Mechanical Strength Properties of Multilayer Ceramic Chip Capacitors

by Jim Bergenthal

Presented at The 11th Capacitor and Resistor Technology Symposium (CARTS) on March 4 - 7, 1991

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F-2106 6/91
Reprinted 5/95

MECHANICAL STRENGTH PROPERTIES OF MULTILAYER CERAMIC CHIP CAPACITORS

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SUMMARY

The mechanical strengths of multilayer ceramic (MLC) chip capacitors are examined. The importance of test methods and parameters such as sample size, calculation of data, and test fixtures are addressed. Research data and empirical analysis are presented which relate strength to process and material characteristics.

INTRODUCTION

The mechanical strength of multilayer ceramic chip capacitors has been investigated at various times[4,5]. It has been difficult to classify. In fact some previous reports have made observations such as . . . the difficulty in characterizing ceramic chip capacitors arises from their really small size . . . can the flexural strength be measured accurately and precisely . . . can consistent results be obtained. All too often the answers to the questions have been uncertain, or even negative.

Research by KEMET Electronics and others[1], has now found mechanical strength can be categorized and measured. In addition, the factors that influence the mechanical strength can be understood and improvements made in the mechanical strength of the product.

MECHANICAL STRENGTH CHARACTERISTICS

The mechanical strength of multilayer ceramic chip capacitors involves more than one attribute. During the surface mount placement process the capacitor is subjected to stresses from the placement machine. Similar stresses can also occur during the tape and reel packaging or testing process at the manufacturers' location. The mechanical strength characteristic used to classify the capacitor's ability to withstand these types of stresses is break strength (sometimes referred to as flexural strength).

After the part is mounted to the substrate and fixed in place via the soldering process, other types of stresses may be applied. The board and the parts may be subjected to stresses in depanelization, handling, testing, or in subsequent system assembly processes. These stresses typically result from forces which bend or flex the substrate. They are transmitted to the capacitor through the solder fillet. The mechanical strength test used to classify the capacitor's ability to withstand these type of stresses is a Flex test. This test is not presently well defined. The parameters involved with flex tests and the capacitors ability to withstand stresses of this nature are under investigation. This should be the topic of another article at a later date.

FLEXURAL OR BREAK STRENGTH CHARACTERISTICS

The mechanical break strength of MLC chip capacitors has historically been measured with the 3 point bend test. The capacitor is mounted in a fixture with the part supported on its terminations. A standard support span distance is used depending on the size of the capacitor. The fixture is then loaded in a strength testing machine such as that manufactured by Instron. A force is applied to the center of the capacitor through a 0.5 mm radius pin or edge. See Figure 1 for a sketch of the test scheme.

Figure 2 explains the general construction of a MLC chip capacitor. The strength properties of MLC chip capacitors were thought to be affected by the combination of the materials and the processes used in the manufacture of the capacitor. The properties of the ceramic material and the electrode materials contribute to the overall strength. In addition, the strength may be weakened as a result of internal or external defects. Internal defects such as voids are known as volume flaws.

Modulus of Rupture (MOR) has been found to be a useful characteristic for normalizing break strength data. The Modulus of Rupture (MOR) is calculated using the following equation.

$$\sigma = \frac{3PL}{2bd^2}$$

where σ = Modulus of Rupture (MOR)
P = Break Strength
L = Fixture Span Length
b = Capacitor width dimension
d = Capacitor thickness dimension

Test data has verified the accuracy of this normalization equation. However other factors need to be considered. (See the following section regarding Bulk Factors). (Additional information regarding calculation and units of measurement regarding MOR are included in Appendix A).

TEST RESULTS

A large number of parts, from a representative cross section of MLC chip capacitor manufacturers, were tested for break strength. The initial tests were conducted using capacitors of X7R dielectric materials. A 1206 size 0.1 μ farad part was selected for ease of comparison. Other dielectric materials and sizes were tested later, and the results are presented in the following paragraphs.

Mean

The mean values of the Modulus of Rupture (MOR) are presented in Figure 3. A significant span in the mean values is seen, ranging from 160 mega Pascals to 330 mega Pascals. Numerous reasons for the difference in MOR means were suggested. No theories proposed made logical sense. The basic ingredient in the X7R dielectrics tested is Barium Titanate. Thus one might not expect the MOR to vary as widely as the test data indicates. The results were compared to some known variables in an empirical fashion. This comparison yielded some interesting results.

The Modulus of Rupture mean values are plotted again in Figure 4. The comparison variable in this case is the percentage of Silver in the capacitors' electrode material. The range of silver used in the electrodes varies from 0% in the capacitors from manufacturers "A" and "B," to 75 % of those in manufacturer "H". The relationship of break strength to the electrode material composition has been an interesting and consistent observation. It has been observed in X7R dielectric capacitors from many manufacturers. The author has not yet tested X7R capacitors from any manufacturer that have digressed from this relationship.

The reason for this relationship has not been firmly established. It is possible that it is related to the microstructure of the ceramic material and the flexural strength properties of the electrode material. Youngs Modulus of Elasticity, for various combinations of palladium and silver, increases as the percentage of silver increases. The microstructure of the ceramic material is probably a larger factor. The microstructure is a function of the base material (largely Barium Titanate), the effects of the material additives on the grain boundary structure, and the size of the grain boundaries. All of these could be distinctive in capacitors from various manufacturers. The manufacturer considers the composition of the selected materials in choosing the firing temperature. The firing temperature will also have an effect on the microstructure. The firing temperature chosen then will determine the electrode material that can be used. Lower firing temperatures will allow the use of higher percentages of silver in the electrodes.

Variation

The variation of MOR is also important. Figures 5 thru 9 show this variation in histogram format. A good distribution should be statistically normal and tightly distributed. The variation of MOR for capacitors from manufacturer "H" appears to be the smallest. Variation of MOR for capacitors from manufacturers "B" and "E" are also small with only one straggler. The variation of MOR for other manufacturers capacitors may not be as normally distributed.

When the MLC chip capacitor is stressed in the break strength test, the failure initiates at a "defect" site in the capacitor. These sites can be small voids, delaminations, weaknesses in the grain boundaries, or defects on the surface of the part. Manufacturers "B", "E" and "H", whose capacitors have smaller variations in break strength, utilize carefully controlled clean rooms in the manufacture of the capacitor. Clean room manufacturing has become very important as one step in the elimination of internal defect sites. Minimizing critical size defect sites have been found to improve the Thermal Robustness as well as the Mechanical Robustness of the capacitor [2,3]. Destructive Physical Analysis of the parts have also confirmed the relative absence of internal defects in parts from these manufacturers.

Analysis of variation is difficult to perform without care in the accuracy of measurements. See the following paragraphs regarding accuracy.

MOR AND BREAK STRENGTH VS. THICKNESS

Knowing that MLC chip capacitors can have different MOR will permit improved estimations of suitability for Surface Mount applications. Calculated break strength values are plotted versus capacitor thickness in Figure 10, for parts with various MOR mean values. To confirm the accuracy of the technique, the break strength was measured on parts manufactured with various thicknesses by the same manufacturer ("H"). These have the same MOR value. The measured break strengths agree with the calculated values, and are also shown in Figure 10 (points on the top curve indicated with a box).

