

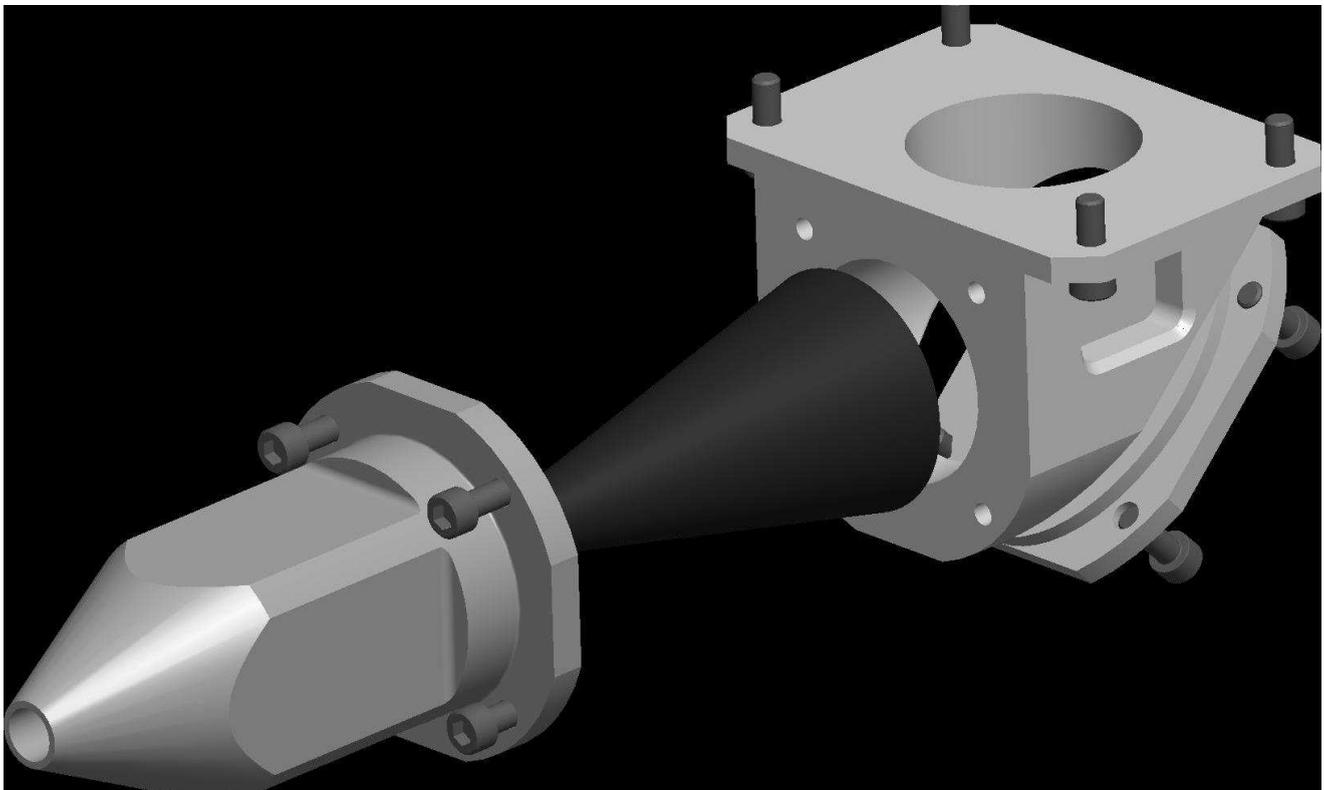


Thomas Keating Ltd
 Station Mills, Daux Road
 Billingshurst, West Sussex
 RH14 9SH, UK

Tel: +44 (0)1403 782045
 Fax: +44 (0)1403 785464

<http://www.terahertz.co.uk/>

Project Title	JPL Load		
Customer Reference	SR AP17-006226 / TK Job No. 23040		
Document Title	Thermal analysis on JPL Load and operational instructions		
Document Number	JPL-TK-F001-Load_TN_1001	Issue	2
Date	8/1/2016	Customer	JPL
TK Contact	Richard Wylde	Customer Contact	hamid.h.javadi@jpl.nasa.gov



Change Record

Issue	Date	Affected Sections	Remarks
1	15/09/2015	All	Issued for internal discussion
2	7/01/2016	All	Updated after manufacture

