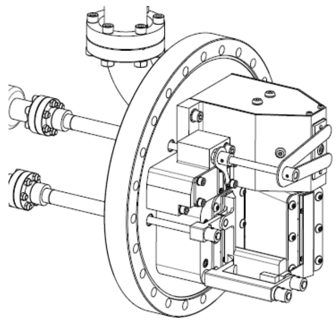
Resistive Bolometer/AXUV Diode Shutter Bowing

NSTXU CALC-40-03-00

Date November 23 2016



Prepared by R. Ellis	Reviewed by P. Titus
Robert Ellis Digitally signed by Robert Ellis DN: cn=Robert Ellis, o=Princeton Plasma Physics Laboratory, ou=Mechanical Engineering Division, email=rellis@pppl.gov, c=US Date: 2016.11.28 09:53:01 -05'00'	Peter H. Titus Digitally signed by Peter H. Titus DN: cn=Peter H. Titus, o, ou=Princeton Plasma Physics Laboratory, email=ptitus@pppl.gov, c=US Date: 2016.11.28 09:41:51 -05'00'

PPPL Calculation Form

Calculation # **NSTXU-CALC-40-03-00** Revision # **00** ____ WP #, **1672** (ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

The purpose of this calculation is to evaluate shutter deformations when exposed to radiative heating from the plasma for a full 5 second pulse

References

These are included in the body of the calculation, in section 6.2

Assumptions (Identify all assumptions made as part of this calculation.)

Adiabatic back side, no radiation except from the plasma

Calculation (Calculation is either documented here or attached)

These are included in the body of the following document

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

Deformations are small (.007 inches) and there is no danger that the shutter will close the .1 inch clearance to the pin hole.

Cognizant Engineer's printed name, signature, and date

Matthew L. Reinke Digitally signed by Matthew L. Reinke
Date: 2016.11.29 18:50:02 -05'00'

Matthew Reinke

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

Checker's printed name, signature, and date

Peter H. Titus Digitally signed by Peter H. Titus
DN: cn=Peter H. Titus, o, ou=Princeton Plasma Physics Laboratory, email=ptitus@pppl.gov, c=US
Date: 2016.11.28 09:42:16 -05'00'

Peter Titus

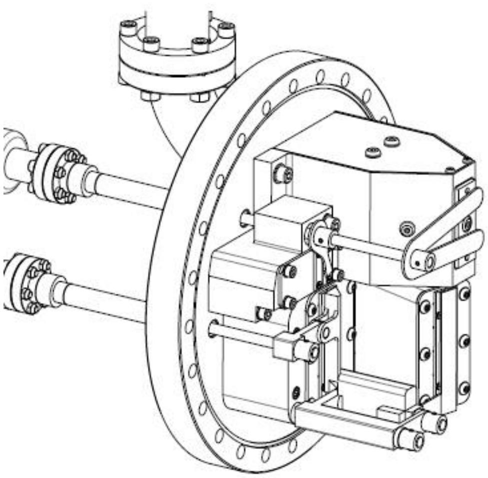
2.0 Table of Contents

3.0 Revision Status Table

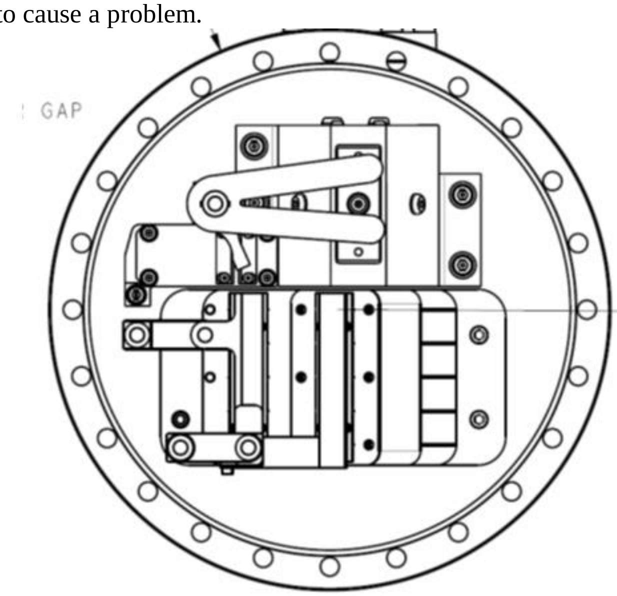
Rev 0	Initial Issue

4.0 Executive Summary

There is a “vee” shaped shutter on the Bay G Resistive Bolometer and AXUV Diodes that might deform due to a thermal gradient between the plasma facing side and the back side. This could contact the pin hole and might produce arcing during a disruption, or not operate properly due to closing the .1 inch clearance between the shutter and pin hole. Hand calculations and FEA checkers calculations produced a .007 inch displacement of the shutter fingers – not enough to cause a problem.



