MI-0132

FE Thermal Stress Analysis of the Main Injector Dipole Coil

Eric Haggard

September 22, 1994

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MI Note MI-0132

Fermilab

FE THERMAL STRESS ANALYSIS OF THE MAIN INJECTOR DIPOLE COIL

Eric Haggard
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9-22-94

MODEL STRUCTURE AND ASSUMPTIONS

LOAD CASES AND MODEL DESCRIPTION

RESULTS OF DIFFERENT MODELS

OVERALL RESULTS

ANSYS SOLUTION PLOTS

ANSYS INPUT FILE SEGMENTS

INTRODUCTION

The analysis of the Main Injector dipole magnet coil is undertaken to find the stresses internal to the coil at various stages of the coils life. The suspicion is that epoxy stresses are high when the coil is under power and that fatigue will cause failure of the coil during cycling over a long period of time. Finite element modeling is employed to solve this problem. Hand calculations of deflections are offered to gauge that the FEA results are not erroneous. The maximum tensile strength of epoxy (without glass) is at room temperature between 5000 and 6000 psi. Fatigue data has not been found for epoxy and glass-epoxy systems but will eventually be used to predict if stress levels are high enough to cause epoxy failure.

MODEL STRUCTURE AND ASSUMPTIONS

- ONE QUARTER OF THE COIL IS MODELED IN 2-D DUE TO PLANES OF SYMMETRY

- DISPLACEMENT RESTRAINTS ARE PLACED ON THE COIL WHERE IT WOULD OTHERWISE MEET MORE COIL

- DISPLACEMENT RESTRAINTS ARE ALSO PLACED WHERE THE CURED COIL IS FASTENED TO THE IRON BY ADHESIVE WHERE APPLICABLE.

ELEMENTS PROPERTIES

- FOR COPPER:

MODULUS OF ELASTICITY=17.0E06 psi
COEFF OF THERMAL EXPAN.= 9.8E-06 in/in°F
POISSONS RATIO =.377
THERMAL CONDUCTIVITY=67680 btu in/sec in^2

- FOR EPOXY:

MODULUS OF ELASTICITY=1.5E5 psi
COEFF OF THERMAL EXPAN.= 3.3E-05 in/in°F
POISSONS RATIO =.34
THERMAL CONDUCTIVITY=261 btu•in/sec in^2

ANSYS 5.0
SEP 6 1994
10:50:55
PLOT NO. 2
ELEMENTS
TYPE NUM

ZV =1
DIST=69.025
XF =62.75
YF =5.375
CENTROID HIDDEN

POSITIVE DISPLACEMENT

Y

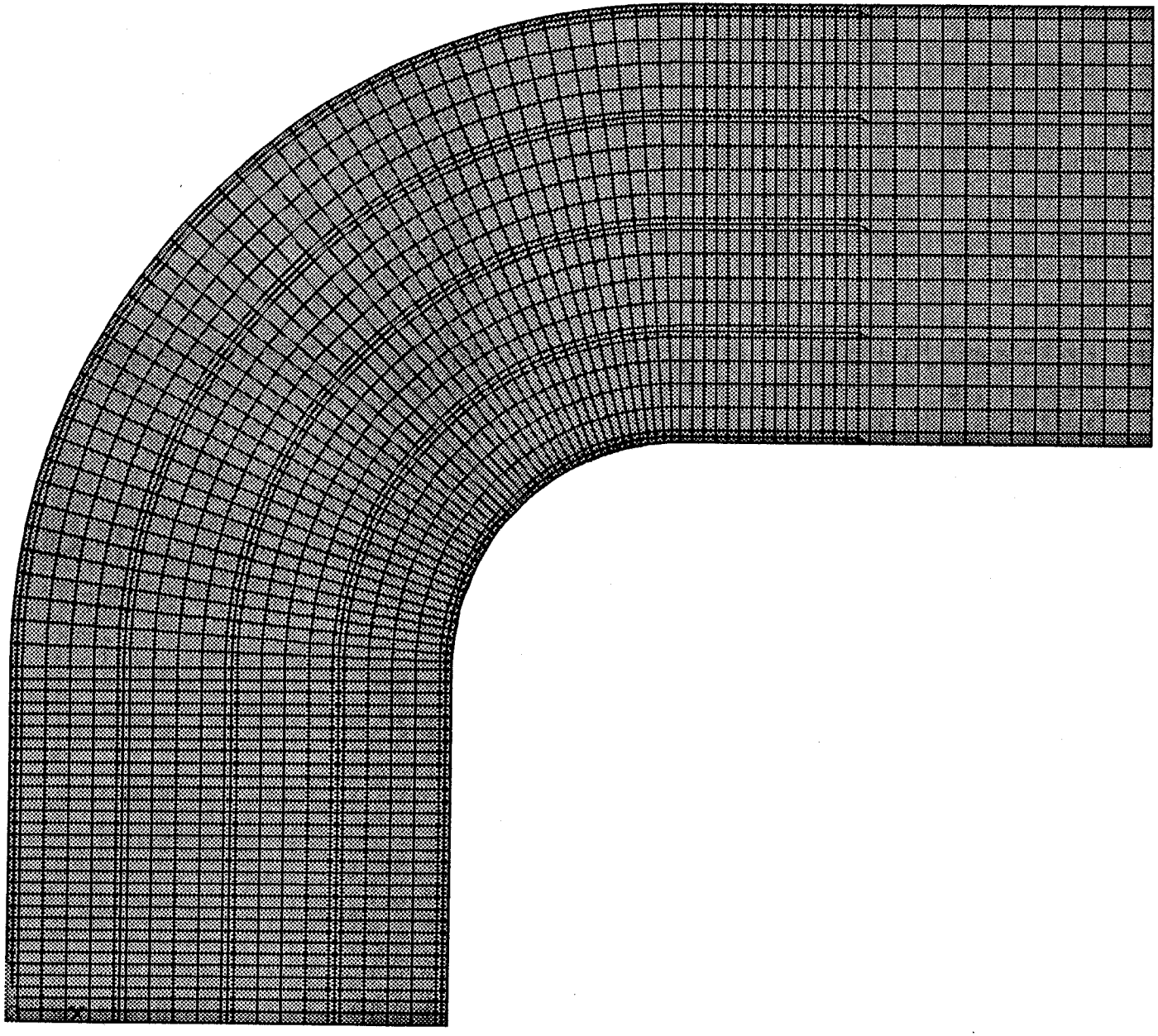
X

POSITIVE DISPLACEMENT

GENERAL ANSYS RESULT CONVENTION

- POSITIVE STRESS IS TENSILE
- NEGATIVE STRESS IS COMPRESSIVE

MI DIPOLE MAGNET COIL (2-D)



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PLOT NO. 1
ELEMENTS
TYPE NUM

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YF =5.375
CENTROID HIDDEN

MI DIPOLE MAGNET COIL (2-D) (GENERAL CASE)

FOUR MAJOR LOAD CASES AND THREE STRESS STATES ARE DEFINED AS FOLLOWS

CASE 1:CURING THE COIL AT 250°F AND COOLING TO ROOM TEMPERATURE

- NODAL DISPLACEMENT RESTRAINTS ARE PLACED IN THE X ON THE X=125.0" AND IN THE Y DIRECTION ON THE Y = 0.0"
- NODAL TEMPERATURES ARE SPECIFIED AT 72 ° F STARTING FROM A REFERENCE TEMPERATURE OF 250 ° F (TOFFSET WAS 460°).

CASE 2:COOLING THE COIL WITH WATER

- NODAL DISPLACEMENT RESTRAINTS ARE PLACED IN THE X ON THE X=125.0" AND Y ON THE Y = 0.0", NODAL DISPLACEMENT RESTRAINTS IN UY ARE PLACED ON BOUNDARY NODES BETWEEN X = 110.0" AND X - 125.0" TO SIMULATE ADHESIVE, X DISPLACEMENTS ARE FREE AT THESE NODES TO DISABLE SHEAR LOADING.
- NODAL TEMPERATURES ARE SPECIFIED AT 48 ° F STARTING FROM A REFERENCE TEMPERATURE OF 72 ° F (TOFFSET WAS 460°).

CASE 3:COIL UNDER POWER 9500 AMPS (COLD WATER SUPPLY TO INNER TURN)

- NODAL DISPLACEMENT RESTRAINTS ARE PLACED IN THE X ON THE X=125.0" AND Y ON THE Y = 0.0", NODAL DISPLACEMENT RESTRAINTS IN UY ARE PLACED ON BOUNDARY NODES BETWEEN X = 110.0" AND X - 125.0" TO SIMULATE ADHESIVE, X DISPLACEMENTS ARE FREE AT THESE NODES TO DISABLE SHEAR LOADING.
- NODAL TEMPERATURES ARE SPECIFIED AS UNIQUE TEMPERATURES STARTING FROM A REFERENCE TEMPERATURE OF 48 ° F (TOFFSET WAS 460°). THE INDIVIDUAL COIL TEMPERATURES ARE 71.6° F , 74.8° F , 84.7° F , 93.2° F (INNER TO OUTER). THE TEMPERATURES ARE GENERATED FROM MEASUREMENTS OF COIL TEMPERATURES FROM AN ACTUAL 9500 AMPS(COLD TO INNER) TEST WITH TEMPERATURES NOT VARYING WITH COIL LENGTH. THERMAL SOLUTION GENERATES EPOXY TEMPERATURE DISTRIBUTION WHICH IS INPUT TO STRESS SOLUTION.

CASE 5:COIL UNDER POWER 9500 AMPS (COLD WATER SUPPLY TO OUTER TURN)

- SAME BOUNDARY CONDITIONS AS CASE 3

• THE INDIVIDUAL COIL TEMPERATURES ARE 77.7° F , 83.1° F , 94.1° F , 98.6° F (INNER TO OUTER). THE TEMPERATURES ARE FROM COIL MEASUREMENTS FROM A 9500 AMPS (COLD TO OUTER) TEST. TEMPERATURES AGAIN NOT VARYING WITH COIL LENGTH. THERMAL SOLUTION GENERATES EPOXY TEMPERATURE DISTRIBUTION WHICH IS INPUT TO STRESS SOLUTION.

STEP 12: IS SIMPLY A SUMMATION OF CASES 1 AND 2

PHYSICALLY THE SUMMATION REPRESENTS THE STRESS STATE OF THE COIL BEFORE POWER HAS BEEN APPLIED.

STEP 123: IS THE SUMMATION OF CASES 1 ,2 AND 3

IT REPRESENTS THE STRESS STATE OF THE COIL UNDER OPERATION WHEN COOLING WATER IS SUPPLIED TO THE INNER TURNS FIRST

STEP 125: IS THE SUMMATION OF CASES 1,2 AND 5

PHYSICALLY, IT REPRESENTS THE STRESS STATE OF THE COIL UNDER POWER OF 9500 AMPS WHEN THE COOLING WATER IS SUPPLIED TO THE OUTER TURNS FIRST.

DEFLECTION RESULTS

A comparison of hand calculations, measurements and Ansys results yields this table.

CASE/COMPONENT	HAND CALC	ANSYS RESULT	MEAS. RESULT
CURING UX	-0.219	-0.22	N/A
CURING UY	-0.019	-0.023	N/A
COOL DOWN UX	-0.030	-0.030	N/A
COOL DOWN UY	-0.003	-0.0029	N/A
UNDER POWER UX (CTI)	0.041	0.041	.042
UNDER POWER UY (CTI)	0.0034	0.0048	N/A
UNDER POWER UX (CTO)	0.050	0.050	.038
UNDER POWER UY (CTO)	0.004	0.0041	N/A
TOTAL UX	-.211	-.213	N/A
TOTAL UY	-.0175	-.024	N/A

Negative resuts are contractions and positive are extensions.

STRESS RESULTS

Since there are many cumbersome plots to sift through, the stress results have been plotted for various points of interest. The first point of interest is at the turn. The first point taken lies in the epoxy between the inner turn and third turn at a 135° angle from the x axis. The second point lies on the same angle and between the outer turn and second turn. The next points of interest are at the point where the coil is first fastened to the steel with adhesive. Both epoxy points lie on the exterior of the coil, one on the outer turn, one at the inner turn. The last points are taken at the long straight section about 25" away from the turn section. The outside point is taken between the outer and 2nd turn, the inside point is taken between the inner and 3rd turn. The plots show the addition of stress as you increment through the load cases. In each case, the epoxy starts out stress free at 250° F and undergoes each of the load steps. Sketches of the points appears below.

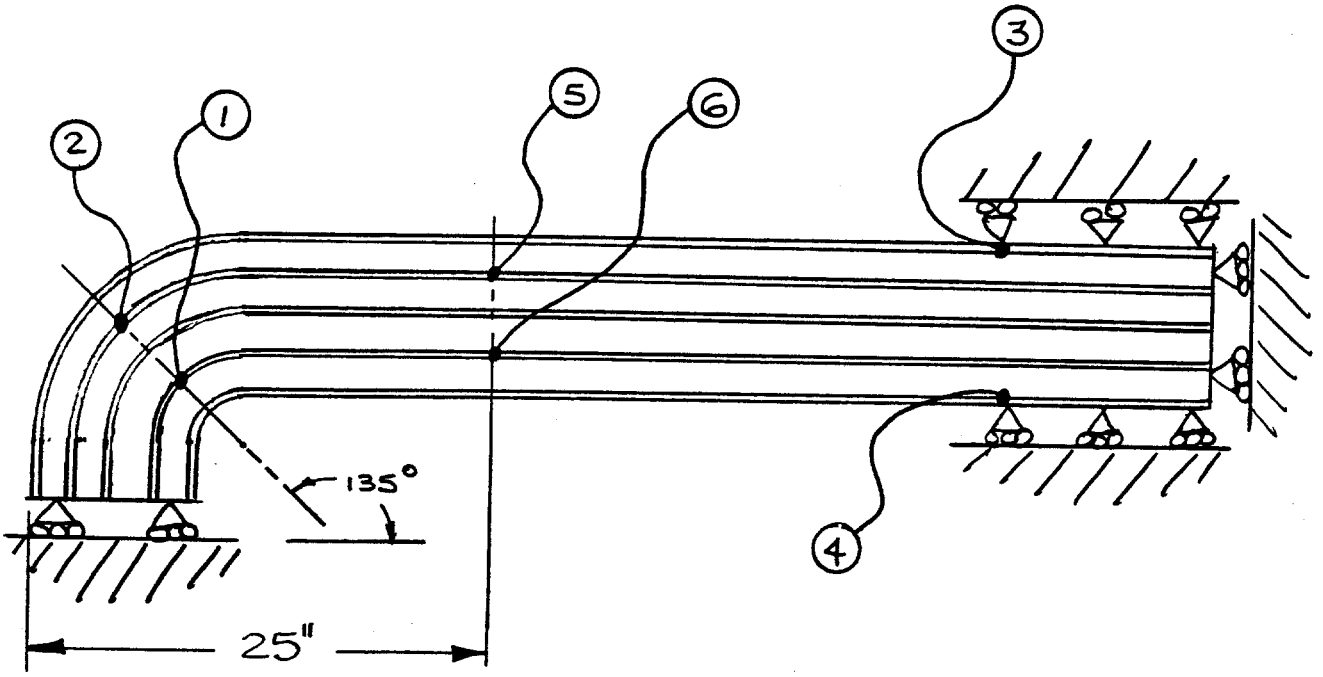
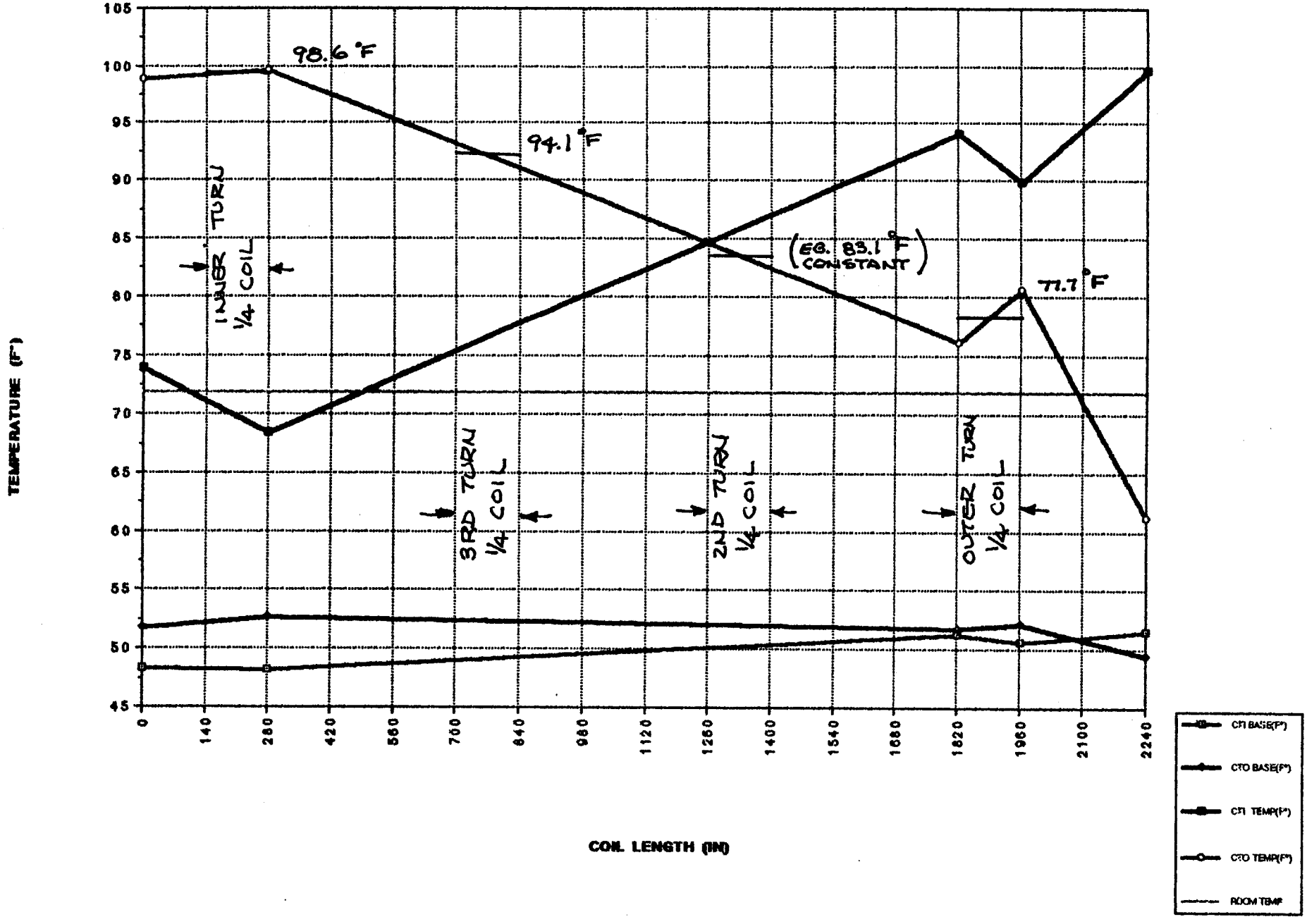
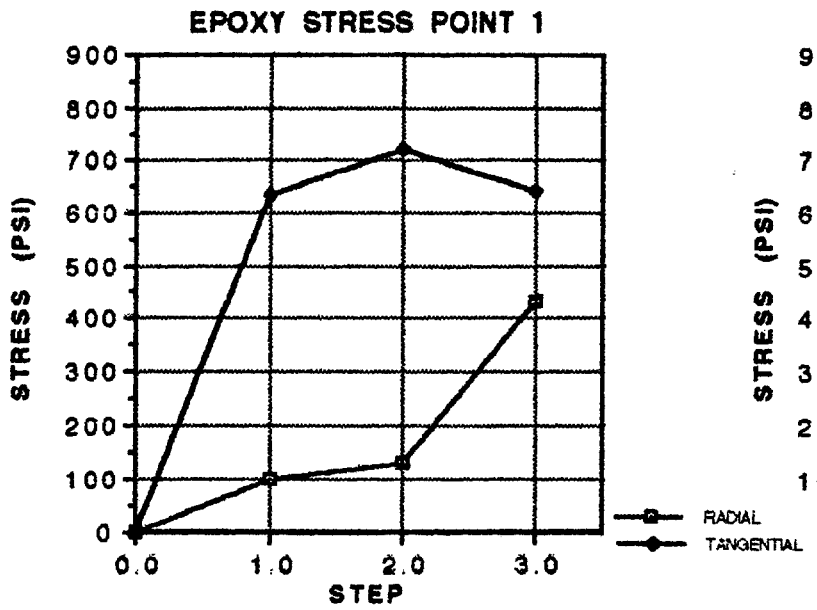
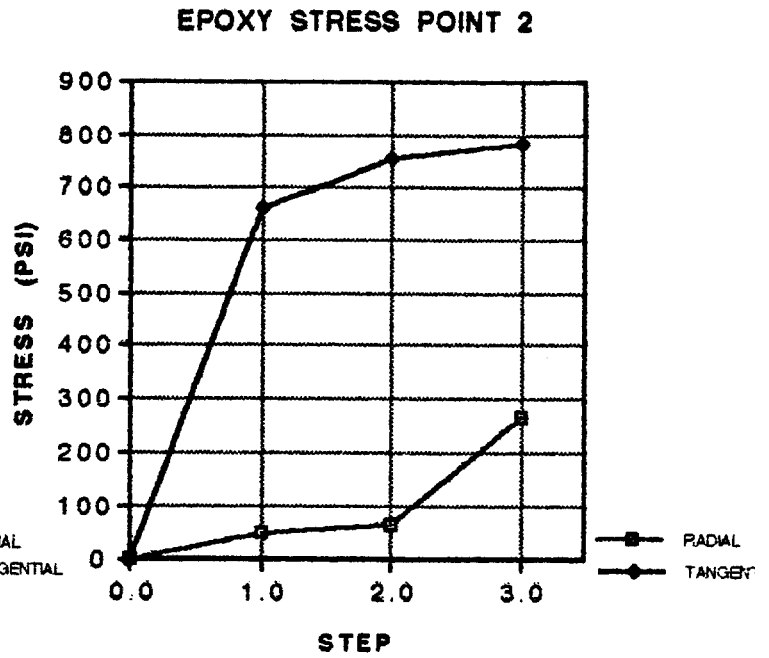


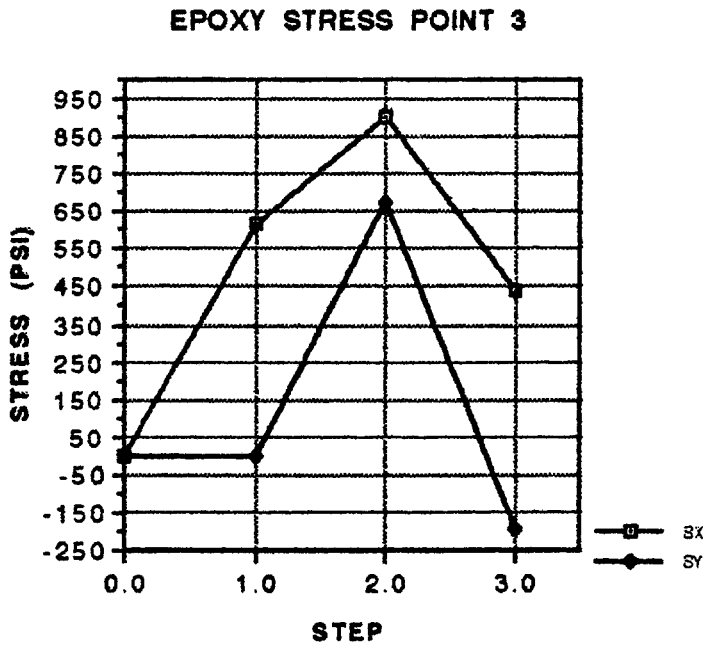
FIGURE 3: POINTS OF INTEREST FOR TABULAR DATA

