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STRESS RELIEF OF COPPER-CLAD MICROWAVE CIRCUIT LAMINATES TO REDUCE AND PREVENT WARPAGE

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STRESS RELIEF OF COPPER-CLAD MICROWAVE CIRCUIT LAMINATES TO REDUCE AND PREVENT WARPAGE

Abstract

Stresses, inherent in copper-clad microwave circuit laminates, cause warpage when a circuit is etched on one side of the board. The stresses are caused by the process of laminating copper to the plastic board. Prior to etching, the stresses may be eliminated to prevent warpage; after etching, they may be eliminated to reduce warpage. Elimination of stresses in microwave circuit boards is effected by treating the boards cryogenically. The temperature required to stress relieve a board depends upon the composition of the plastic board. A copper-clad fiber glass/styrene copolymer board, which was studied, required -80°C to prevent warpage during etching and to eliminate warpage resulting from etching.

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STRESS RELIEF OF COPPER-CLAD MICROWAVE CIRCUIT LAMINATES TO REDUCE AND PREVENT WARPAGE

INTRODUCTION

A common occurrence in the production of microwave components is warpage of copper-clad plastic laminates when a microwave circuit is etched on one side of the laminate. Because two boards are mated, with circuits facing, to form a sandwich structure, to say that this creates a problem is a gross understatement. Although the boards are flexible enough to be pulled together with screws, the effects of performing such an operation can be disastrous.

As a prerequisite for an explanation of this problem, we shall review a brief history of strip line microwave component technology and establish the cause of warpage.

HISTORY OF STRIP LINE MICROWAVE COMPONENT TECHNOLOGY

As early as 1949 the possibility of using flat-strip transmission line to replace coaxial cable and waveguide hardware for UHF microwave components was introduced at the Air Force Cambridge Research Center. The new design cut down tremendously on volume and weight of components and offered higher reliability. Since coming into widespread use in the late 1950's and early 1960's, this technology has been subject to many advances and problems.

Flat-strip transmission line consists of flat conductors, supported on a rigid dielectric medium, utilizing printed circuit techniques of manufacture. Two of the precision printed circuit boards are mated to form a "sandwich." Each board has a flat copper circuit, which is actually one-half of the electrical circuit, on one side, A microwave circuit laminate with copper on both sides is manufactured by first making sheets of the plastic. Fiber glass/styrene copolymer sheets are made by polymerizing styrene and another monomer in the presence of fiber glass. There are many different types of boards with varying dielectric properties. Among these are a styrene copolymer and polyethylene.

Once the sheet is prepared, the copper foil must be applied to both sides. Either the monomer of the board substrate or some other suitable adhesive is employed for bonding copper to the board. Lamination is carried out at elevated temperatures under pressure and the product from this process is the laminate for making circuit boards. This operation is the root of the warpage problem. To eliminate it would mean elimination of the warpage problem, but not without sacrificing the copper-clad board.

Why is the lamination process the source of trouble? To find that answer one must look at the physical properties of the plastic board, the physical properties of the copper, and the lamination process, which was said earlier to be a heat and pressure process. The pertinent physical property to examine is the coefficient of linear thermal expansion. For the fiber glass/styrene copolymer, the coefficient is higher than that of copper, and we find that the lamination process takes place at 150°C. Thus we know that two materials with different coefficients of linear thermal expansion are heated. From this wealth of information may we assume stresses are imposed during lamination? Since warpage of any kind is the result of unequal stresses, it should be a safe assumption. Now we shall see how the unequal stresses develop.

Using the coefficients of linear expansion and a temperature of 150°C as the lamination temperature, it is easier to explain this particular warpage than most warpage caused by unequal stresses. A check of data sheets revealed that the coefficient of linear thermal expansion of the board under investigation was $5.7 \times 10^{-5}\ {}^{\circ}C^{-1}$; and, for copper (at 20° C), it was $1.65 \times 10^{-5}\ {}^{\circ}C^{-1}$. If we study the lamination of copper to a board with a length of nine inches and assume the coefficients of expansion to be linear (a gross error), the stresses can be visualized.

