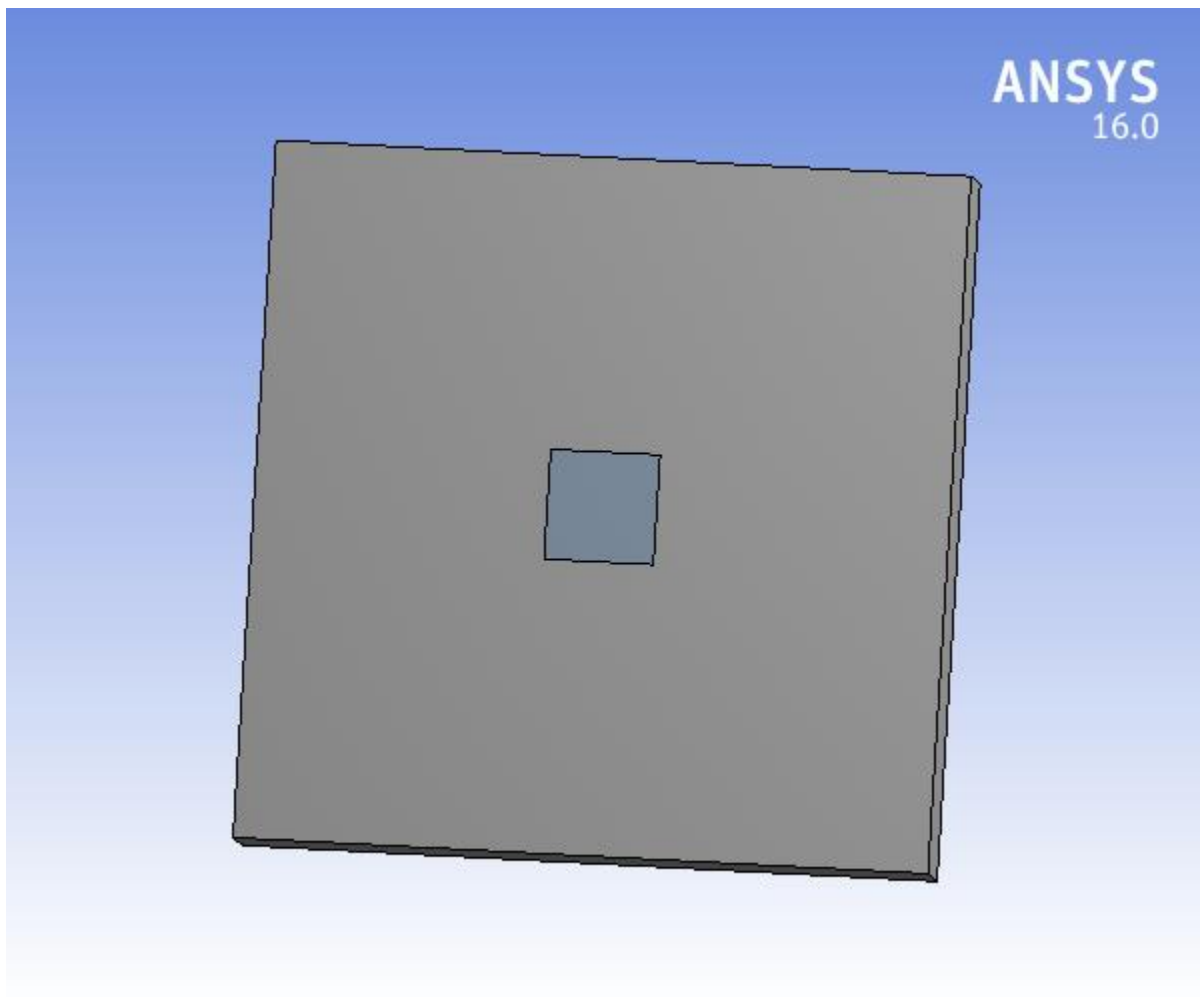




TGT-CALC-16-006

Author	Dave Meekins
Subject	Titanium foil target thermal analysis
First Saved	Friday, July 8, 2016
Last Saved	Monday, July 18, 2016
Product Version	16.0 Release
Save Project Before Solution	No
Save Project After Solution	No



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Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Kelvin
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Kelvin

Comment
Dave Meekins

Thermal analysis of Ti foil target for E12-14-012. The foil is assumed to be 1.5 mm thick with 100 microA of beam at 11 GeV. Energy loss in target is calculated in TGT-CALC-16-001. The heat flux is 2.3×10^9 W/m³. The target edges are assumed to be cooled to 150K. Titanium properties are from MPDB.

Model (B4)

Geometry

TABLE 2
Model (B4) > Geometry

Object Name	Geometry
-------------	----------

State	Fully Defined
Definition	
Source	D:\Meekins\GoogleDrive\JLAB\E12-14-012\ANSYS\Ti-assy.iam
Type	Inventor
Length Unit	Centimeters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	1.27e-002 m
Length Y	1.27e-002 m
Length Z	1.5e-003 m
Properties	
Volume	2.4194e-007 m ³
Mass	1.0887e-003 kg
Scale Factor Value	1.
Statistics	
Bodies	2
Active Bodies	2
Nodes	69769
Elements	14928
Mesh Metric	None
Basic Geometry Options	
Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	No
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\David\AppData\Local\Temp
Analysis Type	3-D
Mixed Import Resolution	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (B4) > Geometry > Parts

Object Name	Ti-foil:1	Ti-foil-beam:1
State	Meshed	
Graphics Properties		

Visible	Yes	
Transparency	1	
	Definition	
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default Coordinate System	
Reference Temperature	By Environment	
	Material	
Assignment	Titanium	
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
	Bounding Box	
Length X	1.27e-002 m	2.e-003 m
Length Y	1.27e-002 m	2.e-003 m
Length Z	1.5e-003 m	
	Properties	
Volume	2.3594e-007 m³	6.e-009 m³
Mass	1.0617e-003 kg	2.6999e-005 kg
Centroid X	-2.742e-003 m	
Centroid Y	-5.1117e-003 m	
Centroid Z	3.5997e-020 m	3.7646e-020 m
Moment of Inertia Ip1	1.4823e-008 kg·m²	1.4062e-011 kg·m²
Moment of Inertia Ip2	1.4823e-008 kg·m²	1.4062e-011 kg·m²
Moment of Inertia Ip3	2.9247e-008 kg·m²	1.7999e-011 kg·m²
	Statistics	
Nodes	67708	2061
Elements	14544	384
Mesh Metric	None	

Coordinate Systems

TABLE 4
Model (B4) > Coordinate Systems > Coordinate System

Object Name	<i>Global Coordinate System</i>
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. m
Origin Y	0. m
Origin Z	0. m
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Connections

TABLE 5
Model (B4) > Connections

Object Name	<i>Connections</i>
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 6
Model (B4) > Connections > Contacts

Object Name	<i>Contacts</i>
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	4.5058e-005 m
Use Range	No
Face/Face	Yes
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
Statistics	
Connections	1
Active Connections	1

TABLE 7
Model (B4) > Connections > Contacts > Contact Regions

Object Name	<i>Contact Region</i>
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Contact	4 Faces
Target	4 Faces
Contact Bodies	Ti-foil:1
Target Bodies	Ti-foil-beam:1
Definition	
Type	Bonded
Scope Mode	Automatic
Behavior	Program Controlled
Trim Contact	Program Controlled
Trim Tolerance	4.5058e-005 m

