Calculation No: NSTXU-CALC-11-22-00 # **Revision No: 00 #**

Fish-scale directionality of OBD12

Purpose of Calculation:

Calculation performed is to verify direction and magnitude of fish-scaling features used in the OBD12 design for the NSTX-U PFC Recovery Project.

Codes and versions:
Hand calculations

References (List any source of design information including computer program titles and revision levels.)
NSTX-U-RQMT-SRD-003-01

Assumptions (Identify all assumptions made as part of this calculation.)
Axisymmetric heat fluxes (specified in SRD), 0.004" surface profile tolerance on tiles, 0.010" inter-tile tolerance due to mounting variances (i.e. OBD Cu "slats" corrected with OBD12 transition plates to within 0.010").

Calculation (Calculation is either documented here or attached)
See attached work sheets.

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)
A tile ramping angle of 0.55 degrees with an additional castellation angle of 0.6 degrees will satisfy PFC SRD. The heat flux enhancement factor for cases 1/2/3 are 2.15/1.23/1.26 respectively. Looking from the narrow part of the tile, the highest part of the castellation should be to the right.

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

Robert Ellis Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.27 16:43:09 -04'00'

Preparer's printed name, signature and date

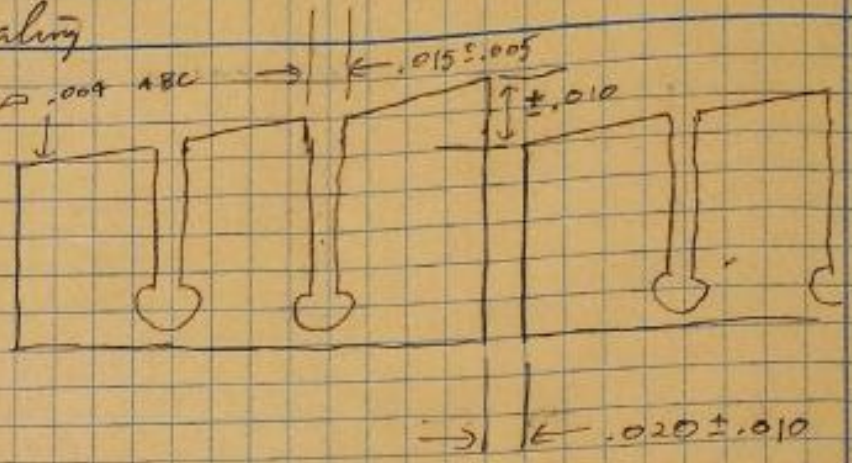
Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.27 16:32:04 -04'00'

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

Checker's printed name, signature, and date

Michael Jaworski Michael Jaworski Digitally signed by Michael Jaworski Date: 2018.09.23 00:45:14 -04'00'

9/6/18 Tile Scaling



Ref. PFC RD
table 4.4-1
&
fig. 2.3-1

Inter-Tile: step height needed to shield leading edge based on 5 degree angle of incidence (case 2) and .003" in erosion

$v = (.020+.010)\tan 5^\circ + 2(.010) + .003 + .004$
$= .039$ in

Ramp over 3 cubes (2.675 in min) $\Rightarrow \tan^{-1}(.030/2.675) = .64^\circ$

Similarly, inter-cube

$v = (.015+.005)\tan 5^\circ + .004 + .003 = .0087$ in (use .009)

Ramp over one cube $(2.675/3)\ \tan^{-1}(.009/.892) = .58^\circ$

note that, because the inter-cube scaling gave us an additional .009" of step between tiles, we can reduce the steepness of the .64° ramp
∴ reduce 7-cube ramp from .030" to .025"
$\Rightarrow .54^\circ$

Use .55° full tile .025"
.60° inter cube .009"

