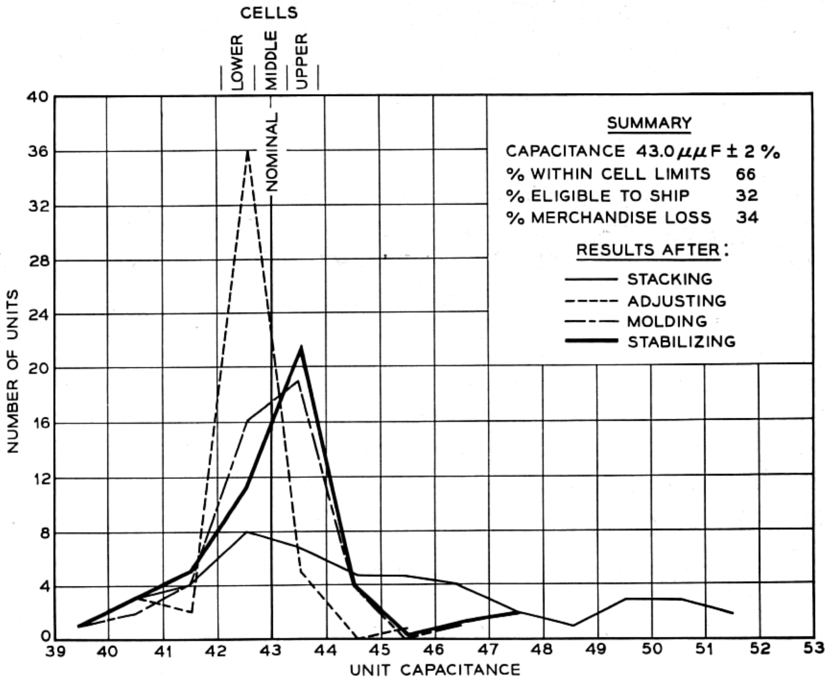


Fig. 9 — A summarized frequency distribution of a 43-mmf mica condenser at various stages of manufacture.

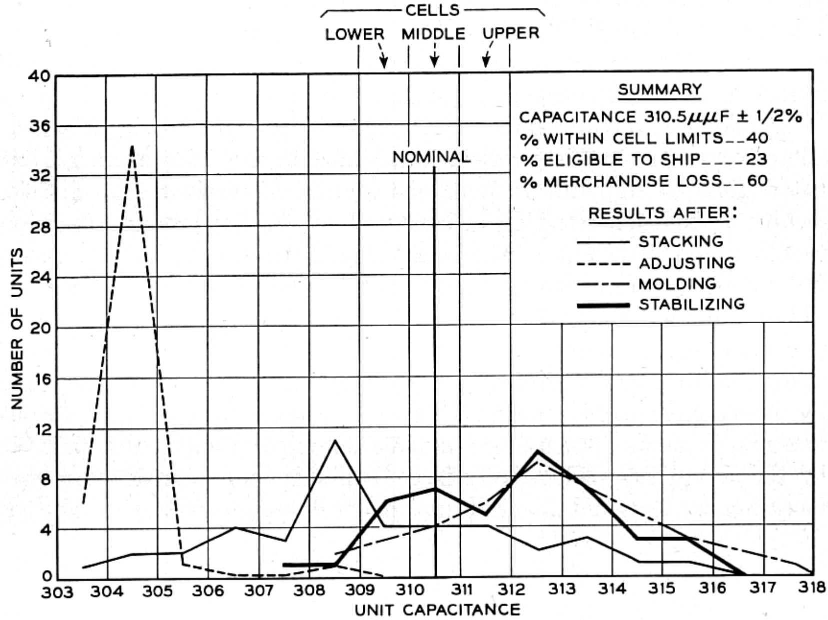


Fig. 10 — A summarized frequency distribution of a 310.5-mmf mica condenser at various stages of manufacture.

3.32 *Quartz Disc Capacitors*

The quartz disc capacitors are made by the addition of a silver coating to fused quartz discs which have been lapped to an exact thickness. The final adjustment for capacitance is obtained by the mechanical removal of small areas of the silver before the application of a protective finish. The nature of the manufacturing process and the quantities produced requires the three-cell method. A typical requirement is 9.8 ± 0.1 mmf which requires the measurement and classification of the product into cell widths of 0.067 mmf each. Capacitance measurements, including the use of reference standards, combined with careful adjusting procedures, have resulted in shipping approximately 99 per cent of the capacitors produced.