Table of Contents

Reference Documents	3
Abbreviations	3
1. JPL Conical Load - Introduction	4
1.1 Construction	4
2. Construction and wiring information	5
2.1 PRT.....	5
2.2 Heaters.....	6
3. Test of Thermal Circuits.....	7
3.1 Continuity tests.....	7
Temperature sensors	7
Heaters	7
3.2 Active tests	7
Conditions.....	7
Data analyses	8
Time dependence	8
Comparison of temperatures	9
3.3 Comment on results.....	10
4. NLT analysis - principles of calculation.....	10
5. NLT analysis - limitation of analysis	10
6. NLT analysis - results.....	13
7. NLT Validation.....	17
8. Appendix	20

Reference Documents

Abbreviations

AD	Applicable Document
AIT	Assembly, Integration, Test
BB	Bread Board
BOL	Beginning of Life
C	Compliant
CAD	Computer Aided Design
CDR	Critical Design Review
CVCM	Collected Volatile Condensable Material
DUT	Device under Test
EMC	Electromagnetic Compatibility
EM	Engineering Qualification Model
ESD	Electrostatic Static Discharge
EU	Electronics Unit (for temperature read-out)
FEA	Finite Element Analysis
FEM	Finite Element Method
FM	Flight Model
GRP	Glass-fibre Reinforced Plastic
HLS	High Level Sine
IAP	University of Bern, Institute of Applied Physics
ICD	Interface Control Document I/F Interface
IR	Infrared
ITS	International Temperature Scale
KO	Kick-Off
LLI	Long Lead Item
LLS	Low-Level Sine
MLI	Multi-Layer Insulation
NC	Non-Compliant
NIR	Near Infrared
NPL	UK National Physical Laboratory
PDR	Preliminary Design Review
PRT	Platinum Resistance Thermometer
RGA	Residual Gas Analyzer
RML	Recovered Mass Loss
S11	Scattering parameter S_{11} (from a port back to itself).
S/C	Space Craft
SOW	Statement of Work
SPRT	Secondary Platinum Resistance Thermometer
TBC	To Be Confirmed
TBD	To Be Determined
TK	Thomas Keating (Ltd.)
TML	Total Mass Loss
TMM	Thermal Mathematical Model
TRB	Test Review Board
TRP	Temperature Reference Point
TV	Thermal Vacuum
UK	United Kingdom

1. JPL Conical Load - Introduction

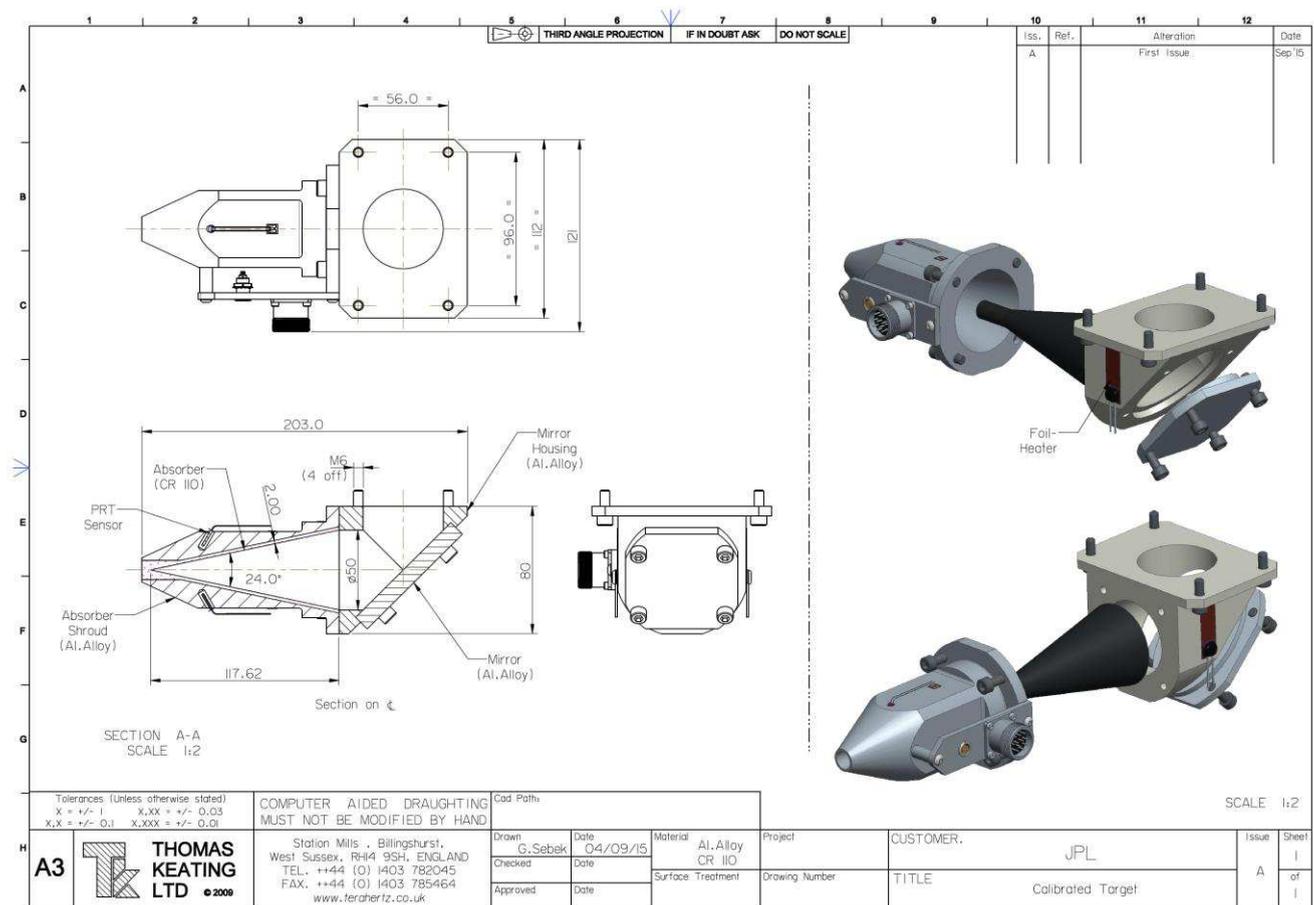
JPL have ordered from TK a simple conical load for use as a Calibration Target from 266-270 GHz and 647-600 GHz.