ISOMETRIC VIEW



5.0 Digital Coil Protection System.

There is no input to the DCPS planned for diagnostics

6.0 Design Input

6.1 Criteria

Operation of the shutter shall not be impaired by thermal gradients developing in the shutter during normal operation. The shutter temperature must remain below a reasonable temperature – this was checked against criteria in [2]

6.2 References

[1] NSTX-U Design Point Spreadsheet, **NSTXU-CALC-10-03-00** C. Neumeyer, http://w3.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[2] ' Analysis of Diagnostic and Diagnostic Shutter " NSTXU-CALC-40-01-00 Rev 0 July 2011 Prepared By: Joseph Boales (Drexel Co-op Student, Signed by P. Titus for J. Boales

[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz

[4] ITER material properties handbook, ITER document No. G 74 MA 15, file code: ITER-AK02-22401.

[5] Final Design Review of Bay-G Resistive Bolometers and AXUV Diodes Res. Bolometry FDR B-252 (PPPL) 11/10/2016, M.L. Reinke (ORNL)

[6] Global Thermal Analysis of Center Stack Heat Balance,NSTXU-CALC-11-01-00 A. Brooks June 1, 2011

[7] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 6, P. Titus, August 3 2015, Original issue by C. Neumeyer, March 30, 2009

6.3 Photos and Drawing Excerpts

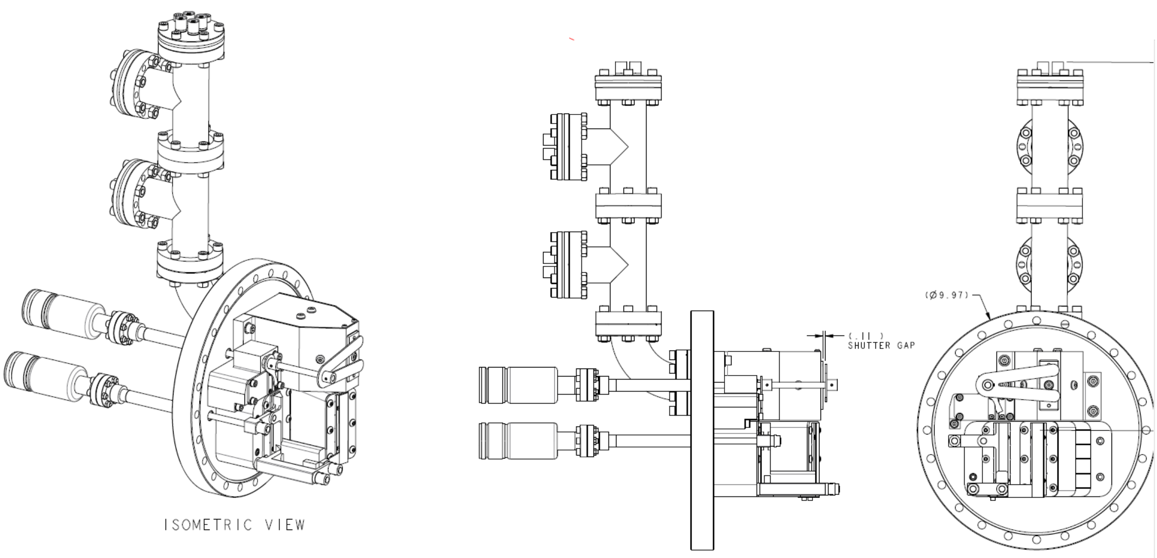


Figure 6.3-1 Divertor Flange Details

6.4 Material properties

```
mptemp,1,0.,227.,477.,727.,977.,1227.
mptemp,7,1977.,3227.
!Steel
*do,imat,10,100,1
mpdata,kxx,imat,,15.48,15.48,15.48,15.48,15.48      ! Thermal Conductivity
mpdata,rsvx,imat,,7.7e-7,7.7e-7,7.7e-7,7.7e-7,7.7e-7
mpdata,c, imat ,, 513 , 513 , 513 , 513 , 513
mpdata,dens,imat,,7900,7900,7900,7900,7900,7900
*enddo
```

```
*do,imat,1,100
ex,imat,200e9              ! Youngs Modulus
alpx,imat,16e-6            ! Alpha or COE
dens,imat,7500             ! Density
*enddo
```

