Calculation No: NSTXU-CALC-11-12-00 **Revision No: 0**

Electromagnetic Loads Calculation for OBD Tiles Row 4 and Row 5

Purpose of Calculation:

Determine the Lorentz forces and eddy moments for CSA row 5 and row 6 electromagnetic loads.

Codes and versions:

Internal PPPL guidelines and acceptance criteria were used. See NSTXU-CALC-11-08-00 for details.

References:

NSTXU-CALC-11-08-00
NSTX-U-RQMT-RD-003-00_Disruptions

Assumptions:

The following assumptions were made:

1) The value of peak background fields and peak dBdts were taken from NSTXU-CALC-11-08-00. All assumptions described in the fields and dBdts document are valid for this analysis.

2) Per NSTX-U-RQMT-RD-003-00_Disruptions, halo currents are assumed to strike in a toroidal band of 20 cm poloidal width. The halo current incident on each tile was factored based on poloidal width of the tile.

3) Current is assumed to flow thru the conducting support structure into the casing. The casing was extended about 2.5 cm below the tile and the casing face was grounded (zero volts)

Calculation:

This calculation is for Halo loads and Eddy Moments for OBD Row 4 and Row 5. See calculation and results sections for more detail.

Conclusion:

EM loads have been calculated. There is no specific requirement for load values but the loads may be imported into a structural model to determine the stresses resulting from these loads.

Cognizant Individual (or designee) printed name, signature, and date

Michael Jaworski   Michael Jaworski   Digitally signed by Michael Jaworski Date: 2018.09.27 16:51:28 -04'00'

Preparer's printed name, signature and date:

Wassee Syed   Wassee Syed   Digitally signed by Wassee Syed Date: 2018.09.27 15:55:09 -04'00'

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Han Zhang   Han Zhang   Digitally signed by Han Zhang Date: 2018.09.27 16:02:55 -04'00'

National Spherical Torus eXperiment - Upgrade

NSTX-U

Electromagnetic Load Calculation for OBD Tiles Row 4 and Row 5

NSTXU-CALC-11-12-00

Sep. 24, 2018

Wassee Syed   Digitally signed by Wassee Syed Date: 2018.09.27 15:55:30 -04'00'

Prepared By
Wassee Syed

Han Zhang   Digitally signed by Han Zhang Date: 2018.09.27 16:03:18 -04'00'

Reviewed By
Han Zhang

Michael Jaworski   Digitally signed by Michael Jaworski Date: 2018.09.27 16:51:11 -04'00'

Approved By – Responsible Engineer
Michael Jaworski

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	9/24/18	Initial Release	

Executive Summary

This report documents the methodology and results of an Electromagnetic Finite Element Analysis performed on specific PFCs - OBD row 4 and row 5. The EM load reactions presented in this report may be imported into a Multiphysics model as inputs to determine the overall response of the PFCs when exposed to structural, thermal, and EM loading.

Introduction

PFCs experience Lorentz forces induced by plasma disruptions. Fluctuations in electric and magnetic fields due to plasma disruptions induce eddy currents in the PFCs and the conductive support structures. Additionally, plasma contact with the PFCs may also generate halo currents. The halo currents strike the structure at one poloidal and toroidal location, flow thru the conductive structures and exit at another location.

The magnitudes and directions of the induced Lorentz loads depend on a number of factors including plasma shapes, movement, current decay, structure material properties and geometry. Several assumptions must be made in order to determine "worst case" values for the Lorentz loads.

Method of Analysis

Analysis Software

ANSYS Workbench version 19.1 was used for preprocessing – this includes meshing and defining surfaces for load and constraints application. The solution and post-processing was performed in APDL version 19.1

Geometry, Material and Contacts

Figure 1 shows the geometry for the upper and lower bays. Five tiles were analyzed and are labelled for reference throughout this document. Figure 2 shows a cross section of tile 1 along with the material specifications. Separate analyses were conducted for each individual tile.