This note covers both information on the size and assembly of the load, and details of thermal FEA analysis performed upon the design.

1.1 Construction

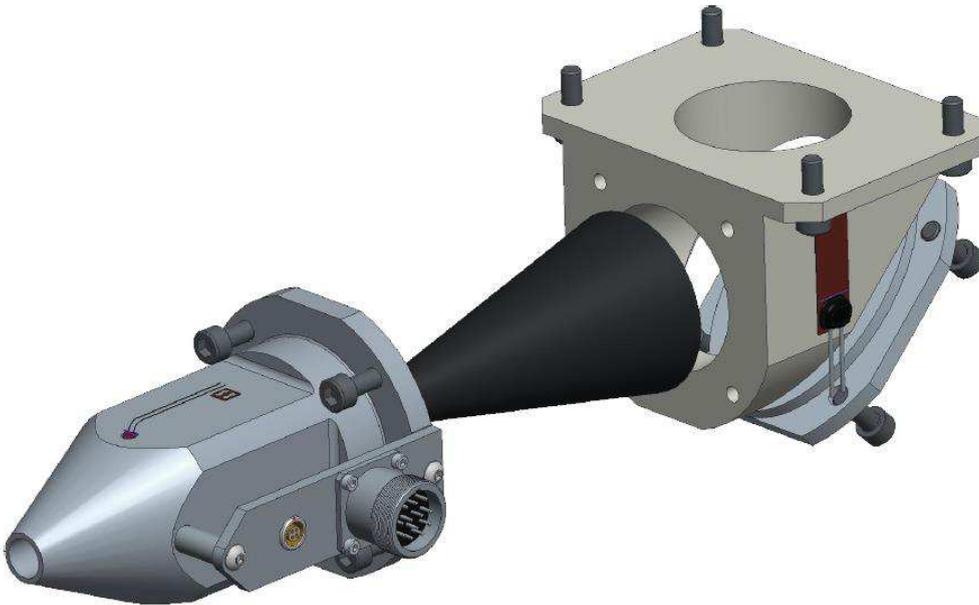
An internal cone made absorber 2mm thick of CR110 is backed by an aluminium cone. A 90-degree bend, incorporating a flat mirror (A mirror that can be changed to alter its focal length— currently flat, i.e. infinite) allow the radiometer's beam (in a time reversed view) to enter the cone and be absorbed close to the cone's apex.

