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# Thermal Analysis of NSTX Center Stack and Outboard Divertor Tiles


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# NSTX

To: Distribution

Subject: **THERMAL ANALYSIS OF NSTX CENTER STACK AND OUT BOARD DIVERTOR TILES**

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## Abstract

Thermal analysis was performed on the Center Stack[CS] and Divertor tiles assuming that the CS tiles would be thermally isolated from the stack and the heat transfer would be by radiation only, while the divertor would be cooled by conduction into the stainless steel mounting plates.

A one dimensional, transient heat transfer program [TILE.TEMP.1] was written in QUICKBASIC to derive the temperature vs time, in four layers of graphite tiles in the NSTX center stack. The temperatures in both the CS and the divertor were analyzed by P-THERMAL 2.5.[1]

The BASIC program was designed to give a rough approximation of the thermal profile of a 1-D tile. It allowed quick turnaround and served as a guideline during conceptual design of the tiles and, later, as a litmus test to validate thermal analyses done with commercial finite element (FEA) codes. The BASIC code was in fairly good agreement with the commercial codes and peak temperatures calculated for the two varied by only 10%.

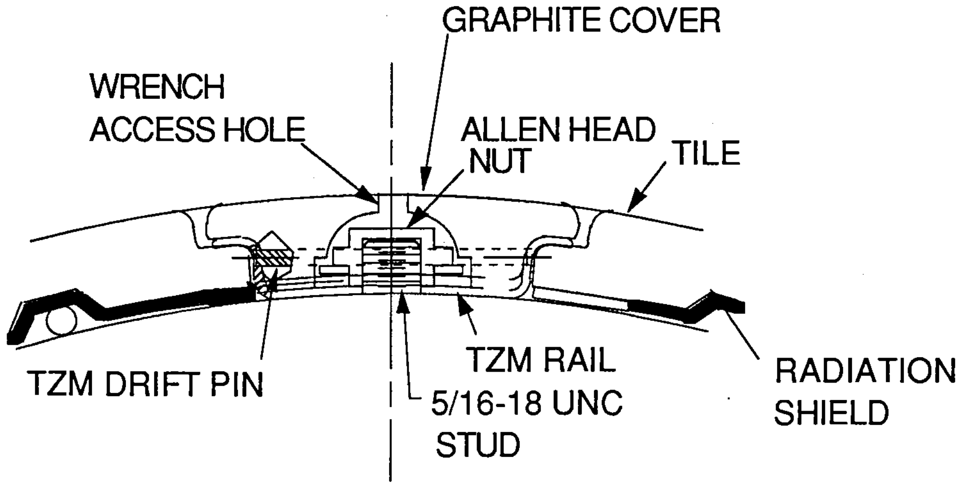
## Center Stack Thermal Analysis

### Overview

The BASIC code was derived using the solution for transient heat transfer in a 1-D, semi-infinite plate, exposed to a constant flux, as the starting point. This solution is relatively accurate for 1.25 cm thick tiles for the first 2-3 seconds of a five second pulse,. This corresponds to the time period during which the temperature effects are small and the rear of the plate is relatively unchanged. Time periods exceeding this result in increasing inaccuracies.

The solution for an infinite plate assumes that the material properties, i.e. specific heat, thermal conductivity, and diffusivity remain unchanged with temperature. Of course, these constants change very dramatically in graphite materials so temperature compensation was required. An iterative approach was used, calculating the mean temperatures and corresponding material

# FIGURE 1. BASELINE DESIGN




FEATURES

- RAIL BOTTOMS OUT ON EMBOSSED FEET
- RAIL RETAINS & INDEXES TILES
- TILES COMPRESS WAVE WASHERS

material properties over that time period. A second compensation method was also employed whereby the energy balance was checked and the temperature profile was shifted by an exponential function until balance matched within 10%. The layers were weighted by an algorithm according to distance back and time into the pulse ( penetration into the tile). This procedure does not give exact solutions for the boundary conditions, but it is less time consuming, much less complex then a true numeric solution, and it is more accurate than simply assuming an overall average bulk material property. As will be seen, it gives adequate results for first cut designs.

Description

Analysis was done assuming temperature dependent material properties of a known graphite and using tile thickness, flux, heating time, cooling time, center stack temperature and torus temperature as input variables. The early runs were done assuming POCO, FMI-4D, and ATJ graphites. Later, analyses were added to include Allied Signal's composite graphite product 865-19-4 C-C (AS) when its advantages became evident. Output of the code was temperature of each layer at each iterative time period, mean value material properties of the layers, total heat in, calculated heat balance, radiative heat to center column, and a graph of temperature vs time for each layer. The specific heat, thermal conductivity, and diffusivity were graphed and then curve fit with higher order polynomials, which were used by the code to solve for the material constants at each time iteration (typically 0.1 seconds). The same procedure was used to obtain the Gaussian error function for arguments from 0 to 2. The code was run until the peak temperature and cool down temperature reached steady state. During the cool down period the tile was assumed to have a constant(bulk) temperature through its thickness. This can be shown to be an acceptable assumption for slow radiative heat loss using the criteria for "lumped analysis".[2]

Tiles were assumed to have no thermal contact with the center stack, that is, all loses were radiative. One layer of heat shielding was assumed on the center stack side of the tile. During cool down the material properties were recalculated for each time iteration (typically 4 seconds)

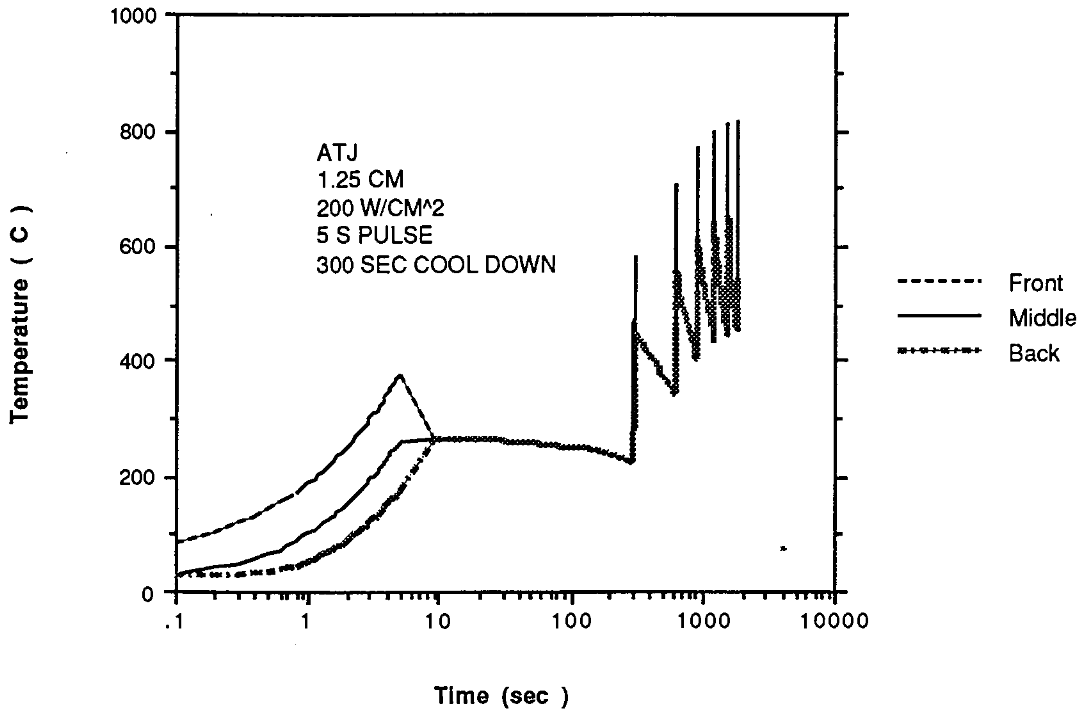
A typical run for a 1.25 cm tile is shown in Fig. 2.

* FMI-4D refers to the coarse weave carbon-carbon graphite manufactured by Fiber Materials Inc.

Typical Runs

| Material | POCO | POCO | POCO | FMI-4D* | ATJ |
|---|---|---|---|---|---|
| Thickness | 1.25 | 2.54 | 5.08 | 1.25 | 1.25 |
| Heat flux (w/cm^2) | 320 | 320 | 320 | 320 | 320 |
| Pulse length (sec) | 5 | 5 | 5 | 5 | 5 |
| Cooling Time (sec) | 300 | 300 | 300 | 300 | 300 |
| Center stack and torus temp. (K) | 300 | 300 | 300 | 300 | 300 |

**Figure 2. Tile Temperature as a Function of Repetitive Cycling**




Results- steady state values

| Material | POCO | POCO | POCO | FMI-4D | ATJ |
|---|---|---|---|---|---|
| Thickness | 1.25 | 2.54 | 5.08 | 1.25 | 1.25 |
| Peak face temp (C) | 1210 | 1283 | 1330 | 1124 | 1176 |
| Peak rear temp during pulse (C) | 638 | 636 | 685 | 682 | 657 |
| Peak bulk temp. after shot (C) | 865 | 818 | 794 | 865 | 861 |
| Bulk temperature at cool down C) | 523 | 624 | 684 | 540 | 514 |
| Time to steady state (cycles) | 6 | 8 | 12 | 6 | 6 |

Peak radiative heat to center column 0.5 w/cm^2

A run performed with a 1.25 cm tile (POCO) and the torus and center stack temperature held at 473 K results in the following:

Peak face temperature 1220

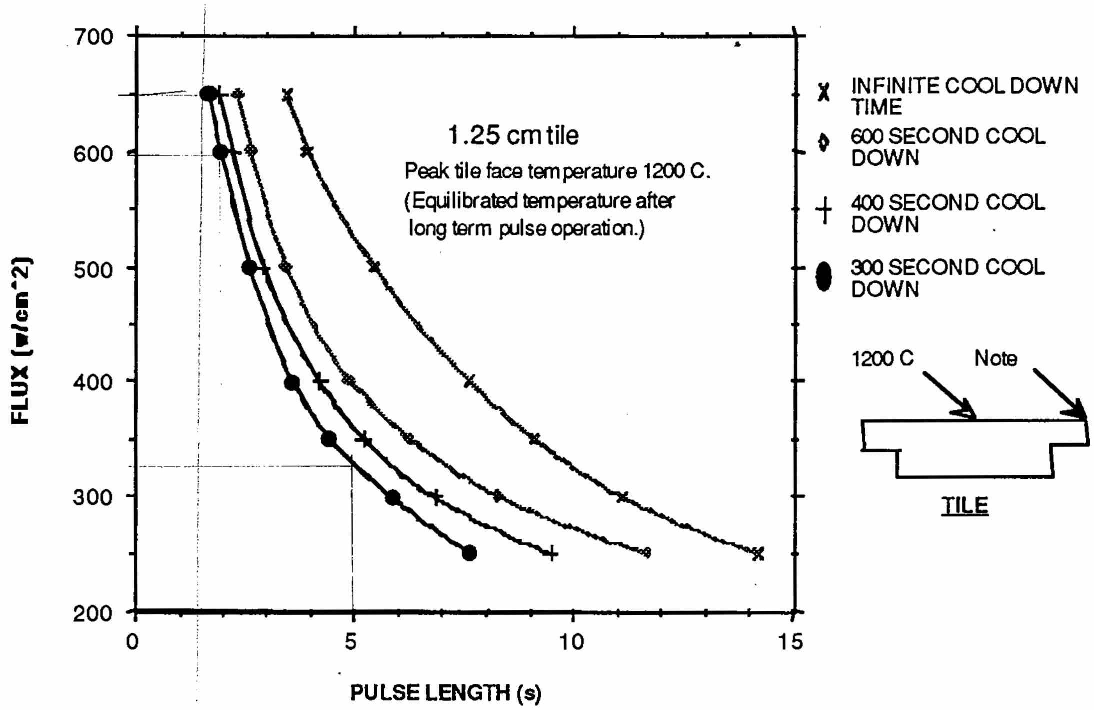
Peak rear temperature 693

| | |
|---|---|
| Peak bulk temp. after shot | 901 |
| Bulk temp. at cool down | 544 |
| Time to steady state | 6 cycles |

As might be expected here is very little change in the peak parameters when the environment is operated at 200 C instead of 27 C, this being due to the fact that radiation is considered as the only heat loss and there is little difference in the fourth powers of the temperature differences.

A comparison was done using TILE.Temp.1 to relate pulse times, flux levels and cool down periods which result in a given face temperature of 1200 C. The result is an operating envelope for the NSTX device, assuming that the limiting factor is the maximum temperature of the center stack tiles. Results are plotted in Fig.3.

**Fig. 3 PULSE LENGTH AS A FUNCTION OF FLUX AND COOL DOWN PERIOD**

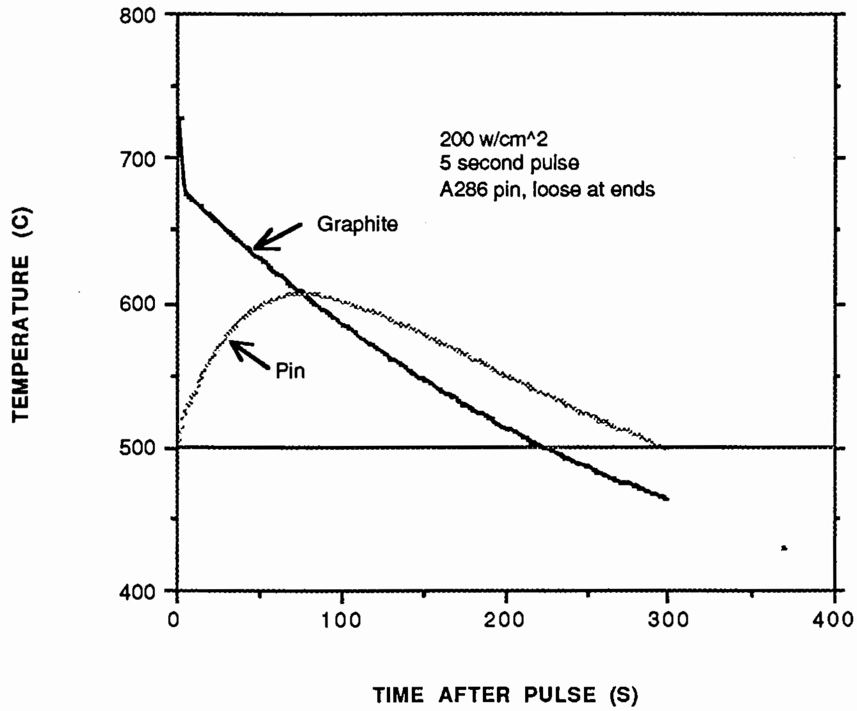



Note: Temperature at corner will run approximately 17-20% higher than face.

<u>Drift pin temperature response</u>

The center stack backet drift pin temperature response was analyzed at steady state with a 200 w/cm^2 heat load and 5 minute cooling periods. To be conservative the pin was assumed to be isolated from the bracket. The results are shown in Figure 4.

FIGURE 4. PIN TEMPERATURE RESPONSE AFTER PULSE DURING STEADY STATE OPERATION




Comparison to other tile thermal results

A run was performed using the parameters of the PPPL Thermal Analysis Document:[3]

| | |
|---|---|
| MATERIAL | ATJ |
| Thickness | 1.3 cm |
| Constant heat flux | 160 w/cm^2 |
| Pulse length | 5 sec |
| Cooling Time | 300 sec |
| Center stack and torus temperature | 323 K |

Cycling was continued until the tile peak temperature and the bulk temperatures between shots reached equilibrium.

| Results | PPPL | TILE.TEMP.1 |
|---|---|---|
| Peak face temperature | 837 C | 770 |
| Peak rear temperature | - | 546 |
| Bulk temperature | 520 C | 445 |

P-THERMAL Runs

- Several 2-D runs were done on P-THERMAL, after the initial design phase was complete, to verify the thermal performance of the tiles.
- 3-D runs of the actual tile model [ProE][4] were also performed. These analyses took into account the detail topographical features such as holes, notches, and asymmetry.
- An additional set of 3-D runs were made of the tile models to determine the effects of changing material to AS graphite and reducing the heat flux.

Summary of Typical Runs - steady state results

| Material | POCO | POCO | FMI-4D | AS |
|---|---|---|---|---|
| Model | 2-D | 2-D | 3-D | 3-D |
| Thickness (cm) | 1.15 | 5.08 | 1.15 | 1.15 |
| Constant heat flux (w/cm^2) | 320 | 320 | 320 | 200 |
| Pulse length (s) | 5 | 5 | 5 | 5 |
| Cooling Time (s) | 300 | 300 | 300 | 300 |
| Center stack and torus temperature (K) | 373 | 373 | 373 | 423 |

Results- steady state values

| Material | POCO | POCO | FMI-4D | AS |
|---|---|---|---|---|
| Model | 2-D | 2-D | 3-D | 3-D |
| Peak face temp during pulse (C) | 1340 C | 1335 | 1160 | 906 |
| Peak corner temp during pulse(C) | 1670 C | 1383 | 1160 | 982 |
| Peak temperature at holes(C) | - | - | 1262 | 906 |
| Bulk temp at cool down(C) | 540 | 540 | 540 | 530 |

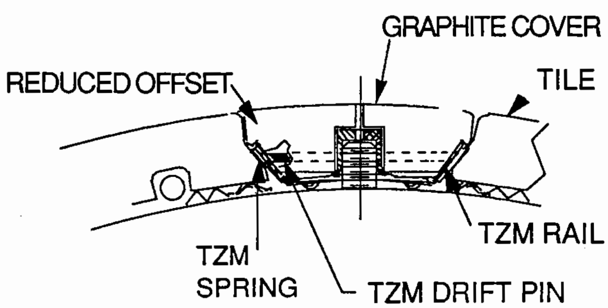
Discussion

There seemed to be no advantage in thicker tiles from a thermal consideration, in fact the equilibrated face temperatures and the bulk temperature between shots actually rose, due primarily to the inability of the large mass to radiate away heat between shots. There is some small advantage in the thicker tiles in that they do take a longer time to reach equilibrium (12 cycles vs 6) and the device could be operated slightly longer before maximum temperature would be reached. After this point, however, a lengthy shutdown would be necessary to allow removal of the heat.
The results indicated that the 1.25 cm rail tiles, at a heat flux of 320 cm^2 were close to the design limit of 1200 C at the face but there was a considerable gradient [330 C] to the edges of the tiles

with overhang. See Fig.3. This was unacceptable and various design changes were studied to find a solution for this effect. Among these were:

- Eliminating the overhangs and using a tapered [beveled] interface. This would essentially eliminate the offset and lower the peak temperatures. The problem is that to do this both rail and tile would have to have hard stops against the stack, otherwise there would be no firm indexing point to align the tile faces. This would be possible by retaining the tiles with spring fingers (Fig. 5) which would hold the tile firm against the center stack but permit thermal flexibility. This concept proved to be very difficult and expensive. The fingers had to be separate components, the full width of the tiles, to prevent over stressing, and even then required very tight tolerances, thin gauges and intricate shapes.

**FIG. 5 CENTER COLUMN - BEVELED TILE CONCEPT**




FEATURES
- SEPARATE SPRING RETAINS TILES
- SPRING MUST BE FULL WIDTH OF RAIL AND THINNER GAUGE
- RIVETS OR SPOT WELDS TO RAIL CHANNEL

CONCLUSIONS
- SPRING THEORETICALLY WORKS
- TIGHT TOLERANCES AND PRECISION DESIGN REQUIRED
- EXPENSIVE, INTRICATE

- Bolting all the tiles just as in the divertor and passive plate designs

This would require doubling the number of center stack studs and required composite graphite for all tiles ( machining considerations).

The only practical design solution found was a compromise in which the inner and outer tile overhang radii were increased. This had the effect of shortening the thermal path and also reducing the incidence angle of the plasma flux on the tile edge.

Analysis showed that the result was marginally within the 1200 C constraint at 320 w/cm^2 and well within if the thermal loads were reduced to 200 w/cm^2.

Pin temperatures were shown to stay under 600 C during pulse operation and return to a temperature of under 500 C between shots, acceptable temperatures for inconel alloys.

Conclusion

ATJ and POCO are good candidates for the standard tiles but not for rail tiles. Machining considerations, stress concentrations [4],and excessive temperatures at the rail overhang eliminate all but composite graphites for the application. The standard tiles do not have pins or the overhang on the sides and consequently the stresses are lower and temperatures are more nearly constant across the face. A set of analyses were done on P-THERMAL to determine if changing to AS with its higher conductivity, the heat load reduced to 200 w/cm^2, and the modified radii would alleviate the problem in the rail tile. The results are shown in the attached figures and indicate that everything was well within 1200 C. A decision was made to utilize the Allied Signal material, to gain the advantage of its lower price and shorter procurement time as well as its higher thermal conductivity and subsequent lower temperature gradients. The results showed that TZM was not required for the brackets and pins, and they were changed to inconel 600.

## Outboard Divertor Thermal Analysis

Overview

P-THERMAL runs were done on ATJ divertor tiles with thickness of 1 inch (2.54 cm).The flux was applied in an exponential distribution (Fig 6) $q = q_{peak}*e^{-S/\lambda}$ with a $\lambda$ value of 1.5 to 3 cm. Perfect contact with a Dowtherm cooled backing plate ( 150 C ) was assumed. Runs were continued until the peak temperatures and the cool down temperatures equilibrated.

Runs:

Axisymmetric 1-D and 2-D models

| | |
|---|---|
| Start temperature | 150 C |
| Pulse length | 5 seconds |
| Cool down periods | 300 seconds |

Results

1-D analysis indicated peak temperature of ~1200 C for less than 600 w/cm^2. 2-D analysis showed similar limit, but gave lower temperatures than 2-D due to poloidal conduction along tile.

2-D results:

| Thickness cm | Lamda cm | Peak Flux $w/cm^2$ | Peak Temperature C |
|---|---|---|---|
| 2.54 | 1.5 | 1860 | 2400 |
| 2.54 | 3 | 920 | 1500 |
| 2.54 | 4.5 | 620 | 1100 |

The design point for a double null plasma is a peak flux of approximately 1700 w/cm^2, which is not possible unless some means such as sweeping is used to reduce the apparent flux. The effect of sweep on apparent flux with Lamda =3 is shown in figure 7 and 8. The results are plotted as peak flux vs power flux width in figures 9 and 10, for an infinite distribution on the divertor and also as a truncated plasma distribution where the width is assumed cut off at the e-folding distance.

Conclusions

The analyses showed that the divertor tiles could not be operated within a 1200 C maximum temperature envelope unless the apparent peak flux was limited to approximately 600 w/cm^2. This was shown to be possible for a sweep of 10 cm and $\lambda = 3$ cm. The divertor tiles returned to a bulk temperature of 150 C after the three minute cool down period.

3-D and, 1-D models were run to determine the effect of thicker tiles and the results of both indicated that the major thermal penetration during a 5 second pulses was approximately 0.5 inches, independant of the tile thickness. This indicated that thermal considerations were not a design driver for divertor tile thickness. A one inch tile envelope was adopted, purely out of mechanical attachment considerations.

## REFERENCES


[1] P-THERMAL is a trademark of PDA Engineering Corp.

