NSTX CALCULATION

TITLE TF Coil Thermal/Hydraulic Analysis

CALC. NO. 13-7 DATE 3/17/97

ORIGINATOR A Brooks CHECKER Rev. 0

PURPOSE:

To determine temperatures resulting from ohmic heating during normal operation in TF Coil inner leg, outer legs and jumpers and to verify adequacy of cooling configuration to recool coils in requisite time.

REFERENCES:

System Requirments Document "NSTX-SRD-13-015 r0 dD, Magnet Systems"

Project Spreadsheet "NSTX TF Coils 1/29/97" located on NSTX_Project_Folder Fileshare under Technical Info/TF Coils

ASSUMPTIONS:

See attached writeup.

CALCULATION:

Calculations were performed using a 1D Transient Thermal/Hydaulic finite difference Fortran code called "cool1db.f" , previously developed and presently modified for NSTX, running on NERSC A machine.

CONCLUSION:

See attached writeup.

NSTX TF Coil Thermal/Hydraulic Analysis

A 1-D transient thermal/hydraulic analysis was performed on the NSTX TF Coils to assess ohmic heating during low field (0.3 T) and high field (0.6 T) pulsing. Calculations were performed using a 1D Transient Thermal/Hydaulic finite difference Fortran code called "cool1db.f" , previously developed and presently modified for NSTX, running on NERSC A machine. The modifications allowed for uncooled conductor sections electrically in series with cooled sections. Previous modifications made for NSTX allows for additional heating from inleakage from surrounding structure (ie the CS tiles in the case of the OH Coils). This was not needed for the TF since it is buffered by the OH.

Because of symmetry, only 1 hydraulic turn was modeled. While there is some difference between inner and outer turns of the inner leg and between the 3 turns of each outer leg, they are not thermally significant. The TF Coils are assumed to be OFHC copper conductors, which are cooled using chilled water at 10 C. Water enters the at the bottom of the CS inner leg turns at 5 m/s, flows up the CS, is jumper to the outer leg without cooling the electrical jumpers, and flows down and out the outer leg. The jumpers are assumed to be uncooled (air cooling ignored) except by axial conduction to the inner and outer legs. The small crossection inner leg conductors were sized originally to passively withstand a 6.0 sec ESW at 35.6 KA while limiting the temperature rise to 100 dC (from 20 C to 120 C). With the NSTX machine at D-site the available power supplies have reduce the required ESW for the low field pulse to 5.3 s. for an I2t of 6.70e9 a2s. Similar reductions have made the high field pulse now thermally less severe with an I2t of 6.00e9 a2s at the required 0.6s flattop.

Material Properties

The following are the material properties for the copper and water used within cool1db.f

```
c SI UNITS (m, kg, s, C)
c  Conductor Material - OFHC Copper ( 101 )
     CuDens(t)=8942.  ! kg/m3
     CuSpht(t)=386.   ! J/kg-C
     CuCond(t)=400.   ! w/m-C
     CuRho(t)=1.724e-8*(1+.0041*(t-20.))  ! ohm-m

c  Coolant Material - Water
     Wdens(t)=999.9-(t+5.462)**2/265.84 ! kg/m3
     Wdvisc(t)=2.916e-4+2.0747e-7*(t-85.0)**2 ! N-s/m2
     Wcond(t)=0.6818-(t-114.1)**2/1.124e5 ! w/m-C
     Wspht(t)=4174.0+(t-52.78)**2/54.32 ! J/kg-C
```

Geometery and other Inputs

The coil geometry was taken from the referenced spreadsheet "NSTX TF Coils 1/29/97" by Charley Neumeyer and confirmed against attached drawings. The geometry is modeled using 0.1 m long elements as inputted below. Note the data input follows the coolant path. (starting with half the lower jumper, the inner leg, the upper jumper, the outer leg and finally the second half of the lower jumper)

The following is the free formatted input to cool1db.f for the .3 T case:

```
NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s$                    / title
142                                                                 / n, number of conductor nodes
142*0.1                                                             / dx, element size
4*3.226e-3, 57*6.7420e-4, 8*3.226e-3, 69*3.7356e-3 4*3.226e-3 / Ac, conductor area
142*10.0                                                            / s, conductor shape factor
142*1.5                                                             / f, conductor gradient factor
4*3.127e-5, 57*3.127e-5, 8*3.127e-5, 69*1.267e-4, 4*3.127e-5   / Aw, coolant area
4*.0198, 57*.0198, 8*.0198, 69*.0400,4*.0198                       / Pw, coolant wetted perimeter
142*5.0                                                             / v, coolant velocity
4*0 57*1 8*0 69*1 4*0                                               / icool - flag to turn on(1) or off(0)
                                                                    cooling at node
5                                                                   /ncur, number of values
                                                                    in time vs current table
    0.  00000.
    0.  35556.
    5.30  35556.
    5.30  00000.
   300.  00000.
15                          / npul, number of pulses
30.                         / dtpr. printout interval for all Length plots
1.                          / dtpr2 printout interval for all Time plots
8                           / npr  number of nodes to save output
1  5  61 65 66 70  138  142 / node numbers for plots
10.                         / t0, initial temperature and coolant temperature
100.                        / tmax, max temperature for plots
4200. 4500.                 / tstart, tend for T vs length plots
1.00                        / dTmax  max change in T for iteration
142*0.                      / Ql additional heating per unit length
1                           / nrep number of times to repeat geometry ( #turns)
```

For the high field (0.6 T) scenario, a the following waveform obtained from Charley Neumeyer and digitized by hand was used:

```
29       ncur,   number of values in time vs current table
0.0  0.0
0.05  0.0        SOP
0.1  11000.
0.2  28000.
0.3  40000.
0.4  50000.
0.5  58000.
0.6  65000.
0.7  70000.
0.74 71111.      SOFT
1.34 71111.      EOFT
1.4  63000.
1.5  53000.
1.6  43000.
1.7  34000.
1.8  28000.
1.9  24000.
2.0  19000.
2.1  15000.
2.2  12000.
2.3  10000.
2.4   9000.
2.5   7000.
2.6   6000.
2.7   5000.
2.8   4000.
2.9   3000.
3.0   2000.
3.2     0.       EOP
```

For the waveform above, the following I2t information is obtained:

Current rise	1.69e9 a2s
6 s Flat top	3.03e9 a2s
Current decay	1.29e9 a2s
Total	6.01e9 a2s

Results

The attached plots show the results of five cases run:

0.3 Tesla Field for 5.3 s ESW, run until fully ratcheted (15 pulses at 5 minute rep rate)
0.6 Tesla Field wavefrom driven (Adiabatic response with 20 C Initial Temperature), First Pulse Only
0.6 Tesla Field waveform driven (20 C Water at 5 m/s), First Pulse Only
0.6 Tesla Field wavefrom driven (Adiabatic response with 10 C Initial Temperature), First Pulse Only
0.6 Tesla Field waveform driven (10 C Water at 5 m/s), First Pulse Only

There are 13 figures associated with each case. On each Temperature vs Path Length Figure are plots at select times during the transient. On each Temperature vs Time figure are plots of Conductor Average Temperature, Conductor Max Temperature, Conductor (Water) Surface Temperature, and Water Temperature. Please note that the Conductor average temperature and the Water temperature are the basic nodal values calculated. The Conductor max temperature and surface temperature are extrapolated and interpolated respectively from those basic nodal values based on inputted data.

Figure 1	Conductor Average Tempertature vs Path Length
Figure 2	Water Tempertature vs Path Length
Figure 3	Conductor Max Tempertature vs Path Length
Figure 4	Conductor Surface Tempertature vs Path Length
Figure 5	Pressure Drop vs Path Length
Figure 6	Node 1 Temperature vs Time (Lower Jumper)
Figure 7	Node 5 Temperature vs Time (Inner Leg Bottom at Water Inlet)
Figure 8	Node 61 Temperature vs Time (Inner Leg Top at Water Outlet)
Figure 9	Node 65 Temperature vs Time (Upper Jumper)
Figure 10	Node 66 Temperature vs Time (Upper Jumper)
Figure 11	Node 70 Temperature vs Time (Outer Leg Top at Water Inlet)
Figure 12	Node 138 Temeprature vs Time (Outer Leg Bottom at Water Outlet
Figure 13	Node 142 Temperature vs Time (Lower Jumper)

Conclusions

Low Field (0.3 T)

For low field only an equivalent square wave was run since the rampup and decay are relatively short. The maximum temperature which occurs at EOP/EOFT in the inner leg during low field operation is 92 C without cooling present and 87 C with 5 m/s water cooling. The inner leg fully cools in about a litte more than a minute hense without ratcheting while the outer leg ratchets for about 5-6 pulses and the jumpers continue to ratchet for about 15 pulses.

The maximum fully ratchet temperature in the outer leg is 32 C and occurs after the pulse has ended since it is being heated not only ohmically but by warm water from the inner leg(see expanded scale of figure 11 of first plot set)

The jumpers will ratchet to 33 C midway between the inner and outer legs during low field operation based on the assumption of negligible air cooling.

High Field (0.6 T)

Below are the inner leg temperatures at end of pulse (eop), at the end of the 0.6 sec flattop (eoft 0.6) and for a reduced 0.5 s flat top (eoft 0.5)

	Teop, C	T eoft 0.6	T eoft 0.5
Adiabatic from 20C	95	76	69
Cooling from 20 C	92	75	69
Adiabatic from 10 C	82	64	58
Cooling from 10 C	78	63	57

Please note the above numbers represent average temperatures at a conductor cross section. For the "with cooling" cases a temperature gradient of approximately 2 C exists at eoft, making the differences between adiabatic and with cooling less significant.

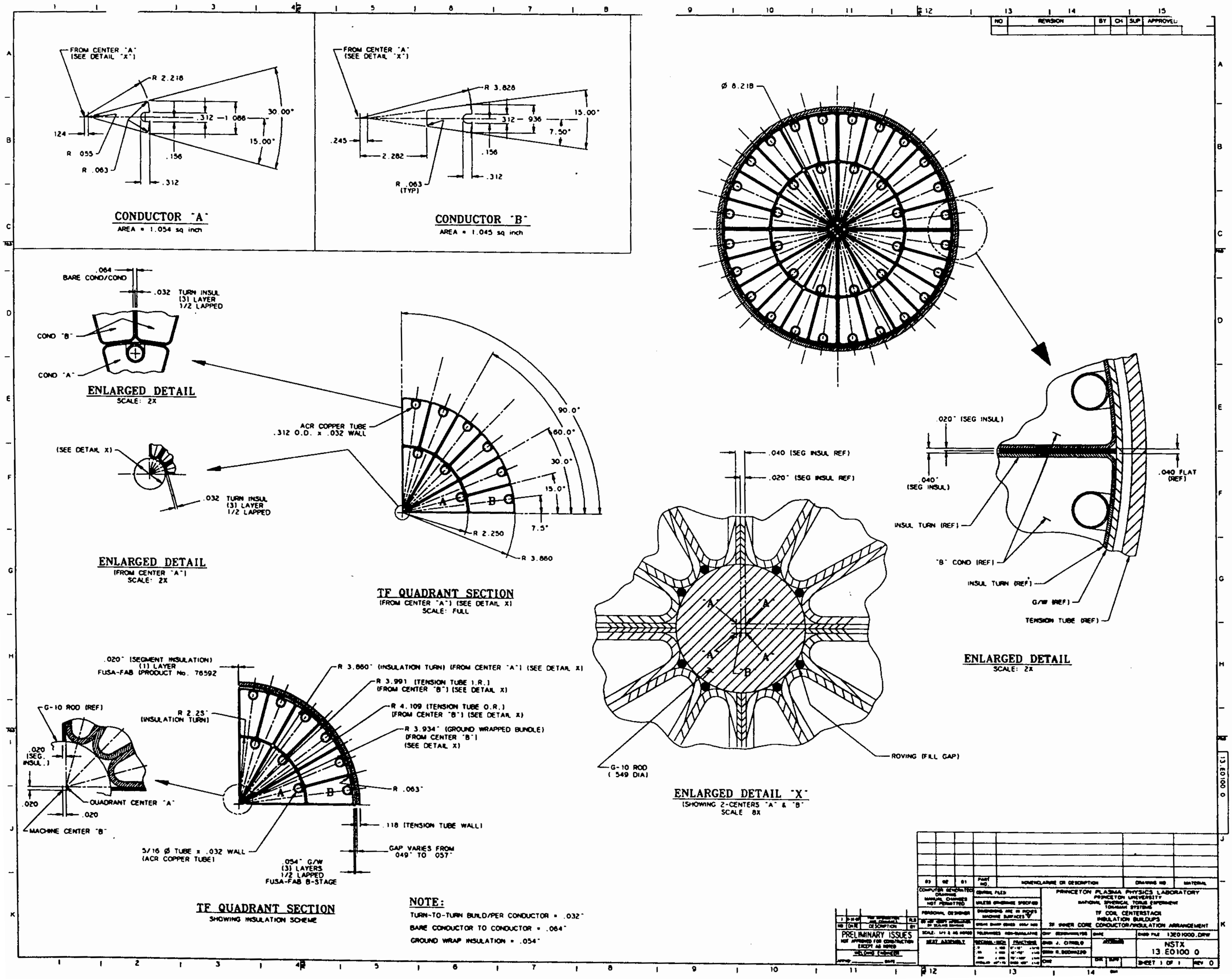
The resulting adiabatic temperatures in the inner leg for the first pulse with 10 C water temperature are:

SOFT 27 C
EOFT 64 C
EOP 82 C

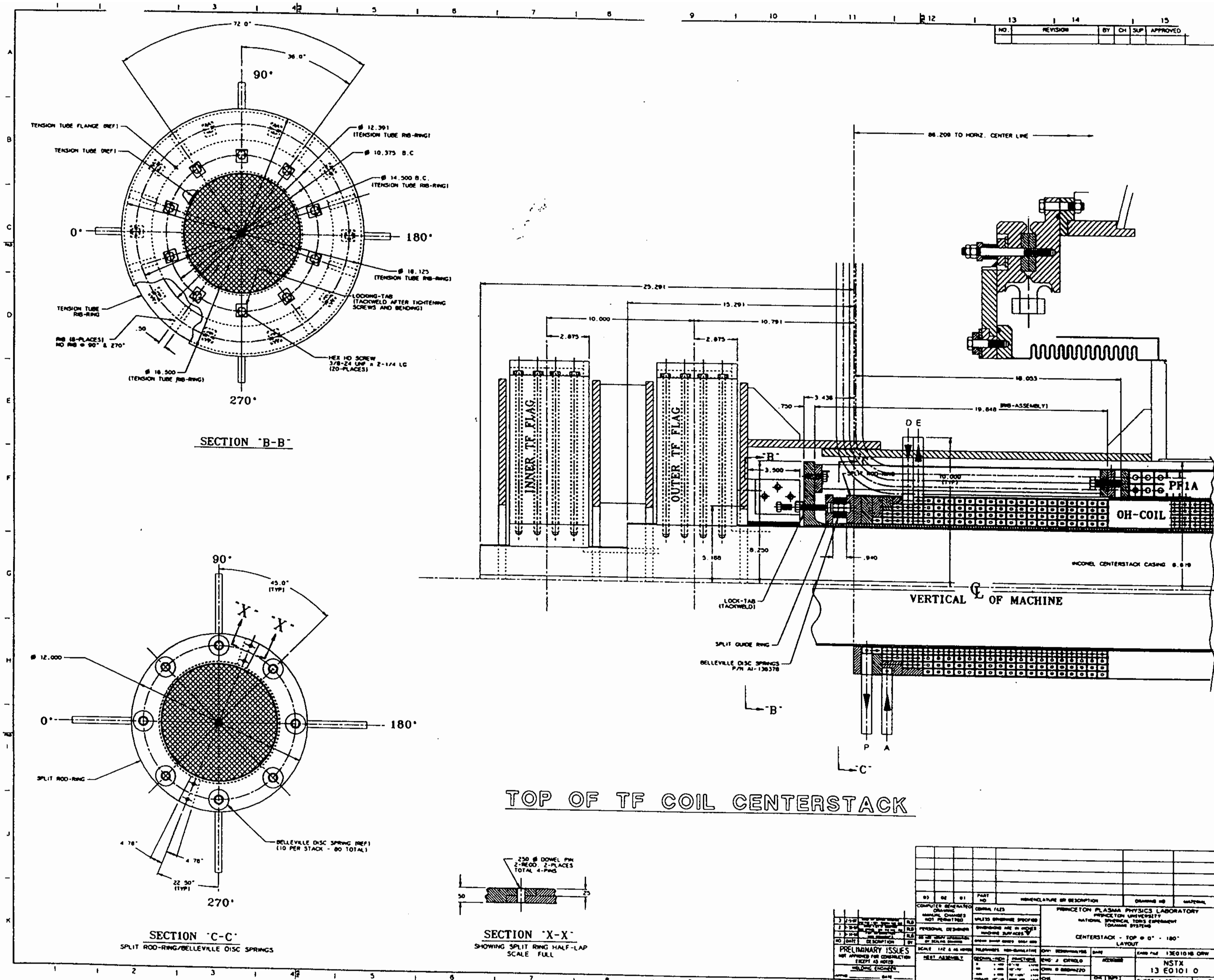
and for the outer leg:

SOFT < 10.5 C
EOFT 11.5 C
EOP 12.0 C

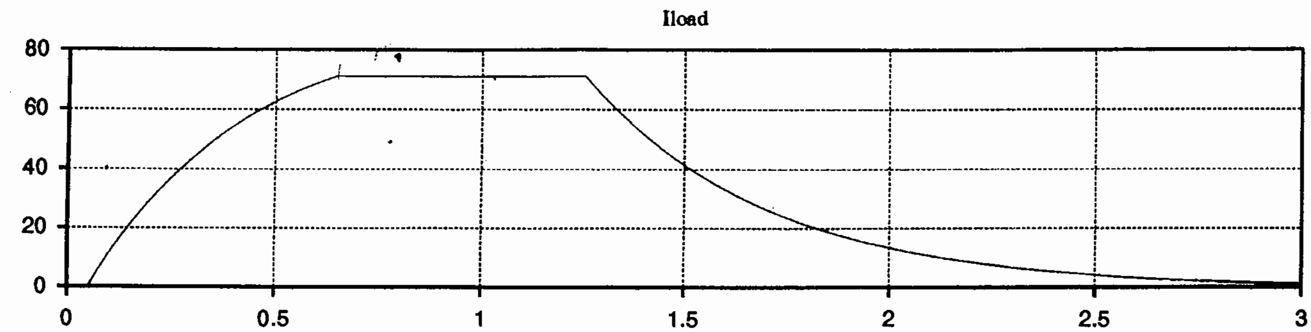
The inner leg fully cools after each pulse; the outer leg will ratchet. The fully ratchetted temperatures for the high field were not run since it is less servere than low field (I2t = 6.7e9 a2s).

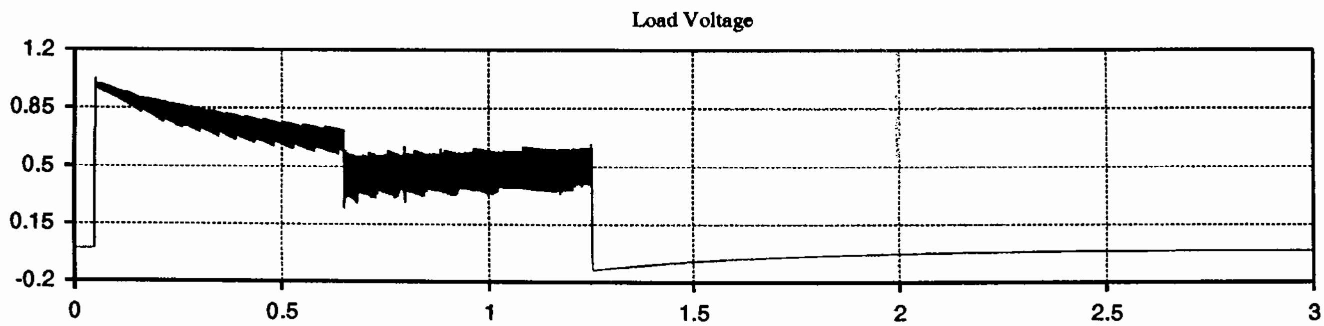


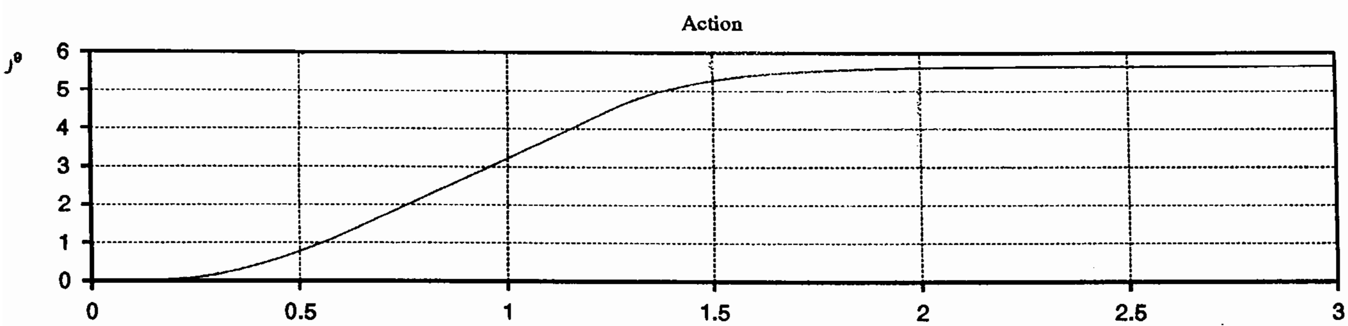
CONDUCTOR "A"
AREA = 1.054 sq inch
FROM CENTER "A" (SEE DETAIL "X")
R 2.218
R .055
R .063
.312
1.086
30.00°
15.00°
.156
124
CONDUCTOR "B"
AREA = 1.045 sq inch
FROM CENTER "A" (SEE DETAIL "X")
R 3.828
.936
15.00°
7.50°
.245
2.282
R .063 (TYP)
.156
.312
Ø 8.218
ENLARGED DETAIL
SCALE: 2X
.064 BARE COND/COND
.032 TURN INSUL (3) LAYER 1/2 LAPPED
COND "B"
COND "A"
ACR COPPER TUBE .312 O.D. x .032 WALL
(SEE DETAIL X)
.032 TURN INSUL (3) LAYER 1/2 LAPPED
ENLARGED DETAIL
(FROM CENTER "A")
SCALE: 2X
90.0°
60.0°
30.0°
15.0°
7.5°
R 2.250
R 3.860
TF QUADRANT SECTION
(FROM CENTER "A") (SEE DETAIL X)
SCALE: FULL
.020" (SEG INSUL)
.040" (SEG INSUL)
.040 FLAT (REF)
INSUL TURN (REF)
"B" COND (REF)
INSUL TURN (REF)
G/W (REF)
TENSION TUBE (REF)
ENLARGED DETAIL
SCALE: 2X
.040 (SEG INSUL REF)
.020" (SEG INSUL REF)
G-10 ROD (.549 DIA)
ROVING (FILL GAP)
ENLARGED DETAIL "X"
(SHOWING 2-CENTERS "A" & "B")
SCALE 8X
.020" (SEGMENT INSULATION) (1) LAYER FUSA-FAB (PRODUCT No. 78592
R 2.25" (INSULATION TURN)
R 3.860" (INSULATION TURN) (FROM CENTER "A") (SEE DETAIL X)
R 3.991 (TENSION TUBE I.R.) (FROM CENTER "B") (SEE DETAIL X)
R 4.109 (TENSION TUBE O.R.) (FROM CENTER "B") (SEE DETAIL X)
R 3.934" (GROUND WRAPPED BUNDLE) (FROM CENTER "B") (SEE DETAIL X)
R .063"
.118 (TENSION TUBE WALL)
GAP VARIES FROM .049" TO .057"
.054" G/W (3) LAYERS 1/2 LAPPED FUSA-FAB B-STAGE
5/16 Ø TUBE x .032 WALL (ACR COPPER TUBE)
G-10 ROD (REF)
.020 (SEG. INSUL.)
QUADRANT CENTER "A"
.020
MACHINE CENTER "B"
TF QUADRANT SECTION
SHOWING INSULATION SCHEME
NOTE:
TURN-TO-TURN BUILD/PER CONDUCTOR = .032"
BARE CONDUCTOR TO CONDUCTOR = .064"
GROUND WRAP INSULATION = .054"
PRELIMINARY ISSUES
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL SPHERICAL TORUS EXPERIMENT
TF COIL CENTERSTACK
INSULATION BUILDUPS
CONDUCTOR/INSULATION ARRANGEMENT
NSTX
13 E0100 0
SHEET 1 OF 1
REV 0
13 E0100 0