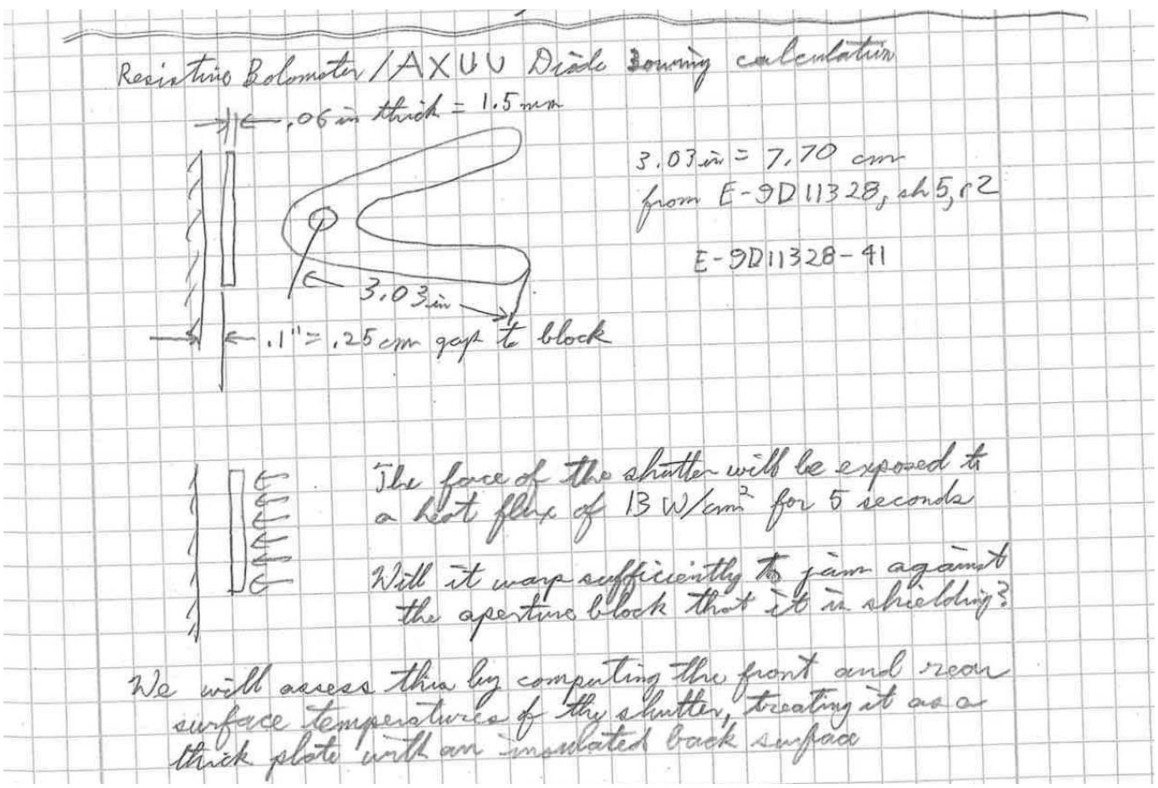
6.5 Heat Sources

Heat balance based on the GRD assuming full auxiliary heating for 5 seconds with 30 %of the power going to the divertor and the rest radiating from the plasma surface, produces .13MW/m^2 [2] to .14 MW/m^2 . This is worse than the actual due to shielding of the Bay-G flange from the plasma by the neutral beam dump.