Two 2000 Ohm PRT's embedded into the aluminium part of the cone will give accurate monitoring of the cone temperature



2. Construction and wiring information

2.1 PRT



The image below shows the assembly of the potted Goodridge PRT's



Serial Numbers of the Rosemount Aerospace 118MF200A (inspection Lot 2015014021) PRT's are potted into the structure and have the following offsets to the nominal 2000 Ohms

- AD621 2004.18 Ohms Green twisted pairs
- AD622 2004.85 Ohms Blue twisted pairs

<http://dpk3n3gg92jwt.cloudfront.net/domains/minco/pdf/HK6900.pdf>

Details of the conversion from resistance to temperature are given in the Appendix

2.2 Heaters

Two Minco HK6900 (Batch 15100^AAN-302) 3.7 Watt, 28 volt heaters are provided and wired to the larger of the two connectors.

Provides heat where it's needed to reduce operating costs.

Fast and efficient thermal transfer. Uniform thermal performance by custom profiling. Customized options for turnkey thermal solutions.

Custom options:

- Customized options (i.e. SMT components, flex leads, connectors, and laminated to heatsinks) offer turnkey solutions to drastically reduce assembly time and increase productivity
- Custom profiling gives uniform thermal performance of the heating output to improve processing yields and productivity
- Custom shapes and sizes:
 - Polyimide / FEP – 22" x 42" (560 x 1065 mm)
 - Polyimide / WA/ULA – 22" x 72" (560 x 1825 mm)
- Custom resistance:
 - Polyimide / FEP – 450 Ω/in² (70 Ω/cm²)
 - Polyimide / WA/ULA – 1500 Ω/in² (233 Ω/cm²)
- WA or ULA internal adhesive is more economical than FEP for most custom designs that operate below 150°C
- NASA approval is available in nearly all of the standard size Polyimide heaters
- TÜV or UL recognition marking is optional
- Tighter resistance tolerance
- RoHS compliance

Attributes

Mounting	Acrylic Adhesive (PSA)
Thickness (in)	0.045
Min Temp (°F)	-26
Max Temp (°F)	212
Weight (oz)	0.06
Style	Etched Kapton/WA
X dim (in)	0.50
Y dim (in)	1.00
R (Ω)	210.13
AWG	26
Area (in ²)	0.3731
Volt	28.00
Watt	3.7
External Tab	.500" wide x .400" long
Availability	4-6 weeks
Watt Density (w/in ²)	10.00

More details can be found at

<http://dpk3n3gg92jwt.cloudfront.net/domains/minco/pdf/HK6900.pdf>

The wires are connected into pins 8&5 and 1&4 to form two pairs.

3. Test of Thermal Circuits

Tests of the electrical thermal circuits were performed on the black-body calibration target for JPL on 05/01/2016.

3.1 Continuity tests

A Fluke 87V multimeter was used to test the circuits.

Temperature sensors

The PRT sensors resistances were determined to be near their nominal resistances: 2.2 k Ω at room temperature. No electrical connection between the sensors was found.

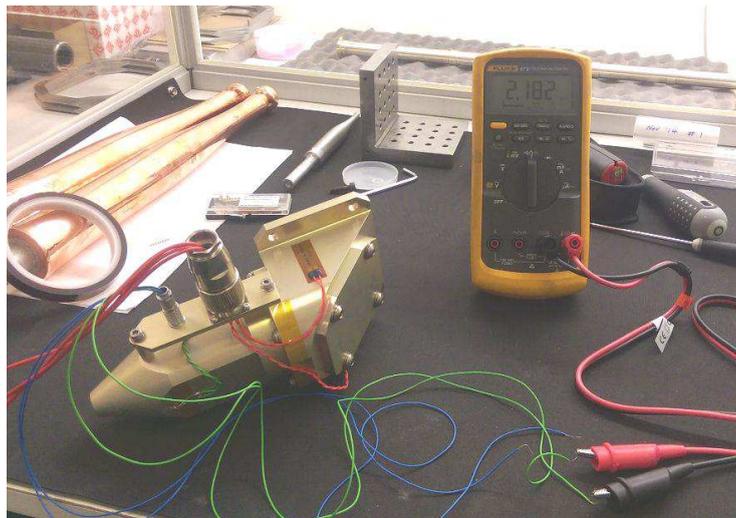
Heaters

The heater circuit resistances were determined to be near their nominal heater resistances: 218 k Ω actual, 210 k Ω nominal. No electrical connection between the heaters was found.

