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SSC 401

# TOOLING AND PROCESS PARAMETER IMPROVEMENTS LEADING TO IMPROVED DIMENSIONAL CONTROL OF THE CURED SSC DIPOLE COILS

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## Abstract

Several factors which contribute to sizing errors of molded 50mm SSC dipole model coils are analyzed and corrections for improving these factors are suggested. These corrections include trimming in of the tooling, adjusting the process sequence, modulating the material characteristics, and modifying the cure schedule.

## Introduction

The SSCL efforts at FNAL include winding and curing 40mm long and short dipole coils and, most recently, 50mm short dipole coils. All of these coils have been measured for aximuthal size every three inches along the straight sides of the coils. This data was analyzed to find correlations to the individual elements of the curing mold tooling. A parallel study was also done on "ten stacks" of 40mm inner cable to determine how varying the curing parameters of cure temperature and cure time would effect the size and modulus of elasticity of the final coil.

Table 1 lists the factors which contribute to the finished coil size.

The first factor is the tolerances of the construction materials. In order to review their effect on sizing, Table 2 displays the accumulation of tolerances for the 50mm inner coil. These tolerances are "given" by the individual specifications and must be compensated for by the next two factors.

## Table 1. Factors Contributing to the Finished Coil Size

1. **Construction Materials**
   - A. Cable
   - B. Kapton Film
   - C. Glass Tape
2. **Tooling**
   - A. Winding Key
   - B. Sizing Bars
   - C. Mandrel
   - D. Liner
   - E. Optional Shims
3. **Curing Process Parameters**
   - A. Temperature of Cure
   - B. Length of Cure
   - C. Percent of Epoxy in Glass Tape
   - D. Cavity Pressure
   - E. Curing Press Sequence
   - F. Mold Release Compound

## Table 2. Tolerances of Construction Materials

50mm Inner Coil (19 turns, 3 wedges)

| Material | Tolerance | Total Occurances | Variation |
|---|---|---|---|
| Cable | ± .0002" | 19 Turns | ± .0038" |
| Kapton (tm) | ± .00005" | 4 X 22 Layers<br>(including wedges) | ± .0044" |
| Wedges | ± .001" | 3 | ± .003" |
| Total Possible Variation(without glass-epoxy tape) | | | ± .0112" |
| Glass-epoxy Tape | ± .0005" | 22 | ± .011" |
| Total Variation with Tape | | | ± .0222" |

Estimated Displacement of the Glass-Epoxy Tape During Cure:

| | | |
|---|---|---|
| .0001" minimum | 22 Layers | .0022" |
| .0002" maximum | 22 Layers | .0044" |

Apparent Variation Which Must Be Accomodated By the Tooling and Process .040"

The second factor is the tooling elements which are illustrated in Figure 1. It can be seen that the mandrel, sizing bars and the key form a closed cavity once the platen is closed against the platen stop bars. In this view it is apparent that the final azimuthal size of the cured coil is dependent on the tolerances of the two sizing bars, the key bar, and the thickness of the platen stop. Not only do these elements each directly control the absolute size of the left and right sides of the cured coil but the differences of symmetry in the tooling can effect both the absolute sizes and relative difference in size of each side. For example, if the left sizing bar is .002" larger than the right sizing bar the result could be that <u>both</u> sides of the coil are .001" smaller because the key bar and the coil may have low enough friction with the sides of the liner to slide .001" counter-clockwise. However, in the inner coil tooling the inner coil fills an arc of about 72° on each side of the tool (Figure 2) which increases the friction between the coil and the liner enough so that if the left sizing bar again was .002" larger than the right bar, the coil would <u>not</u> slide counter-clockwise and the left side of the coil would be cured .002" smaller than the right side.

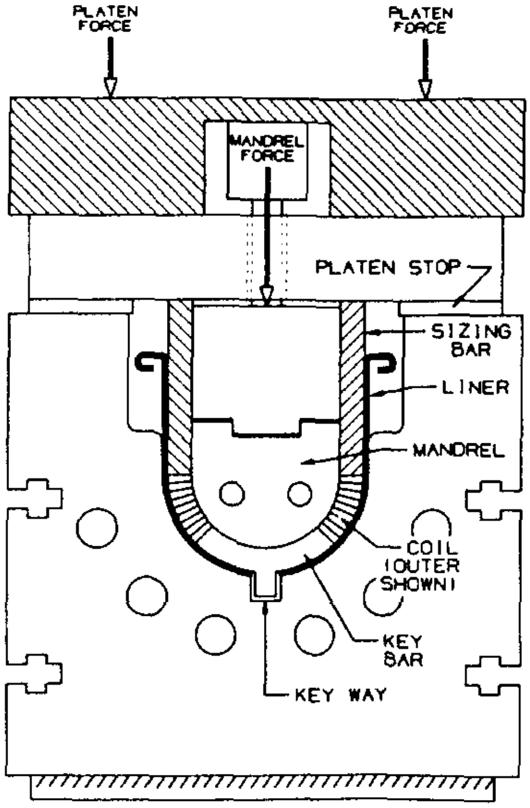


Figure 1. SSC 50mm Curing Tool Elements With Outer Coil in Place.

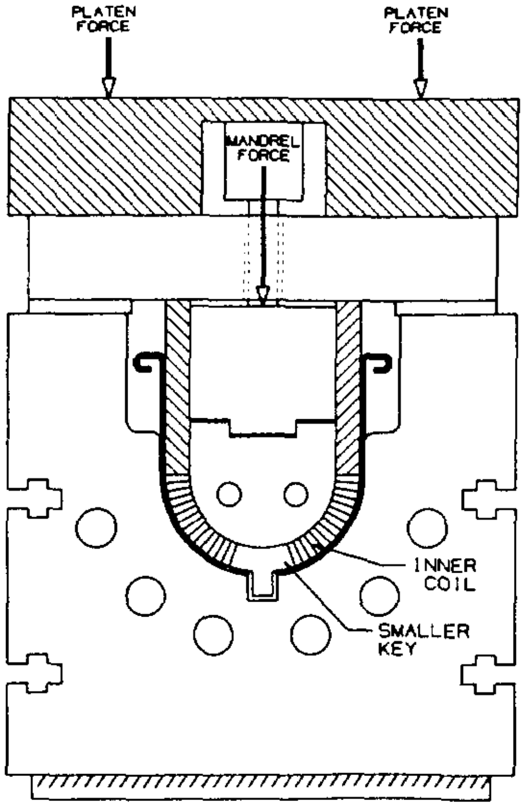


Figure 2. Curing Tool With Inner Coil in Place.

These are just a few of the possible scenarios taking place in the curing mold. A new graphical method has been developed to aid in sorting and analyzing these scenarios.

The third factor contributing to the finished coil size is the curing process parameters. Studies performed on "ten stacks" of cable have revealed how the various construction elements of the cable displace during the curing process and their relationship to time and temperature. These relationships suggest ways to control final size and modulus of elasticity by varying time and temperature of the cure cycle.

## Measuring the Azimuthal Coil Size

The established method of coil sizing first divides the coil to be measured into 3-inch segments running along the straight sections of both sides of the coil (Figure 3). Although much of this work was performed on the 40mm long and short SSC dipole coils at Fermilab, this discussion will generally confine itself to the 50mm short SSC dipole coils manufactured during late 1990 and early 1991. These short coil segments were defined as shown in Figure 3. Notice that these coils have 14 segments on each side of the coil. The sides of the coil are referred to as Quadrants I/III or Quadrants II/IV, referring to their future positions in the assembled coil. This naming follows the names of the quadrants in mathematical graphing.

The sizing fixture is composed of a hydraulic cylinder which drives a three-inch wide rectangular ram down on a captured three-inch segment of the coil and an electronic displacement measuring device to report how far the ram deviates from the size of a steel "master" segment that was measured earlier.

Presently, the ram is pressurized to 8,000 and 12,000 coil psi and size deviation readings taken at all of the 14 segments on both quadrants , i.e. both sides, of the coil. In addition, size deviation readings are taken at 6,000 and 10,000 coil psi at segment positions 3, 6, 9, and 12 on both sides of the coil. The displacements are recorded while going up in pressure and again while going down in pressure.

The 8,000 and 12,000 coil psi size deviation readings are used to compute the modulus of elasticity of the coil segment while the 6K, 8K, 10K, 12K, 10K, 8K, 6K psi sequence size deviation readings are used to study hysteresis effects in the coil.