Amplification factor for 5° $F = \frac{\sin(5+.60+.55)}{\sin 5} = 1.23$

Full area is melted

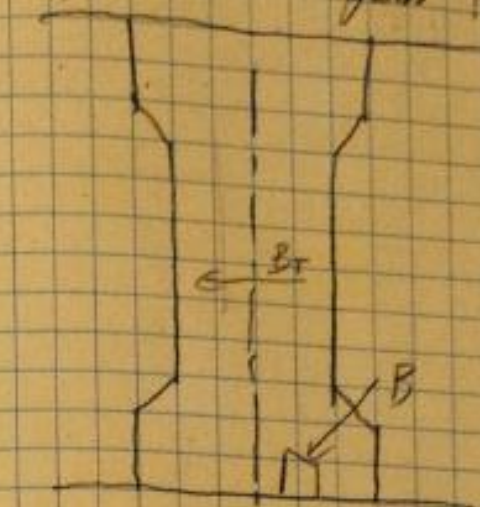
Now, look at 1° incidence (Case 1)

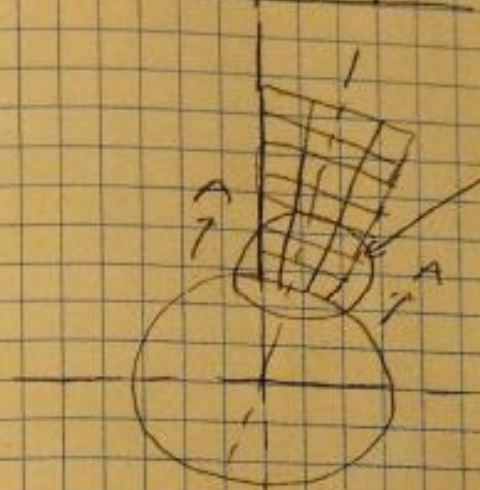
$F = \frac{\sin(1+.60+.55)}{\sin 1^\circ} = 2.15$

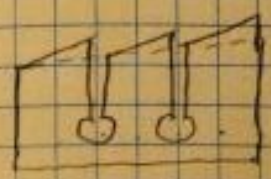
Inter-tile vertical step is $(.025+.009) - .020 - .009 - .003 = .007$
Shaded extent toroidally is $(.007"/\tan 1^\circ) - (.020 \pm .010) = .39/.371$
Inter-cube vertical step is $.009 - .004 - .003 = .002$
Shaded extent is $(.002/\tan 1^\circ) - (.015 \pm .005) = .105/.085$

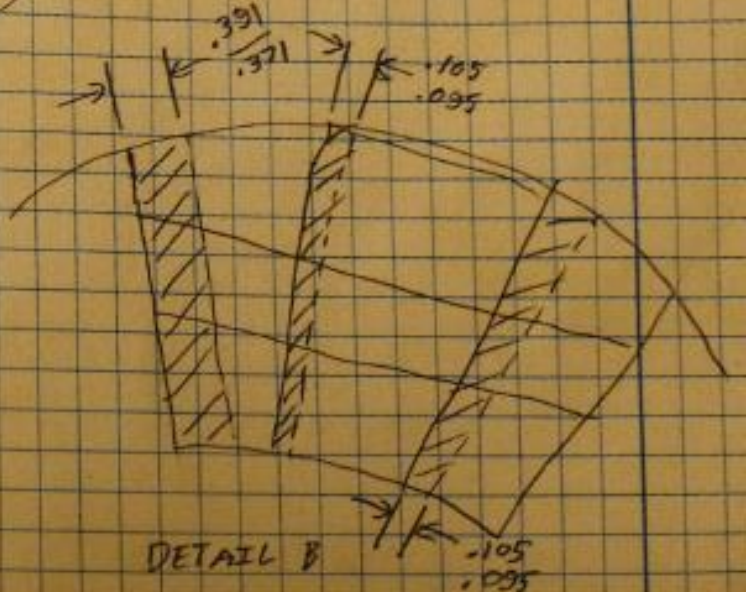
what is the direction of the scaling?
See figure 2.3-1 from PFC RD (IBDH & OBD)

B_T is clockwise when viewed from above






VIEW A-A



Look at case 3 amplification factor

$$F = \frac{\sin(4.4 + .55 + .60)}{\sin(4.4)} = 1.26$$

Case	1	2	3
Range (m)	R<0.7	R<0.7	.70<R<.81
Extent (cm)	13	10	full
Max Angle (deg)	1.0	5.0	4.4
Min Angle (deg)	1.0	5.0	2.6
Heat Flux (MW/m^2)	(5.4)	(5.4)	3.3
Duration (sec)	1.5	5	5