Suppressed	No
Advanced	
Formulation	Program Controlled
Detection Method	Program Controlled
Elastic Slip Tolerance	Program Controlled
Thermal Conductance	Program Controlled
Pinball Region	Program Controlled
Geometric Modification	
Contact Geometry Correction	None
Target Geometry Correction	None

Mesh

TABLE 8
Model (B4) > Mesh

Object Name	<i>Mesh</i>
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	1.5e-003 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No

Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	69769
Elements	14928
Mesh Metric	None

Steady-State Thermal (B5)

TABLE 9
Model (B4) > Analysis

Object Name	<i>Steady-State Thermal (B5)</i>
State	Solved
Definition	
Physics Type	Thermal
Analysis Type	Steady-State
Solver Target	Mechanical APDL
Options	
Generate Input Only	No

TABLE 10
Model (B4) > Steady-State Thermal (B5) > Initial Condition

Object Name	<i>Initial Temperature</i>
State	Fully Defined
Definition	
Initial Temperature	Uniform Temperature
Initial Temperature Value	130. K

TABLE 11
Model (B4) > Steady-State Thermal (B5) > Analysis Settings

Object Name	<i>Analysis Settings</i>
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Solver Pivot Checking	Program Controlled
Radiosity Controls	

Radiosity Solver	Program Controlled
Flux Convergence	1.e-004
Maximum Iteration	1000.
Solver Tolerance	0.1 W/m ²
Over Relaxation	0.1
Hemicube Resolution	10.
Nonlinear Controls	
Heat Convergence	Program Controlled
Temperature Convergence	Program Controlled
Line Search	Program Controlled
Output Controls	
Calculate Thermal Flux	Yes
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	D:\Meekins\GoogleDrive\ANSYS\E12-14-012_files\dp0\SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

TABLE 12
Model (B4) > Steady-State Thermal (B5) > Loads

Object Name	Temperature	Internal Heat Generation
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	4 Faces	1 Body
Definition		
Type	Temperature	Internal Heat Generation
Magnitude	150. K (ramped)	2.3e+009 W/m³ (ramped)
Suppressed	No	

FIGURE 1
Model (B4) > Steady-State Thermal (B5) > Temperature

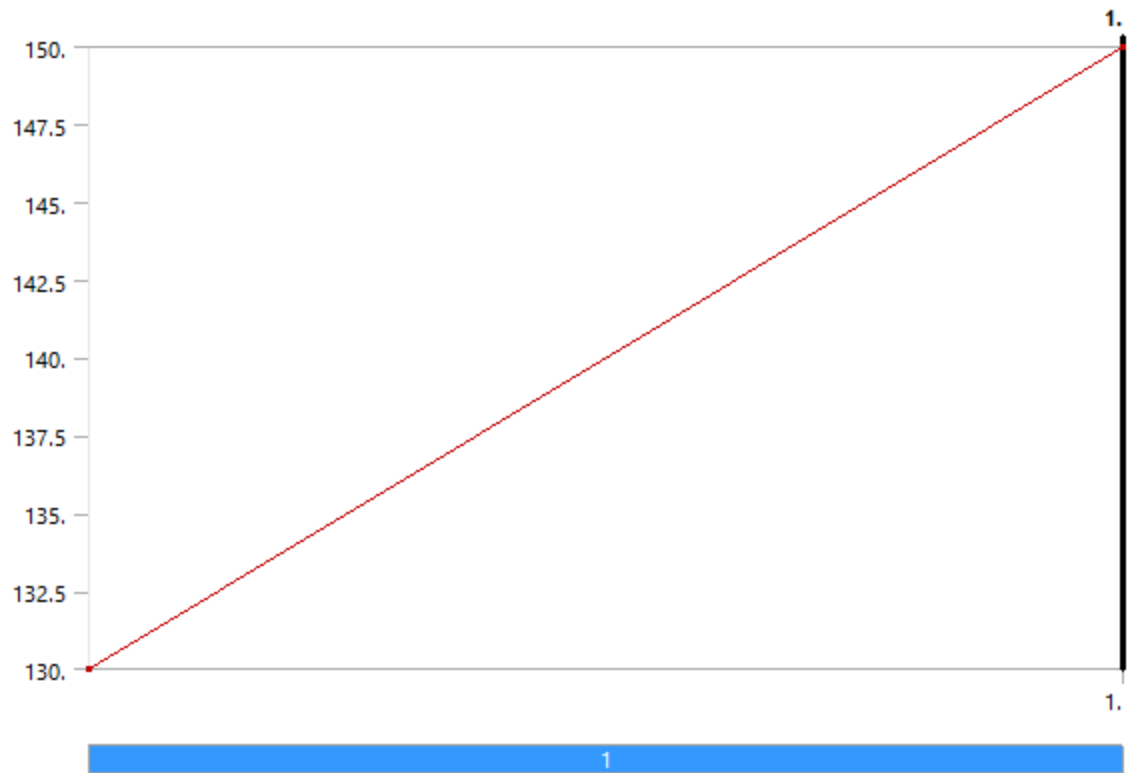


FIGURE 2
Model (B4) > Steady-State Thermal (B5) > Temperature > Figure
Edges maintainted at 150K