[2] D. R. Pitts, *Theory an Problems of Heat Transfer*, Schaum's Outline Series, p. 75, McGraw-Hill Publishing Company, New York, NY, 1977.

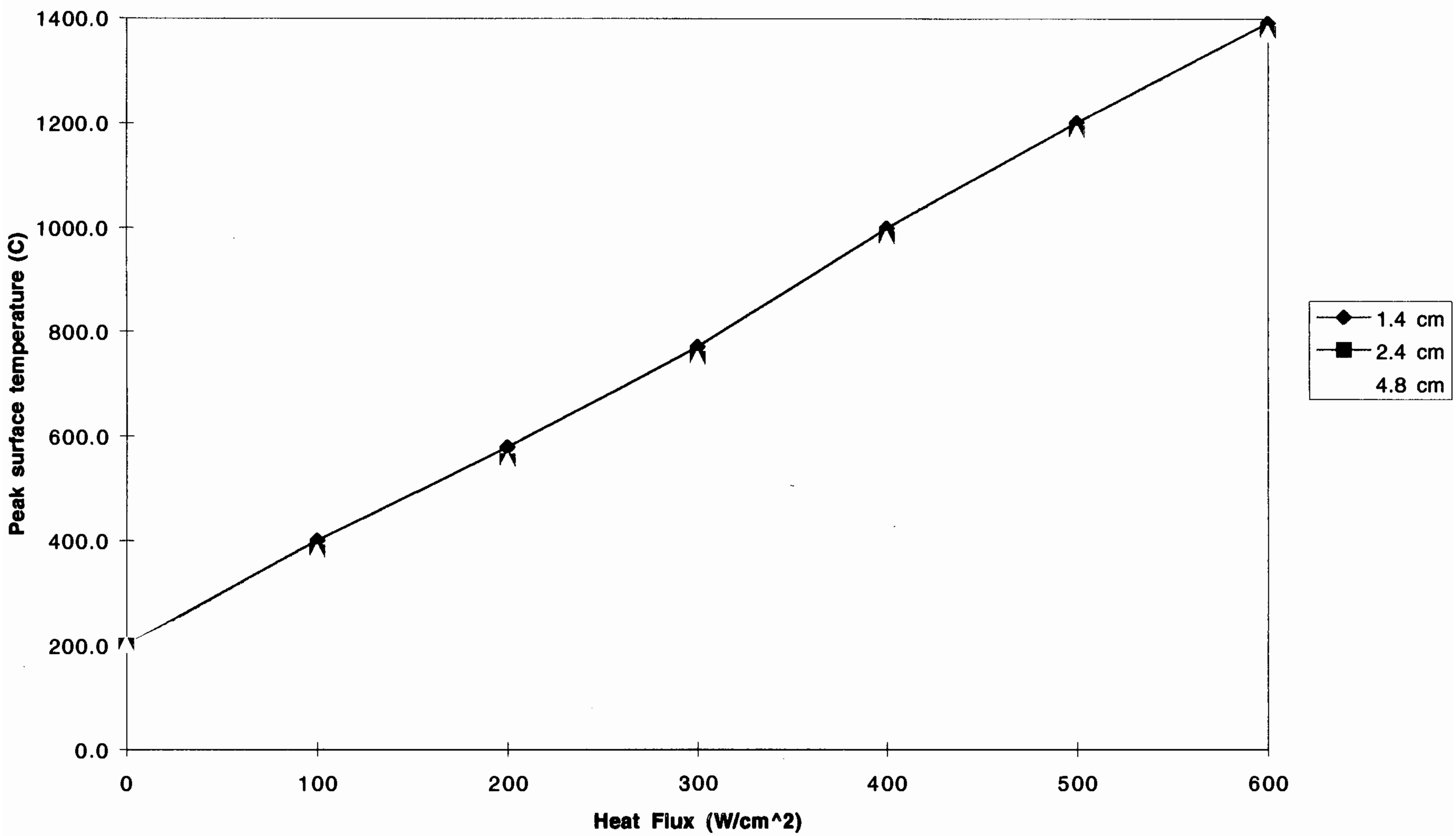
[3] A. Brooks, *Center Stack PFC Thermal Analysis/Fault Analysis*, PPPL Report 13-970217-AWB-01, Princeton, New Jersey, 17 February 1997.

[4] Pro/Engineer is a trademark of Parametric Technology Corporation.

[5] Goranson, Nelson, *NSTX Center Stack Tile Analysis and Testing,* LMES Report 11-980501-PLG-02, May 1998.

## Peak Surface Temperature vs Heat Flux,

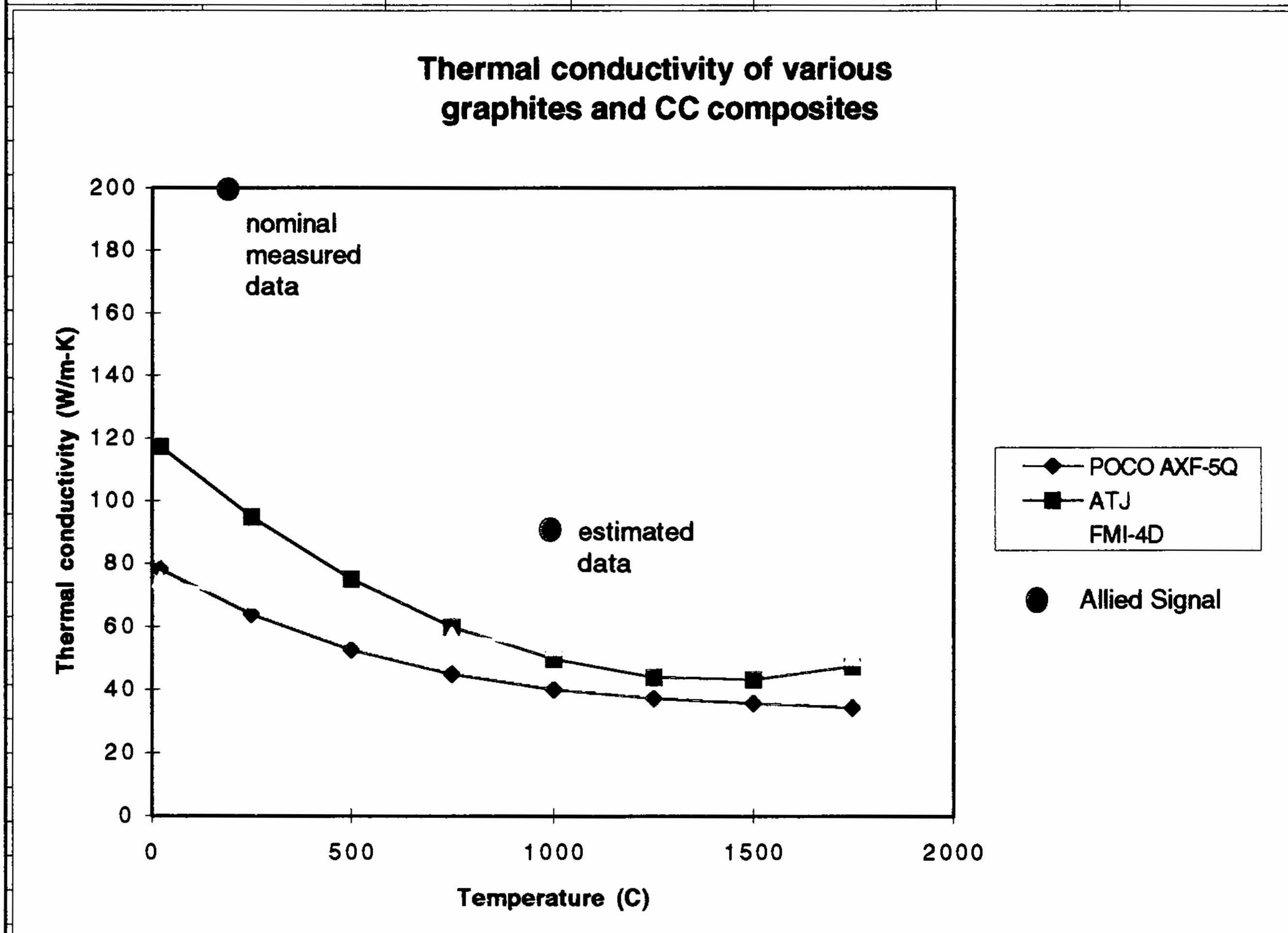
**for various tile thicknesses, 1-D calc.**
**ATJ, 5 seconds on, 300 seconds off,**
**Fixed equilibrium temperature of 200C**

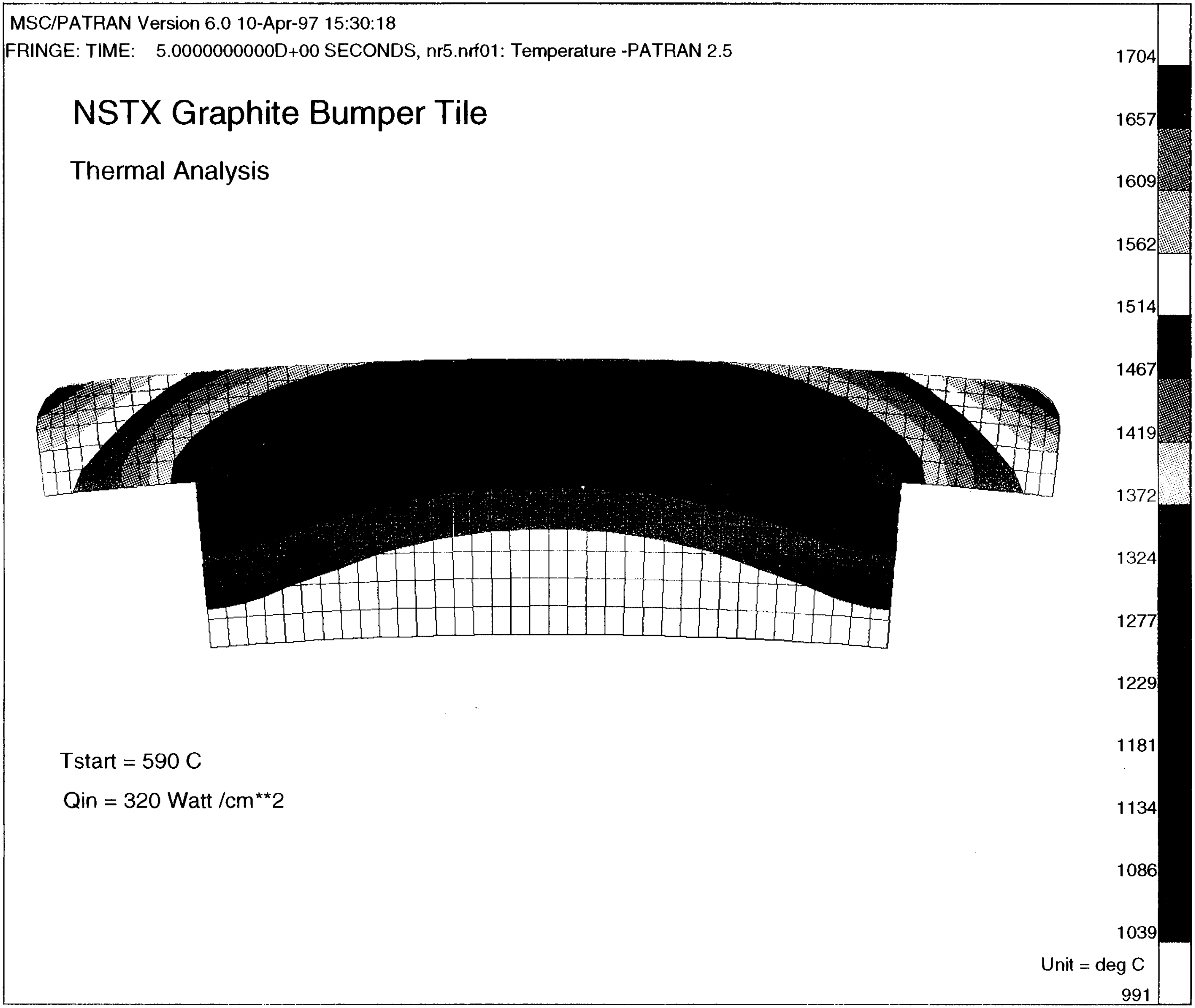


## Thermal conductivity comparison for different graphites

| | Thermal Conductivity, (W/m-K) | | | |
|---|---|---|---|---|
| Temperature | POCO AXF-5Q | ATJ | FMI-4D | Allied Signal |
| 20 | 78 | 117 | 75 | 200 |
| 250 | 64 | 95 | 68 | |
| 500 | 52 | 75 | 62 | |
| 750 | 45 | 60 | 57 | |
| 1000 | 40 | 50 | 54 | 100* |
| 1250 | 37 | 44 | 51 | |
| 1500 | 35 | 43 | 50 | |
| 1750 | 34 | 47 | 51 | |

* estimated data

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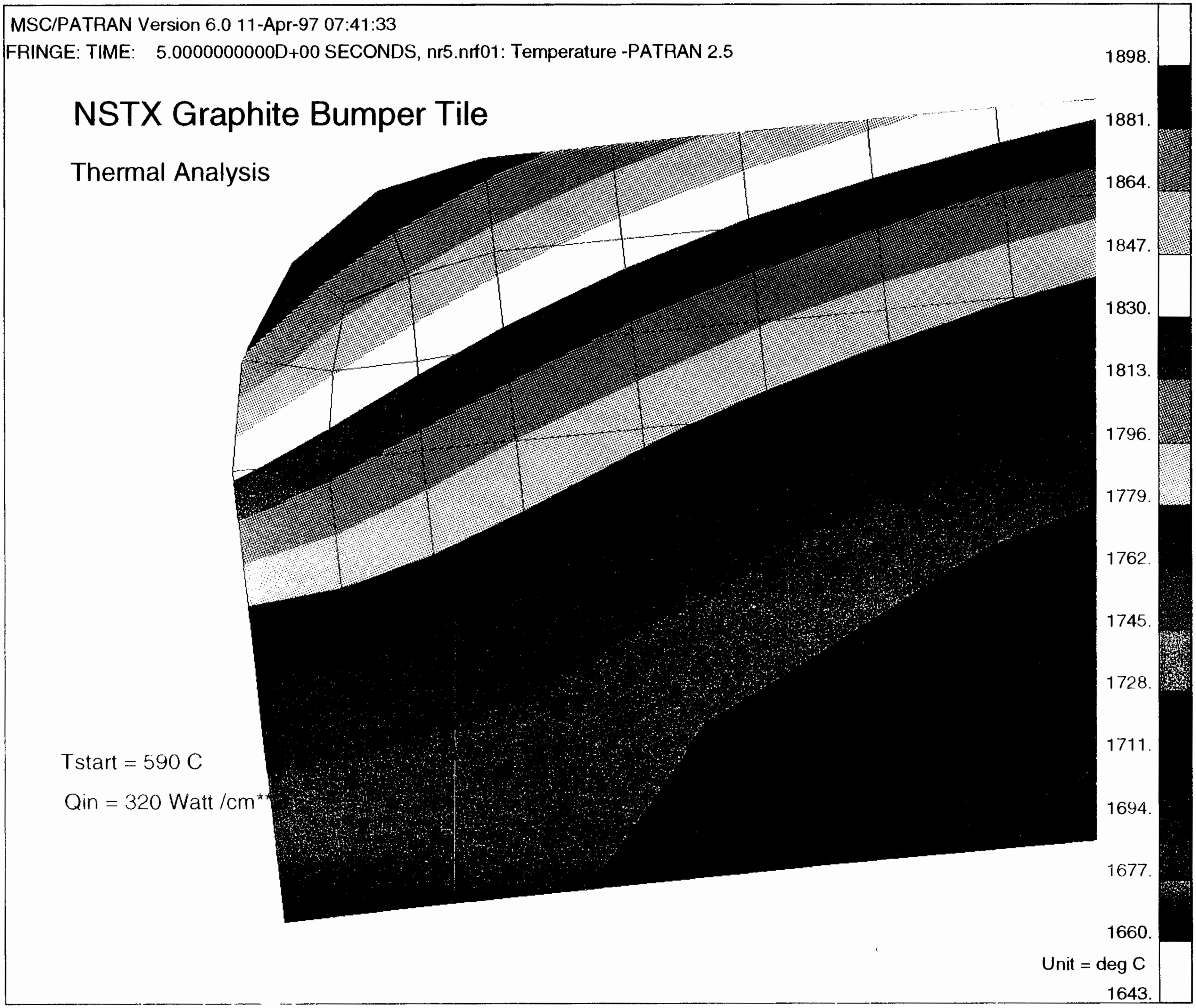
Thermal Analysis
Tstart = 590 C
Qin = 320 Watt /cm**2
1704
1657
1609
1562
1514
1467
1419
1372
1324
1277
1229
1181
1134
1086
1039
Unit = deg C
991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Thermal Analysis
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Qin = 320 Watt /cm**
1898.
1881.
1864.
1847.
1830.
1813.
1796.
1779.
1762.
1745.
1728.
1711.
1694.
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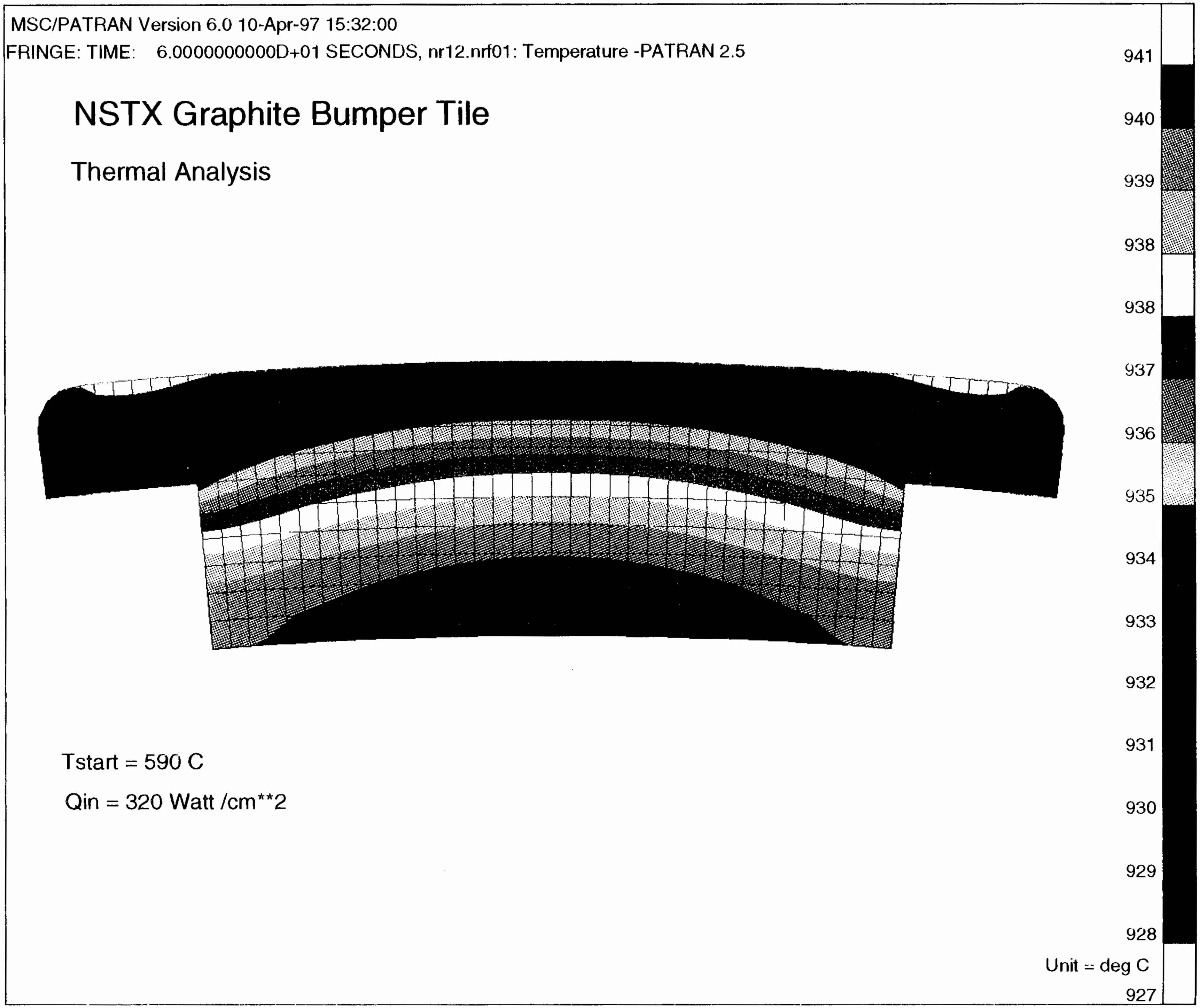
Unit = deg C
1643.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Thermal Analysis
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Qin = 320 Watt /cm**2
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940
939
938
938
937
936
935
934
933
932
931
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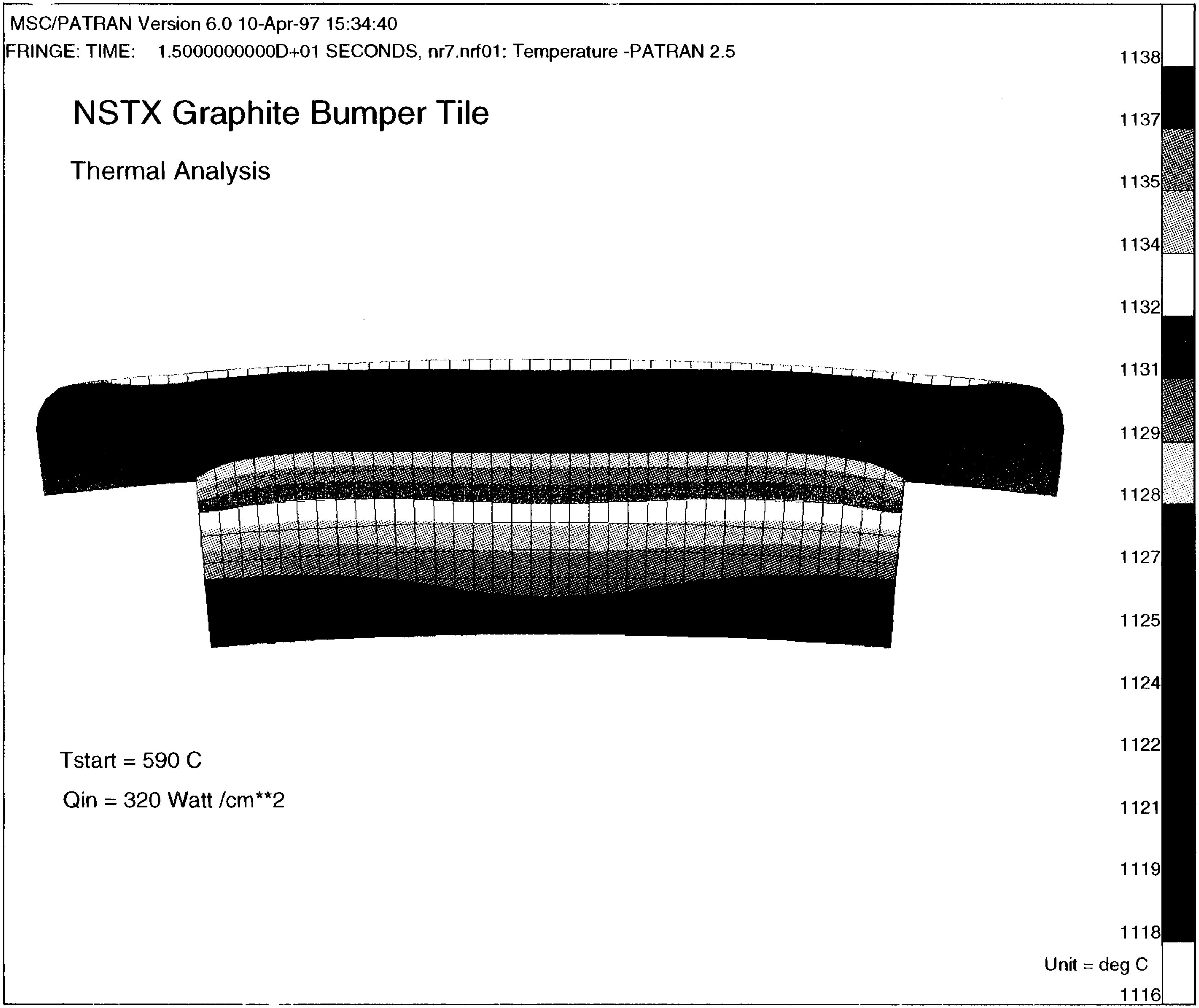
928
Unit = deg C
927