3.2 Active tests

Conditions

The tests were undertaken in a linear flow clean cabinet, as shown in the photograph, below.



The heater circuits were wired together in parallel and connected to a power supply, which was set to control its output using the voltage it measured. The power supply was set to 26 V output, giving 3.1 W per 218 Ω heater. (The maximum 28 V for the heaters was just above that achievable by this power supply.)

The resistance of the PRTs was measured using the Fluke 87V multimeter. A single unit was used to allow a better indication of similarity between the temperatures measured. Measurements were therefore taken a few seconds apart.

An ATP DT-8862 infrared thermometer was used to take temperature measurements of the environment and of the black-body surface.

The calibration target was laid on its side on the rubber mat of the laminar flow clean cabinet, except where explicitly stated.

Data analyses

The nominal resistance of the PRTs at is 2000 Ω at 0 °C, 2157.23 Ω at 20 °C and 2313.56 Ω at 40 °C (taken from the PRT information sheets). These values were scaled (rather than offset) by the calibrated resistances at 0 °C supplied with the PRTs: 2004.18 Ω for AD621 and 2004.85 Ω for AD622.

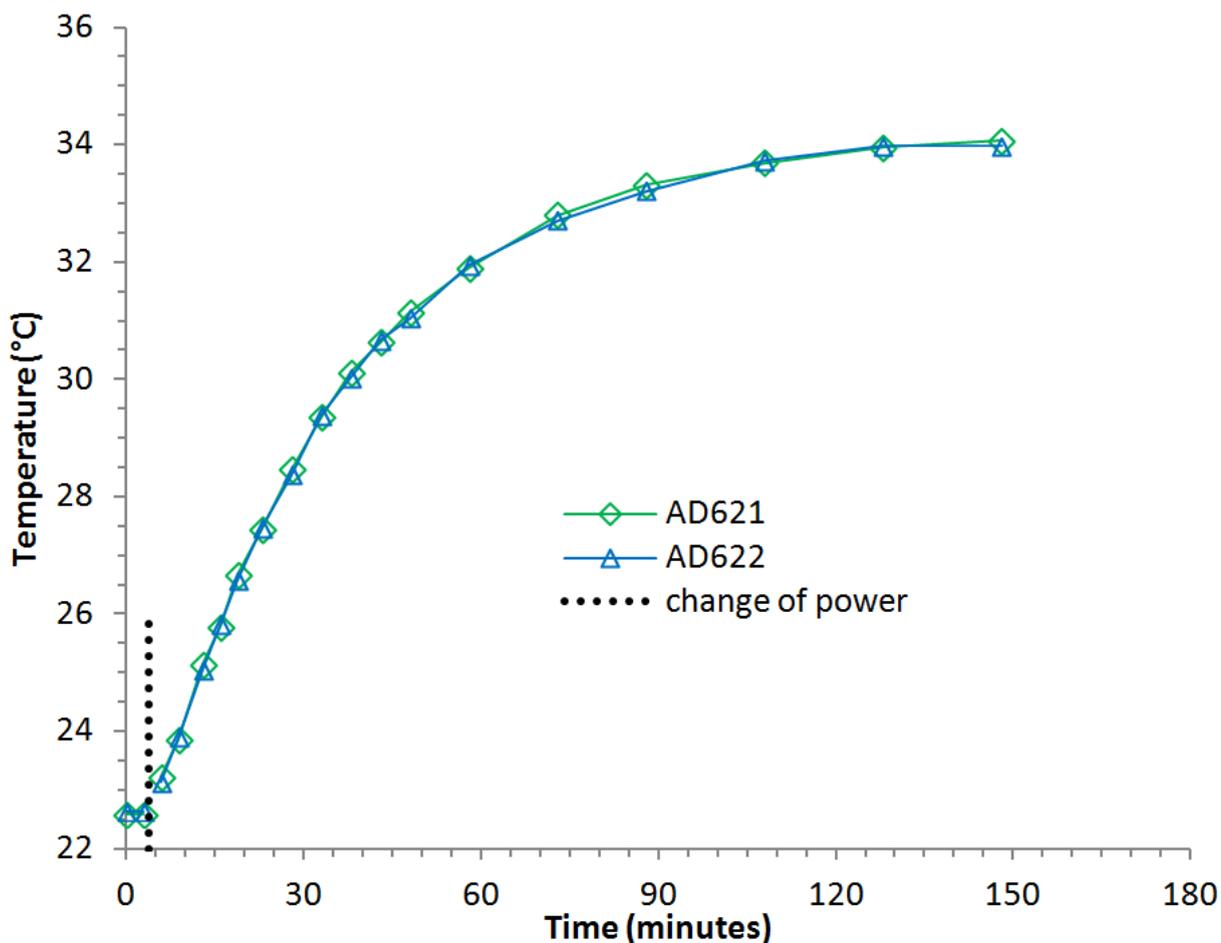
Temperatures were calculated using a linear interpolation between these 20 and 40 °C calculated values. Whilst a polynomial interpolation would be more accurate this is considered to be not useful because of the uncertainty from the multimeter.