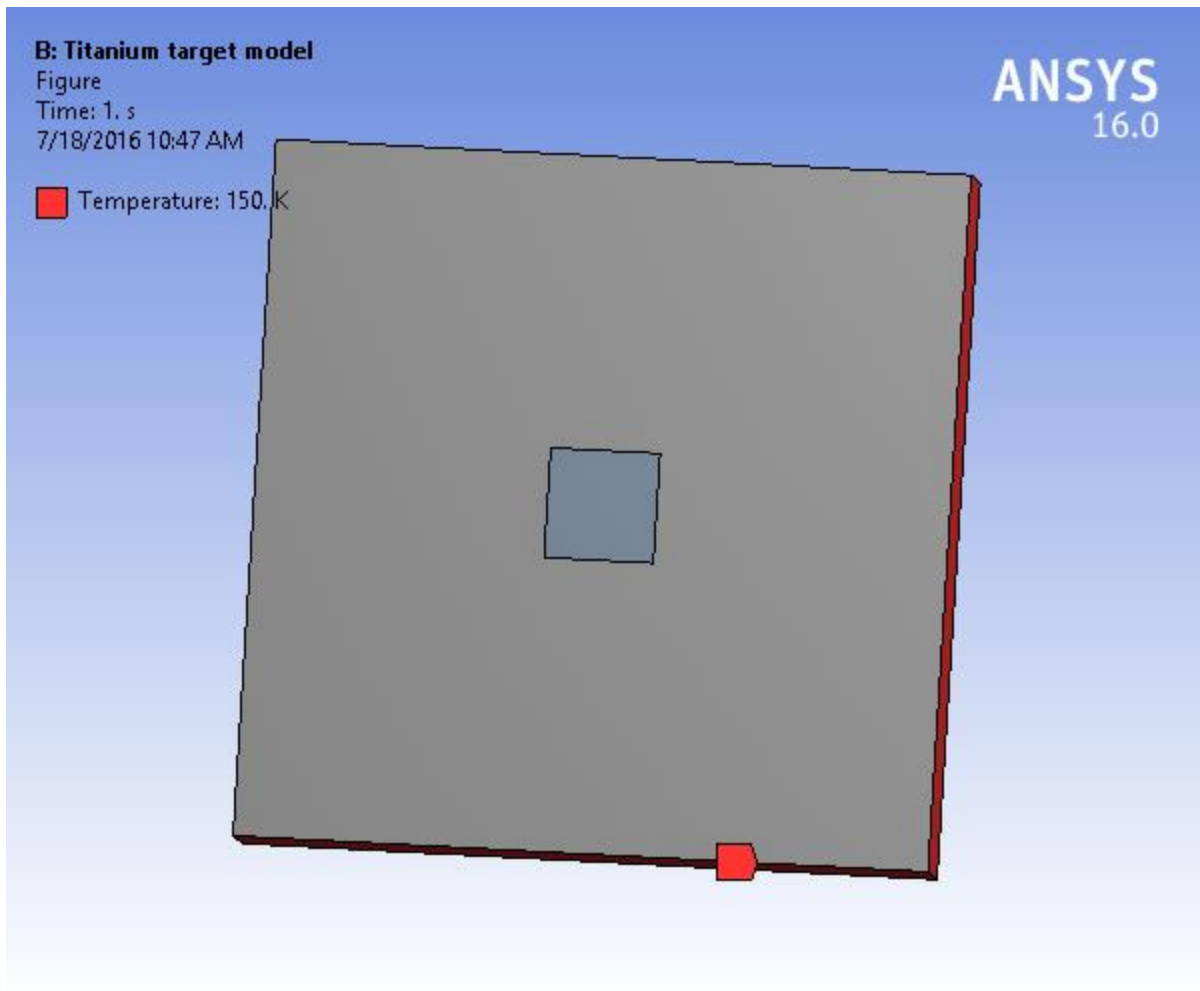


FIGURE 3
Model (B4) > Steady-State Thermal (B5) > Internal Heat Generation

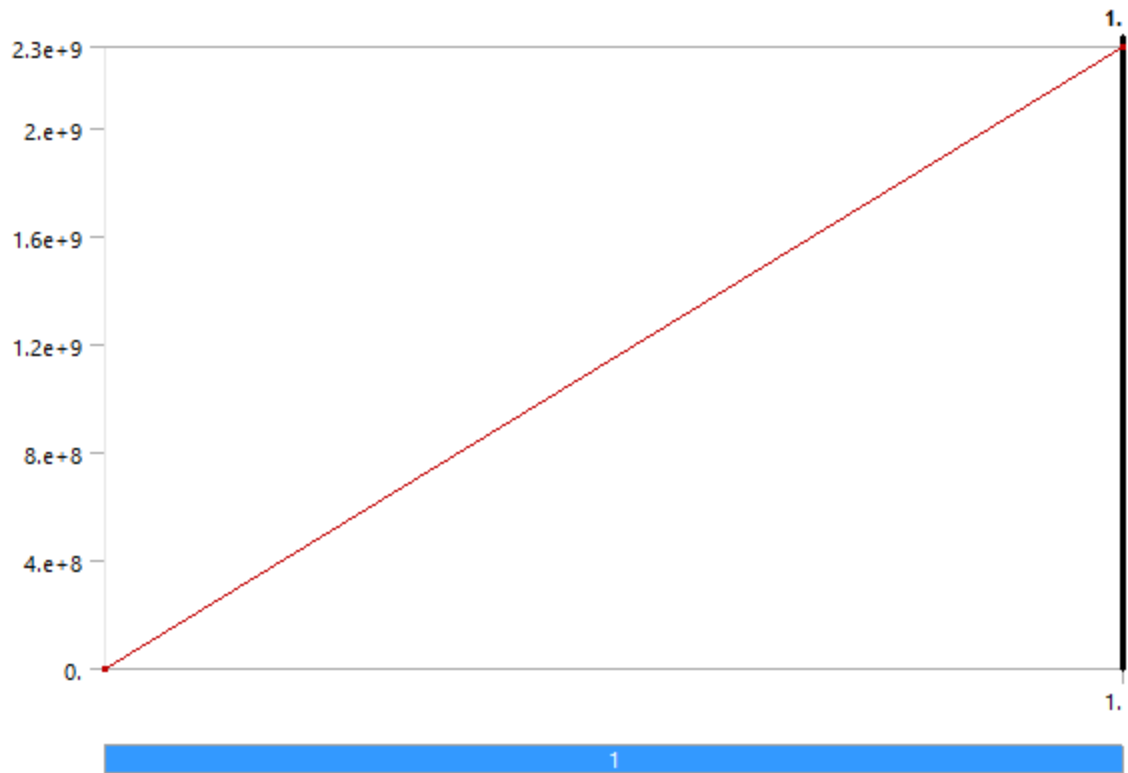
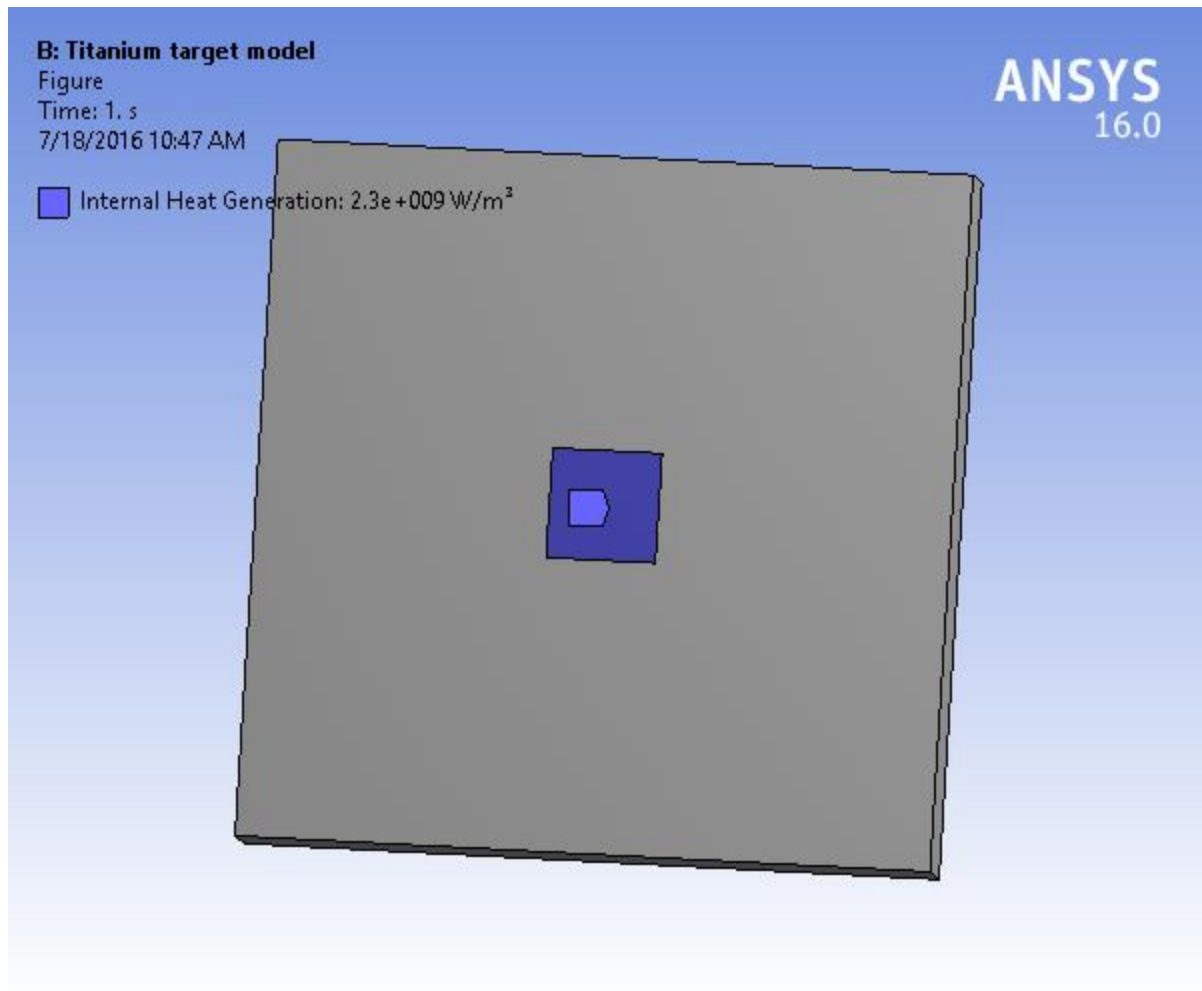


