NSTX

13-970122-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: ANALYSIS OF TF JOINT HEATING

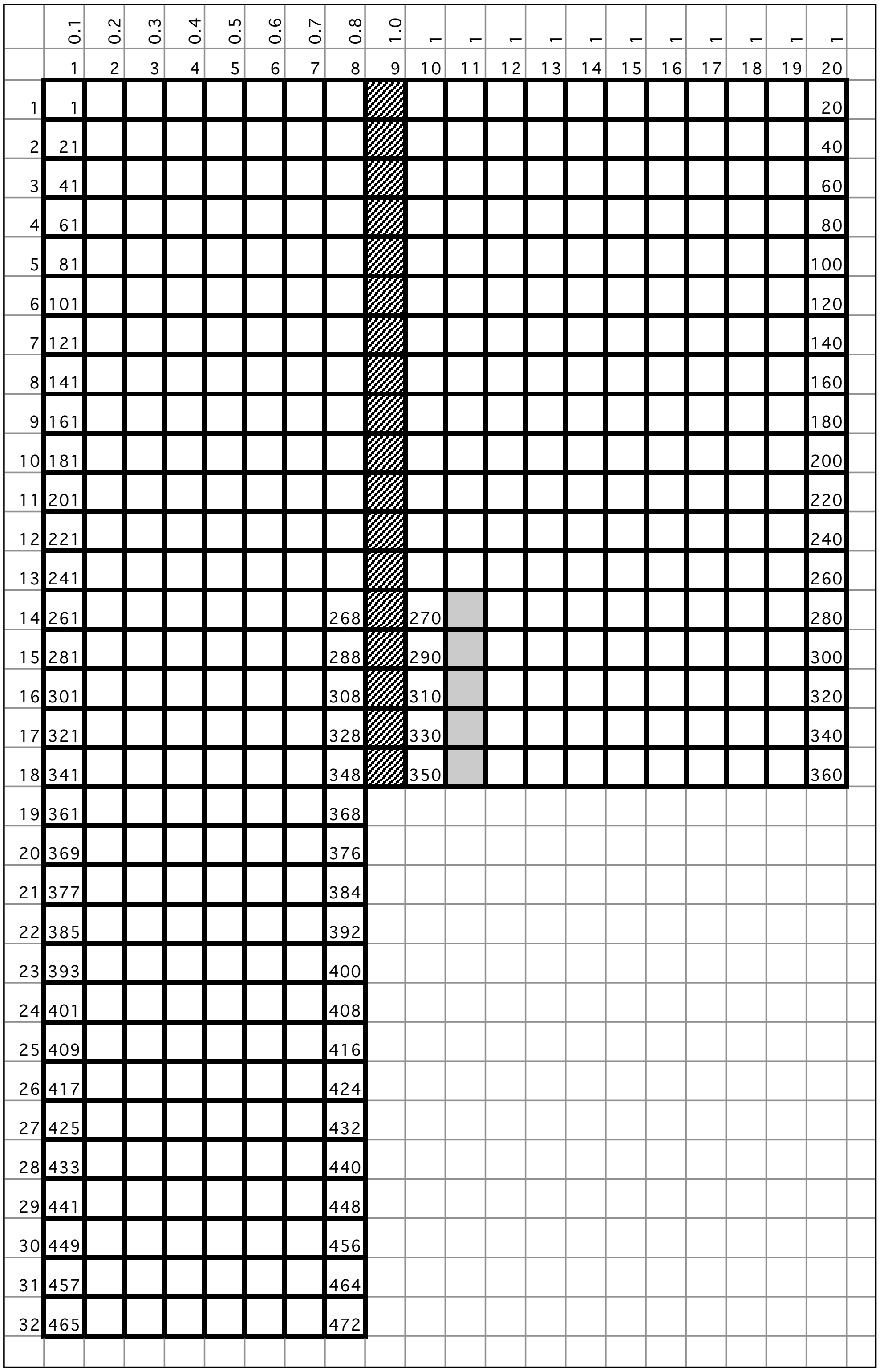
This memo presents the results of a preliminary analysis of the heating of the joint between the TF inner legs and flags. The current density in this joint is relatively high, due to the limited available space.