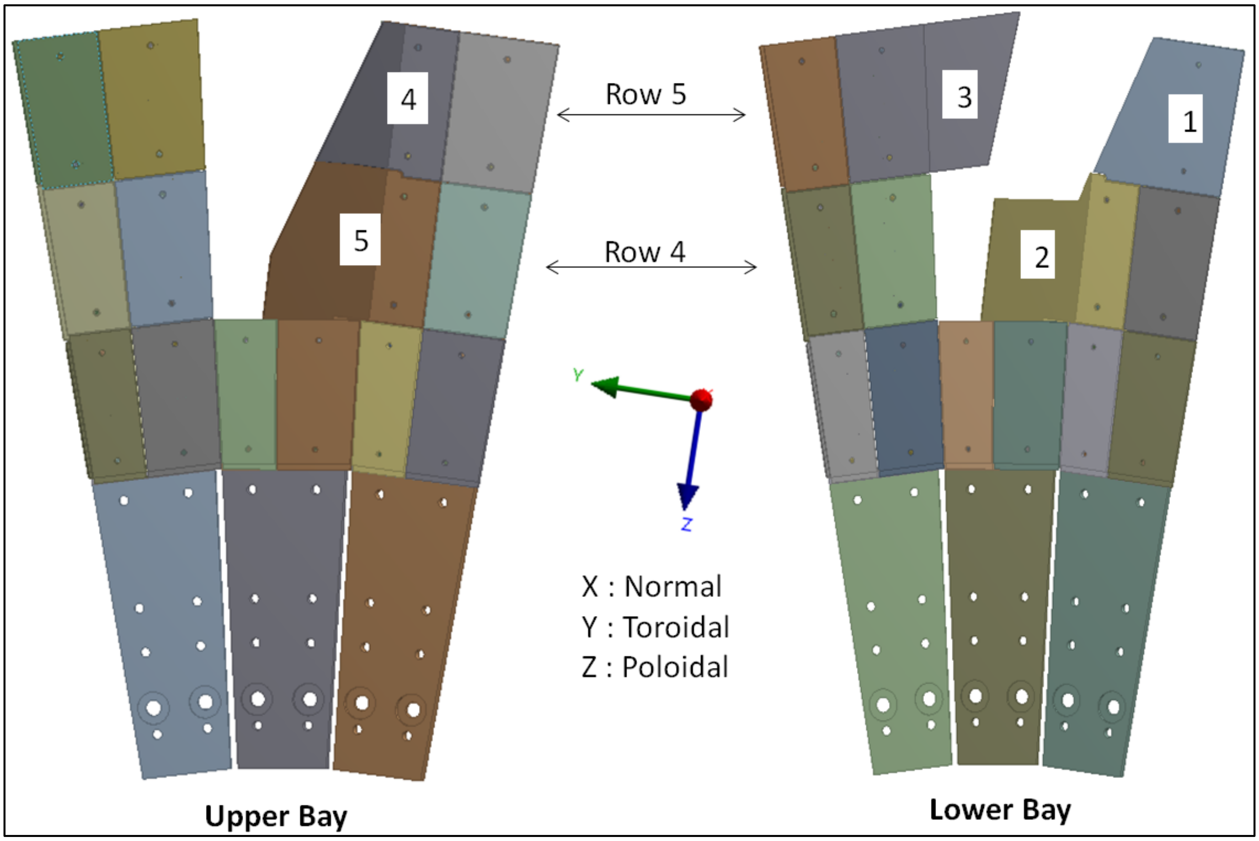

Figure 1: Geometry and Lables

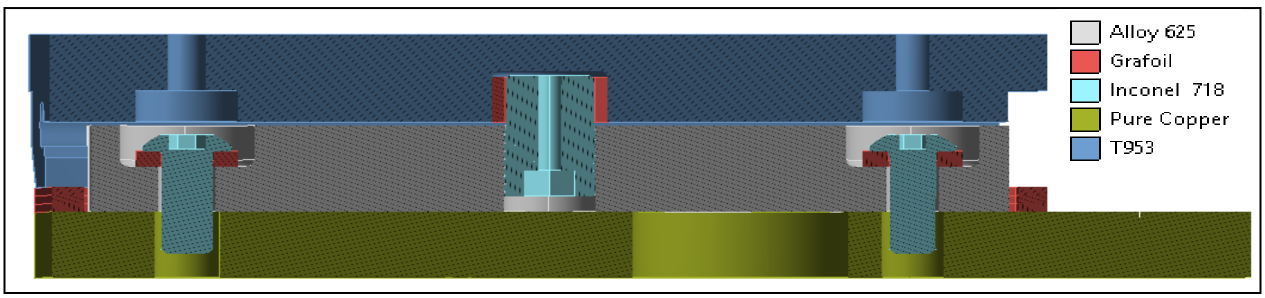

Figure 2 : Tile 1 Cross Section and Material Specifications

Table 1: Electrical Resistivity at 70 ◦F

Material	Electrical Resistivity [ohm.m]
Alloy 625*	1.29 E-02
Grafoil*	1.17 E-05
Inconel 718	1.30 E-06
Pure Copper	1.68 E-08
T953	1.50 E-05

*For this analysis electrical resistivities for Alloy 625 and Grafoil should have been 1.26E-6 ohm.m and 150E-4 ohm.m respectively. However utilizing these properties will give lower loads, and the current analysis is more conservative. See the results section for more detail.