$5.4 * 2.15 = 11.6$

$5.4 * 1.23 = 6.64$

Checks for Calculation No: NSTXU-CALC-11-22-00# Revision No: 00 #

Fish-scale directionality of OBD12

Component was checked against latest design

Latest drawing of tile and assembly is E-ED1408

All required load cases are included and current

Load cases match those of SRD revision 01 (current as of the time of the calculation)

Discuss method used in the calculation

Hand calculations are used to determine the required fish-scale angle over an entire tile plus the additional required step height to protect inter-castellation leading edges. Assumptions are made for the inter-tile alignment tolerance (0.01")

Discuss how the calculation was checked (*)

Calculation is compared against checker's own tile-ramp calculation methodology using the design's tolerance stack-up. The resulting enhancement factors over a range of angles is compared with those of the original calculation.

Directionality of the fish-scaling is made by direct comparison of the drawing with the SRD figures.

See attached sheets for work.

List issue identified and how they were resolved

No issues were identified.

Checker's name: Michael Jaworski

Peter H. Titus Digitally signed by Peter H. Titus
Date: 2018.09.27 16:49:16 -04'00'

Technical Authority:_____(sign and date)

(*) independent calculations can be appended

Fish-scale angle calculation, independent check

Previous studies have developed independent tools for calculating fish-scale angles. The design assumptions and tolerances for OBD12 are summarized in this table:

Key geometric features, Drawing E-ED1408				
Name	Symbol	Value	unit	Drawing sht and quadrant
Castellation gap	g_c	0.03	inch	sht 6, C-10
Cast. Gap tol	dg_c	0.005	inch	sht 6, C-10
Tile gap	g_t	0.02	inch	Calc. assump.
tile gap tol.	dg_t	0.01	inch	Calc. assump.
Grafoil height	h_g	0.063	inch	sht 5, B-10
grafoil height tol	dh_g	0.002	inch	see text
Base plate height	h_b	0	inch	Calc. assump.
base plate tol	dh_b	0.01	inch	Calc. assump.
Tile height (typ)	h_1	1.966	inch	sht 3, F-14
tile height tol	dh_1	0.004	inch	sht 6, C-12
Surface profile tol	ds	0.004	inch	sht 6, C-12
Erosion "tolerance"	d_e	0.003	inch	SRD
Tile length (OBD12)	L_2	3.357	inch	sht 6, D-14
N_CAST GAPS L2	N_2	2		sht 6, D-14

An assembly is not available for checking at this time so the tile-gap, inter-tile tolerance for this gap, and achieved base-plate tolerances are taken from the calculation. The grafoil thickness tolerance is taken from the "GRAFOIL Flexible Graphite Engineering Design Manual, 2nd Edition" (Edited by M. Pollock, GRAFTECH, Cleveland, OH, 2002). The erosion tolerance is specified in the SRD. All other features can be references directly to E-ED1408. The table shows the sheet and quadrant where each dimension can be found.

The minimum castellation step to guarantee no leading edges:

$$h_{c,req} = (g_c + dg_c)\tan(\alpha) + d_e + d_s$$

Where alpha is the maximum design angle in table 4.4-1 of the NSTX-U-RQMT-SRD-003-01 document (5 degrees for OBD12).

The minimum step-height between tiles to guarantee no leading edges is:

$$h_t = (g_t + dg_t)\tan(\alpha) + d_e + 2 \times (\frac{dh_1}{2} + dh_g + ds + dh_b)$$

This assumes no shims are used to correct out surface profile errors in the mounting surface.