Starting with a nine inch length of the fiber glass/styrene copolymer board and a nine inch length of copper foil, we find the lengths at laminating temperature to be as follows: $\ell_{t_f} = \ell_{t_i}\ [1 + \alpha\ (t_f - t_i)]$ where ℓ is the length in inches, α is the coefficient of linear expansion, t_f is the 150°C lamination temperature, and t_i is ambient temperature, 20°C. The length of the board at 150°C is given by:

$$\ell_{t_f} = \ell_{t_i}\ [1 + (5.7 \times 10^{-5}\ {}^{\circ}C^{-1})\ (150\ {}^{\circ}C - 20\ {}^{\circ}C)]$$

$$= 9\text{ in.}\ [1 + 741 \times 10^{-5}] = 9\text{ in.} + 66.69 \times 10^{-3}\text{ in.}$$

$$= 9.067\text{ in.}$$

Thus we see that nine inches of board at 20°C would be 9.067 inches at 150°C. This figure is nice to know, but it has little importance. Of more interest is the length of copper foil since it, having the lower coefficient of expansion, is the limiting length factor. Its length at the lamination temperature of 150°C is given by:

$$\ell_{t_f} = \ell_{t_i}\ [1 + (1.65 \times 10^{-5}\ {}^{\circ}C^{-1})\ (150\ {}^{\circ}C - 20\ {}^{\circ}C)]$$

$$= 9\text{ in.}\ [1 + 21.4 \times 10^{-4}]$$

$$= 9\text{ in.} + 193.05 \times 10^{-4}\text{ in.}$$

$$= 9.019\text{ in.}$$

Thus, the length of copper foil at the lamination temperature is 9.019 inches. This figure also represents the length of board, at 150°C, which is bonded to the copper.

When the lamination process is complete, the laminate returns to room temperature (20°C for our purposes). As the laminate cools, the materials contract, but, because of differences in expansion coefficients, the length of the copper at 20°C should be greater than that of the board as shown below: For this board, $\ell_{20\,^\circ C} = \ell_{150\,^\circ C}\,[1 + \alpha_B\,(20\,^\circ C - 150\,^\circ C)]$. Solving this equation to find the length of 9.019 inches of board cooling from 150° C to 20° C:

$$\begin{aligned}\ell_{20\,^\circ C} &= 9.019 \text{ in.} \quad [1 + (5.7 \times 10^{-5}\,{}^\circ C^{-1})\,(20\,^\circ C - 150\,^\circ C)] \\ &= 9.019 \text{ in.} - 66.84 \times 10^{-3} \text{ in.} \\ &= 8.952 \text{ in.}\end{aligned}$$

Thus, the length of board equal in length to 9.019 inches of copper at 150°C would normally be 8.952 inches at 20°C, but the copper will be 9.000 inches. Since the board is bonded on both sides by this copper, it will only contract to 9.000 inches. This means the board is held extended .048 inch beyond its normal length and is stressed.

The board cannot contract farther than 9.000 inches because of the copper on both sides, but, as we discussed earlier, a circuit is produced on one side of the board by removal of all but a small portion of the copper. What happens to the fiber glass/styrene copolymer board when the copper is removed from that side? That side, because it no longer has copper holding it extended, tends to contract to its normal length of 8.952 inches. Since the opposite side of the board still has its supporting copper intact, unequal stresses develop. Contraction of one side of the board actually pulls a bow or warp into the board.

Although some assumptions were made for this illustration, they do not negate what actually happens. The figures obtained are by no means realistic, but they show the mechanism of warpage of fiber glass/styrene copolymer and other board materials that exhibit coefficients of expansion greater than that of copper.

If we had been dealing with a board material with a coefficient of expansion less than that of copper, what differences would the calculations performed earlier produce? We would find that the copper is held extended by the board.

Etching a circuit on one side of a board having the copper extended would also result in warpage, but in a direction opposite that observed in the first illustration. Warpage in a direction away from the circuit is caused by contraction of copper on the side opposite the circuit. This contraction is made possible by the removal of stress-equalizing copper when putting the circuit on the board.

REDUCTION AND PREVENTION OF WARPAGE

Now that the warpage cause has been established, we shall study the methods for preventing and reducing this problematic effect. To prevent warpage, inherent stresses must be eliminated before a circuit is etched on the board. To remove or reduce warpage, stresses present in the warped board must be equalized or removed. Each of the above situations will be discussed separately.