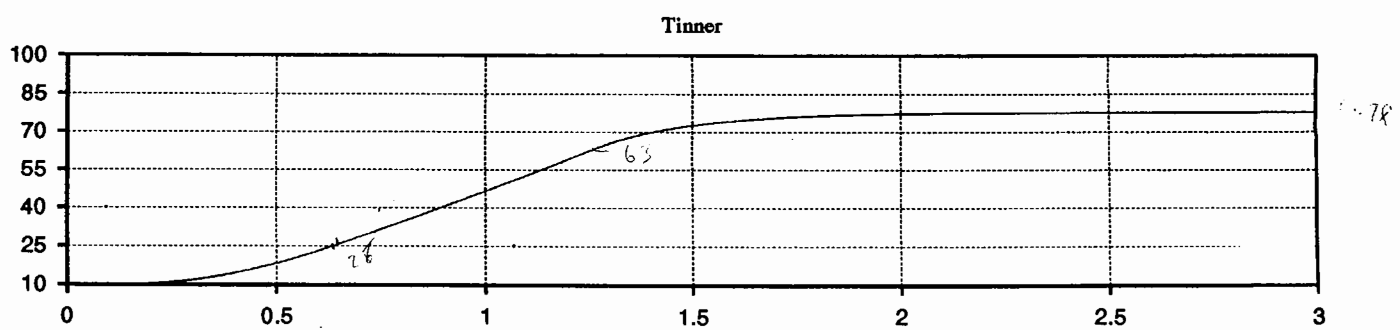


TOP OF TF COIL CENTERSTACK
INNER TF FLAG
OUTER TF FLAG
OH-COIL
PF1A
VERTICAL ℄ OF MACHINE
86.208 TO HORZ. CENTER LINE
25.291
15.291
10.000
10.791
2.875
18.053
19.848 (RIB-ASSEMBLY)
3.438
.750
3.500
5.188
8.250
.940
10.000 (TYP)
INCONEL CENTERSTACK CASING 8.819
LOCK-TAB (TACKWELD)
SPLIT GUIDE RING
BELLEVILLE DISC SPRINGS P/N AI-138378
SPLIT ROD-RING
D
E
P
A
B
C
SECTION 'B-B'
TENSION TUBE FLANGE (REF)
TENSION TUBE (REF)
TENSION TUBE RIB-RING
RIB (8-PLACES) NO RIB @ 90° & 270°
Ø 12.391 (TENSION TUBE RIB-RING)
Ø 10.375 B.C.
Ø 14.500 B.C. (TENSION TUBE RIB-RING)
Ø 18.125 (TENSION TUBE RIB-RING)
Ø 16.500 (TENSION TUBE RIB-RING)
LOCKING-TAB (TACKWELD AFTER TIGHTENING SCREWS AND BENDING)
HEX HD SCREW 3/8-24 UNF x 2-1/4 LG (20-PLACES)
72.0°
36.0°
.50
0°
90°
180°
270°
SECTION 'C-C'
SPLIT ROD-RING/BELLEVILLE DISC SPRINGS
Ø 12.000
SPLIT ROD-RING
BELLEVILLE DISC SPRING (REF) (10 PER STACK - 80 TOTAL)
45.0° (TYP)
22.50° (TYP)
4.78°
X
SECTION 'X-X'
SHOWING SPLIT RING HALF-LAP
SCALE FULL
.250 Ø DOWEL PIN 2-REQD, 2-PLACES TOTAL 4-PINS
50
25
PRELIMINARY ISSUES
PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY
NATIONAL SPHERICAL TORUS EXPERIMENT
CENTERSTACK - TOP @ 0° - 180°
LAYOUT
NSTX
13 E0101 0
SHEET 1 OF 1