An example of the effect of MOR on the strength of the ceramic chip capacitor follows. From Figure 10A, Supplier "H"'s mean break strength for an X7R chip manufactured at 0.040 inches thick would be 19 Kilograms (See box 1). Parts from the same manufacturer made with a thickness of 0.028 inches would demonstrate a mean break strength of 9 Kilograms (box 2). On the other hand, parts manufactured by "A" with a thickness of 0.040 inches would demonstrate a mean break strength of less than 9 Kilograms (box 3). Parts from "A" manufactured with a thickness of 0.028 inches would demonstrate a mean break strength of slightly more than 4 Kilograms (box 4).

(TO INSURE ADEQUATE BREAK STRENGTH IN THE APPLICATION, A MANUFACTURER USING MATERIALS AND PROCESSES WHICH RESULT IN LOWER MOR VALUES MUST MANUFACTURE THE CHIP WITH A GREATER THICKNESS. A MANUFACTURER USING MATERIALS WITH HIGHER MOR VALUES WILL BE ABLE TO USE LESS THICKNESS TO OBTAIN THE SAME OR HIGHER BREAK STRENGTH).

OTHER DIELECTRIC MATERIALS

As shown above, the mean MOR value is a function of the flexural strength of the ceramic materials, the contribution of the electrode materials, and the effects of the internal and external defect sites. Also important is the microstructure of the fired body of the finished part. MLC chips manufactured from X7R dielectrics appear to have strength ranges where all of the above factors can contribute significantly to the measured value. The other dielectric materials (NPO and Z5U) have strength ranges where one of the above factors appears to dominate over the other.

NPO

The break strength of NPO chip capacitors have historically not been of concern. The break strength is generally higher than the break strength of X7R dielectrics. Parts made with NPO dielectrics have not been reported to be broken during a controlled placement process.

The test data of MLC chip capacitors manufactured with NPO dielectrics is not extensive. Parts from manufacturer "H" were tested. A histogram of the results is shown in Figure 11. The mean MOR is 323 mega Pascals. This is in the same range as the MOR of parts manufactured by "H" with X7R dielectric. Less extensive testing of parts from manufacturer "A" and "B" with NPO dielectric indicate mean MOR of 305 and 315 mega Pascals respectively. These also are in the same high range.

NPO dielectrics also utilize Barium Titanate as one of the main ingredients. The barium titanate percentage is less than that used in the X7R dielectrics. The grain structure is generally finer in NPO dielectrics than in X7R dielectrics. This may be the reason for the high range of MOR values observed.

With the higher value of mean MOR, the variation becomes less important. The variation will be as a result of the same factors as the variation in X7R dielectrics. This appears to be confirmed by the restricted test data taken in NPO dielectrics.

Z5U & Y5V

The break strength characteristics of Z5U and Y5V dielectrics appear to behave very similar to each other. Historically, Z5U and Y5V dielectrics have been considered to be weaker than X7R and NPO dielectrics.

Figure 12 presents the range of MOR mean values for MLC chip capacitors manufactured with Z5U and Y5V dielectrics. Unlike MLC chip capacitors manufactured with X7R dielectric materials, the MOR mean values for Z5U and Y5V dielectrics show little difference from manufacturer to manufacturer. The mean values for the Z5U and Y5V materials are closer to the values of the lower end X7R dielectric manufacturers. (The range of X7R and NPO dielectrics are included for reference in Figure 12).

Z5U and Y5V dielectric materials have larger grain sizes after firing than the NPO and X7R materials. It was thought that materials with larger fired grain sizes were weaker. The failures were thought to propagate along the grain boundaries. Because of this, it appeared that MLC chip capacitors manufactured with Z5U or Y5V materials would characteristically have lower MOR than those made with X7R or NPO dielectric materials. This is supported by the data in Figure 12.

Summary of Ranges

The general ramges of MOR for all dielectrics are shown in Figure 14. Manufacturers E and H have demonstrated the ability to improve the weaker dielectrics. E has improved the Z5U to make it equivalent to its X7R. H has demonstarted the ability to improve the Z5U and X7R to be equivalent to the NPO (See Figure 15).

BULK FACTORS

The Modulus of Rupture is used as a normalization tool. It has been shown to be very effective in comparing samples of a specific chip size, and can be used to calculate the break strength as a function of chip thickness. However, another factor must be included when comparing the MOR of differing chip sizes. Since the presence of volume flaws plays an important role in determination of MOR, MOR is a function of chip size. The larger the chip size, the higher the probability that a flaw will be present to initiate failure. The volume effect is predictable and can be estimated [1]. Figure 13 presents measured MOR values as a function of effective volume, for chip sizes 1206, 1210 and 5819. MOR estimations are then shown for chip sizes 0603, 0805, and 1812. This technique should be reliable provided the volume flaw density remains the same from chip size to chip size. This would not be reliable in comparing more than one manufacturers' parts, as the volume defect density would most likely be different. (The effective volume is calculated by multiplying length times width of the part and assumes a constant thickness. The MOR calculation considers the effect of chip thickness).

MEASUREMENT DISCUSSIONS

The accuracy of mechanical strength measurements is difficult to predict. Quinn [1] was able to demonstrate that the measurements could be performed with good correlation from laboratory to laboratory. They did isolate a number of important techniques to be used to assure some degree of accuracy. These are presented below, along with some discovered in our own analysis.

Sample Size The accuracy of determination of population mean and distribution of data is very dependent on the sample size. Quinn presents the statistical analysis of sample size. We have found good correlation of mean values when the sample size is 30 or more. Larger sample sizes will improve the estimation of the population distribution.

Sample Selection The mechanical strength values can be affected by external defects. Parts with external defects should be eliminated from the sample population.

Sample Preparation The samples should be tested as a complete part. Some concern exists regarding the termination size. The data may be slightly altered if one termination is larger than the other. The force then may not be applied in a perpendicular manner and result in some small error. However, we have found that removing the termination by chemical or mechanical means can increase the risk of exterior damage and stress sites which lower the MOR. The risk of external damage is higher than the error caused by measurement with the termination in place. This also represents the stresses of the application. For technical laboratory analysis, the most accurate measurements can be obtained by testing capacitors that have not been terminated.

Test Techniques The test instruments should be thoroughly cleaned after each sample is tested. The operator should be trained to insure samples are inserted in a like manner. Some error in reading has also been shown to exist in larger test samples, due to the friction of the test pin. This error may be reduced by allowing the pin to rotate during the measurement. More discussion of this is presented in Reference 1.