If the decision is made to prevent warpage from occurring, the first question to come to mind is how to go about eliminating the stresses inherent in the boards due to the lamination process. We found earlier that the lamination process was thermal-oriented, a fact which rules out a heat treatment type of stress relief. Thus, it appears that, if stress relief is to be effected, it must be done at a low temperature. Investigations revealed that this method indeed provides stress relief for materials such as copper-clad fiber glass/styrene copolymer. This laminate, treated at -80°C for one to two hours, will not warp when a circuit is produced on one side of the board by the etching process. In a similar manner, etched boards that are warped can be flattened. They need only to be restrained in a flat position and subjected to - 80°C for one to two hours.

Before discussing the details of the processes, we should try to answer the common question concerning why a treatment such as this prevents or reduces warpage. To be honest, the answer is not simple. There are many factors entering into stress relieving this type of material, and few can be understood. One factor is an apparent slippage of the bond between copper and board. From our examination of the relative coefficients of expansion, we know the fiber glass/styrene copolymer board will contract more than the copper. We also know that the board, prior to the cryogenic treatment, is held extended by the copper. Thus, even without cooling to effect contraction, the board is tending toward that end. Evidently, there occurs a slight slippage of the bond between the copper and the board, which neutralizes the extension of the board by the copper. It is useless to try to calculate or estimate this effect using coefficients of expansion because of non-linearity of the coefficients in this temperature region and other contributing factors. One of the other factors is an inexplicable change in the crystalline structure of the fiber glass/styrene copolymer.

The influence of this change on stress relief is not fully known, but it has been shown not to affect the physical or electrical properties of the microwave board. The change in structure has been noted through the use of x-ray analysis, but that is the only knowledge one has of this phenomenon.

Other factors influencing the stress relief at this low temperature are not known, but it is evident that slippage of the bond is the major contributor. One may ask, "if the bond slips, shouldn't the copper be extended when the laminate returns to room temperature?" The answer to this is a qualified "yes". The extent has to be small, probably because the mass difference between copper and board makes warpage caused by this condition very remote.

It is known that there is an optimum stress-relieving temperature for different types of laminates. The optimum temperature for the fiber glass/ styrene copolymer which was under investigation is -80°C if that temperature is maintained for one to two hours. Lower temperatures for the same duration result in reverse warpage; i. e., warpage caused by extended copper, and higher temperatures are insufficient to complete stress relief. These points add to the case for slippage of the bond as a major factor. The reverse warpage must be due to copper extended beyond its normal length more severely than that found to result from optimum temperature slippage. Subsequent etching or removal of copper from one side of the board allows the copper on the opposite side to contract toward its normal length.

Now, with the theories aside, the cryogenic treatment of the fiber glass/ styrene copolymer board will be studied in detail. This material is representative of microwave circuit board materials and has been the object of study by IBM-Huntsville in cooperation with its subcontractors.

It should be brought out at this point that cryogenically treating boards to prevent warpage must be done with flat boards. If the unetched boards are warped to any degree (which is inexplicably the case in some instances), they must be physically flattened prior to the cryogenic treatment as must be etched boards which are warped. If this is not done, the treated boards will retain the shape they displayed prior to treatment.

The warped boards are placed in an oven and slowly heated to 100°C. This operation serves one purpose only: to make the boards flexible enough to be physically flattened with the least amount of stress or strain on the board. It is important that this heat operation not be interpreted as having any other purpose. While the boards are hot, they are clamped between two pieces of aluminum or other flat material. The clamping operation could be performed on boards at room temperature; but unnecessary stresses would be put on the boards and the possibility of cracking exists, expecially if any holes had been drilled at this point.

The clamped boards are then slowly cooled to a temperature of -80°C. Once this temperature is reached, it is maintained for one to two hours before it is allowed to return to room ambient. Some heat may be used to decrease the time required to raise the temperature, but a minimum of one-half hour should be used in reaching room ambient. The boards are then unclamped. At this point, hey are flat and sufficiently stress relieved to prevent warpage during etching or, in the case of etched boards, to remain flat. Such is the treatment for warped boards, etched or unetched.

Unetched, flat boards to be cryogenically treated for prevention of warpage during etching need not be heated or clamped prior to taking to -80°C. The full treatment for these boards is the cycle from room ambient to -80°C and back to room ambient as discussed for warped boards. Boards so treated will go through etching with little or no warpage.