All these master and deviation readings are entered into an Excel (Trademark of Microsoft, Inc.) spreadsheet which processes this raw data into the typical statistical information shown in Table 3.

This data is then plotted to display the Quadrant I/III size with respect to the master and the modulus of elasticity for segments 3, 6, 9, and 12 as shown in Figure 4. The same is done for Quadrant II/IV as shown in Figure 5.

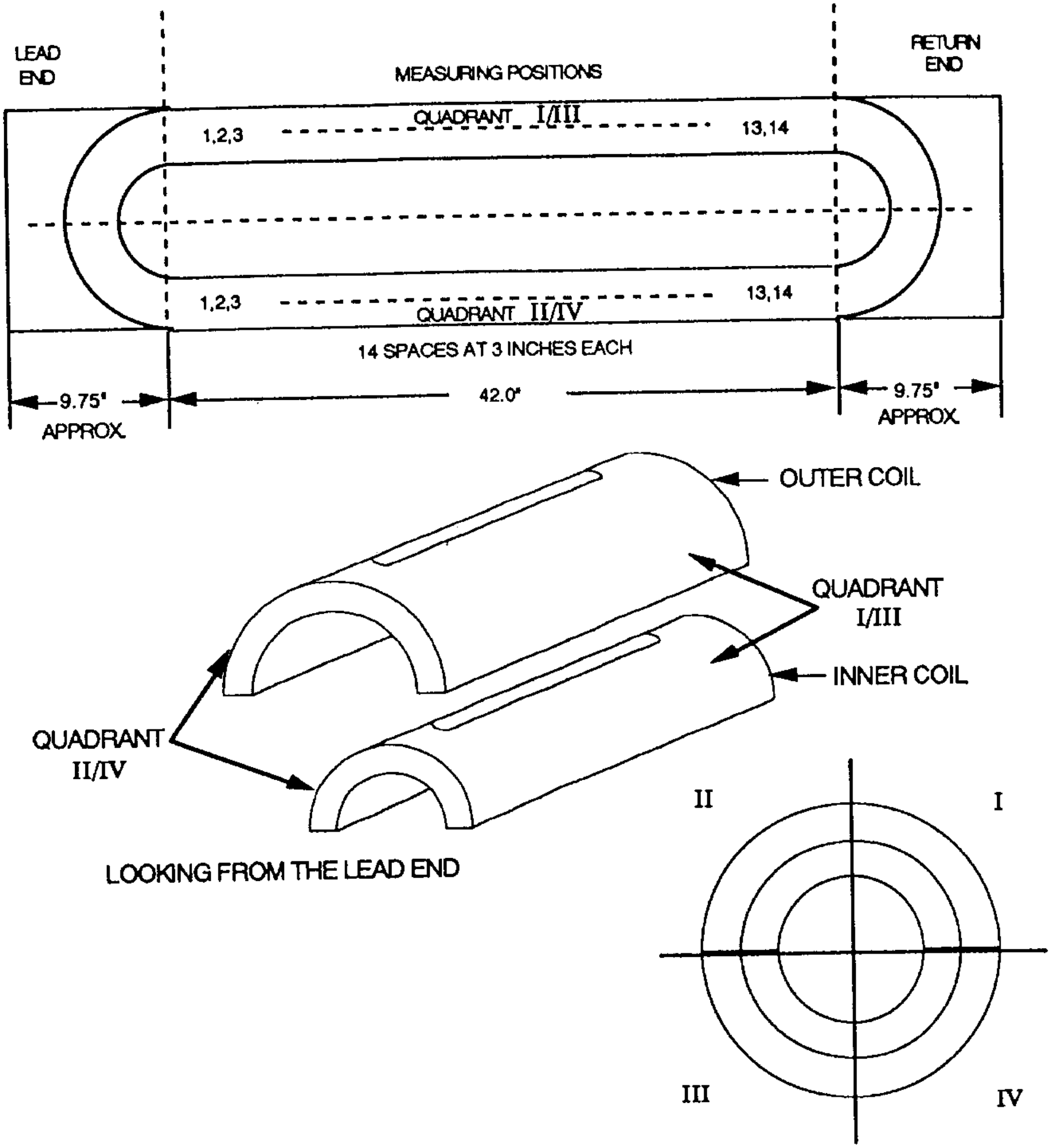


Figure 3. Method of Defining the Measuring Positions

# Table 3. Typical Azimuthal Measurment Report
# For 50mm Inner Coil

SHORT 50MM Inner Coil # 1M-50-117

Master Used - Inner Master #1 Shim Size Used - No Shim Used

Machine Serial Number Used - Not Available Mean Arc of Master - 1.5946"

| QUADRANT I/III POSITION 1-14 | 8 kpsi | 12 kpsi | MOE |
|---|---|---|---|
| AVERAGE | 0.0087 | 0.0057 | 2.43E+06 |
| STD DEV | 0.0010 | 0.0014 | 2.37E+05 |
| RANGE | 0.0025 | 0.0054 | 4.95E+05 |
| MAX. | 0.0100 | 0.0079 | 2.78E+06 |
| MIN. | 0.0075 | 0.0025 | 2.28E+06 |

| QUADRANT II/IV POSITION 1-14 | 8 kpsi | 12 kpsi | MOE |
|---|---|---|---|
| AVERAGE | 0.0097 | 0.0064 | 2.33E+06 |
| STD DEV | 0.0004 | 0.0014 | 8.76E+04 |
| RANGE | 0.0009 | 0.0049 | 1.75E+05 |
| MAX. | 0.0101 | 0.0083 | 2.46E+06 |
| MIN. | 0.0092 | 0.0034 | 2.28E+06 |

| WHOLE COIL | 8 kpsi | 12 kpsi | MOE |
|---|---|---|---|
| AVERAGE | 0.0092 | 0.0061 | 2.38E+06 |
| STD DEV | 0.0009 | 0.0014 | 1.74E+05 |
| RANGE | 0.0026 | 0.0058 | 4.95E+05 |
| MAX. | 0.0101 | 0.0083 | 2.78E+06 |
| MIN. | 0.0075 | 0.0025 | 2.28E+06 |

(AVERAGES, STD DEV, RANGE, MIN, MAX, FOR CALCULATIONS ABOVE ARE FROM THE COIL WITH RESPECT TO THE MASTER)