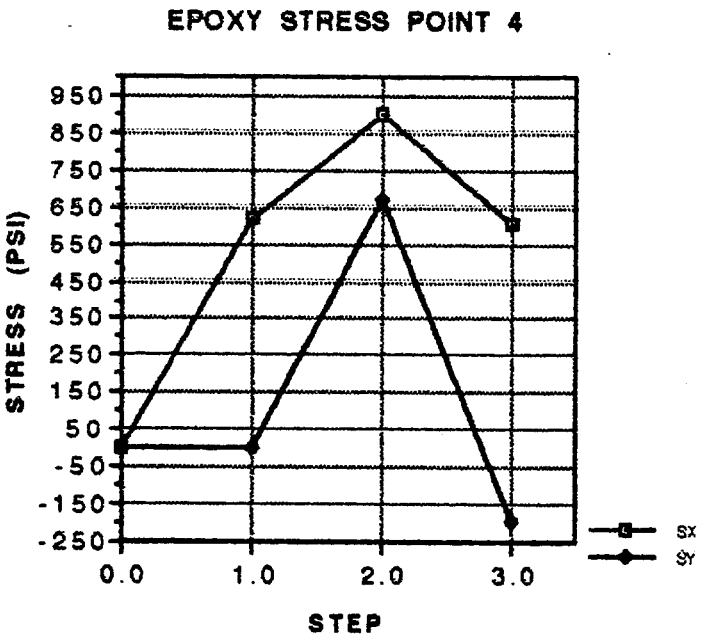
TEMPERATURE PROFILES FOR 9500 AMP MIR DIPOLE COILS (MEASURED VALUES)




EPOXY STRESS POINT 1
STRESS (PSI)
900
800
700
600
500
400
300
200
100
0
0.0
1.0
2.0
3.0
STEP
RADIAL
TANGENTIAL


EPOXY STRESS POINT 2
STRESS (PSI)
900
800
700
600
500
400
300
200
100
0
0.0
1.0
2.0
3.0
STEP
RADIAL
TANGENT


EPOXY STRESS POINT 3
STRESS (PSI)
950
850
750
650
550
450
350
250
150
50
-50
-150
-250
0.0
1.0
2.0
3.0
STEP
SX
SY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STRESS (PSI)
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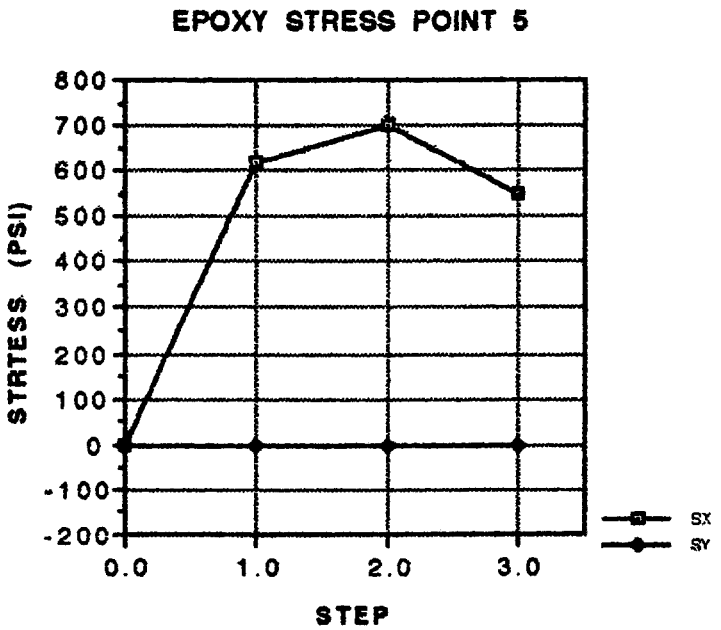
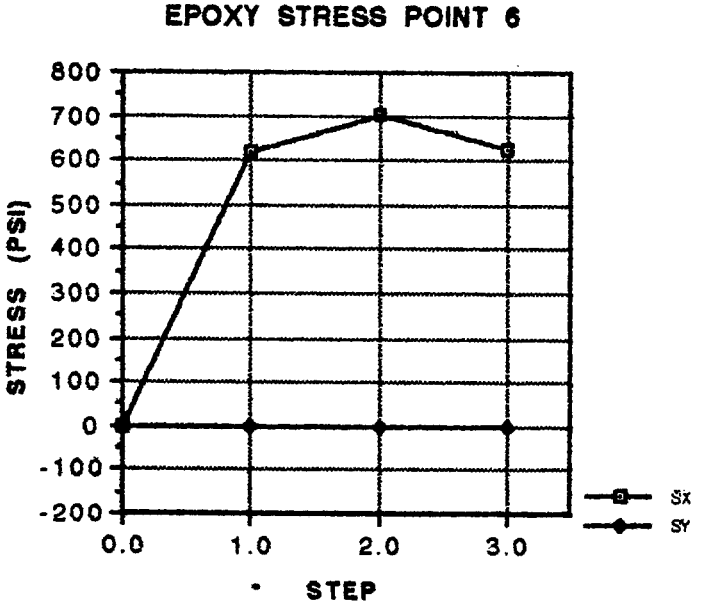
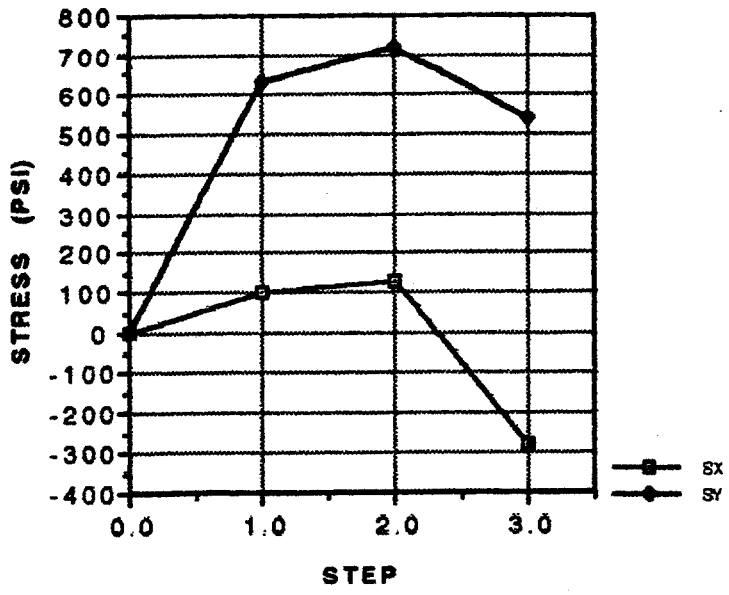
850
750
650
550
450
350
250
150
50
-50
-150
-250
0.0
1.0
2.0
3.0
STEP
SX
SY

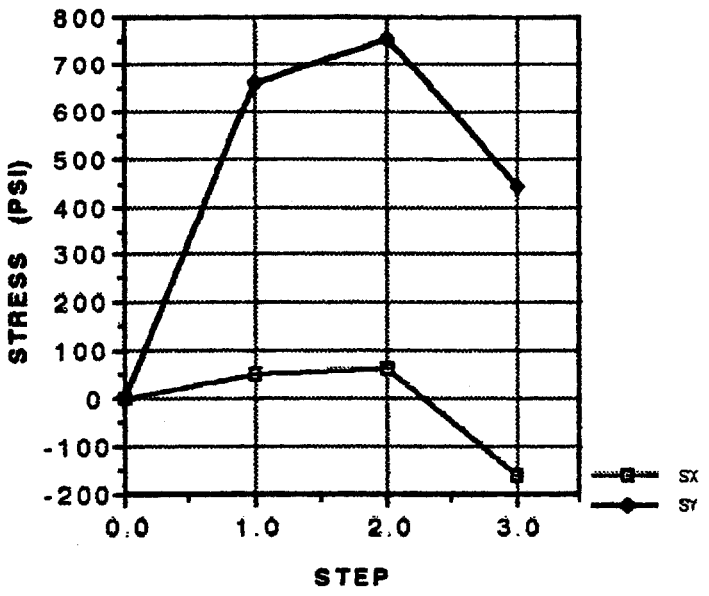

EPOXY STRESS POINT 5
STRTESS (PSI)
800
700
600
500
400
300
200
100
0
-100
-200
0.0
1.0
2.0
3.0
STEP
SX
SY


EPOXY STRESS POINT 6
STRESS (PSI)
800
700
600
500
400
300
200
100
0
-100
-200
0.0
1.0
2.0
3.0
STEP
SX
SY

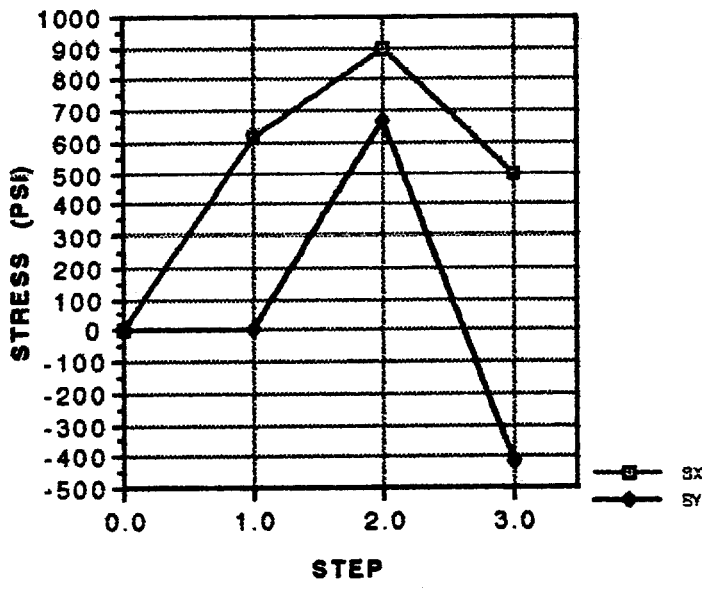
EPOXY STRESS CTO POINT 1



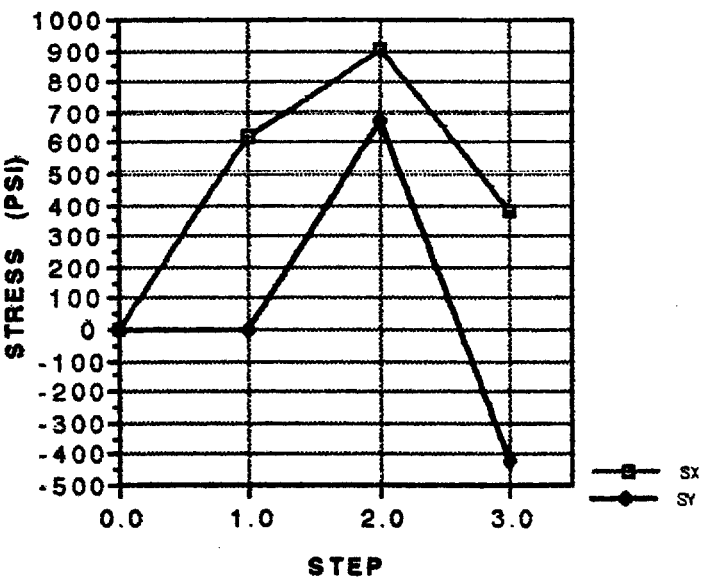
EPOXY STRESS CTO POINT 2



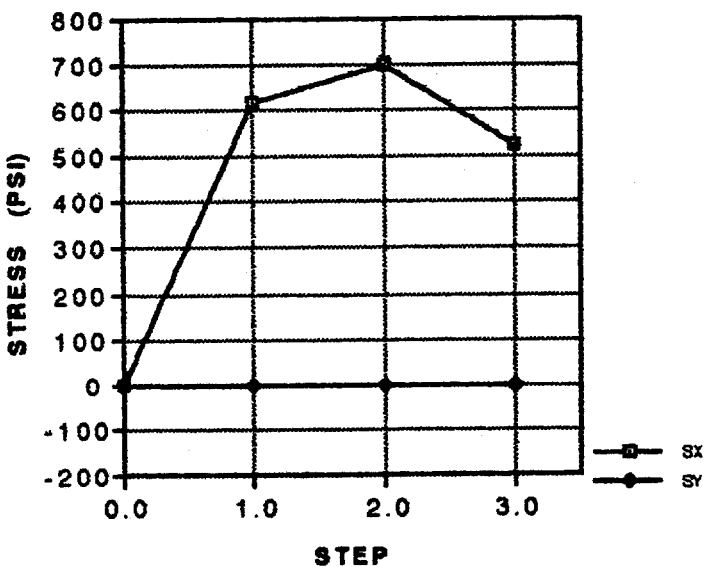
EPOXY STRESS CTO POINT 3



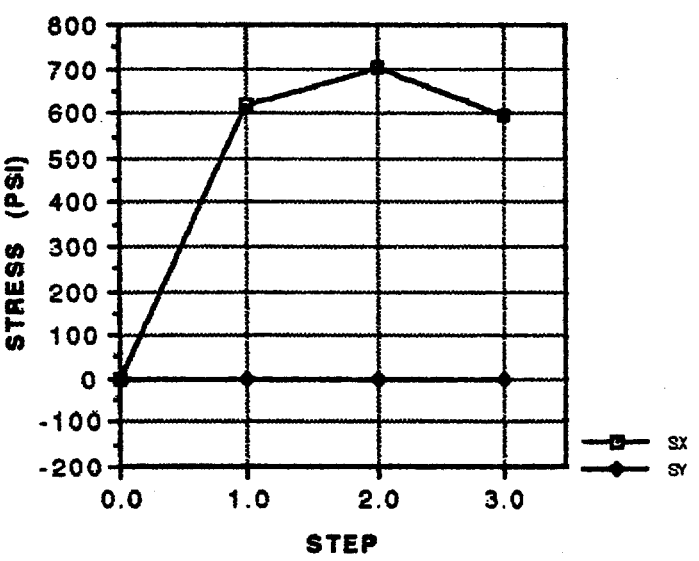
EPOXY STRESS CTO POINT 4



EPOXY STRESS CTO POINT 5



EPOXY STRESS CTO POINT 6



MIR LOAD CASE STRESS DATA

DESCRIPTION	STEP 1	STEP 2	STEP 12	STEP 3	COMBINED 123	STEP 5	COMBINED 125
TURN POINT 1 RADIAL STRESS	100	31	131	300	430	-437	-280
TURN POINT 1 TAN. STRESS	632	87	719	-81	615	-322	540
TURN POINT 2 RADIAL STRESS	50	14	64	200	225	-217	-160
TURN POINT 2 TAN. STRESS	661	95	756	29	630	-178	440
GLUED END POINT 3 SX	616	283	899	-460	439	-395	500
GLUED END POINT 3 SY	0	670	670	-964	-257	-997	-419
GLUED END POINT 4 SX	620	283	903	-300	565	-519	375
GLUED END POINT 4 SY	0	670	670	-864	-200	-997	-419
LONG STRAIGHT POINT 5 SX	617	83	700	-150	550	-100	595
LONG STRAIGHT POINT 5 SY	0	0	0	0	0	0	0
LONG STRAIGHT POINT 6 SX	629	84	703	-80	633	-179	525
LONG STRAIGHT POINT 6 SY	0	0	0	0	0	0	0
END DISPLACEMENT UX	0.22	0.03	0.25	-0.041	0.208	-0.05	0.2
END DISPLACEMENT UY	-0.023	-0.0029	0.026	0.0048	-0.021	0.0041	-0.024
"GLUED END" DISPL. FROM STEP 1	-0.068						

NOTE: ALL STRESS IN PSI

LOAD STEP 1: 250 - 72 DEG F
LOAD STEP 2: 72 - 48 DEG F
LOAD STEP 3: 48 DEG F TO STEP (COLD TO INNER TURN)
LOAD STEP 5: 48 DEG F TO STEP (COLD TO OUTER TURN)
STEP 12: SUMMATION OF STEP 1 AND 2
STEP 123: SUMMATION OF STEP 1,2 AND 3
STEP 125: SUMMATION OF STEP 1,2 AND 5

THE MECHANISMS AT WORK

Stress produced on the coil section is due to four major mechanisms

- difference of coefficients of thermal expansion in the composite straight section
- difference of coefficients of thermal expansion in the composite turn section
- thermal deflection in turns at different temperatures
- thermal deflection in the adjacent cross section

OTHER MODELS

There where small models done to understand the behavior of the coil.

CASE 6:LONG STRAIGHT SECTION OF COIL

This model was done to find the effect of different coefficients of thermal expansion between epoxy and copper. It showed only this effect which turned out to be a uniform 618 psi tensile stress in epoxy and a 120 psi compressive stress to the copper.

CASE 7:FULL MODEL W/LONG STRAIGHT & TURN EPOXY REMOVED

This model was intended to show bending stress in the long straight section due to short end epoxy and copper contraction. The model showed a bending stress of 36 psi on outer turn and 44 psi on the inner turn copper.

CASE 8:MODEL OF TURN ELEMENTS ONLY W/TEMPERATURE DROP FROM 250 DEG F TO 72 DEG F

This model show the bending stress developed due to differential contraction between copper and epoxy. generally speaking the copper wants to deflect .0017" radially and the epoxy only wants to deflect 0.0007" so must be compressed by the copper. This compression generates an amount of unsatisfied tangential deflection in each of the copper layers. The unsatisfied tangential deflection produces bending forces and a bending moment which is tensile to the outer and 2nd turn long straight section and compressive on the 3rd and inner turn of the long straight section. The magnitude of the bending stress is about 2075 psi tensile/2170 psi compressive to the copper straight section. Note that the long straight sections are not in this model but the goal of this model is to find the effect the turn has upon the long straight section.

CASE 9:MODEL OF TURN ELEMENTS ONLY W/TEMPERATURE RISE FROM 48 DEG F TO STEP TEMPERATURES REFLECTING THE COLD WATER TO INNER TURN CASE

This model shows the bending stress developed due to differential contraction between copper and epoxy and the effect of different coil temperatures. The turn again develops bending loads and bending stress which is tensile on the outer and 2nd turn straight sections and compressive on the 3rd and inner turn straight section. The magnitude is 890 psi tensile to long straight section and 612 compressive to long straight section. Again, the long straight sections are not in this model but the goal of this model is to find the effect the turn has upon the long straight section.

CASE 10:MODEL OF TURN ELEMENTS ONLY W/TEMPERATURE RISE FROM 48 DEG F TO STEP TEMPERATURES REFLECTING THE COLD WATER TO OUTER TURN CASE

This model shows the bending stress due differential temperatures and coefficients of thermal expansion. The effect is reversed in this case with a bending stress being developed which compressive to the outer turns of the coil and tensile to the inner turns. Again this is due to unsatisfied tangential deflection caused by the effect of epoxy and copper radial deflection mismatch. The epoxy always wants to deflect less than the copper and must be forced to its final position thus generating the internal stresses which "hold up" copper deflection and generates the tangential deflection deficit. The magnitude of the stress is 1340 psi tensile to outer long straight section copper and 1360 psi compressive to long straight section copper.

OVERALL RESULTS:

The maximum numerical stress occurs in STEP 12 at the point where the epoxy is fastened to the steel with adhesive. It was 900 psi in the x direction. A good argument can be made that the boundary conditions are not representative of the real coil because the joint is in reality primarily a shear joint on the top and bottom of the coil not the sides as modeled. Also, the thickness of the adhesive has not been taken into account which would have the effect of lowering this stress concentration by providing a more compliant joint. The model results are conservative and not significantly higher than other stresses which are considered to be accurately modeled so no further effort will be taken to remodel the analysis.

The next highest stress state, ignoring the adhesive joint, occurs in the turn section of STEP 12 and is 756 psi tangential stress. Generally speaking, the epoxy in a coil at room temperature has a prestress of 620 psi tensile from which it either unloads or loads. The maximum increase in load in the epoxy normal to the coil cross section would be 156 psi and the maximum unload would be -160 psi or a state of 756 psi and 440 psi respectively. The radial stress developed at the inside in the turns has a maximum 400 psi for STEP 123 and a minimum of -280 psi in STEP 125, built upon a room temperature preload of 131 psi. The straight section epoxy stress normal to the cross section lies in the range of 525 psi to 633 psi throughout all the load steps.

To sum up, the highest epoxy stress state found was 900 psi in the adhesive joint area in the center of the coil which is well below the 6000 psi tensile limit. Loads were found to be transmitted by normal stress in the adjacent straight sections, not shear stress as was originally assumed. The turns generate a bending stress for the straight sections which must bow in response. The stress state of the epoxy generally is dominated by the normal stress preload which exists after curing.