There are two variants of the subject joint, one of which connects the inner leg-inner turn to the outer leg, the other the inner leg-outer turn to the outer leg. The results reported here are based on the former. It is thought that this is the most severe case due to the shape of the inner leg conductor, but strictly speaking no comparative analysis was performed.

Inner leg conductor dimensions were obtained from NSTX drawing "TF Coil Centerstack, Insulation Buildups, Conductor/Insulation Arrangement" dated 1/8/97. Based on a discussion with L. Morris the flag was assumed 1" x 5" in cross section.

The joint was modeled using the grid shown in the following figure. Characteristics of the model are as follows:

- height and length of all grid elements the same
- width of grid elements varies to simulate triangular cross section of inner leg, total inner leg cross sectional area (CSA) equal 1.054 in^2 per existing inner leg design, after accounting for cooling hole.
- 20 radial slices, 32 azimuthal slices, total 472 elements
- outside of contact zone (radial slice #9) current and heat allowed to flow from each element to all neighboring elements, heat stored in thermal capacity of each element
- inside contact zone, current and heat flow allowed radially only, no heat storage capacity
- outside of contact zone, copper properties used for electrical and thermal conductivity, and specific heat. Initial temperature assumed 20C everywhere.
- inside contact zone, joint electrical and thermal conductivity were inputs which could be varied. While the electrical conductivity was varied, the thermal conductivity was held constant at a value of 5.0 watts/deg C-cm^2 (a film resistance was assumed).
- outside the contact zone, the resistivity could be varied with temperature, although a switch was included to enable/disable this feature.
- inside the contact zone, the resistivity was held constant independent of temperature.



• an additional feature was included to allow the exclusion of any selected set of the elements by setting their thermal and electrical resistivities to 100 times normal value (e.g. shaded nodes #271, 291, 311, 331, 351) in figure.

The CSA lost to the through bolts in the flag and inner leg is not accounted for herein.

To solve for the current flow through the model, the impedance [Z] matrix method[1] was used, with the impedance based strictly on DC resistance (no inductive effects were included). Using this method, once the [Z] matrix is constructed the voltages on all nodes can be solved for as follows:

$$[V] = [Z][I]$$

Where [V] is a vector containing all of the node voltages, and [I] is a set of injected currents. For the subject calculation, currents were injected into the nodal elements at the bottom of the inner leg (nodes 465 through 472) at equal current density such that the total injected current was equal to the desired valued (35.5kA for 0.3T, 71.1kA for 0.6T). The nodes at the end of the flag (20, 40, 60, 80....etc....360) were grounded.

Once the node voltages are known, the current flow between nodes is calculated based on the known resistance in between.

When the variation of the resistance with temperature was not enabled, the [Z] matrix calculation was performed once, and the transient heating calculated based on constant resistance. When the variation was enabled, the [Z] matrix was recalculated during each time step of the transient heating simulation.

Data saved for each run included the current distribution through the contact zone (currents through all elements in radial slice #9) and temperature distribution along the critical row (azimuthal slice #18, through the inner leg and then on the bottom edge of the flag.

Current was injected in a square wave fashion, assuming 35.555kA/5.5 sec for 0.3T, and 71.111kA/1.375 sec for 0.6T.

Values of 4, 6, and 8 $\mu\Omega$/in^2 were used for contact resistance, based on the curve shown below[2].