MEASUREMENT DATA

Coil # 1M-50-117 Coil Type: Inner Date: 3/15/91 MEAS. BY: K. Kriksey

| | Stress: | ---- 6000 ---- | | ---- 8000 ---- | | --- 10000 ---- | | --- 12000 --- | | COIL SIZE WITH RESPECT TO THE MASTER | | DEVIATION FROM THE WHOLE COIL AVERAGE AT 12000 | MODULUS OF ELASTICITY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pos # | Coil | Master | Coil | Master | Coil | Master | Coil | Master | 8000 | 12000 | | |
| Quad. I/III | 1 | | | | | | | 0.9966 | 0.9941 | | 0.0025 | -0.0036 | |
| | 2 | | | | | | | 0.9985 | 0.9941 | | 0.0044 | -0.0017 | |
| | 3 UP | 1.0087 | 1.0000 | 1.0054 | 0.9979 | 1.0027 | 0.9960 | 0.9988 | 0.9941 | 0.0075 | 0.0047 | -0.0014 | 2.28E+06 |
| | 3 DN | 1.0052 | 0.9993 | 1.0027 | 0.9974 | 1.0006 | 0.9957 | 0.9988 | 0.9941 | | | | |
| | 4 | | | | | | | 0.9997 | 0.9941 | | 0.0056 | -0.0005 | |
| | 5 | | | | | | | 0.9990 | 0.9941 | | 0.0049 | -0.0012 | |
| | 6 UP | 1.0097 | 1.0000 | 1.0064 | 0.9980 | 1.0032 | 0.9961 | 1.0002 | 0.9941 | 0.0084 | 0.0061 | 0.0000 | 2.78E+06 |
| | 6 DN | 1.0062 | 0.9993 | 1.0037 | 0.9974 | 1.0017 | 0.9957 | 1.0002 | 0.9941 | | | | |
| | 7 | | | | | | | 1.0009 | 0.9941 | | 0.0068 | 0.0007 | |
| | 8 | | | | | | | 1.0014 | 0.9941 | | 0.0073 | 0.0012 | |
| | 9 UP | 1.0116 | 1.0000 | 1.0080 | 0.9980 | 1.0046 | 0.9960 | 1.0014 | 0.9941 | 0.0100 | 0.0073 | 0.0012 | 2.37E+06 |
| | 9 DN | 1.0081 | 0.9993 | 1.0053 | 0.9974 | 1.0029 | 0.9957 | 1.0014 | 0.9941 | | | | |
| | 10 | | | | | | | 1.0008 | 0.9941 | | 0.0067 | 0.0006 | |
| | 11 | | | | | | | 1.0020 | 0.9941 | | 0.0079 | 0.0018 | |
| | 12 UP | 1.0102 | 1.0000 | 1.0066 | 0.9979 | 1.0032 | 0.9960 | 1.0001 | 0.9942 | 0.0087 | 0.0059 | -0.0002 | 2.28E+06 |
| | 12 DN | 1.0065 | 0.9993 | 1.0039 | 0.9974 | 1.0017 | 0.9957 | 1.0001 | 0.9942 | | | | |
| | 13 | | | | | | | 0.9995 | 0.9942 | | 0.0053 | -0.0008 | |
| | 14 | | | | | | | 0.9992 | 0.9942 | | 0.0050 | -0.0011 | |
| Quad. II/IV | 1 | | | | | | | 1.0014 | 0.9942 | | 0.0072 | 0.0011 | |
| | 2 | | | | | | | 1.0024 | 0.9942 | | 0.0082 | 0.0021 | |
| | 3 UP | 1.0117 | 1.0000 | 1.0081 | 0.9980 | 1.0048 | 0.9961 | 1.0016 | 0.9943 | 0.0101 | 0.0073 | 0.0012 | 2.28E+06 |
| | 3 DN | 1.0080 | 0.9994 | 1.0054 | 0.9975 | 1.0031 | 0.9958 | 1.0016 | 0.9943 | | | | |
| | 4 | | | | | | | 1.0008 | 0.9942 | | 0.0066 | 0.0005 | |
| | 5 | | | | | | | 1.0008 | 0.9942 | | 0.0066 | 0.0005 | |
| | 6 UP | 1.0111 | 1.0000 | 1.0075 | 0.9979 | 1.0042 | 0.9961 | 1.0010 | 0.9942 | 0.0096 | 0.0068 | 0.0007 | 2.28E+06 |
| | 6 DN | 1.0075 | 0.9993 | 1.0049 | 0.9974 | 1.0026 | 0.9957 | 1.0010 | 0.9942 | | | | |
| | 7 | | | | | | | 0.9995 | 0.9942 | | 0.0053 | -0.0008 | |
| | 8 | | | | | | | 0.9996 | 0.9942 | | 0.0054 | -0.0007 | |
| | 9 UP | 1.0114 | 1.0000 | 1.0078 | 0.9979 | 1.0046 | 0.9961 | 1.0013 | 0.9942 | 0.0099 | 0.0071 | 0.0010 | 2.28E+06 |
| | 9 DN | 1.0079 | 0.9993 | 1.0053 | 0.9974 | 1.0029 | 0.9957 | 1.0013 | 0.9942 | | | | |
| | 10 | | | | | | | 1.0024 | 0.9941 | | 0.0083 | 0.0022 | |
| | 11 | | | | | | | 1.0004 | 0.9941 | | 0.0063 | 0.0002 | |
| | 12 UP | 1.0107 | 1.0000 | 1.0072 | 0.9980 | 1.0039 | 0.9961 | 1.0008 | 0.9942 | 0.0092 | 0.0066 | 0.0005 | 2.46E+06 |
| | 12 DN | 1.0071 | 0.9993 | 1.0045 | 0.9974 | 1.0023 | 0.9957 | 1.0008 | 0.9942 | | | | |
| | 13 | | | | | | | 0.9985 | 0.9943 | | 0.0042 | -0.0019 | |
| | 14 | | | | | | | 0.9977 | 0.9943 | | 0.0034 | -0.0027 | |

NOTE: POSITION #1 IS LOCATED ON THE LEAD END OF THE COIL AND POSITION #14 IS LOCATED ON THE RETURN END OF THE COIL.
QUADRANTS ARE IN REFERENCE TO THE COILS AS PLACED IN A COMPLETED MAGNET LOOKING FROM THE LEAD END.
QUADRANT I/III ARE THE UPPER RIGHT QUADRANT / LOWER LEFT QUADRANT.
QUADRANT II/IV ARE THE UPPER LEFT QUADRANT / LOWER RIGHT QUADRANT.

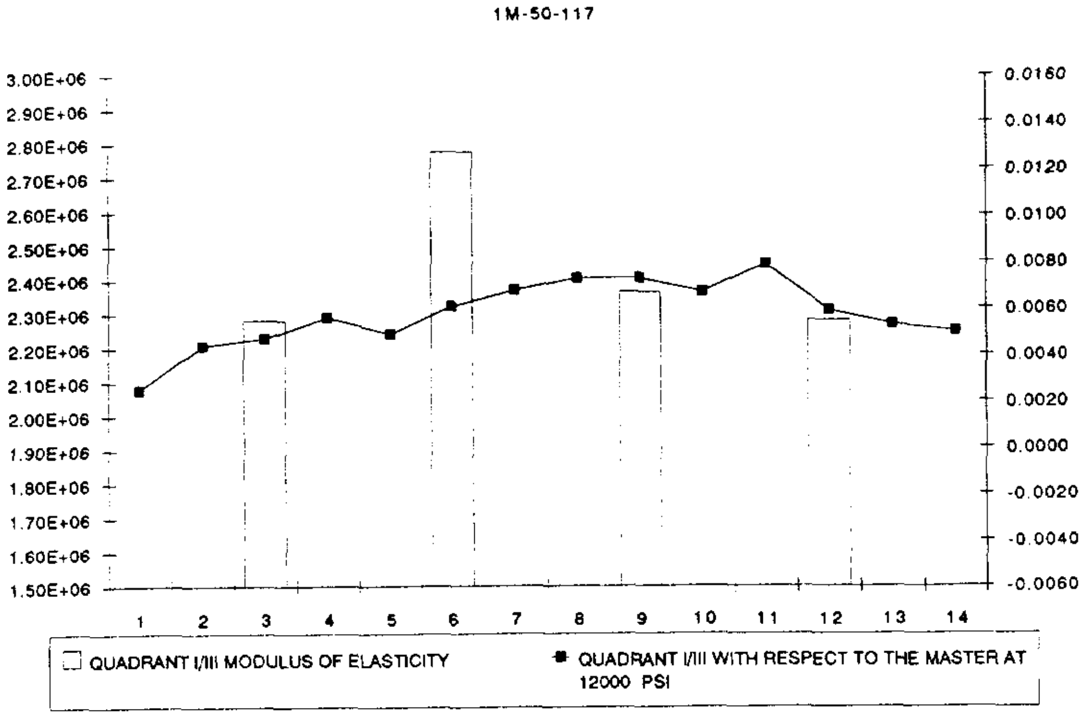


Figure 4. Typical Quadrant I/III Sizing and Modulus of Elasticity Curve.

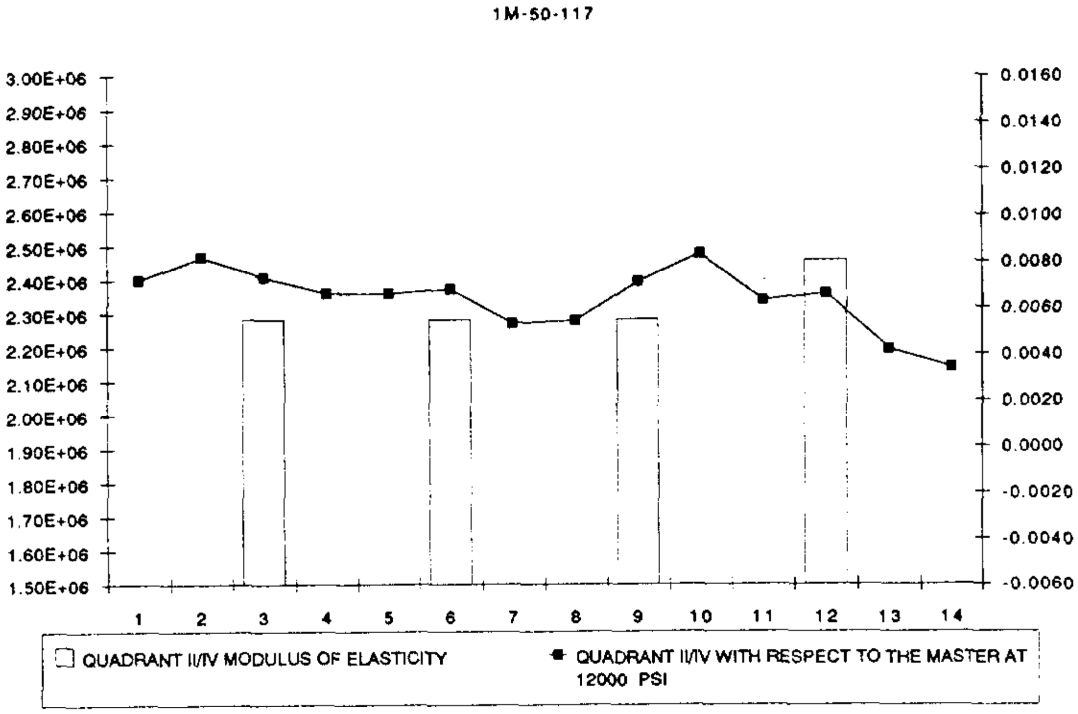


Figure 5. Typical Quadrant II/IV Sizing and Modulus of Elasticity Curve.