INDEX TO PLOTS

PLOT 1 THRU 4:	TEMPERATURE PROFILES OF STEPS 1,2,3 &5
PLOT 5 THRU 13:	EPOXY STRESS SR(SX IN RSYS 11), ST (SY IN RSYS 11), SX, SY, UX, UY OF POINTS OF INTEREST IN STEP 123 (COLD TO INNER)
PLOT 14 THRU 21:	EPOXY STRESS SR(SX IN RSYS 11), ST (SY IN RSYS 11), SX, SY, UX, UY OF POINTS OF INTEREST IN STEP 125 (COLD TO OUTER)
PLOT 22 THRU 23:	EPOXY STRESS SX AND SY FOR STEP 12 CURING AND COOLING CASE COMBINED. SHOWS MAXIMUM STRESS IN ALL CASES.
PLOT 24 THRU 25:	STRESS IN X DUE TO DIFFERENT COEFFICIENTS OF THERMAL CONTRACTION.
PLOT 26:	BENDING STRESS DUE TO END EPOXY AND COPPER CONTRACTION
PLOT 27 THRU 30:	TURN ONLY MODEL 250 DEG F TO 72 DEG F
PLOT 31 THRU 34:	TURN ONLY MODEL 48 DEG F TO STEP COLD TO INNER
PLOT 35 THRU 39:	TURN ONLY MODEL 48 DEG F TO STEP COLD TO OUTER

```
/BATCH
/TITLE,MI DIPOLE MAGNET COIL (2-D)
/UNITS,SIN
/FILNAME,CASE1
/PREP7
/CON
/CON NODE DEFINITIONS
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N,1,4.625,0.,0.
N,2,4.5625,0.,0.
N,3,4.5,0.,0.
N,4,4.25,0.,0.
N,5,4.,0.,0.

A LONG LIST OF NODE LOCATIONS


N,12727,125.25,8.5,0.
N,12728,125.25,8.75,0.
N,12729,125.5,8.375,0.
N,12730,125.5,8.75,0.
N,12731,125.5,8.5,0.
/CON
/CON MATERIAL PROPERTIES
EX,        1,  1.500000E+05
NUXY,      1,  3.490000E-01
DENS,      1,  7.317373E-04
ALPX,      1,  3.300000E-05
KXX,       1,  261.0
EX,        2,  1.700000E+07
NUXY,      2,  3.770000E-01
DENS,      2,  7.317373E-04
ALPX,      2,  9.800000E-06
KXX,       2,  67680.0
/CON
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/CON ELEMENT COORDINATE SYSTEM DEFINITION
/CON
/CON PHYSICAL PROP TABLE IN SIN:       1, LABEL:       1 IS REAL TABLE:       1
/CON
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ET,   1,  PLANE55,   0,   0,   0,   0,   0,   0
R,2,4.,0.,0.,0.,,
R,3,4.,0.,0.,0.,,
R,4,4.,0.,0.,0.,,
R,5,4.,0.,0.,0.,,
TYPE,  1 $ REAL,      1 $ MAT,      1
ESYS,  0
EN,1,26,27,54,53
EN,2,25,26,53,52
TYPE,  1 $ REAL,      2 $ MAT,      2
ESYS,  0
EN,3,24,25,52,51
EN,4,23,24,51,50
EN,5,22,23,50,49

ALONG LIST OF ELEMENT DEFINITIONS


TYPE,  1 $ REAL,      3 $ MAT,      2
ESYS,  0
EN,12151,12728,12724,12725,12730
EN,12152,12727,12728,12730,12731
SAVE
RESUME
FINISH
/SOLUTION
ANTYPE,STATIC
NROP,AUTO
/CON
/CON                TEMPERATURE SOLUTION
/CON
/CON Constraint set       1
CPDELE, 1, 0, 1
CEDELE, ALL
/CON
/CON Restraint set       1
DDELE, 1, ALL,  12731
/CON
/CON NODAL DISPLACEMENT RESTRAINTS
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D,2,UY,0....
D,3,UY,0....
D,4,UY,0....
D,5,UY,0....
D,6,UY,0....
D,7,UY,0....
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D,9,UY,0....
D,10,UY,0....
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D,15,UY,0....
D,16,UY,0....
D,17,UY,0....
D,18,UY,0....
D,19,UY,0....
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D,21,UY,0....
D,22,UY,0....
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D,25,UY,0....
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D,12590,UX,0....
D,12607,UX,0....
D,12609,UX,0....
D,12611,UX,0....
D,12633,UX,0....
D,12640,UX,0....
D,12660,UX,0....
D,12665,UX,0....
D,12681,UX,0....
D,12686,UX,0....

D,12700,UX,0....
D,12703,UX,0....
D,12713,UX,0....
D,12716,UX,0....
D,12723,UX,0....
D,12725,UX,0....
D,12729,UX,0....
D,12730,UX,0....
D,12731,UX,0....
/CON
/CON Load set       1
/CON
/CON NODAL TEMPERATURE LOADS
TREF,250
TOFFST,460
SALL
Nall
D,          ALL,   TEMP, 72
SALL
NALL
SOLVE
FINISH
/CON
/CON
/CON   STRESS SOLUTION ONE (FULL ANALYSIS)
/CON
/CON
/TITLE,MI DIPOLE MAGNET COIL (2-D) FULL BOUNDARY CONDITIONS
/PREP7
ET,   1,  PLANE42,   0,   0,   3,   0,   0,   0
FINISH
/SOLUTION
LDREAD,TEMP, , , , ,CASE1,rth
TOFFST,460
/CON
/CON NODAL DISPLACEMENT RESTRAINTS
D,1,UY,0....
D,2,UY,0....
D,3,UY,0....
D,4,UY,0....
D,5,UY,0....
D,6,UY,0....
D,7,UY,0....
D,8,UY,0....
D,9,UY,0....
D,10,UY,0....
D,11,UY,0....
D,12,UY,0....
D,13,UY,0....
D,14,UY,0....
D,15,UY,0....
D,16,UY,0....
D,17,UY,0....
D,18,UY,0....
D,19,UY,0....
D,20,UY,0....
D,21,UY,0....
D,22,UY,0....
D,23,UY,0....
D,24,UY,0....
D,25,UY,0....
D,26,UY,0....
D,27,UY,0....
D,12556,UX,0....
D,12558,UX,0....
D,12560,UX,0....
D,12590,UX,0....
D,12607,UX,0....
D,12609,UX,0....
D,12611,UX,0....
D,12633,UX,0....
D,12640,UX,0....
D,12660,UX,0....
D,12665,UX,0....
D,12681,UX,0....
D,12686,UX,0....
D,12700,UX,0....
D,12703,UX,0....
D,12713,UX,0....
D,12716,UX,0....
D,12723,UX,0....
D,12725,UX,0....
D,12729,UX,0....
D,12730,UX,0....
D,12731,UX,0....
SOLVE
FINISH

THIS SEGMENT IS FROM STEP 2 ROOM TEMPERATURE TO 48 DEG F...

/CON
/CON
/CON          LOAD SET 2 THERMAL 72 TO 55
/CON
/CON
/CON
/CON NODAL TEMPERATURE LOADS
TOFFST,460
TREF,72
SALL
NALL
DDELE,ALL,ALL
D,          ALL,   TEMP, 48.0
SALL
NALL
SOLVE
FINISH

THE STRESS SOLUTION IS THE SAME AS ABOVE
WITH ADDITION OF THIS SEGMENT...

/CON
NALL
NRSEL,X,108.125,125.5
NRSEL,Y,6.124,6.126
D,ALL,UY,0....
NALL
NRSEL,X,108.125,125.5
NRSEL,Y,10.74,10.76
D,ALL,UY,0....
NALL

THIS IS THE THERMAL SOLUTION SEGMENT FROM STEP 3 (48 DEG F TO STEP CTI)...

/CON
/CON
/CON
/CON          LOAD SET 3 THERMAL 48 TO STEP TEMP
/CON
/CON
/CON NODAL TEMPERATURE LOADS
TREF,48
TOFFST,460
SALL
NALL
ERSEL,REAL,2
NELEM
D,          ALL,   TEMP, 93.2
SALL
NALL
ERSEL,REAL,3
NELEM
D,          ALL,   TEMP, 84.7
SALL
NALL
ERSEL,REAL,4
NELEM
D,          ALL,   TEMP, 74.8
SALL
NALL
ERSEL,REAL,5
NELEM
D,          ALL,   TEMP, 71.6
SALL
NALL
SOLVE
FINISH

BOUNDARY CONDITIONS ARE THE SAME AS STEP 2
CASE 1 PLUS THIS SEGMENT...

NALL
NRSEL,X,108.125,125.5
NRSEL,Y,6.124,6.126
D,ALL,UY,0....
NALL
NRSEL,X,108.125,125.5

NRSEL,Y,10.74,10.76
D,ALL,UY,0....
NALL

LOAD STEP 5 (48 DEG F TO STEP CTO)...

/CON
/CON
/CON          LOAD SET 5 THERMAL 55 TO STEP TEMP
/CON
/CON
/CON
/CON NODAL TEMPERATURE LOADS
TREF,48
TOFFST,460
DDELE,ALL, ALL,
SALL
NALL
ERSEL,REAL,2
NELEM
D,          ALL,   TEMP, 77.7
SALL
NALL
ERSEL,REAL,3
NELEM
D,          ALL,   TEMP, 83.1
SALL
NALL
ERSEL,REAL,4
NELEM
D,          ALL,   TEMP, 94.1
SALL
NALL
ERSEL,REAL,5
NELEM
D,          ALL,   TEMP, 98.6
SALL
```
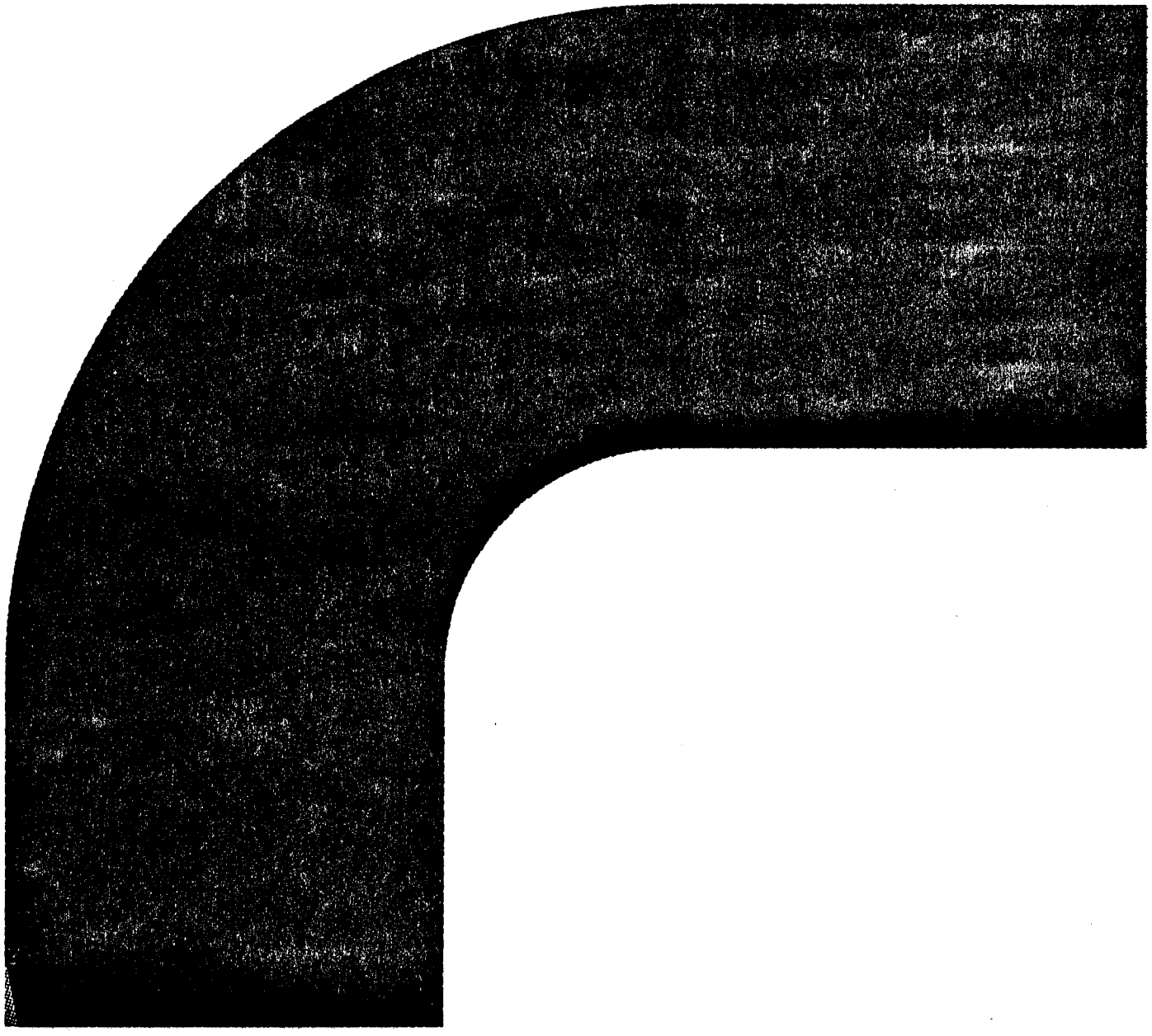
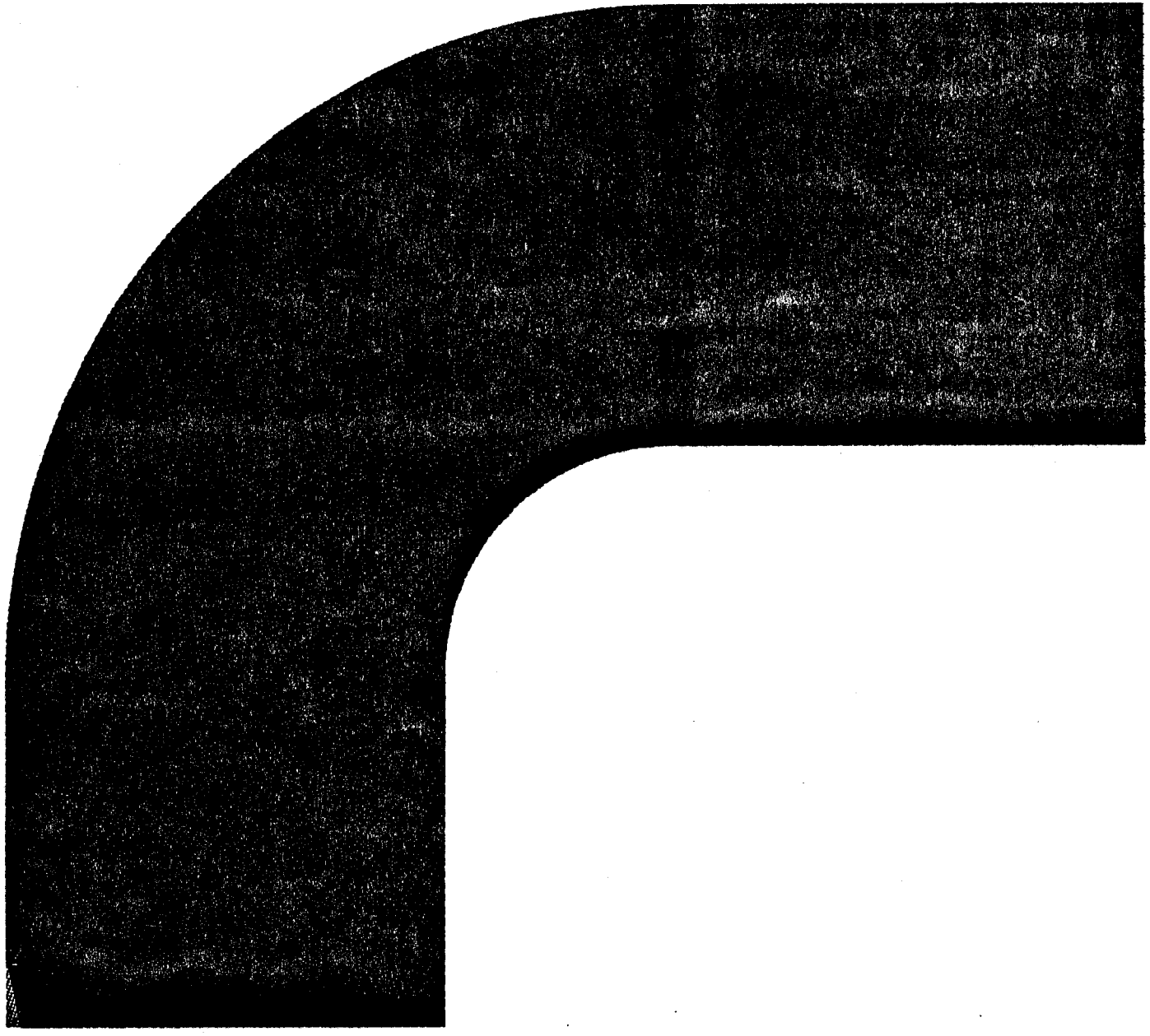



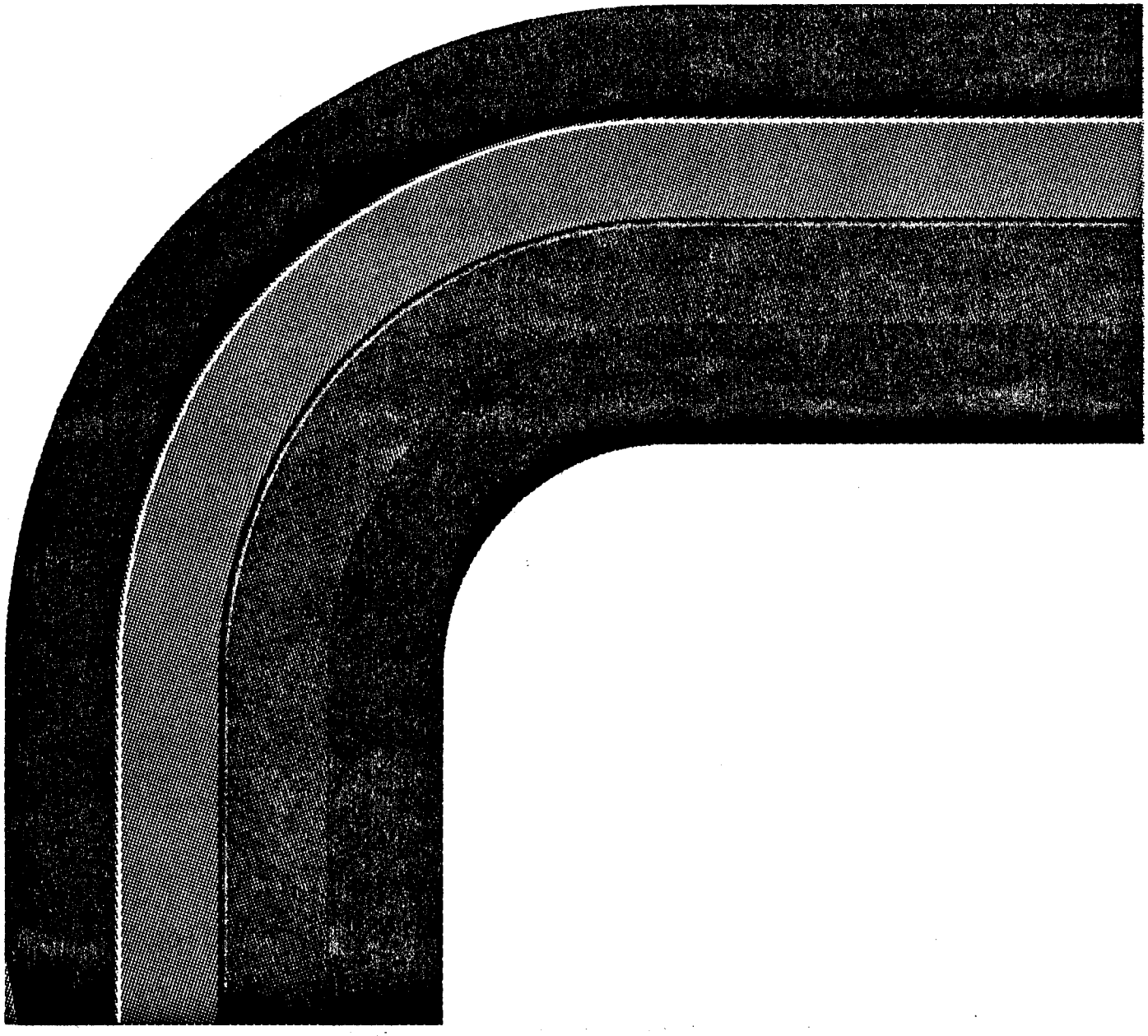
ANSYS 5.0
SEP 21 1994
10:33:54
PLOT NO. 4
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP
TEPC=0.652E-05
SMN =72
SMX =72

MI DIPOLE MAGNET COIL (2-D) (STEP 1: 250 DEG TO 72 DEG)



ANSYS 5.0
SEP 21 1994
10:18:52
PLOT NO. 3
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP
TEPC=0.652E-05
SMN =48
SMX =48

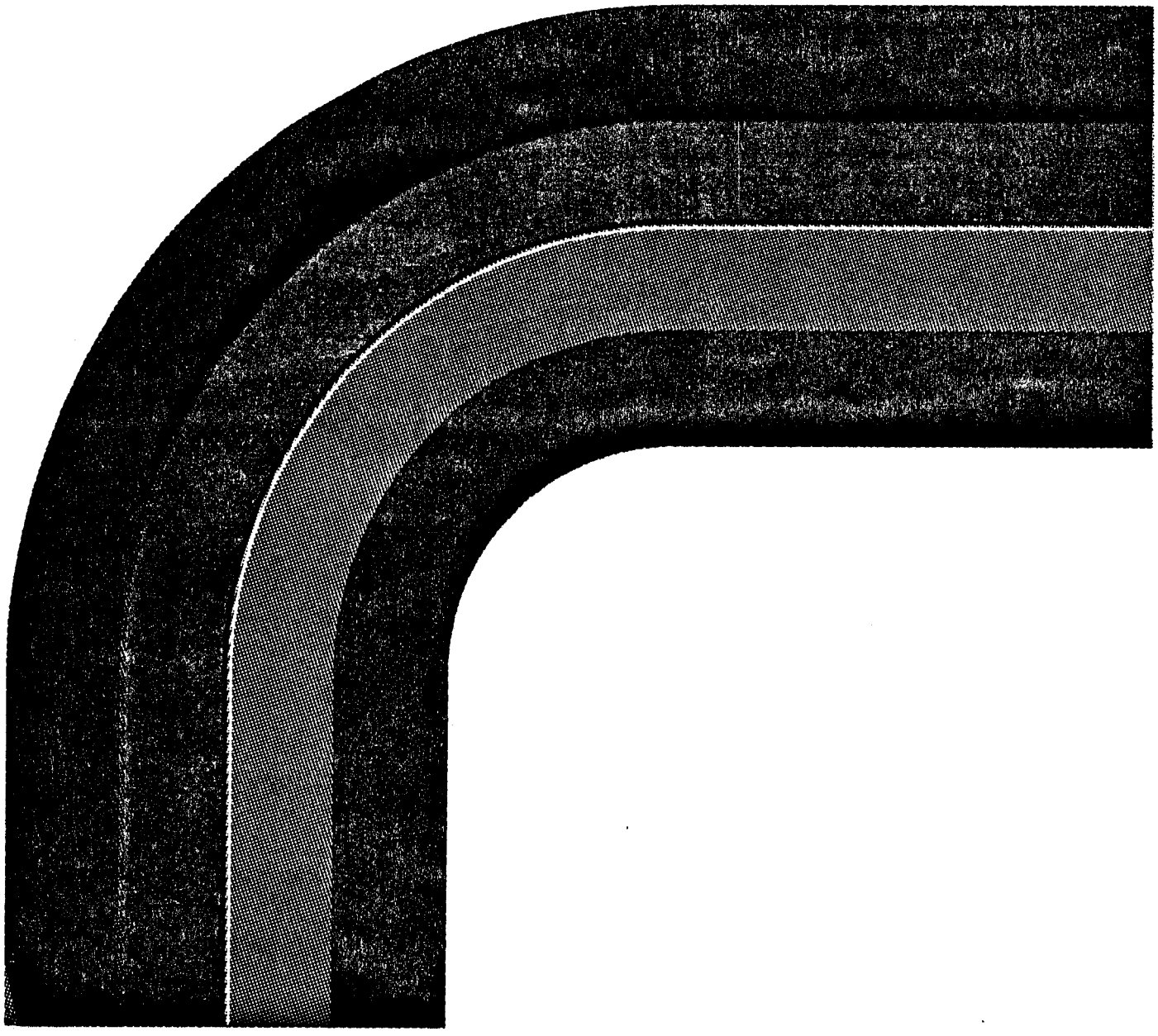
MI DIPOLE MAGNET COIL (2-D) (STEP 2: 72 DEG TO 48 DEG)



ANSYS 5.0
SEP 21 1994
10:11:55
PLOT NO. 2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP
TEPC=36.211
SMN =71.6
SMX =93.2