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1138
1137
1135
1134
1132
1131
1129
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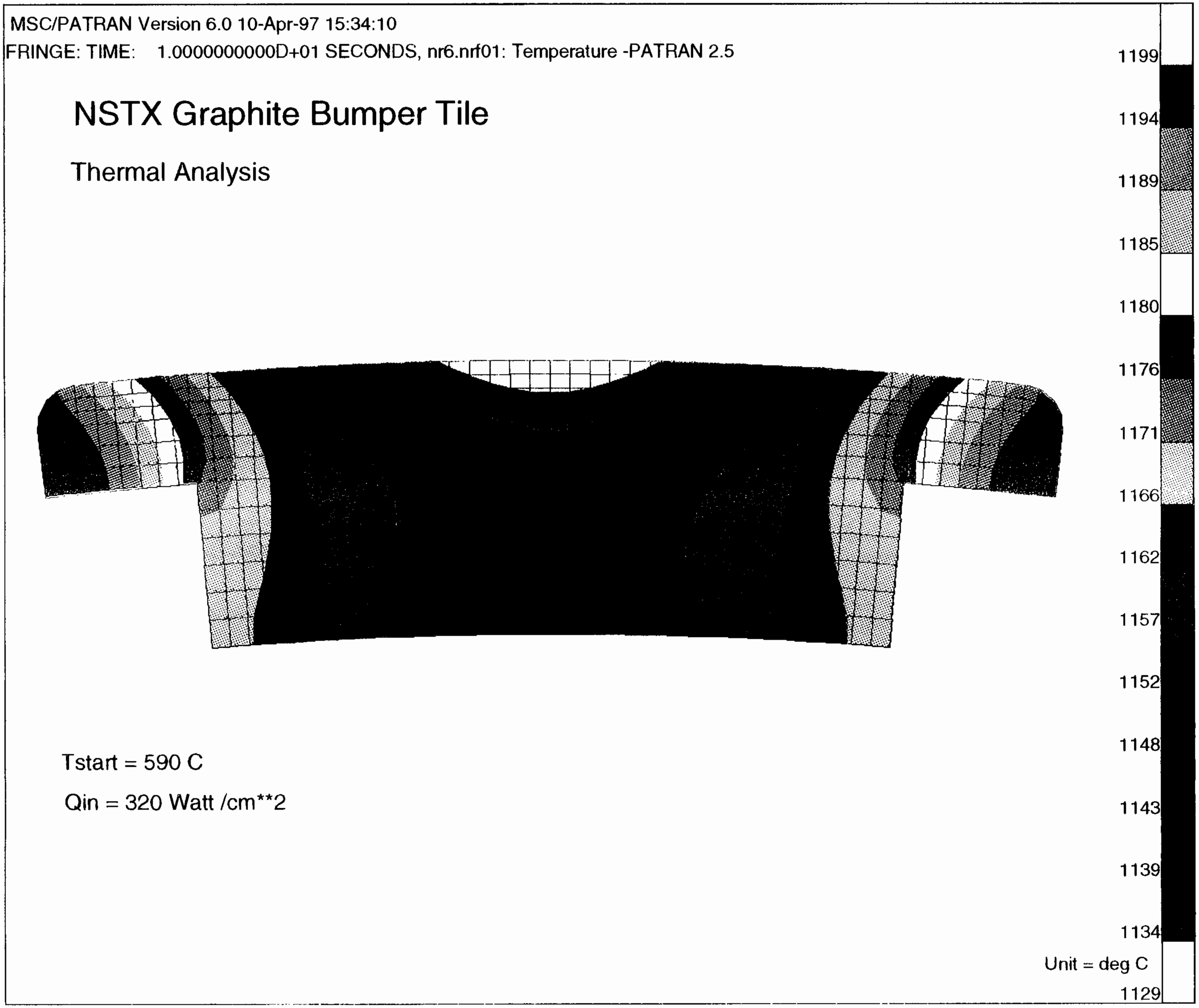
1118
Unit = deg C
1116



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1194
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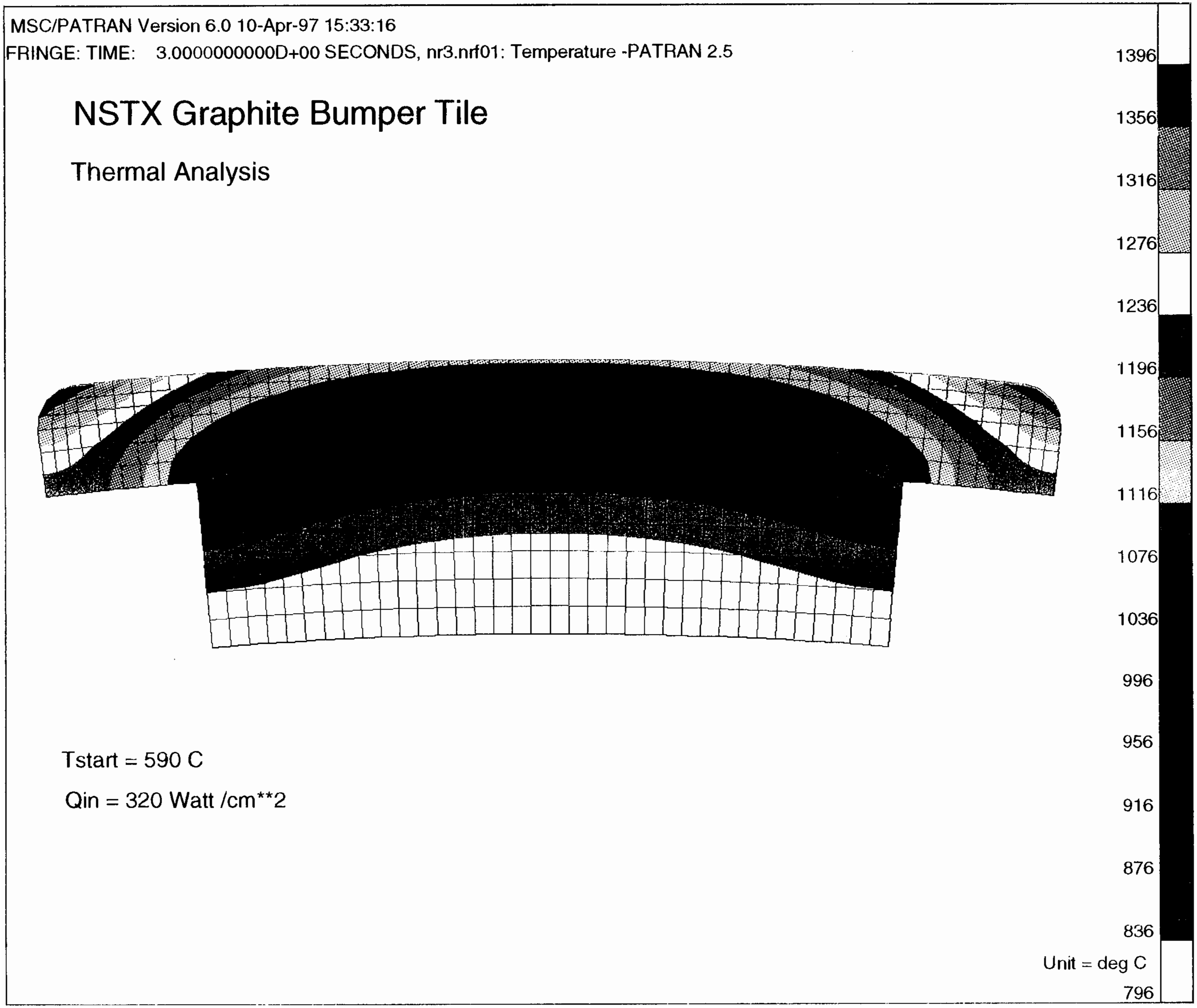
Unit = deg C
1129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1276
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1116
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1036
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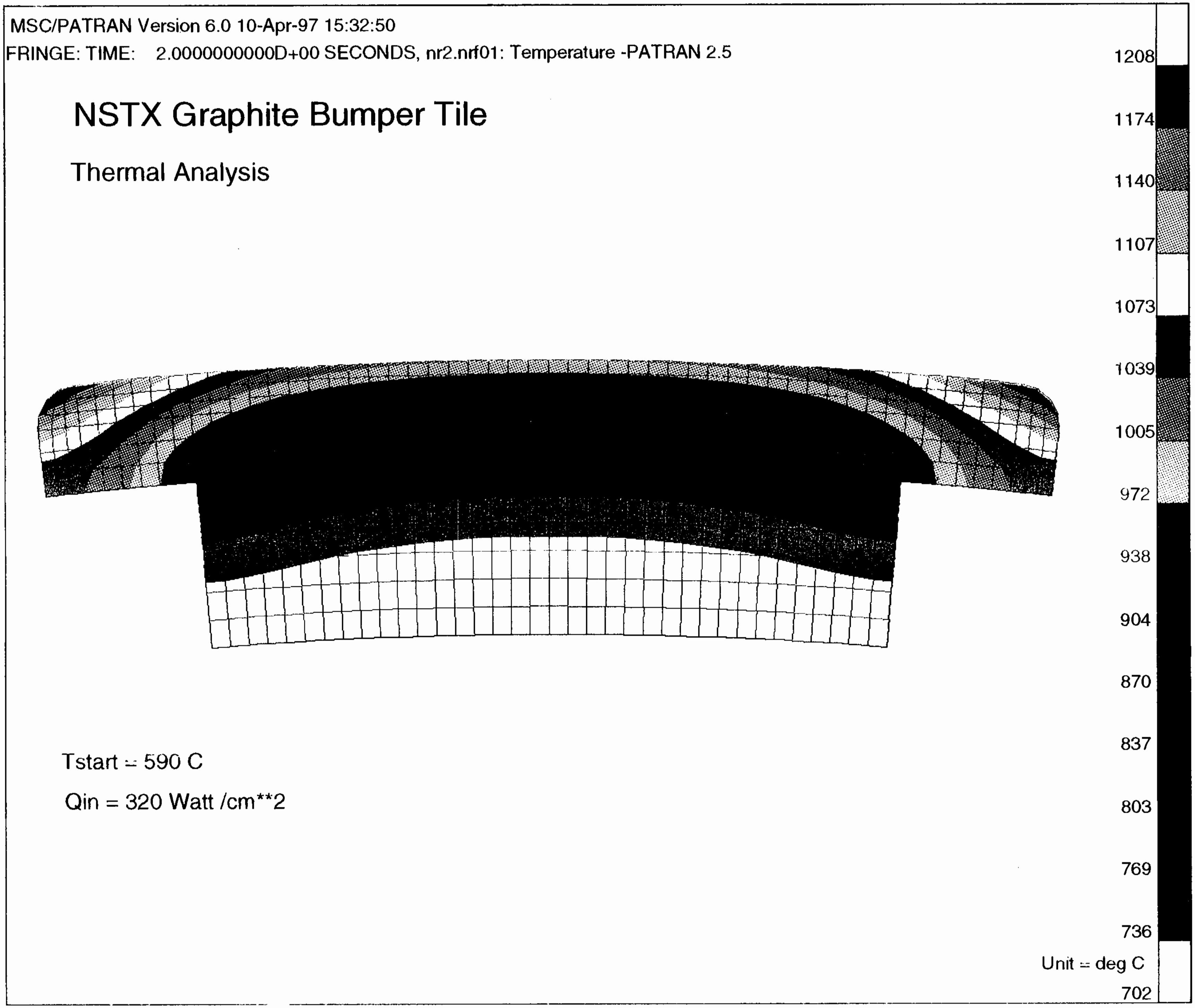
956
916
876
836
Unit = deg C
796



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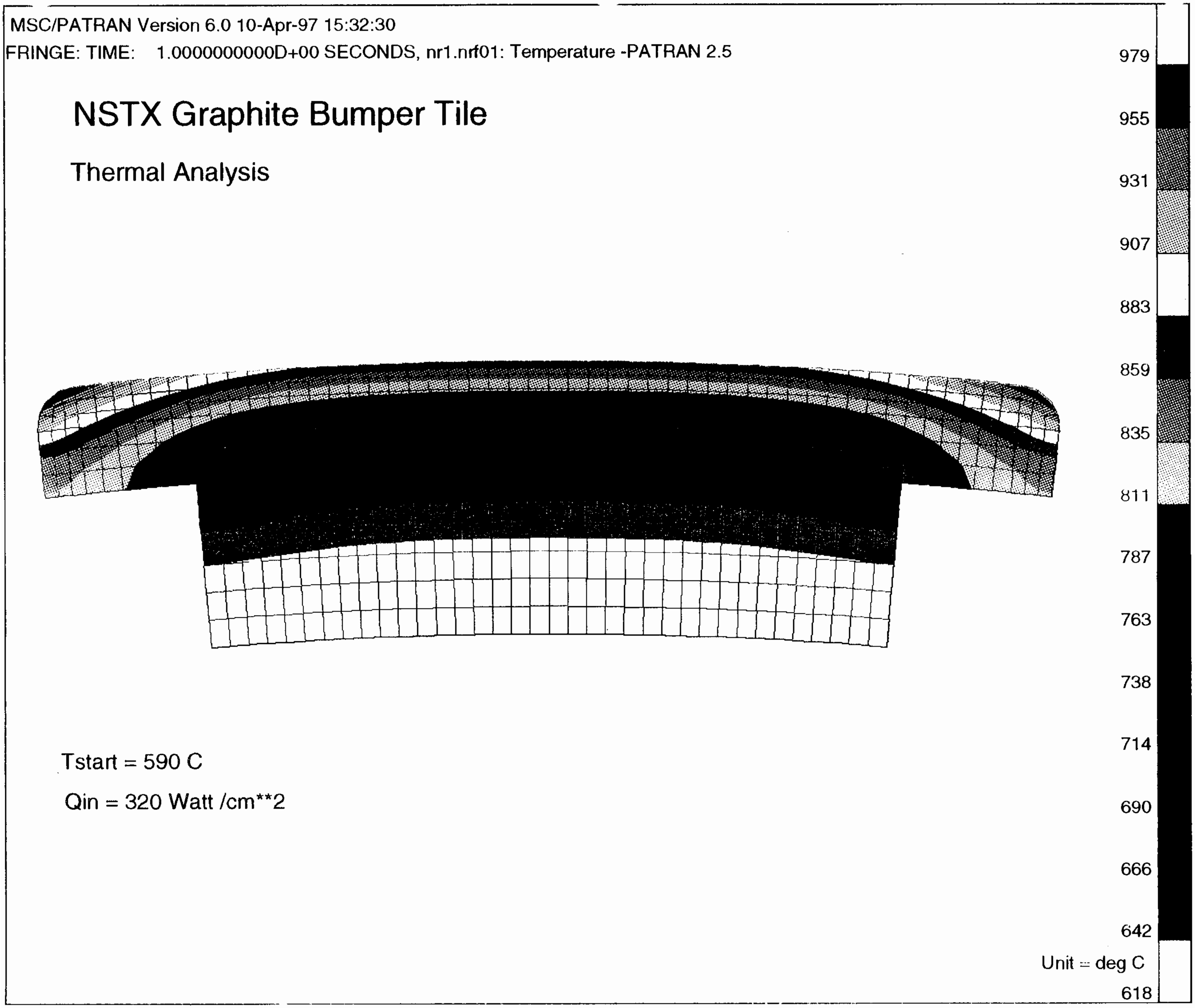
1039
1005
972
938
904
870
837
803
769
736
Unit = deg C
702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907
883
859
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811
787
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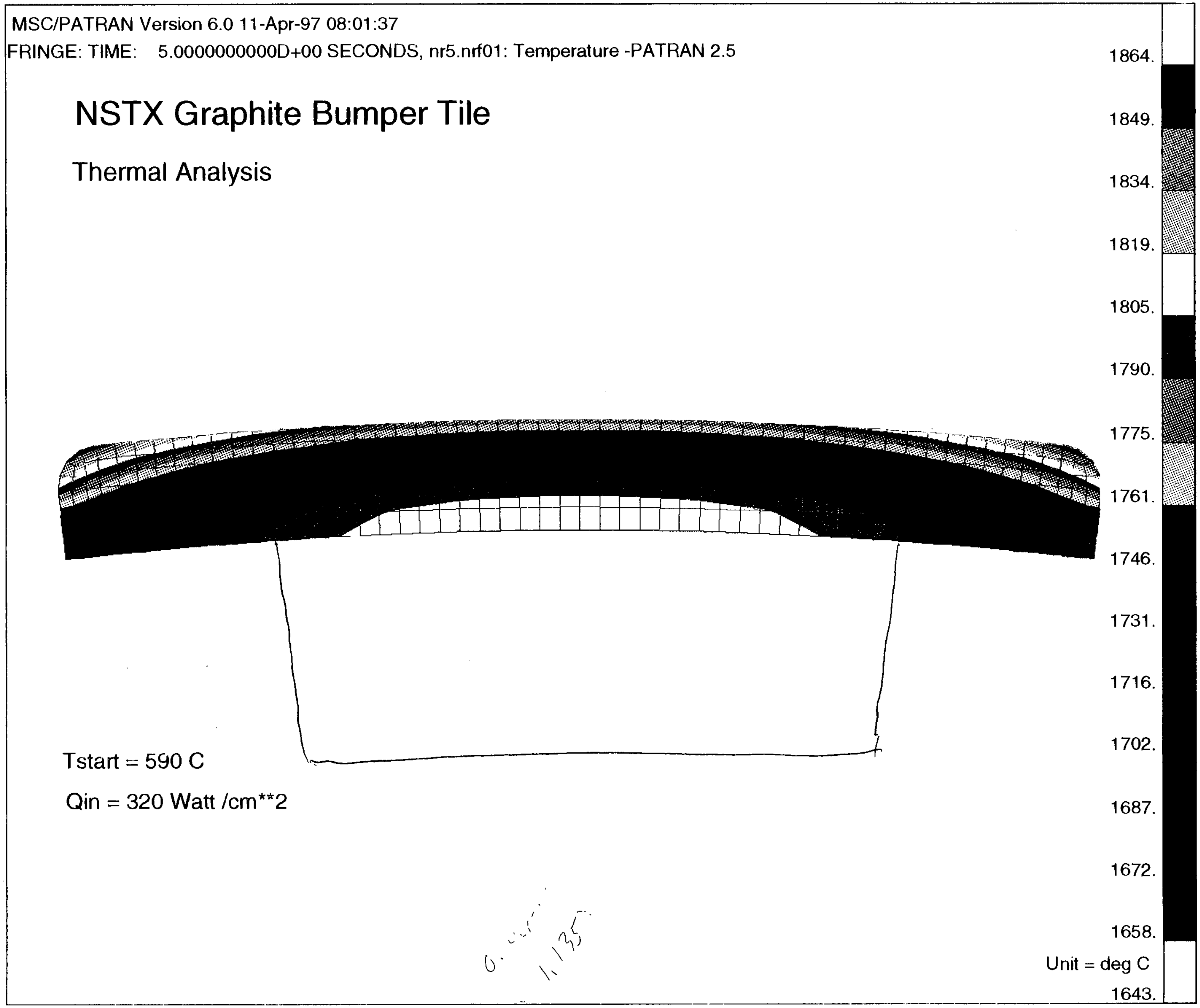
738
714
690
666
642
Unit = deg C
618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1849.
1834.
1819.
1805.
1790.
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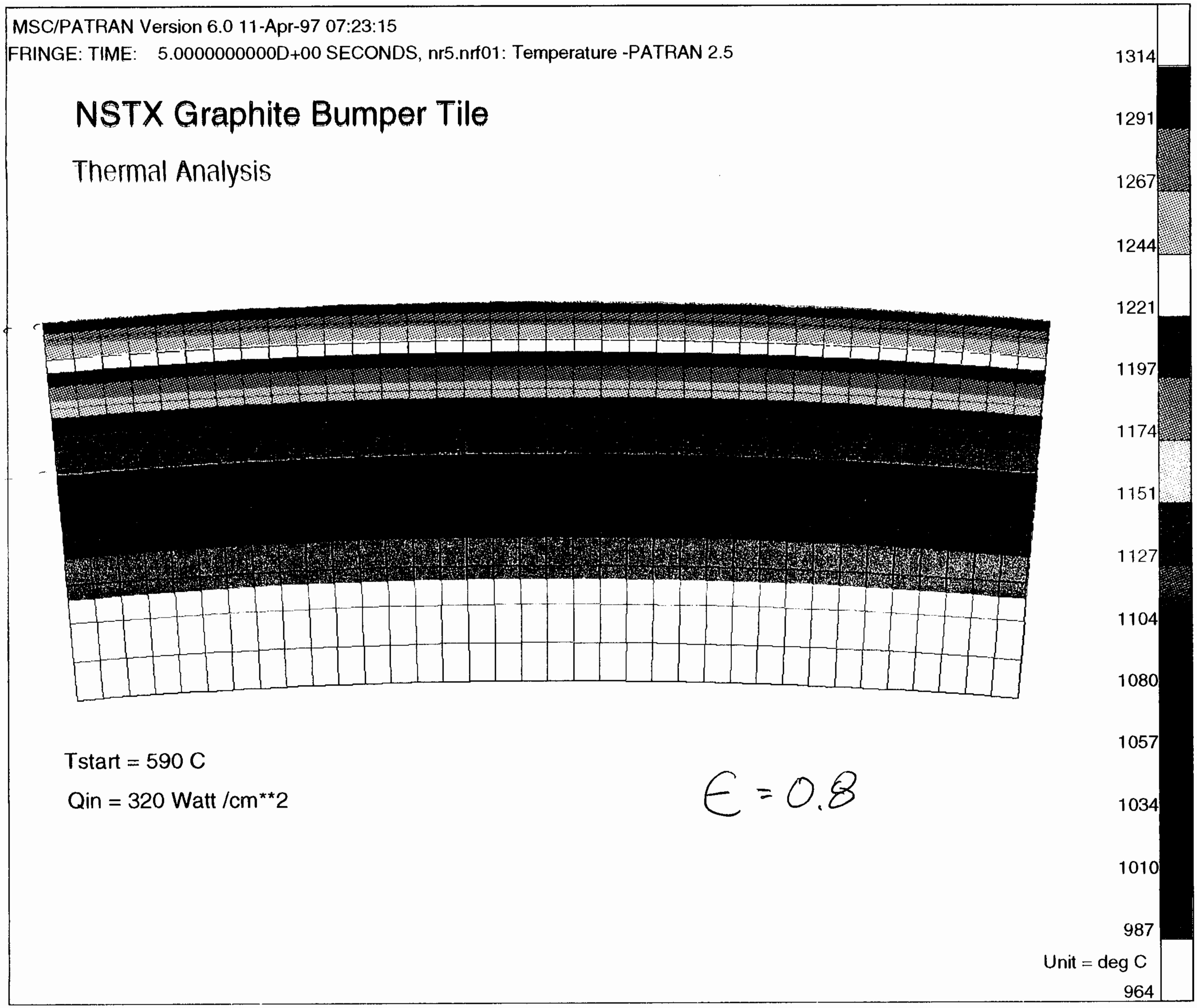
1761.
1746.
1731.
1716.
1702.
1687.
1672.
1658.
Unit = deg C
1643.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Thermal Analysis
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Qin = 320 Watt /cm**2
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1291
1267
1244
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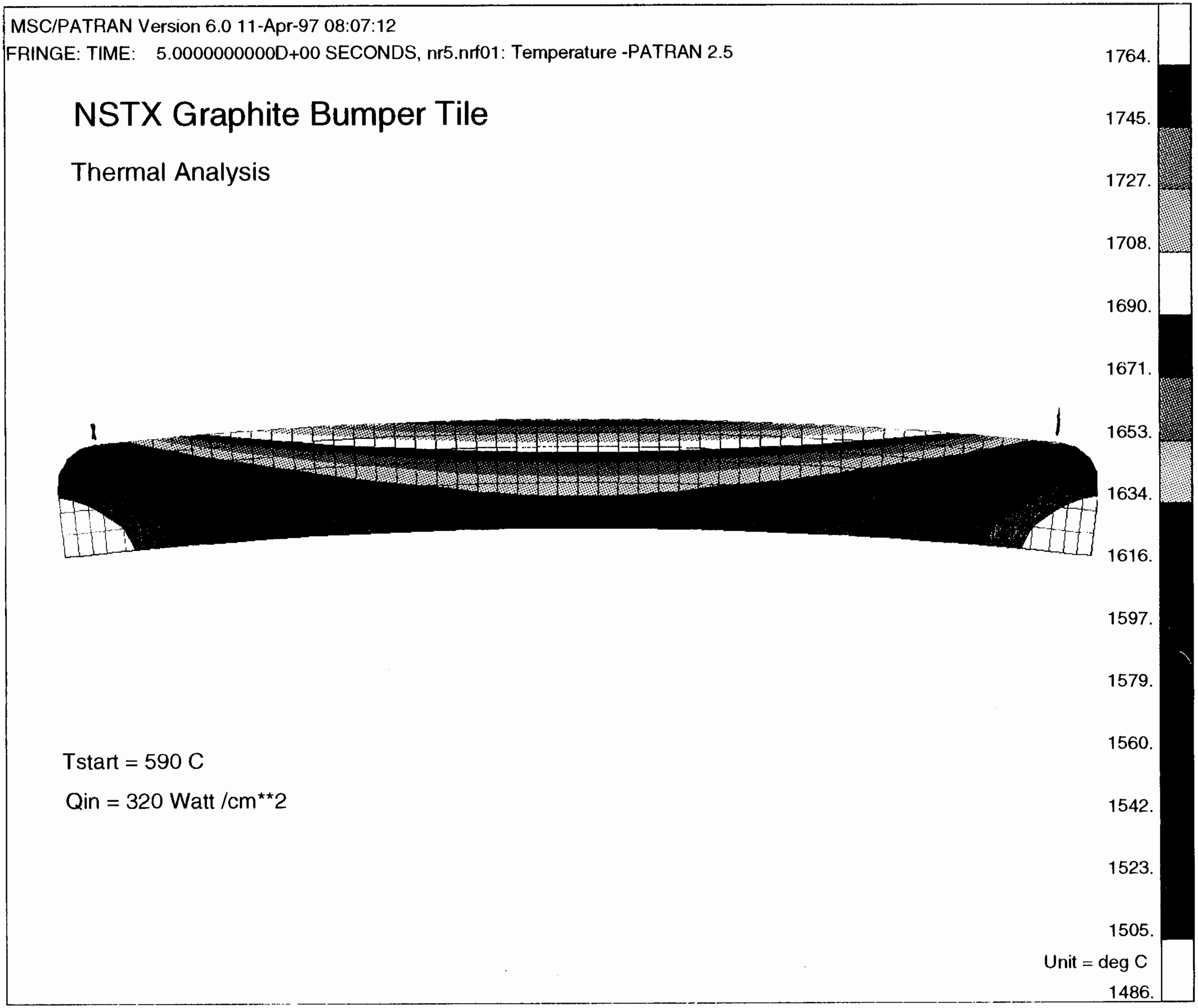
1104
1080
1057
1034
1010
987
Unit = deg C
964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Thermal Analysis
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Qin = 320 Watt /cm**2
1764.
1745.
1727.
1708.
1690.
1671.
1653.
1634.
1616.
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1560.
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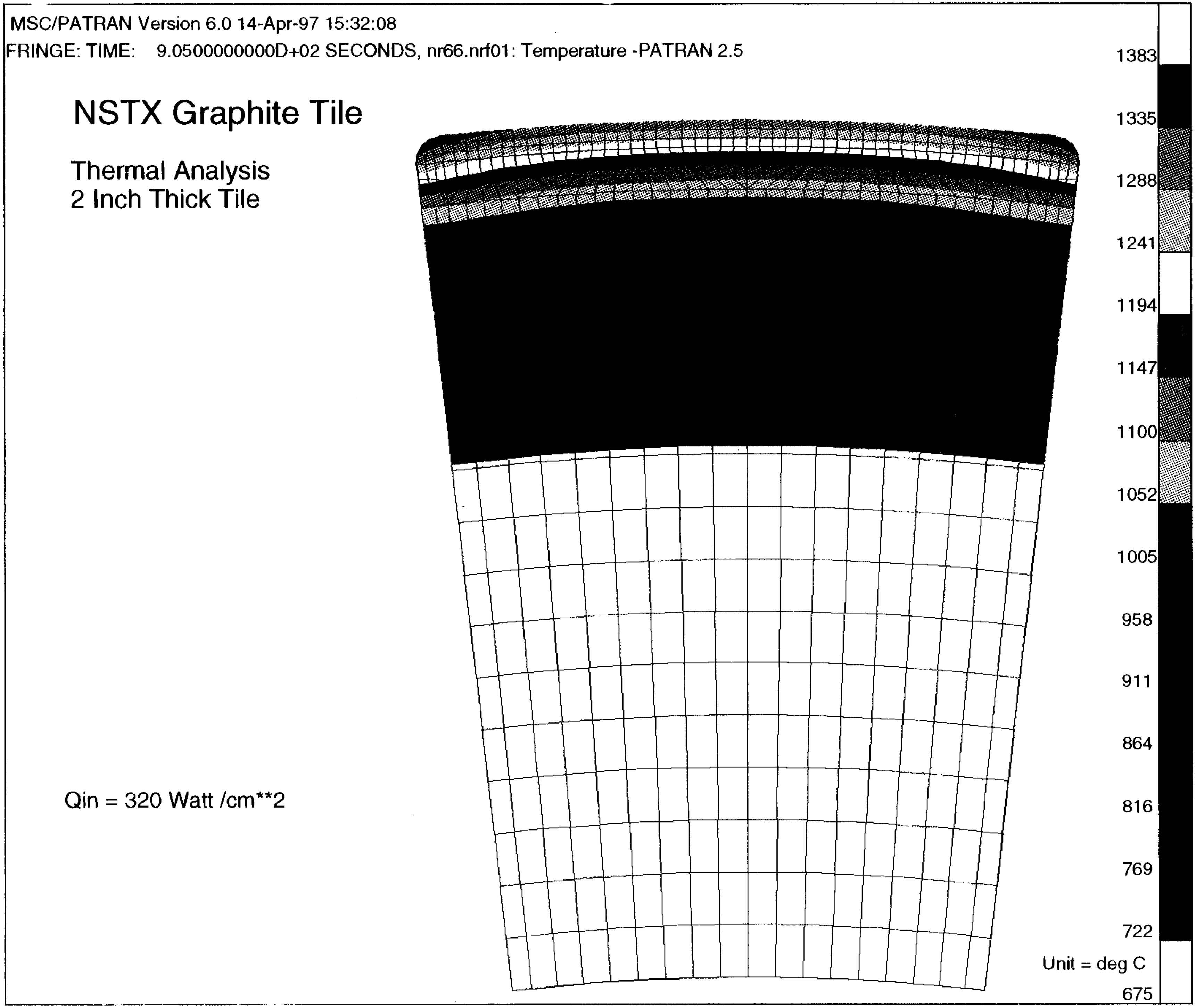
Unit = deg C
1486.