## Analyzing the Sizing Errors

Although comparison of the above spreadsheets from coil to coil will reveal some correlations to tooling tolerances, a clearer breakdown of errors was sought. Upon examining sizing plots of Quadrant I/III coil sides plotted on top of Quadrant II/IV, it was observed that the mathematical difference between these left and right coil side plots could be explained by either the left or right movements of the key bar in the keyway (See Figure 6) or a size delta between the two sizing bars. This difference error was named "horizontal error".

It was also observed that the remaining coil size error was when the left side and right side sizing errors increased or decreased together. This was named the "vertical error". Vertical error is caused by such variables as shims placed under the platen stops, sizing bar errors that are the same on both sides, mandrel size error and liner size error.

Figure 7 depicts highly simplified, normalized sizing error plots with either all horizontal error or all vertical error. The difference of the normalized errors or the sum of normalized errors must be divided by two as if computing the average; however, these values have directional significance as in a vector.

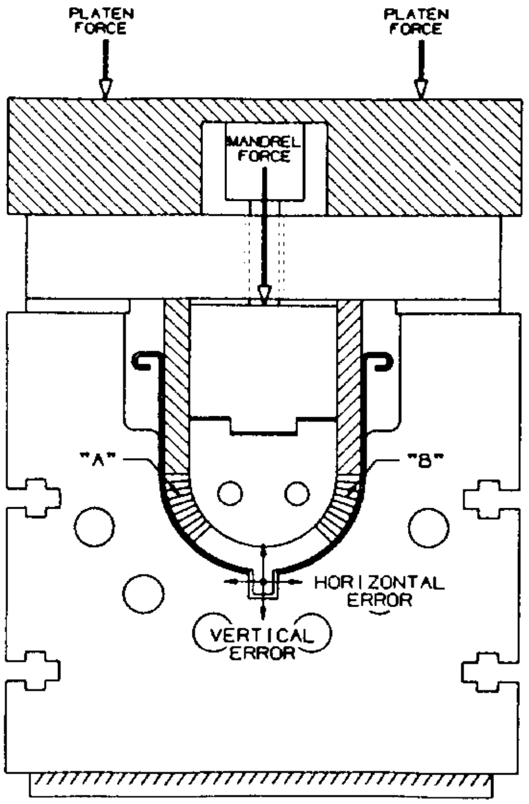


Figure 6. Tooling Error Definitions

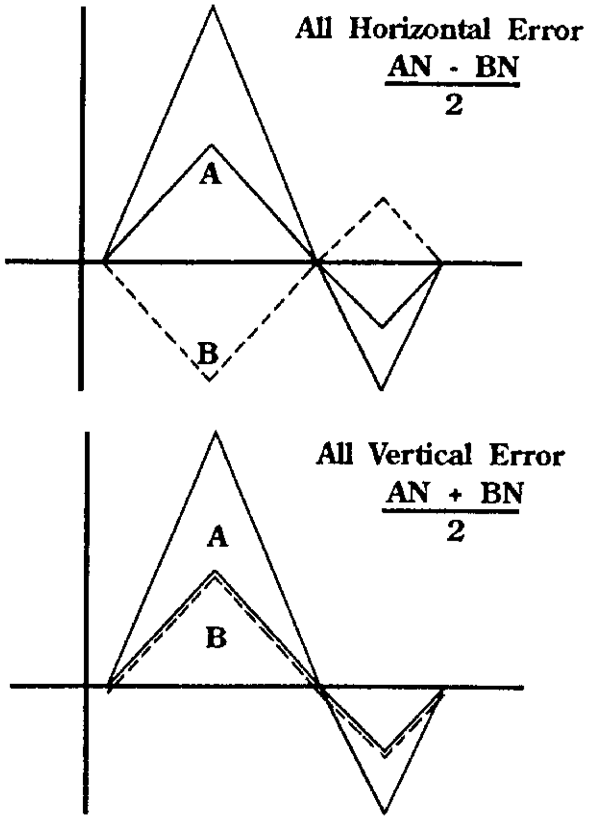
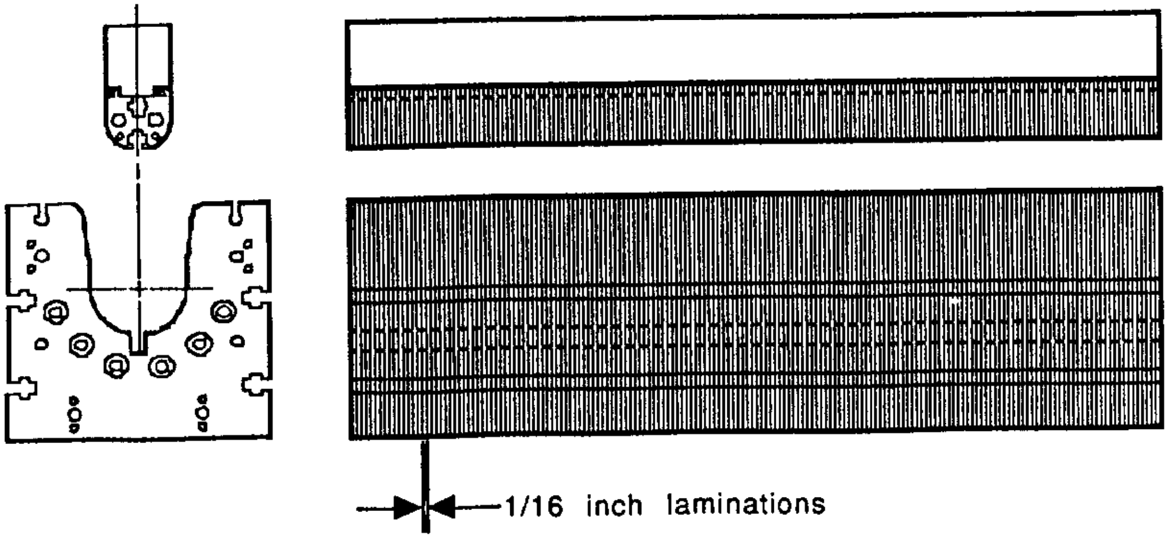
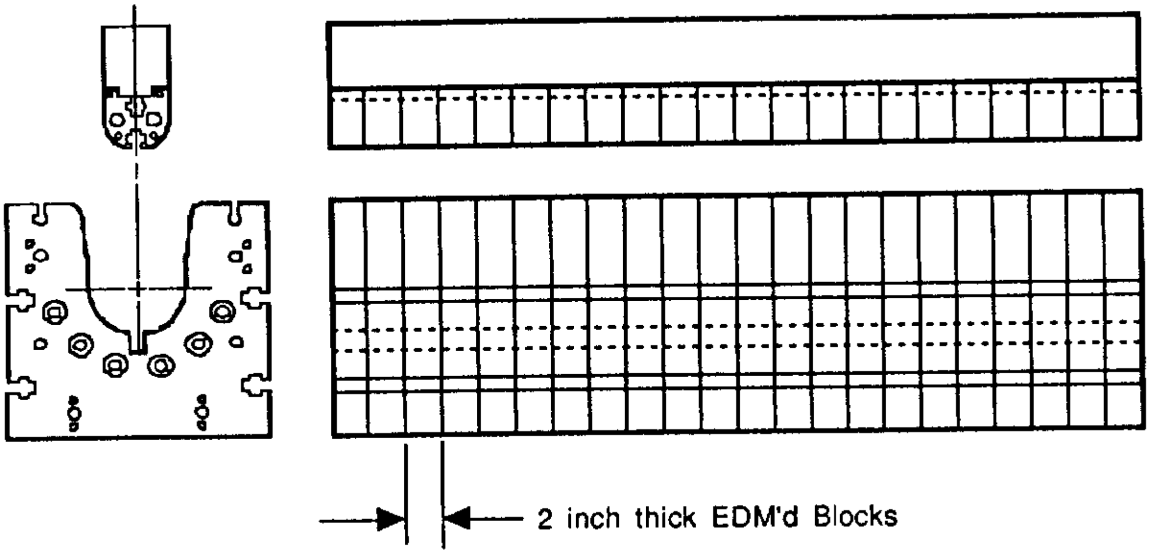


Figure 7. Graphical Definitions of Horizontal and Vertical Error.