6.6 Design Currents and Lorentz Forces

Disruptions can develop eddy currents in the shutter. These are qualified in [2]

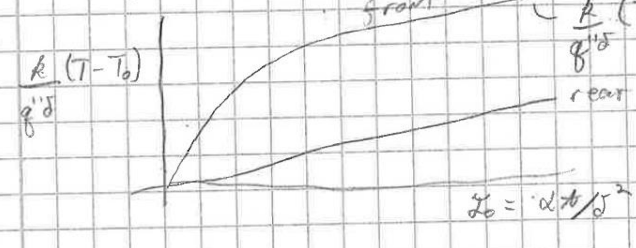
7.0 Hand Calculations



Let us calculate the thermal diffusivity

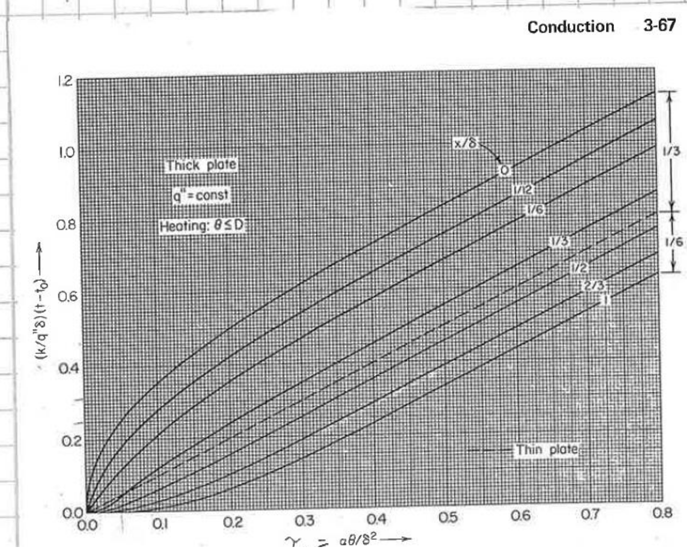
$$\alpha = \frac{k}{\rho C_p} = \frac{.16\ W/cm\,K}{8.03\,g/cm^3\,(.5\ J/g\,K)} = .040\ cm^2/s$$

Rohsenow & Hartnett give us the transient response of a thick plate with insulated rear surface and front surface exposed to heat flux q''



Compute the Fourier number for $t = 5$ sec, $\delta = .15$ cm

$$\tau_0 = \frac{\alpha t}{\delta^2} = \frac{.040\ cm^2/s\ (5\,s)}{(.15\ cm)^2} = 8.9$$



We are clearly in the linear part of the curve

$$T_f = \frac{q''\delta}{k}(\tau_0 + 1/3)$$

$$= \frac{13(.15)(8.9 + 1/3)}{.16}$$

$$= 112.5\ K$$

$$T_r = \frac{q''\delta}{k}(\tau_0 - 1/6)$$

$$= 106.4\ K$$

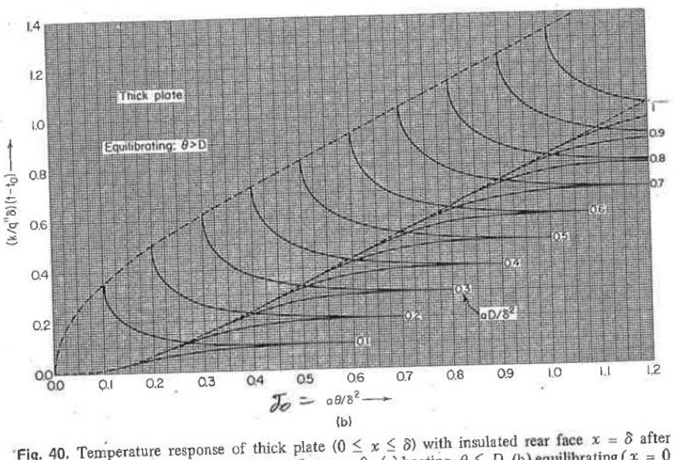


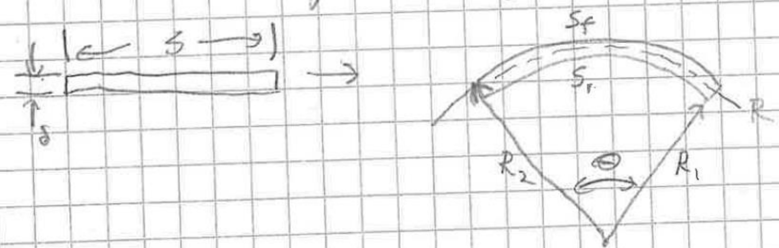
Fig. 40. Temperature response of thick plate ($0 \le x \le \delta$) with insulated rear face $x = \delta$ after sudden exposure to constant heat input q'' at $x = 0$: (a) heating, $\theta \le D$, (b) equilibrating ($x = 0$ insulated), $\theta > D$.