71.6
74
76.4
78.8
81.2
83.6
86
88.4
90.8
93.2

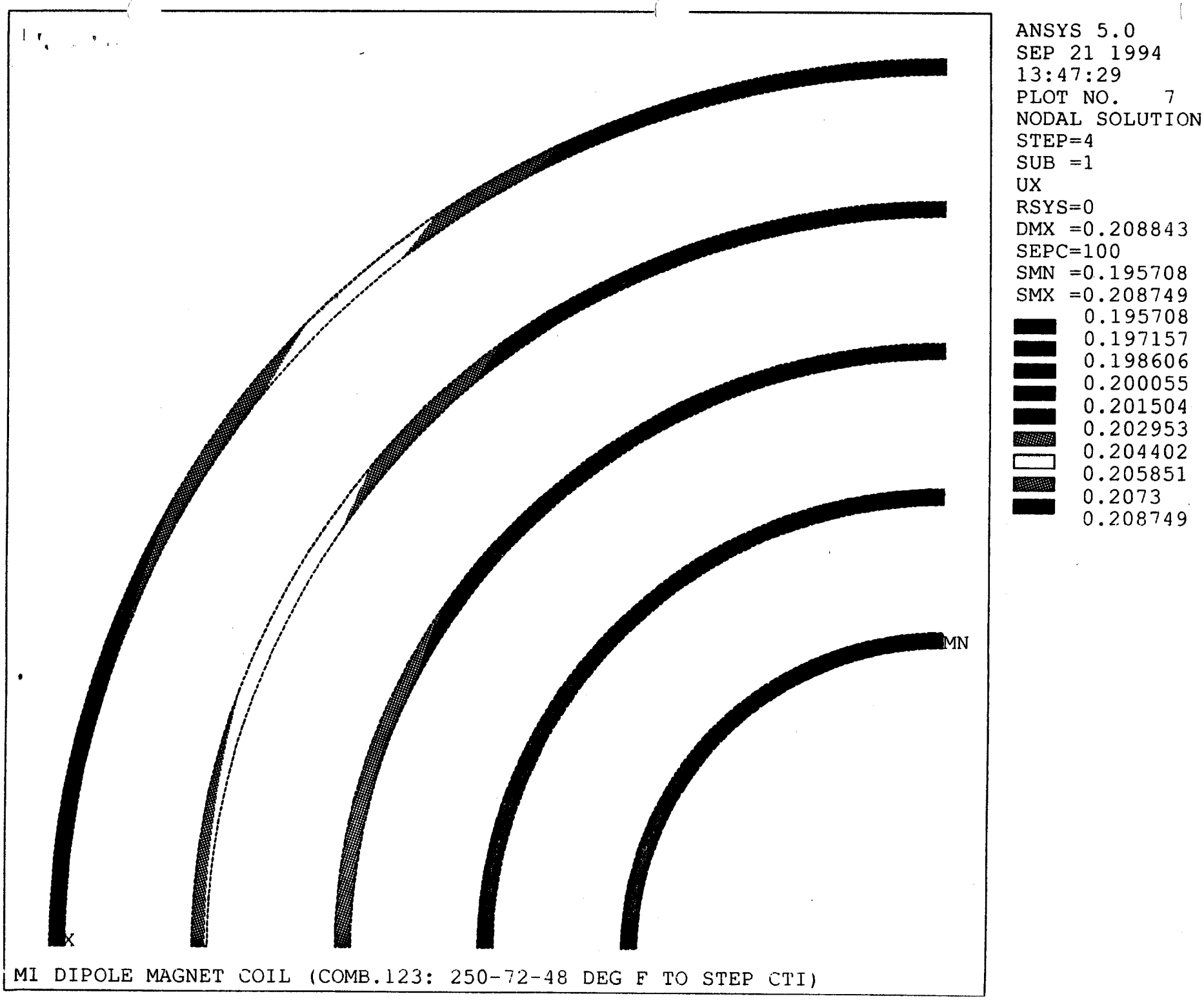
MI DIPOLE MAGNET COIL (2-D)(DIFF. TURN TEMPS)(COLD TO INNER)

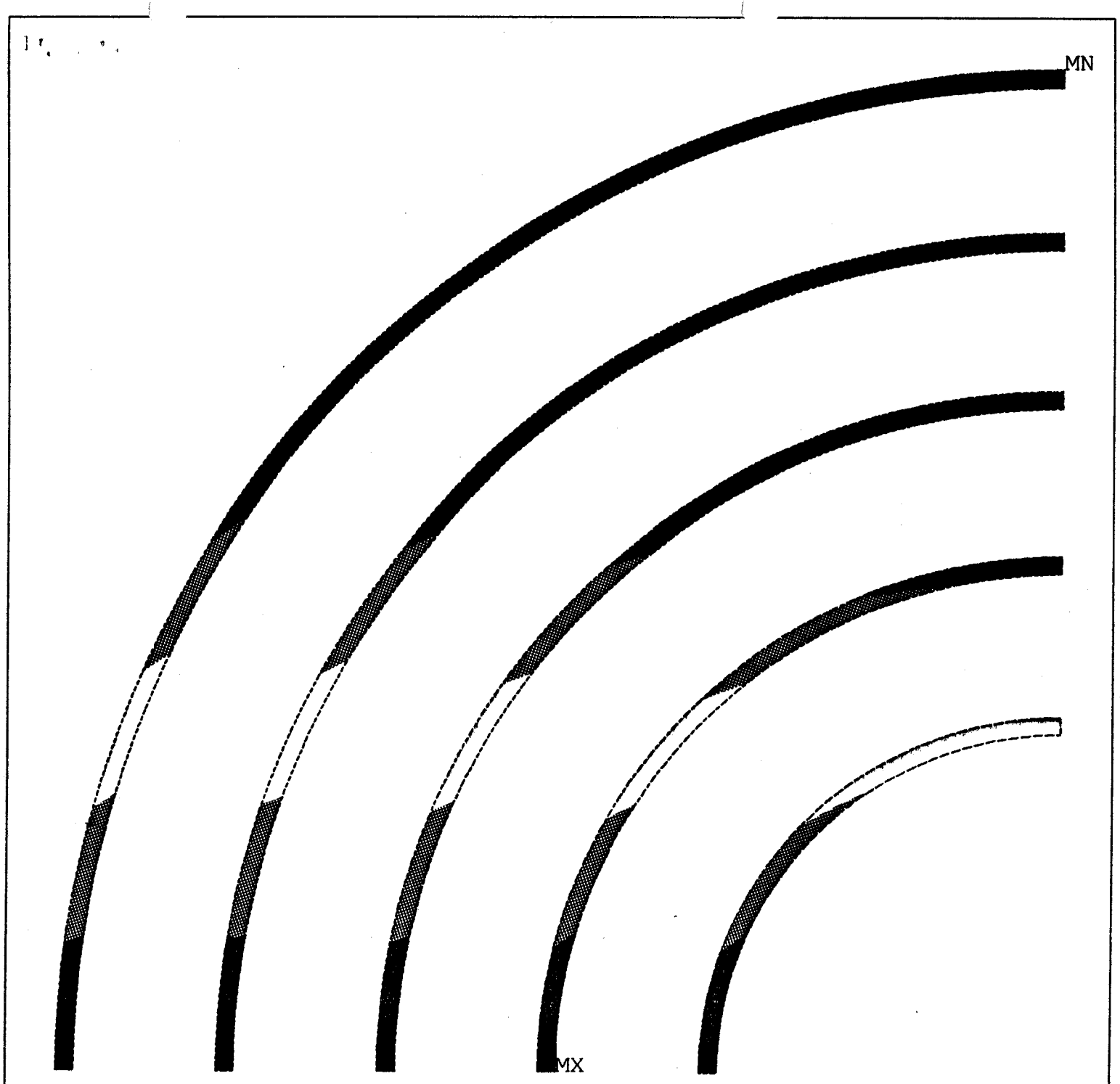


ANSYS 5.0
SEP 21 1994
10:04:03
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP
TEPC=36.288
SMN =77.7
SMX =98.6

77.7
80.022
82.344
84.667
86.989
89.311
91.633
93.956
96.278
98.6

M1 DIPOLE MAGNET COIL (2-D)(DIFF. TURN TEMPS)(COLD TO OUTER)

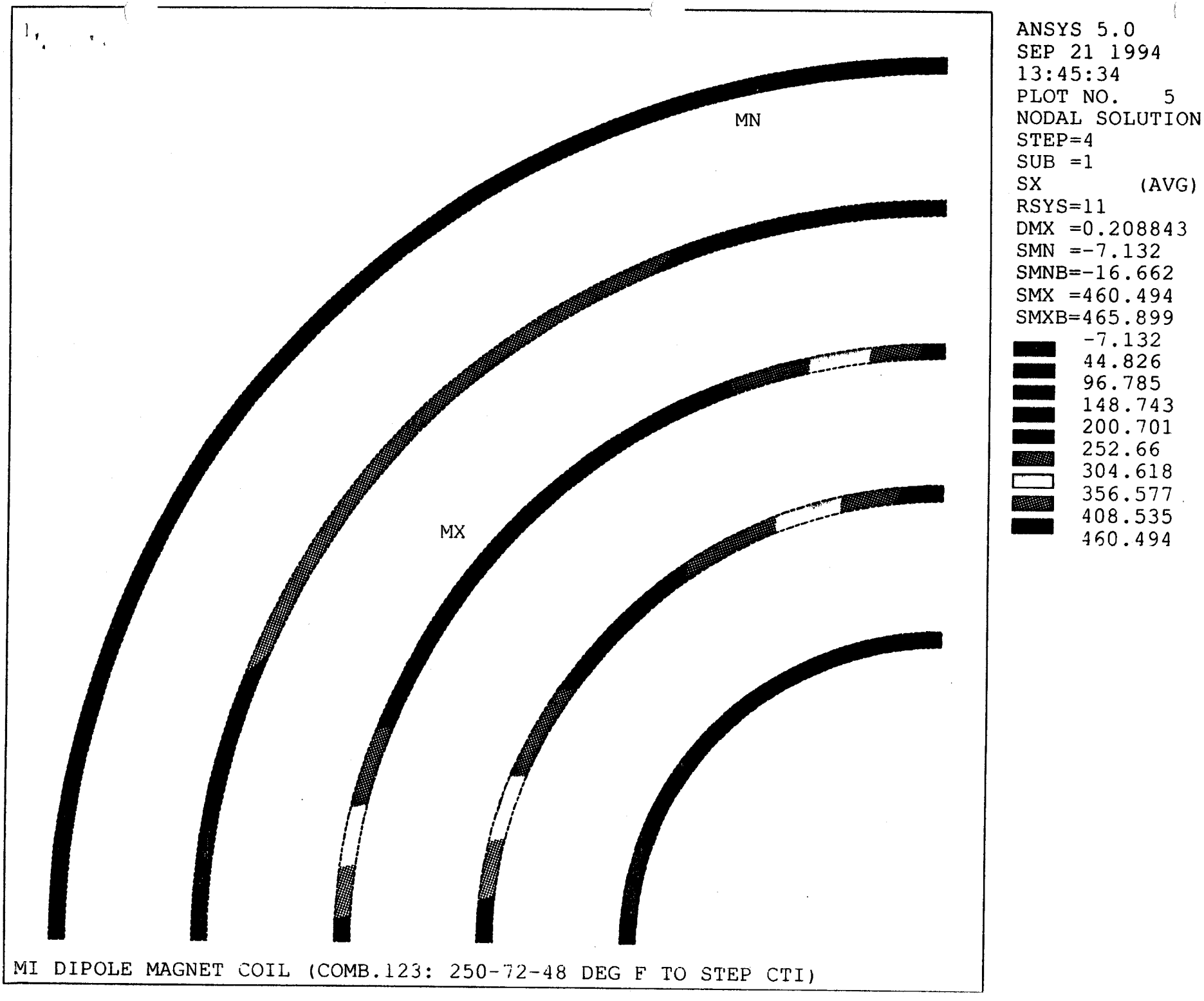

ANSYS 5.0
SEP 21 1994
13:47:29
PLOT NO. 7
NODAL SOLUTION
STEP=4
SUB =1
UX
RSYS=0
DMX =0.208843
SEPC=100
SMN =0.195708
SMX =0.208749
0.195708
0.197157
0.198606
0.200055
0.201504
0.202953
0.204402
0.205851
0.2073
0.208749
MN
MX
MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)

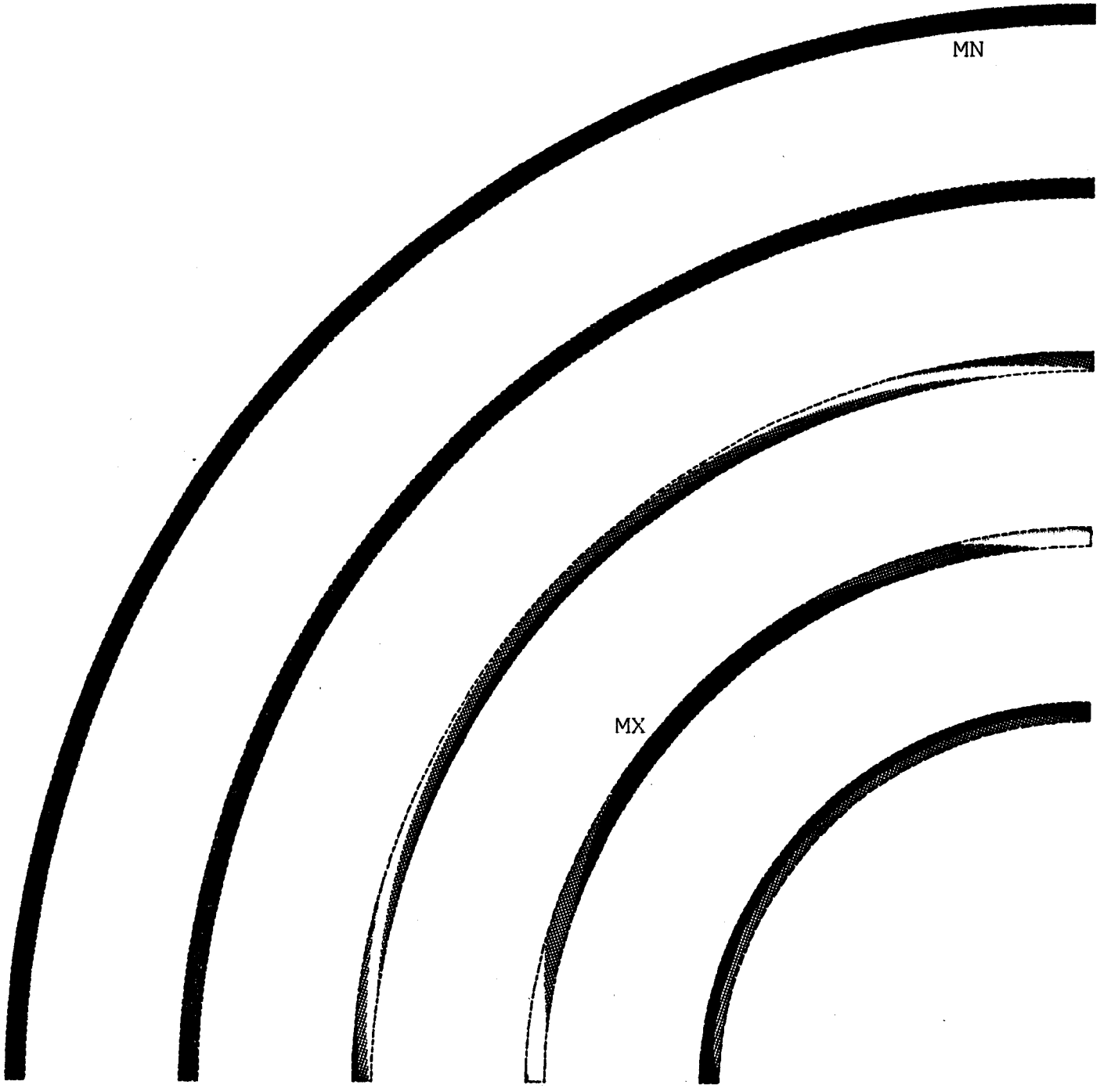


ANSYS 5.0
SEP 21 1994
13:48:38
PLOT NO. 8
NODAL SOLUTION
STEP=4
SUB =1
UY
RSYS=0
DMX =0.208843
SEPC=100
SMN =-0.020775
SMX =-0.00614

-0.020775
-0.019149
-0.017523
-0.015897
-0.01427
-0.012644
-0.011018
-0.009392
-0.007766
-0.00614

MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)

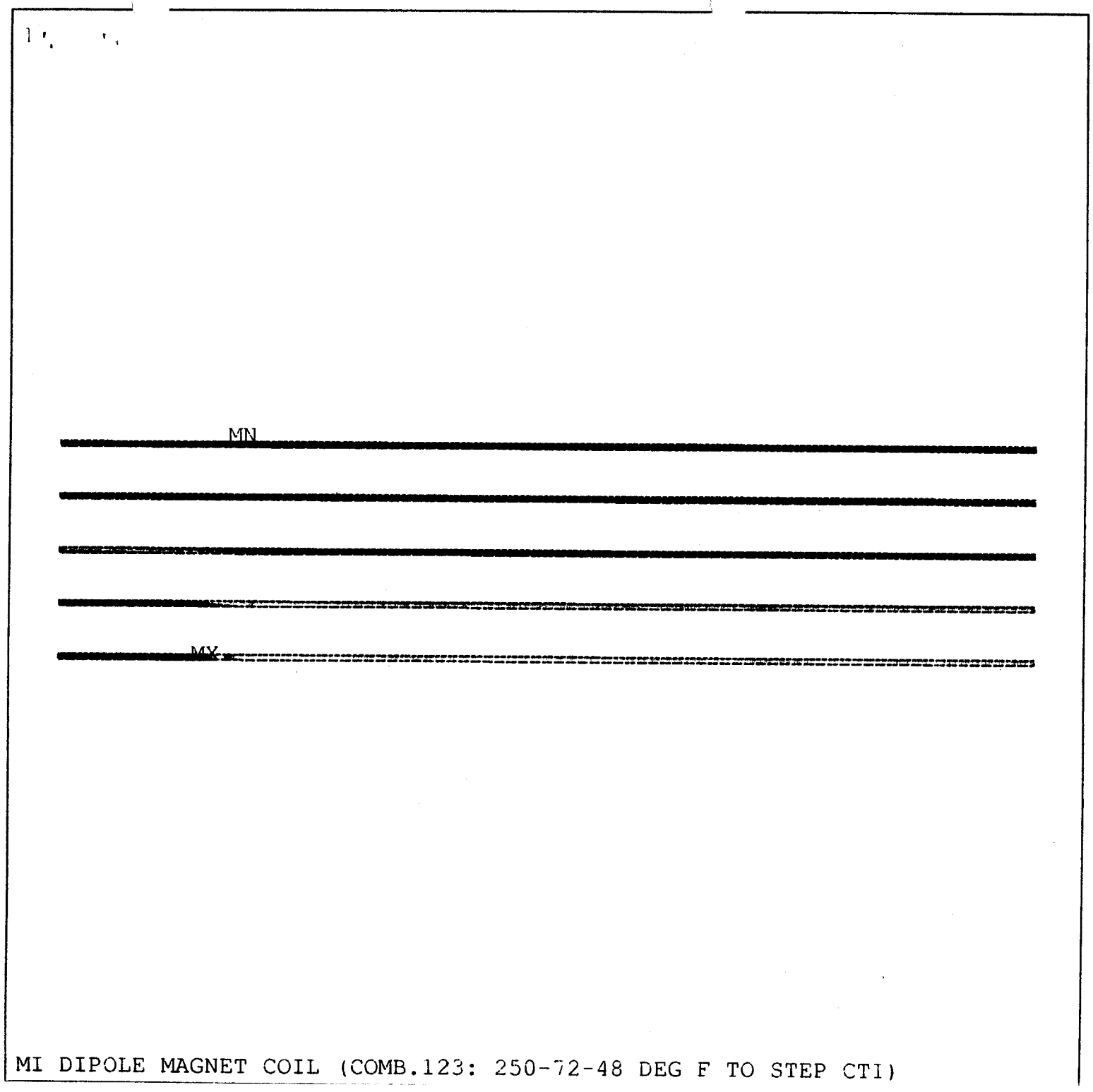

MN
MX
ANSYS 5.0
SEP 21 1994
13:45:34
PLOT NO. 5
NODAL SOLUTION
STEP=4
SUB =1
SX (AVG)
RSYS=11
DMX =0.208843
SMN =-7.132
SMNB=-16.662
SMX =460.494
SMXB=465.899
-7.132
44.826
96.785
148.743
200.701
252.66
304.618
356.577
408.535
460.494
MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)



ANSYS 5.0
SEP 21 1994
13:46:31
PLOT NO. 6
NODAL SOLUTION
STEP=4
SUB =1
SY (AVG)
RSYS=11
DMX =0.208843
SMN =519.854
SMNB=510.498
SMX =776.518
SMXB=781.925

519.854
548.373
576.891
605.409
633.927
662.446
690.964
719.482
748
776.518

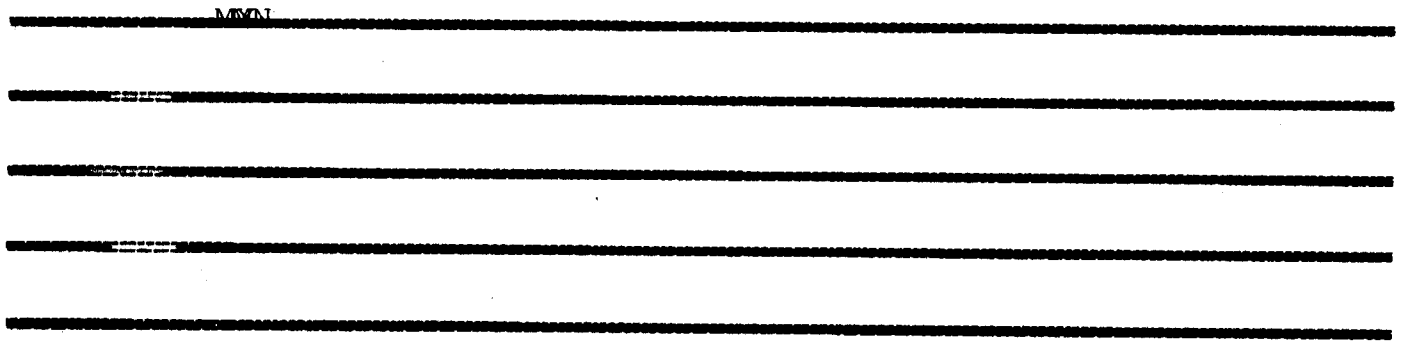
MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)



ANSYS 5.0
SEP 21 1994
13:39:01
PLOT NO. 1
NODAL SOLUTION
STEP=4
SUB =1
SX (AVG)
RSYS=0
DMX =0.074633
SMN =439.64
SMNB=420.845
SMX =641.333
SMXB=653.561

439.64
462.05
484.46
506.871
529.281
551.691
574.102
596.512
618.923
641.333

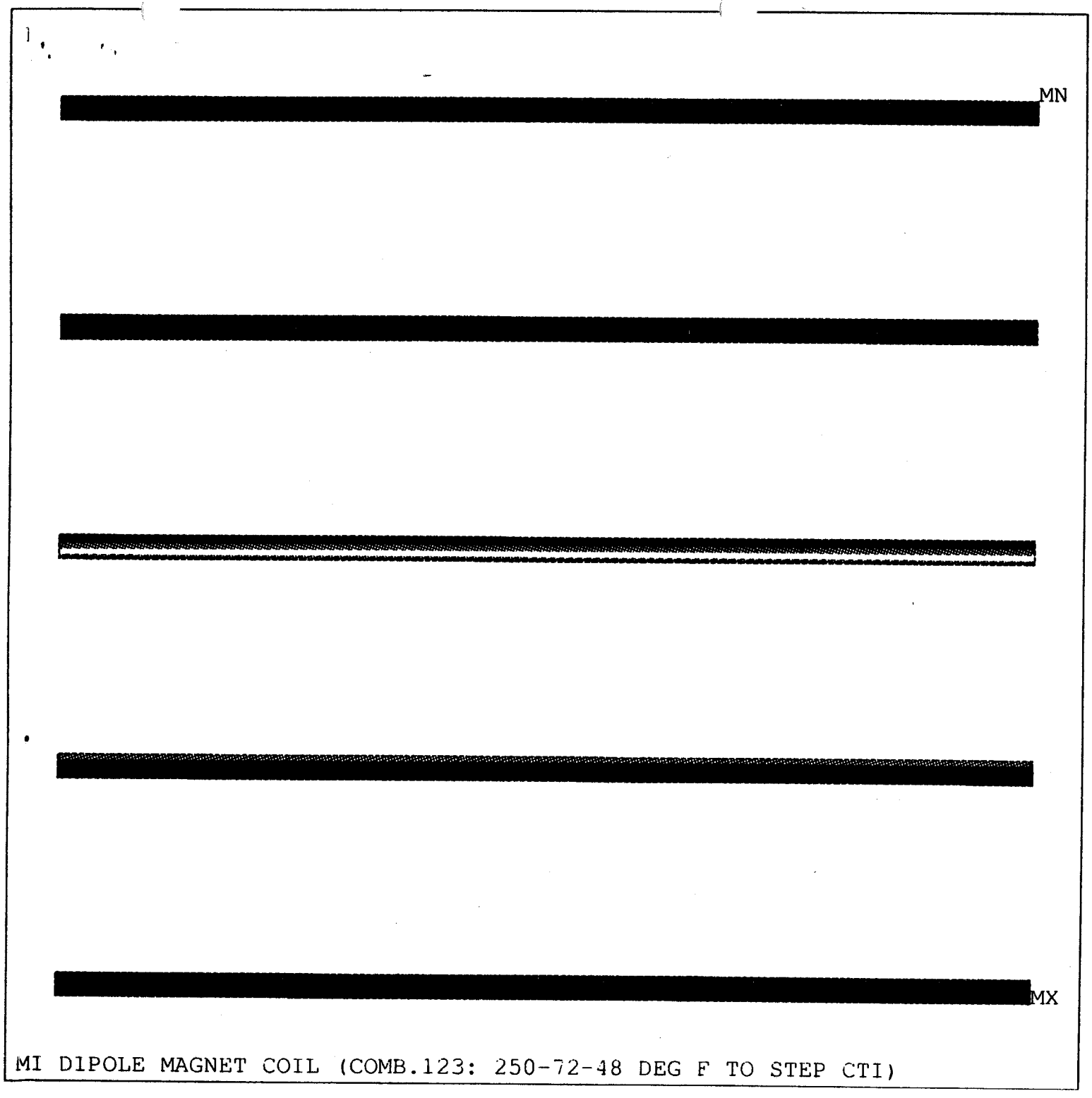
MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)