Before proceeding with the error analysis, it is important to note at this point that the 50mm short coil tooling was made by EDM cutting two inch thick blocks of steel as a scheduling expediency while the punches and die sets were being made for the final laminated tooling (See Figure 8). These two-inch increments become significant in the following discussion.



Laminated Tooling



EDM'd Tooling

Figure 8. SSC E.D.M. and Laminated Tooling.

Figure 9 displays the vertical error over a range of ± .004" for seven 50mm inner short coils. The horizontal axis is marked off in the 14 measuring segments, each three inches wide. The vertical lines are the two-inch EDM tooling sections. Also marked are the ends of the 24-inch sizing bars and the 36-inch liner sections.

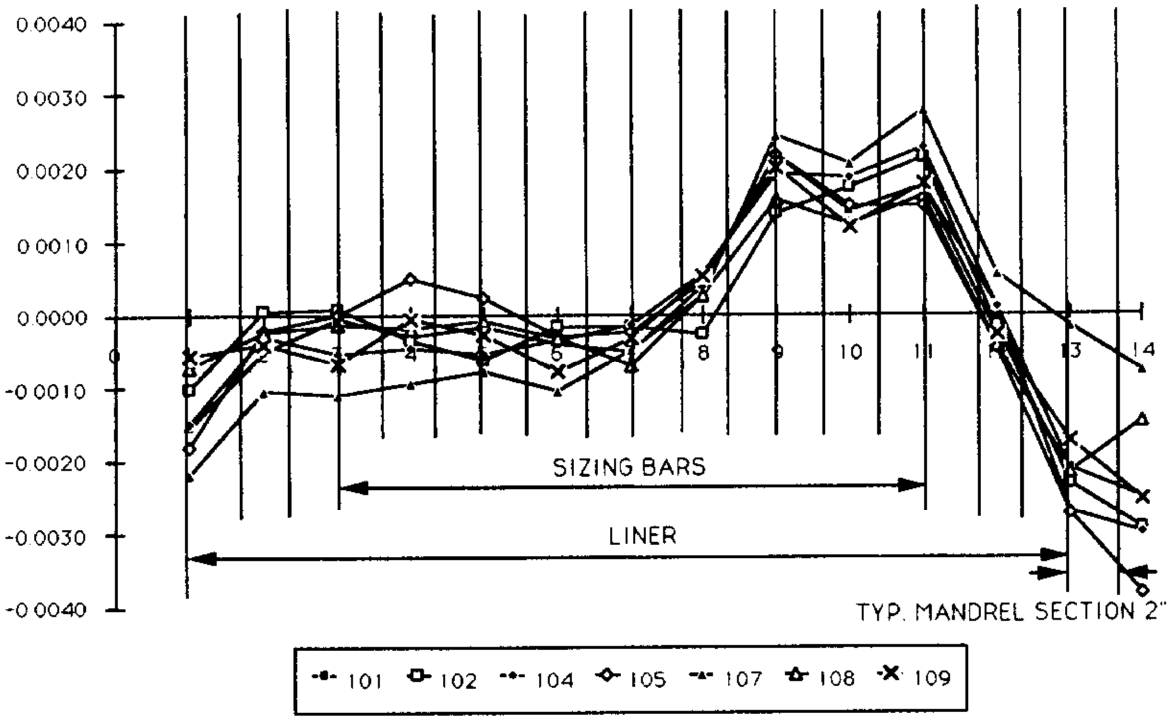


Figure 9. 50mm Short inner Coil Vertical Error for Seven Coils.

The most prominent features of this vertical error graph are:

1. The delta of the systematic error is about .001".
2. There is a .0025" high "bump" about 6 to 8 inches wide between sections 9 to 11.
3. Both the left and right ends apparently "pinch down" in size.
4. There is a strong correlation with the ends of the sizing bars, particularly the right end.
5. The right end of the middle liner is causing a discontinuity.

An analysis of the individual tooling elements showed only that two center sizing bars had an increasing difference to the right of about .001", not enough to explain the hump. Besides, this inner coil does not respond well to sliding left-right in the mold because of coil-to-liner friction, which is what would have to occur to allow the difference in sizing bars to show up as vertical error.

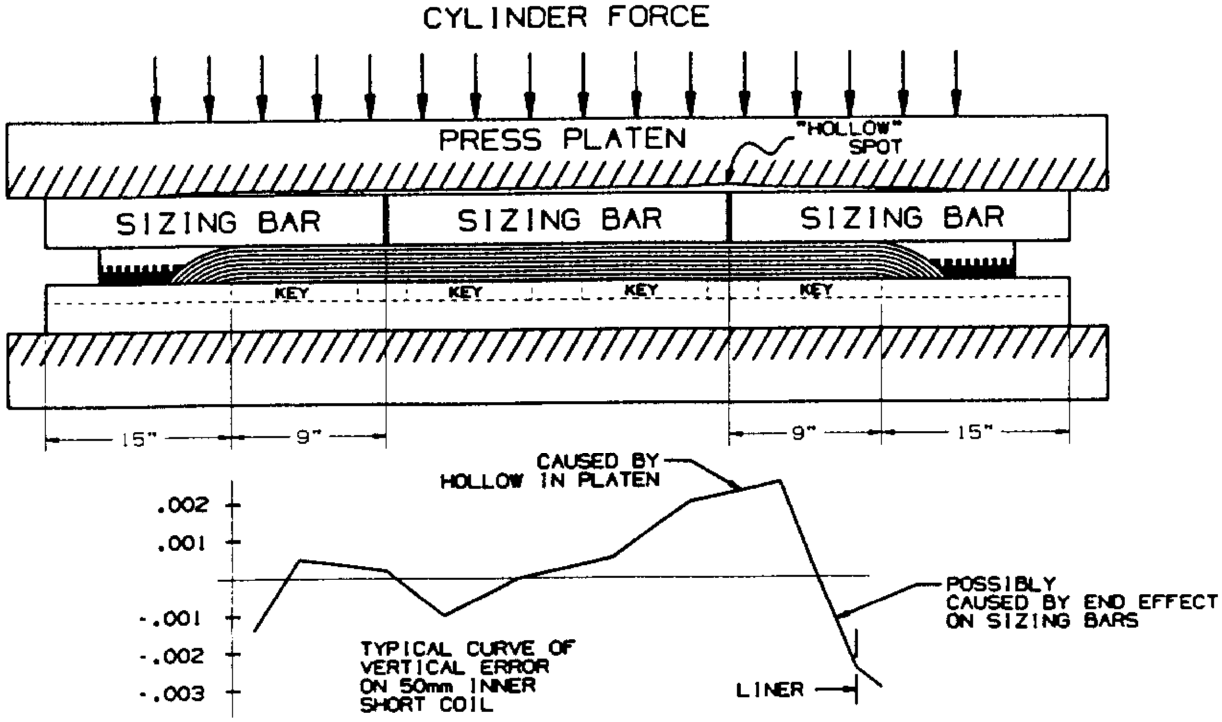


Figure 10. 50mm Short Curing Press, Side View.

Reasons for a better fit to this error curve are shown in Figure 10. It turns out that the upper press platen has a "hollow spot" of about .003" high and roughly 8 inches wide located just above the right end of the center sizing bar and left end of the right sizing bar. (Figure 10 has been exaggerated for illustration clarity.) It was noted that this hollow spot goes away after the press heats up.