FIGURE 4
Model (B4) > Steady-State Thermal (B5) > Internal Heat Generation > Figure
Internal heat generation



Solution (B6)

TABLE 13
Model (B4) > Steady-State Thermal (B5) > Solution

Object Name	<i>Solution (B6)</i>
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
Post Processing	
Calculate Beam Section Results	No

TABLE 14
Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Solution Information

Object Name	<i>Solution Information</i>
State	Solved
Solution Information	

Solution Output	Solver Output
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 15
Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Results

Object Name	<i>Temperature</i>
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Temperature
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	
Suppressed	No
Results	
Minimum	150. K
Maximum	290.49 K
Minimum Occurs On	Ti-foil:1
Maximum Occurs On	Ti-foil-beam:1
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	4

FIGURE 5
Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Temperature

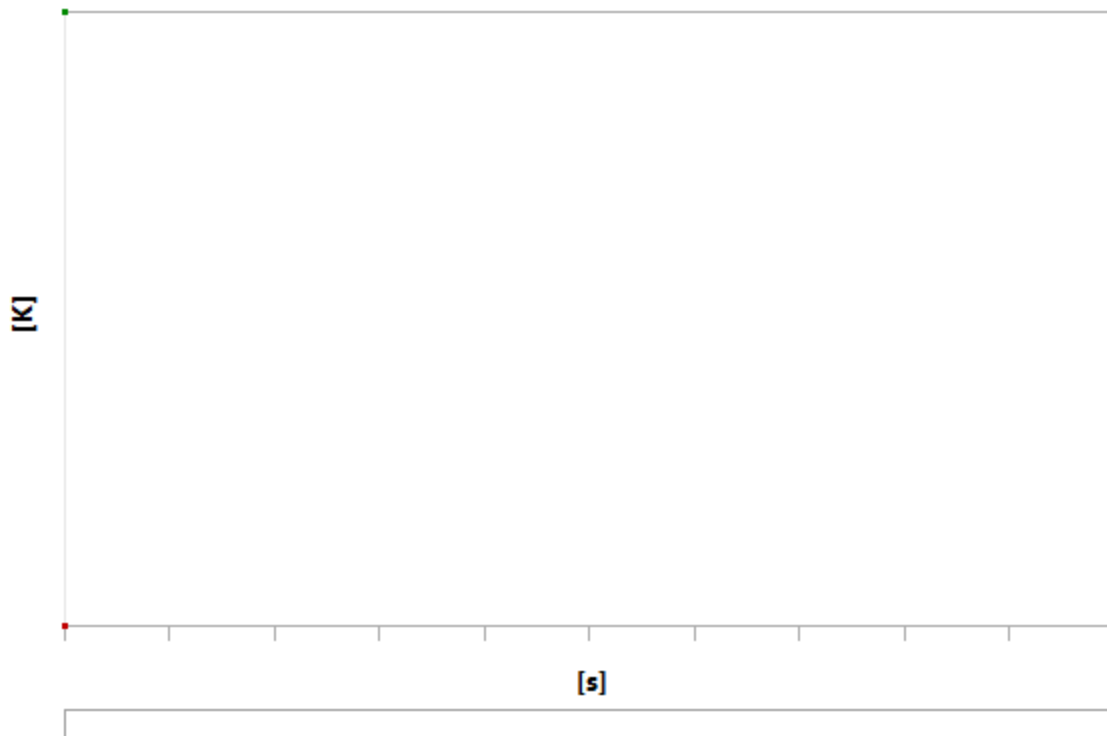


TABLE 16
Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Temperature

Time [s]	Minimum [K]	Maximum [K]
1.	150.	290.49

Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Temperature > Comment
Dave Meekins

Maximum temperature is well below the first phase transition

FIGURE 6
Model (B4) > Steady-State Thermal (B5) > Solution (B6) > Temperature > Figure
Temperature profile for Ti foil

B: Titanium target model

Figure

Type: Temperature

Unit: K

Time: 1

7/18/2016 10:47 AM

ANSYS
16.0



Material Data

Titanium

TABLE 17
Titanium > Compressive Yield Strength

Compressive Yield Strength Pa	Temperature C
2.8872e+008	-196.15
2.8428e+008	-189.12
2.7988e+008	-182.09
2.7551e+008	-175.06
2.7117e+008	-168.03
2.6687e+008	-161
2.6261e+008	-153.97
2.5838e+008	-146.94
2.5418e+008	-139.91
2.5002e+008	-132.88
2.4589e+008	-125.85

2.418e+008	-118.82
2.3775e+008	-111.79
2.3373e+008	-104.76
2.2974e+008	-97.726
2.2579e+008	-90.695
2.2187e+008	-83.665
2.1799e+008	-76.635
2.1414e+008	-69.605
2.1033e+008	-62.574
2.0655e+008	-55.544
2.0281e+008	-48.514
1.991e+008	-41.483
1.9543e+008	-34.453
1.9179e+008	-27.423
1.8819e+008	-20.392
1.8462e+008	-13.362
1.8108e+008	-6.3318
1.7759e+008	0.69848
1.7412e+008	7.7288
1.7069e+008	14.759
1.673e+008	21.789
1.6394e+008	28.82
1.6062e+008	35.85
1.5733e+008	42.88
1.5407e+008	49.911
1.5085e+008	56.941
1.4767e+008	63.971
1.4452e+008	71.002
1.414e+008	78.032
1.3832e+008	85.062
1.3527e+008	92.092
1.3226e+008	99.123
1.2929e+008	106.15
1.2635e+008	113.18
1.2344e+008	120.21
1.2057e+008	127.24
1.1773e+008	134.27
1.1493e+008	141.3
1.1216e+008	148.33
1.0943e+008	155.37
1.0674e+008	162.4
1.0407e+008	169.43
1.0145e+008	176.46
9.8853e+007	183.49
9.6295e+007	190.52
9.3772e+007	197.55
9.1284e+007	204.58
8.8831e+007	211.61