3.4 BORO-CARBON RESISTORS

3.41 *Introduction*

The stringent requirements for L3 carrier line amplifiers and impedance matching and balancing networks prevented the use of commercially available composition type resistors due to their high temperature coefficient and lack of stability. Fortunately a new unit, known as a boro-carbon resistor was under development and could be utilized. The boro-carbon films employed in this unit have a maximum temperature coefficient of resistance of 0.01 per cent per °C compared to ordinary deposited carbon films which may have an average temperature coefficient of 0.03 per cent per °C.

Two types of boro-carbon resistors covering approximately 45 resistance values are being produced for the L3 system. These types are the 200A resistors, held to a tolerance of ±3 per cent and the 200B resistor held to a tolerance of ±1 per cent. Both types are available in resistance values from 5 ohms to 9999 ohms inclusive. Of the 45 values used in L3 equipment, approximately 40 are of the 200A type and 5 are of the more precise 200B type.

3.42 *Manufacturing Procedure*

The core of the 200-type resistor consists of a high grade alkaline earth porcelain of special composition. The resistance film is produced by placing the cores in a heated furnace containing a reducing atmosphere of hydrogen and injecting a combination of a hydro-carbon gas and boron trichloride into the furnace. Subsequently, cracking occurs depositing a thin film of boro-carbon over the surfaces of the cores. The resistance value of the film thus formed is dependent on the relative gas concentrations and the duration of exposure in the furnace. By suitable control, blanks having a resistance range from 5 to 250 ohms are produced. After removal from the furnace a band of silver paste, consisting of silver flake in a suitable binder, is applied to each end of the coated ceramic and baked. These bands form the contact surfaces for the terminals.

The resistors are next sorted into resistance groups preparatory to adjustment to the desired resistance value. Resistors having values between 35 ohms and 50 ohms are used to produce the higher resistance values between 250 ohms and 9999 ohms. The resistors falling outside the 35 to 50 ohm range are held for simple adjustment by rubbing. The method used to obtain higher resistance values is to cut a helix through the carbon film using a diamond cutting wheel. Resistance values may be raised by as much as 1000 times by proper selection of the pitch of the spiral groove.

After helixing, these resistors together with those initially outside the 35 ohm to 50 ohm range are fitted with a lead assembly at each end. Final adjustment of the resistance value is obtained by abrading the entire coated surface uniformly to reduce the coating thickness. An adjustment of 15 per cent increase may be obtained by this means. After adjustment, resistors are given a protective coating, code marked and subjected to ten accelerated aging cycles over a temperature range of −50° C to 85° C.

3.43 *Use of Control Charts*

Since the manufacturing processes are essentially common within certain ranges of resistance it has been found possible to maintain control charts associated with the three-cell method for combinations of different values of resistance. In order to handle such combinations the characteristic under control is expressed as a percent deviation from the specified nominal. The control chart for averages then consists of averages of these percent deviations and the range chart is expressed in similar terms. This procedure permits a single chart to represent a large number of resistance values.

Control charts are used at two points in the manufacture of the 200-type resistors. The first chart is applied to the resistance value after adjustment either by rubbing, in the case of lower values, or by the combination of helixing and rubbing used for the higher resistance values.

Estimates based on preliminary studies predict that at half life this type of resistor will age upward by an average of 0.5 per cent. Manufacturing requirements for the nominal resistance values are set 0.5 per cent low in order to compensate for this condition.

The second chart is kept on the finished product after the accelerated aging cycles. This chart is also kept in terms of the percentage deviation from nominal. A comparison of the charts for the product after cycling, which represents the units which are candidates for stock, with those charts at the earlier resistance adjusting operation will show up changes in value due to processing. Appropriate changes in processing or adjustment bogies are made to obtain a more nearly centered value.

3.44 *Shipment of Product*

Although resistor production consists of a series of batch operations with each batch readily segregated and identified, the small quantities involved have resulted in the decision to package all of the product in accordance with the three-cell method.

The use of control charts after adjusting and after cycling has resulted in a more uniform product for the 200A resistors than would have been possible by conventional manufacturing techniques. Initial production experience indicated that the "natural tolerance" of the 200A resistor is better than the ±4 per cent "A" limit originally specified, and this limit was reduced to ±3 per cent.

3.5 2504-TYPE TRANSFORMER

The 2504-type transormer, due to its critical function in the operation of the L3 amplifier circuit, has necessitated the use of completely new materials and methods not usually associated with transformer production. For instance the windings of this transformer are formed by diamond grinding the threads in fused quartz forms upon which a silver coating is bonded by a firing process. The grooves are then filled with electroplated copper, thus producing a winding intimately bonded to the quartz forms. Since the whole manufacturing process is unique and must be controlled in each small detail, application of statistical quality control procedures is essential.