Graphical Analysis The results should be plotted in a graphical fashion. Histograms are used here, however Weibull analysis may also be used (See Appendix A). Graphical analysis can impart information that may not be seen with a statistical review of the results. For instance, X7R parts manufactured by "A" have a calculated MOR mean of approximately 160 mega Pascals. Based on the observation that the mean MOR varies with the percent silver in the electrode, we would expect the parts manufactured by "B" to have a mean MOR of nearly the same as those manufactured by "A". The test data indicates otherwise. The MOR mean for "B" is approximately 190 mega Pascals. A review of the histograms in Figures 5 through 9, indicates that "B"'s variation is small and well distributed. Parts manufactured by "A" present a poor distribution with many parts on the low end. Further examination of the "A" histogram, indicates a peak at approximately 190 mega Pascals. The poor distribution is distorting the capability of the parts from "A". They may have the same capability as the parts from "B".

Total Error It is difficult to measure mechanical strength. With proper care and sufficient sample size, measurement correlation within 10 to 20% should be obtainable. With extreme care 10% should be obtainable.

RELATIONSHIP TO THE APPLICATION

Direct comparison of break strength values to placement machine stresses is complex. The stresses applied by placement machines can be unique from machine to machine. Some placement machine pipettes are designed to place large quantities of chips. These pipettes are usually made of hard metal. Other machines have soft compliant tips, which may wear out more often. Some machines are designed to be adjusted, others have fixed travel distances. The placement machine industry as a whole has not considered the full range of strengths of ceramic chip capacitors when designing the equipment.

On the other hand, the majority of users of ceramic chip capacitors are not reporting large problems with chip breakage. Some problems with the weaker ceramic chips are being reported, when used on certain types of placement machines. The Surface Mount industry has improved to the point that lower ppm category failures are now being investigated. It is possible that some of these failures are mechanical in nature. Flex strength is a definite consideration, however the probability is high that some of these failures are a result of low break strength.

CONCLUSIONS

1. The measurement and calculation of mechanical break strength is possible and repeatable. MOR is a useful tool for describing and comparing break strength.

2. The mean value of MOR for X7R dielectric capacitors can be estimated empirically. This estimation can be based on the electrode material of the capacitor.

3. Traditionally, the mechanical strength of NP0 capacitors has been the highest followed by X7R and then Z5U dielectrics. This need not be the case as all three dielectrics can be made with high strength.

4. The variables affecting break strength are better understood. The MOR is affected by
   A. The microstructure of the ceramic materials, as influenced by the additives used in the composition.
   B. The electrode materials used, and the influence these have on the fired microstructure of the capacitor.
   C. The volume flaws of the fired capacitor. Increases in strength can be obtained by decreases in volume flaw density. These play a dominant role in the distribution of the MOR values.
5. MOR values do change with chip size. The changes are predictable if the volume flaw density remains similar from size to size.

NOTE: Manufacturer H is KEMET Electronics

ACKNOWLEDGMENTS

This work could not have been accomplished without the valuable assistance of Ms. Beth Scheimann. Dr. C. R. Koripella supplied continuous assistance and technical knowledge that focused the efforts of the work. Dr. L. Mann and Dr. J. Piper provided excellent guidance and advice to improve on the work and the presentation. This article is the result of a fine team effort.

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APPENDIX A

CALCULATIONS

Modulus of Rupture (MOR) and units.

$$\sigma = \frac{3PL}{2bd^2}$$

where σ = Modulus Of Rupture (MOR)
P = Break Strength
L = Fixture Span Length
b = Capacitor width dimension
d = Capacitor thickness dimension

In this calculation P (break strength) is measured in Kilograms, L (fixture span) is measured in cm., and b (capacitor width) and d (capacitor thickness) are measured in cm.

The units of σ (MOR) then are kilograms per square centimeter.

A conversion to mega Pascals is made by dividing $Kg./cm^2$ by 10.2179.

A further conversion to psi is made by multiplying mega Pascals by 145.

Weibel Analysis

Mechanical break strength data is sometimes presented in Weibull graphs. The strengths and probabilities of failure are graphed where the abscissa is the natural log of stress, and the ordinate is ln ln (1(1-Pf)). A least squares rescission line is applied. For more information, the reader is referred to Ref. 1.