The clue here is to notice that the outer 15 inches of the outer sizing bars is pressing on the "turn around" portion of the coil ends as well as the coil end form which is presently being made from machined G-10 glass-epoxy tube. The point is that this last 15-inch portion of the sizing bars is bearing down on a part of the coil structure which is not as dense as the first 6 inches of these end sizing bars. In fact, the very ends of the sizing bars are unsupported. Now adding the fact that although some of the platen end cylinders have been turned off to reduce the "end effect", it is quite possible for the right end sizing bar to tilt (or deflect) to the right because of the hollow spot in the platen. The center sizing bar's right end can also deflect upward into the hollow spot. The left end of the left sizing bar is deflected downward a smaller amount soley because of the softer left end of the coil being cured.

The upper platen is being replaced during the writing of this paper.

Figure 11 displays the inner coil <u>horizontal</u> <u>error</u> of seven coils. The major source of this large error appears to be the friction of the inner coil against the liners because of the use of a rather "sticky" mold release compound. The inner coil covers more of the curved bottom portion of the mold and the sizing bar's centering force is dissipated by this friction (See Figure 2). An inorganic wax-type mold release with high lubricity will be tried in April 1991.

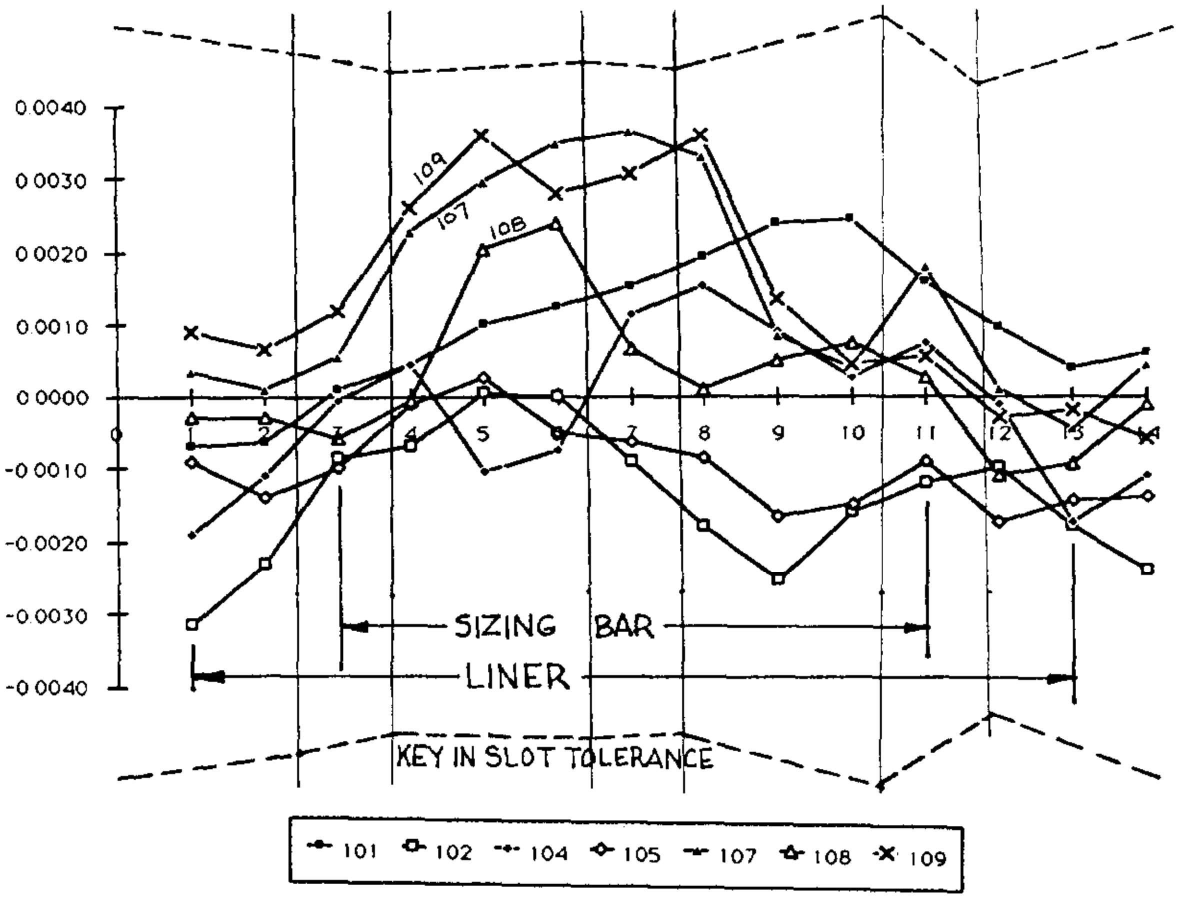


Figure 11. 50mm Short Inner Coil Horizontal Error.

The two dashed lines at the top and bottom of the Figure 11 horizontal error graph are the measured clearance to the key at the bottom of the key bar. This approximately .010" clearance is grossly out of tolerance and should have been about .002", which would help to reduce, but not eliminate, this horizontal error. The clearance should be greatly reduced when FNAL switches to the final laminated tooling.

The outer coil vertical error is shown in Figure 12. The thicker coil areas on either side of measuring segments 3, 7, and 11 are caused by the mandrel sections on either side of these sections being .001" to .002" larger than the other mandrel sections. It turns out that these slightly larger sections were made in a different machine shop than the other sections. The larger mandrel causes a larger coil mold by pressing on the floating key section and holding it "away" from the coil.

Again, this tooling error appears to be peculiar to the EDM-style tooling and may disappear when the switch is made to the laminated tooling.

The outer coil horizontal error is shown in Figure 13. The major error here is caused by the differences in the sizing bars which are all tapered about .0007". Apparently, the larger area of the outer coil key bars, along with the friction of the sticky mold release, prevents the key bars from sliding on the liner. If the coil could

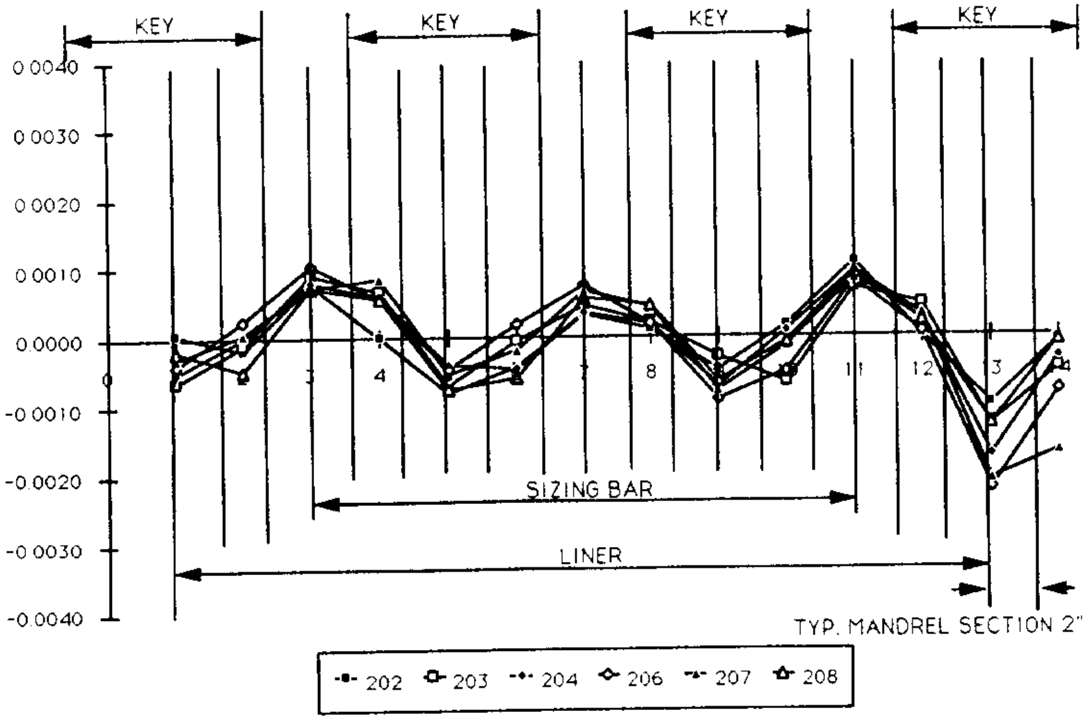


Figure 12. 50mm Short Outer Coil Vertical error (for 6 Coils)