Control of the leakage flux of this transformer, capacitance across the high impedance winding, and the capacitance to ground from the high potential terminal of its high impedance winding is of particular importance. To achieve the desired control of these characteristics, care must be taken to maintain a number of mechanical dimensions to tolerances far more precise than those on any transformer previously made by the Western Electric Company.

For example, the inner diameter of the quartz form, bearing the outer winding, is held to 0.7280 ± 0.0005 inches, while the thickness of the form between the inner diameter and the root diameter of the threads is held to 0.0310 ± 0.0005 inches. Dimensions of other component parts of the transformer must be held to comparable tolerances. To do this, it has been found necessary to keep all facilities — chemical, electrical and mechanical — under careful control at all times.

The facilities provided for the machining of the component parts are such that all critical dimensions which affect the final overall electrical characteristics of the transformer are held to approximately one-third of the design tolerances. By this means, it is expected the resulting transformers produced will meet the desired distribution. In the initial stages of production, records are being kept on 14 mechanical dimensions on each unit, checking them at each critical state of manufacture. The use of extensive mechanical tolerance controls on the components of this transformer is necessitated by the non-adjustable nature of its design. If controls were not applied, it would be impossible to obtain the close electrical uniformity required by the end product. By means of special circuits and testing techniques developed for electrically measuring the characteristics of this transformer it has been found possible to indicate microscopic variations in secondary mechanical dimensions not directly under control.

The problem of bringing this transformer under control is not completely solved. Progress to date in the analysis of the data obtained indicates that the mechanical variations of the parts have complex inter-relations to the electrical requirements; however, manufacturing variations in the parasitic impedances mentioned above are being controlled to an order of magnitude better than on any transformer previously produced.

3.6 VACUUM TUBES

3.61 *General*

Three new vacuum tubes, the 435A, 436A and 437A have been developed for use in the L3 amplifiers. These tubes were described in detail in an article appearing in The Bell System Technical Journal of October, 1951.[5] Two of them, the 435A and 436A are high transconductance tetrodes and the third tube, the 437A is a high transconductance triode. By applying the latest advances in design and in manufacturing techniques to tubes of conventional basic type, substantially higher levels of broadband amplifier performance have been realized.

The key to improvement in broadband amplification lies in an increase in figure of merit or transconductance to capacitance ratio. Figure of merit is a direct measure of the bandwidth over which the required level of amplification can be obtained. In general a given increase in figure of merit can be directly reflected in a wider transmission band which will provide more communication channels.

The higher transconductances and higher figures of merit obtained with the 435A, 436A and 437A over earlier broadband amplifying tubes are a direct result of advances in the art of manufacturing fine pitch grids of sufficient accuracy and rigidity to permit extremely close grid to cathode spacing. The basic objective is to provide a grid which can be placed very close to the cathode to act as a uniform potential plane controlling the cathode current without offering any physical obstruction to the passage of the current. This objective is approached by winding the grid with many turns of very small diameter wire.

The conventional method of grid manufacture consists of winding the grid lateral wire in a spiral around two side rods, usually of nickel. A groove is cut in the side rods at each point where the lateral crosses it and the lateral is placed in this groove. The groove is closed by swaging to fix the lateral in place. In the L3 tubes, the grid lateral wire is approximately 0.0003″ in diameter and the grid to cathode spacing is approximately 0.002″. A ten per cent change in grid cathode spacing would result in a change in transconductance of fourteen per cent. It is important, therefore, that the control grid be maintained very accurately to insure proper grid to cathode spacing. A conventional grid made with such small diameter lateral wire would not be self-supporting in the length of span required and could not be made with the accurate control of diameter needed. Since the size of lateral wire used and the close spacing of adjacent turns preclude notching and swaging, some other method of holding the laterals in place must be employed. Accordingly, a new type of grid construction is used. This consists of making a supporting frame from two large side rods joined together by cross straps located at the ends of the grid proper. On this rigid frame the fine lateral wires are wound. This frame type of grid was described in previous articles.[5, 6] In the L3 grids, the lateral wires have been bonded to the support rods by a glass suspension sprayed along the edge of the support rods. This glass glaze is sintered at a temperature of approximately 700°C to hold the laterals firmly in place. The earlier design used a gold brazing operation to secure the laterals. This brazing was done at a temperature of approximately 1070° C. The newer method at the lower temperature produces less stretching of the laterals and as a result higher residual tension is obtained. This is a distinct advantage in reducing noise and the possibility of grid to cathode shorts.