Break Strength Test Fixture

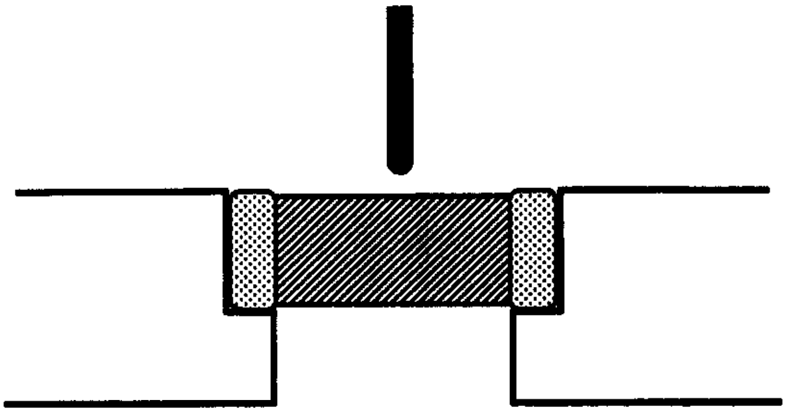


Figure 1

Typical Monolithic Ceramic Chip Capacitor

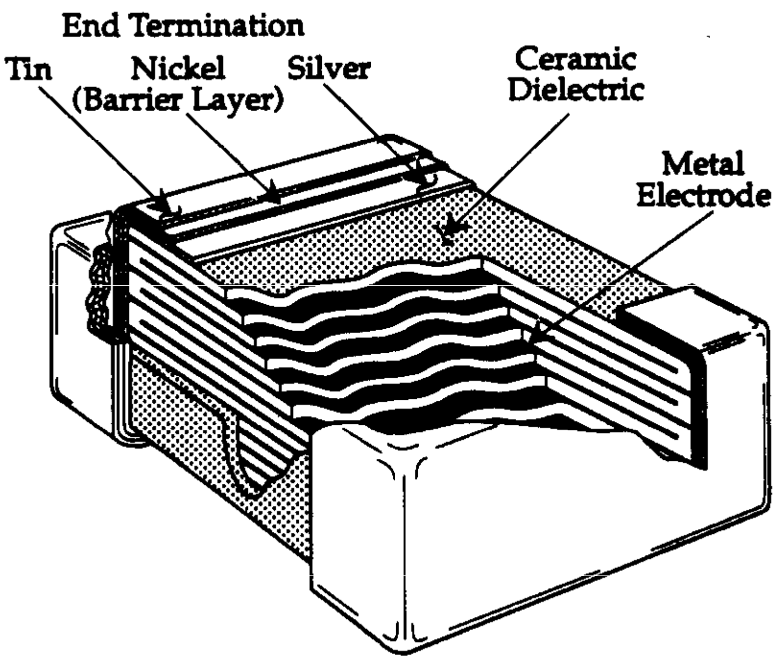


Figure 2

MODULUS OF RUPTURE

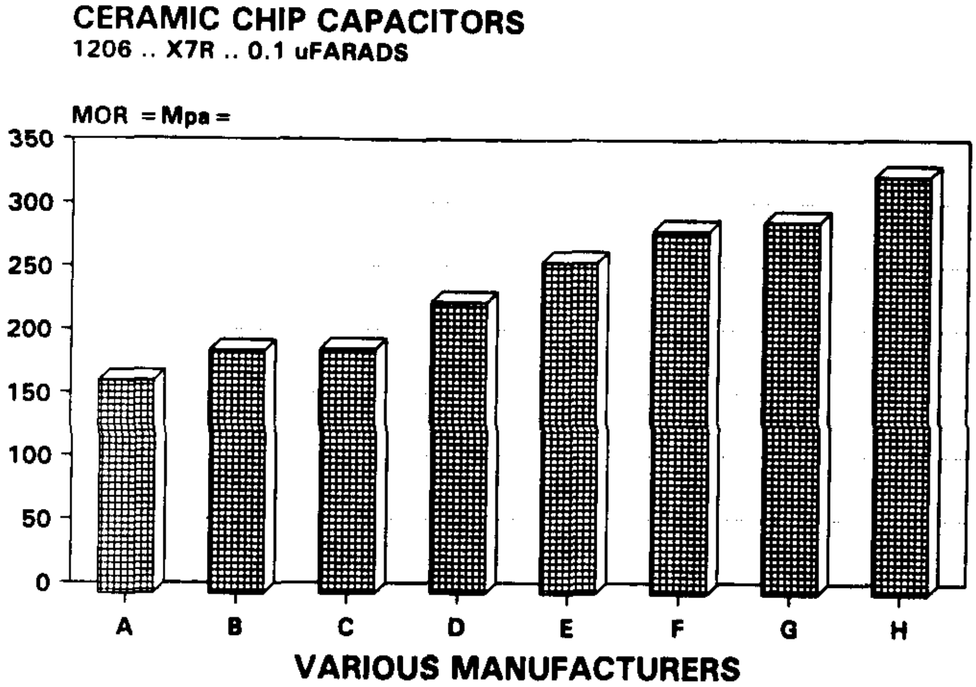


Figure 3