The ramp-height over a single castellation that results is calculated as follows:

$$h_r = \frac{h_t + Nh_{c,req}}{N+1}$$

An individual castellation length can be calculated as:

$$L = \frac{L_2 - Ng\_c}{N+1}$$

The effective angle of the PFC surface is thus found:

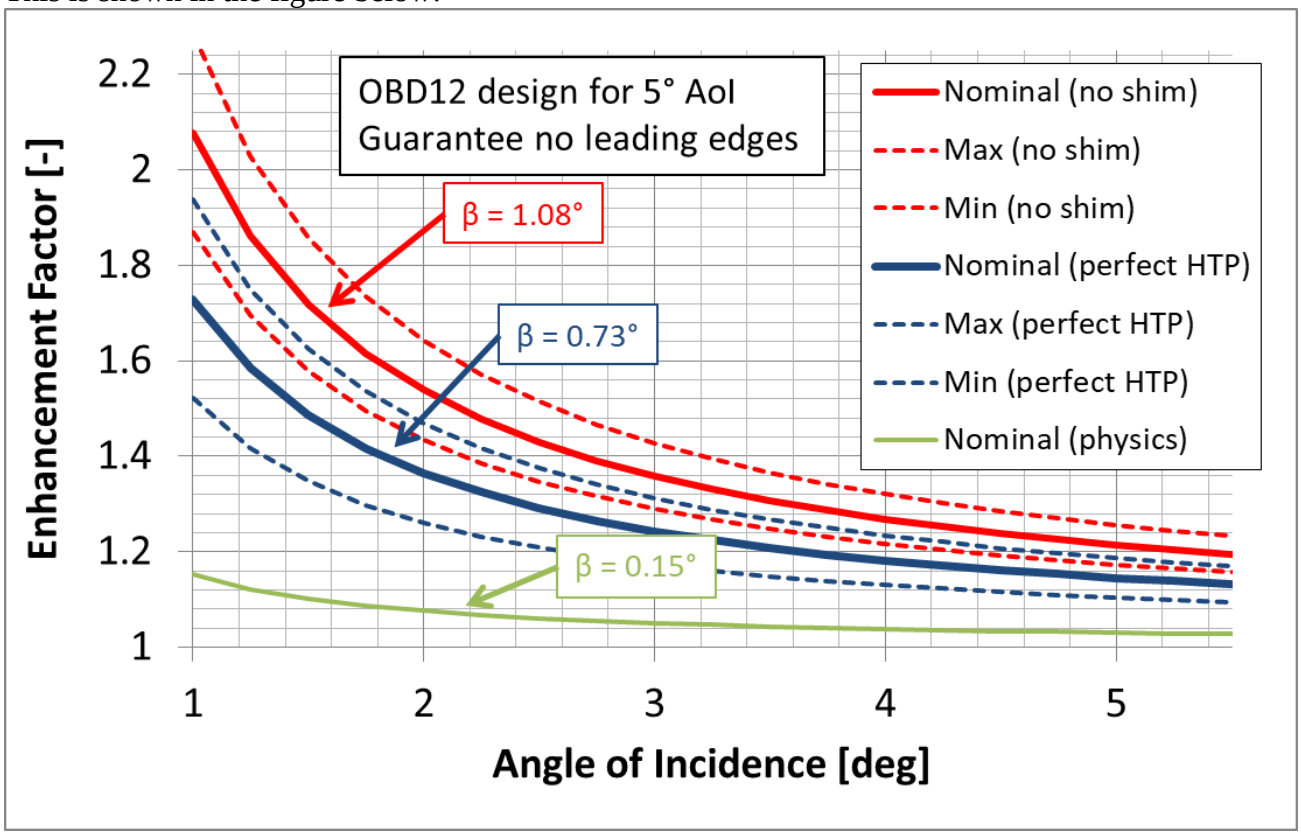
$$\beta = \arctan(\frac{h_r}{L})$$

For the set of values in the table above, the following is found:
$h_{c,req}$ = 0.01”
h_t = 0.042”
h_r = 0.021”
L = 1.099”
β = 1.08°

The heat flux enhancement factor as a function of the incidence angle is calculated:

$$f_{enh} = \frac{\sin(\alpha + \beta)}{\sin(\alpha)}$$

This is shown in the figure below:



The figure indicates heat flux enhancement factors of 2.08 at 1 degree and 1.21 at 5 degrees. The original calculation shows enhancement factors of 2.15 and 1.23. These values are substantially similar to the independent calculation carried out here, differing only by 3.4% or 1.7% respectively, and in a direction so as to result in a conservative result.

The results of this calculation for heat flux enhancement including the expected tolerance stack-up are deemed appropriate.