Bonded contact was defined at five interfaces as shown in Figure 3. Frictional contact with a coefficient of friction of 0.10 was defined at all other interfaces.

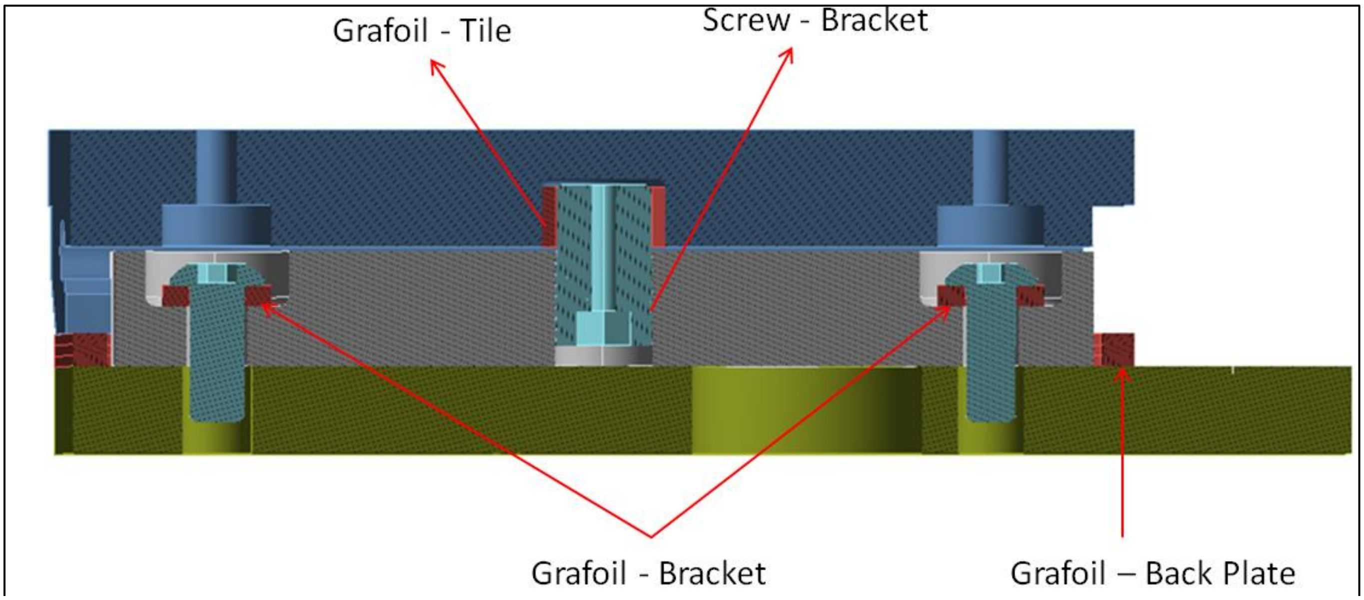

Figure 3 : Location of interfaces with bonded contacts

<u>**Finite Element Mesh**</u>

SOLID232 (Current-based Electric Element) elements were utilized for the halo current simulation, while SOLID237 (Electromagnetic Element) elements were used for the eddy current analysis. Both are 10-node tetrahedral elements.

Figure 4 and Figure 5 show the mesh detail. The element type and mesh sizing settings were identical for all tiles.