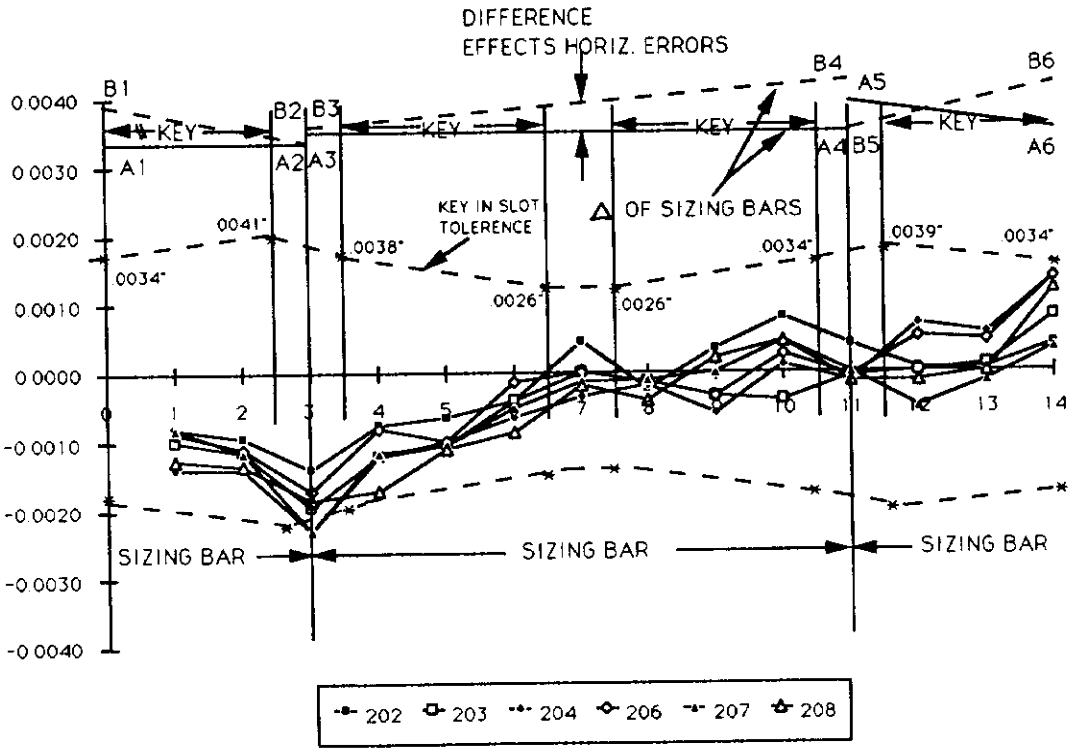


Figure 13. Short Outer Coil Horizontal Error.

slide the key bars to equalize the difference between the sizing bars or deltas of key bar width, there would be virtually no horizontal error.

## Curing Process Parameters

Some improvement in centering the tooling has been achieved by sequencing the pressure on the mandrel and the sizing bars during press warm-up. The mandrel force is first brought up to about half its final pressure to bring the coil in contact with the liner and to "bottom" the liner and key bars against the mold. Next the platen force is brought up to about half its final value. When the mold reaches 140°F the end jack force is increased to its full value, the mandrel force is reduced to near zero, and then the platen force is reduced to near zero. This is to allow the end jacks to "pack" the end turns into the mold. The platen force is increased to full value and then the mandrel force is increased to full value. This last sequence is intended to center the coil and key bar in the mold. The temperature is then raised to its final value and held for a prescribed time to cure the epoxy in the glass-epoxy tape.

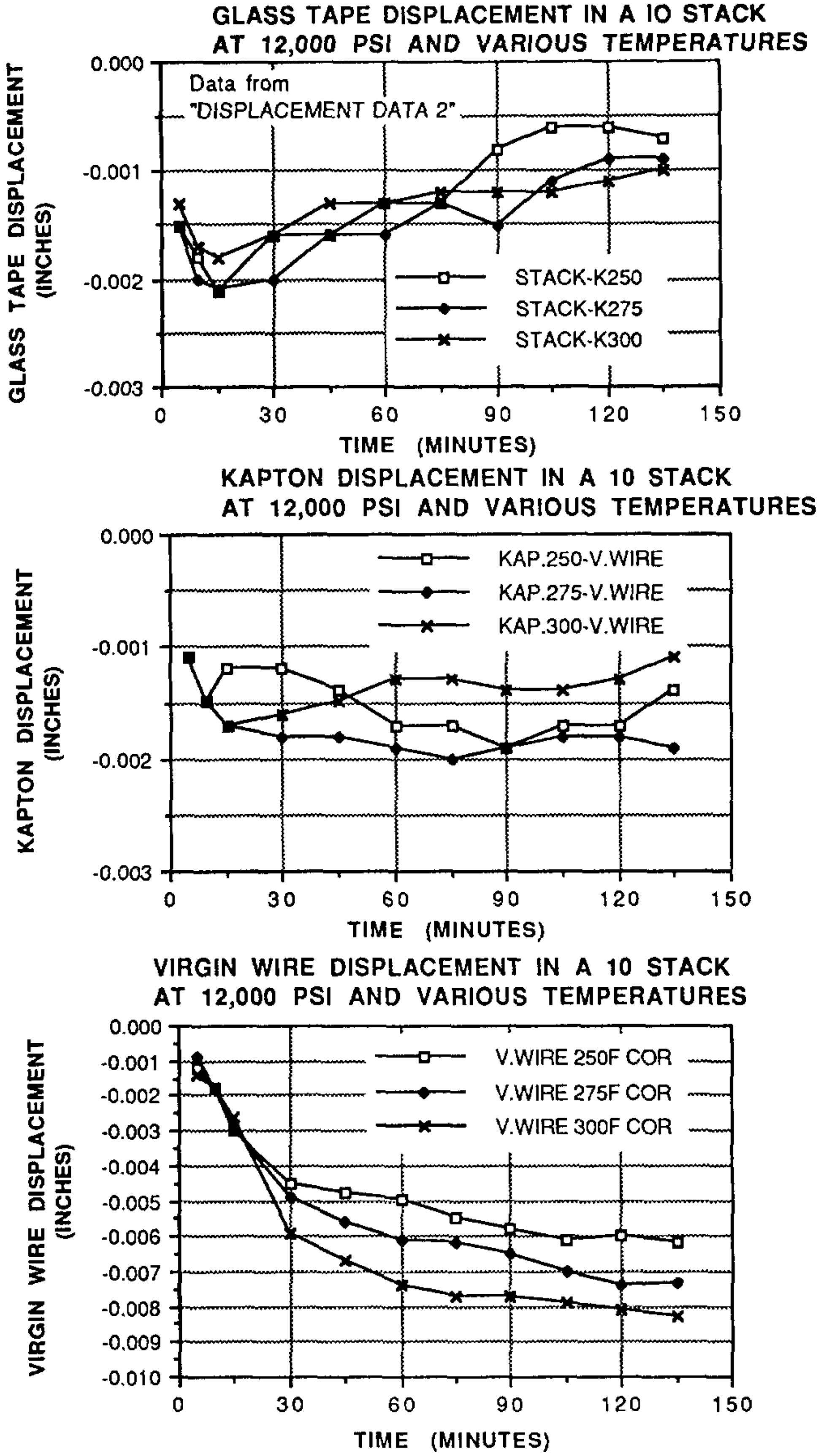
To more conveniently study the effects of varying cure time and cure temperature, "ten stacks" were utilized. Ten stacks are made by stacking four-inch samples of inner coil cable in a three-inch long "U-shaped" block of brass which is the same width as the tooling cavity. The cable sections are stacked with the tapered edge alternating left and right so that the stack comes out straight vertical instead of curved as in the coil configuration. These stacks are placed in compression of 12,000 psi by a three-inch section of sizing bar equivalent and then cured on a grid schedule of 250°F, 275°F, and 300°F while monitoring how much these stacks deflected (compressed) every 15 minutes of cure time out to 135 minutes.

Some of the results of these studies are shown in Figure 14. The displacements of the individual cable elements was separated by measuring complete ten stacks under cure and then stacks without glass tape and then without glass tape or Kapton. The mold was shimmed on the side walls by an equivalent thickness of Kapton for the missing materials to prevent any unreal spreading of the cable. New cable samples were used for each curing run. Error due to heating of the measuring fixture has been subtracted out.

The peculiar upward drift of the glass tape in the top graph of Figure 14 after displacing .002" is thought to be the shrinkage of the epoxy after it has wetted to the Kapton film. The gathering effect is similar to placing one's hand flat on a piece of paper which is on a flat desk and pulling in the fingers a small amount. The result is that the paper puckers into waves and could be thought of as getting thicker.

The Kapton displacement curve does not show the same effect because the glass tape was not present for this data. However, the kapton does get deformed by the flat cable strand surfaces causing bulk modulus extrusion effects on the film.