ANSYS 5.0
SEP 21 1994
13:40:14
PLOT NO. 2
NODAL SOLUTION
STEP=4
SUB =1
SY (AVG)
RSYS=0
DMX =0.074633
SMN =-257.222
SMNB=-283.46
SMX =51.806
SMXB=76.081

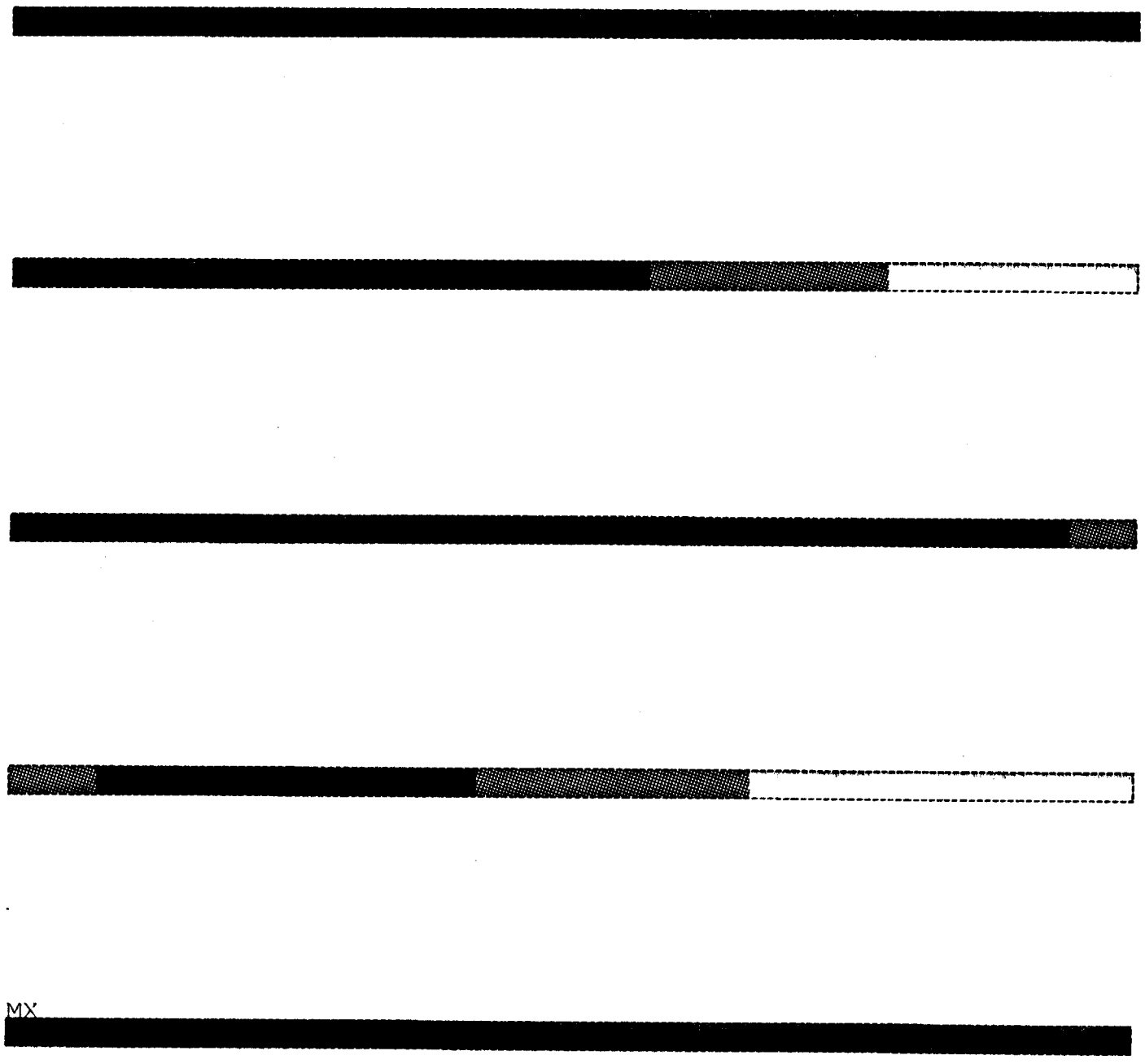
-257.222
-222.886
-188.549
-154.213
-119.876
-85.54
-51.203
-16.867
17.47
51.806

MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)



ANSYS 5.0
SEP 21 1994
13:42:22
PLOT NO. 3
NODAL SOLUTION
STEP=4
SUB =1
SX (AVG)
RSYS=0
DMX =0.178852
SMN =526.73
SMNB=526.725
SMX =633.848
SMXB=633.854

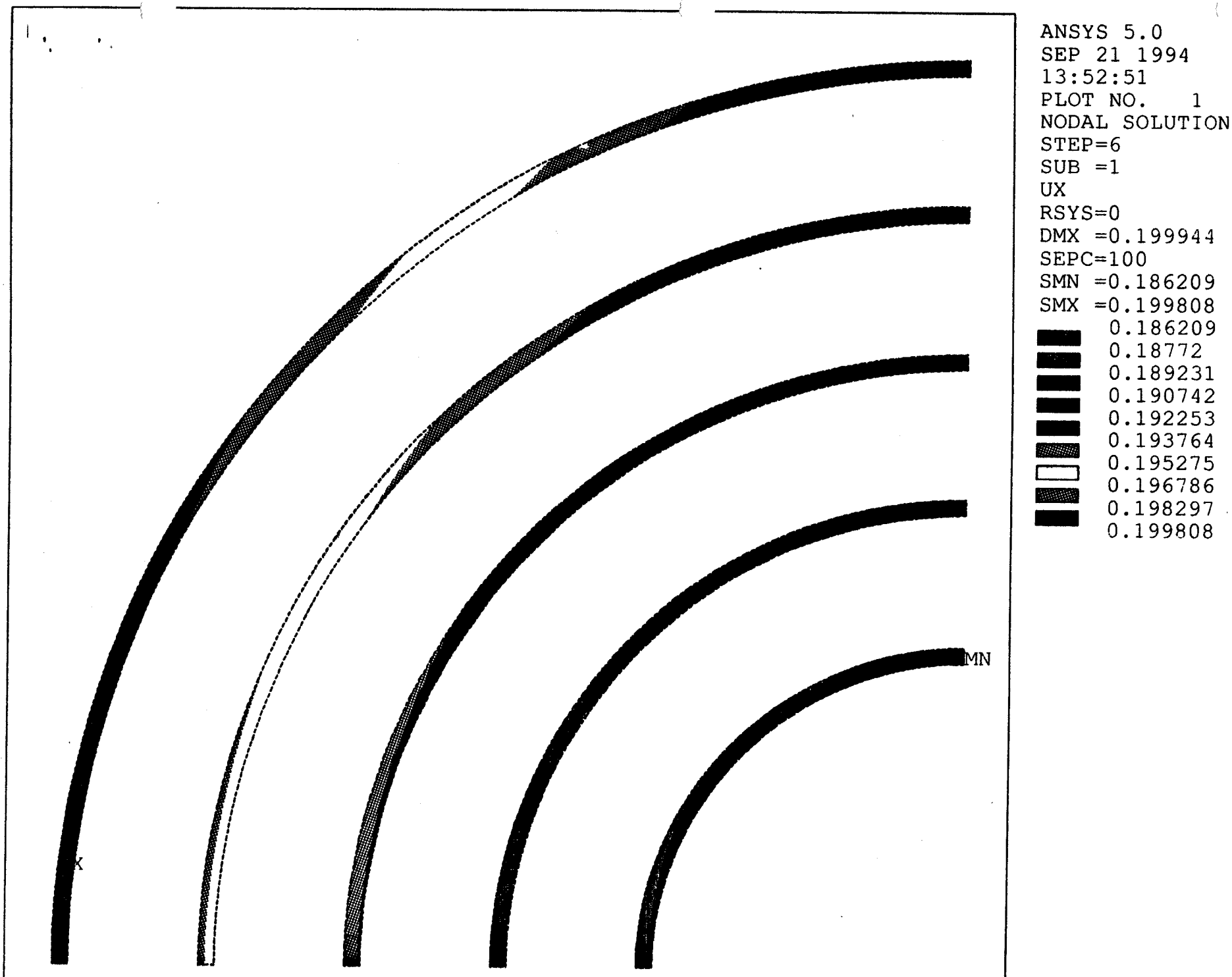
526.73
538.632
550.534
562.436
574.338
586.24
598.142
610.044
621.946
633.848



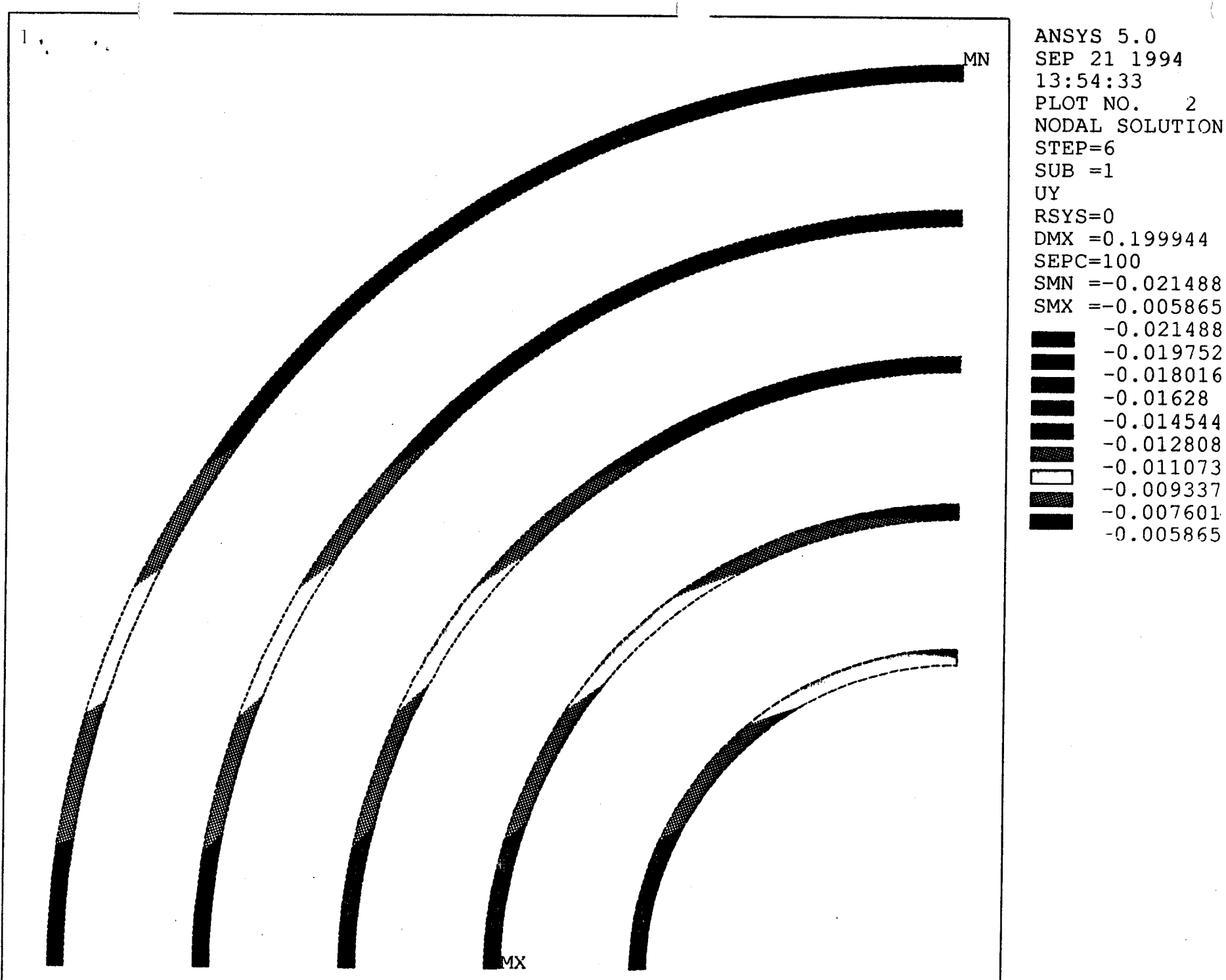
ANSYS 5.0
SEP 21 1994
13:43:15
PLOT NO. 4
NODAL SOLUTION
STEP=4
SUB =1
SY (AVG)
RSYS=0
DMX =0.178852
SMN =-0.039155
SMNB=-0.040194
SMX =0.001791
SMXB=0.007206

-0.039155
-0.034605
-0.030056
-0.025506
-0.020957
-0.016407
-0.011858
-0.007308
-0.002759
0.001791

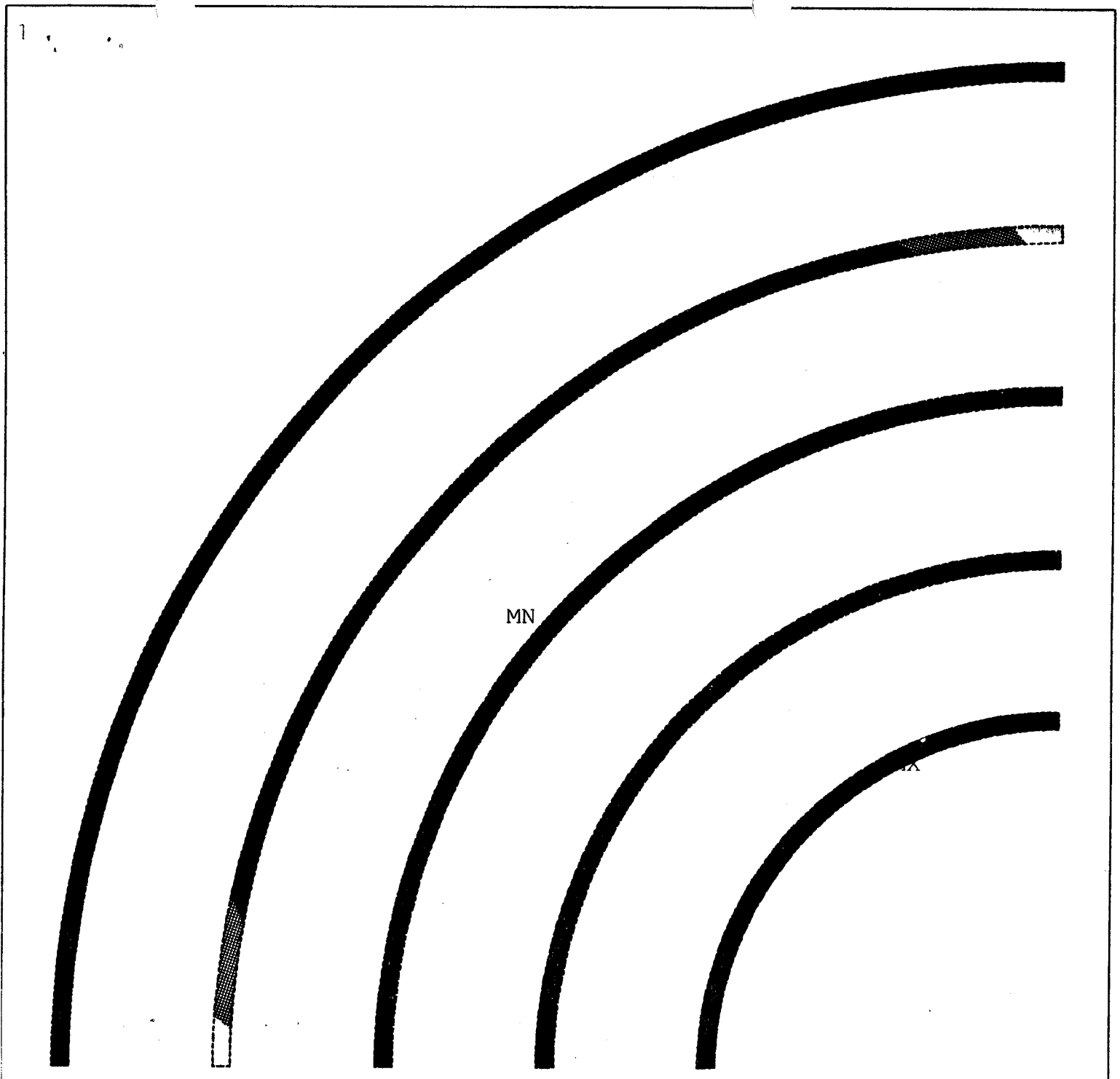
MI DIPOLE MAGNET COIL (COMB.123: 250-72-48 DEG F TO STEP CTI)



MI DIPOLE MAGNET COIL (COMB.125 250-72-48 TO STEP CTO)



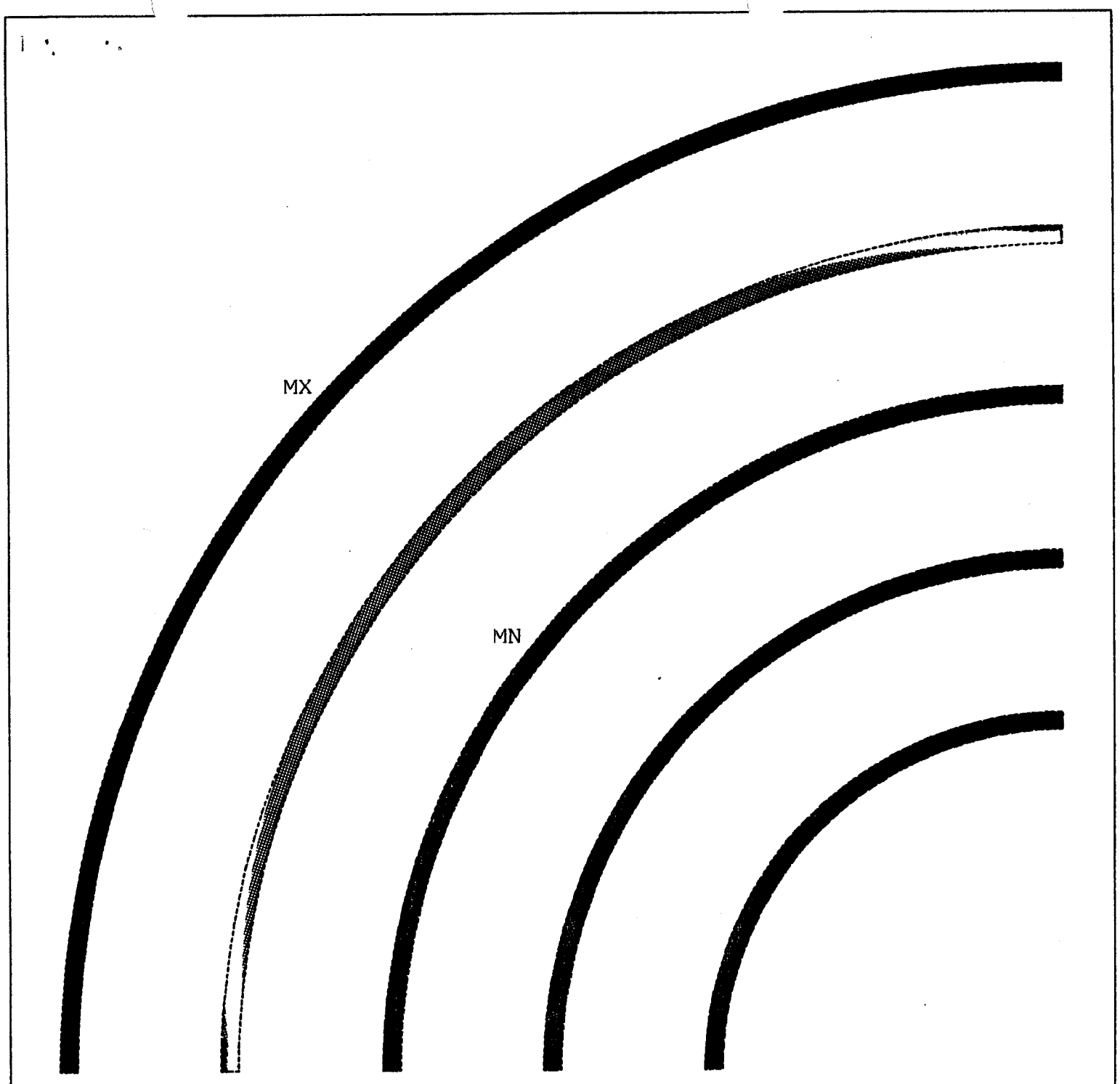
MI DIPOLE MAGNET COIL (COMB.125 250-72-48 TO STEP CTO)



ANSYS 5.0
SEP 21 1994
13:55:41
PLOT NO. 3
NODAL SOLUTION
STEP=6
SUB =1
SX (AVG)
RSYS=11
DMX =0.199944
SMN =-336.481
SMNB=-348.969
SMX =20.375
SMXB=29.333

-336.481
-296.831
-257.18
-217.529
-177.879
-138.228
-98.577
-58.927
-19.276
20.375