Table 2: Mesh Statistics

Tile #	Number of Elements	Number of Nodes
1	580,755	861,663
2	534,416	797,618
3	746,182	1,096,398
4	467,889	695,989
5	619,633	918,283

Figure 4 : Tile 1 Mesh

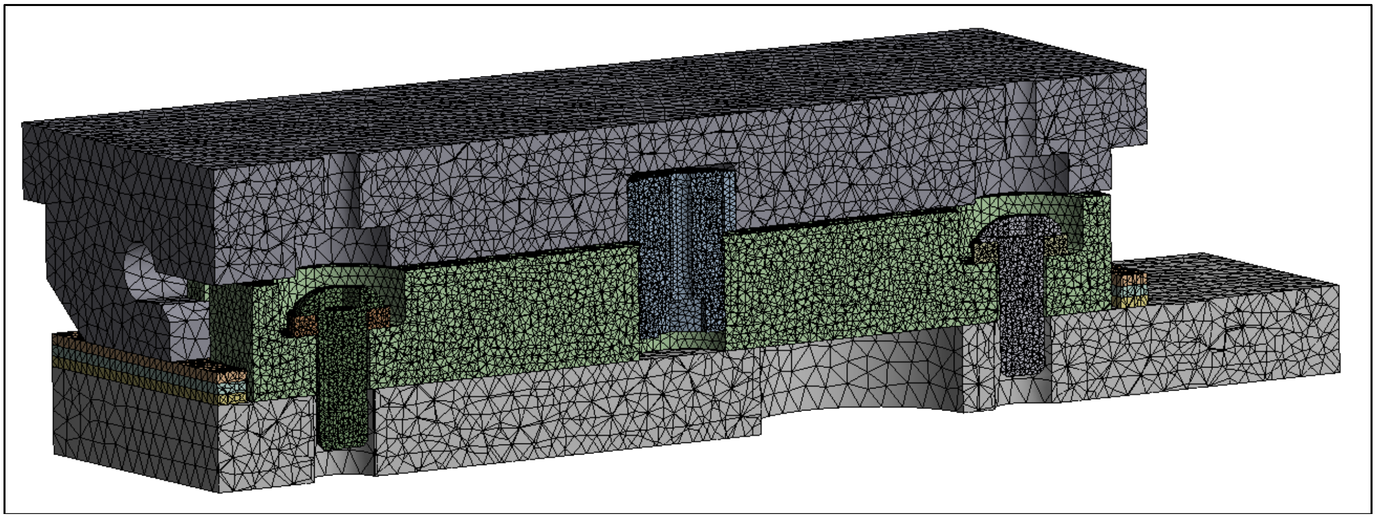

Figure 5: Tile 1 Cross Section Mesh

Halo Current Calculation

The poloidal width of the tiles is not constant. For halo current calculations, an average width was calculated by dividing the surface area with the tile length. The halo current incident on the tile is proportional to the poloidal width. Below is the halo current calculation for tile 1. The halo currents for tiles 4-5 were calculated using the same method, and are summarized in Table 2.

Plasma Current, Ip = 2E6 Amps
Halo Current Factor, hf = 0.35
Toroidal Peak Factor, Tp = 2.0
Number of Tiles in Row, Nt = 48
Average Poloidal Tile Width, W = 10.64 cm

Ih = Ip*hf*Tp*W/(Nt*20) = 15,511 Amps

Table 3: Average poloidal widths and halo currents

Tile #	Surface Area [cm^2]	Toroidal Length [cm]	Average Poloidal Width [cm]	Halo Current [Amps]
1	132.39	12.45	10.64	15,511
2	157.82	13.98	11.29	16,458
3	194.30	17.93	10.84	15,806
4	107.24	10.95	9.80	14,285
5	170.42	14.00	12.17	17,752

Static and Dynamic Magnetic Field

The inputs for the magnetic fields are summarized in Table 4. Refer to NSTXU-CALC-11-08-00 for assumptions and analysis on which these values are based.

Table 4: Magnetic Field Components and dbdts [x: Radial, y: Toroidal, z: Poloidal]

	Radius [m]	Bx	By	Bz	db/dx	db/dy	db/dz
OBD Row 4	1.03	-0.79	0.91	-0.91	883	0	732
OBD Row 5	1.15	-0.64	0.81	-1.05	478	0	865

Load and Boundary Conditions

- Uniform halo current is applied on tile surface
- Constant background magnetic field is applied using an APDL macro
- Casing surface is grounded (V = 0)

The regions for halo current and ground application are highlighted in Figure 6.