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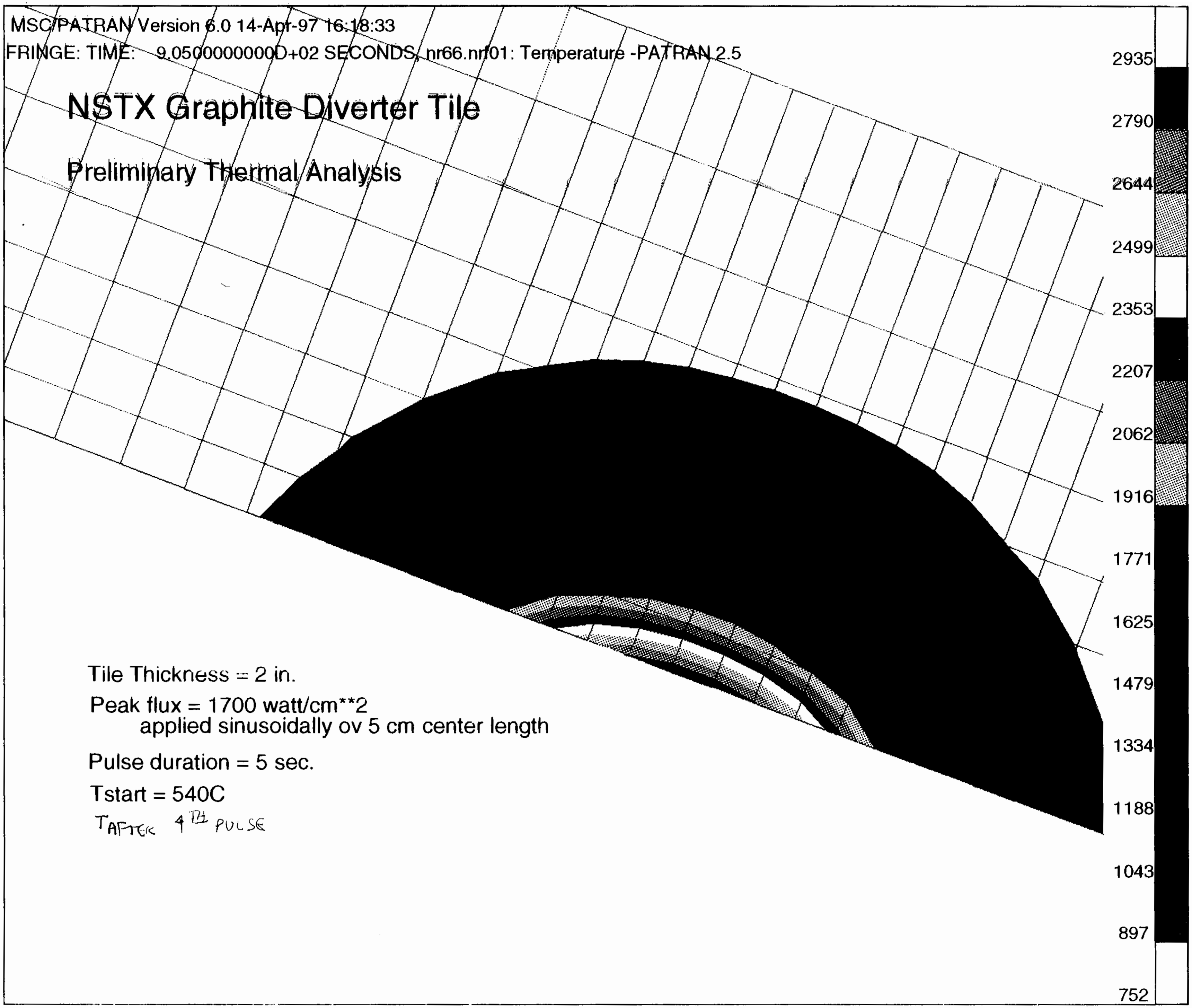
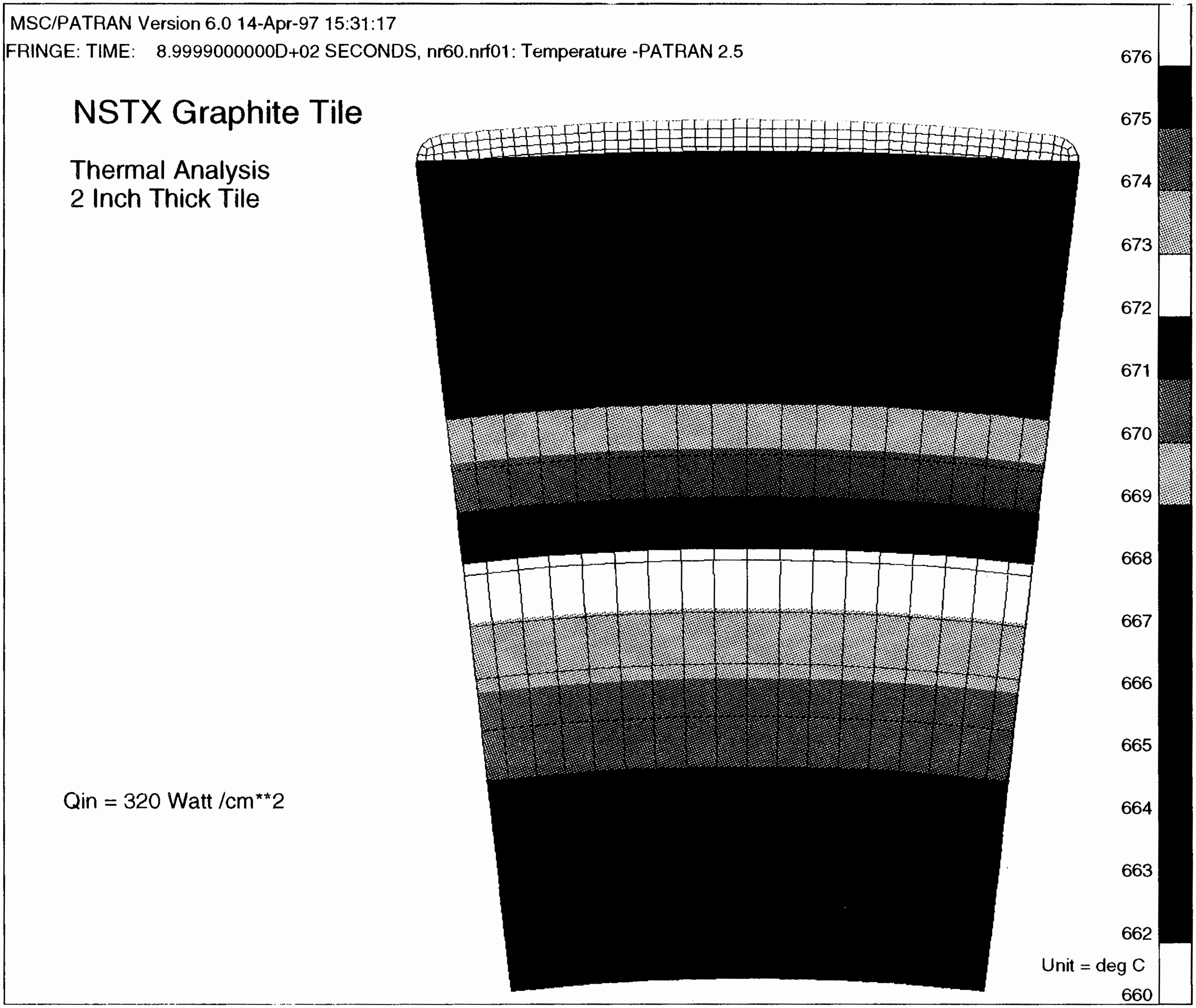
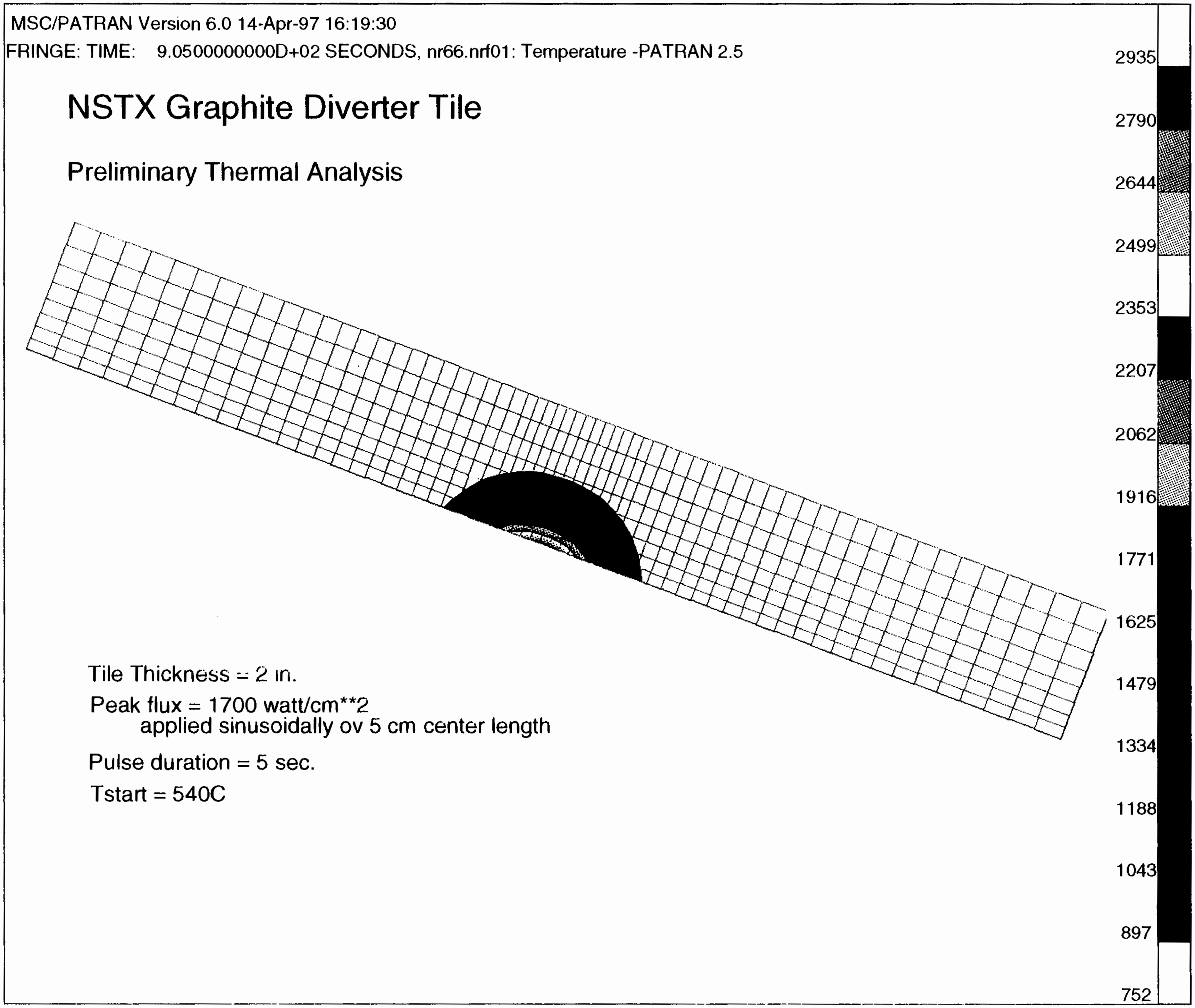
NSTX Graphite Tile
Thermal Analysis
2 Inch Thick Tile
Qin = 320 Watt /cm**2
1383
1335
1288
1241
1194
1147
1100
1052
1005
958
911
864
816
769
722
Unit = deg C
675


MSC/PATRAN Version 6.0 14-Apr-97 16:18:33
FRINGE: TIME: 9.0500000000D+02 SECONDS, nr66.nrf01: Temperature -PATRAN 2.5
NSTX Graphite Diverter Tile
Preliminary Thermal Analysis
Tile Thickness = 2 in.
Peak flux = 1700 watt/cm**2
applied sinusoidally ov 5 cm center length
Pulse duration = 5 sec.
Tstart = 540C
TAFTER 4TH PULSE
2935
2790
2644
2499
2353
2207
2062
1916
1771
1625
1479
1334
1188
1043
897
752



MSC/PATRAN Version 6.0 14-Apr-97 15:31:17
FRINGE: TIME: 8.9999000000D+02 SECONDS, nr60.nrf01: Temperature -PATRAN 2.5
NSTX Graphite Tile
Thermal Analysis
2 Inch Thick Tile
Qin = 320 Watt /cm**2
676
675
674
673
672
671
670
669
668
667
666
665
664
663
662
Unit = deg C
660