Iload
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3

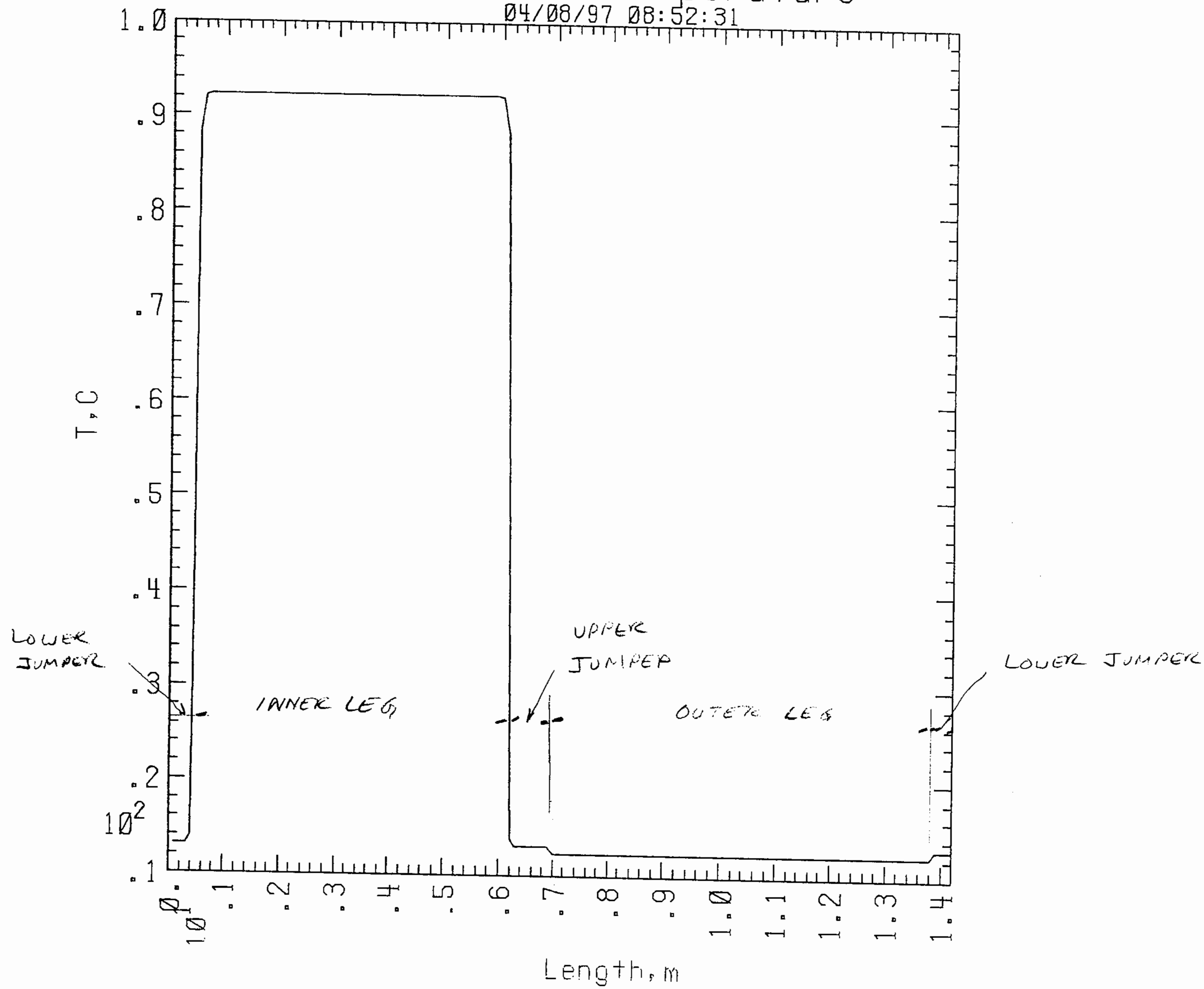

Load Voltage
1.2
0.85
0.5
0.15
-0.2
0
0.5
1
1.5
2
2.5
3

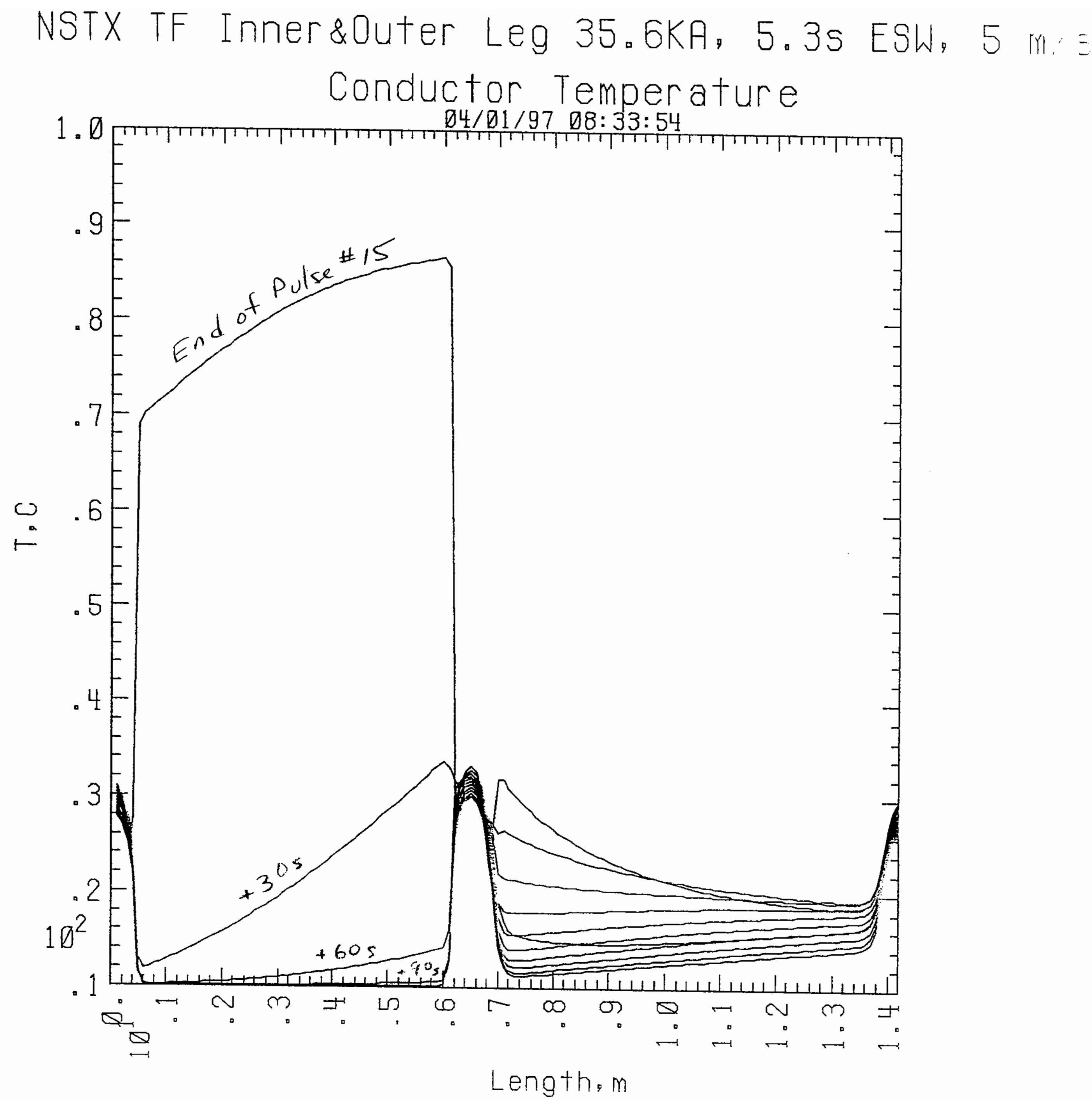

Action
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
3


Tinner
100
85
70
55
40
25
10
0
0.5
1
1.5
2
2.5
3
63

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, Adiabatic

Conductor Temperature




NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Conductor Temperature
04/01/97 08:33:54
T,C
10^2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
10^0
0.
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
Length, m
End of Pulse #15
+30s
+60s
+90s

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m s

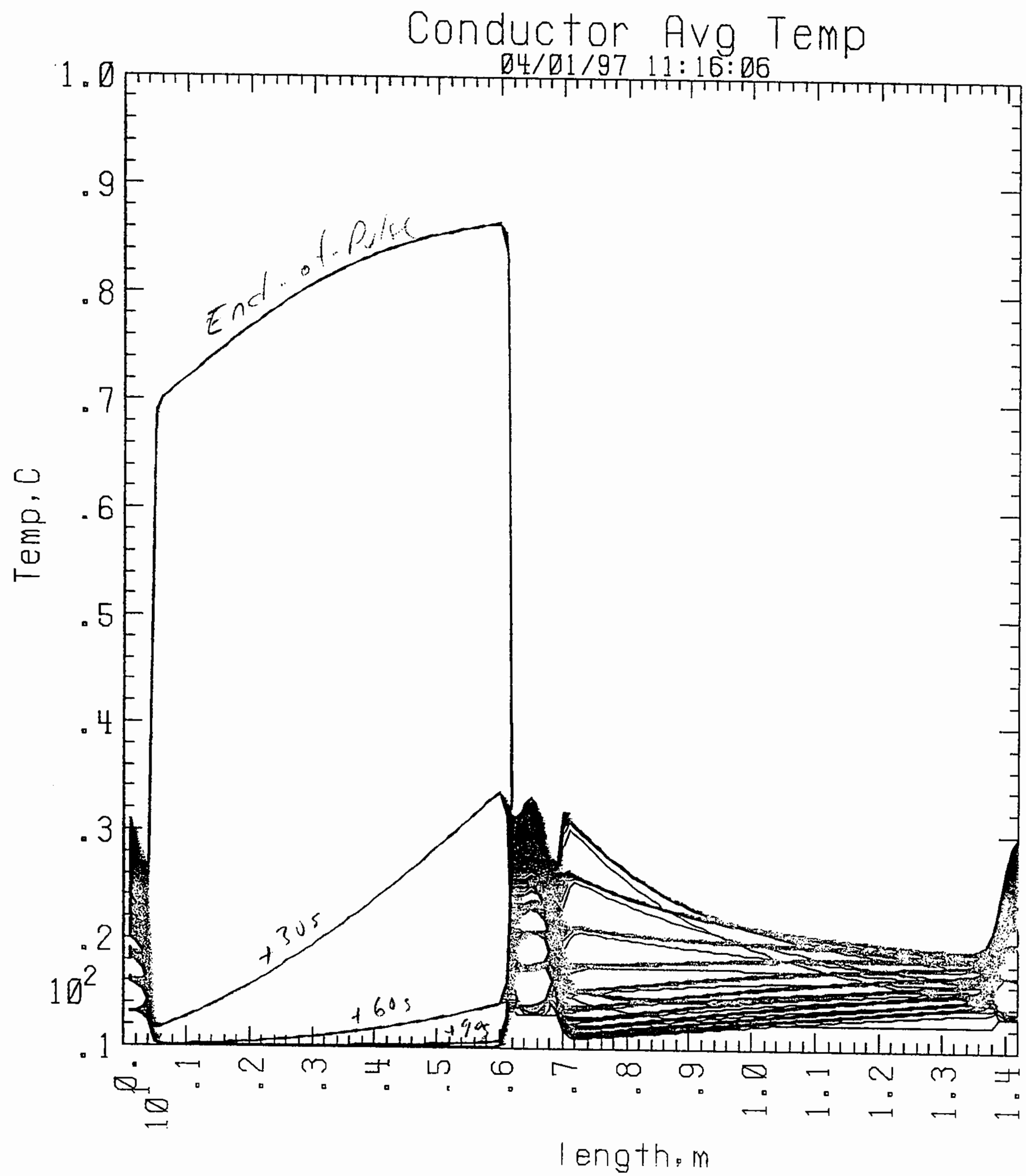


figure 1

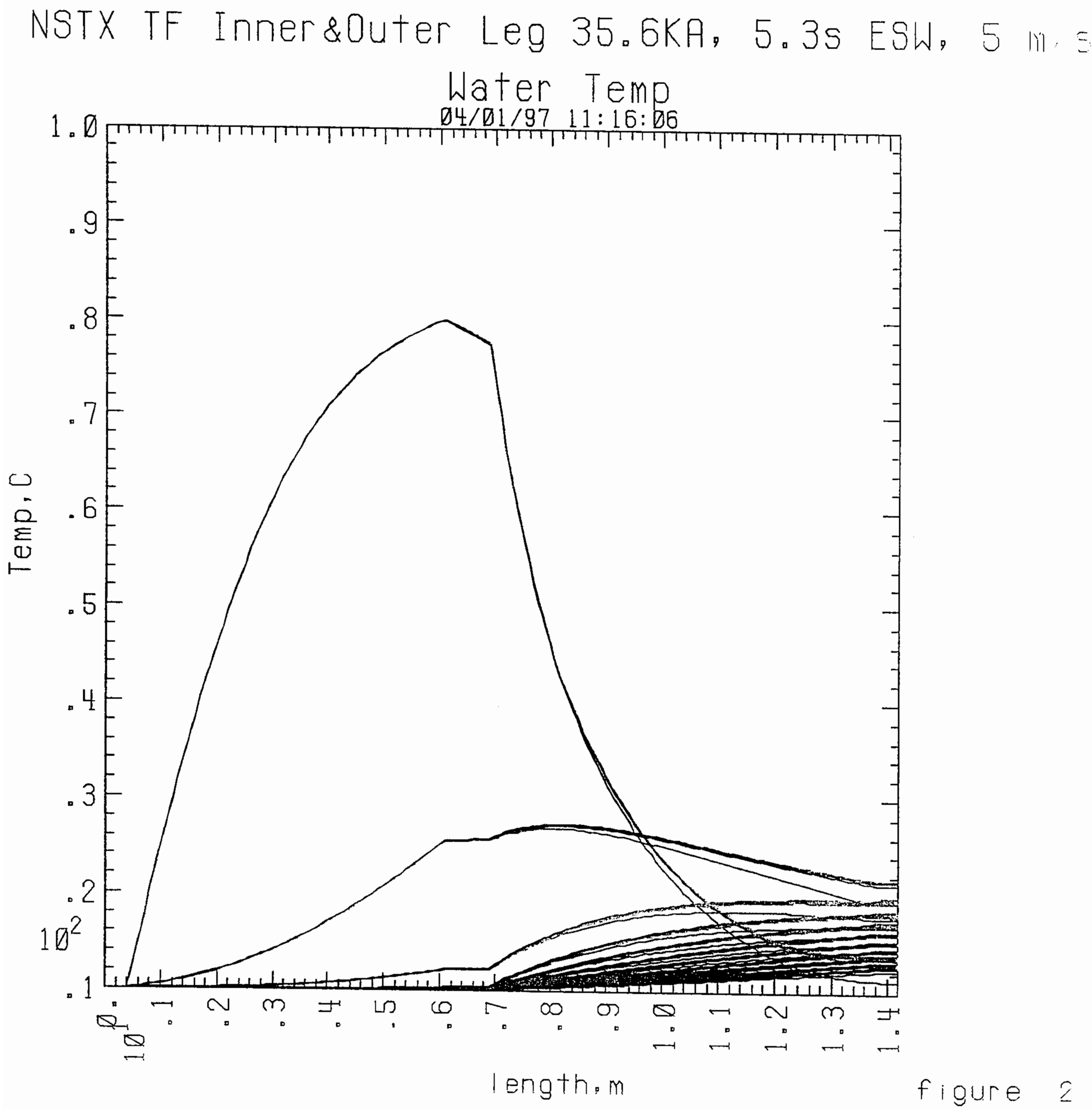

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Water Temp
Ø4/Ø1/97 11:16:Ø6
Temp,C
1.Ø
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
10^1
Ø.
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.Ø
1.1
1.2
1.3
1.4
length,m