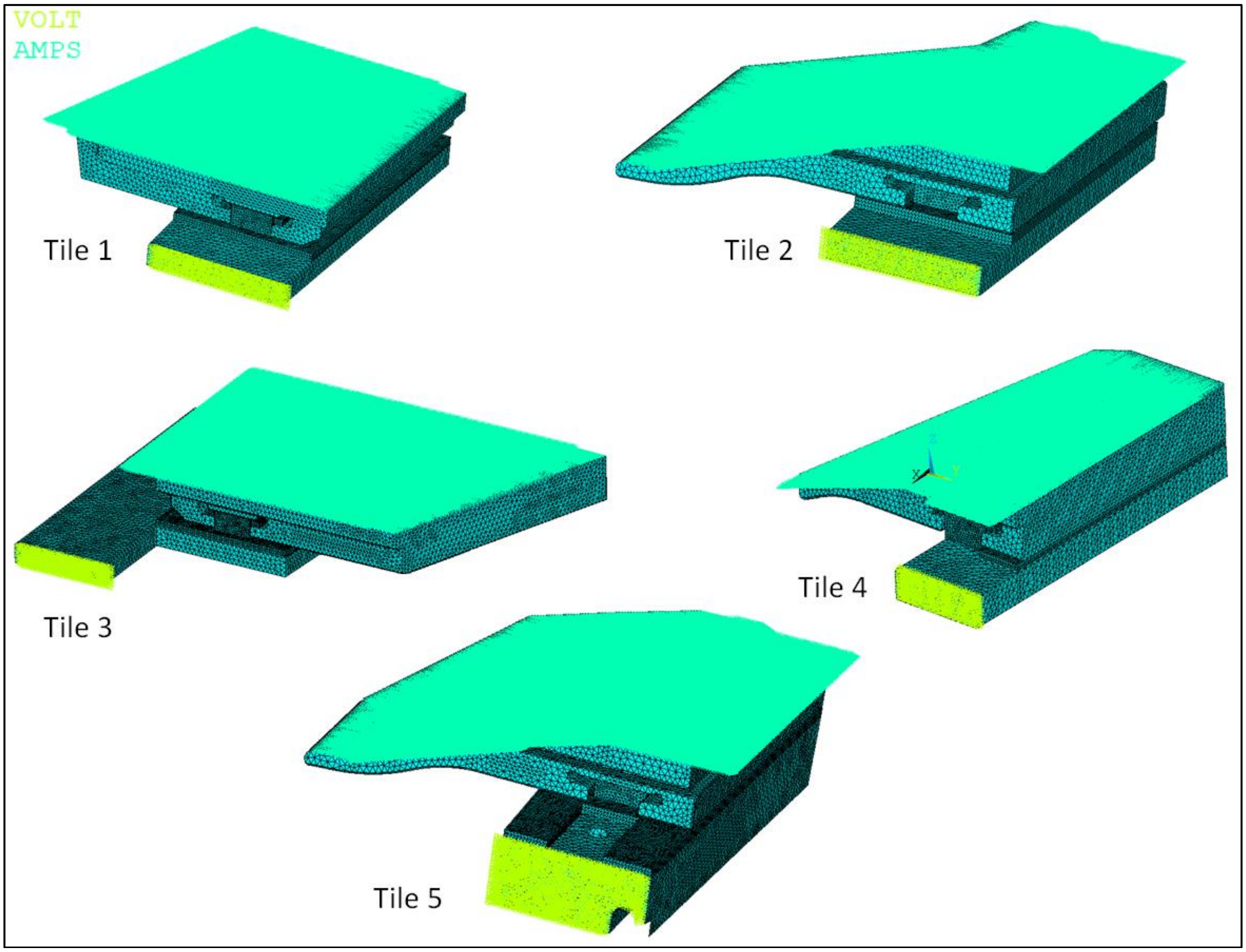

Figure 6: Halo Current and Ground Application

Each tile was analyzed individually with a halo strike on its top surface. The grounding location allows the current to flow from the tile through the T-bar into the base plate.

Results

Table 5 shows a summary of the results. Subscript "r" refers to resultant. The forces are determined for every node in the FE model. The force values shown in the table are the sums of the nodal loads on the tile bodies. Relevant nodal data (nodal coordinates, forces and volumes) were also stored in text files for import to structural FE models as needed.