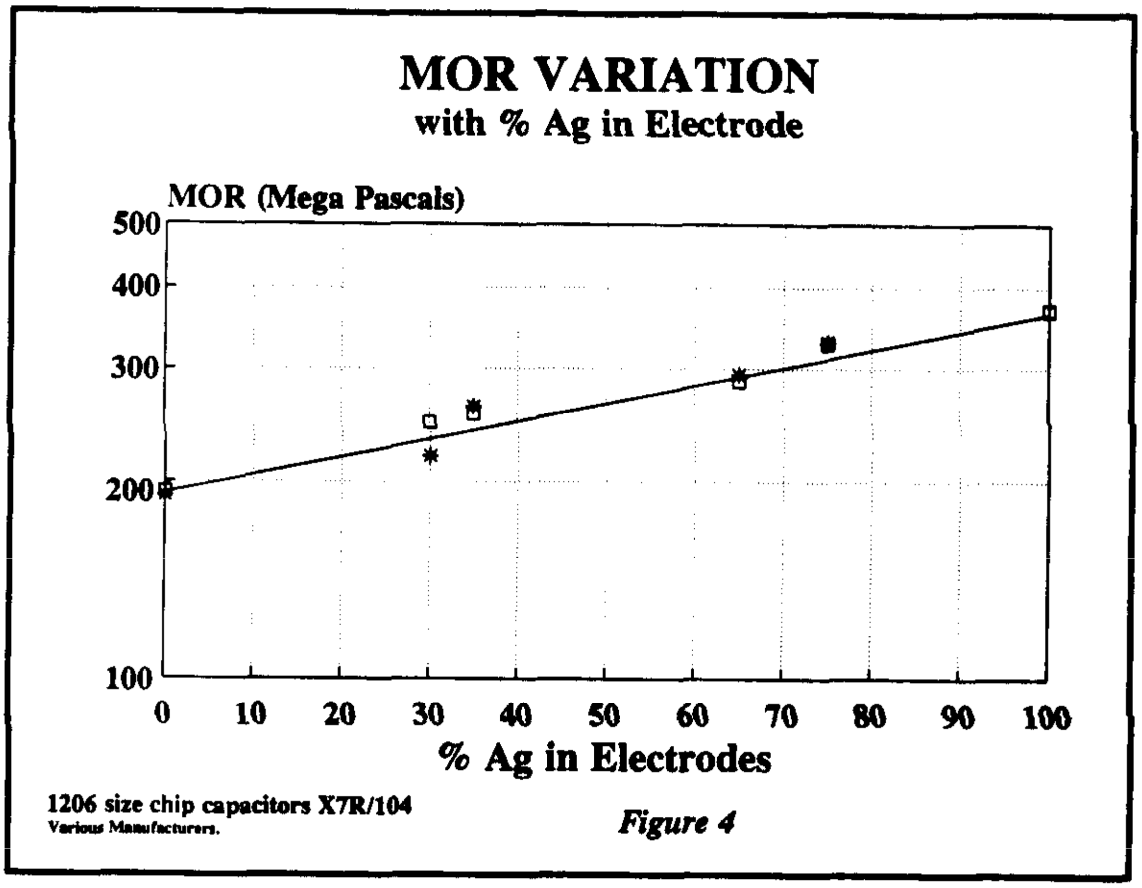


Figure 4

CERAMIC CHIP CAPACITORS
HISTOGRAM

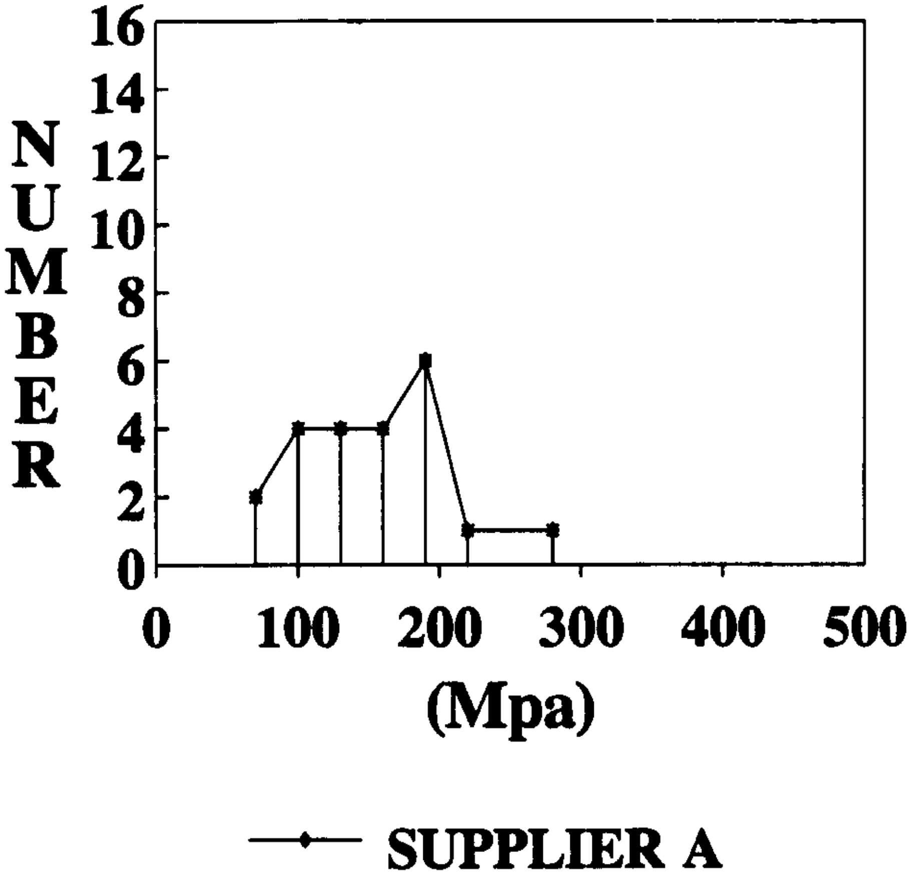


Figure 5

CERAMIC CHIP CAPACITORS
HISTOGRAM

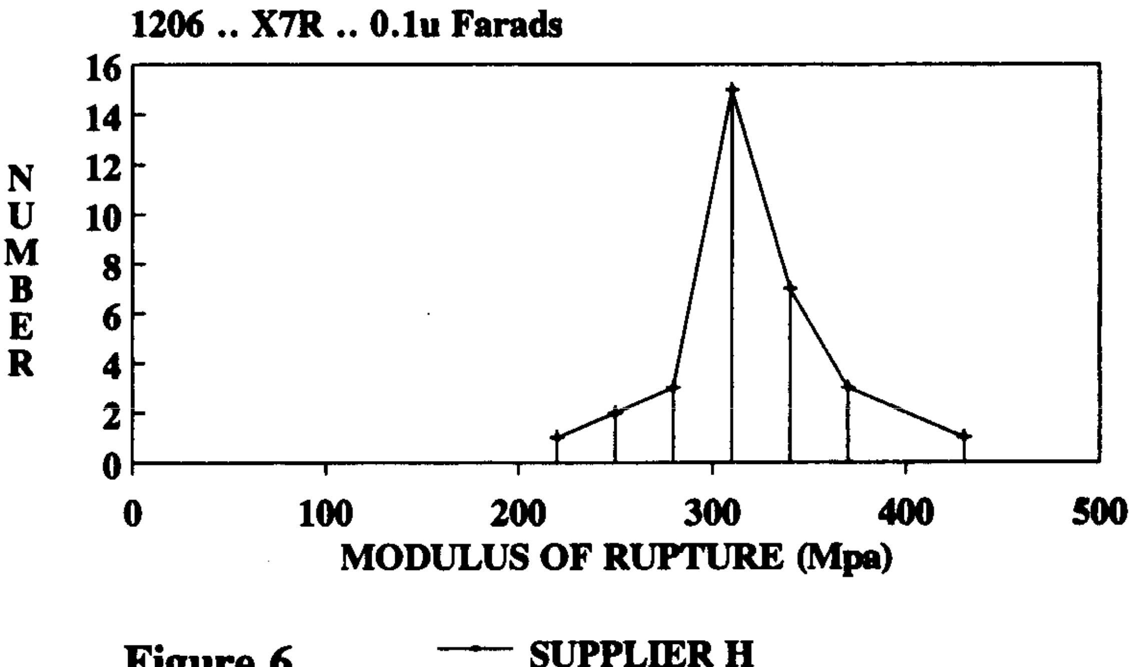


Figure 6

CERAMIC CHIP CAPACITORS
HISTOGRAM