figure 2

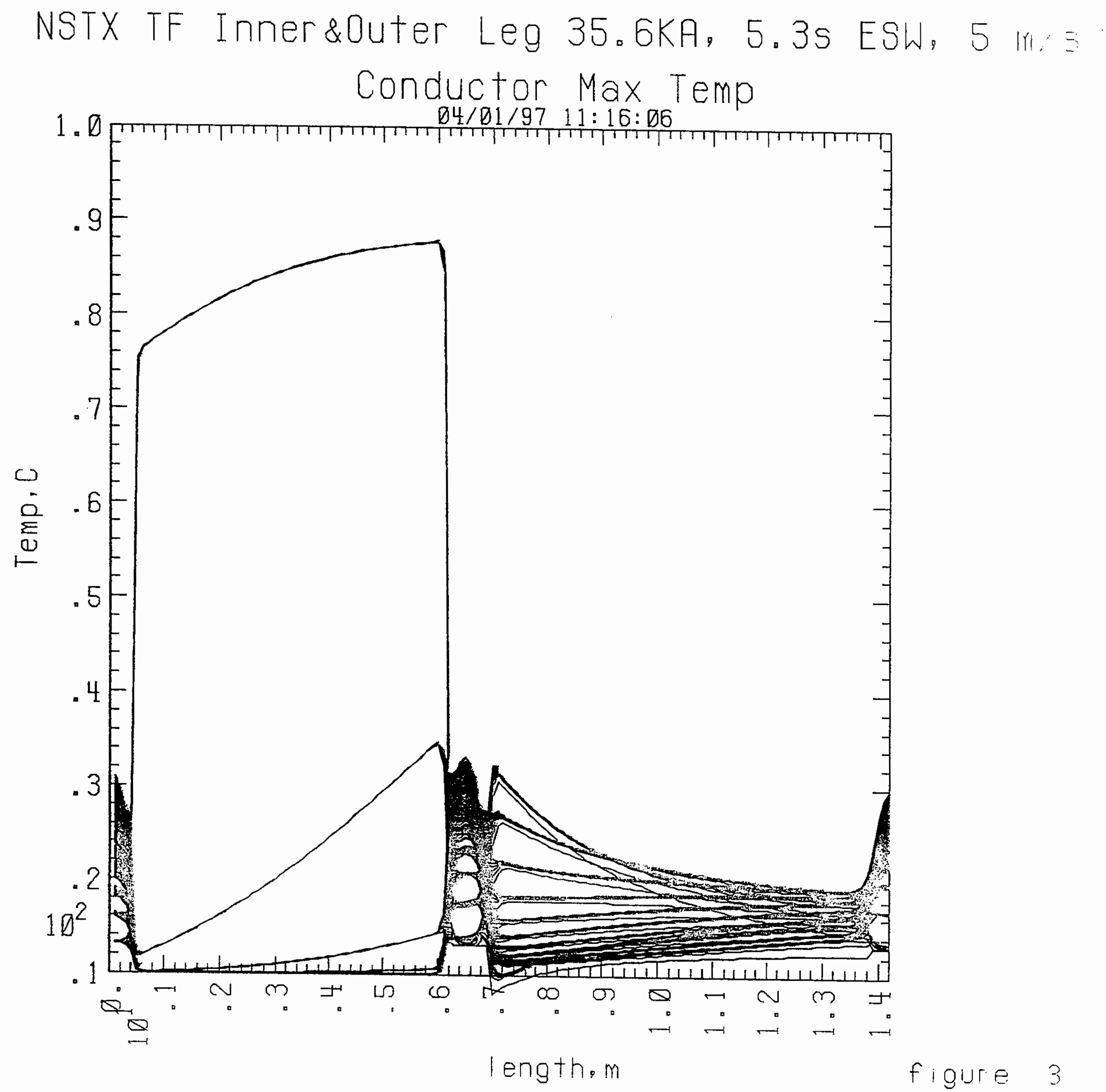

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Conductor Max Temp
04/01/97 11:16:06
Temp,C
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
10^1
0.
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
length,m

figure 3

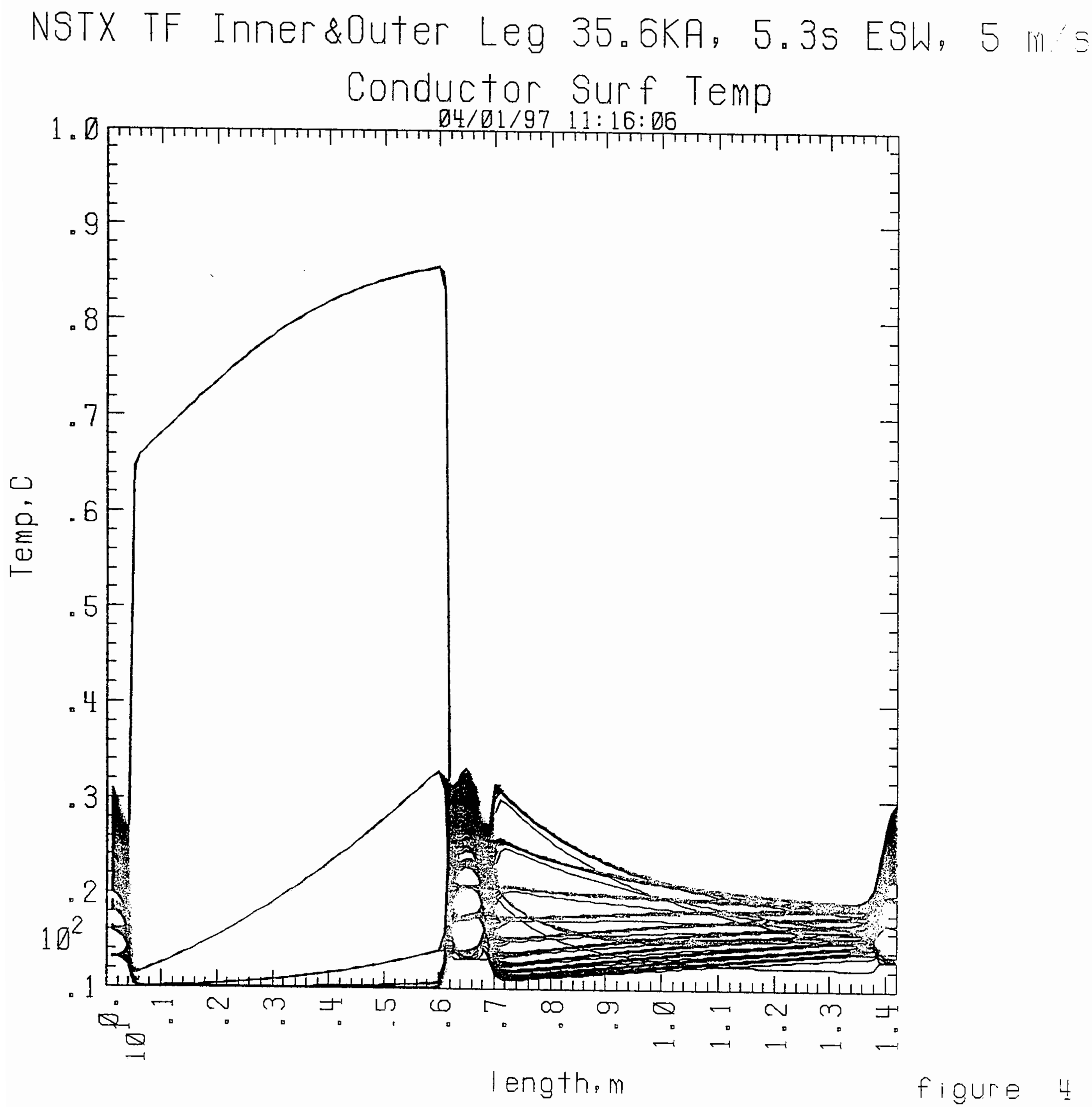
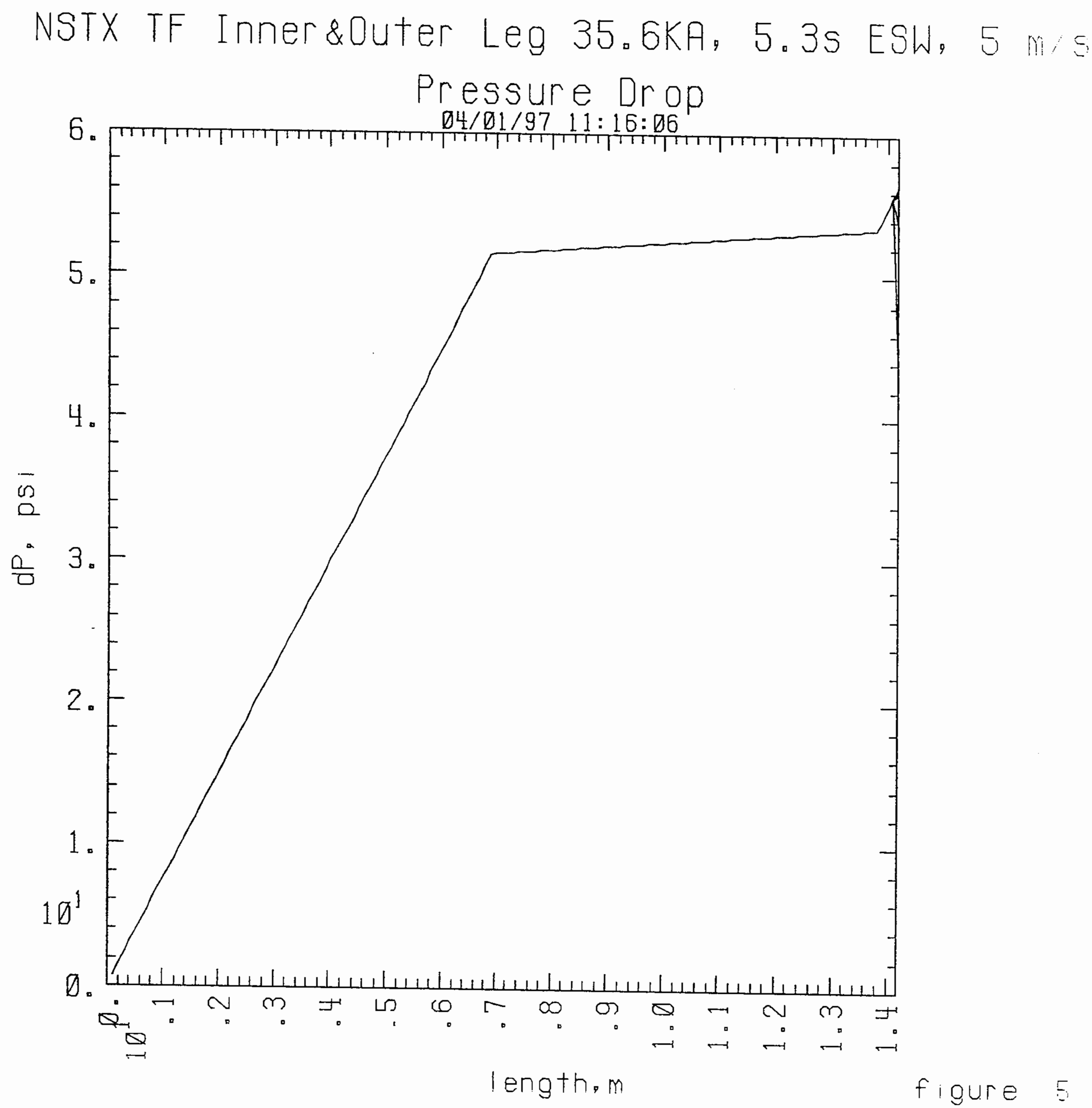