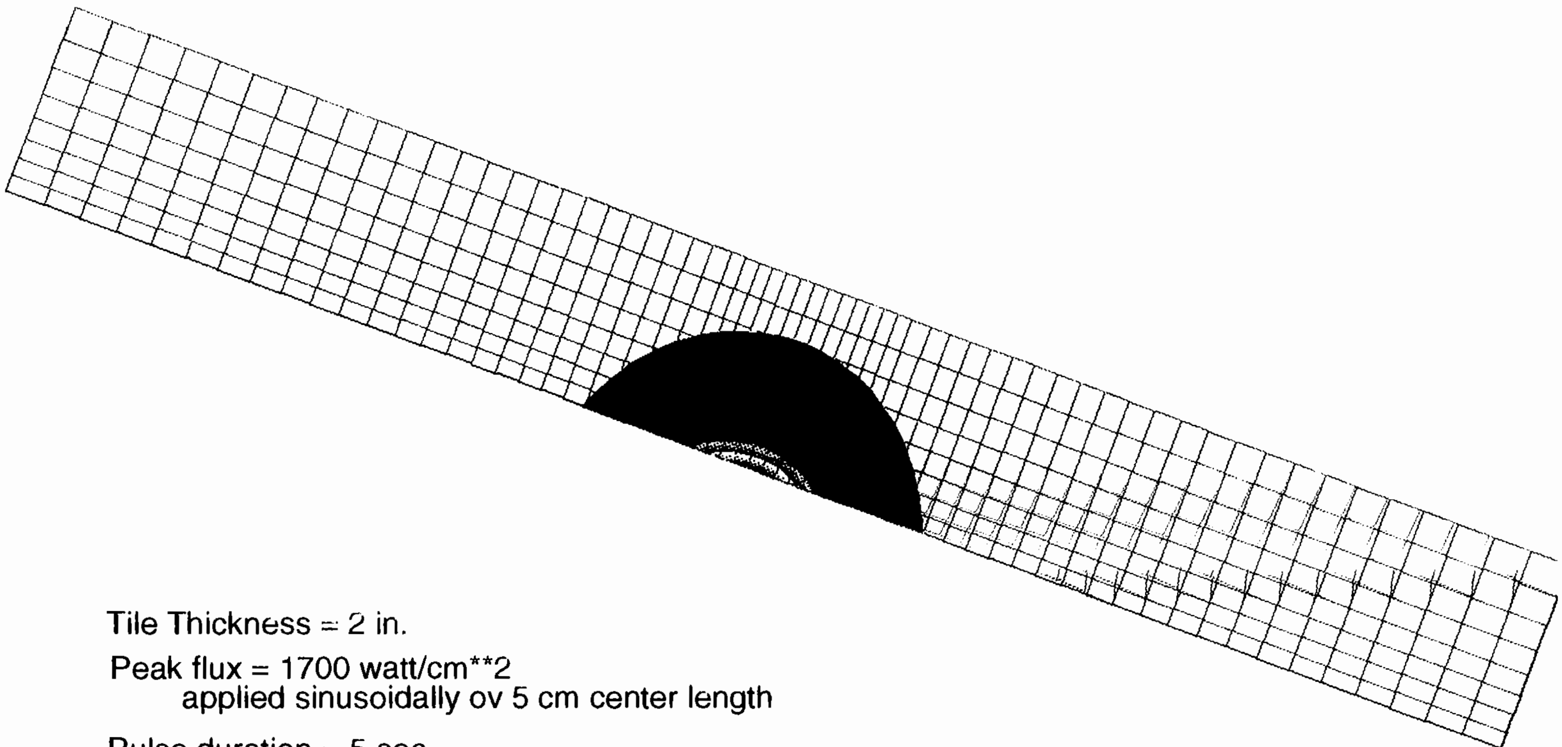
MSC/PATRAN Version 6.0 14-Apr-97 16:19:30
FRINGE: TIME: 9.0500000000D+02 SECONDS, nr66.nrf01: Temperature -PATRAN 2.5
NSTX Graphite Diverter Tile
Preliminary Thermal Analysis
Tile Thickness = 2 in.
Peak flux = 1700 watt/cm**2
applied sinusoidally ov 5 cm center length
Pulse duration = 5 sec.
Tstart = 540C
2935
2790
2644
2499
2353
2207
2062
1916
1771
1625
1479
1334
1188
1043
897
752

MSC/PATRAN Version 6.0 14-Apr-97 15:37:39

FRINGE: TIME: 5.0000000000D+00 SECONDS, nr5.nrf01: Temperature -PATRAN 2.5

# NSTX Graphite Diverter Tile

## Preliminary Thermal Analysis



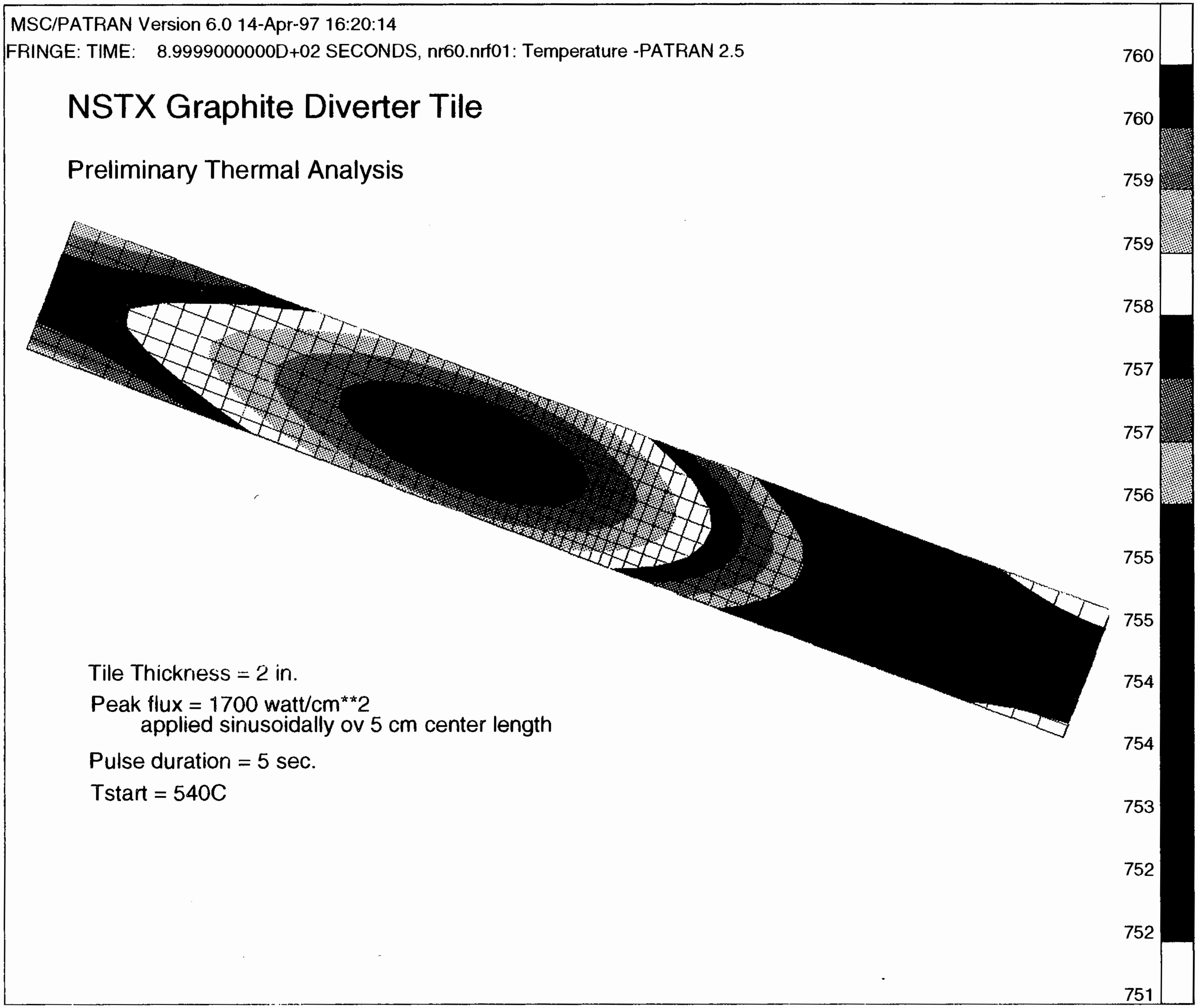

Tile Thickness = 2 in.

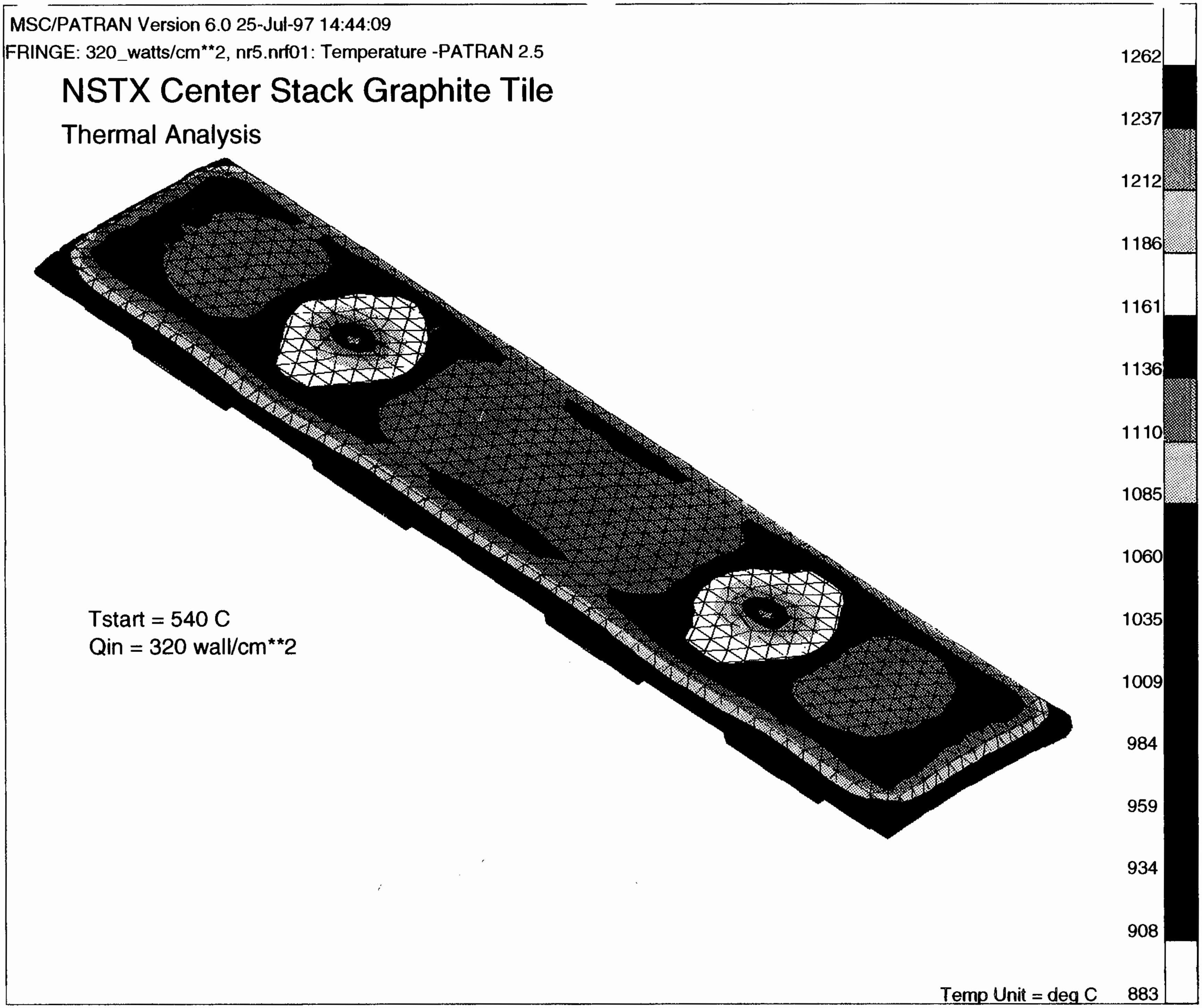
Peak flux = 1700 watt/cm**2
applied sinusoidally ov 5 cm center length

Pulse duration = 5 sec.

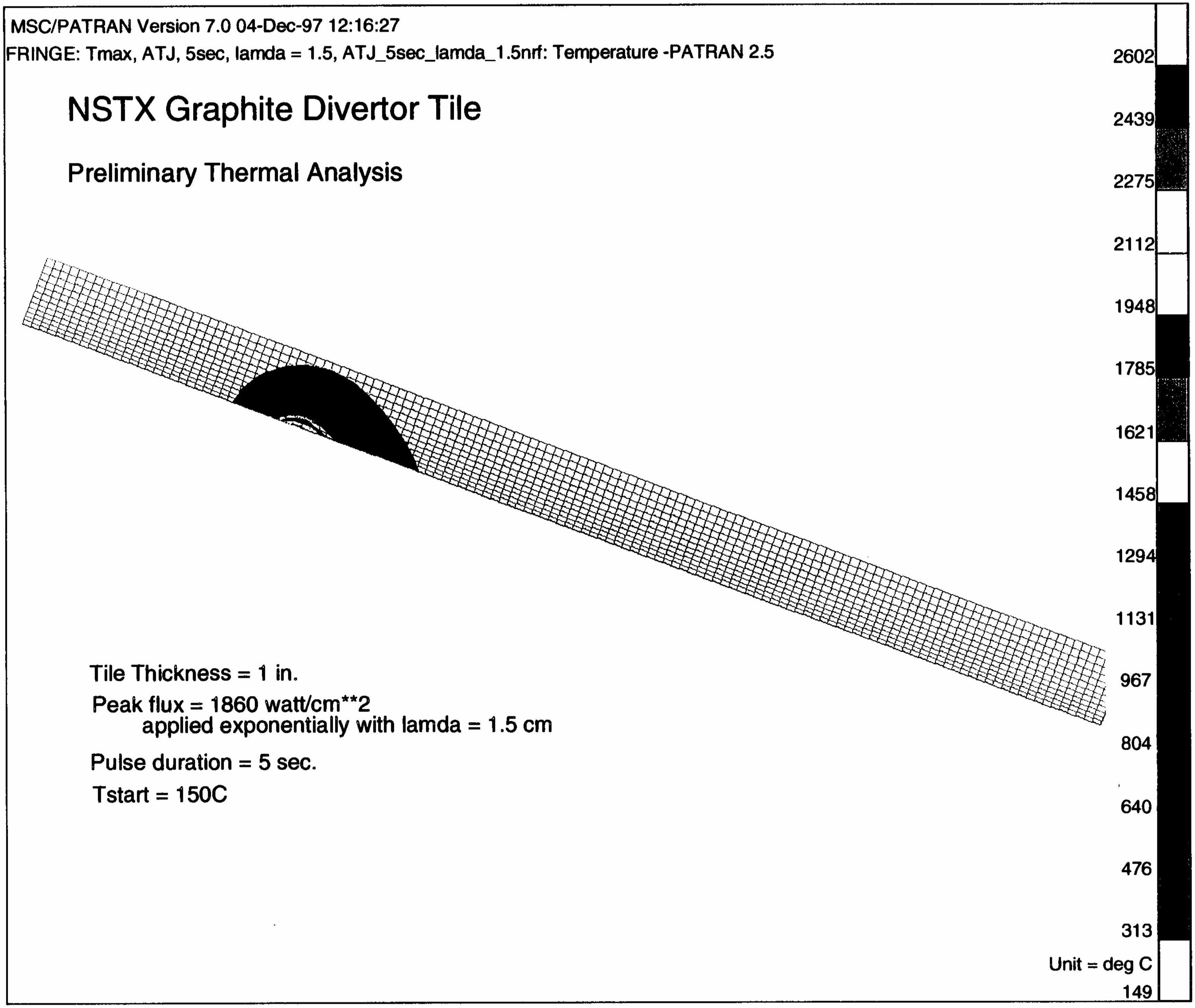
Tstart = ~~540C~~ 0

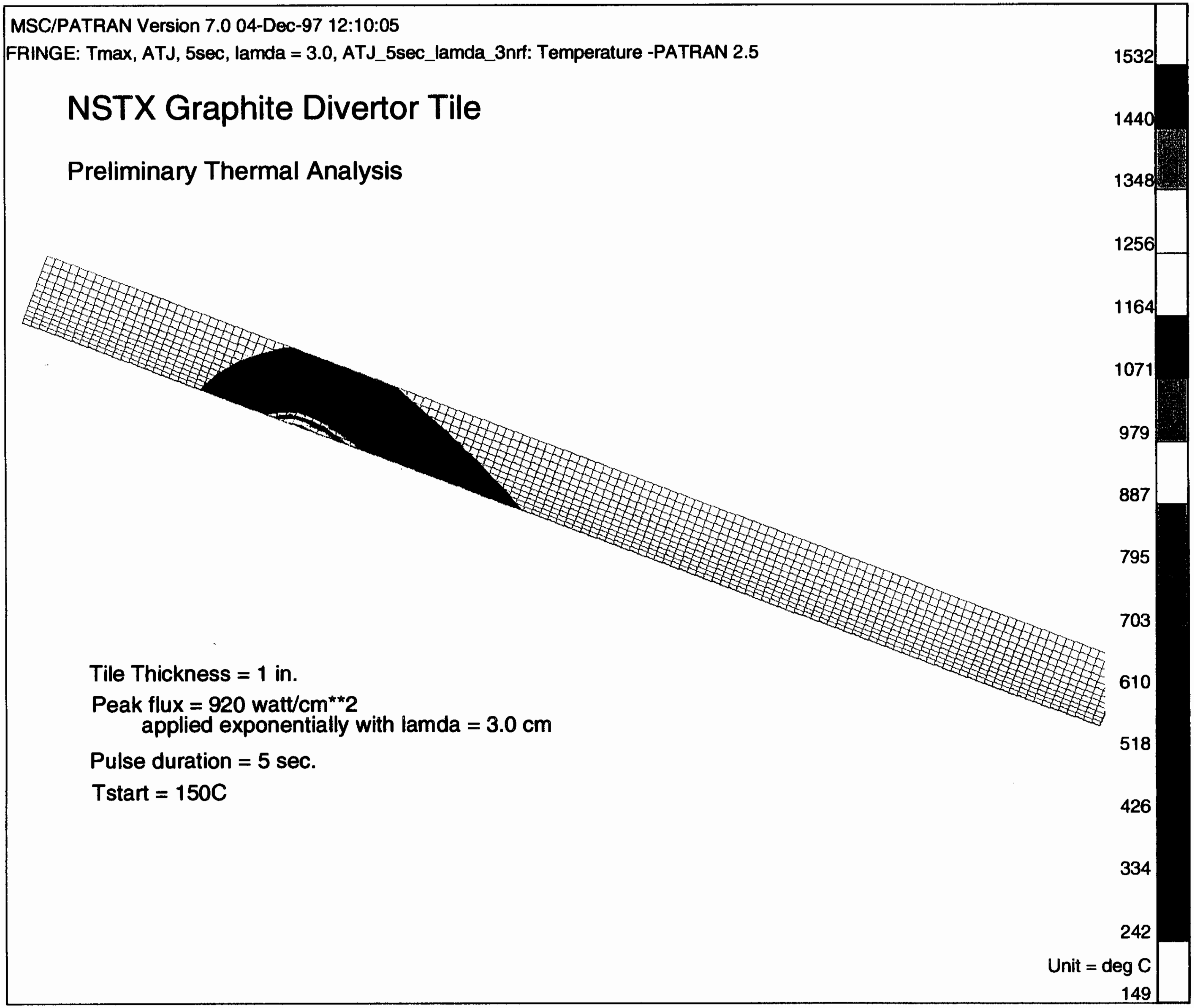
Conductivity = 2X Poco

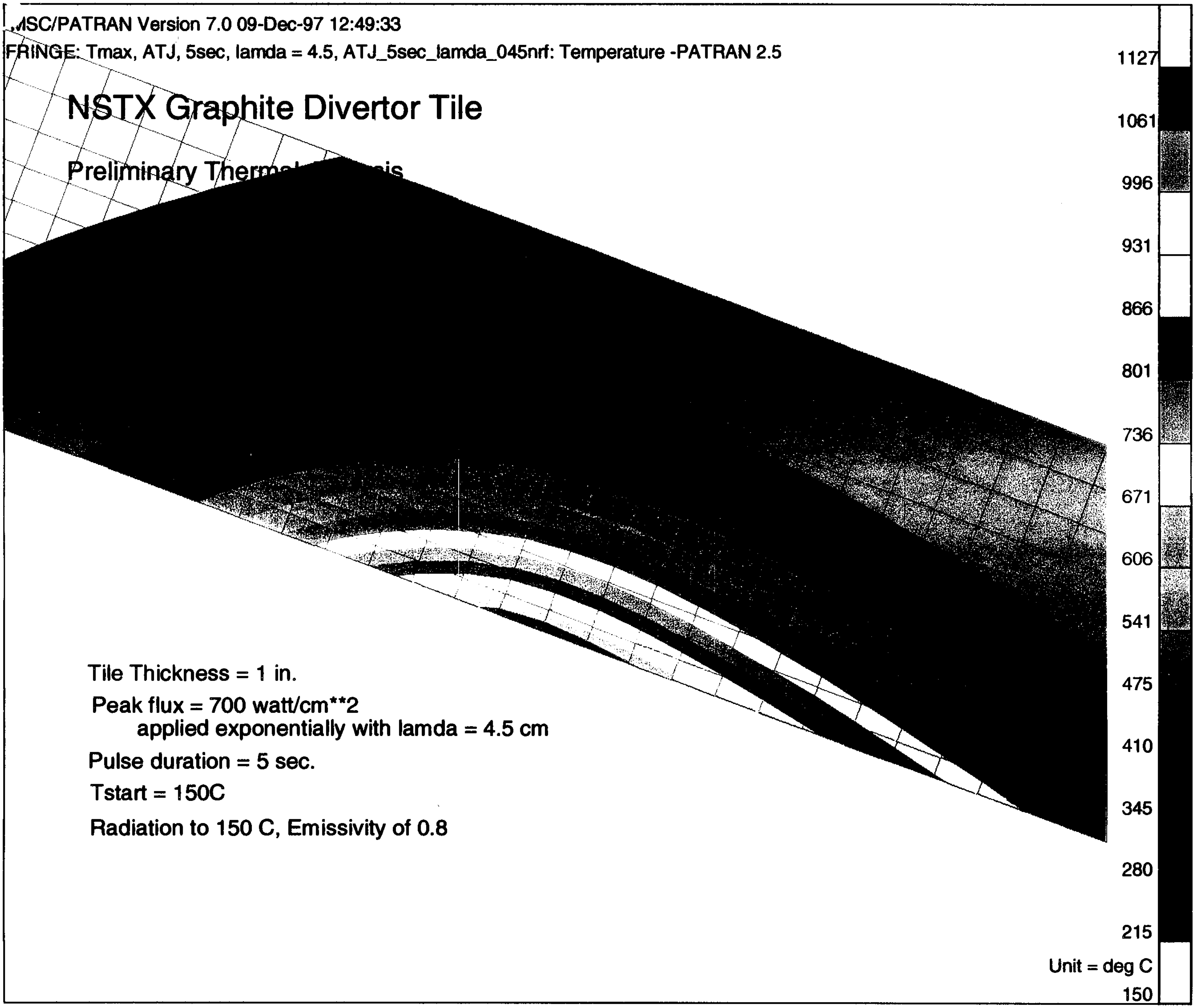

MSC/PATRAN Version 6.0 14-Apr-97 16:20:14
FRINGE: TIME: 8.9999000000D+02 SECONDS, nr60.nrf01: Temperature -PATRAN 2.5
NSTX Graphite Diverter Tile
Preliminary Thermal Analysis
Tile Thickness = 2 in.
Peak flux = 1700 watt/cm**2
applied sinusoidally ov 5 cm center length
Pulse duration = 5 sec.
Tstart = 540C
760
760
759
759
758
757
757
756
755
755
754
754
753
752
752
751