Check on direction of fish-scale

The direction of the fish-scales are checked by direct comparison with the SRD description in figure 2.3-1:

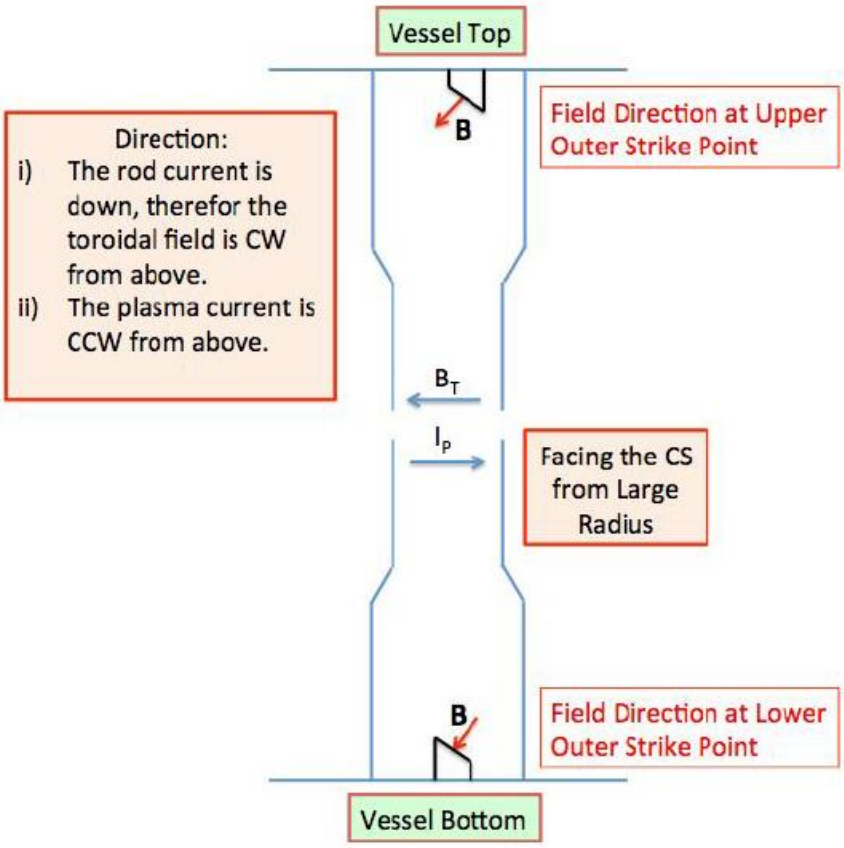
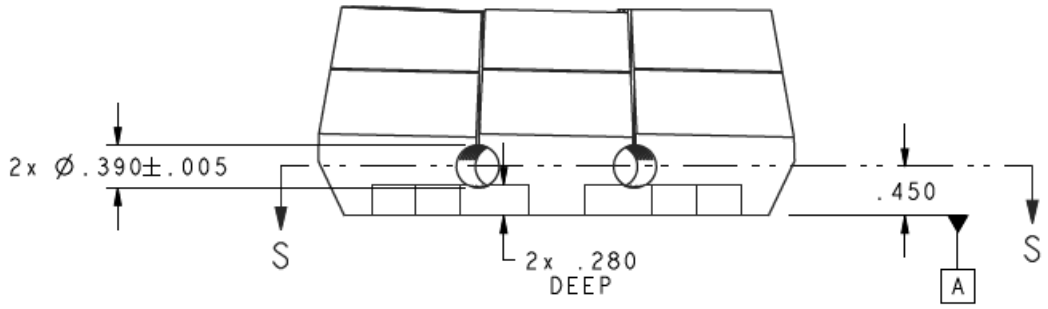


***Fig: 2.3-1**: Field line direction on the horizontal target for "Standard Helicity"*

NSTX-U-RQMT-SRD-003-01

Drawing E-ED1408 conveniently includes a projection of the tile looking inward on sheet 6, quadrant D-3.



The direction of the fish-scales matches what is shown in figure 2.3-1 of the SRD.

This part of the calculation is deemed appropriate.

Minimum Requirements for Checking Calculations

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

2. 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

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

4. An appropriate calculation method was used.

5. The results are reasonable compared to the inputs.

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

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.