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[1]Code developed for prior work based on technique outlined in "Power Systems Analysis", A. R. Bergen, Prentice Hall, Inc., Englewood Cliffs, NJ

[2]From Copper Development Association (CDA) publication "Copper for Busbars", ch. 5, p. 82

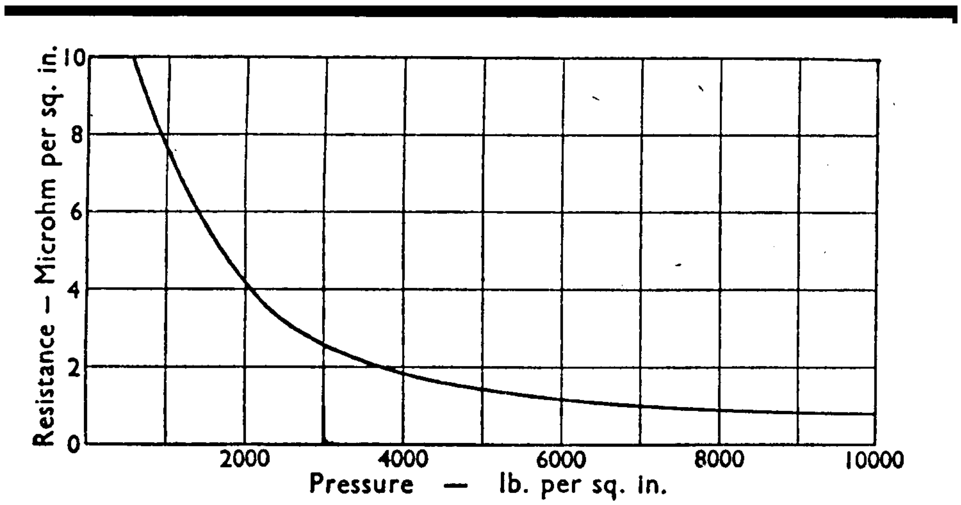


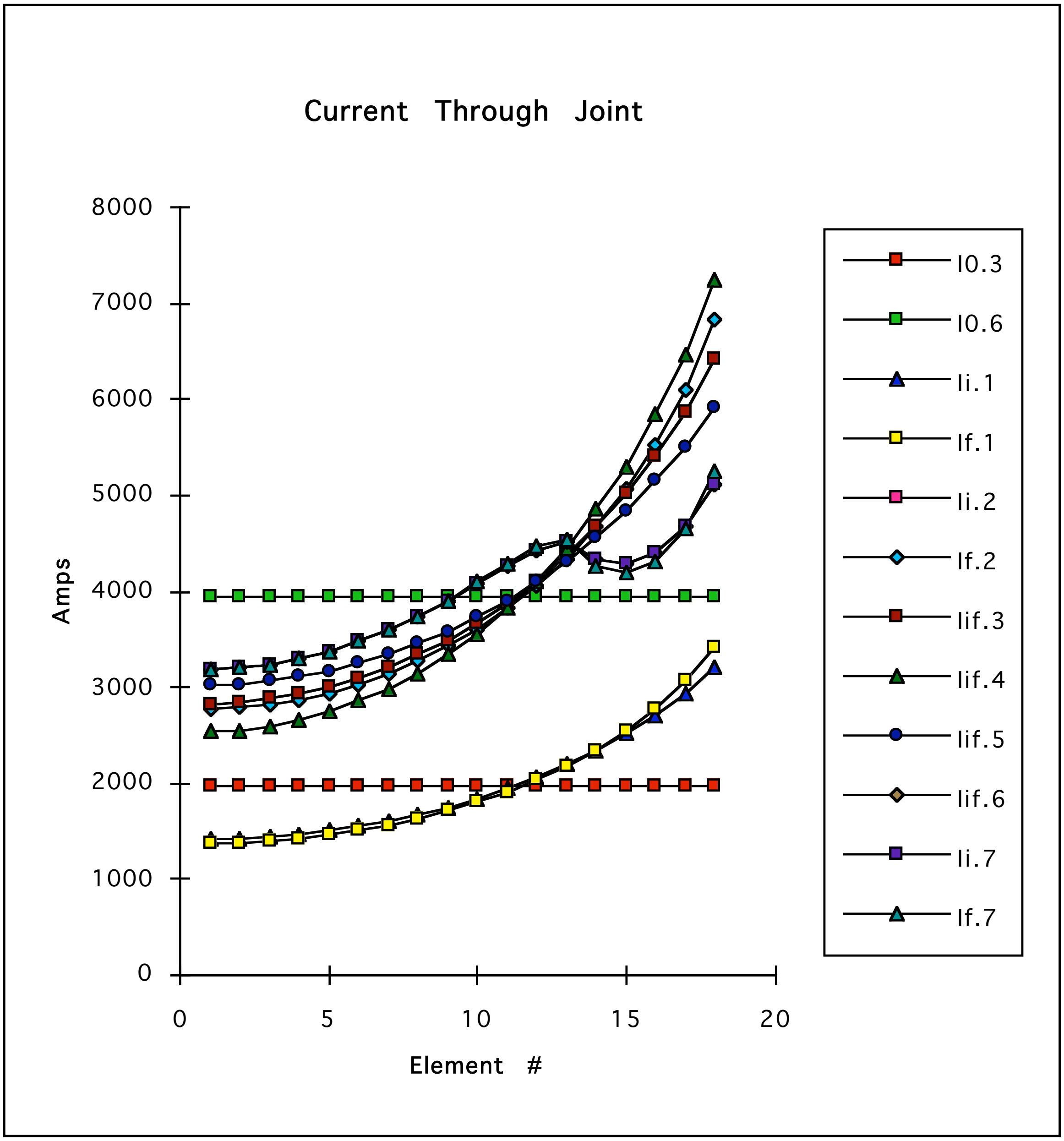
FIG. 20.—The effect of pressure on the contact resistance of a joint between two copper conductors. (To obtain the total joint resistance, *divide* the ordinates by the contact area in sq. in.)