Tables I and II give figures to show the effectiveness of both methods, i.e., treatment of boards prior to and after etching. As can be seen in Table I, boards that had not been treated cryogenically prior to etching warped as much as 0.5 inch along a 9.0 inch length. Subsequent treatment reduced this warpage to a negligible amount or to none at all. In comparison, Table II shows the effect of treating boards prior to etching. The amount of warpage as a result of etching treated boards is essentially nil. Note that the first two samples shown in Table II gave results that were not too much to brag about, but these were obtained during the establishment of optimum conditions for cryogenically treating this material.

One may ask, "What effect does this treatment have on the board?" Admittedly, it would seem that a change in crystalline structure of the board and slippage of the copper-to-board bond would leave "after-effects", but this is not the case. The boards do not become embrittled by the process nor is the bond weakened to any noticeable degree. Components made from boards treated in the manner have passed vibrational and other tests designed to qualify units for flight.

As stated earlier, optimum conditions must be established for different materials. To give an example of the variance in temperatures required, copper-clad polyethlene is quenched in liquid nitrogen by one manufacturer immediately after laminating copper to the board. Polyethylene has a linear coefficient of expansion of 17×10^{-5}, which is much greater fiber glass/styrene copolymer. Were it not for the cryogenic treatment of quenching in liquid nitrogen, these boards would literally curl up when the copper is removed from one side of the laminate.

A point to be clarified is that the treatment discussed here is for materials commonly used for microwave circuits. Printed circuit boards, which are usually constructed of epoxy/fiber glass, differ from microwave circuit boards in thickness, in rigidity, and, of greater importance, in electrical characteristics. Printed circuit boards normally do not have copper remaining on one side as a shield. This does not mean that there are no warpage problems associated with printed circuit boards; indeed, these problems exist, but they are not related to warpage experienced with microwave boards. Most warpage problems in printed circuit boards can be traced to elevated temperature processing of boards constructed of epoxy that is not completely cured.

Table 1. Results of Treating Fiber Glass/ Styrene Copolymer Boards Warped by Etching

Board Size (in inches)	Warpage (2) Prior to Treatment (1) (in inches)	Warpage After Treatment (in inches)
5 x 9	0. 5	0. 008
5 x 9	0. 5	None
3 x 9	0. 3	0. 010
4 x 4	0. 25	None

(1) Treatment performed as described in this report.

(2) Warpage measured as maximum height from flat surface along the length of the board.

(3) Relatively poor results in first two boards were due to establishing optimum conditions.

Table 2. Results of Treating (1) Fiber Glass/Styrene Copolymer Boards Prior to Etching

Board Size (in inches)	Warpage (2) Caused by Etching (in inches)
5 x 9	0. 10 (3)
5 x 9	0. 08 (3)
5 x 9	None
5 x 9	None
5 x 9	None
5 x 9	0. 008
5 x 9	None

If there are limitations or restrictions to the cryogenic treatment of microwave circuit laminates, they are few. The only limitation of which we are aware is that, once the boards are treated, they should not be subjected to elevated temperatures. Fiber glass/styrene copolymer should remain below 100°C, but other materials would have different temperature limitations. As a matter of interest, it should be noted that, if the unetched boards are not warped and equal amounts of copper are to be removed from both sides of the board, the cryogenic treatment is not necessary.

It may be difficult to explain fully the mechanism of stress relieving microwave circuit boards by a cryogenic treatment, but this is relatively new technology as is stress relief of metal parts, after heat treating, by treating cryogenically. Tremendous results have been obtained in this latter area but the reasons for the results are very elusive to investigators.