With the new method of holding the laterals in place, the grids are gold plated after the glazing operation is completed. Gold plating is necessary in order to minimize thermionic emission from the grid wires due to the closeness of the grid to the hot cathode and the possibility that active cathode coating material may be deposited on the grid during processing and operation.

3.62 *Distribution Requirements*

Distribution requirements haved been place on transconductance as well as the most critical inter-electrode capacitances, the input capacitance, $C_{g_1-kg_2}$, for the 435A and 436A tubes and the grid to plate capacitance, C_{g-p}, for the 437A. In the case of the 435A and 437A tubes, control of modulation is also required. Since transconductance is of primary importance, this characteristic has been selected as the one which governs shipment of product. Inter-electrode capacitance and modula-

TABLE IV — CHARACTERISTICS OF VACUUM TUBES STUDIED

435A and 436A	437A
Cathode current (I_k)	Plate current (I_b)
Grid-plate capacitance (C_{g_1-p})	Plate resistance (R_p)
Plate-cathode, screen grid cap. (C_{p-kg_2})	Heater-cathode cap. (C_{h-k})
Grid-heater cap. (C_{g_1-h})	Heater-grid cap. (C_{h-g})
Heater-cathode, screen grid cap. (C_{h-kg_2})	Heater-plate cap. (C_{h-p})
Heater-plate cap. (C_{h-p})	Grid-cathode cap. (C_{g-k})
	Plate-cathode cap. (C_{p-k})

tion are subject to the requirements of the Records method previously described.

In addition to the characteristics mentioned above, control charts were maintained on a number of other electrical characteristics at final test in order to determine process capabilities and to aid in setting final test specification limits. Among the characteristics that were studied were those given in Table IV. It was recognized at the beginning of production of these vacuum tubes that control of the test characteristics could not be achieved without similar control of the critical piece parts and processes going into the assembly of the tubes. Accordingly, control charts were started on the parts and processes, given in Table V, and have been maintained throughout the manufacture of the product.

Production of vacuum tubes represents a complex interlinking of many separate processes, each of which is essentially a batch type of manufacture. These batches vary considerably in size depending on the process or part involved. No part or process can usually be singled out as the controlling effect which would isolate one group of tubes from another. For example, a given lot of 100 tubes would probably be made from cathode blanks taken from a supplier's production run of 5 to 10 thousand parts. The cathode coating would be applied in batches of 50 to 200 parts. The control grid side rods used in making the grid frames would have come from a production run of perhaps 5000 parts and the

TABLE V — PARTS AND PROCESSES ON WHICH CONTROLS CHARTS WERE USED

Cathode blank	Outside diameter
Coated cathode	Outside diameter
Control grid support rod	Outside diameter
Control grid wire diameter	Unplated
Gold thickness	Control grid wire
Control grid	Minimum lateral resonance frequency
Screen grid	Minor axis, outside diameter
Plate	Inside diameter

fine grid wire used in winding the grid might be from a lot of 300 to 1000 meters etched to size at one time. The mounts are generally sealed into their glass envelopes in lots of 50 to 200 and pumped in lots of approximately 50 tubes.

Since the individual batches of parts and processing lots are of such different sizes, the final product does not result in groups of tubes that can be readily segregated into distinctive lots. As the tubes are assembled on a regular running basis the production is treated as being of a continuous nature and the Continuous Production method is applied. Mounts made from each week's production are identified by a serial number and, at test, samples from each week's production are used in determining conformance to the requirements of the distribution specification.

In the application of control charts to the L3 carrier vacuum tubes, the charts kept on the characteristics required by the test specification have been plotted against the C, D and E limits derived from the specifications. The charts kept on the parts and on other test characteristics have control limits derived from the process capabilities. In some cases these natural limits have been compatible with the original drawing limits and in others they have been at variance. Wherever incompatibility was established, an attempt was made to improve the process or where correlation studies justified the action, agreement was reached with the design engineers to increase the drawing tolerances.