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Conductor Surf Temp
04/01/97 11:16:06
Temp,C
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
0.
10^1
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
length,m

figure 4



NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Pressure Drop
Ø4/Ø1/97 11:16:Ø6
dP, psi
6.
5.
4.
3.
2.
1.
1Ø¹
Ø.
Ø.
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.Ø
1.1
1.2
1.3
1.4
1Ø
length,m

figure 5

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 M/5

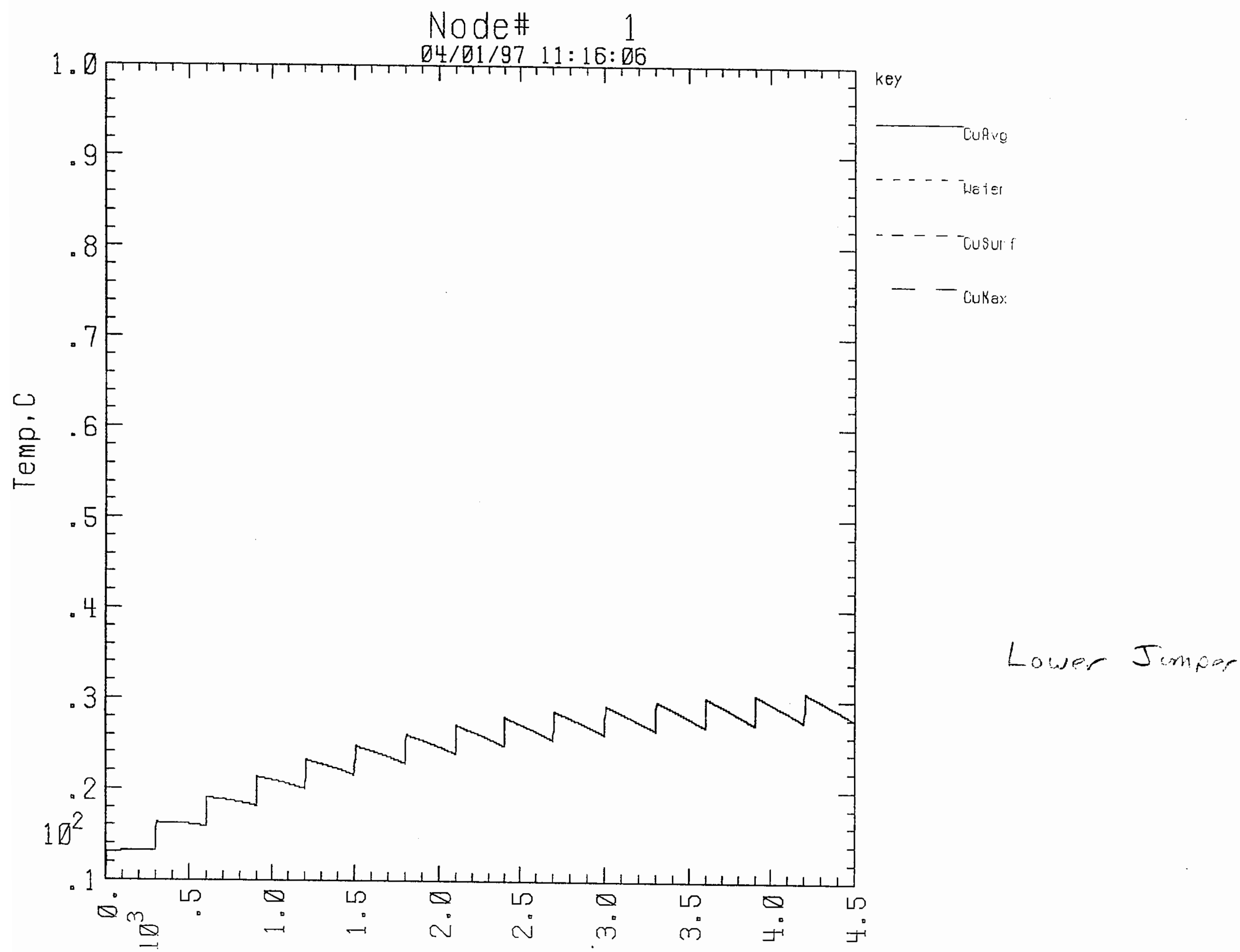
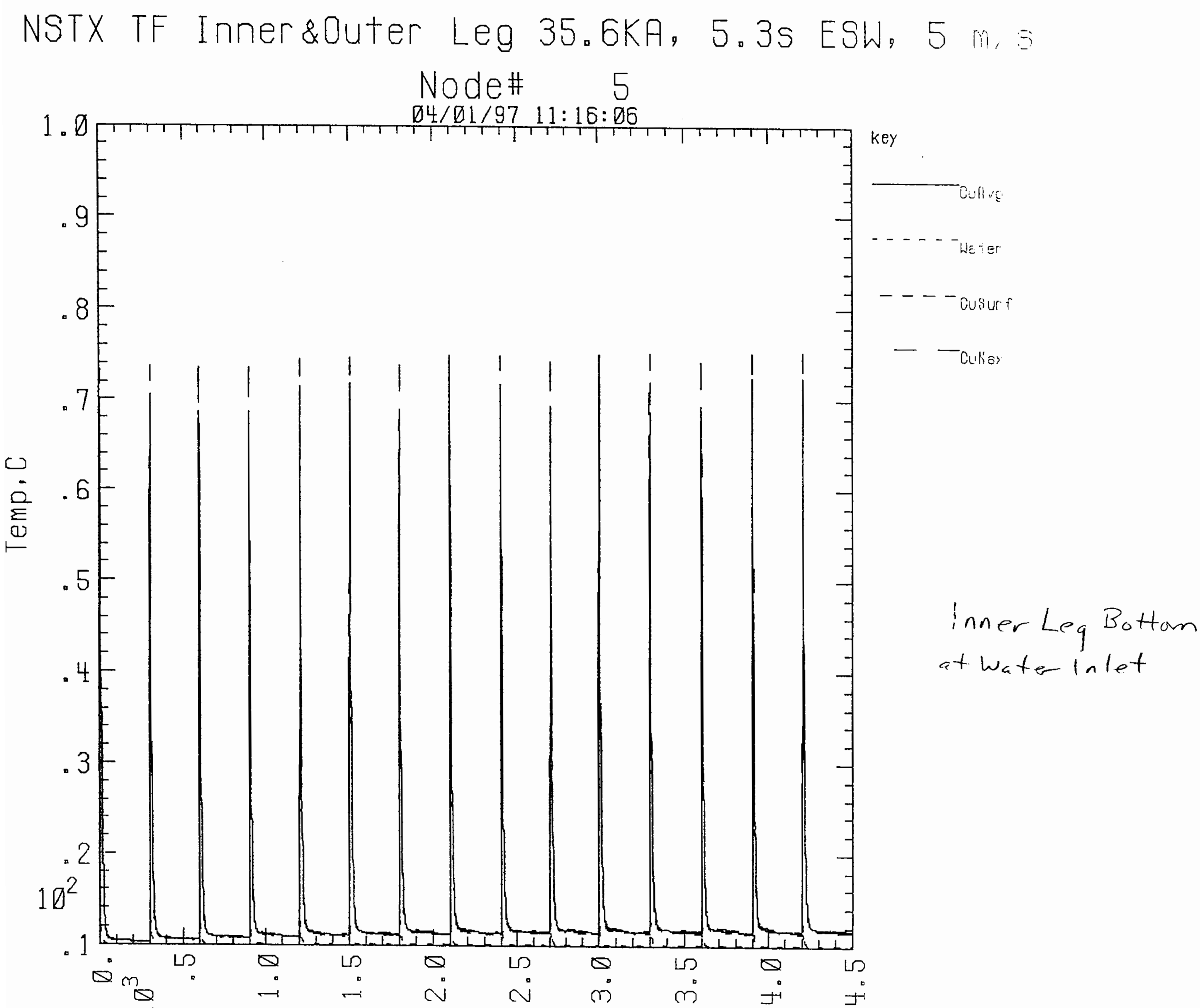


figure 6



NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Node# 5
04/01/97 11:16:06
key
CuAvg
Water
CuSurf
CuMax
Temp,C
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
0.
10^3
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time,sec
Inner Leg Bottom
at Water Inlet

figure 7

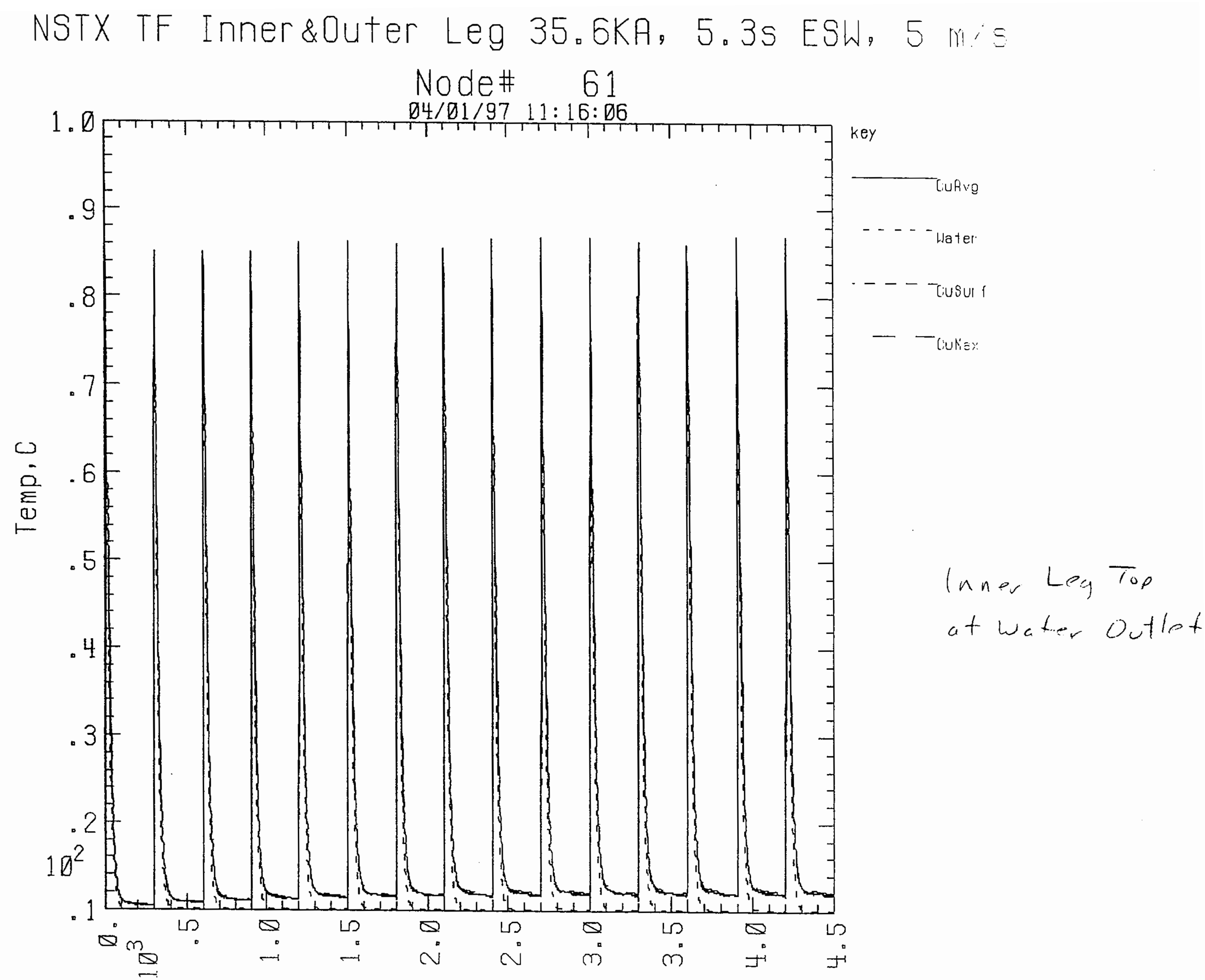

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Node# 61
04/01/97 11:16:06
Temp,C
Time,sec
key
CuAvg
Water
CuSurf
CuMax
Inner Leg Top
at Water Outlet