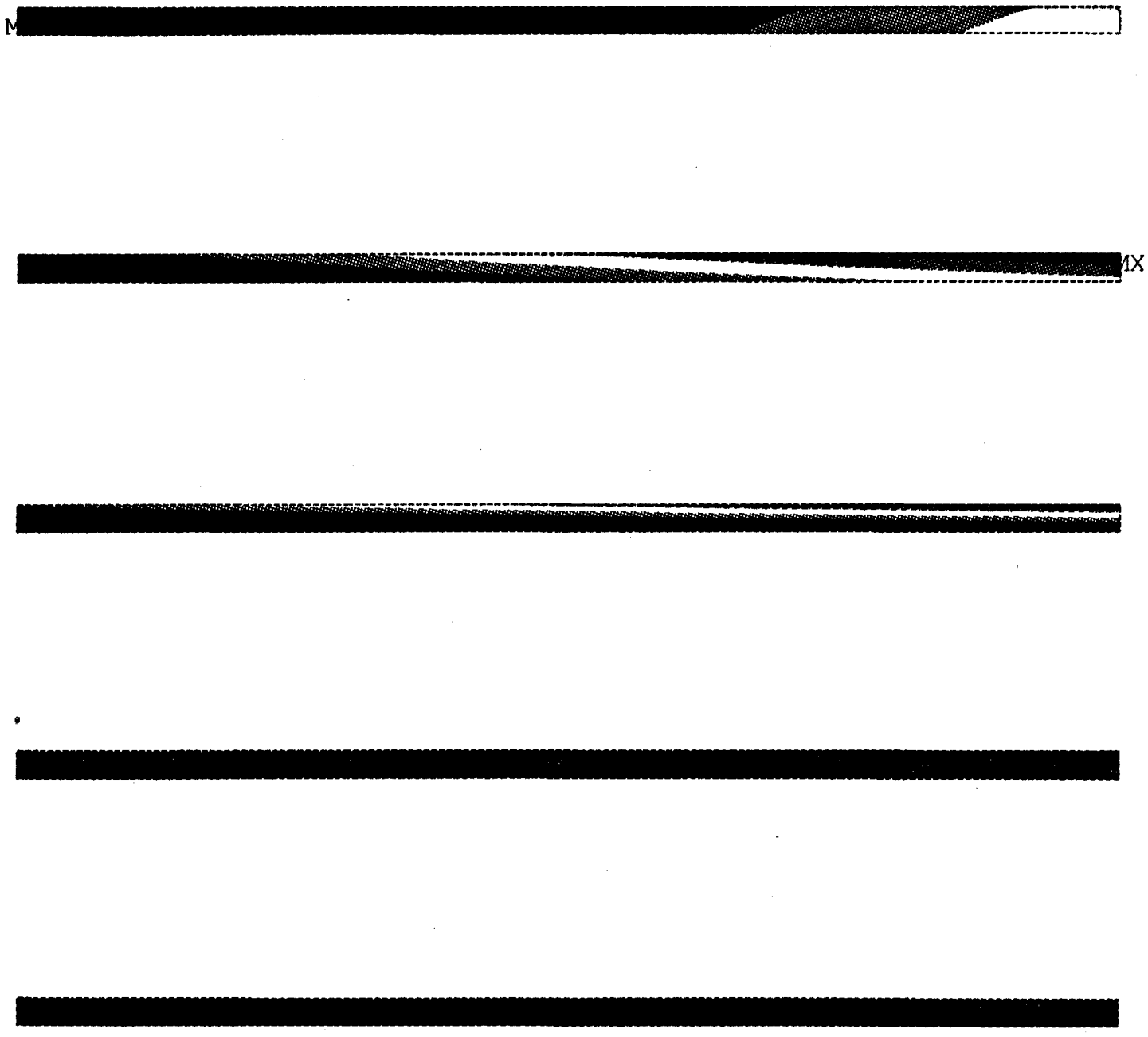
MI DIPOLE MAGNET COIL (COMB.125 250-72-48 TO STEP CTO)



ANSYS 5.0
SEP 21 1994
13:56:41
PLOT NO. 4
NODAL SOLUTION
STEP=6
SUB =1
SY (AVG)
RSYS=11
DMX =0.199944
SMN =432.37
SMNB=419.891
SMX =610.987
SMXB=621.833

432.37
452.216
472.063
491.909
511.755
531.602
551.448
571.294
591.14
610.987

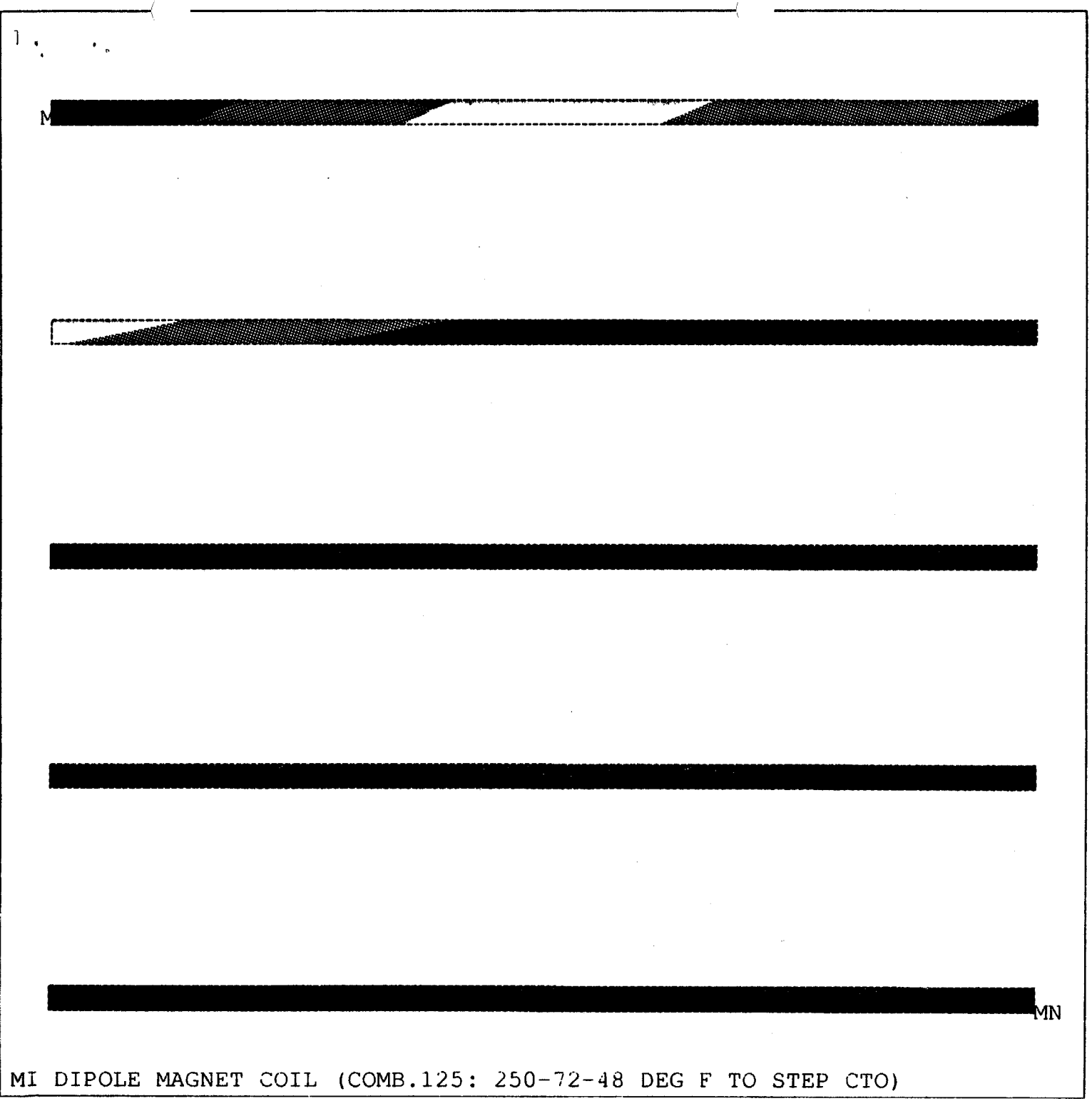
MI DIPOLE MAGNET COIL (COMB.125 250-72-48 TO STEP CTO)

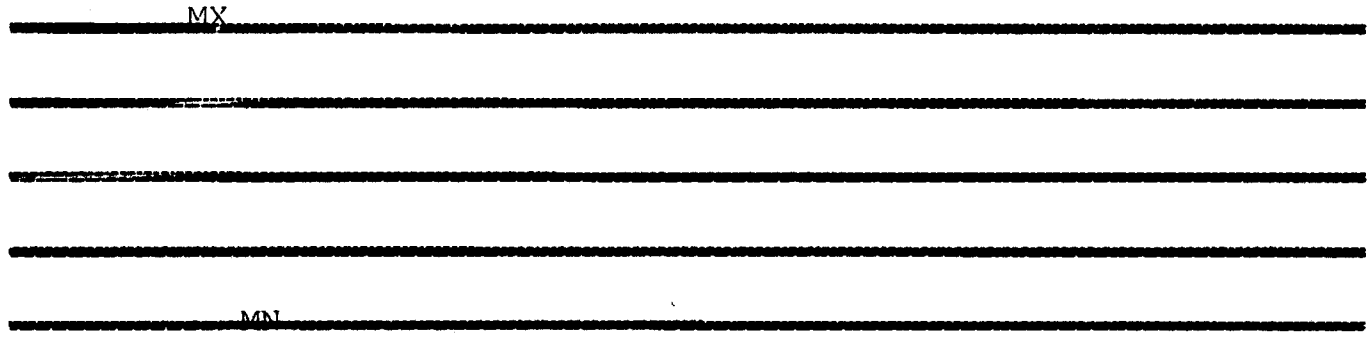


ANSYS 5.0
SEP 21 1994
13:57:54
PLOT NO. 5
NODAL SOLUTION
STEP=6
SUB =1
SX (AVG)
RSYS=11
DMX =0.172442
SMN =473.407
SMNB=473.405
SMX =554.392
SMXB=554.395

473.407
482.405
491.404
500.402
509.4
518.399
527.397
536.395
545.394
554.392

MI DIPOLE MAGNET COIL (COMB.125: 250-72-48 DEG F TO STEP CTO)

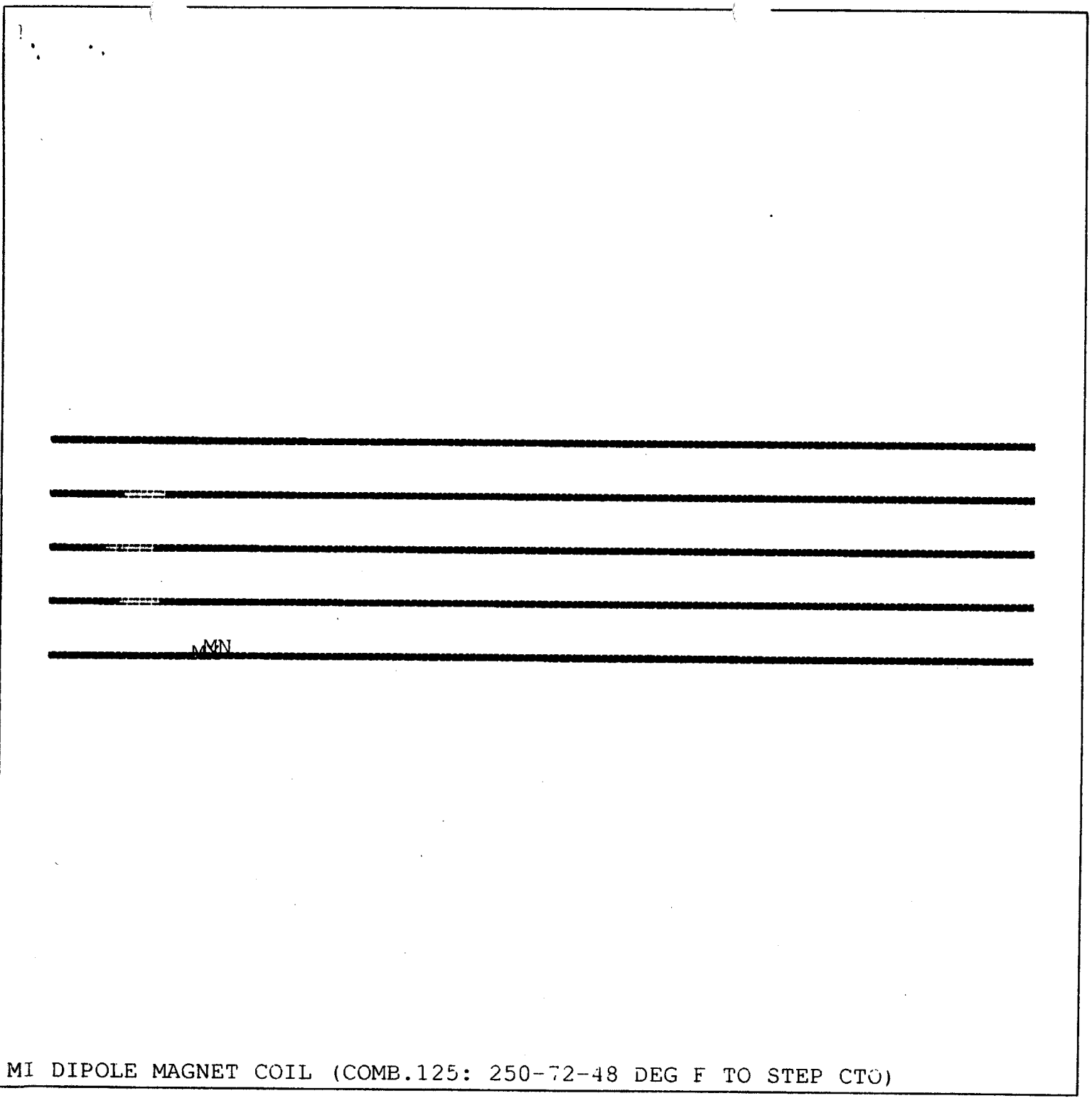

M
MN
ANSYS 5.0
SEP 21 1994
13:58:44
PLOT NO. 6
NODAL SOLUTION
STEP=6
SUB =1
SY (AVG)
RSYS=11
DMX =0.172442
SMN =8.803
SMNB=8.801
SMX =137.259
SMXB=137.261
8.803
23.076
37.349
51.622
65.895
80.168
94.441
108.714
122.986
137.259
MI DIPOLE MAGNET COIL (COMB.125: 250-72-48 DEG F TO STEP CTO)



ANSYS 5.0
SEP 21 1994
14:00:01
PLOT NO. 7
NODAL SOLUTION
STEP=6
SUB =1
SX (AVG)
RSYS=11
DMX =0.073857
SMN =374.332
SMNB=342.666
SMX =617.441
SMXB=644.149

374.332
401.344
428.356
455.368
482.38
509.392
536.405
563.417
590.429
617.441

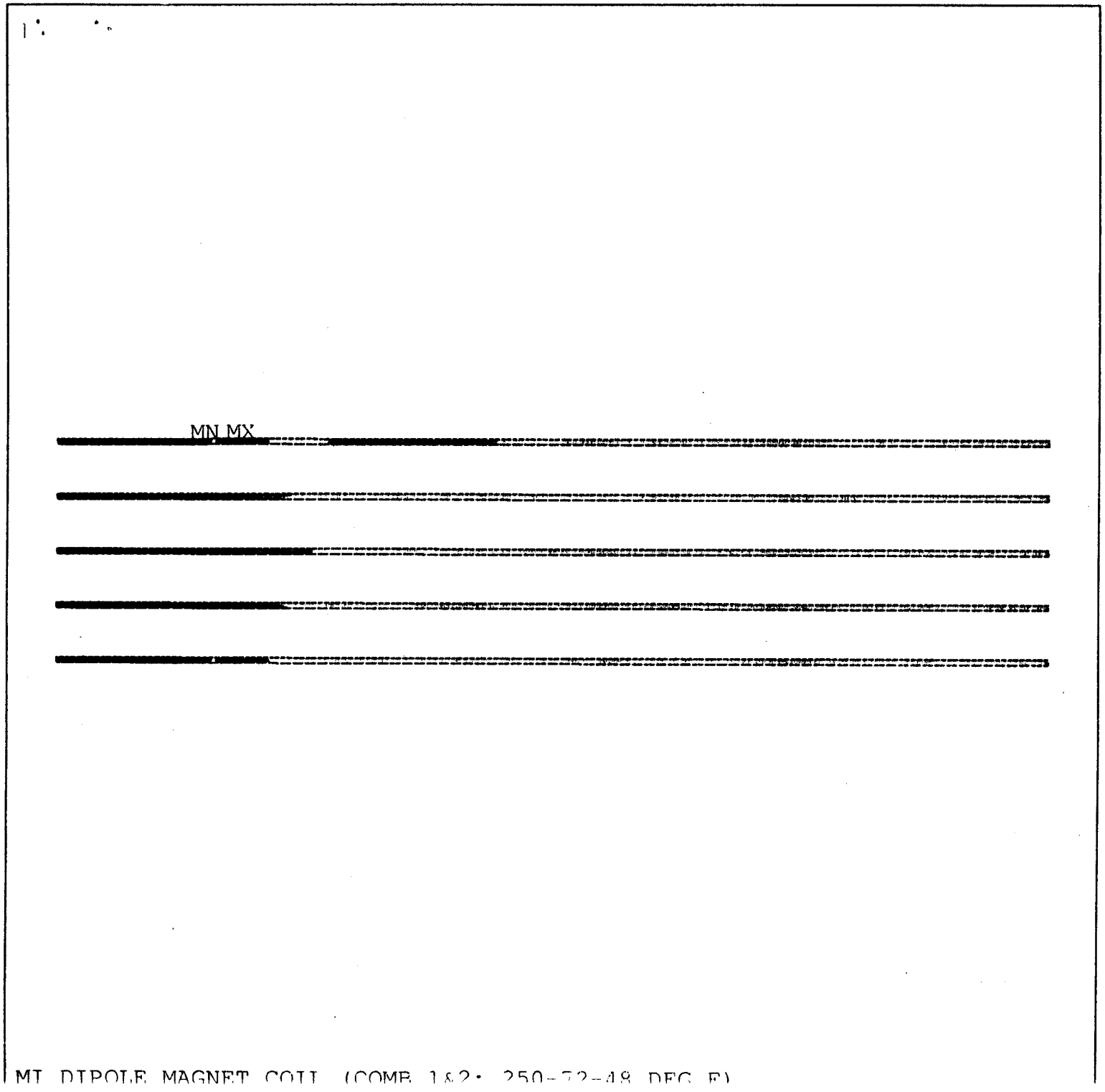
MI DIPOLE MAGNET COIL (COMB.125: 250-72-48 DEG F TO STEP CTO)

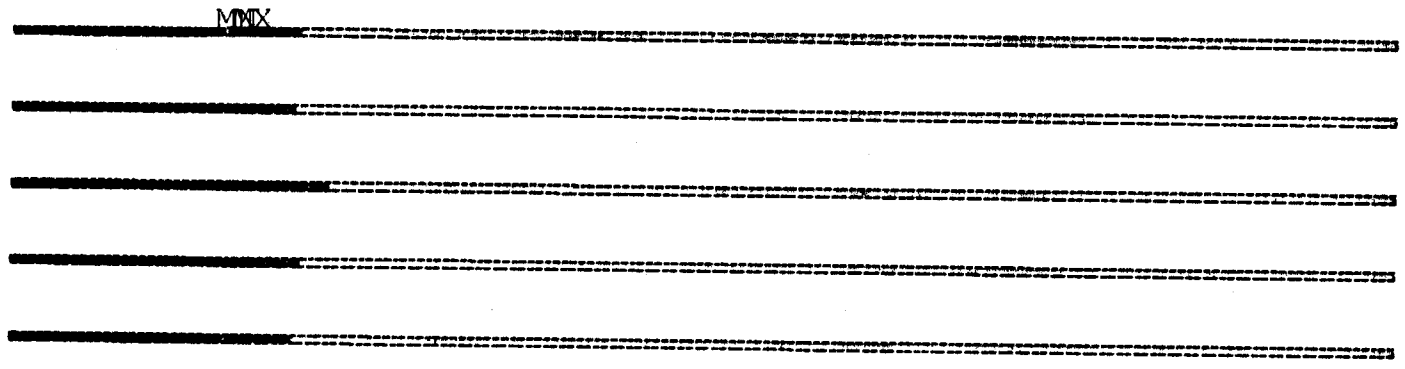


ANSYS 5.0
SEP 21 1994
14:01:00
PLOT NO. 8
NODAL SOLUTION
STEP=6
SUB =1
SY (AVG)
RSYS=11
DMX =0.073857
SMN =-419.908
SMNB=-464.273
SMX =83.807
SMXB=123.655

-419.908
-363.94
-307.971
-252.003
-196.035
-140.066
-84.098
-28.13
27.838
83.807

MI DIPOLE MAGNET COIL (COMB.125: 250-72-48 DEG F TO STEP CTO)

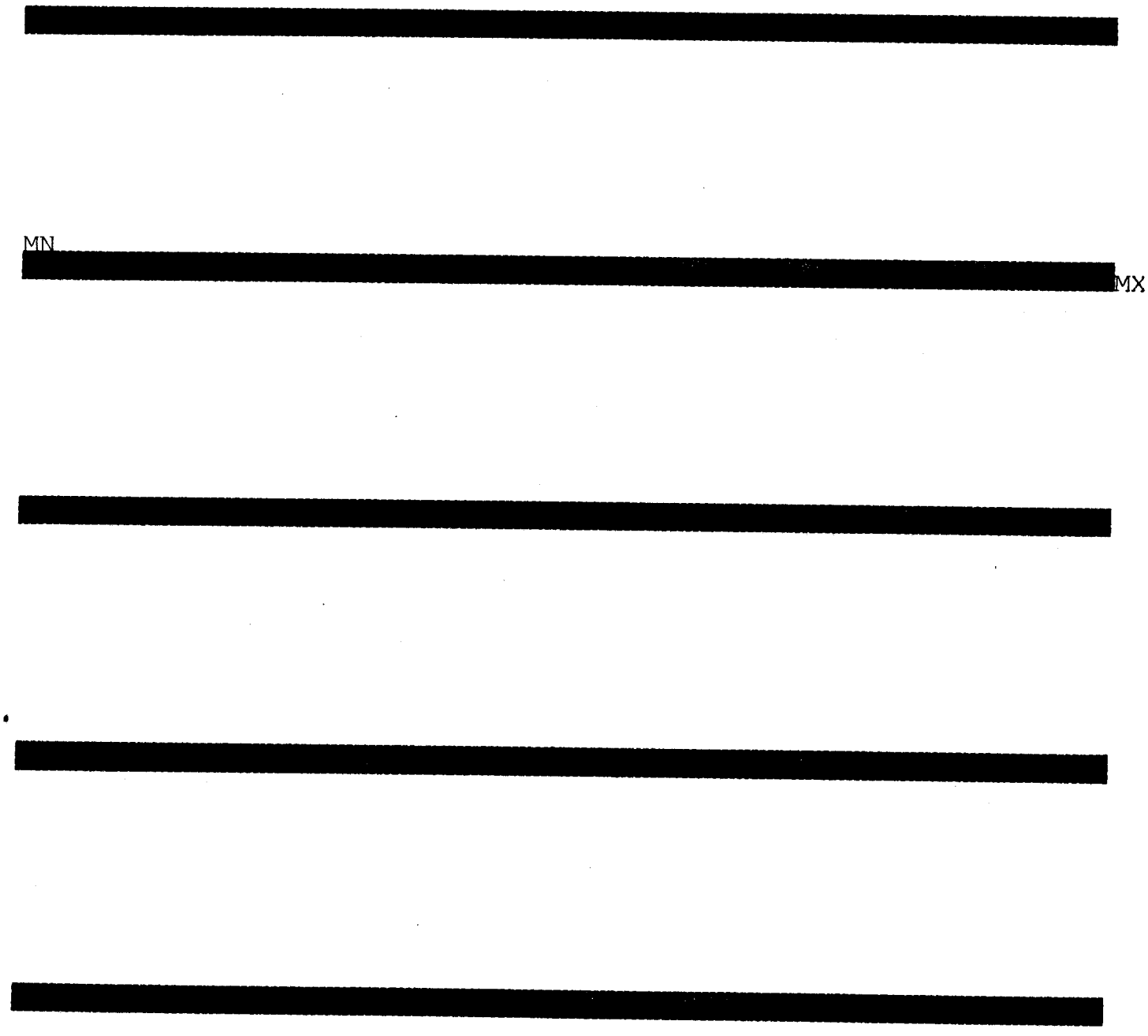

MN MX
ANSYS 5.0
SEP 21 1994
13:32:47
PLOT NO. 1
NODAL SOLUTION
STEP=12
SUB =1
SX (AVG)
RSYS=0
DMX =0.079097
SMN =689.326
SMNB=651.541
SMX =899.754
SMXB=944.524
689.326
712.707
736.087
759.468
782.849
806.23
829.611
852.992
876.373
899.754
MT DIPOLE MAGNET COIL (COMB 1&2: 250-72-48 DEG F)



ANSYS 5.0
SEP 21 1994
13:33:47
PLOT NO. 2
NODAL SOLUTION
STEP=12
SUB =1
SY (AVG)
RSYS=0
DMX =0.079097
SMN =-122.315
SMNB=-180.056
SMX =607.589
SMXB=670.308