3.63 *Application of Control Charts*

3.631 *Cathodes*

The cathodes used in the 435A, 436A and 437A are purchased from an outside supplier. A maximum variation from nominal of ±0.0002″ was specified for the minor axis outside diameter. These limits are tighter than for any previous similar cathode used, the narrowest limits heretofore being ±0.0005″. A control chart established on the first lot of cathodes produced for the 436A and 437A tubes indicated that a standard deviation (σ) of 0.00021″ was obtainable. The 3-sigma limits thus derived of ±0.00063″ in addition to the displacement in the average ($\bar{X}$) for the lot of +0.00026″ represented a completely unsatisfactory condition. By selection of cathode blanks the nominal was reduced to 0.03121″, approximately equivalent to the maximum permitted by the drawing. A much narrower range resulted from this selection. The standard deviation for selected cathodes amounted to 0.000066″ corresponding to 3-sigma limits of ±0.00020″. However, this distorted distribution was still unsatisfactory and attempts were made to obtain cathodes more nearly conforming to the design requirements. In the meantime a sizing operation was introduced in the shop to adjust the existing cathodes to size. By the additional sizing operation, the nominal value was reduced to 0.03102″ almost exactly the desired value. However, the standard deviation of 0.00014″ and 3-sigma spread of ±0.00042″ were still twice the design intent.

A second run of cathodes was obtained in which the average measured 0.03099″ and the 3-sigma limits were ±0.00021″. This substantially fulfilled the design requirements but made it imperative that the average be held precisely at nominal. To avoid differences between measuring instruments an agreement was reached to use a common type of electronic micrometer at both the suppliers' plant and the Western Electric Company. Control charts are kept by the supplier using a modification of the Continuous Production method outlined in the distribution specification. The application of this procedure has resulted in maintaining close control of the averages. Correlation studies on tubes manufactured with these cathodes, have shown that the limits for individual cathodes could be expanded to ±0.00033″.

3.632 *Coated Cathodes*

Three characteristics of oxide coated cathodes are particularly important in producing adequate emissive qualities, satisfactory life and the close spacing required in the L3 carrier tubes. These characteristics are weight of coating, density and coated dimensions particularly length and minor axis. In order to eliminate cathode blank variations from the measurements, dummy cathodes of known weight and precise diameter are included with each spray rack load of 41 cathodes. Measurements of gain in weight and of the increase in diameter due to coating are made on these dummy cathodes. The density can be calculated from these measurements. In addition to the measurements made on the dummy cathodes, control charts are kept on coated length and coated diameter on sample cathodes from each coating lot.

3.633 *Control Grid*

Close control of the minor axis for the frame type of control grid used in all three tube types is obtained by precision manufacture of the molybdenum side rods used in making the grid frame. The design specifications require a tolerance of ±0.0001″ on the diameter of these rods. Adjustment of this diameter is obtained by tumbling the parts, which rounds the ends of the rods at the same time to permit easy insertion of the grid in the support micas. Initial production was measured with a barrel micrometer read to the nearest 0.0001″. The resulting data indicated a standard deviation of 0.00013″. The 3-sigma limits of ±0.00039″ were four times the desired spread. Some portion of this spread was undoubtedly due to the measuring instrument which could not be read with sufficient precision. Subsequent production was measured with a Brown and Sharpe dial indicating barrel micrometer which was calibrated with standard gage blocks. Production measured under these conditions indicated the standard deviation to be 0.00007″ for process limits of ±0.0002″. Fortunately, correlation studies indicated this tolerance to be acceptable. Control charts are kept on the product after the tumbling operation. The desired average is maintained by sampling the side rods for diameter several times during the tumbling operation.

The lateral wire used in winding the control grid is tungsten, etched to a diameter of 0.00029″ ± 0.00001″. The diameter of the wire is measured with a Bausch and Lomb metallurgical microscope equipped with a Filar eyepiece. The magnification used is approximately 450×. During initial production, it was not certain that wire of this size could be obtained consistently to a given nominal value and a chart was prepared adjusting the specified winding turns per inch to accommodate wire sizes from 0.00027″ to 0.00032″.

Control charts kept on the wire diameter have shown that it is possible to make wire consistently to a diameter of 0.00029 ± 0.00001″. Correlation studies have been made comparing grids of various wire sizes and corresponding turns per inch against the related tube characteristics. From these studies it was determined that with wire controlled to 0.00029″ ± 0.00001″, a single winding pitch for each tube could be substituted for the chart of turns per inch originally used. Subsequently, studies were made which enabled a common grid to be used in the 436A and 437A tubes.

After winding, the grids are gold plated. The desired increase in lateral wire diameter as a result of plating is 20 micro inches with limits of ±10 micro inches. This measurement is also made with the microscope equipped with a Filar eyepiece.

Considerable difficulty has been encountered with measurement of wire diameter. Variations between operators have been encountered as well as differences between successive readings made at the same point on the wire. This difficulty has been minimized by careful training of the operators and by taking several readings at each point and averaging them.