Consider equilibration: find t such that $\mathcal{T}_o = 0.5$

$$\frac{\alpha t}{\delta^2} = \frac{.040\,t}{.15^2} = .5$$

$t = .28$ sec

What is the radius of curvature of the shutter blade?



$S_f - S = \alpha_{TE}\, S\, T_f$

$S_r - S = \alpha_{TE}\, S\, T_r$

here α_{TE} is the coefficient of thermal expansion. T_f and T_r represent $T_f - T_o$ and $T_r - T_o$

$S_f - S_r = \alpha_{TE}\, S\,(T_f - T_r)$

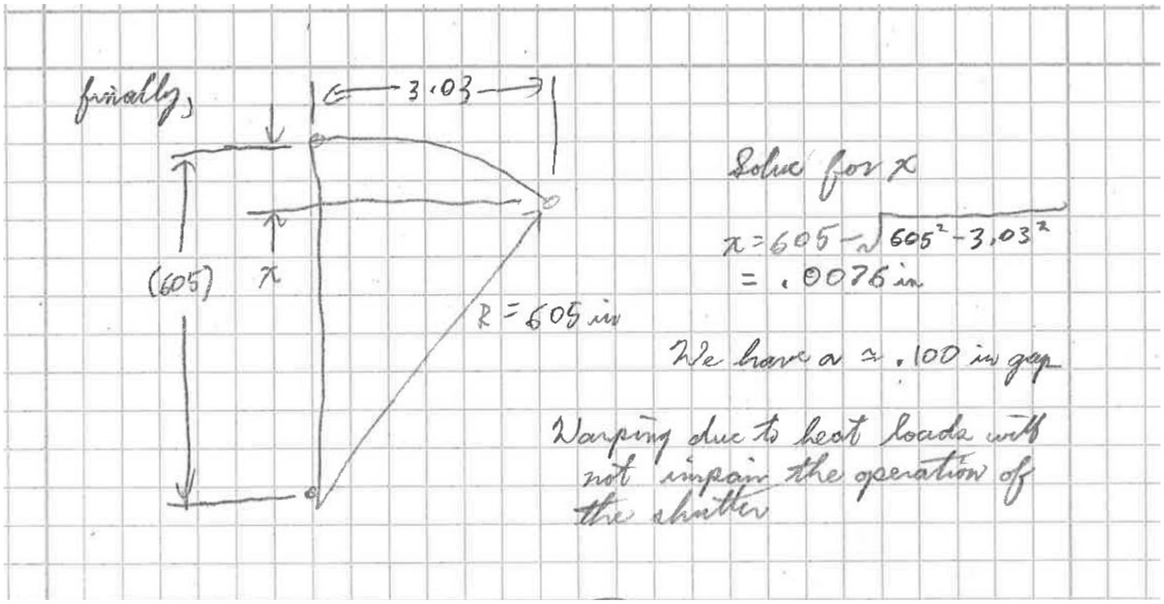
also, let $S = R\Theta$, $S_f = R_2\Theta$, $S_r = R_1\Theta$

$S_f - S_r = \alpha_{TE} R\Theta\,(T_f - T_r)$

$S_f - S_r = R_2\Theta - R_1\Theta = (R_2 - R_1)\Theta = \delta\Theta$ $\Rightarrow$ $R = \dfrac{\delta}{\alpha_{TE}(T_f - T_r)}$

for 316 SS, $\alpha_{TE} = 1.6 \times 10^{-5}$/K (Matweb)

$$R = \frac{.15\text{ cm}}{(1.6\times10^{-5}/K)(6.1\,K)} = 1540\text{ cm} = 605\text{ in}$$



8.0 Checkers Calculation

In this treatment of the problem a finite element solution is used. First a transient thermal analysis is performed applying the surface heat from the plasma. Second a structural pass is applied reading the thermal results file for each load step. For simplicity, all other surfaces do not have radiation connection to the vessel surfaces modeled. The issue is that a fast transient surface heat flux could produce a through thickness temperature gradient that could in turn cause warping of the shutter. This could happen only within the timing of a pulse and for most of the length the finger. The issue is not thermal ratcheting. This has been qualified by [2] and figure 8.0-2. Mainly for numerical stability the hub of the shutter is held at 300C, but the mass of rod will provide thermal inertia making the modeling physical.