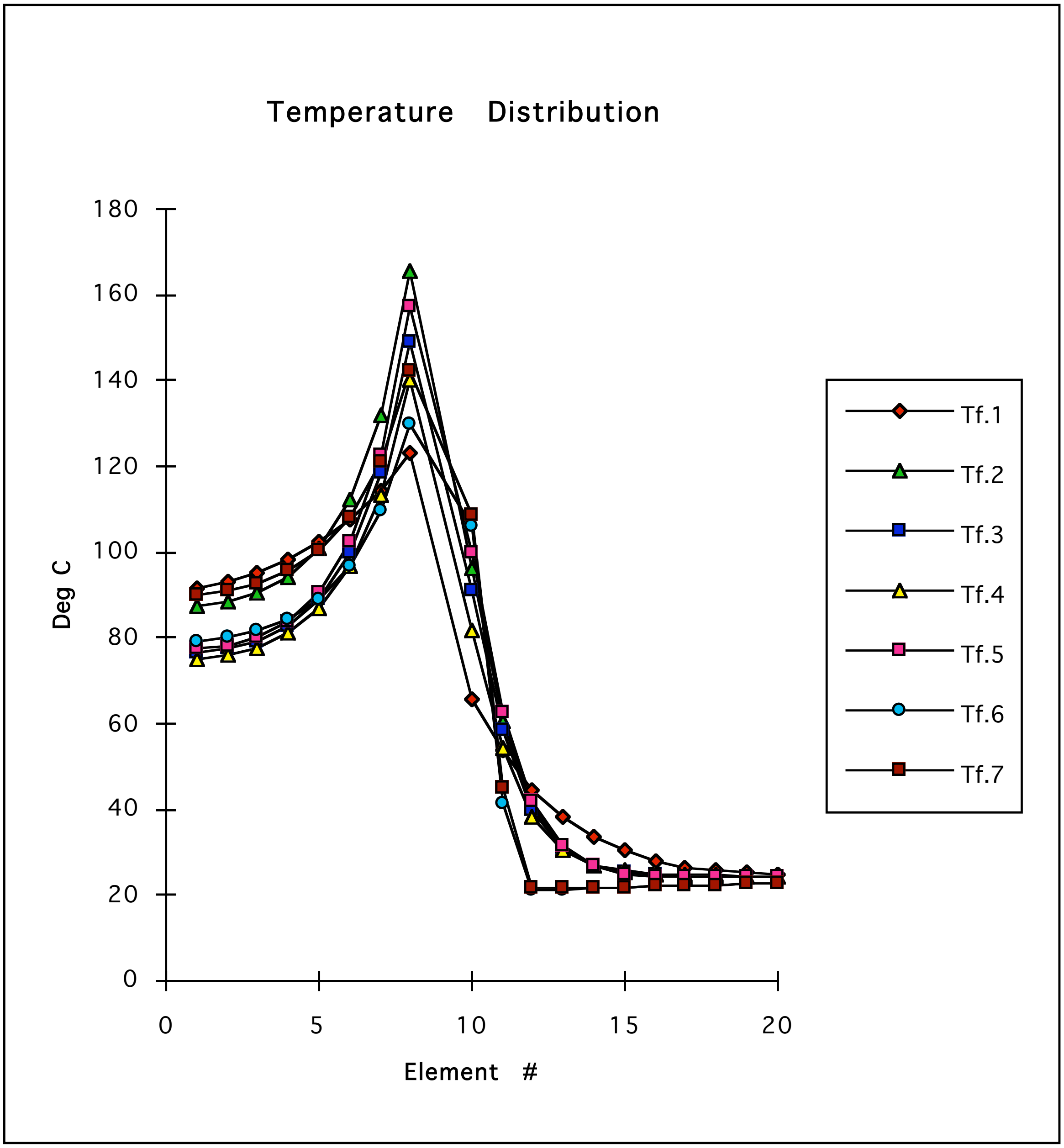
With contact resistance at $6\mu\Omega/in^2$ the total effective resistance of the model was found to be $0.36\mu\Omega$.