figure 8

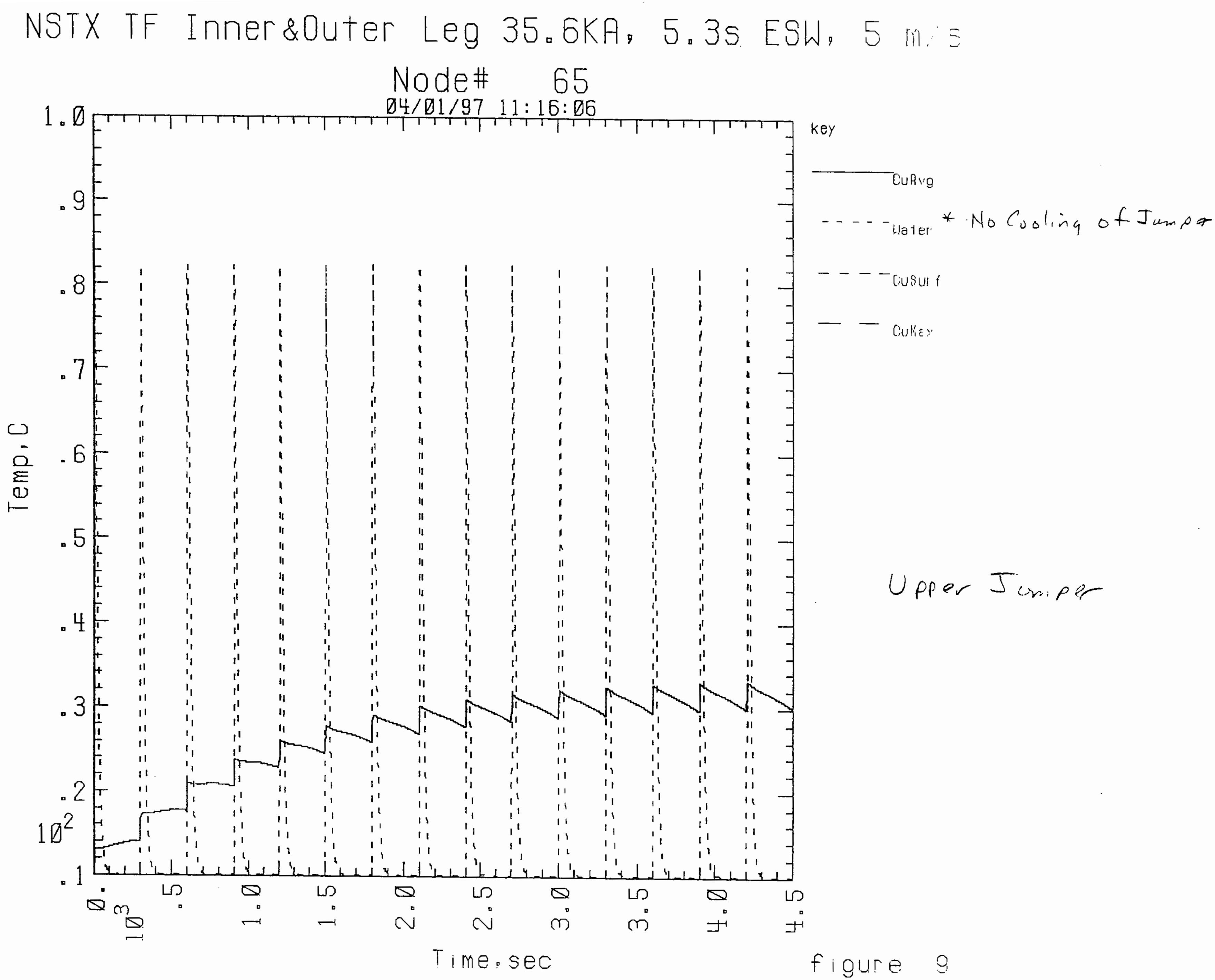

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Node# 65
04/01/97 11:16:06
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
Temp, C
0.
10^3
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time, sec
key
CuAvg
Water
* No Cooling of Jumper
CuSurf
CuKey
Upper Jumper

figure 9

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m s

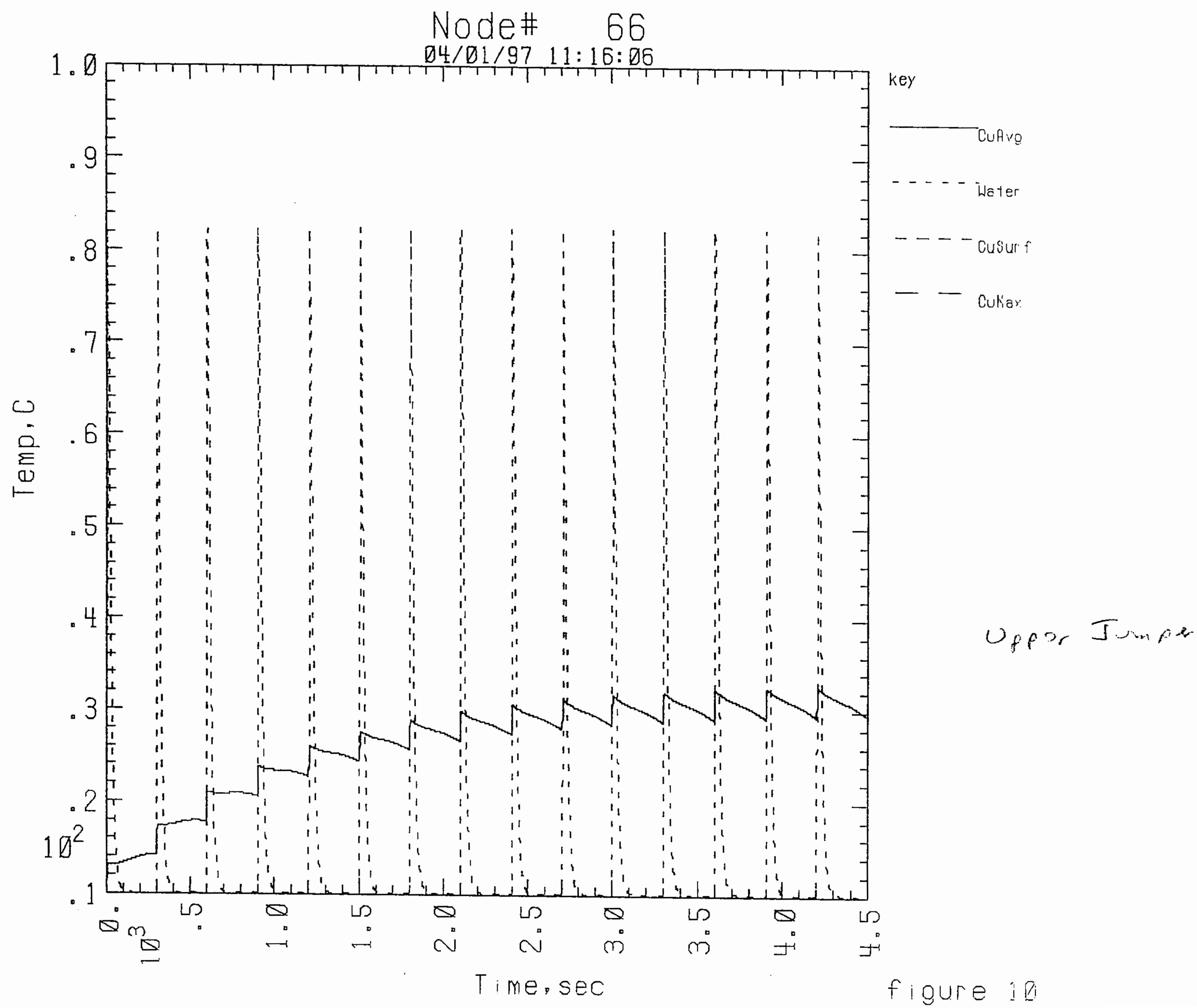
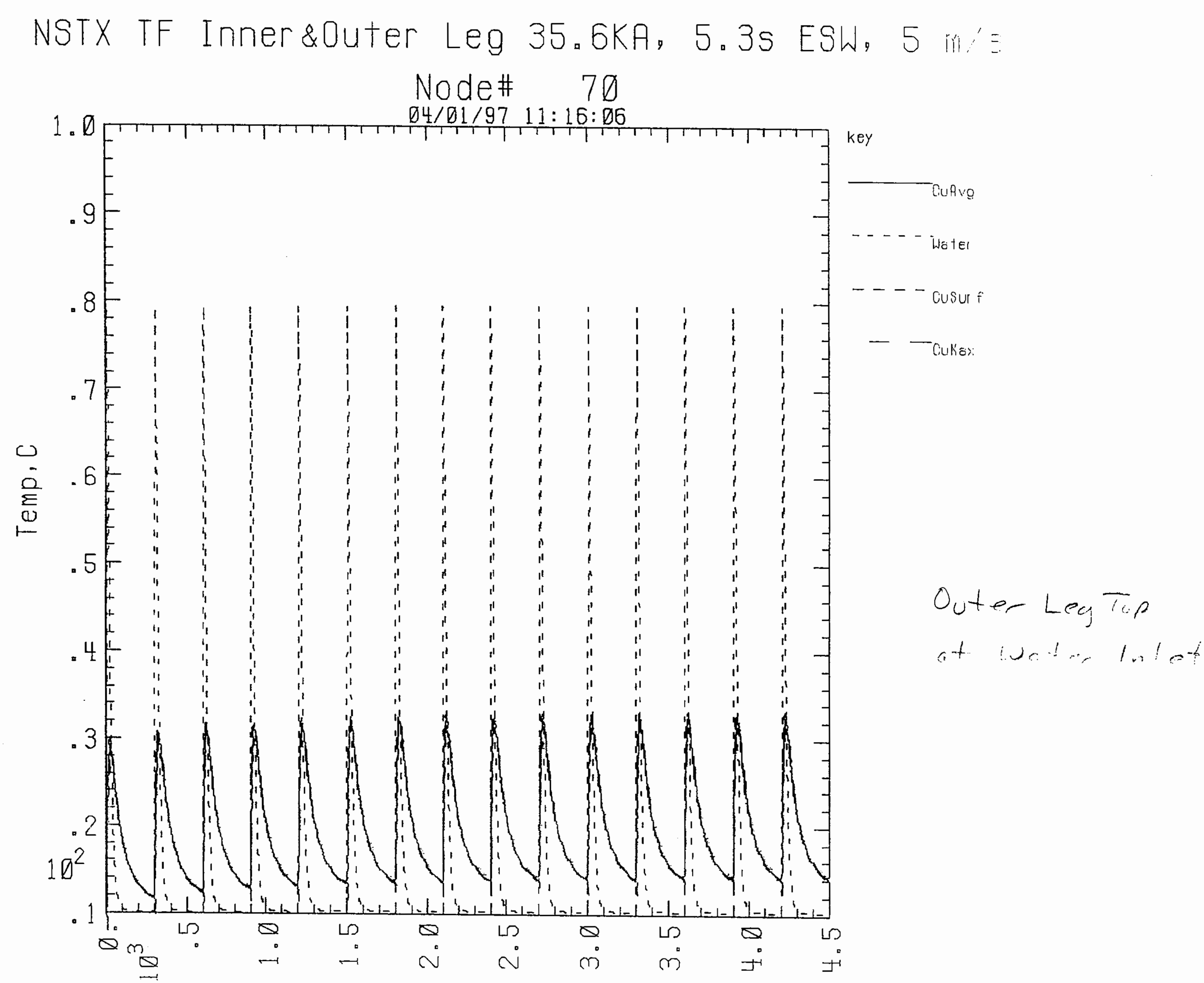
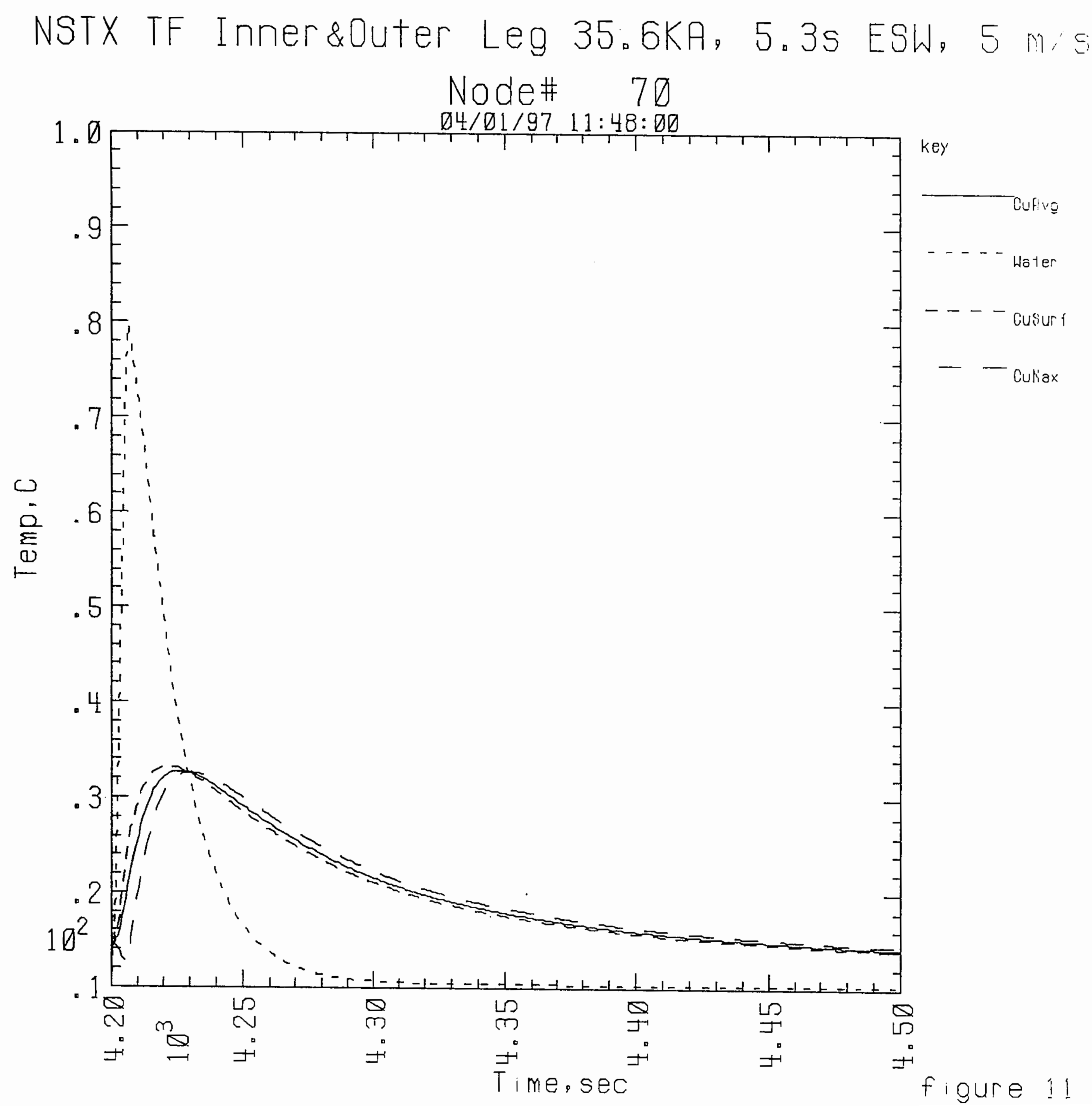