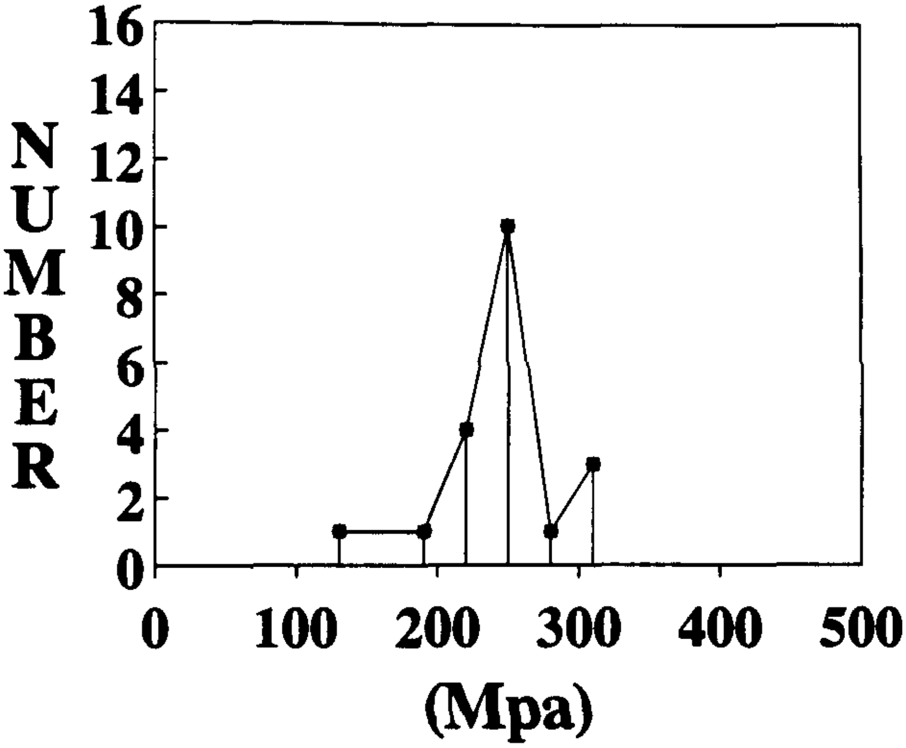


Figure 7 SUPPLIER E

CERAMIC CHIP CAPACITORS
HISTOGRAM

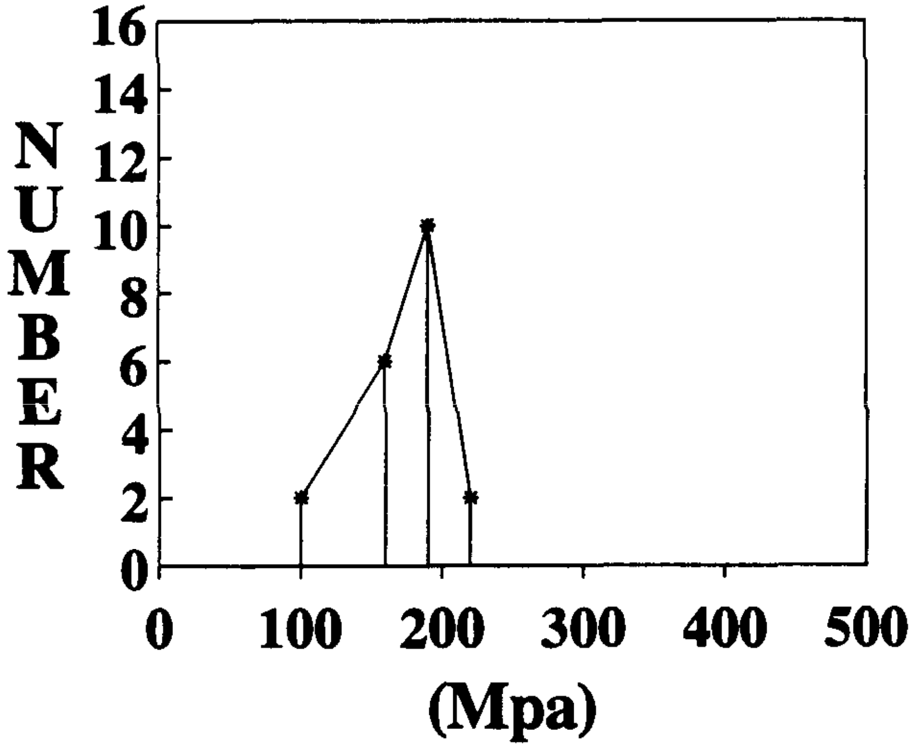


Figure 8 SUPPLIER B

CERAMIC CHIP CAPACITORS

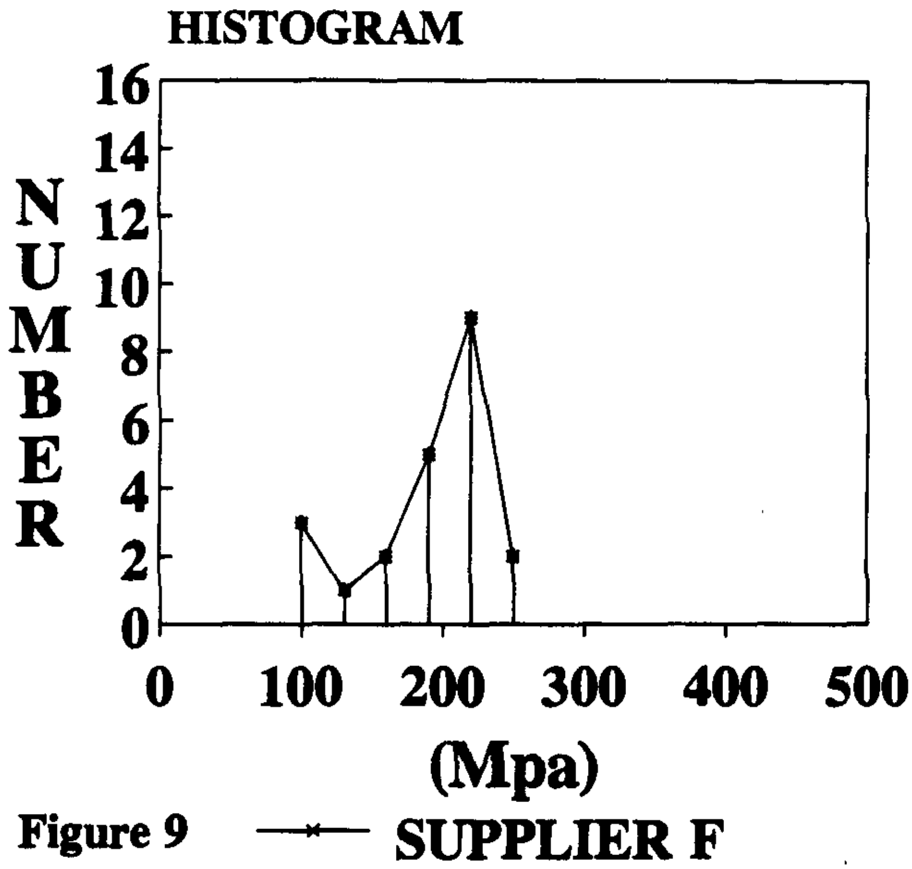


Figure 9