8.6413e+007	218.64
8.4029e+007	225.67
8.1681e+007	232.7
7.9367e+007	239.73
7.7088e+007	246.76
7.4844e+007	253.79
7.2635e+007	260.82
7.0461e+007	267.85
6.8321e+007	274.88
6.6216e+007	281.91
6.4147e+007	288.94
6.2112e+007	295.97
6.0112e+007	303
5.8146e+007	310.03
5.6216e+007	317.06
5.432e+007	324.09
5.246e+007	331.12
5.0634e+007	338.15
4.8843e+007	345.18
4.7087e+007	352.21
4.5366e+007	359.24
4.3679e+007	366.27
4.2028e+007	373.3
4.0411e+007	380.33
3.8829e+007	387.37
3.7282e+007	394.4
3.577e+007	401.43
3.4292e+007	408.46
3.285e+007	415.49
3.1442e+007	422.52
3.007e+007	429.55
2.8732e+007	436.58
2.7429e+007	443.61
2.616e+007	450.64
2.4927e+007	457.67
2.3729e+007	464.7
2.2565e+007	471.73
2.1436e+007	478.76
2.0342e+007	485.79
1.9283e+007	492.82
1.8259e+007	499.85

TABLE 18
Titanium > Density

Density kg m ⁻³	Temperature C
4520.2	-273.15
4520.2	-261.59
4520.1	-250.04
4520.1	-238.48

4520	-226.93
4519.9	-215.37
4519.7	-203.82
4519.3	-192.26
4518.7	-180.71
4518.1	-169.15
4517.3	-157.59
4516.4	-146.04
4515.5	-134.48
4514.6	-122.93
4513.5	-111.37
4512.5	-99.817
4511.4	-88.261
4510.2	-76.706
4509.1	-65.15
4507.9	-53.594
4506.7	-42.039
4505.5	-30.483
4504.3	-18.928
4503	-7.3722
4501.8	4.1833
4500.5	15.739
4499.2	27.294
4497.9	38.85
4496.6	50.406
4495.2	61.961
4493.9	73.517
4492.5	85.072
4491.1	96.628
4489.8	108.18
4488.4	119.74
4487	131.29
4485.6	142.85
4484.1	154.41
4482.7	165.96
4481.3	177.52
4479.8	189.07
4478.4	200.63
4476.9	212.18
4475.5	223.74
4474	235.29
4472.5	246.85
4471.1	258.41
4469.6	269.96
4468.1	281.52
4466.6	293.07
4465.1	304.63
4463.6	316.18

4462.1	327.74
4460.6	339.29
4459.1	350.85
4457.6	362.41
4456.1	373.96
4454.6	385.52
4453	397.07
4451.5	408.63
4450	420.18
4448.5	431.74
4446.9	443.29
4445.4	454.85
4443.8	466.41
4442.3	477.96
4440.8	489.52
4439.2	501.07
4437.6	512.63
4436.1	524.18
4434.5	535.74
4432.9	547.29
4431.4	558.85
4429.8	570.41
4428.2	581.96
4426.6	593.52
4425	605.07
4423.4	616.63
4421.8	628.18
4420.1	639.74
4418.5	651.29
4416.9	662.85
4415.2	674.41
4413.5	685.96
4411.9	697.52
4410.2	709.07
4408.5	720.63
4406.8	732.18
4405.1	743.74
4403.3	755.29
4401.6	766.85
4399.8	778.41
4398	789.96
4396.2	801.52
4394.4	813.07
4392.6	824.63
4390.7	836.18
4388.8	847.74
4386.9	859.29
4385	870.85

TABLE 19
Titanium > Tensile Yield Strength

Tensile Yield Strength Pa	Temperature C
3.5585e+008	19.85
3.4625e+008	25.729
3.3692e+008	31.608
3.2785e+008	37.486
3.1904e+008	43.365
3.1047e+008	49.244
3.0215e+008	55.123
2.9407e+008	61.002
2.8622e+008	66.88
2.786e+008	72.759
2.7121e+008	78.638
2.6403e+008	84.517
2.5707e+008	90.395
2.5031e+008	96.274
2.4375e+008	102.15
2.374e+008	108.03
2.3123e+008	113.91
2.2525e+008	119.79
2.1946e+008	125.67
2.1385e+008	131.55
2.0841e+008	137.43
2.0313e+008	143.3
1.9803e+008	149.18
1.9308e+008	155.06
1.8829e+008	160.94
1.8365e+008	166.82
1.7916e+008	172.7
1.7482e+008	178.58
1.7061e+008	184.46
1.6654e+008	190.33
1.626e+008	196.21
1.5879e+008	202.09
1.551e+008	207.97
1.5153e+008	213.85
1.4808e+008	219.73
1.4475e+008	225.61
1.4152e+008	231.49
1.384e+008	237.37
1.3538e+008	243.24
1.3246e+008	249.12
1.2964e+008	255
1.2691e+008	260.88
1.2427e+008	266.76
1.2172e+008	272.64
1.1926e+008	278.52
1.1687e+008	284.4

1.1457e+008	290.27
1.1234e+008	296.15
1.1018e+008	302.03
1.081e+008	307.91
1.0608e+008	313.79
1.0413e+008	319.67
1.0224e+008	325.55
1.0041e+008	331.43
9.8643e+007	337.3
9.6931e+007	343.18
9.5274e+007	349.06
9.3669e+007	354.94
9.2115e+007	360.82
9.061e+007	366.7
8.9152e+007	372.58
8.7738e+007	378.46
8.6368e+007	384.33
8.504e+007	390.21
8.3753e+007	396.09
8.2504e+007	401.97
8.1292e+007	407.85
8.0117e+007	413.73
7.8976e+007	419.61
7.7869e+007	425.49
7.6794e+007	431.37
7.5751e+007	437.24
7.4738e+007	443.12
7.3755e+007	449
7.28e+007	454.88
7.1873e+007	460.76
7.0974e+007	466.64
7.01e+007	472.52
6.9253e+007	478.4
6.8431e+007	484.27
6.7634e+007	490.15
6.6862e+007	496.03
6.6114e+007	501.91
6.539e+007	507.79
6.469e+007	513.67
6.4014e+007	519.55
6.3362e+007	525.43
6.2733e+007	531.3
6.2129e+007	537.18
6.1549e+007	543.06
6.0993e+007	548.94
6.0462e+007	554.82
5.9956e+007	560.7
5.9476e+007	566.58

5.9022e+007	572.46
5.8595e+007	578.33
5.8195e+007	584.21
5.7823e+007	590.09
5.7481e+007	595.97
5.7168e+007	601.85

TABLE 20
Titanium > Tensile Ultimate Strength

Tensile Ultimate Strength Pa	Temperature C
5.0732e+008	19.85
4.9773e+008	25.729
4.8804e+008	31.608
4.7826e+008	37.486
4.6843e+008	43.365
4.5855e+008	49.244
4.4864e+008	55.123
4.3873e+008	61.002
4.2883e+008	66.88
4.1896e+008	72.759
4.0912e+008	78.638
3.9934e+008	84.517
3.8963e+008	90.395
3.8001e+008	96.274
3.7047e+008	102.15
3.6104e+008	108.03
3.5173e+008	113.91
3.4254e+008	119.79
3.3348e+008	125.67
3.2457e+008	131.55
3.1581e+008	137.43
3.0721e+008	143.3
2.9878e+008	149.18
2.9051e+008	155.06
2.8243e+008	160.94
2.7452e+008	166.82
2.668e+008	172.7
2.5927e+008	178.58
2.5194e+008	184.46
2.448e+008	190.33
2.3786e+008	196.21
2.3111e+008	202.09
2.2457e+008	207.97
2.1824e+008	213.85
2.121e+008	219.73
2.0617e+008	225.61
2.0044e+008	231.49
1.9491e+008	237.37
1.8959e+008	243.24