SUMMARY

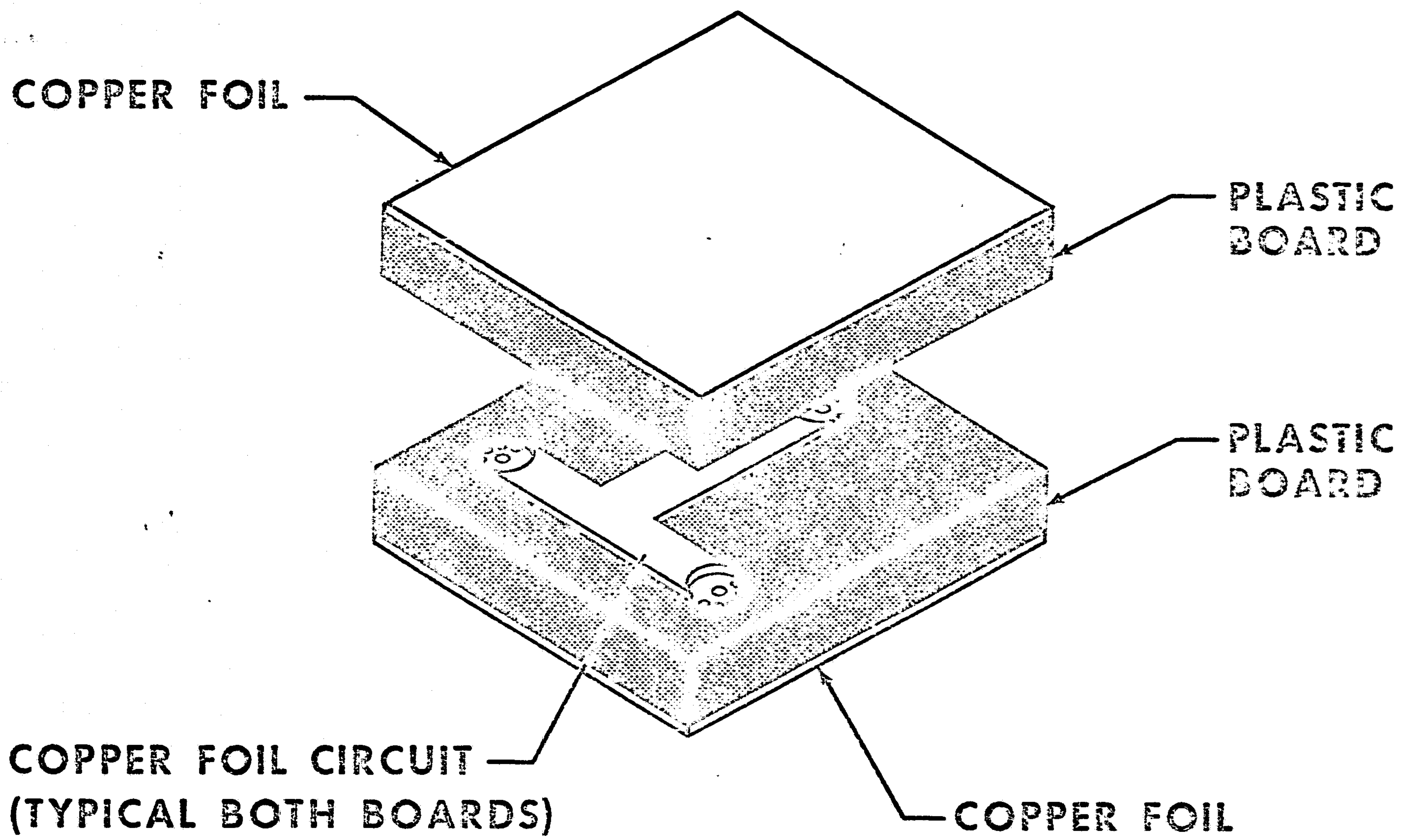
In review, we see that the problem under investigation was warpage of copper clad materials exhibiting dielectric constants suitable for use in the ultra high frequence strip-line circuit boards in microwave components. The process of applying copper foil to both sides of the board induces stresses in the board by causing copper or board to be held extended from its normal length, depending upon relative coefficients of linear expansion. When the microwave circuit is etched on one side of the board, the supporting stress on that side of the board is removed and warpage occurs. The direction of warpage (i. e., toward or away from the etched side) is dependent upon whether the copper or the board is the stressed material. With copper-clad fiber glass/styrene copolymer boards, the substrate has a higher coefficient of expansion than copper and is the stressed material. Warpage in a system such as this is toward the etched board.

Prevention of this warpage problem is accomplished by stress relieving the copper clad board at cryogenic temperature (-80°C for the fiber glass/styrene copolymer) prior to etching. If this process is not employed and an etched, warped board exists, the warpage can be removed by physically flattening the boards at an elevated temperature and maintaining them in the flat conditions while treating cryogenically. Boards treated in this manner emerge flat and remain so unless subjected to elevated temperatures which would simulate the copper lamination process.