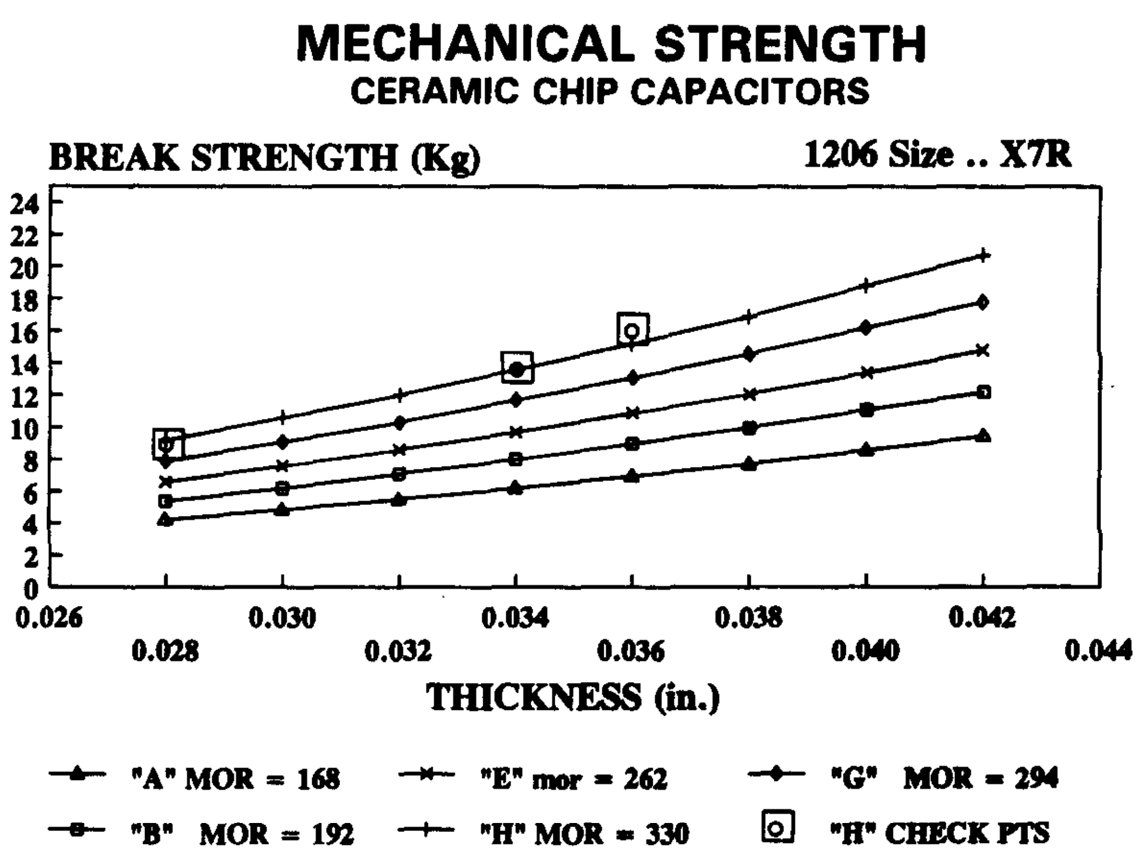


Figure 10

MECHANICAL STRENGTH
CERAMIC CHIP CAPACITORS

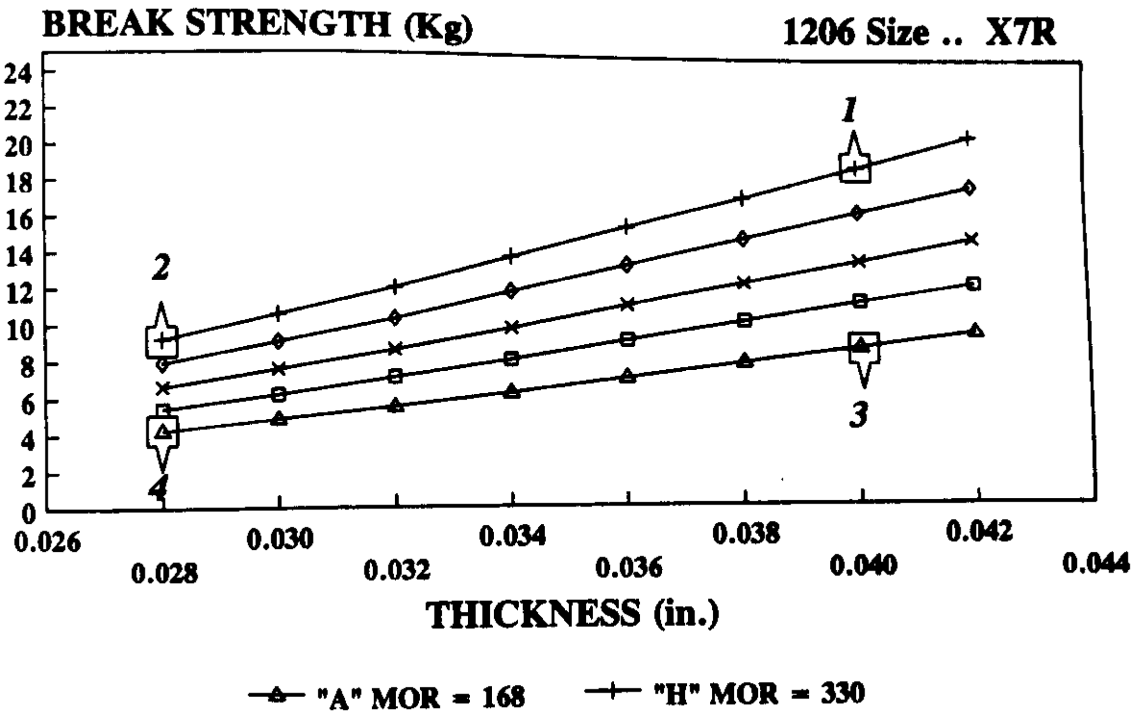


Figure 10 A

CERAMIC CHIP CAPACITORS
HISTOGRAM

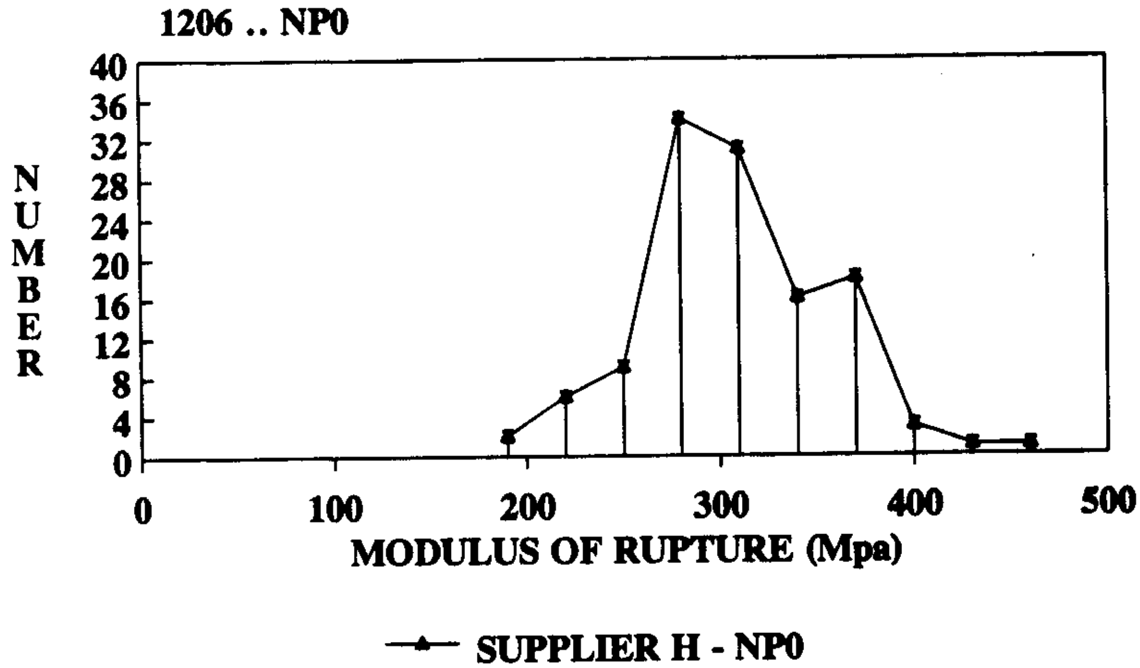
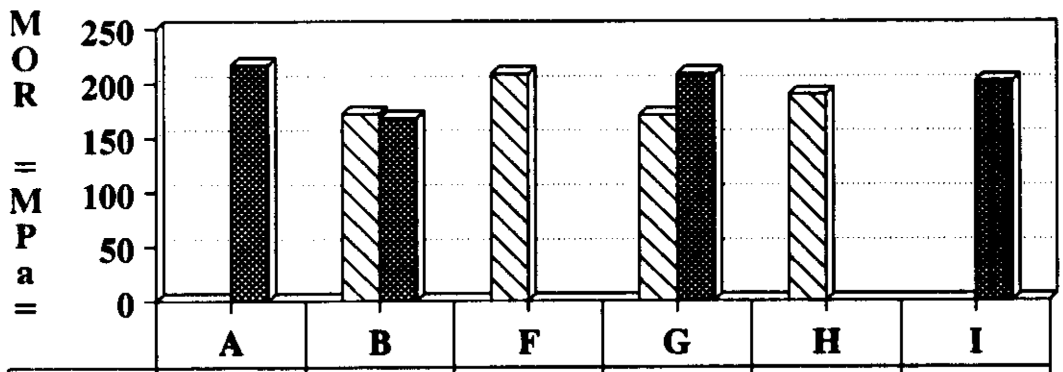