figure 10



NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Node# 70
04/01/97 11:16:06
Temp,C
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
0.
10^3
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Time,sec
key
CuAvg
Water
CuSurf
CuKax
Outer Leg Top
at Water Inlet

figure 11



NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s
Node# 70
04/01/97 11:48:00
1.0
.9
.8
.7
.6
.5
.4
.3
.2
10^2
.1
Temp,C
4.20
10^3
4.25
4.30
4.35
4.40
4.45
4.50
Time,sec
key
CuAvg
Water
CuSurf
CuMax

figure 11

NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5 m/s

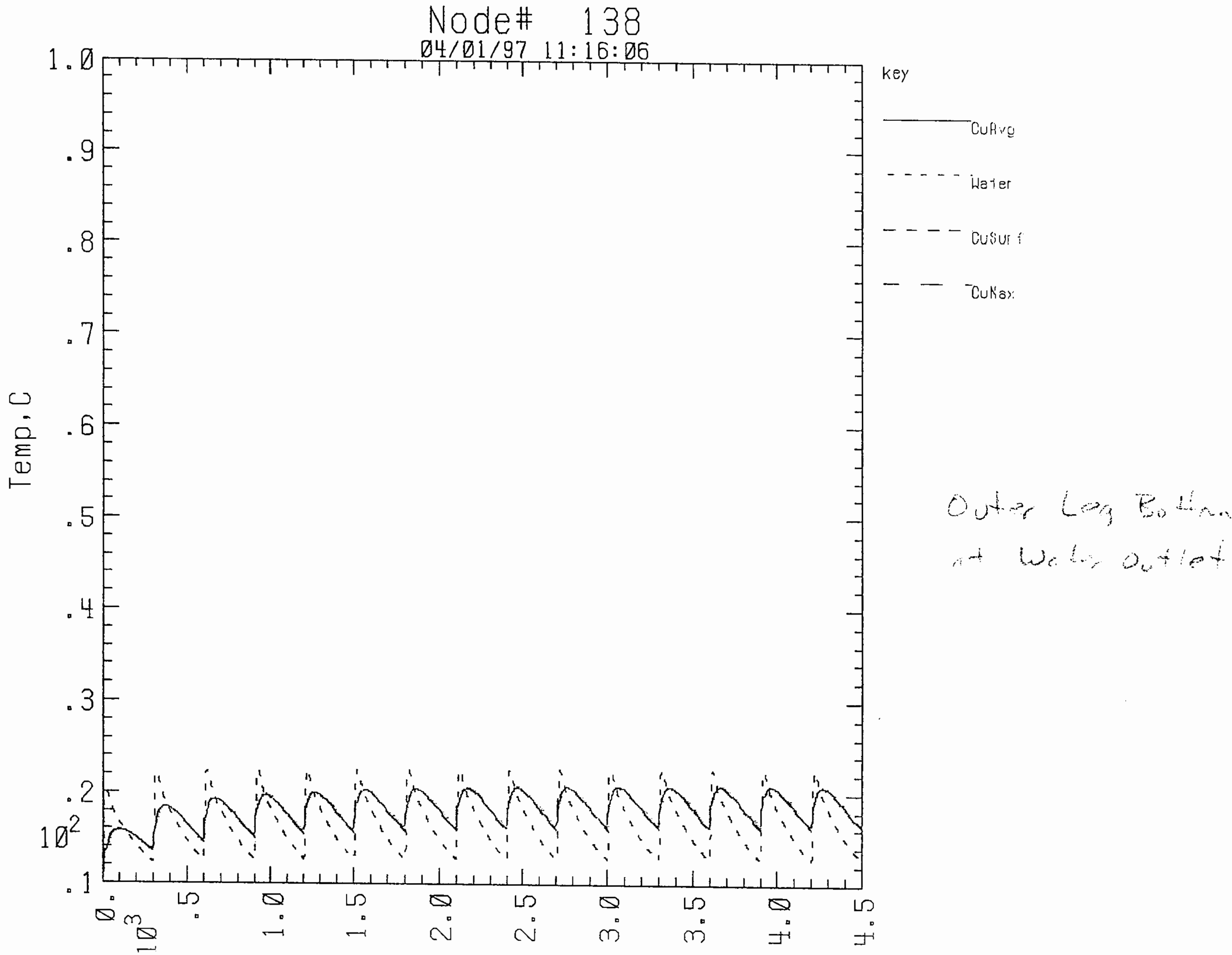
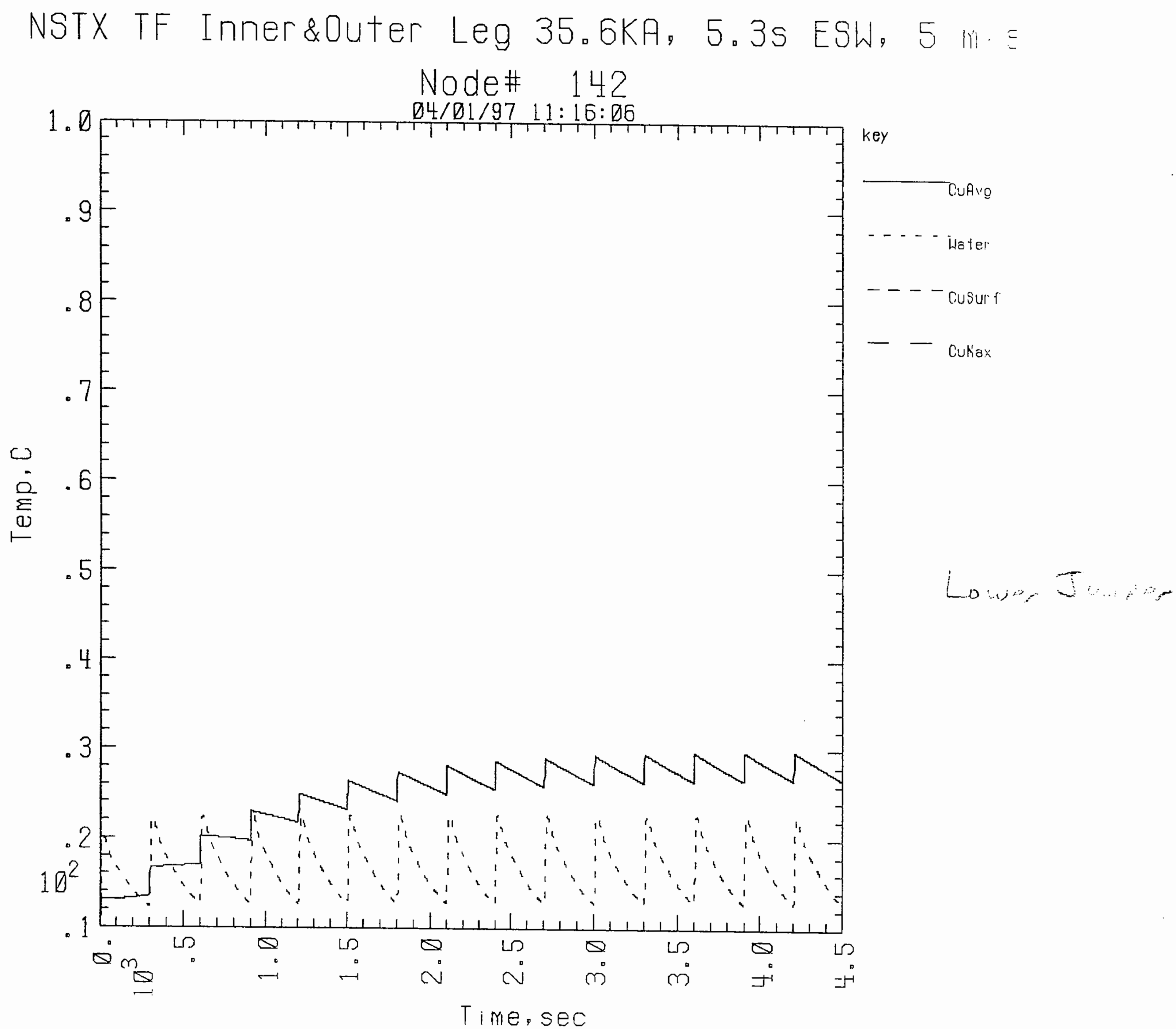


figure 12


NSTX TF Inner&Outer Leg 35.6KA, 5.3s ESW, 5
Node# 142
04/01/97 11:16:06
Temp,C
Time,sec
key
CuAvg
Water
CuSurf
CuMax
Lower Jumper