Table 5: Results Summary [x: Normal, y: Toroidal, z: Poloidal]

Halo Forces [N]					Eddy Moments [NM]			
Tile #	**Fx**	**Fy**	**Fz**	**Fr**	**Mx**	**My**	**Mz**	**Mr**
1	-179	-356	-166	432	0.15	3.79	2.83	4.73
2	941	113	-704	1,180	-0.27	4.23	4.47	6.16
3	-440	-399	-40	595	0.14	4.07	3.96	5.68
4	344	-180	-348	521	0.00	2.10	1.58	2.63
5	389	-440	778	974	-0.50	5.39	5.82	7.95

As specified under the material properties section, the electrical resistivities for Alloy 625 and Grafoil used for the analysis were different from the intended values. Instead of re-running all the analyses two tiles were selected for a re-run. Tile 2 and Tile 5 result in the top two loads and were re-run for halo loads (Eddy Moments does not require a re-run since we are not modifying the tile material properties).

Table 6: Updated Halo Loads for Highest Loaded Tiles

Uploaded Halo Forces [N]				
Tile #	**Fx**	**Fy**	**Fz**	**Fr**
2	692	-12	-612	924
5	600	-146	-670	911

The resultant loads have reduced for both tiles. The Fx for tile 5 increases while the other two components reduce. The X direction load will be countered by the preload, and can handle up to 5,000 N. It can be concluded that the results shown in Table 5 are acceptable as is.

Total Current Density, Jt [Amps / M^2]