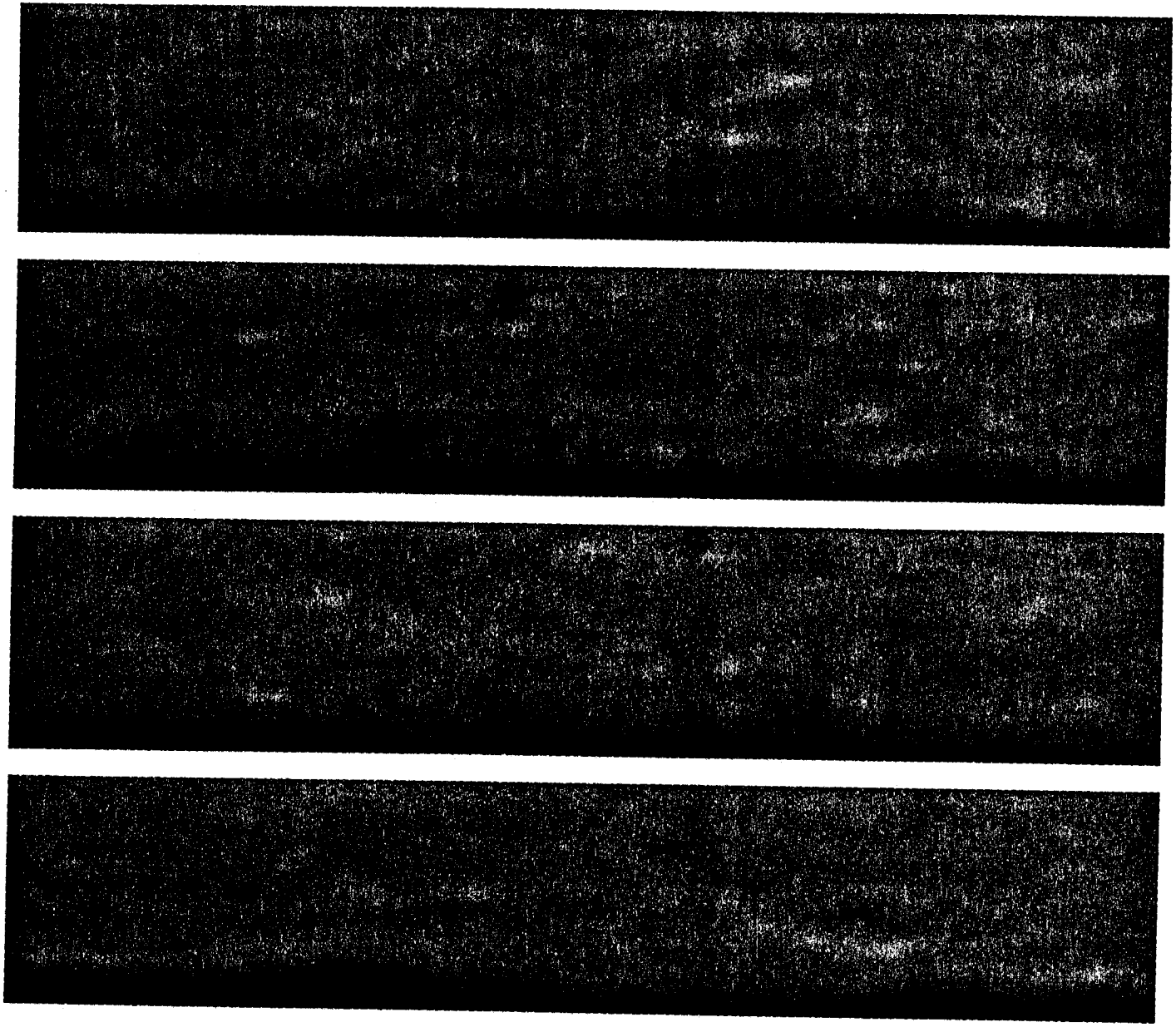
-122.315
-41.215
39.886
120.986
202.087
283.187
364.288
445.388
526.489
607.589

MI DIPOLE MAGNET COIL (COMB.1&2: 250-72-48 DEG F)



ANSYS 5.0
SEP 12 1994
16:17:30
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=0
DMX =0.185143
SMN =618.321
SMNB=618.307
SMX =618.367
SMXB=618.373
618.321
618.367

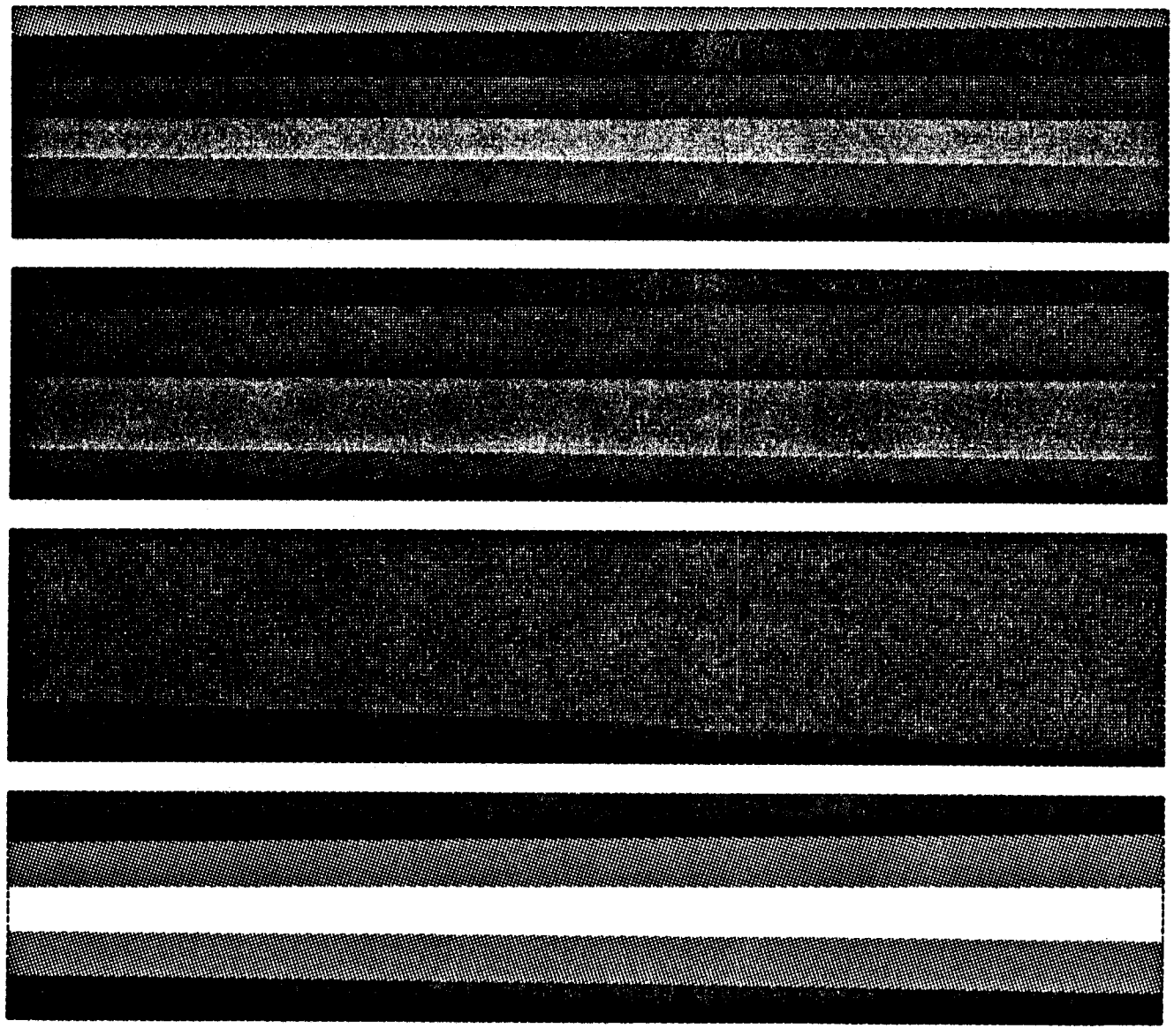
POLE MAGNET COIL (2-D) CASE SIX (CHOPPED OFF END)



ANSYS 5.0
SEP 12 1994
16:20:01
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=0
DMX =0.080396
SMN =-120.777
SMNB=-120.777
SMX =-120.776
SMXB=-120.776
-120.777
-120.776

MI DIPOLE MAGNET COIL (2-D) CASE SIX (CHOPPED OFF END)

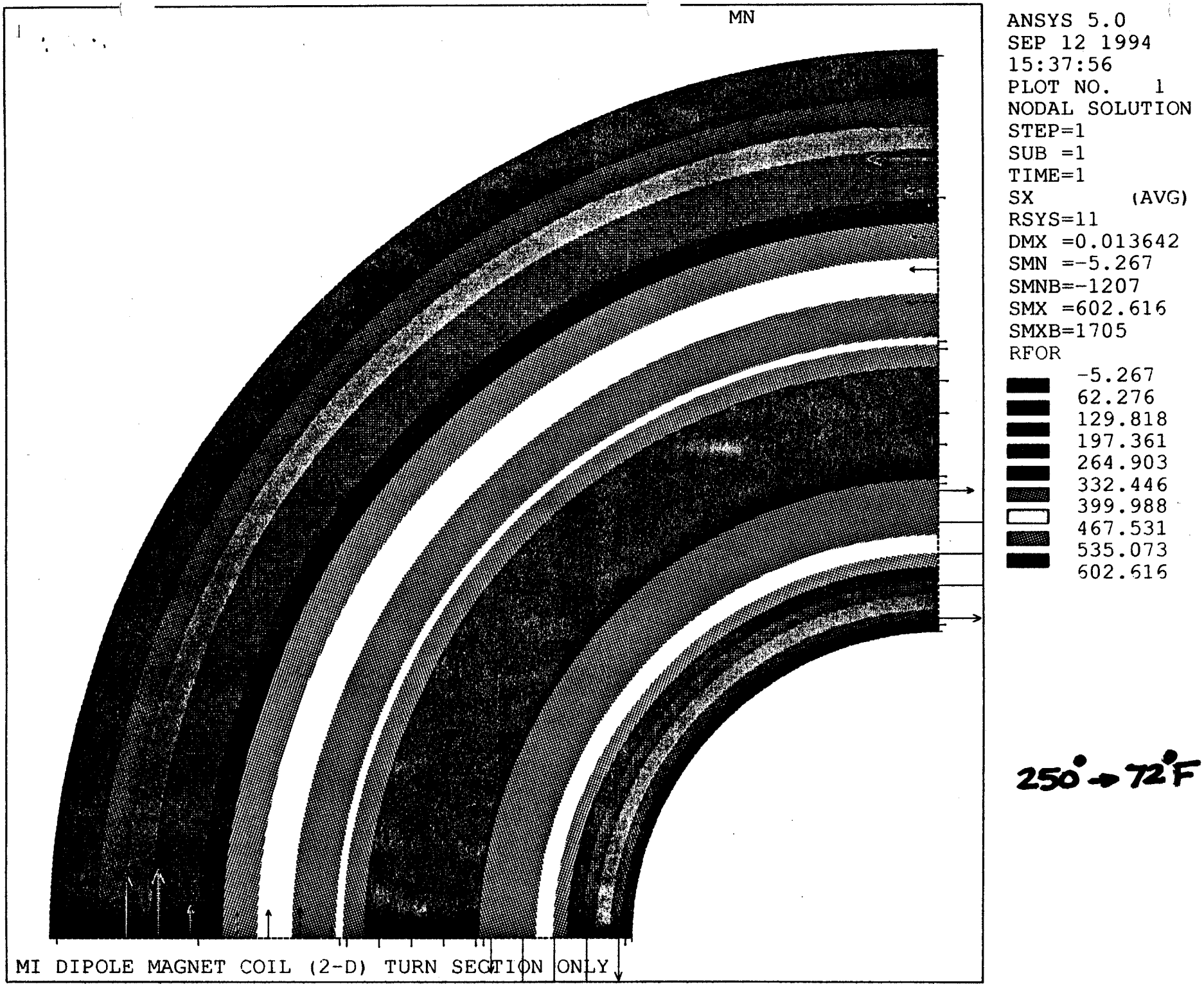
1



ANSYS 5.0
SEP 21 1994
14:25:23
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=0
DMX =0.132384
SMN =-36.033
SMNB=-36.111
SMX =44.38
SMXB=44.476
CP

-36.033
-27.099
-18.164
-9.229
-0.294076
8.641
17.576
26.51
35.445
44.38

MI DIPOLE MAGNET COIL (2-D)(REMOVE TURN AND LG STRGHT EPOXY)


MN
ANSYS 5.0
SEP 12 1994
15:37:56
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=11
DMX =0.013642
SMN =-5.267
SMNB=-1207
SMX =602.616
SMXB=1705
RFOR
-5.267
62.276
129.818
197.361
264.903
332.446
399.988
467.531
535.073
602.616
250° → 72°F
MI DIPOLE MAGNET COIL (2-D) TURN SECTION ONLY

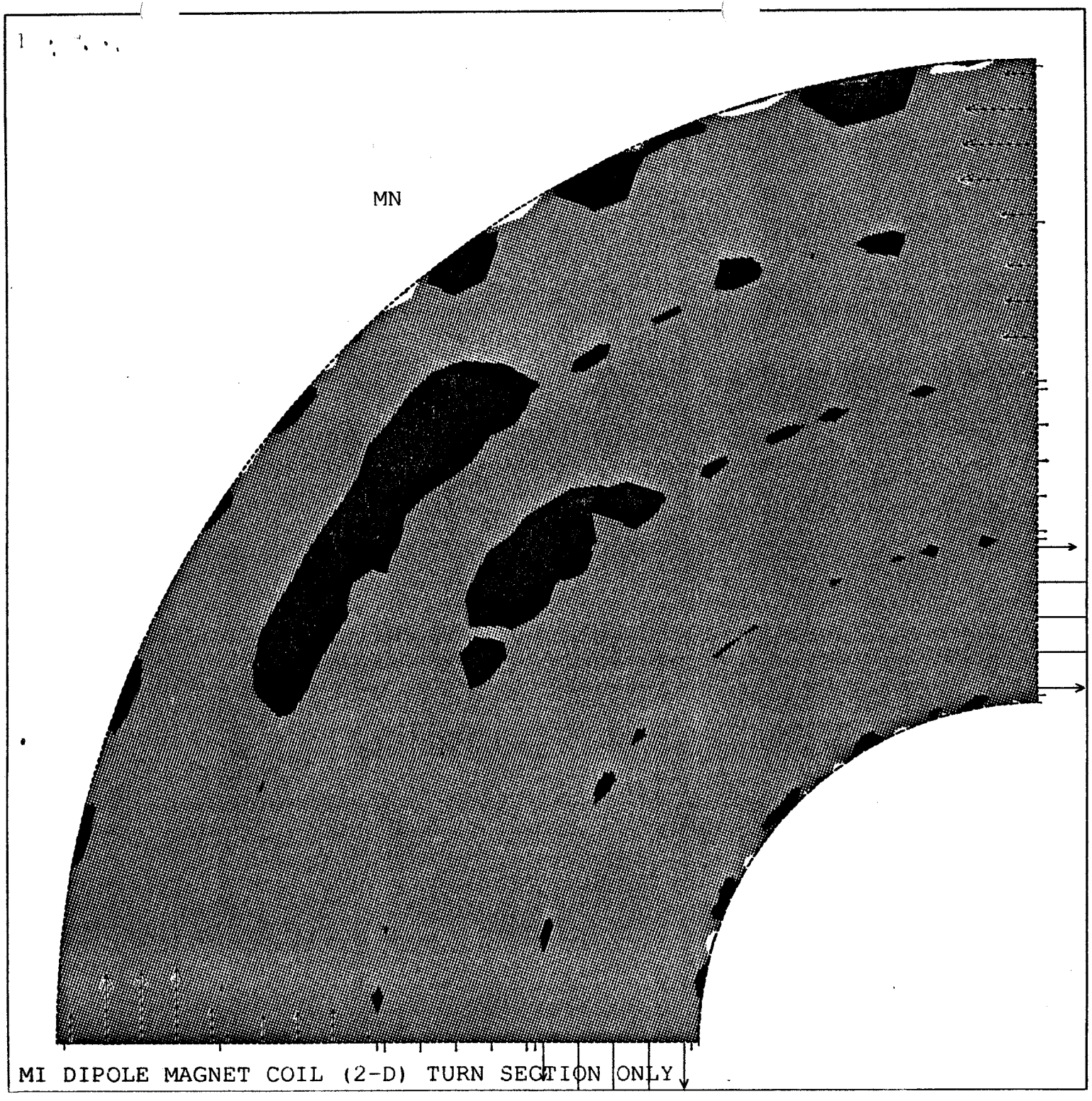
ANSYS 5.0
SEP 12 1994
15:38:16
PLOT NO. 2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SY (AVG)
RSYS=11
DMX =0.013642
SMN =-2075
SMNB=-3094
SMX =2168
SMXB=2795
RFOR
-2075
-1603
-1132
-660.287
-188.856
282.576
754.008
1225
1697
2168
MI DIPOLE MAGNET COIL (2-D) TURN SECTION ONLY

250° → 72°F

ANSYS 5.0
SEP 12 1994
15:38:34
PLOT NO. 3
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UX
RSYS=11
DMX =0.013642
SEPC=62.185
SMN =-0.013642
SMX =-0.003104
RFOR

-0.013642
-0.012471
-0.0113
-0.01013
-0.008959
-0.007788
-0.006617
-0.005446
-0.004275
-0.003104