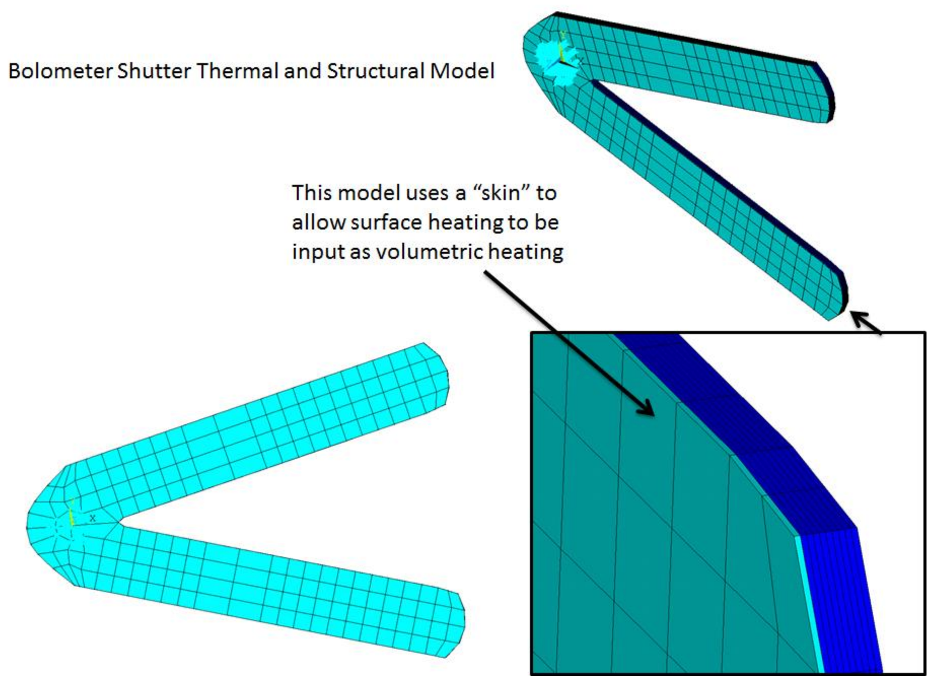


Figure 8.0-1 FEA model Used for Both the Thermal And Structural Pass

The model is meshed outside of ANSYS, and in the scripts in Appendix A and B the mesh is contained in bol2.mod

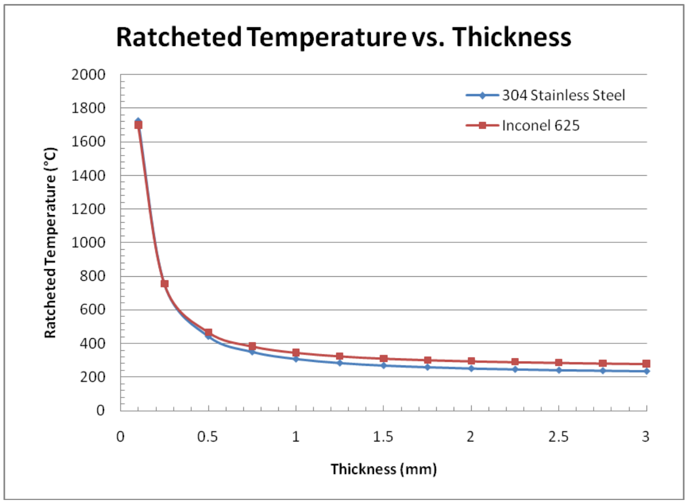


Figure 8.0-2 Ratcheted Temperature of Shutters vs. Thickness from [2]

From [2] A ratcheting analysis of the shutters was done for each shutter type. In this analysis, the shutters are subjected to a heat flux of 0.13 MW/m2 for fifteen five-second pulses with a cool-down time of fifteen minutes between pulses.