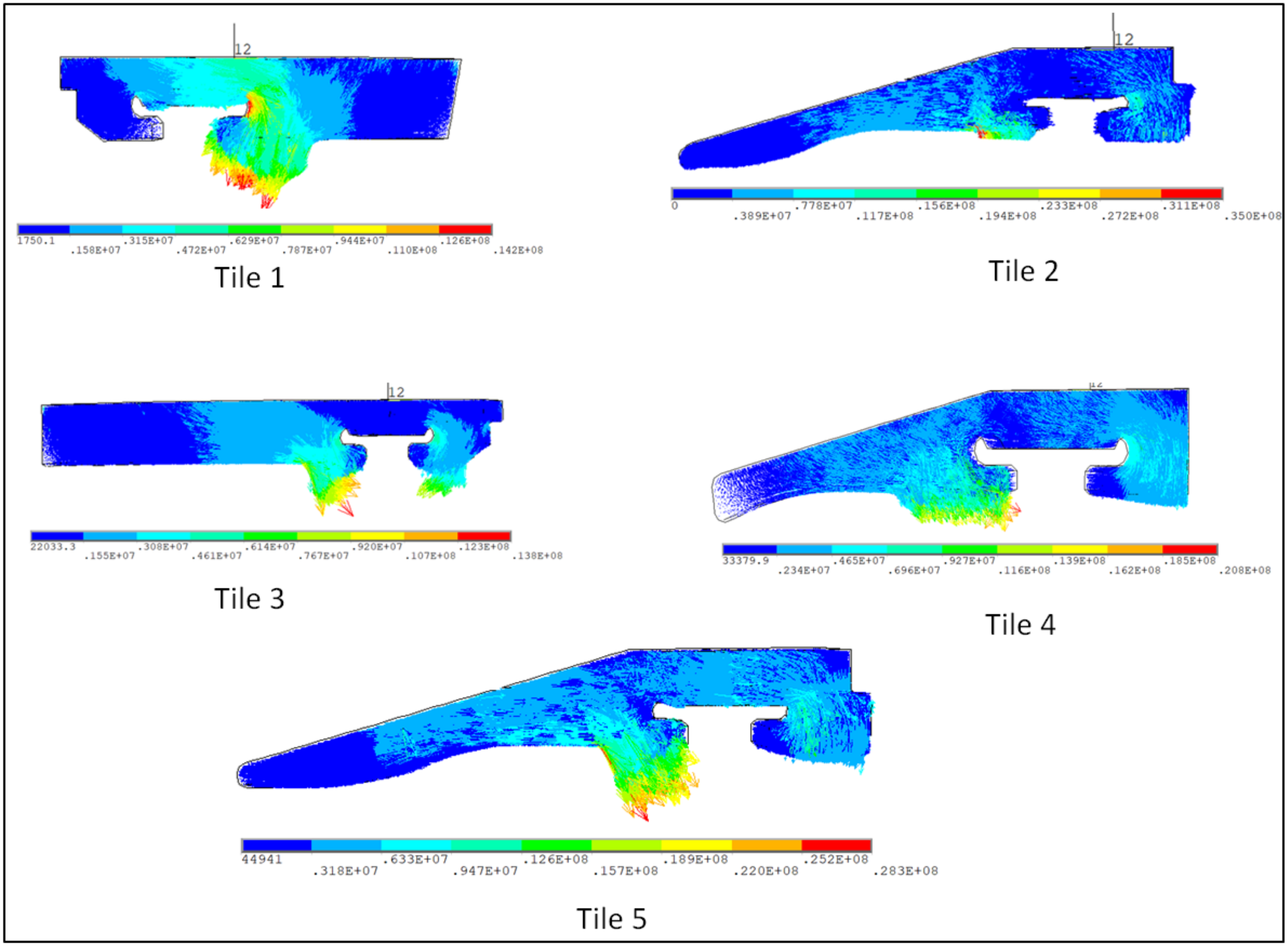

Figure 7: Total Current Density, Tiles 1-5

Magnetic Force [N

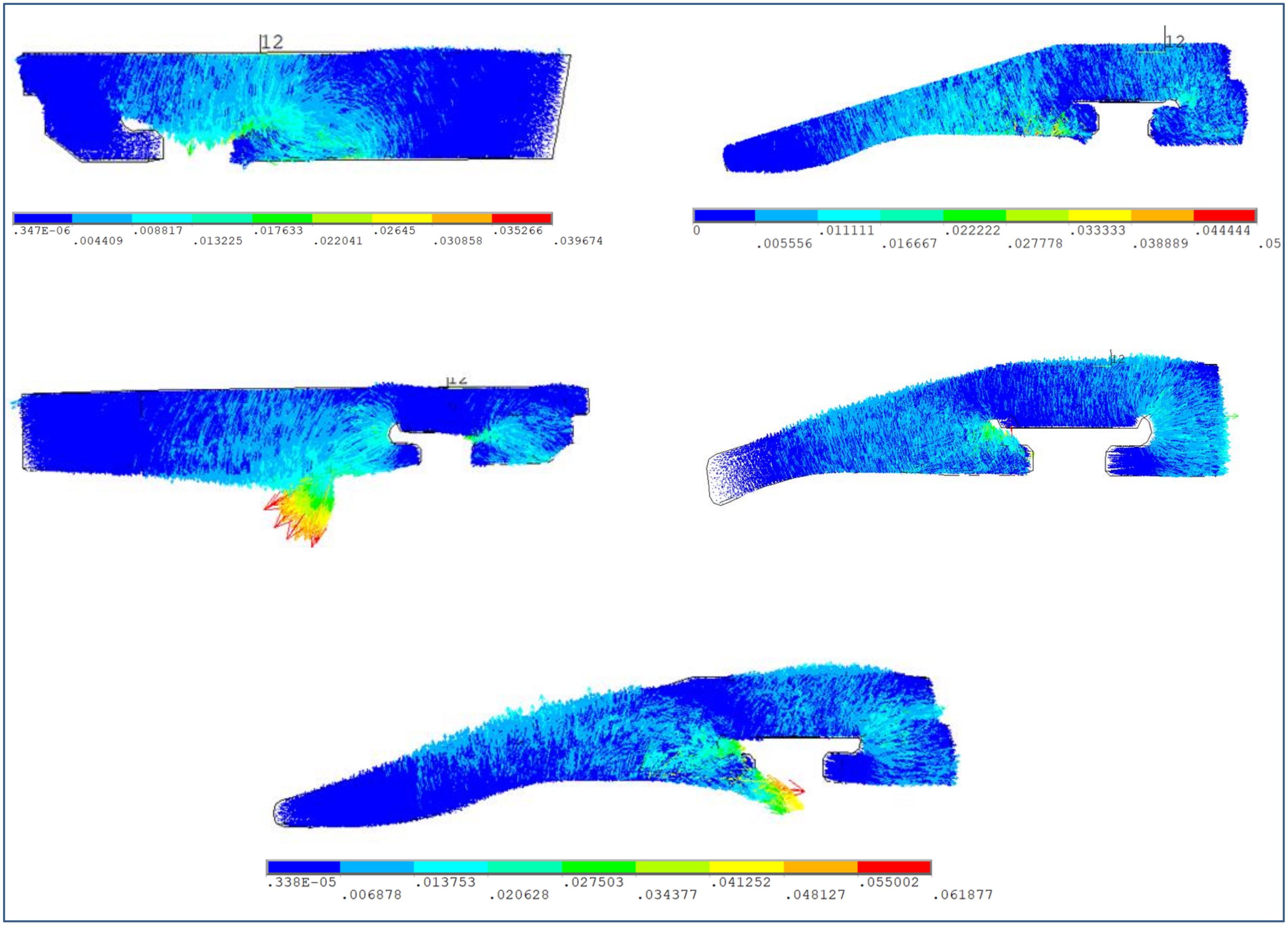

Figure 8 : Magnetic Force, Tiles 1-5

Conclusion

Electromagnetic forces and moments have been determined for OBD row 4 and row 5 tiles. There are no specified load criteria for the tiles. However, the stresses resulting from these loads must be below established allowable stress limits.