1.8446e+008	249.12
1.7953e+008	255
1.7479e+008	260.88
1.7025e+008	266.76
1.6589e+008	272.64
1.6173e+008	278.52
1.5774e+008	284.4
1.5394e+008	290.27
1.5031e+008	296.15
1.4685e+008	302.03
1.4357e+008	307.91
1.4044e+008	313.79
1.3747e+008	319.67
1.3466e+008	325.55
1.3199e+008	331.43
1.2947e+008	337.3
1.2709e+008	343.18
1.2484e+008	349.06
1.2271e+008	354.94
1.2071e+008	360.82
1.1883e+008	366.7
1.1706e+008	372.58
1.1539e+008	378.46
1.1382e+008	384.33
1.1235e+008	390.21
1.1096e+008	396.09
1.0966e+008	401.97
1.0843e+008	407.85
1.0728e+008	413.73
1.062e+008	419.61
1.0517e+008	425.49
1.042e+008	431.37
1.0329e+008	437.24
1.0242e+008	443.12
1.0159e+008	449
1.0079e+008	454.88
1.0003e+008	460.76
9.9303e+007	466.64
9.8596e+007	472.52
9.791e+007	478.4
9.7241e+007	484.27
9.6585e+007	490.15
9.5941e+007	496.03
9.5305e+007	501.91
9.4675e+007	507.79
9.4049e+007	513.67
9.3425e+007	519.55
9.2802e+007	525.43

9.2178e+007	531.3
9.1554e+007	537.18
9.0929e+007	543.06
9.0302e+007	548.94
8.9676e+007	554.82
8.905e+007	560.7
8.8427e+007	566.58
8.7808e+007	572.46
8.7196e+007	578.33
8.6594e+007	584.21
8.6005e+007	590.09
8.5434e+007	595.97
8.4884e+007	601.85

TABLE 21
Titanium > Isotropic Secant Coefficient of Thermal Expansion

Coefficient of Thermal Expansion C ⁻¹	Temperature C
5.0347e-006	-273.15
5.3174e-006	-261.59
5.5819e-006	-250.04
5.8292e-006	-238.48
6.0603e-006	-226.93
6.2759e-006	-215.37
6.477e-006	-203.82
6.6643e-006	-192.26
6.8386e-006	-180.71
7.0007e-006	-169.15
7.1513e-006	-157.59
7.2911e-006	-146.04
7.4208e-006	-134.48
7.541e-006	-122.93
7.6523e-006	-111.37
7.7553e-006	-99.817
7.8507e-006	-88.261
7.9388e-006	-76.706
8.0203e-006	-65.15
8.0956e-006	-53.594
8.1651e-006	-42.039
8.2294e-006	-30.483
8.2889e-006	-18.928
8.3439e-006	-7.3722
8.3948e-006	4.1833
8.442e-006	15.739
8.4859e-006	27.294
8.5266e-006	38.85
8.5646e-006	50.406
8.6001e-006	61.961
8.6334e-006	73.517
8.6647e-006	85.072

8.6943e-006	96.628
8.7223e-006	108.18
8.7489e-006	119.74
8.7744e-006	131.29
8.7988e-006	142.85
8.8224e-006	154.41
8.8453e-006	165.96
8.8676e-006	177.52
8.8894e-006	189.07
8.9108e-006	200.63
8.9319e-006	212.18
8.9528e-006	223.74
8.9736e-006	235.29
8.9942e-006	246.85
9.0148e-006	258.41
9.0353e-006	269.96
9.0559e-006	281.52
9.0766e-006	293.07
9.0973e-006	304.63
9.118e-006	316.18
9.1389e-006	327.74
9.1598e-006	339.29
9.1807e-006	350.85
9.2017e-006	362.41
9.2228e-006	373.96
9.2439e-006	385.52
9.2649e-006	397.07
9.286e-006	408.63
9.307e-006	420.18
9.3279e-006	431.74
9.3487e-006	443.29
9.3695e-006	454.85
9.39e-006	466.41
9.4104e-006	477.96
9.4306e-006	489.52
9.4506e-006	501.07
9.4704e-006	512.63
9.4899e-006	524.18
9.5092e-006	535.74
9.5282e-006	547.29
9.5469e-006	558.85
9.5654e-006	570.41
9.5837e-006	581.96
9.6018e-006	593.52
9.6196e-006	605.07
9.6373e-006	616.63
9.6549e-006	628.18
9.6724e-006	639.74

9.6899e-006	651.29
9.7075e-006	662.85
9.7252e-006	674.41
9.7432e-006	685.96
9.7615e-006	697.52
9.7802e-006	709.07
9.7996e-006	720.63
9.8196e-006	732.18
9.8406e-006	743.74
9.8625e-006	755.29
9.8858e-006	766.85
9.9104e-006	778.41
9.9367e-006	789.96
9.9649e-006	801.52
9.9953e-006	813.07
1.0028e-005	824.63
1.0063e-005	836.18
1.0102e-005	847.74
1.0144e-005	859.29
1.0189e-005	870.85
Reference Temperature C	
19.85	

TABLE 22
Titanium > Specific Heat

Specific Heat J kg ⁻¹ C ⁻¹	Temperature C
298.75	-173.15
345.25	-154.52
383.2	-135.9
414.01	-117.27
438.94	-98.645
459.11	-80.019
475.51	-61.392
488.99	-42.766
500.25	-24.14
509.87	-5.5136
518.29	13.113
525.42	31.739
529.8	50.365
534.21	68.991
538.65	87.618
543.1	106.24
547.57	124.87
552.04	143.5
556.51	162.12
560.97	180.75
565.41	199.38
569.84	218
574.23	236.63

578.6	255.25
582.91	273.88
587.18	292.51
591.4	311.13
595.55	329.76
599.64	348.39
603.65	367.01
607.58	385.64
611.42	404.26
615.16	422.89
618.81	441.52
622.34	460.14
625.76	478.77
629.06	497.4
632.23	516.02
635.26	534.65
638.16	553.27
640.9	571.9
643.49	590.53
645.92	609.15
647.27	627.78
648.71	646.41
651.92	665.03
657.5	683.66
665.98	702.28
677.77	720.91
693.21	739.54
712.54	758.16
735.9	776.79
763.36	795.42
794.87	814.04
830.32	832.67
869.49	851.29
912.06	869.92
585.61	888.55
590.81	907.17
596.05	925.8
601.34	944.43
606.67	963.05
612.05	981.68
617.48	1000.3
622.95	1018.9
628.47	1037.6
634.04	1056.2
639.65	1074.8
645.31	1093.4
651.01	1112.1
656.76	1130.7

662.56	1149.3
668.4	1167.9
674.29	1186.6
680.23	1205.2
686.21	1223.8
692.24	1242.4
698.31	1261.1
704.43	1279.7
710.59	1298.3
716.81	1317
723.07	1335.6
729.37	1354.2
735.72	1372.8
742.12	1391.5
748.56	1410.1
755.05	1428.7
761.59	1447.3
768.17	1466
774.8	1484.6
781.47	1503.2
788.19	1521.8
794.96	1540.5
801.77	1559.1
808.63	1577.7
815.53	1596.3
822.49	1615
829.48	1633.6
836.53	1652.2
843.62	1670.8