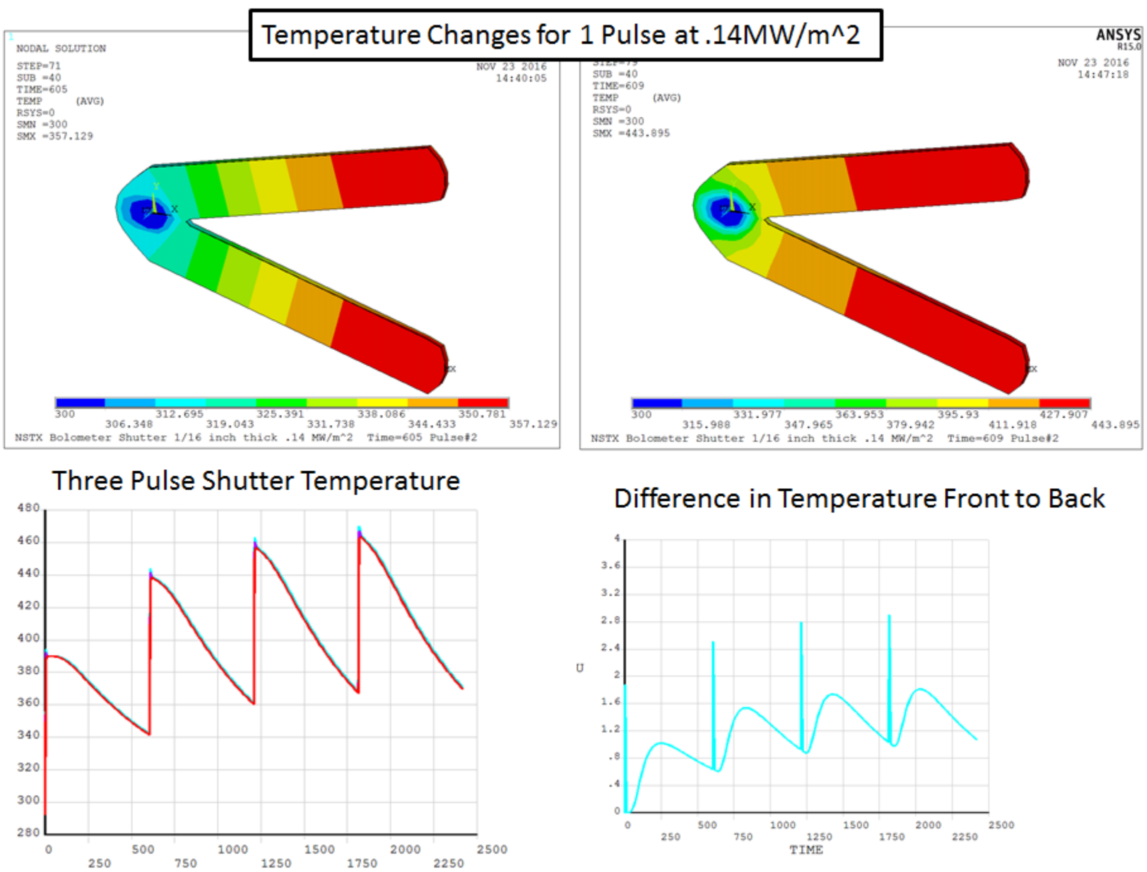


Figure 8.0-3 results of the Thermal Analysis

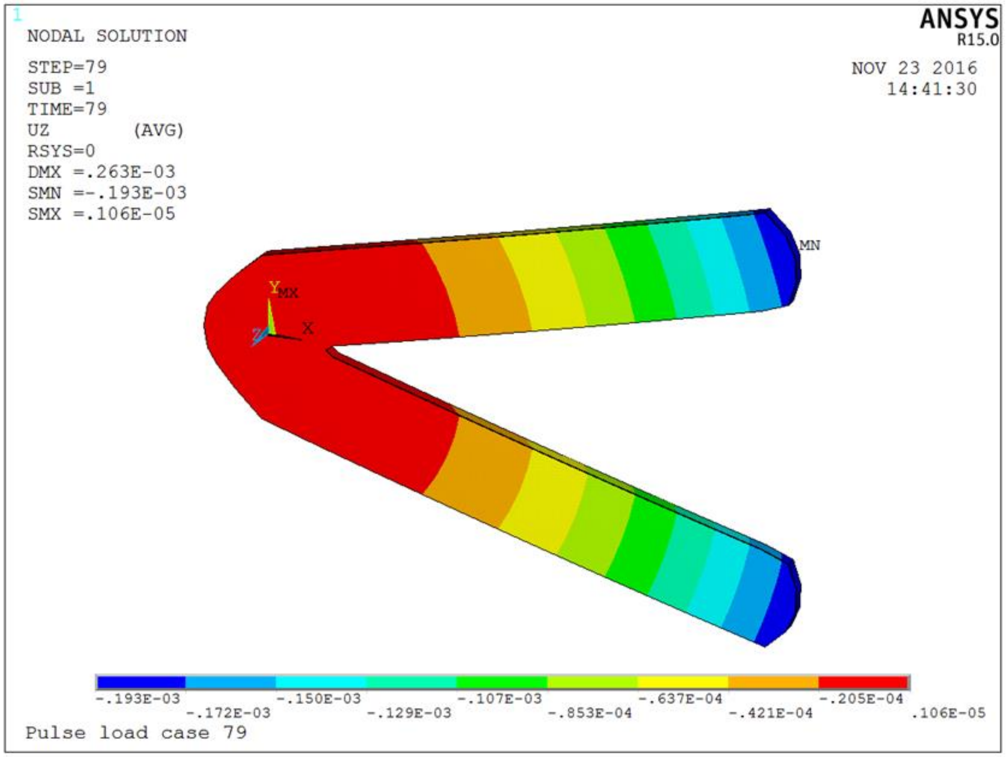


Figure 8.0-4 Results of the Structural Pass with Temperature Gradients from the Thermal Analysis

Appendix A
Thermal Analysis

```
/batch
/filnam,therm
/prep7
antype,trans

emis=.4
stef=5.668e-8
skin=.00625/39.37
SurfHeatFlux=.14e6
!SurfHeatFlux=14.e6
numpulses=4
pulsetime=5              !5 seconds
deltatpulse=pulsetime/10.0
deltatcool=10
ttime=0
cooldown=10*60            !10 Minute Cooldown

et,1,70
et,2,33
et,3,31
mptemp,1,0.,227.,477.,727.,977.,1227.
mptemp,7,1977.,3227.
!Thermal Properties for ATJ Graphite


!Steel
*do,imat,10,100,1
mpdata,kxx,imat,,15.48,15.48,15.48,15.48,15.48
mpdata,rsvx,imat,,7.7e-7,7.7e-7,7.7e-7,7.7e-7,7.7e-7
mpdata,c, imat ,, 513 , 513 , 513 , 513 , 513
mpdata,dens,imat,,7900,7900,7900,7900,7900,7900
*enddo


shpp,off
/input,bol2,mod

!cpdele,all,all
!cpcyc,temp,.0001,5,0,40,0

TREF,292.0
tunif,292
esel,mat,40  $nelem

d,all,temp,300
nall
eall
save
fini
/solu
solcontrol,on
antype,trans
neqit,50
nropt,full,,off
!lnsrch,on
nsubst,40,40,40

/title, NSTX Bolometer Shutter 1/16 inch thick .14 MW/m^2