The loads calculated thru this analysis may be used as inputs to a structural finite element model to determine the resulting stresses in the tile bodies. The moments can be applied to all surfaces of the tiles. The forces should be imported as body force densities (N/M^3), utilizing the stored nodal data.

Checks for Calculation No: NSTXU-CALC-11-12-00# **Revision No: 0**

Title Electromagnetic Loads Calculation for OBD Tiles Row 4 and Row 5

Component was checked against latest design

Yes

All required load cases are included and current

Yes

Discuss method used in the calculation

Ansys workbench is used to process the CAD models, define interfaces and mesh them. Meshed models are then imported to Ansys classic to run. Halo current is assumed to be uniformly distributed on the tile surface and flow from tile surface to backplate toroidal cross-section resistively. EM and halo load calculation assume uniform B field and linear dBdt from Art Brooks.

Discuss how the calculation was checked (*)

FE model "tile_5" and script to run it are checked and use my own code to verify the current density and load calculation.

List issue identified and how they were resolved

Resistivity of Inconel 625 and Grafoil used in the FE model are far from the numbers I have from my references. This is mentioned in Table 1 and following note. This document concluded that after correcting these resistivity numbers, total halo load will be less than previous calculation so that previous current density plot and load numbers are still kept in document. I disagree with this. In this model when calculating halo load, only tile is selected and summed. Actual halo load should include T-bar. With correct resistivity for T-bar (made of Inconel 625), it will pick most of the current (instead of current flow through Grafoil layer like this document) and contribute to halo load and total load may increase, especially in normal direction, i.e. pull out force to the tile, which may reduce the pressure applied to Grafoil, and result in the reduction of both electrical conduction and thermal conduction of Grafoil layer. I will suggest to correct these resistivity and re-run the model and update the load numbers.

Checker's name: Han Zhang Han Zhang Digitally signed by Han Zhang Date: 2018.09.27 16:03:50 -04'00'

Technical Authority: Peter H. Titus Digitally signed by Peter H. Titus Date: 2018.09.27 16:16:05 -04'00' ____________________(sign and date)

(*) independent calculations can be appended

1. **Minimum Requirements for Checking Calculations**

2. Assure that inputs were correctly selected and incorporated into the design.

3. Calculation considers, as appropriate:

   - Performance Requirements (capacity, rating, system output)
   - Design Conditions (pressure, temperature, voltage, etc.)
   - Load Conditions (Electromagnetic (Lorentz Force), seismic, wind, thermal, dynamic)
   - Environmental Conditions (radiation zone, hazardous material, etc.)
   - Material Requirements
   - Structural Requirements (foundations, pipe supports, etc.)
   - Hydraulic Requirements (NPSH, pressure drops, etc.)
   - Chemistry Requirements
   - Electrical Requirements (power source, volts, raceway, and insulation)
   - Equipment Reliability (FMEA)
   - Failure Effects on Surrounding Equipment
   - Tolerance Buildup

4. Assumptions necessary to perform the design activity are adequately described and reasonable.

5. An appropriate calculation method was used.

6. The results are reasonable compared to the inputs.

7. Error bars (range) for inputs used, results / conclusions, assumptions, have been considered and are acceptable.

8. NOTE: IT IS THE RESPONSIBILITY OF THE CHECKER TO USE METHODS THAT WILL SUBSTANTIATE TO HIS/HER PROFESSIONAL SATISFACTION THAT THE CALCULATION IS CORRECT.

BY SIGNING CALCULATION, CHECKER ACKNOWLEDGES THAT THE CALCULATION HAS BEEN APPROPRIATELY CHECKED AND THAT THE APPLICABLE ITEMS LISTED ABOVE HAVE BEEN INCLUDED AS PART OF THE CHECK.