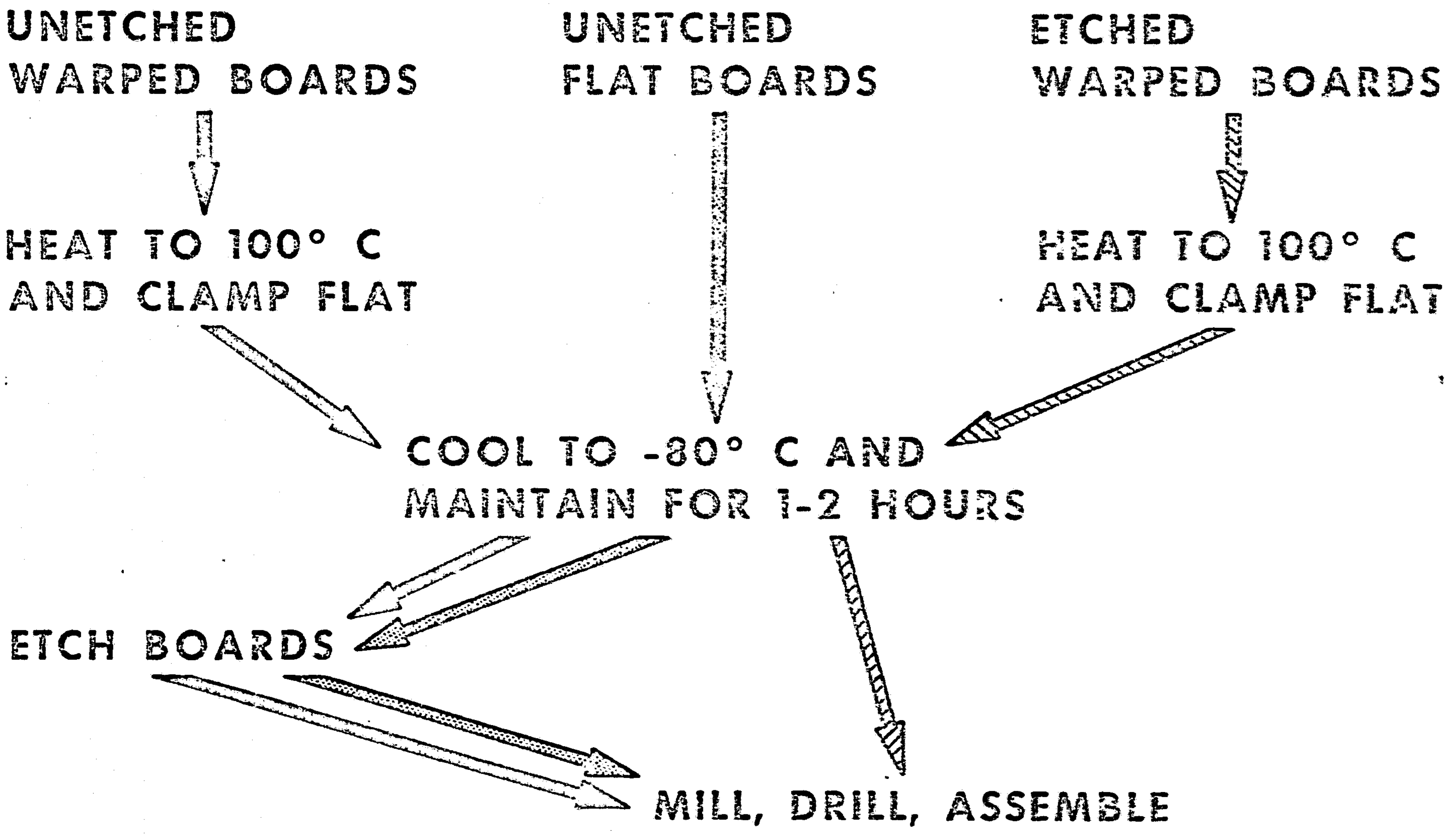
The use of cryogenic treatments as stress relieving or warp-preventing measures appears to be widening and should provide much new technology in the future. Without a doubt, theorists will have exciting times attempting to explain mechanisms, while people in manufacturing will be, for the most part, content with the knowledge that they work.

The following illustrations were used as slides in Mr. Boone's oral presentation.