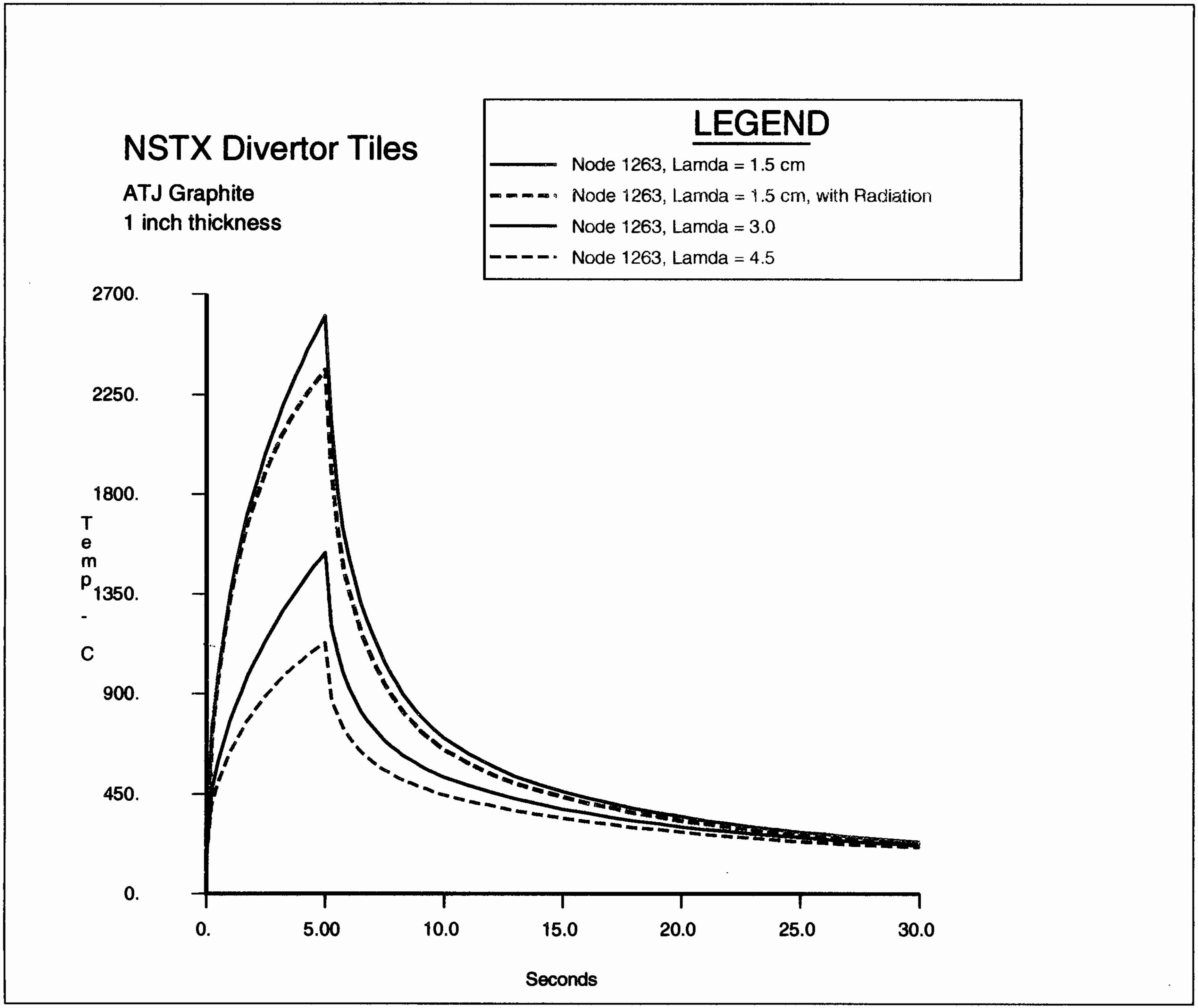


MSC/PATRAN Version 6.0 25-Jul-97 14:44:09
FRINGE: 320_watts/cm**2, nr5.nrf01: Temperature -PATRAN 2.5
NSTX Center Stack Graphite Tile
Thermal Analysis
Tstart = 540 C
Qin = 320 wall/cm**2
1262
1237
1212
1186
1161
1136
1110
1085
1060
1035
1009
984
959
934
908
883
Temp Unit = deg C


MSC/PATRAN Version 7.0 04-Dec-97 12:16:27
FRINGE: Tmax, ATJ, 5sec, lamda = 1.5, ATJ_5sec_lamda_1.5nrf: Temperature -PATRAN 2.5
NSTX Graphite Divertor Tile
Preliminary Thermal Analysis
Tile Thickness = 1 in.
Peak flux = 1860 watt/cm**2
applied exponentially with lamda = 1.5 cm
Pulse duration = 5 sec.
Tstart = 150C
2602
2439
2275
2112
1948
1785
1621
1458
1294
1131
967
804
640
476
313
Unit = deg C
149


MSC/PATRAN Version 7.0 04-Dec-97 12:10:05
FRINGE: Tmax, ATJ, 5sec, lamda = 3.0, ATJ_5sec_lamda_3nrf: Temperature -PATRAN 2.5
NSTX Graphite Divertor Tile
Preliminary Thermal Analysis
Tile Thickness = 1 in.
Peak flux = 920 watt/cm**2
applied exponentially with lamda = 3.0 cm
Pulse duration = 5 sec.
Tstart = 150C
1532
1440
1348
1256
1164
1071
979
887
795
703
610
518
426
334
242
Unit = deg C
149


MSC/PATRAN Version 7.0 09-Dec-97 12:49:33
FRINGE: Tmax, ATJ, 5sec, lamda = 4.5, ATJ_5sec_lamda_045nrf: Temperature -PATRAN 2.5
NSTX Graphite Divertor Tile
Preliminary Therm
Tile Thickness = 1 in.
Peak flux = 700 watt/cm**2
applied exponentially with lamda = 4.5 cm
Pulse duration = 5 sec.
Tstart = 150C
Radiation to 150 C, Emissivity of 0.8
1127
1061
996
931
866
801
736
671
606
541
475
410
345
280
215
Unit = deg C
150

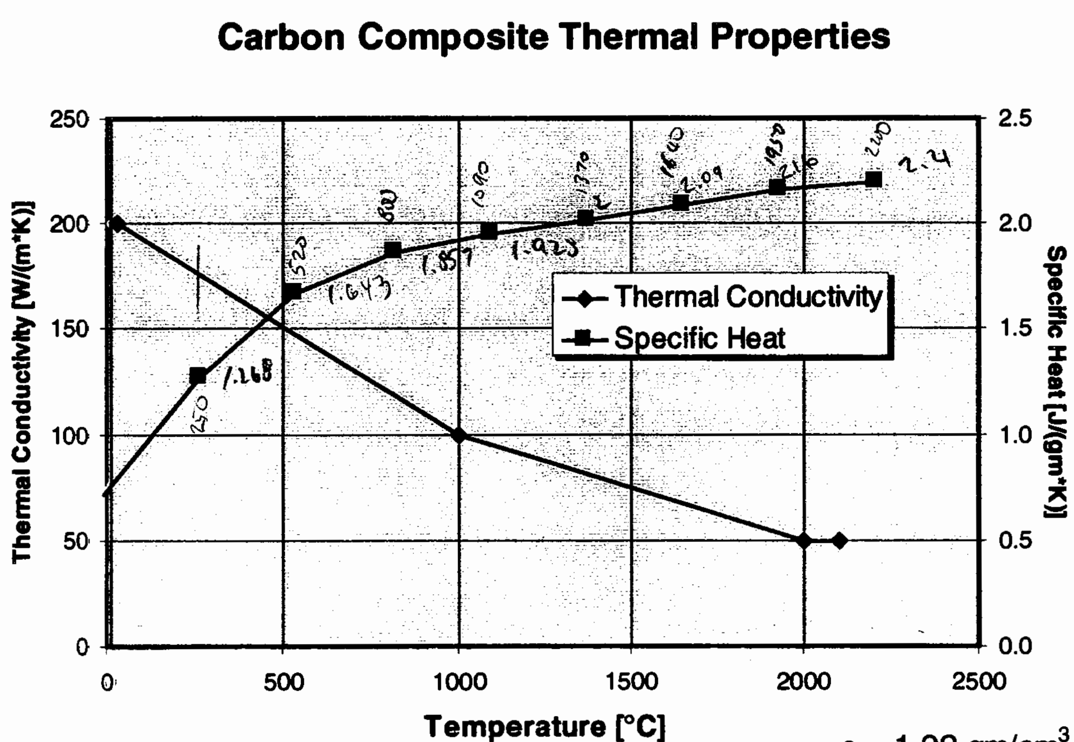

NSTX Divertor Tiles
ATJ Graphite
1 inch thickness
LEGEND
Node 1263, Lamda = 1.5 cm
Node 1263, Lamda = 1.5 cm, with Radiation
Node 1263, Lamda = 3.0
Node 1263, Lamda = 4.5
2700.
2250.
1800.
1350.
900.
450.
0.
Temp - C
0.
5.00
10.0
15.0
20.0
25.0
30.0
Seconds

# NSTX Inner Stack Carbon Tile Thermal Analysis

- Transient simulation: 5 second pulse every 5 minutes.
- Plasma heat flux: 200 $W/cm^2$
- Radiative cooling to 150°C sink, $\varepsilon = 0.8$

- Allied Signal carbon composite material.
- Insufficient data for orthotropic thermal conductivity; employed isotropic thermal properties.

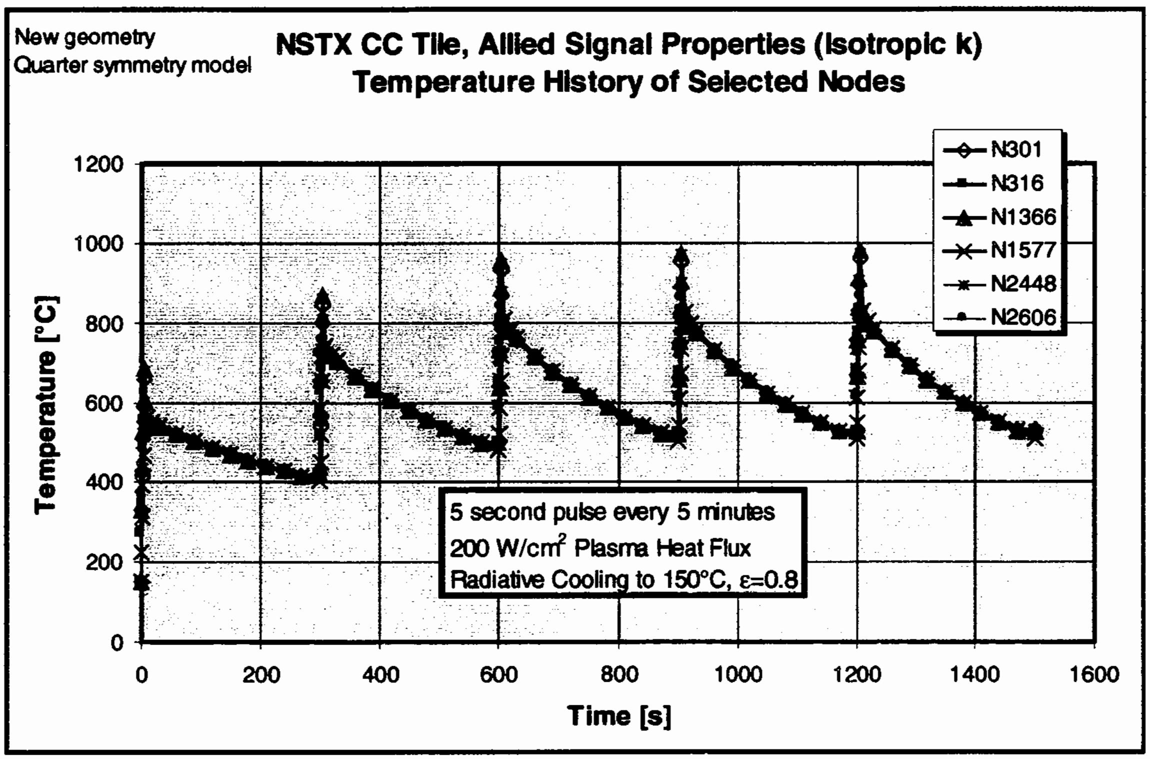
- Quarter symmetry model using recent ProE geometry (Jan. 25.)

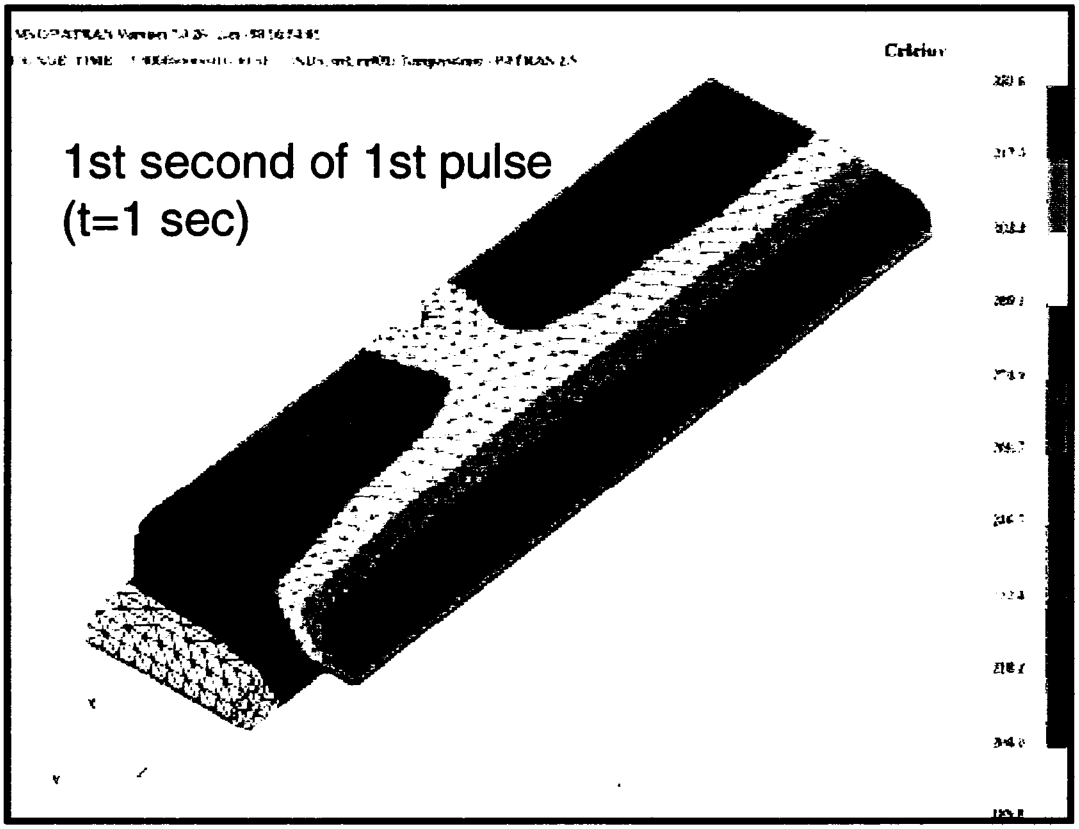



ρ = 1.92 gm/cm³

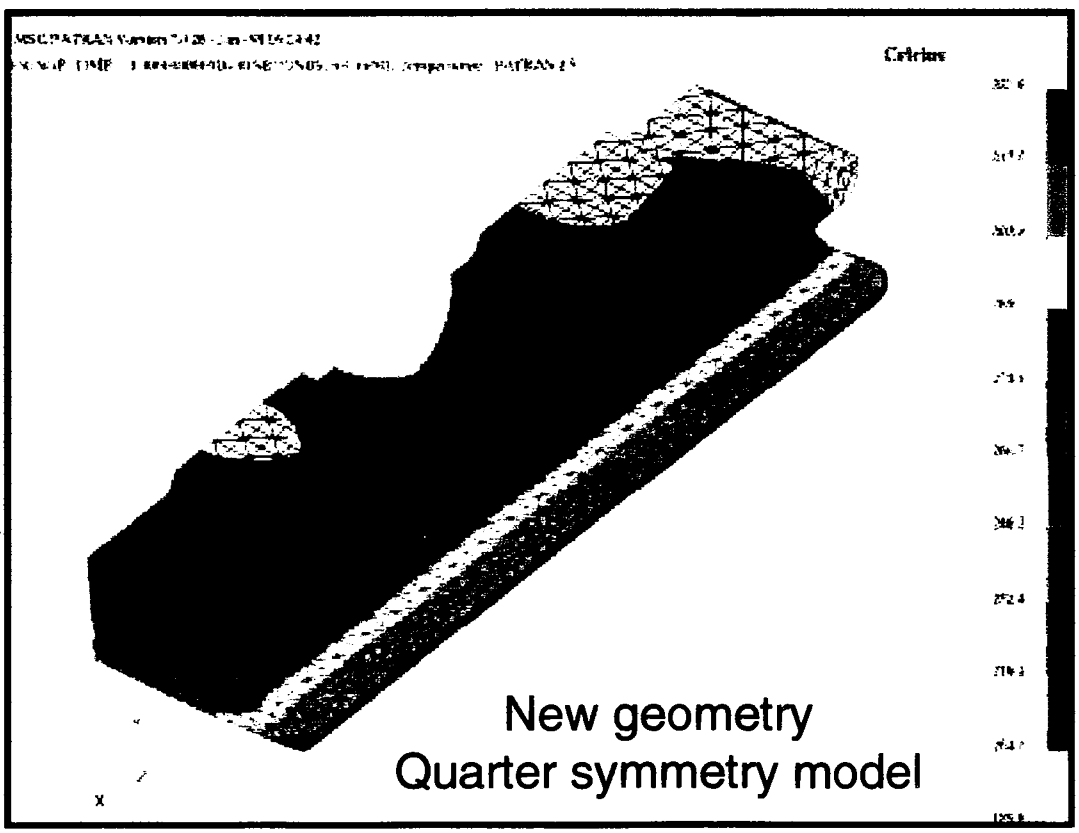
- Maximum temperature at end of 5th pulse is 982°C.

- Pre-pulse temperature after 5 cycles is < 530°C.
  Thermal ratcheting nearly leveled off.