The difficulties with instrumentation encountered with measurements of gold plating thickness make it more difficult to establish the standard deviation of the process. By determining the standard deviation of the measuring method used, it appears that a value of 4 to 5 micro inches may be realized. This corresponds to 3-sigma limits of 12 to 15 micro inches. Fortunately, correlation studies have established that this control has resulted in tube characteristics which have more than met the test requirement.

3.634 *Screen Grids*

The screen grids used in the 435A and 436A tubes are of conventional design. The tolerance for minor axis diameter is $\pm 0.001''$. The grids are first wound in strips on a mandrel which is shaped to the approximate dimensions of the desired finished grid. The strips are next degreased and given a preliminary heat treatment at 700° C for 5 minutes and then stretched longitudinally to straighten the side rods. The strips are then cut into individual grids and the loose grid lateral turns are trimmed from the ends. A heat treatment at 925° C for 15 minutes follows and finally the grids are sized, which consists of stretching the major axis on an expanding set of sizing blades to obtain the desired shape and size.

It was felt that it would be difficult to control the minor axis around a desired nominal since so many operations took place between the winding of the grid and the final sizing operation. Corrections for deviation of the center of the distribution usually consisted of slight changes in the amount of stretch imparted at the sizing operation and major corrections were usually attempted by a change in winding location on the tapered winding mandrel.

Process capability studies revealed a parent distribution of approximately $\pm 0.001''$ which is within the specified tolerance but provides no allowance for shift in average from one lot to another. Successive lots of grids processed in the same manner showed a considerable shift in center of distribution, amounting to as much as $\pm 0.0007''$.

Studies were then made to determine the important variables which needed to be controlled in order to minimize the shift in average value. It was found that for a given spool of grid wire, considerable control of the process average could be obtained by careful attention to two points in the processing. The grid minor axis size varied directly as the tension of the lateral wire was increased at the winding operation. By variation in tension, as much as $0.0005''$ shift in process average could be obtained. Secondly, when a more precisely controlled heat treating oven was used which employed a thermocouple in each heat treating boat, it was established that the final minor axis dimension varied inversely with the heat treating temperature. Temperatures between 850° C and 1000° C could be used satisfactorily with a corresponding shift in process average of 0.0006″. In Fig. 11(a) is shown the variation of grid minor axis with temperature and in Fig. 11(b) the variation of size with tension is indicated.

A procedure was then set up which resulted in a more uniform grid production. Each time a new spool of wire is used, a group of 25 grids is wound using a standard value of tension. These grids are processed through final sizing using 925° C for heat treatment and the standard sizing blades. The distribution of these 25 grids is then plotted. The position of the average is noted and correction is made for displacement of the average by a change in winding tension, a change in heat treating

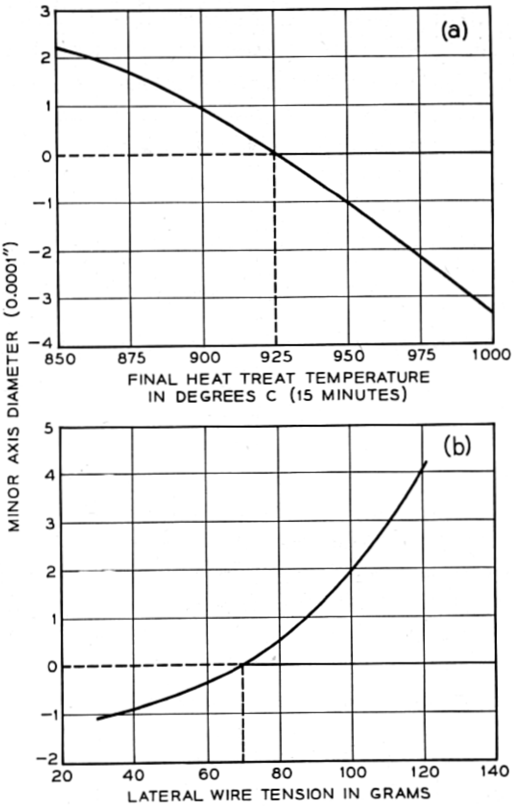


Fig. 11 — Control of grid minor axis in terms of temperature and tension.

temperature or a combination of both. Homogeneous lots of grids, are next run from this spool of wire and are processed up to the sizing operation using the same standard conditions. This test lot of 25 grids is run whenever a new spool of wire is introduced.

The first few grids from each lot are sized on the standard sizing blades and checked against a reset-run chart,[7] a form of sequential analysis. The set-up is satisfactory if the distribution of the minor axis dimension is found to be within 1-sigma (0.0003″) of nominal. If grids pass the reset-run chart the balance of the lot is sized on the standard blades. If the sample does not conform to the reset-run chart, a final correction is made by substituting a larger or smaller set of sizing blades as required.