TYPICAL STRIP-LINE SANDWICH



PROCESSING CHART TO INCLUDE CRYOGENIC TREATMENT



UNETCHED
WARPED BOARDS

HEAT TO 100° C
AND CLAMP FLAT

UNETCHED
FLAT BOARDS

ETCHED
WARPED BOARDS

HEAT TO 100° C
AND CLAMP FLAT

COOL TO -80° C AND
MAINTAIN FOR 1-2 HOURS

ETCH BOARDS

MILL, DRILL, ASSEMBLE

RESULTS OF TREATING (1) FIBER-GLASS/STYRENE COPOLYMER BOARDS PRIOR TO ETCHING

BOARD SIZE (IN INCHES)	WARPAGE (2) CAUSED BY ETCHING (IN INCHES)
5 × 9	0.10(3)
5 × 9	0.08(3)
5 × 9	NONE
5 × 9	NONE
5 × 9	NONE
5 × 9	0.008
5 × 9	NONE

(1) TREATMENT PERFORMED AS DESCRIBED IN THIS REPORT.

(2) WARPAGE MEASURED AS MAXIMUM HEIGHT FROM FLAT SURFACE ALONG THE LENGTH OF THE BOARD.

(3) RELATIVELY POOR RESULTS IN FIRST TWO BOARDS WERE DUE TO ESTABLISHING OPTIMUM CONDITIONS.

RESULTS OF 9.019 INCHES OF FIBER-GLASS/STYRENE COPOLYMER BOARD COOLING TO 20°C FROM 150°C

$$\ell_{t_F} = \ell_{t_i}\left[1 + \alpha_B\,(t_F - t_i)\right]$$

ℓ	LENGTH IN INCHES
α_B	COEFFICIENT OF LINEAR EXPANSION OF BOARD
t_F	20°C
t_i	150°C

$$\ell_{20°C} = 9.019\ \text{IN.}\left[1 + (5.7 \times 10^{-5}\ °C^{-1})\ \ (20°C - 150°C)\right]$$

$$= 9.019\ \text{IN.}\left[1 + (-741 \times 10^{-5})\right]$$

$$= 9.019\ \text{IN.} - 66.84 \times 10^{-3}\ \text{IN.}$$

$$= 8.952\ \text{INCHES}$$

RESULTS OF TREATING FIBER-GLASS/STYRENE COPOLYMER BOARDS WARPED BY ETCHING

BOARD SIZE (IN INCHES)	WARPAGE (2) PRIOR TO TREATMENT (1) (IN INCHES)	WARPAGE AFTER TREATMENT (IN INCHES)
5 × 9	0.5	0.008
5 × 9	0.5	NONE
3 × 9	0.3	0.010
4 × 4	0.25	NONE

(1) TREATMENT PERFORMED AS DESCRIBED IN THIS REPORT.

(2) WARPAGE MEASURED AS MAXIMUM HEIGHT FROM FLAT SURFACE ALONG THE LENGTH OF THE BOARD.

RESULTS OF HEATING A NINE-INCH LENGTH OF COPPER TO 150°C FROM 20°C

$$\ell_{t_F} = \ell_{t_i} \left[1 + \alpha_c \left(t_F - t_i \right) \right]$$

ℓ LENGTH IN INCHES

α_c THE COEFFICIENT OF LINEAR EXPANSION OF COPPER

t_F 150°C

t_i 20°C

$$\ell\ 150^\circ C = 9\ \text{IN.} \left[1 + (1.65 \times 10^{-5} {}^\circ C^{-1})(150^\circ C - 20^\circ C) \right]$$

$$= 9\ \text{IN.} \left[1 + 21.4 \times 10^{-4} \right]$$

$$= 9\ \text{IN.} + 193.05 \times 10^{-4}\ \text{IN.}$$

$$= 9.019\ \text{IN.}$$

RESULTS OF HEATING A NINE-INCH LENGTH OF FIBER-GLASS/STYRENE COPOLYMER BOARD TO 150°C FROM 20°C

$$\ell_{t_F} = \ell_{t_i}\left[1 + \alpha_B\,(t_F - t_i)\right]$$

ℓ	LENGTH IN INCHES
α_B	COEFFICIENT OF LINEAR EXPANSION OF BOARD
t_F	150°C
t_i	20°C

$$\ell\ 150°\mathrm{C} = 9\ \mathrm{IN.}\left[1 + (5.7 \times 10^{-5}\,°\mathrm{C}^{-1})\,(150°\mathrm{C} - 20°\mathrm{C})\right]$$

$$= 9\ \mathrm{IN.}\left[1 + 741 \times 10^{-5}\right]$$

$$= 9\ \mathrm{IN.} + 66.69 \times 10^{-3}\ \mathrm{IN.}$$

$$= 9.067\ \mathrm{IN.}$$