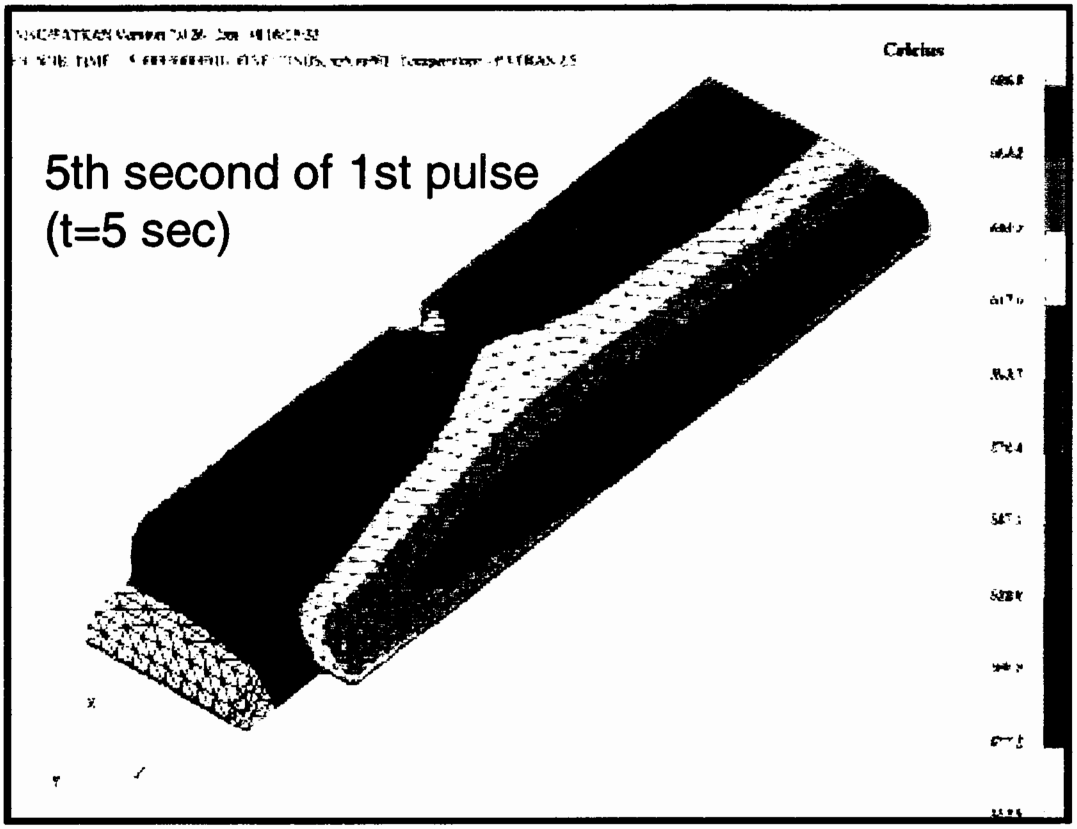


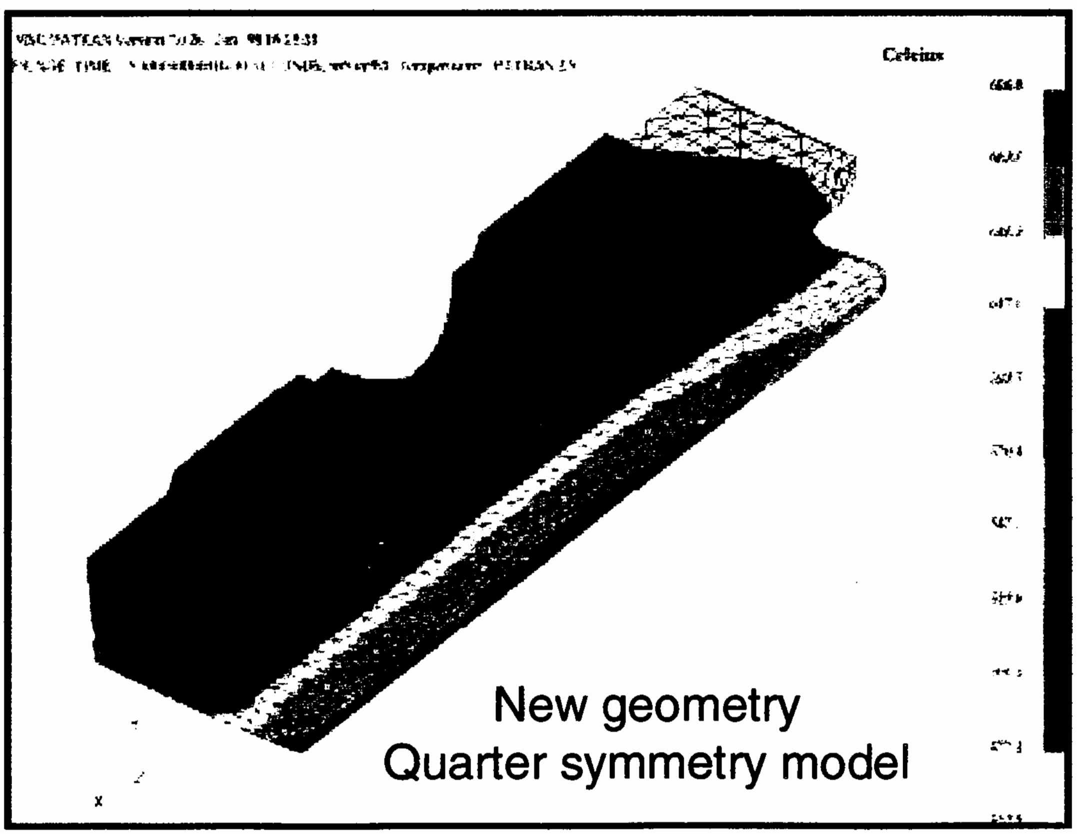


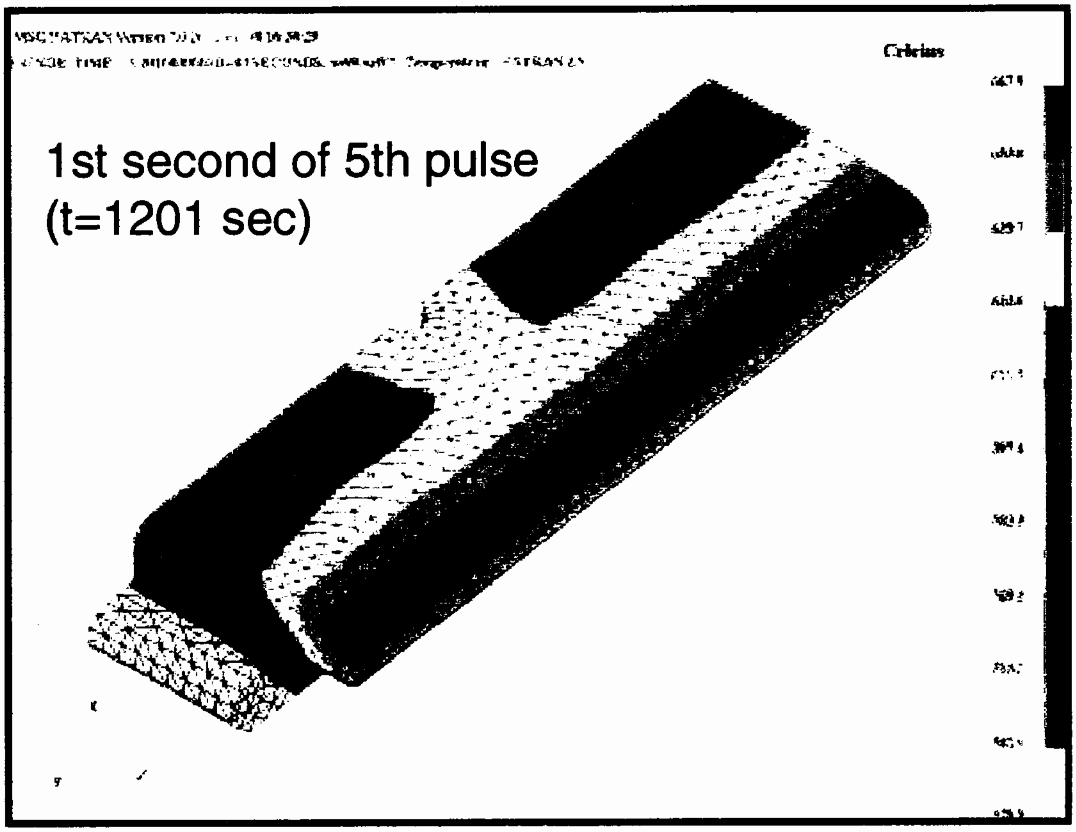
Celsius
1st second of 1st pulse
(t=1 sec)

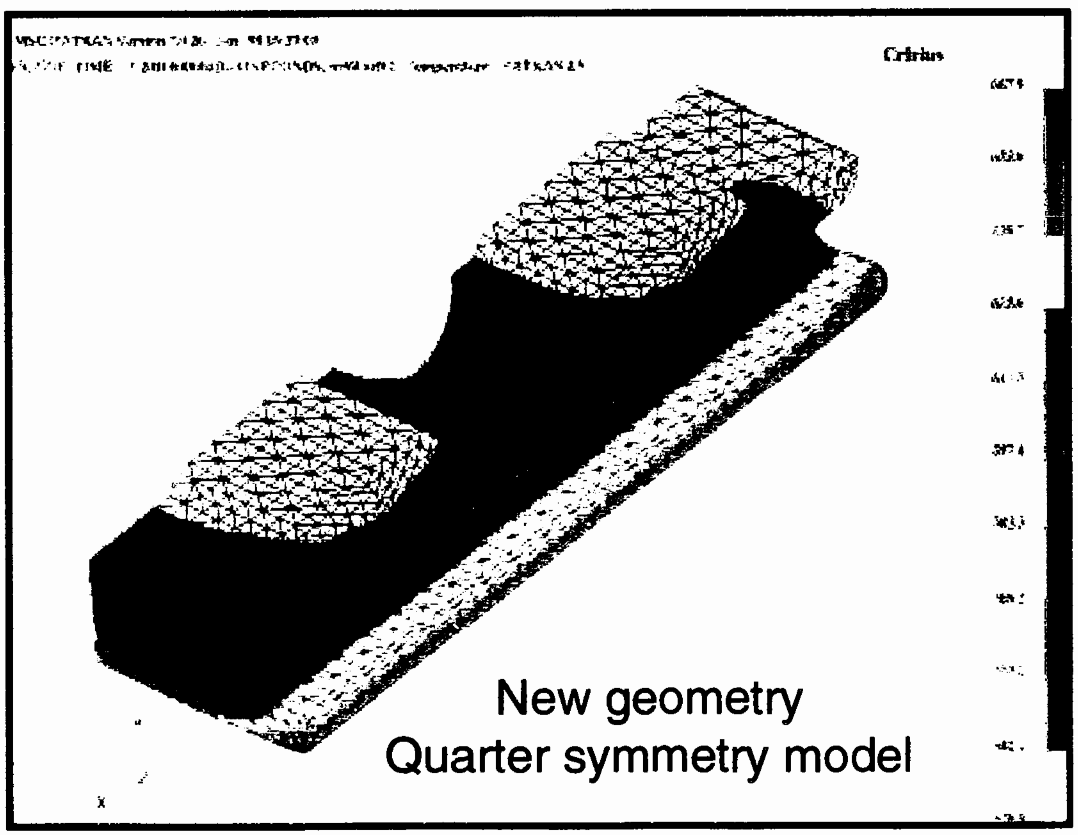



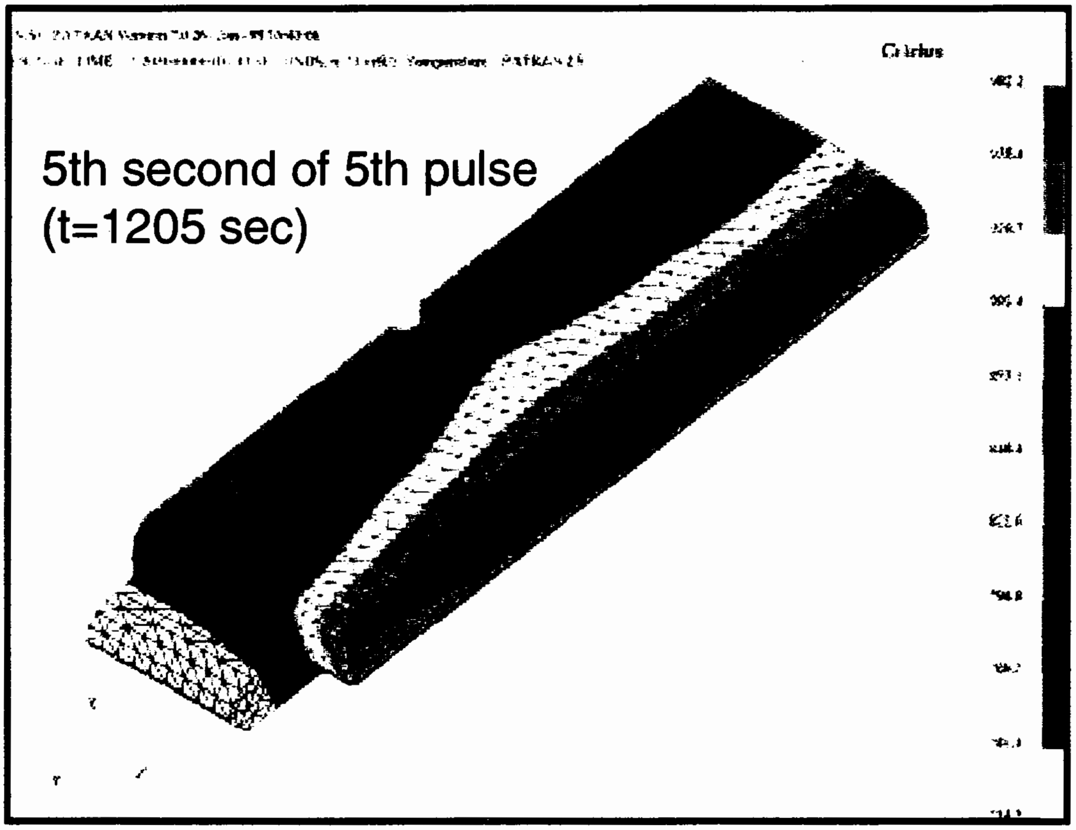
Celsius
New geometry
Quarter symmetry model

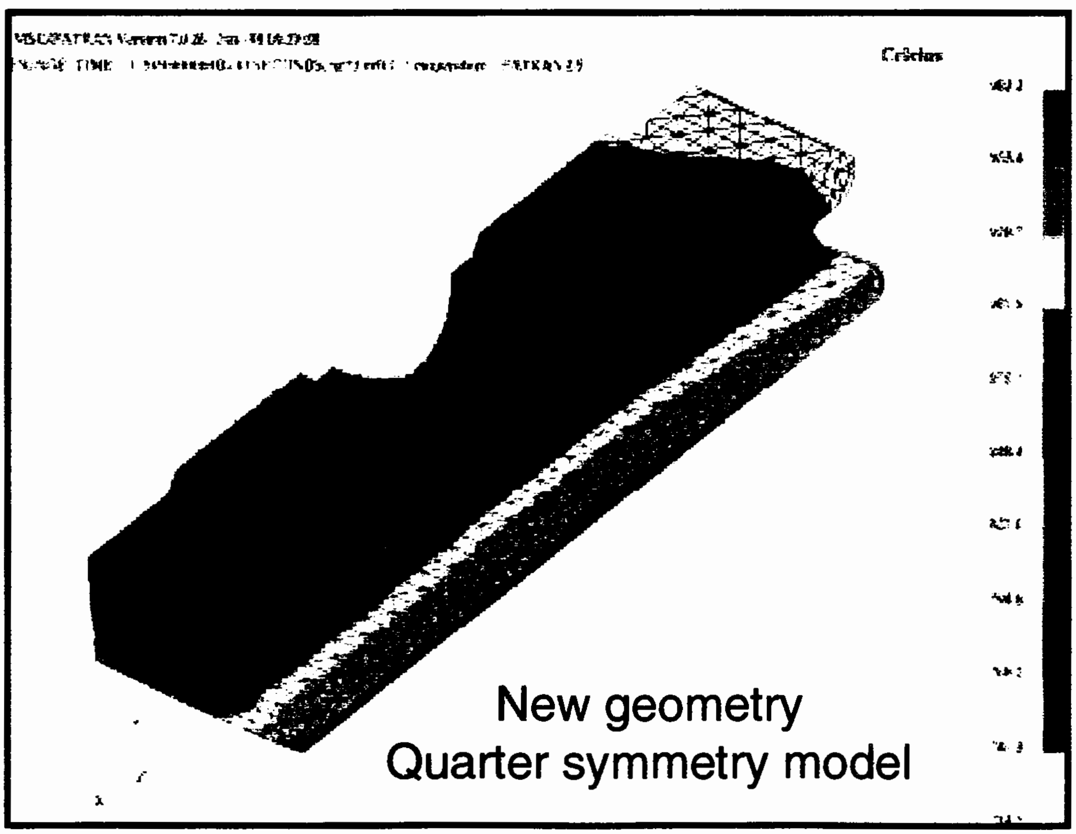

Celcius
5th second of 1st pulse
(t=5 sec)

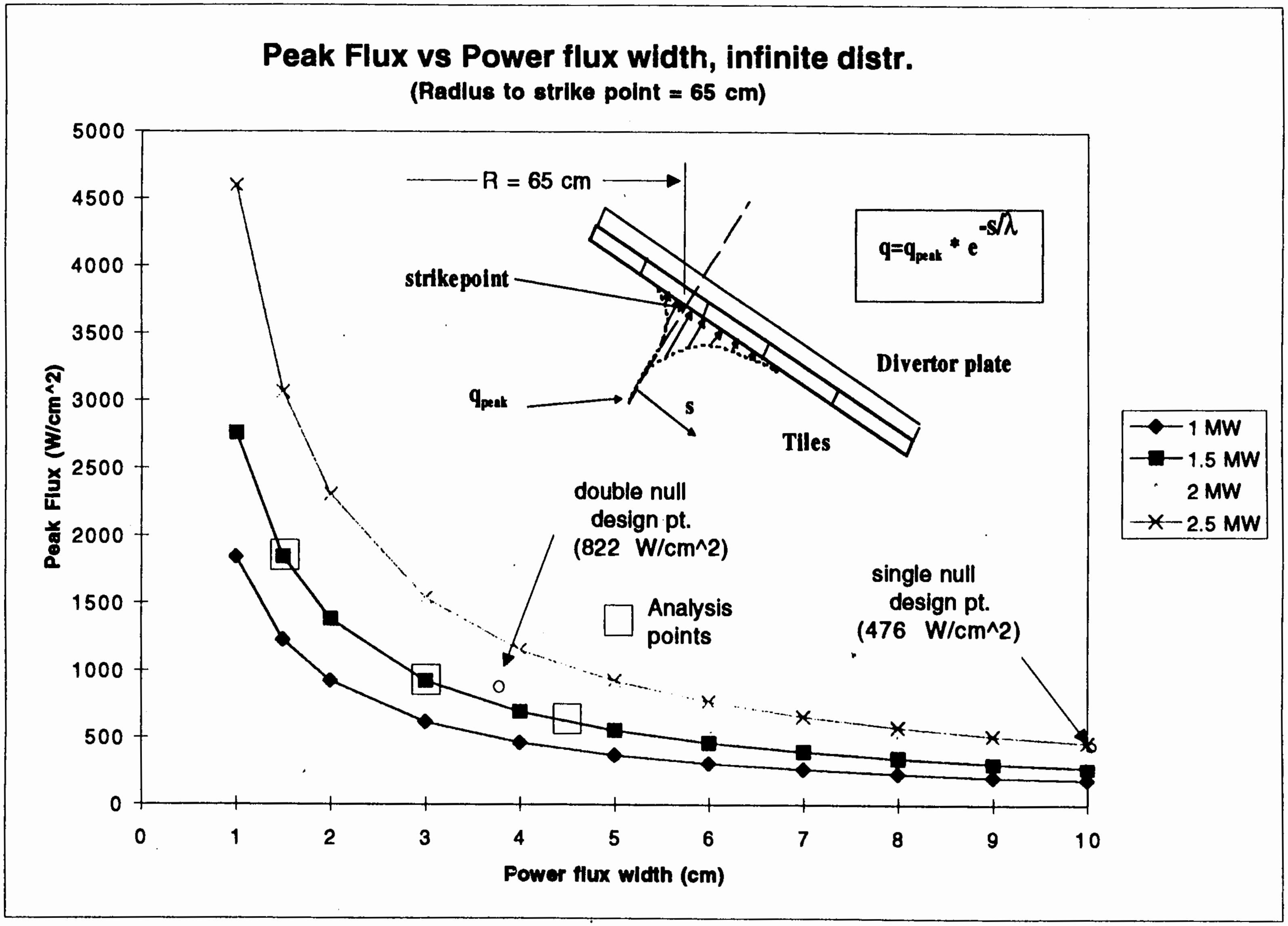

Celcius
New geometry
Quarter symmetry model


1st second of 5th pulse
(t=1201 sec)
Celsius

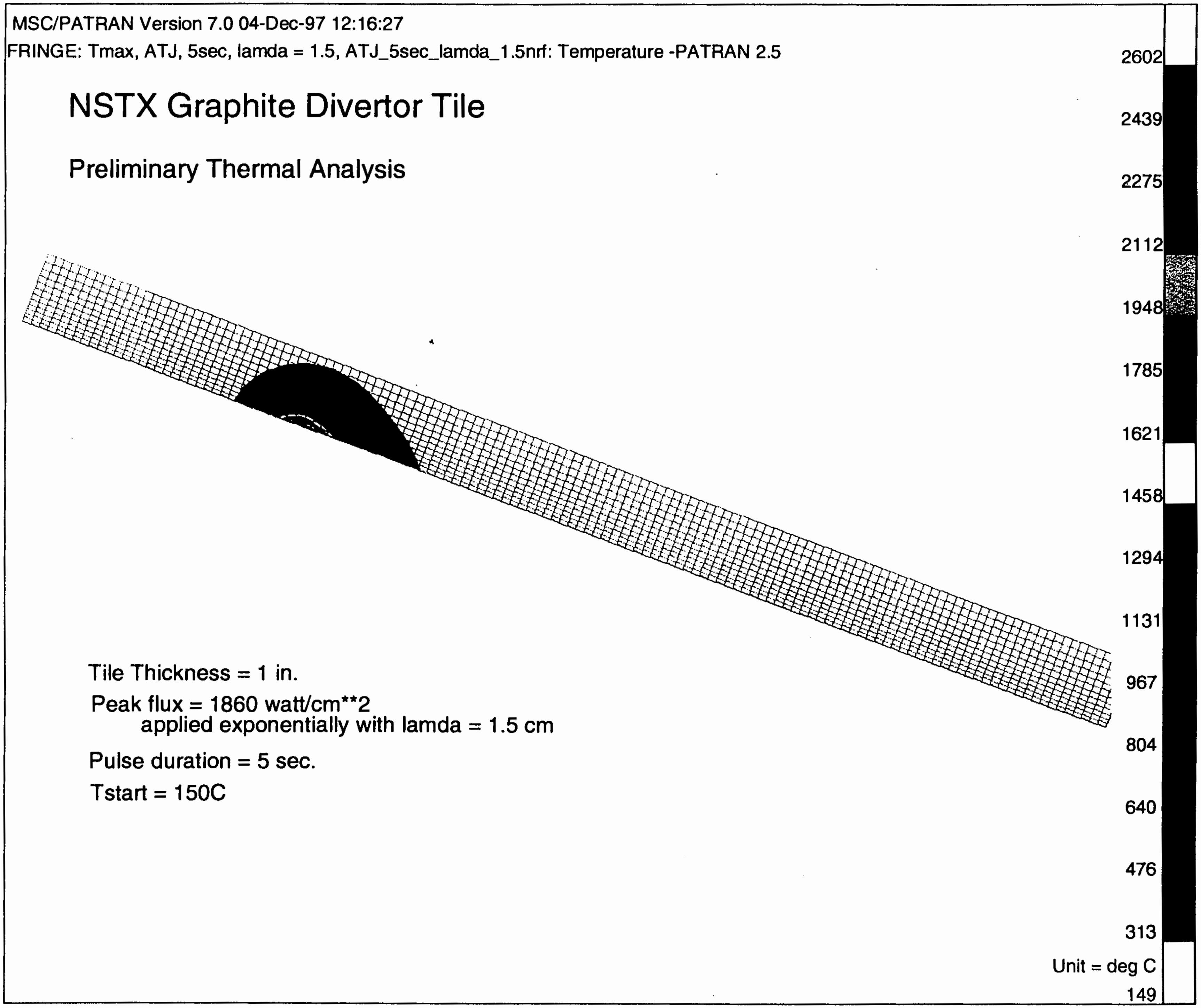

Celsius
New geometry
Quarter symmetry model


Cr:kius
5th second of 5th pulse
(t=1205 sec)


New geometry
Quarter symmetry model



Peak Flux vs Power flux width, infinite distr.
(Radius to strike point = 65 cm)
Peak Flux (W/cm^2)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
Power flux width (cm)
R = 65 cm
strikepoint
$q_{peak}$
s
Divertor plate
Tiles
$q=q_{peak} * e^{-s/\lambda}$
double null
design pt.
(822 W/cm^2)
Analysis
points
single null
design pt.
(476 W/cm^2)
1 MW
1.5 MW
2 MW
2.5 MW

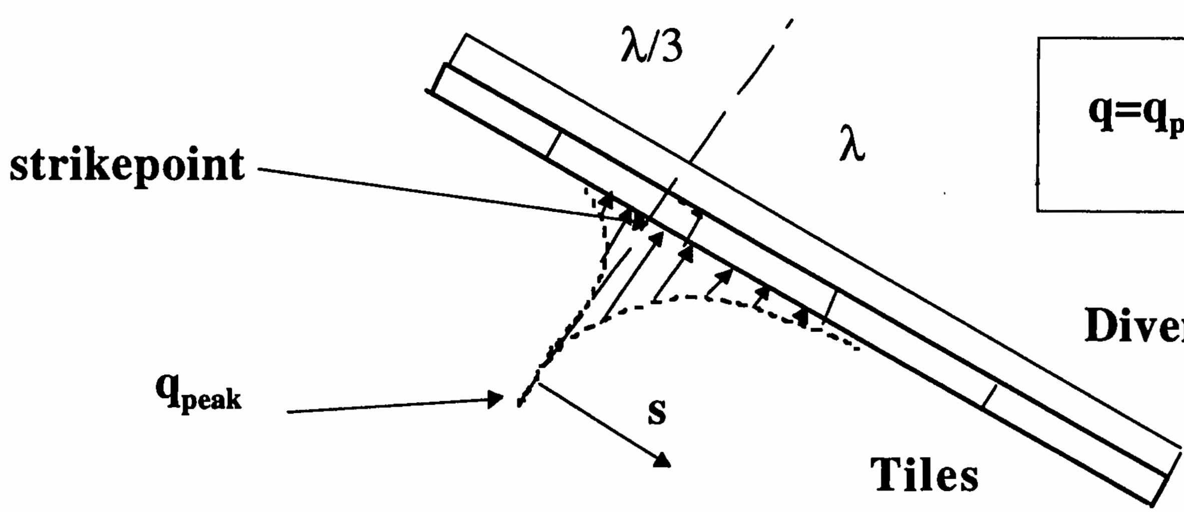

MSC/PATRAN Version 7.0 04-Dec-97 12:16:27
FRINGE: Tmax, ATJ, 5sec, lamda = 1.5, ATJ_5sec_lamda_1.5nrf: Temperature -PATRAN 2.5
NSTX Graphite Divertor Tile
Preliminary Thermal Analysis
Tile Thickness = 1 in.
Peak flux = 1860 watt/cm**2
applied exponentially with lamda = 1.5 cm
Pulse duration = 5 sec.
Tstart = 150C
2602
2439
2275
2112
1948
1785
1621
1458
1294
1131
967
804
640
476
313
Unit = deg C
149