The bottom chart in Figure 14 shows that the cable strands are further deforming into each other and the resulting displacement is dependent on time and



GLASS TAPE DISPLACEMENT IN A 10 STACK AT 12,000 PSI AND VARIOUS TEMPERATURES

KAPTON DISPLACEMENT IN A 10 STACK AT 12,000 PSI AND VARIOUS TEMPERATURES

VIRGIN WIRE DISPLACEMENT IN A 10 STACK AT 12,000 PSI AND VARIOUS TEMPERATURES

Figure 14. Displacement of 40mm Cable Materials During Various Cure Temperatures.

temperature. This dependence on temperature is probably due to the change of the annealing rate to the as drawn hardness of the copper in the cable. Since most curing is done in the 90 to 120-minute window of time where more than 90 percent of the wire displacement has occurred, it appears that cure temperature could be used to modulate the finished coil size to compensate for variations in cable size.

Keeping in mind that this chart was for a ten stack, the .006" to .008" displacement variation of .002" translates to .0002" per cable. If the 12,000 psi of this ten stack test is linearly projected to the estimated 7,000 psi occurring inside the curing cavity, the .0002" per cable drops to .000116" per cable. This may seem small but multiplying by the 19 turns of an inner cable this becomes .0022" of control.

Figure 15 displays how the modulus of elasticity varied with time and temperature of cure but also displays the variation with 12.5 percent epoxy content FNAL tape and 20 percent epoxy content BNL tape. The cable and Kapton used for these tests were from the same FNAL cable run. In the center curve for 275°F the estimated curves for glass tape with 14 percent and 17.5 percent (average) epoxy content have been dashed in. Actual tape will be available in late April 1991 to verify these projections.

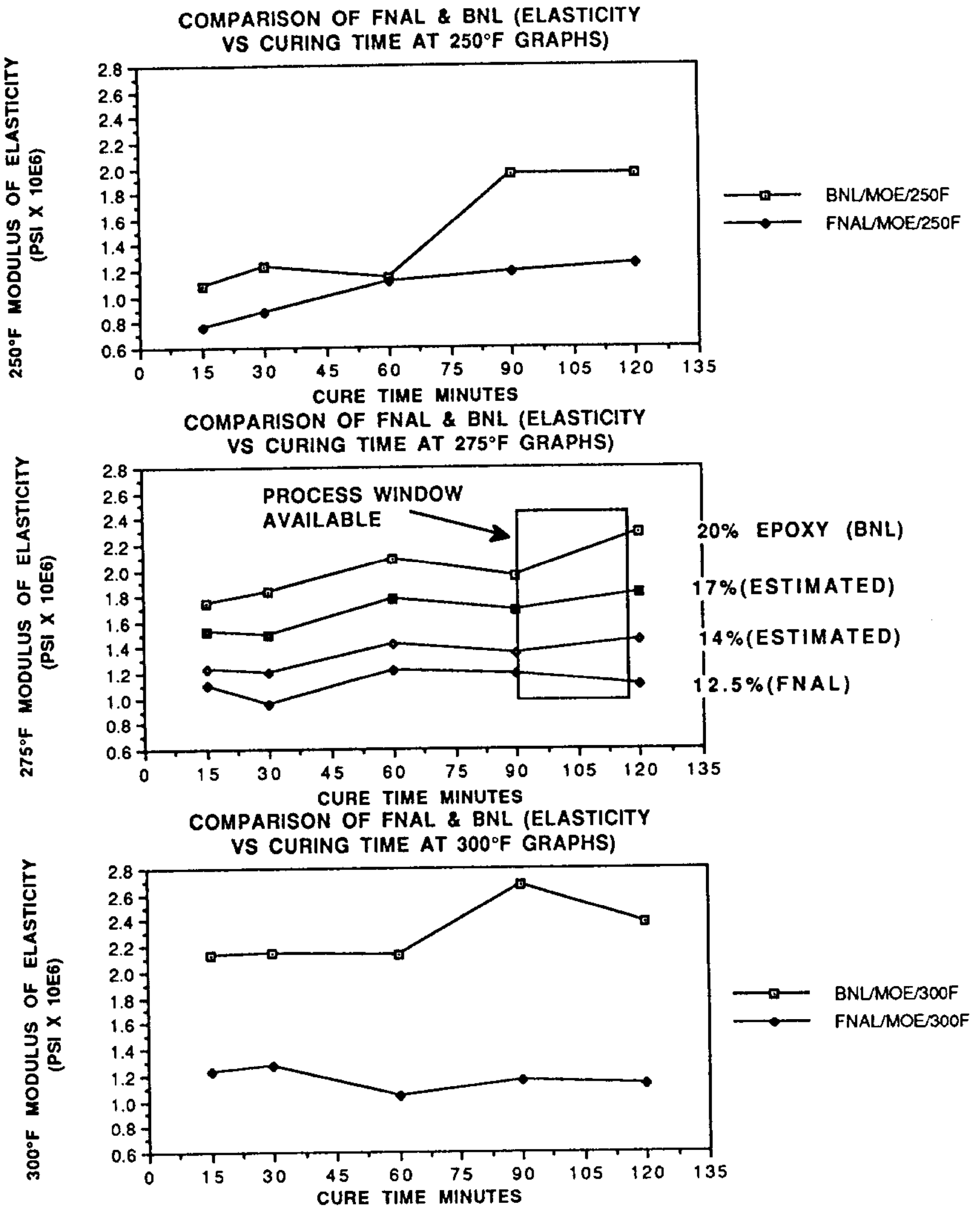
The demonstration here is that the modulus of elasticity can be controlled over the range of about 1.1 X 10E6 to about 2.3 X 10E6 in just the 275°F window by varying the epoxy content. For the inner 50mm coil, this projects to a range in dimension control at the 12,000 psi measuring (and collaring) pressure of about .003". The outer 50mm coil would project to about .0028" of control range.

## Summary

The following tables will summarize the variables found in obtaining control over the finished azimuthal sizing of SSC 50mm dipole coils.

### Table 4. Sources of Sizing Error and Possible Methods of Correction:

1) Key can move (Left, Right) in keyway.
    A) Make key bigger by plating it with nickel.
    B) Sequence the curing press pressures between the platen (sizing bars) and the mandrel to center the coil sides in the mold base. This assumes the coil side will slide along the mold base and mandrel and that nothing is inhibiting the key from centering. Also, the mold release used should promote lubricity between the coil, liner, and mandrel.



COMPARISON OF FNAL & BNL (ELASTICITY VS CURING TIME AT 250°F GRAPHS)

COMPARISON OF FNAL & BNL (ELASTICITY VS CURING TIME AT 275°F GRAPHS)

COMPARISON OF FNAL & BNL (ELASTICITY VS CURING TIME AT 300°F GRAPHS)

Figure 15. Modulus Of Elasticity of Ten Stacks With Varying Epoxy Contents.

2) Retainer (liner) is not to tolerance, particularly at ends. (Presently made from spring steel.)
    A) Open up slot for key so that retainer cannot press on key.
    B) Make the liner out of a relatively soft metal like aluminum with a hardcoat finish for wear. This will allow the liner to conform <u>intimately</u> to the shape of the base mold. (Aluminum liners may have to be replaced periodically.)
    C) Cut ends after fabrication to promote perpendicularity and butt-fit from one liner to another.
    D) Aluminum liners could be made by extrusion and cut12 to 20-foot lengths to minimize the number of end joints.
    E) It has been suggested that a "keyless" tool design would be simpler and self-centering (with help from lubricating mold release) minimizing horizontal error.
3) Sizing Bars are not identical within .0001".
    A) Lap them to size.
4) Curing press main platen surfaces not "flat" over short distances (6" to 8").
    A) Custom fit sizing bars to each 24" location.
    B) Make sizing bars stiffer (taller?)
    C) Use a shimable platen design.

## Table 5. Materials and Process Adjustments Which Affect Coil Size

1) Kapton film rolls could be stocked in small size increments and cross matched to cable size.
2) Modulate the percent of epoxy in the glass tape to vary the modulus of elasticity.
3) Cure time and temperature schedule will vary how much the copper cable will compress due to the annealing effect during the cure schedule. This is a new parameter which can be used to make up for the incoming cable tolerance.
4) Shims added to the curing press stops will directly affect the final size and modulus of elasticity utilizing temperature, pressure, and time as curing press variables. However, they are more interdependent than originally suggested and may require the development of a computer program to reliably predict the sizing outcome.

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