TABLE 23
Titanium > Isotropic Thermal Conductivity

Thermal Conductivity W m ⁻¹ C ⁻¹	Temperature C
1.4556	-272.15
28.809	-252.46
42.182	-232.78
37.754	-213.09
33.978	-193.4
31.171	-173.72
29.099	-154.03
27.564	-134.34
26.398	-114.66
25.465	-94.968
24.662	-75.281
23.918	-55.594
23.193	-35.908
22.48	-16.221
21.803	3.4662
21.221	23.153

20.822	42.84
20.504	62.527
20.096	82.214
19.746	101.9
19.448	121.59
19.198	141.27
18.992	160.96
18.825	180.65
18.694	200.33
18.595	220.02
18.525	239.71
18.481	259.4
18.459	279.08
18.457	298.77
18.472	318.46
18.502	338.14
18.546	357.83
18.601	377.52
18.665	397.2
18.738	416.89
18.817	436.58
18.903	456.26
18.995	475.95
19.091	495.64
19.192	515.32
19.298	535.01
19.408	554.7
19.524	574.39
19.646	594.07
19.774	613.76
19.91	633.45
20.055	653.13
20.211	672.82
20.379	692.51
20.569	712.19
20.705	731.88
20.842	751.57
20.98	771.25
21.119	790.94
21.259	810.63
21.4	830.31
21.542	850
21.686	869.69
21.83	889.38
21.975	909.06
22.122	928.75
22.269	948.44
22.418	968.12

22.568	987.81
22.718	1007.5
22.87	1027.2
23.023	1046.9
23.177	1066.6
23.332	1086.2
23.488	1105.9
23.645	1125.6
23.804	1145.3
23.963	1165
24.123	1184.7
24.285	1204.4
24.447	1224.1
24.611	1243.7
24.775	1263.4
24.941	1283.1
25.108	1302.8
25.276	1322.5
25.444	1342.2
25.614	1361.9
25.785	1381.5
25.958	1401.2
26.131	1420.9
26.305	1440.6
26.48	1460.3
26.657	1480
26.834	1499.7
27.012	1519.4
27.192	1539
27.373	1558.7
27.554	1578.4
27.737	1598.1
27.921	1617.8
28.106	1637.5
28.292	1657.2
28.479	1676.8

TABLE 24
Titanium > Isotropic Resistivity

Resistivity ohm m	Temperature C
1.1845e-007	-196.15
1.3466e-007	-185.82
1.5101e-007	-175.48
1.6749e-007	-165.15
1.841e-007	-154.82
2.0083e-007	-144.48
2.1768e-007	-134.15
2.3465e-007	-123.82
2.5172e-007	-113.48

2.6889e-007	-103.15
2.8617e-007	-92.817
3.0354e-007	-82.483
3.21e-007	-72.15
3.3854e-007	-61.817
3.5616e-007	-51.483
3.7386e-007	-41.15
3.9163e-007	-30.817
4.0946e-007	-20.483
4.2735e-007	-10.15
4.453e-007	0.18333
4.633e-007	10.517
4.8134e-007	20.85
4.9942e-007	31.183
5.1754e-007	41.517
5.3569e-007	51.85
5.5387e-007	62.183
5.7207e-007	72.517
5.9028e-007	82.85
6.0851e-007	93.183
6.2674e-007	103.52
6.4497e-007	113.85
6.6321e-007	124.18
6.8143e-007	134.52
6.9964e-007	144.85
7.1783e-007	155.18
7.3601e-007	165.52
7.5415e-007	175.85
7.7226e-007	186.18
7.9034e-007	196.52
8.0837e-007	206.85
8.2636e-007	217.18
8.4429e-007	227.52
8.6217e-007	237.85
8.7999e-007	248.18
8.9774e-007	258.52
9.1542e-007	268.85
9.3302e-007	279.18
9.5055e-007	289.52
9.6799e-007	299.85
9.8534e-007	310.18
1.0026e-006	320.52
1.0197e-006	330.85
1.0368e-006	341.18
1.0537e-006	351.52
1.0706e-006	361.85
1.0873e-006	372.18
1.1038e-006	382.52

1.1203e-006	392.85
1.1366e-006	403.18
1.1528e-006	413.52
1.1688e-006	423.85
1.1847e-006	434.18
1.2004e-006	444.52
1.216e-006	454.85
1.2314e-006	465.18
1.2467e-006	475.52
1.2617e-006	485.85
1.2766e-006	496.18
1.2914e-006	506.52
1.3059e-006	516.85
1.3202e-006	527.18
1.3343e-006	537.52
1.3483e-006	547.85
1.362e-006	558.18
1.3755e-006	568.52
1.3888e-006	578.85
1.4019e-006	589.18
1.4147e-006	599.52
1.4274e-006	609.85
1.4397e-006	620.18
1.4519e-006	630.52
1.4638e-006	640.85
1.4754e-006	651.18
1.4868e-006	661.52
1.498e-006	671.85
1.5088e-006	682.18
1.5194e-006	692.52
1.5297e-006	702.85
1.5398e-006	713.18
1.5495e-006	723.52
1.559e-006	733.85
1.5682e-006	744.18
1.5771e-006	754.52
1.5856e-006	764.85
1.5939e-006	775.18
1.6019e-006	785.52
1.6095e-006	795.85
1.6168e-006	806.18
1.6238e-006	816.52
1.6304e-006	826.85

TABLE 25
Titanium > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
19.85	1.0941e+011	0.33831	1.1278e+011	4.0877e+010
27.729	1.0894e+011	0.33876	1.1261e+011	4.0689e+010