The following is a summary of the results:

Run #	Contact Resistance ($\mu\Omega/in^2$)	Current/time (kA/sec)	Varying Resistance	Excluded Nodes	Max Final Temperature (degC/node)
1	6	35.55/5.5	Yes	None	123/348
2	6	71.11/1.375	Yes	None	165/348
3	6	71.11/1.375	No	None	149/348
4	4	71.11/1.375	No	None	140/348
5	8	71.11/1.375	No	None	157/348
6	6	71.11/1.375	No	271, 291, 311, 331, 351	130/348
7	6	71.11/1.375	Yes	271, 291, 311, 331, 351	142/348

The following curves depict the current distribution across the joint, and the final temperature distribution along the critical row corresponding to the lower edge of the flag.


Current Through Joint
Amps
Element #
8000
7000
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
I0.3
I0.6
Ii.1
If.1
Ii.2
If.2
Iif.3
Iif.4
Iif.5
Iif.6
Ii.7
If.7



Finally, an additional run was performed at 0.6T, 6.0$\mu\Omega$/in^2, with resistance variation, without excluding any elements, but with a 6" high flag instead of 5". The peak temperature was reduced from 165 to 160C as a result.

Conclusions are as follows:

1) The basic 0.3T pulse results, given the assumptions, in a peak temperature of 123 deg C and is not of concern.

2) If the 165 deg C associated with the 0.6T pulse is acceptable, then the joint is OK as is, assuming that the contact resistance is $\approx 6\mu\Omega$/in^2 as assumed.

3) The current distribution in the joint could be adjusted favorably by cutting a slot in the lower portion of the flag. A significant reduction in maximum temperature (165 down to 142) was demonstrated via this scheme using the model. Instead of leaving the gap empty, it could be filled with a material with high resistance compared to copper but maybe with thermal conductivity and specific heat similar to copper. This would preserve the heat sinking effect but still allow for the current steering.

4) As an alternative to the cutting of a slot, the lower edge of the flag could be extended downward using a carefully considered profile, to optimally steer the current.

5) Increasing the height of the flag would help to some degree.

Finally, it is recommended that this analysis be repeated using ANSYS in order that more variations can be investigated with greater ease than afforded by the custom code described herein.

cc:

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