The distribution of the minor axis after sizing is plotted on control charts. A sample of 5 grids is taken from each tray of 36 grids and $\bar{X}$ and R plotted. If in control the lot is passed. If out of control, the lot is 100% inspected and packaged into three cells. The grids are then shipped to the mount assembly line in the usual 1-3-1 or 0-5-0 distribution. By application of the above controls of processing, variation in the process average from lot to lot has been reduced to ±0.0003″.

In order to keep an accurate record of the grid lots, relating the processes used to the resulting grid distribution, a special lot ticket has been developed. This ticket contains information such as specified tension and temperature along with the reset-run chart and $\bar{X}R$ chart. A ticket of this type accompanies each lot of grids through processing.

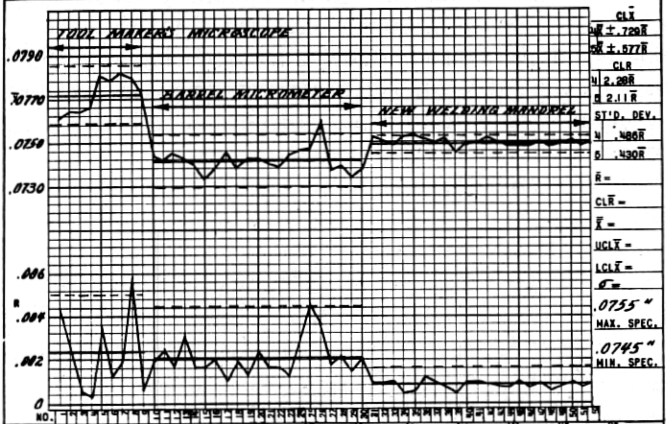
3.635 *437A Plate*

Since the 435A and 436A are tetrodes, the dimensions of the plate in these tubes are not nearly so critical as for the 437A tube, a triode. In the 437A, the plate assembly is made up of two sections welded together on a mandrel. An air press sizing operation is employed to control the inside diameter of the assembly. The drawing requirement for the plate assembly minor axis inside dimension was set at 0.0750 ± 0.0005″. Initial production was measured using a tool maker's microscope sighted on the edge of the plate assembly. Misalignment of the part under the microscope and burrs on the edge of the material contributed to variation in the measured values. In addition, the measurement was made at the edge of the assembly rather than the center which was desired. Results of measurements made with the tool maker's microscope are shown on the first portion of Fig. 12. The plate assemblies appeared to be oversize, although this was at variance with electrical test results on the tubes made from these parts. The standard deviation of 0.00101″ and 3-sigma limits of 0.00303″ were entirely too wide to meet the design intent.