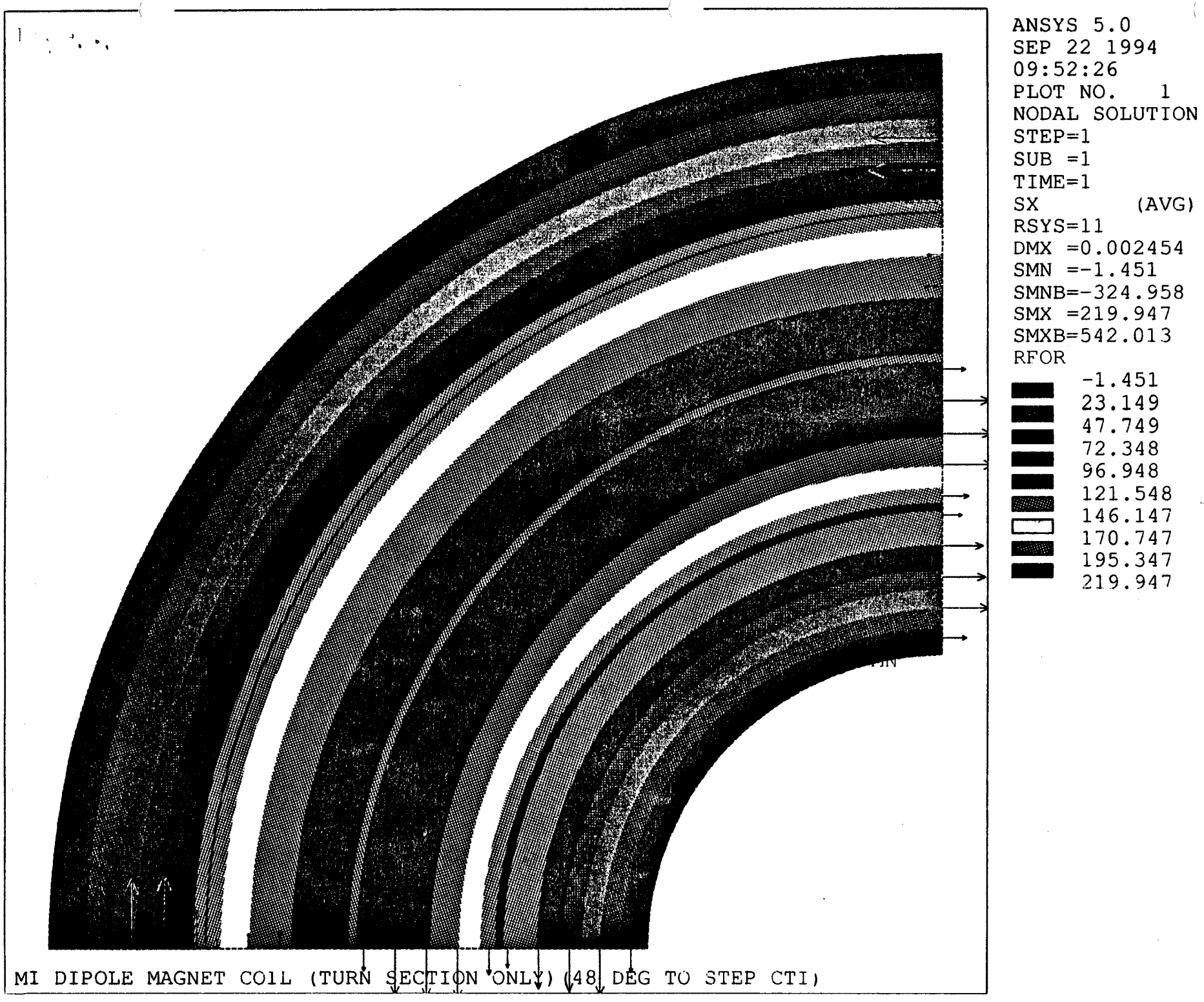
250° → 72°F

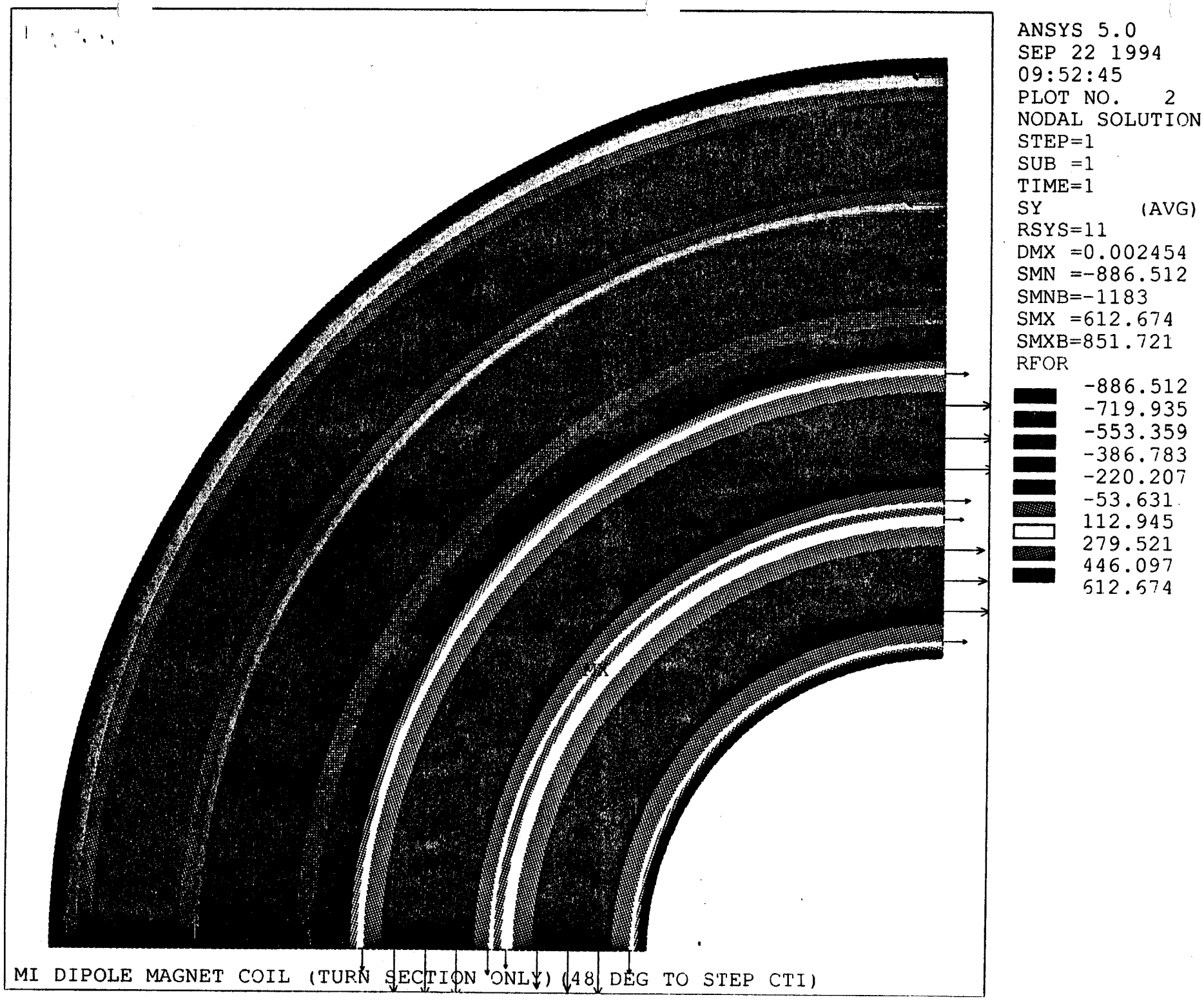


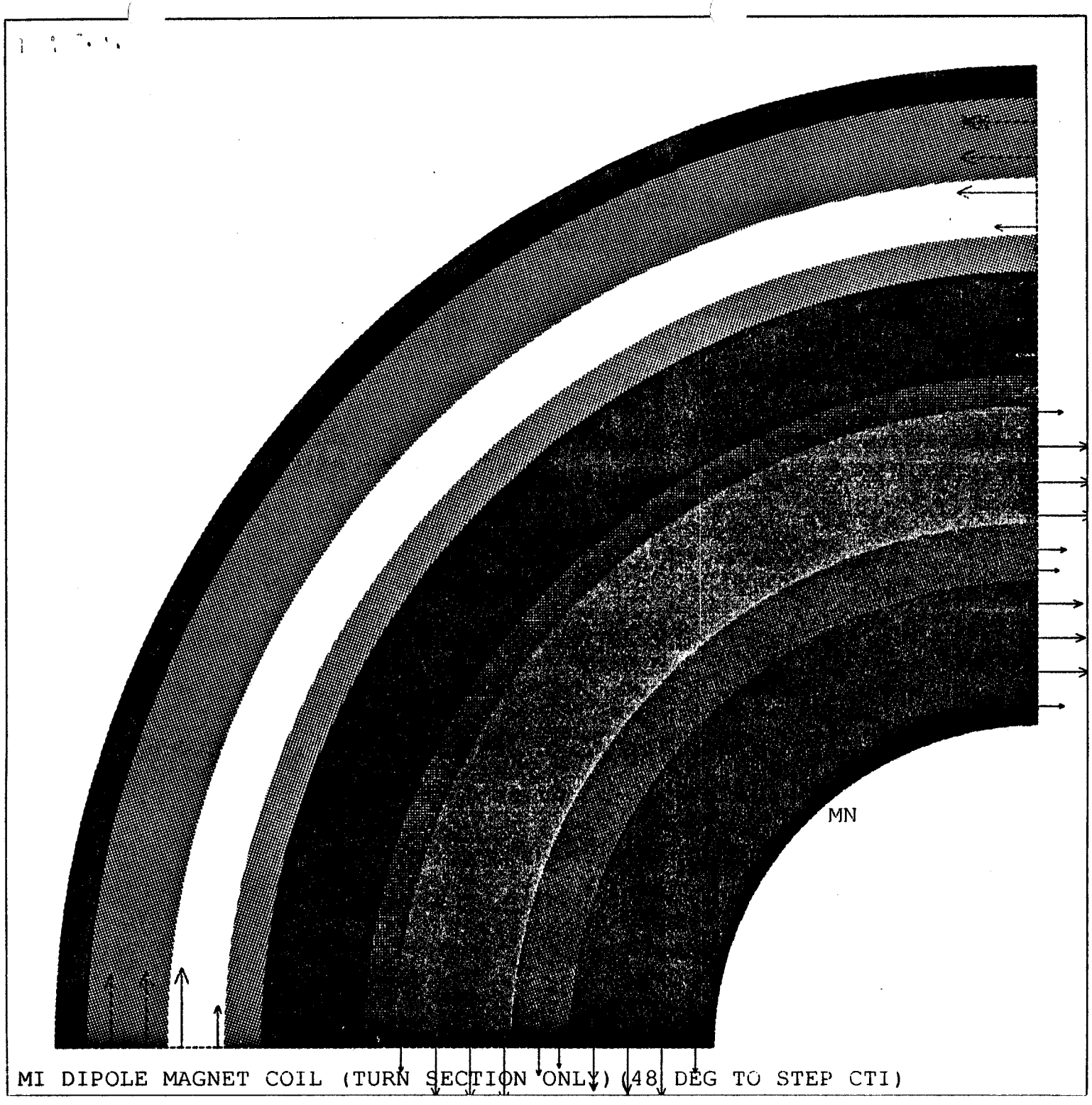
ANSYS 5.0
SEP 12 1994
15:38:53
PLOT NO. 4
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UY
RSYS=11
DMX =0.013642
SEPC=62.185
SMN =-0.421E-06
SMX =0.327E-06
RFOR

-0.421E-06
-0.338E-06
-0.255E-06
-0.172E-06
-0.887E-07
-0.565E-08
0.774E-07
0.160E-06
0.244E-06
0.327E-06

250° → 72°F

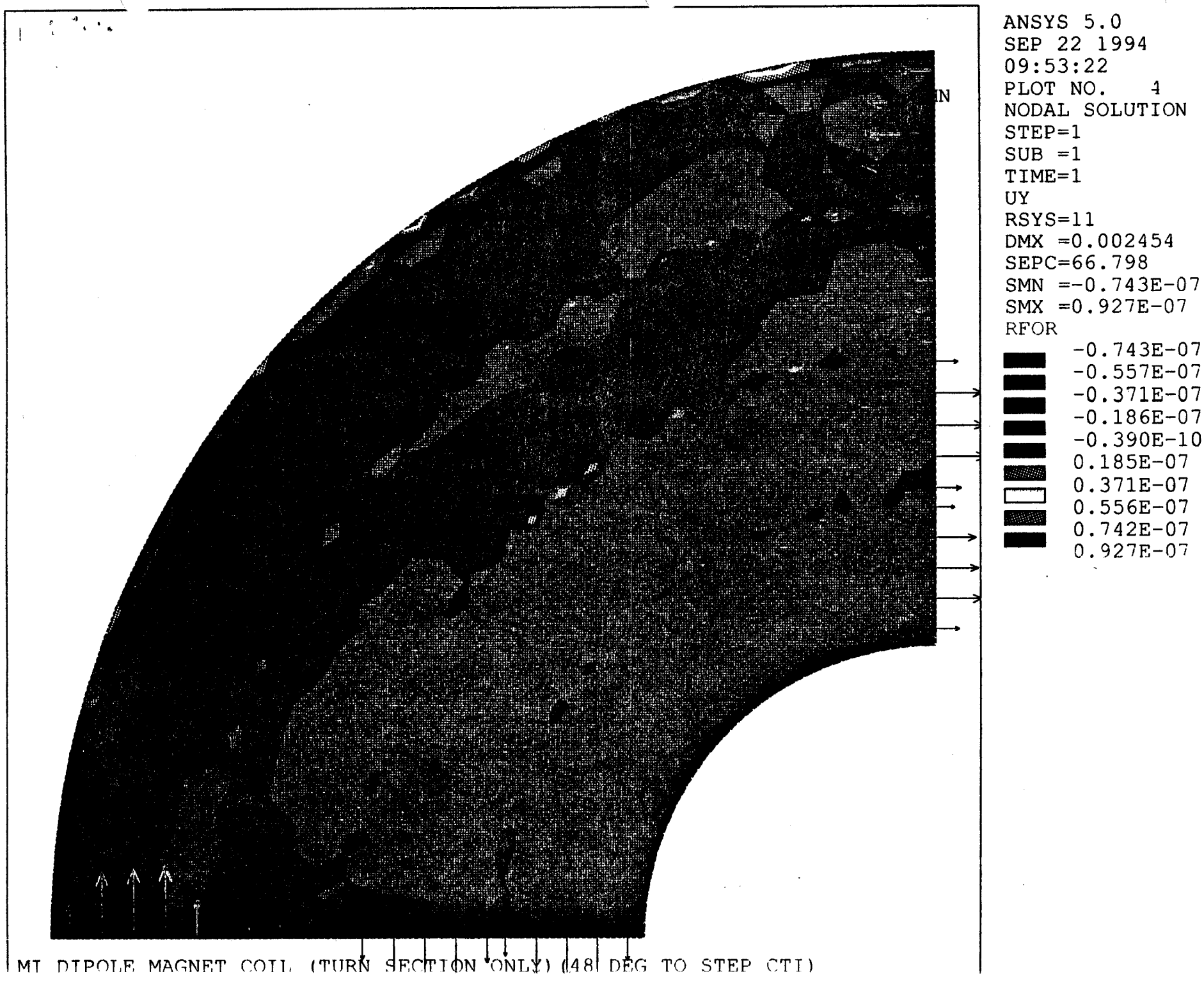

ANSYS 5.0
SEP 22 1994
09:52:26
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=11
DMX =0.002454
SMN =-1.451
SMNB=-324.958
SMX =219.947
SMXB=542.013
RFOR
-1.451
23.149
47.749
72.348
96.948
121.548
146.147
170.747
195.347
219.947
MI DIPOLE MAGNET COIL (TURN SECTION ONLY) (48 DEG TO STEP CTI)

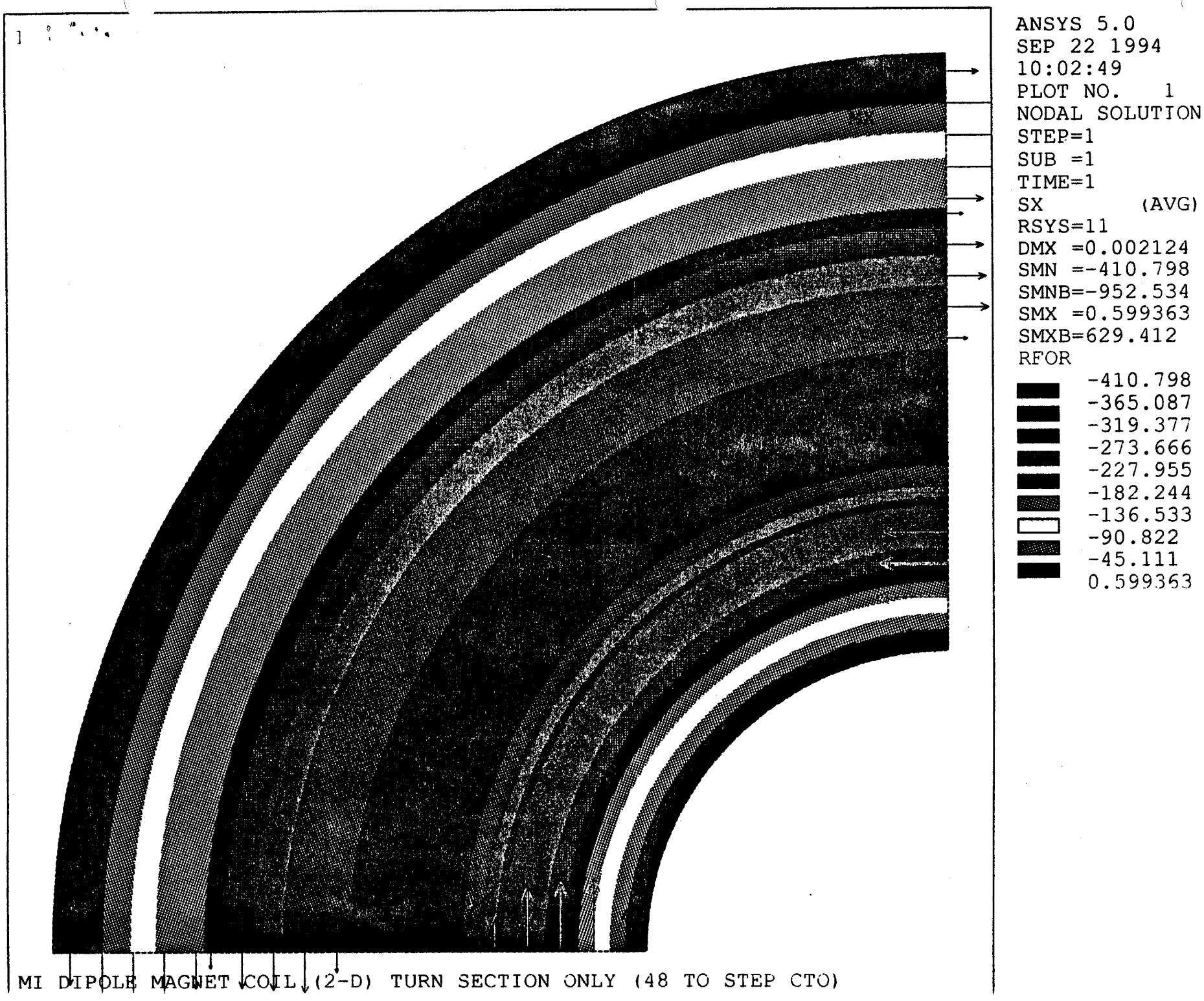

ANSYS 5.0
SEP 22 1994
09:52:45
PLOT NO. 2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SY (AVG)
RSYS=11
DMX =0.002454
SMN =-886.512
SMNB=-1183
SMX =612.674
SMXB=851.721
RFOR
-886.512
-719.935
-553.359
-386.783
-220.207
-53.631
112.945
279.521
446.097
612.674
MI DIPOLE MAGNET COIL (TURN SECTION ONLY) (48 DEG TO STEP CTI)

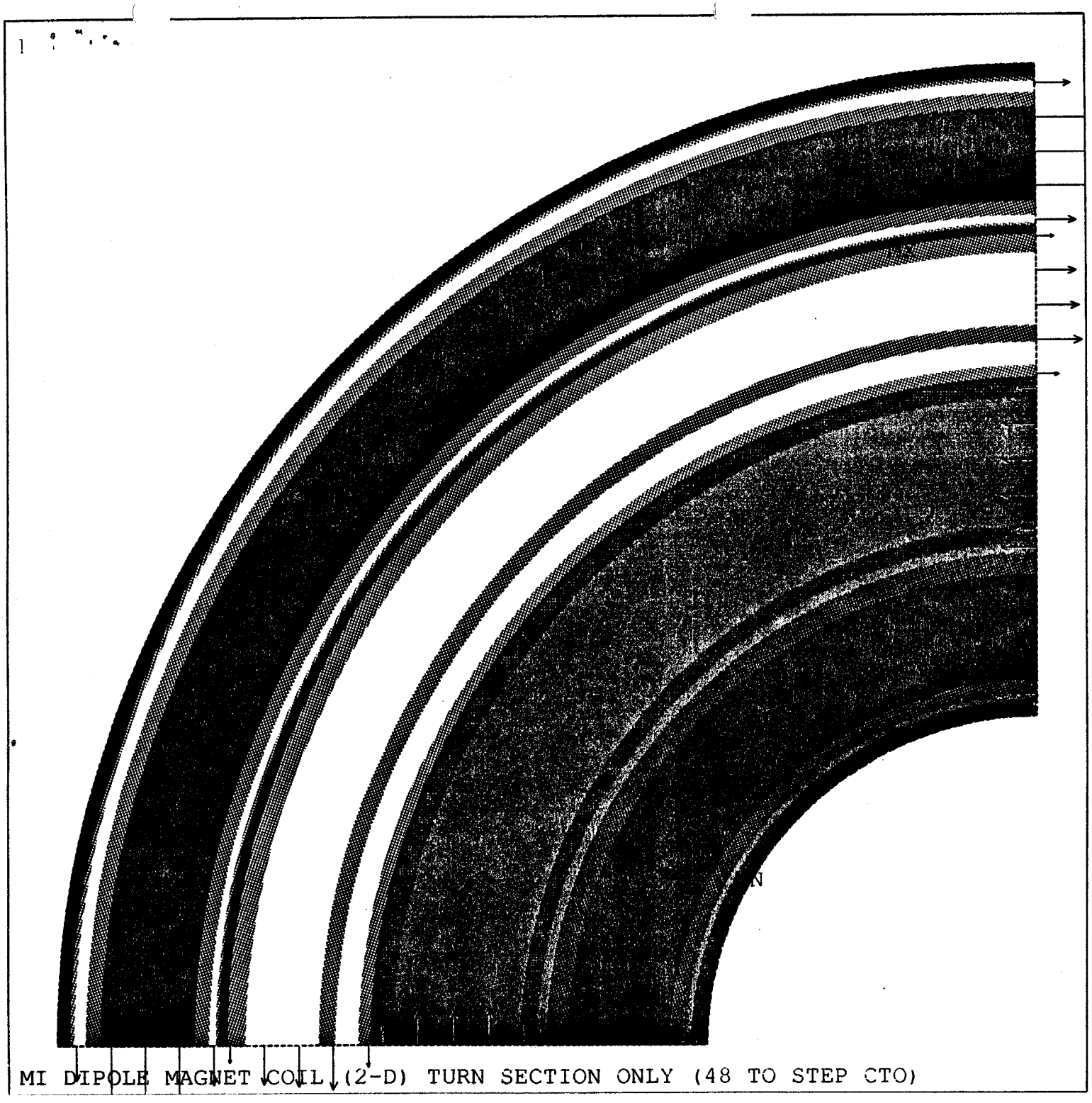


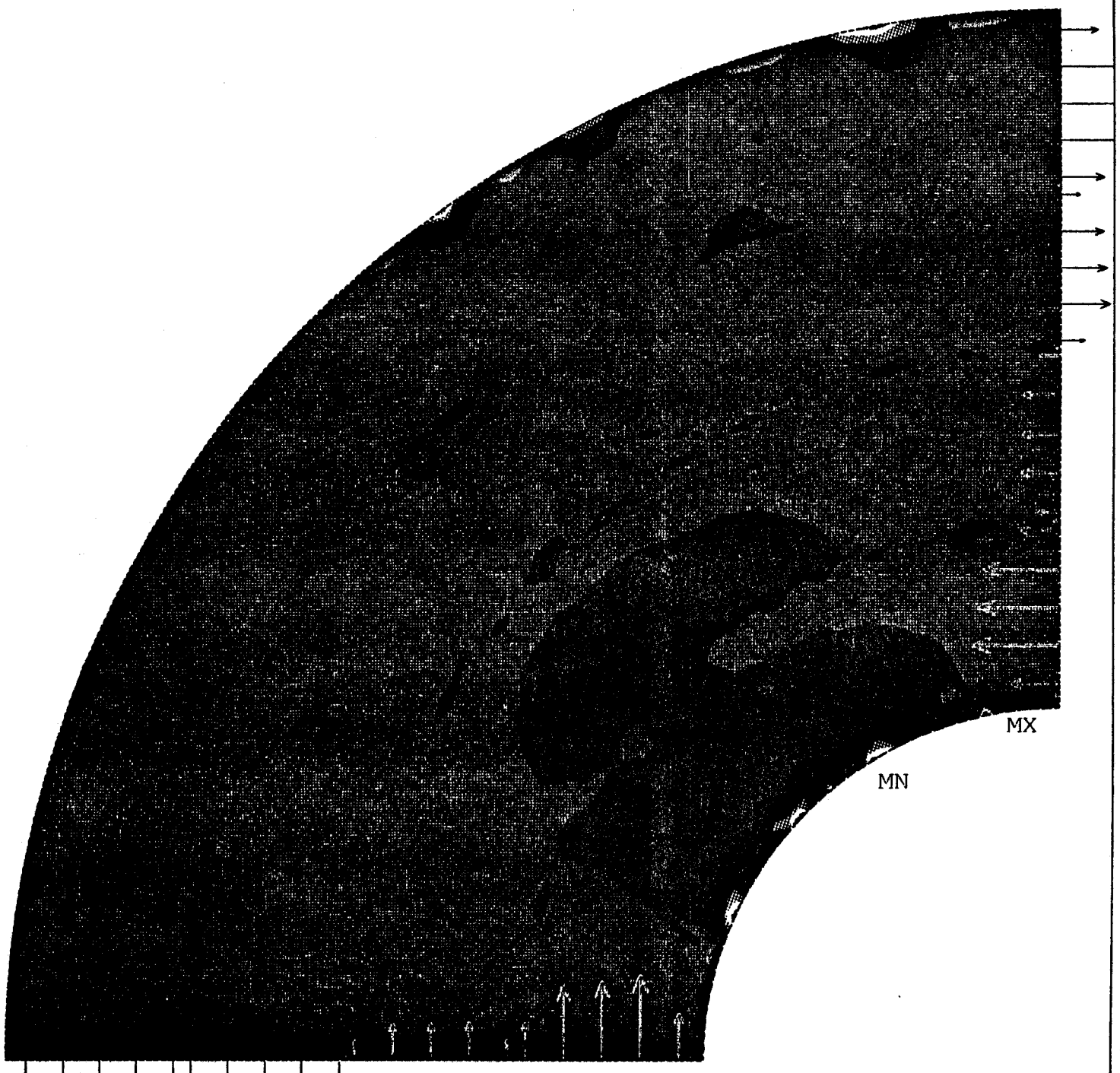
ANSYS 5.0
SEP 22 1994
09:53:04
PLOT NO. 3
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UX
RSYS=11
DMX =0.002454
SEPC=66.798
SMN =0.414E-03
SMX =0.002454
RFOR

0.414E-03
0.640E-03
0.867E-03
0.001094
0.00132
0.001547
0.001774
0.002
0.002227
0.002454


IN
ANSYS 5.0
SEP 22 1994
09:53:22
PLOT NO. 4
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UY
RSYS=11
DMX =0.002454
SEPC=66.798
SMN =-0.743E-07
SMX =0.927E-07
RFOR
-0.743E-07
-0.557E-07
-0.371E-07
-0.186E-07
-0.390E-10
0.185E-07
0.371E-07
0.556E-07
0.742E-07
0.927E-07
MT DIPOLE MAGNET COIL (TURN SECTION ONLY) (48 DEG TO STEP CTI)


ANSYS 5.0
SEP 22 1994
10:02:49
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX (AVG)
RSYS=11
DMX =0.002124
SMN =-410.798
SMNB=-952.534
SMX =0.599363
SMXB=629.412
RFOR
-410.798
-365.087
-319.377
-273.666
-227.955
-182.244
-136.533
-90.822
-45.111
0.599363
MI DIPOLE MAGNET COIL (2-D) TURN SECTION ONLY (48 TO STEP CTO)


ANSYS 5.0
SEP 22 1994
10:03:07
PLOT NO. 2
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SY (AVG)
RSYS=11
DMX =0.002124
SMN =-1357
SMNB=-1834
SMX =1343
SMXB=1890
RFOR
-1357
-1057
-757.171
-457.151
-157.13
142.89
442.91
742.931
1043
1343
MI DIPOLE MAGNET COIL (2-D) TURN SECTION ONLY (48 TO STEP CTO)



ANSYS 5.0
SEP 22 1994
10:03:45
PLOT NO. 4
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UY
RSYS=11
DMX =0.002124
SEPC=72.746
SMN =-0.447E-07
SMX =0.628E-07
RFOR

-0.447E-07
-0.328E-07
-0.208E-07
-0.887E-08
0.308E-08
0.150E-07
0.270E-07
0.389E-07
0.509E-07
0.628E-07

MI DIPOLE MAGNET COIL (2-D) TURN SECTION ONLY (48 TO STEP CTO)