time,.0001
```

```
ttime=time
solve
save

*do,ipulse,1,numpulses,1

*do,itime,1,9,1
/title, NSTX Bolometer Shutter 1/16 inch thick .14 MW/m^2  Time=%ttime% Pulse#%ipulse%
ttime=ttime+deltatpulse
time,ttime
sheat=SurfHeatFlux/skin
esel,mat,12
nelem
bfe,all,hgen,1,sheat
eall
nall
solve
save
*enddo

*do,itime,1,cooldown/deltatcool,1
/title, NSTX Bolometer Shutter 1/16 inch thick .14 MW/m^2 Time=%ttime% Pulse#%ipulse%
ttime=ttime+deltatcool
time,ttime
esel,mat,12
nelem
sheat=.00001
bfe,all,hgen,1,sheat
eall
nall
solve
save
*enddo

*enddo

*do,itime,1,9,1
/title, NSTX Bolometer Shutter 1/16 inch thick .14 MW/m^2 Time=%ttime% Pulse#%ipulse%
ttime=ttime+deltatpulse
nelem
eall
nall
solve
save
*enddo
/exit
```

Appendix B
Structural Analysis

```
/batch
/prep7
runn=1
et,1,45
*do,imat,1,100
ex,imat,200e9
alpx,imat,16e-6
dens,imat,7500
*enddo
runn=1

/input,bol2,mod
```

```
esel,mat,40
nelem
d,all,all,0.0
nall
eall
tref,273
mnum,1
/num,1
save
fini
!/exit

/solu
*do,ld,1,277,1
/title, Pulse load case %ld%
eall
nall
ldread,temp,ld,,,,therm,rth
solve
save
*enddo

/title, End of Day Thermal
ldread,temp,last,,,,therm,rth
solve
save
fini
/exit
```