Figure 11

MECHANICAL STRENGTH
CERAMIC CHIP CAPACITORS

1206 ... OTHER DIELECTRICS



	A	B	F	G	H	I
Z5U		172	209	171	190	
Y5V	217	168		209		202

Z5U Y5V

Figure 12

MECHANICAL STRENGTH
VARIATION WITH CHIP SIZE

X7R Dielectric **Supplier H**

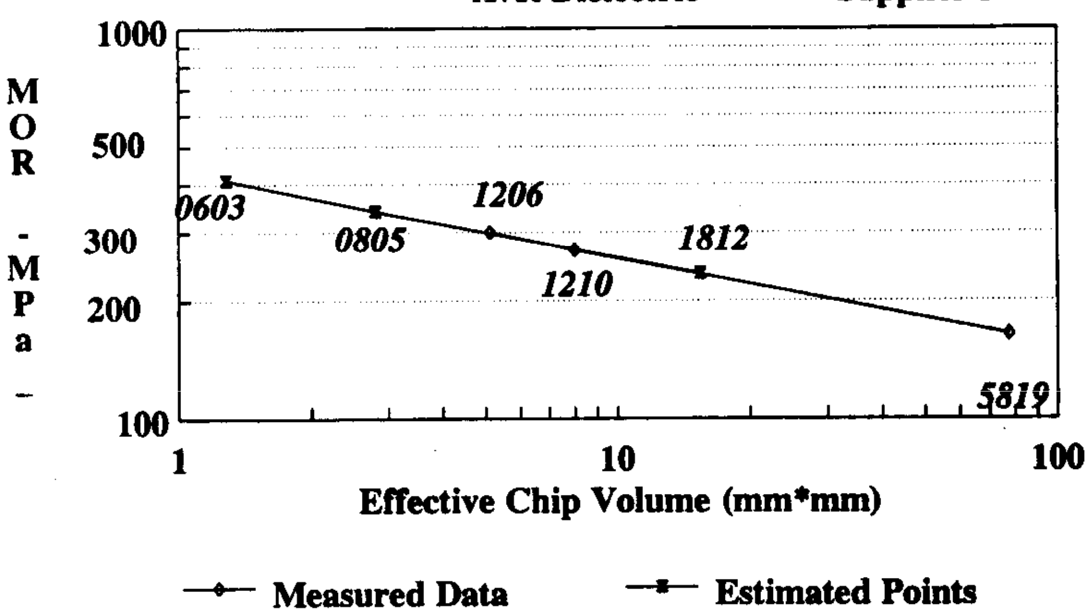


Figure 13

MECHANICAL STRENGTH

GENERAL RANGES

CERAMIC CHIP CAPACITORS ... 1206

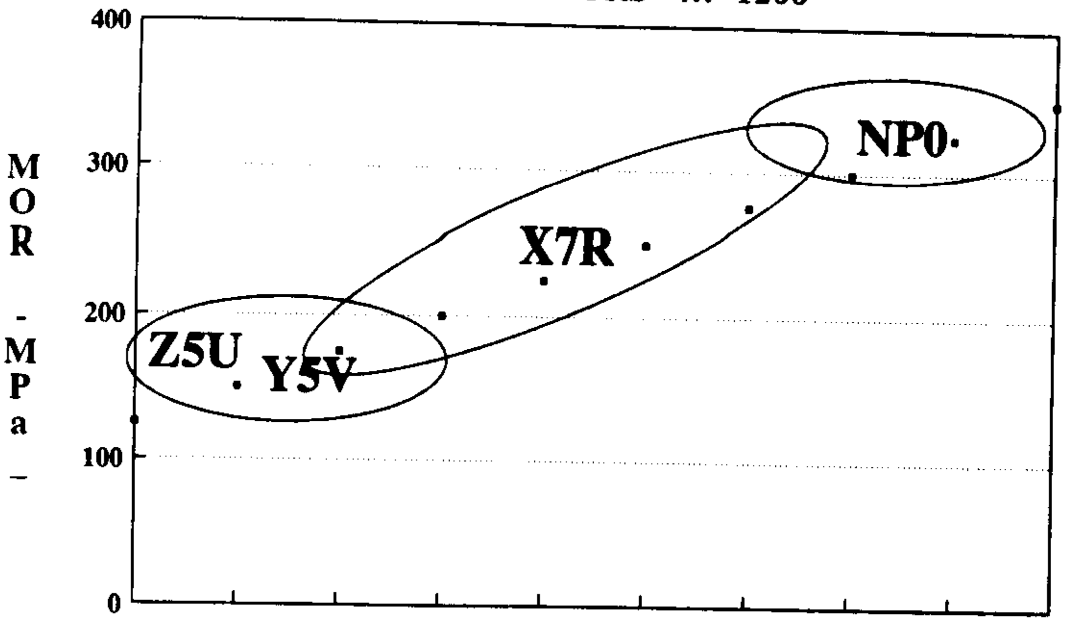


Figure 14

MECHANICAL STRENGTH

IMPROVED PERFORMANCE

CERAMIC CHIP CAPACITORS ... 1206

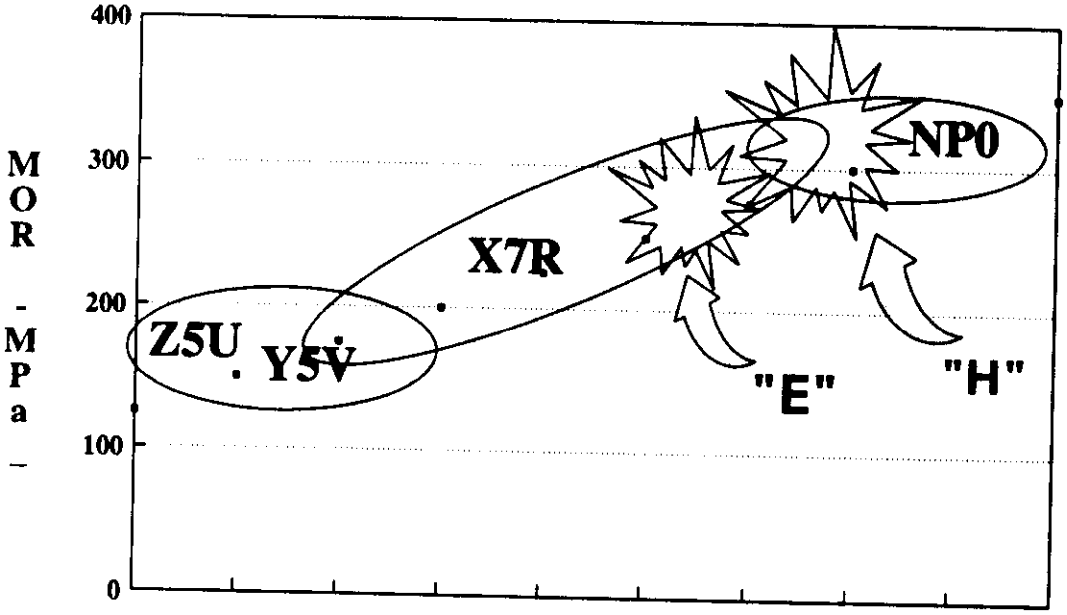


Figure 15