# Outboard Divertor Plate Cooling/thermal analysis

- Copper plate is cooled at 50 to 100 C and baked out to 350C by Dowtherm
- Analysis shows feasibility for divertor tile operating at

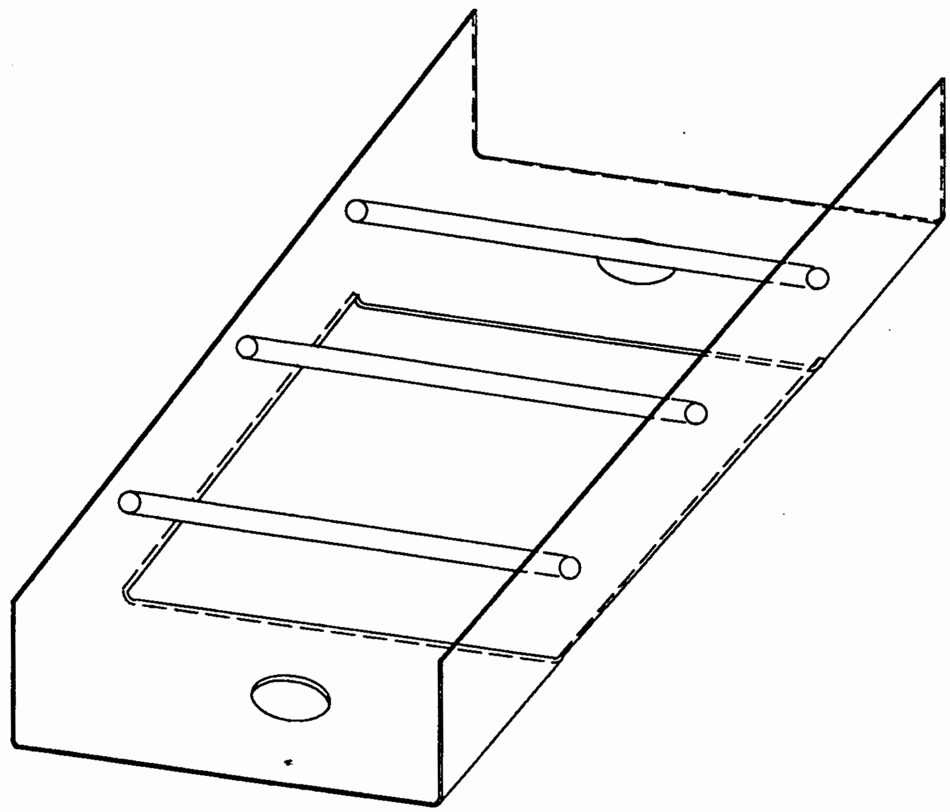
  ~ 600 W/cm^2 w/o sweeping
  ~ 1700 W/cm^2 with sweeping of 10 cm, where $\lambda = 3$ cm

- Divertor tile can be returned to 150C after pulse in 3 minutes

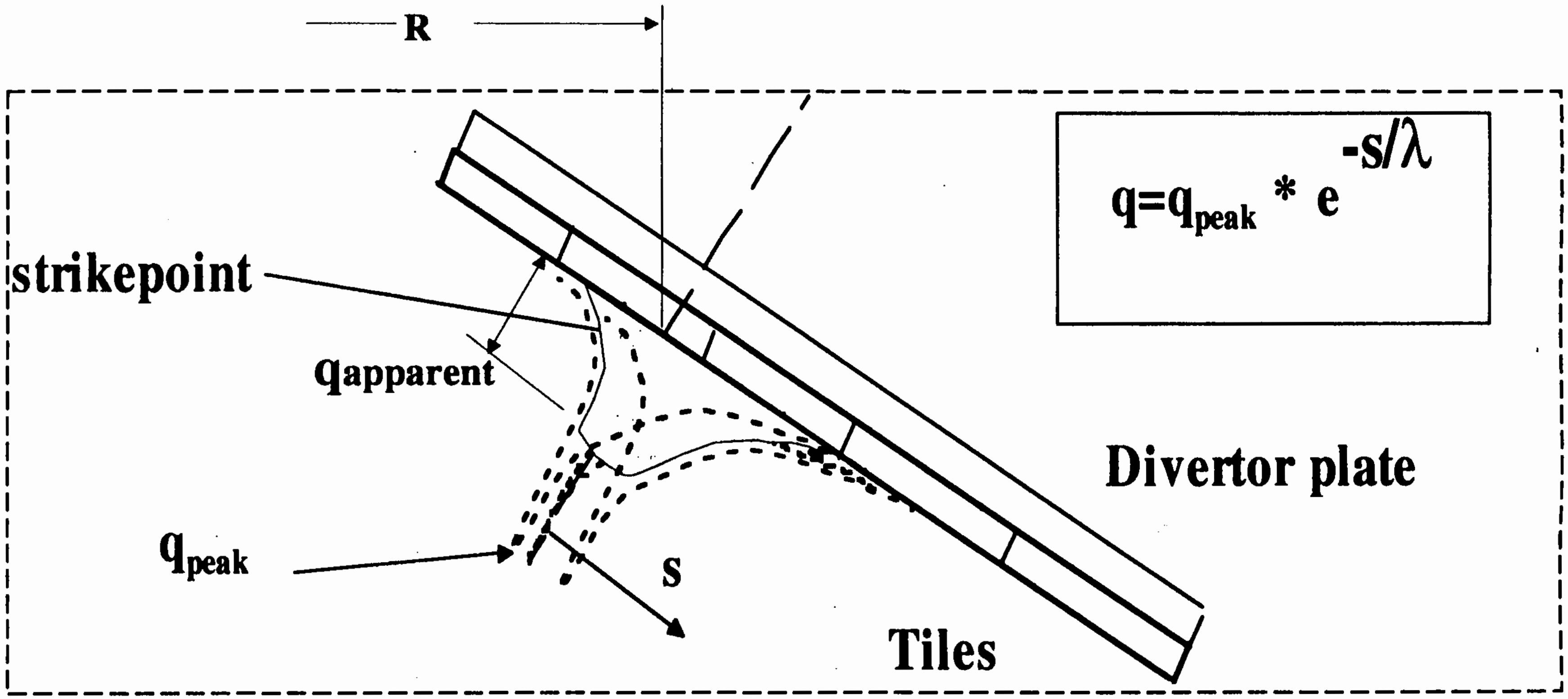


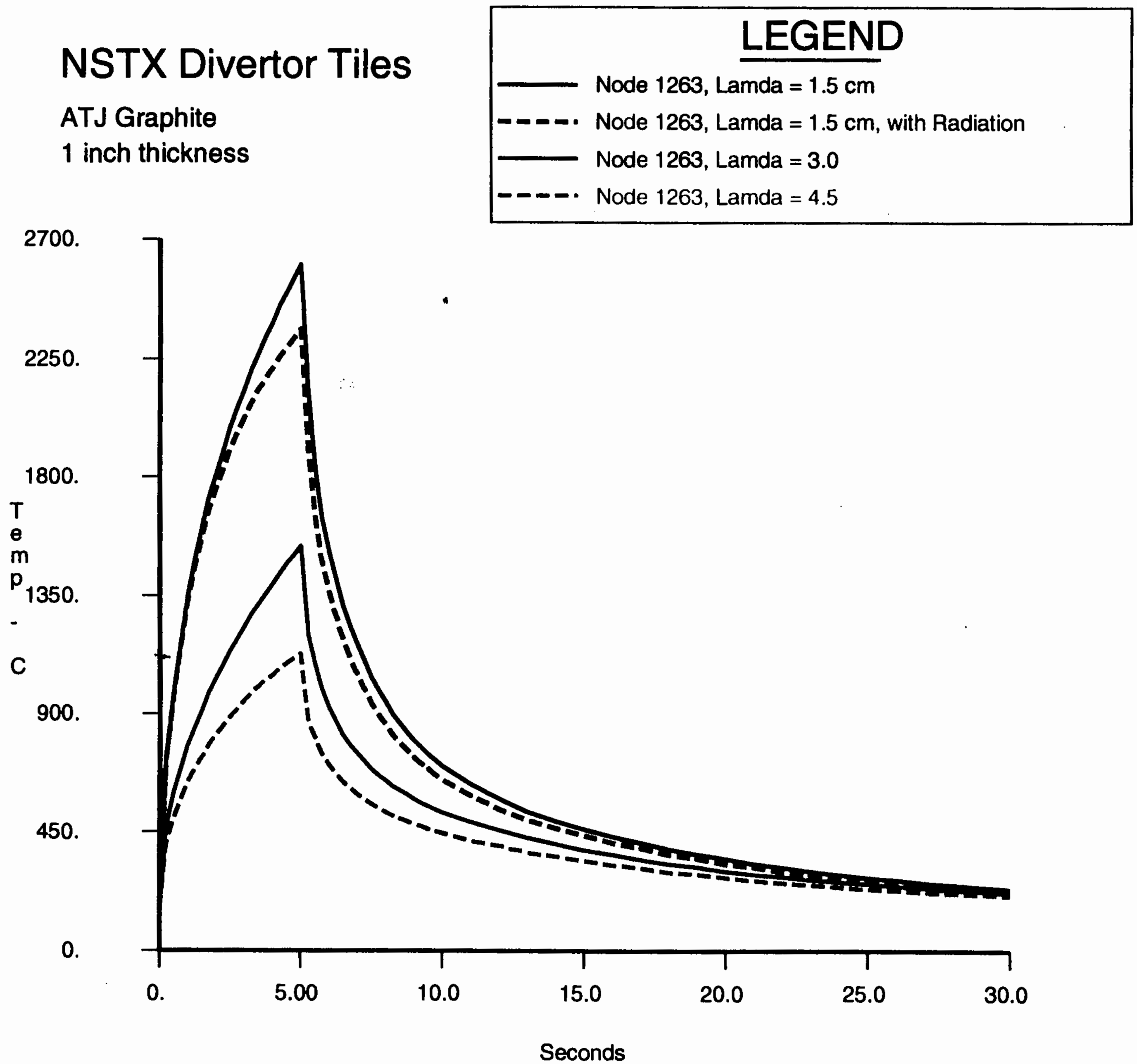

$$q = q_{peak} * e^{-s/\lambda}$$

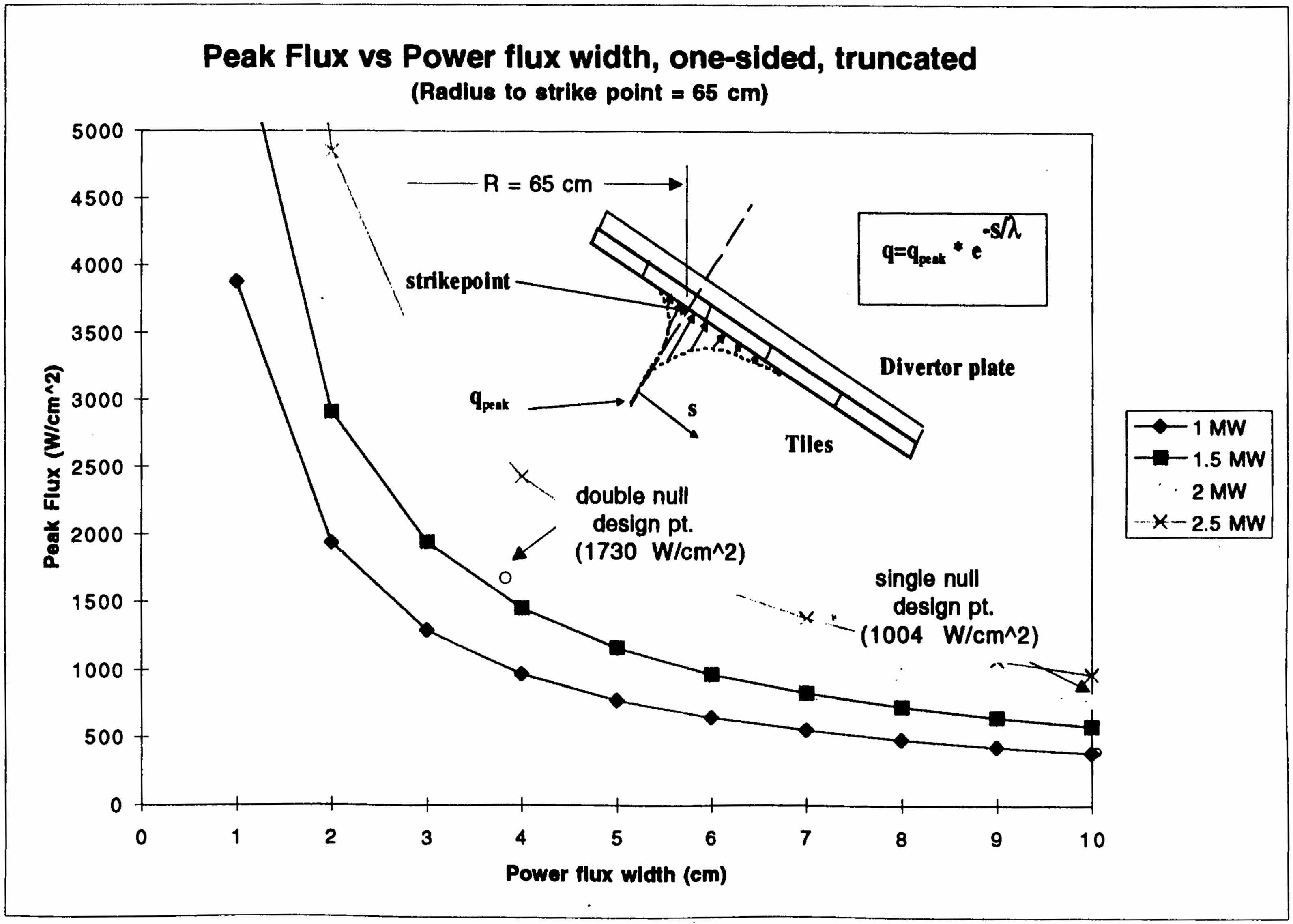
# DIVERTOR TILE MOUNTING BRACKET



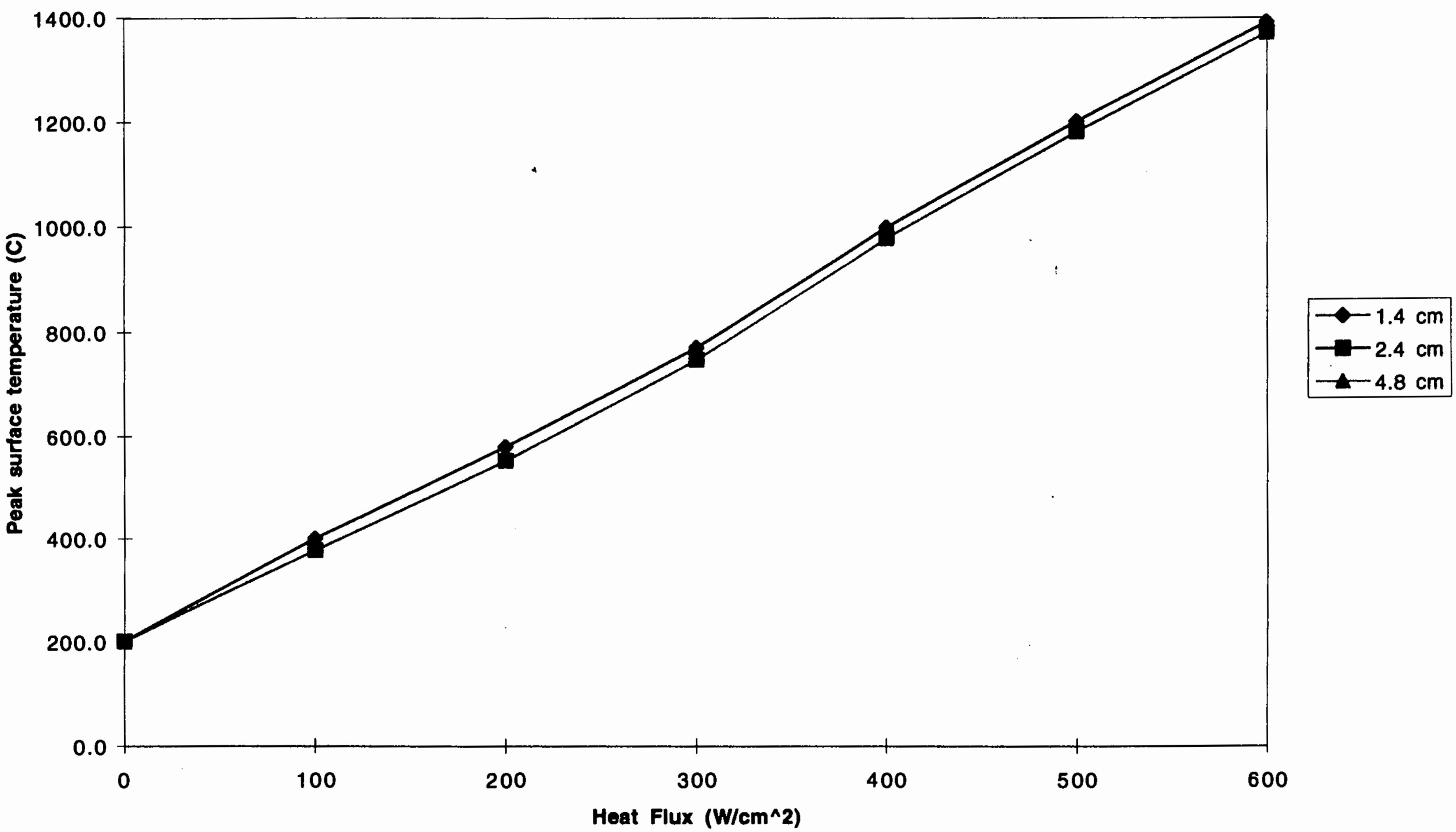
# Sweeping will reduce peak flux

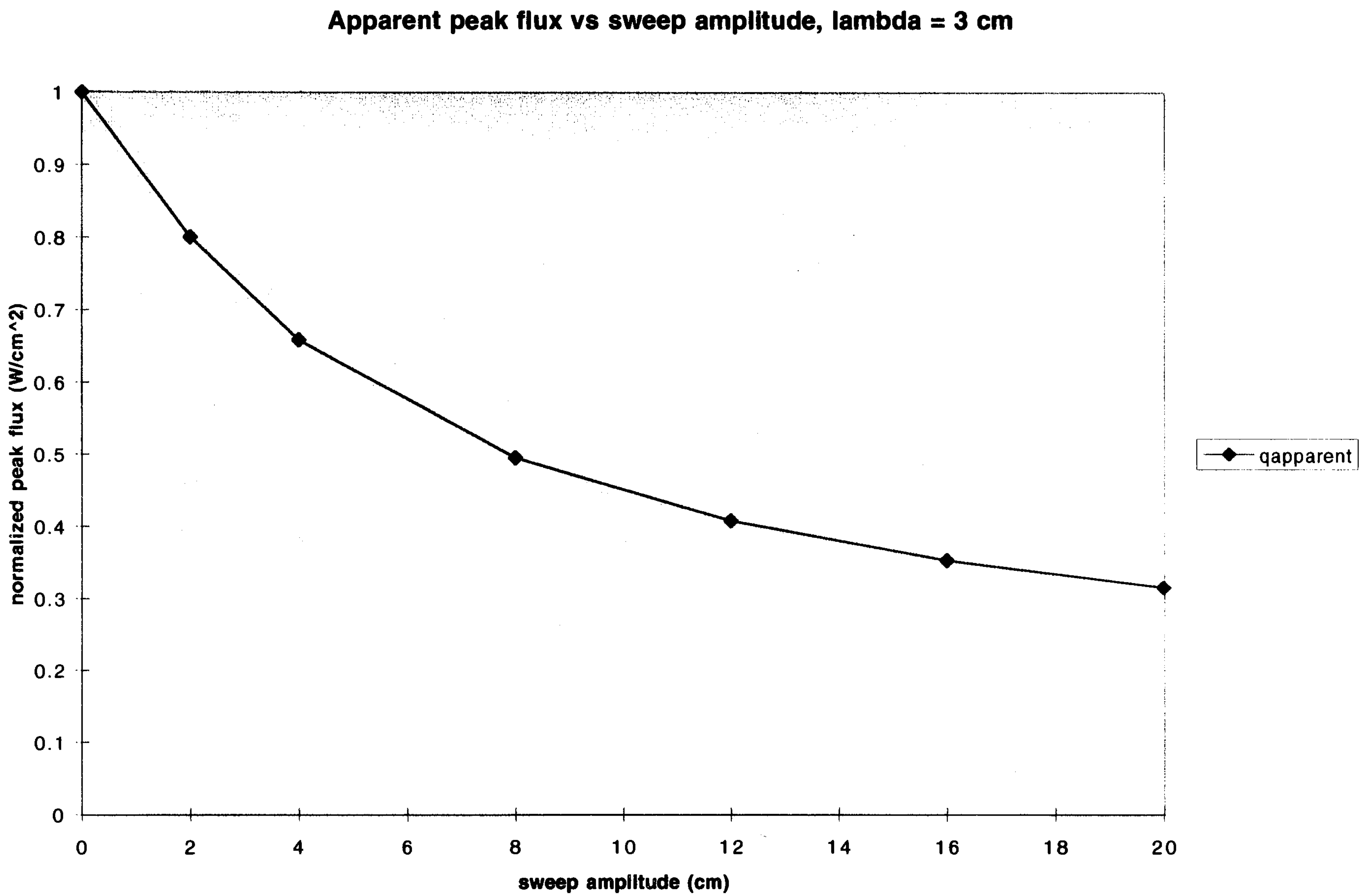



NSTX Divertor Tiles
ATJ Graphite
1 inch thickness
LEGEND
Node 1263, Lamda = 1.5 cm
Node 1263, Lamda = 1.5 cm, with Radiation
Node 1263, Lamda = 3.0
Node 1263, Lamda = 4.5
2700.
2250.
1800.
1350.
900.
450.
0.
Temp - C
0.
5.00
10.0
15.0
20.0
25.0
30.0
Seconds


Peak Flux vs Power flux width, one-sided, truncated
(Radius to strike point = 65 cm)
Peak Flux (W/cm^2)
Power flux width (cm)
R = 65 cm
strikepoint
$q_{peak}$
s
$q=q_{peak} * e^{-s/\lambda}$
Divertor plate
Tiles
double null design pt. (1730 W/cm^2)
single null design pt. (1004 W/cm^2)
1 MW
1.5 MW
2 MW
2.5 MW

**Peak Surface Temperature vs Heat Flux,**
**for various tile thicknesses, 1-D calc.**
**ATJ, 5 seconds on, 300 seconds off,**
**Fixed equilibrium temperature of 200C**




Apparent peak flux vs sweep amplitude, lambda = 3 cm
normalized peak flux (W/cm^2)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
sweep amplitude (cm)
qapparent