510-A (3-52) CONTROL CHART – ALLENTOWN PLANT

PRODUCT 437-A V.T. PLATE ASSEMBLY DEPT. 1510

CHARACTERISTIC MINOR AXIS INSIDE DIMENSION DATE 1-5-53



1	2	3	4	5	6	7	8	9	10	11	12	13
0754	0777	0766	0769	0759	0774	0787	0770	0771	0753	0744	0737	0734
0787	0751	0760	0767	0788	0775	0774	0753	0777	0750	0740	0753	0732
0763	0763	0766	0766	0784	0785	0794	0779	0771	0744	0754	0744	0736
0760	0757	0764	0766	0794	0773	0788	0812	0771	0738	0729	0741	0751
0742	0760	0765	0766	0774	0781	0774	0788	0771	0734	0739	0750	0763
TOTAL												
X̄ 0761	0764	0764	0767	0780	0778	0783	0780	0772	0744	0741	0745	0743
R 0045	0026	0006	0003	0035	0012	0020	0059	0006	0019	0025	0016	0031
14	15	16	17	18	19	20	21	22	23	24	25	26
0745	0795	0746	0749	0733	0746	0743	0746	0735	0738	0759	0755	0754
0731	0742	0732	0746	0747	0741	0753	0733	0750	0750	0752	0743	0727
0747	0732	0731	0745	0727	0748	0739	0749	0736	0745	0742	0741	0764
0742	0735	0751	0751	0743	0735	0750	0740	0742	0746	0731	0726	0767
0733	0725	0735	0741	0741	0744	0728	0735	0734	0742	0750	0772	0740
0739	0733	0739	0746	0738	0742	0742	0740	0739	0744	0746	0747	0760
0016	0017	0020	0010	0020	0013	0025	0016	0016	0012	0028	0046	0037
27	28	29	30	31	32	33	34	35	36	37	38	39
0737	0736	0743	0739	0765	0753	0755	0753	0755	0755	0750	0754	0745
0752	0736	0739	0725	0746	0754	0746	0755	0754	0743	0751	0752	0746
0734	0741	0729	0755	0755	0745	0751	0754	0754	0752	0747	0752	0745
0741	0758	0730	0734	0755	0753	0746	0753	0753	0753	0755	0747	0747
0722	0727	0734	0738	0755	0748	0747	0750	0749	0754	0745	0753	0742
0737	0739	0735	0738	0753	0750	0748	0752	0753	0751	0749	0751	0745
0018	0022	0014	0021	0009	0009	0010	0004	0006	0012	0010	0007	0005
40	41	42	43	44	45	46	47	48	49	50	51	52
0755	0751	0747	0755	0753	0746	0745	0745	0749	0745	0755	0750	0754
0751	0754	0752	0750	0747	0746	0748	0747	0750	0752	0751	0753	0747
0746	0745	0751	0751	0748	0747	0752	0754	0751	0750	0754	0746	0750
0750	0745	0758	0747	0746	0746	0754	0753	0747	0753	0754	0746	0745
0745	0755	0755	0748	0746	0755	0745	0753	0745	0746	0745	0745	0745
0749	0750	0751	0750	0748	0748	0748	0750	0748	0749	0751	0748	0748
0010	0010	0008	0008	0007	0009	0007	0009	0006	0008	0010	0008	0009

Fig. 12 — A control chart showing the results of using different methods of measuring the minor axis of plate assembly of the 437A vacuum tube.

A change was introduced in measuring technique at this point. The plate assemblies were measured at the center with a barrel micrometer. The thickness of the material was determined for each sample and subtracted to obtain the inside dimension. The point at which the new measuring method was introduced is indicated on Fig. 12. It will be noted that the average value shifted downward when the change in measuring was introduced, although no change in the assembly process was made. The standard deviation of 0.00090″ and 3-sigma limits of 0.00270″ although better than obtained with the tool maker's microscope were still unsatisfactory. Based on the new average $\bar{X}$ for the process, a shift in welding mandrel was made directed at producing an average nearer to the 0.0750″ value desired. The new welding mandrel was provided with heavy spring clips to hold the plate sections in position during assembly. A very uniform product resulted from this tool. The third portion of Fig. 12 represents production of plate assemblies using the new welding mandrel. The average $\bar{X}$ of 0.07495″ was almost exactly that desired and the standard deviation of 0.00035″ and 3-sigma limits of 0.00106″ proved satisfactory and a change in the specification was introduced.

3.64 *Final Test Characteristics*

The controls kept on the critical parts as well as on many other parts of comparatively lesser importance have resulted in distribution of end requirements that have been well within the tolerances in the test specifications. In several cases the process average was found to differ from the nominal value specified. An analysis of the control charts enabled the design and manufacturing engineers to arrive at mutually acceptable adjustments of either the process or the test specifications. Where satisfactory performance would be obtained and the shift could be justified on the basis of control chart records, the specified nominal was adjusted to conform with the process average obtained. At the same time narrower limits, assuring a more uniform product to the L3 amplifiers, were adopted wherever it became evident that these were within the process capabilities.

4.0 Conclusions

The quality control methods described in this paper provide practical assurance that the selected characteristic of any component will have an acceptable distribution centered close to the specified nominal value. In this application, various statistical quality control techniques are an actual part of the product specification. The additional effort required in the application of such procedures is compensated for in part by the valuable assistance they provide in controlling the manufacture of the product. The procedures provide:

1. Means for determining compatibility of the product specification and the manufacturing process capabilities including the accuracy and stability of measuring facilities.

2. Useful techniques for improving manufacturing processes and for indicating the need of replacement or repair of worn tools and machines in the factory.

3. A device for promptly focusing attention on deviations due to changes in raw material or components.

All of these items are useful to both the design and manufacturing engineer in evaluating the relationship between the product design and the manufacturing and testing facilities.

The relatively small number of L3 amplifiers produced to date and the introduction of product design changes and modifications in manufacturing methods, which are inevitable during the early production period of a complex product of this nature, make it impossible to form final conclusions relative to the correlation between the distributions of related characteristics of the components and the final amplifier. Experience indicates, however, that these methods are of considerable assistance to the factory during the introduction of new designs of products of this nature and should, in addition, become a permanent and useful part of the production of products having such critical requirements.

5.0 References

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