35.608	1.0848e+011	0.33921	1.1244e+011	4.05e+010
43.486	1.0801e+011	0.33966	1.1227e+011	4.0312e+010
51.365	1.0754e+011	0.34012	1.121e+011	4.0124e+010
59.244	1.0707e+011	0.34057	1.1194e+011	3.9936e+010
67.123	1.0661e+011	0.34103	1.1177e+011	3.9748e+010
75.002	1.0614e+011	0.34149	1.116e+011	3.9561e+010
82.88	1.0567e+011	0.34195	1.1143e+011	3.9373e+010
90.759	1.0521e+011	0.34241	1.1127e+011	3.9185e+010
98.638	1.0474e+011	0.34288	1.111e+011	3.8998e+010
106.52	1.0427e+011	0.34335	1.1094e+011	3.881e+010
114.4	1.038e+011	0.34382	1.1077e+011	3.8622e+010
122.27	1.0334e+011	0.34429	1.1061e+011	3.8435e+010
130.15	1.0287e+011	0.34477	1.1045e+011	3.8248e+010
138.03	1.024e+011	0.34525	1.1029e+011	3.806e+010
145.91	1.0193e+011	0.34573	1.1013e+011	3.7873e+010
153.79	1.0147e+011	0.34622	1.0997e+011	3.7686e+010
161.67	1.01e+011	0.34671	1.0981e+011	3.7498e+010
169.55	1.0053e+011	0.3472	1.0966e+011	3.7311e+010
177.43	1.0006e+011	0.3477	1.0951e+011	3.7124e+010
185.3	9.9597e+010	0.34821	1.0935e+011	3.6937e+010
193.18	9.913e+010	0.34871	1.0921e+011	3.675e+010
201.06	9.8662e+010	0.34922	1.0906e+011	3.6563e+010
208.94	9.8195e+010	0.34974	1.0892e+011	3.6375e+010
216.82	9.7727e+010	0.35026	1.0877e+011	3.6188e+010
224.7	9.726e+010	0.35078	1.0863e+011	3.6001e+010
232.58	9.6793e+010	0.35131	1.085e+011	3.5814e+010
240.46	9.6325e+010	0.35185	1.0836e+011	3.5627e+010
248.33	9.5858e+010	0.35239	1.0823e+011	3.544e+010
256.21	9.5391e+010	0.35294	1.0811e+011	3.5253e+010
264.09	9.4923e+010	0.35349	1.0798e+011	3.5066e+010
271.97	9.4456e+010	0.35405	1.0786e+011	3.4879e+010
279.85	9.3989e+010	0.35461	1.0775e+011	3.4692e+010
287.73	9.3521e+010	0.35518	1.0763e+011	3.4505e+010
295.61	9.3054e+010	0.35576	1.0752e+011	3.4318e+010
303.49	9.2586e+010	0.35634	1.0742e+011	3.4131e+010
311.37	9.2119e+010	0.35693	1.0732e+011	3.3944e+010
319.24	9.1652e+010	0.35753	1.0722e+011	3.3757e+010
327.12	9.1184e+010	0.35814	1.0713e+011	3.357e+010
335	9.0717e+010	0.35875	1.0704e+011	3.3383e+010
342.88	9.025e+010	0.35937	1.0695e+011	3.3195e+010
350.76	8.9782e+010	0.35999	1.0688e+011	3.3008e+010
358.64	8.9315e+010	0.36062	1.068e+011	3.2821e+010
366.52	8.8847e+010	0.36127	1.0674e+011	3.2634e+010
374.4	8.838e+010	0.36192	1.0667e+011	3.2447e+010
382.27	8.7913e+010	0.36257	1.0662e+011	3.226e+010
390.15	8.7445e+010	0.36324	1.0657e+011	3.2073e+010
398.03	8.6978e+010	0.36391	1.0652e+011	3.1885e+010
405.91	8.6511e+010	0.3646	1.0649e+011	3.1698e+010

413.79	8.6043e+010	0.36529	1.0646e+011	3.1511e+010
421.67	8.5576e+010	0.36599	1.0643e+011	3.1324e+010
429.55	8.5109e+010	0.3667	1.0641e+011	3.1136e+010
437.43	8.4641e+010	0.36742	1.064e+011	3.0949e+010
445.3	8.4174e+010	0.36815	1.064e+011	3.0762e+010
453.18	8.3706e+010	0.36889	1.0641e+011	3.0575e+010
461.06	8.3239e+010	0.36964	1.0642e+011	3.0387e+010
468.94	8.2772e+010	0.37039	1.0644e+011	3.02e+010
476.82	8.2304e+010	0.37116	1.0647e+011	3.0013e+010
484.7	8.1837e+010	0.37194	1.0651e+011	2.9825e+010
492.58	8.137e+010	0.37273	1.0656e+011	2.9638e+010
500.46	8.0902e+010	0.37353	1.0662e+011	2.945e+010
508.33	8.0435e+010	0.37434	1.0668e+011	2.9263e+010
516.21	7.9967e+010	0.37516	1.0676e+011	2.9076e+010
524.09	7.95e+010	0.37599	1.0685e+011	2.8888e+010
531.97	7.9033e+010	0.37684	1.0695e+011	2.8701e+010
539.85	7.8565e+010	0.37769	1.0706e+011	2.8513e+010
547.73	7.8098e+010	0.37856	1.0718e+011	2.8326e+010
555.61	7.7631e+010	0.37944	1.0732e+011	2.8139e+010
563.49	7.7163e+010	0.38033	1.0747e+011	2.7951e+010
571.37	7.6696e+010	0.38123	1.0763e+011	2.7764e+010
579.24	7.6229e+010	0.38214	1.078e+011	2.7576e+010
587.12	7.5761e+010	0.38307	1.0799e+011	2.7389e+010
595	7.5294e+010	0.38401	1.0819e+011	2.7201e+010
602.88	7.4826e+010	0.38496	1.0841e+011	2.7014e+010
610.76	7.4359e+010	0.38593	1.0864e+011	2.6826e+010
618.64	7.3892e+010	0.38691	1.0889e+011	2.6639e+010
626.52	7.3424e+010	0.3879	1.0916e+011	2.6452e+010
634.4	7.2957e+010	0.3889	1.0945e+011	2.6264e+010
642.27	7.249e+010	0.38992	1.0975e+011	2.6077e+010
650.15	7.2022e+010	0.39095	1.1008e+011	2.589e+010
658.03	7.1555e+010	0.392	1.1042e+011	2.5702e+010
665.91	7.1088e+010	0.39305	1.1079e+011	2.5515e+010
673.79	7.062e+010	0.39413	1.1117e+011	2.5328e+010
681.67	7.0153e+010	0.39522	1.1158e+011	2.514e+010
689.55	6.9685e+010	0.39632	1.1202e+011	2.4953e+010
697.43	6.9218e+010	0.39744	1.1248e+011	2.4766e+010
705.3	6.8751e+010	0.39857	1.1297e+011	2.4579e+010
713.18	6.8283e+010	0.39971	1.1348e+011	2.4392e+010
721.06	6.7816e+010	0.40088	1.1402e+011	2.4205e+010
728.94	6.7349e+010	0.40205	1.146e+011	2.4018e+010
736.82	6.6881e+010	0.40324	1.1521e+011	2.3831e+010
744.7	6.6414e+010	0.40445	1.1585e+011	2.3644e+010
752.58	6.5946e+010	0.40568	1.1653e+011	2.3457e+010
760.46	6.5479e+010	0.40692	1.1724e+011	2.327e+010
768.33	6.5012e+010	0.40817	1.18e+011	2.3084e+010
776.21	6.4544e+010	0.40944	1.1879e+011	2.2897e+010
784.09	6.4077e+010	0.41073	1.1963e+011	2.2711e+010

791.97	6.361e+010	0.41204	1.2052e+011	2.2524e+010
799.85	6.3142e+010	0.41336	1.2146e+011	2.2338e+010

TABLE 26
Titanium > Multilinear Isotropic Hardening

Stress Pa	Plastic Strain m m ⁻¹	Temperature C
1.0219e+008	0	426.85
1.084e+008	1.5789e-003	426.85
1.1451e+008	3.1579e-003	426.85
1.2049e+008	4.7368e-003	426.85
1.2632e+008	6.3158e-003	426.85
1.32e+008	7.8947e-003	426.85
1.3751e+008	9.4737e-003	426.85
1.4283e+008	1.1053e-002	426.85
1.4794e+008	1.2632e-002	426.85
1.5283e+008	1.4211e-002	426.85
1.5748e+008	1.5789e-002	426.85
1.6188e+008	1.7368e-002	426.85
1.66e+008	1.8947e-002	426.85
1.6984e+008	2.0526e-002	426.85
1.7337e+008	2.2105e-002	426.85
1.7659e+008	2.3684e-002	426.85
1.7946e+008	2.5263e-002	426.85
1.8199e+008	2.6842e-002	426.85
1.8414e+008	2.8421e-002	426.85
1.8591e+008	3.e-002	426.85