Time dependence

The table below shows data take after the voltage to the heaters was increased from 0 to 26 V. The multimeter displays values to the nearest Ω , giving temperature readings in steps of approximately 0.1 °C.

Time (minutes)	AD621 (°C)	AD622 (°C)
4	22.6	22.6
6	23.2	23.1
9	23.9	23.9
13	25.1	25.0
16	25.8	25.8
19	26.7	26.6
23	27.4	27.5
28	28.5	28.4
33	29.4	29.4
38	30.1	30.0
43	30.6	30.7
48	31.1	31.0
58	31.9	31.9
73	32.8	32.7
88	33.3	33.2
108	33.7	33.7
128	33.9	34.0
148	34.1	34.0

The graph below presents the data. It shows an increase in temperature from ambient to a constant 34 °C after 2 hours. Note that no PID or other stability optimisation techniques were used.



The data is described well by a single exponential with a time constant of 33 minutes.

Comparison of temperatures

The infrared thermometer was used to monitor temperatures of the black-body surfaces and the environment. The mirror was removed from the calibration target to enable the temperature measurement of the black-body surface. This mirror was in place for the above time-dependence measurements.

Measurements were taken before the above time-dependence test and ~5 hours later, more than 2 hours after the above data were taken. For the latter measurements, the laminar flow clean cabinet had been turned off and the calibration target was laid on foam rubber.

The temperature of the cabinet mat was 23.5 °C at the start and 24.3 °C after the measurements. This difference is likely to be caused by the cabinet having been turned off.

The table below shows the data for the temperature measurements, including those for the PRTs.

Time (minutes)	AD621 (°C)	AD622 (°C)	IR thermometer (°C)
0	22.59	22.62	23.5
370	37.52	37.55	37.5*

* See the text below.

At time 0 minutes the black-body surface may have been at a slightly higher temperature because of changes to the room temperature. It may also have been affected by the IR thermometer seeing a reflection of itself: the reflectivity of the surface at the wavelength used would need to be determined. The device would have had time to reach the environment temperature for the later measurements.

At 370 minutes, the IR thermometer and PRT temperatures are identical within the step size of the devices used. The temperature measurement by the IR thermometer varied by ± 0.2 °C, depending on the position and the focus of the device. Certain specific orientations produced a reading of 37.1 °C but this is considered to be not representative.

3.3 Comment on results

We consider this agreement between an IR thermometer and the PRT values encouraging.

The temperature rise of some 12 degrees is about half that predicted (i.e. $30C * 3.7/5$) or 22C as outline at the end of section 6 below. Given the presence of both condition to the base and convective cooling, this result is also satisfactory.

4. NLT analysis - principles of calculation

With the arrival of ANSYS's NLT thermal software at TK (funded as part of EUMETSAT's MetOp-SG programme), we have the capability to perform a simple (but computationally intense) calculation of the temperature of the absorbing cone. The need for this is driven by the fact that the effective radiometric temperature of the load is not just that of the PRT-measured temperature of the Al Cone backing, but is the integrated temperature - weighted by fractional absorption/emission) of the absorber. The expectation is that the difference in temperatures can be sufficiently small that the measurement is not compromised or - if it is - that computational generated offsets can be provided between the PRT measured and radiometric temperatures.

5. NLT analysis - limitation of analysis

The basis and limitations of this calculation should be noted.

It is based upon conduction and radiation - no convection in air is computed. The calculation is therefore more suited to operation in Space. One might hope that there is not much convection in a small volume, and what convection there is would even temperatures.

We assume an emissivity of 0.8 in the NIR for the CR110 absorber, 0.9 for the black-paint-covered mirror, and 0.2 for the internal Aluminium surfaces.

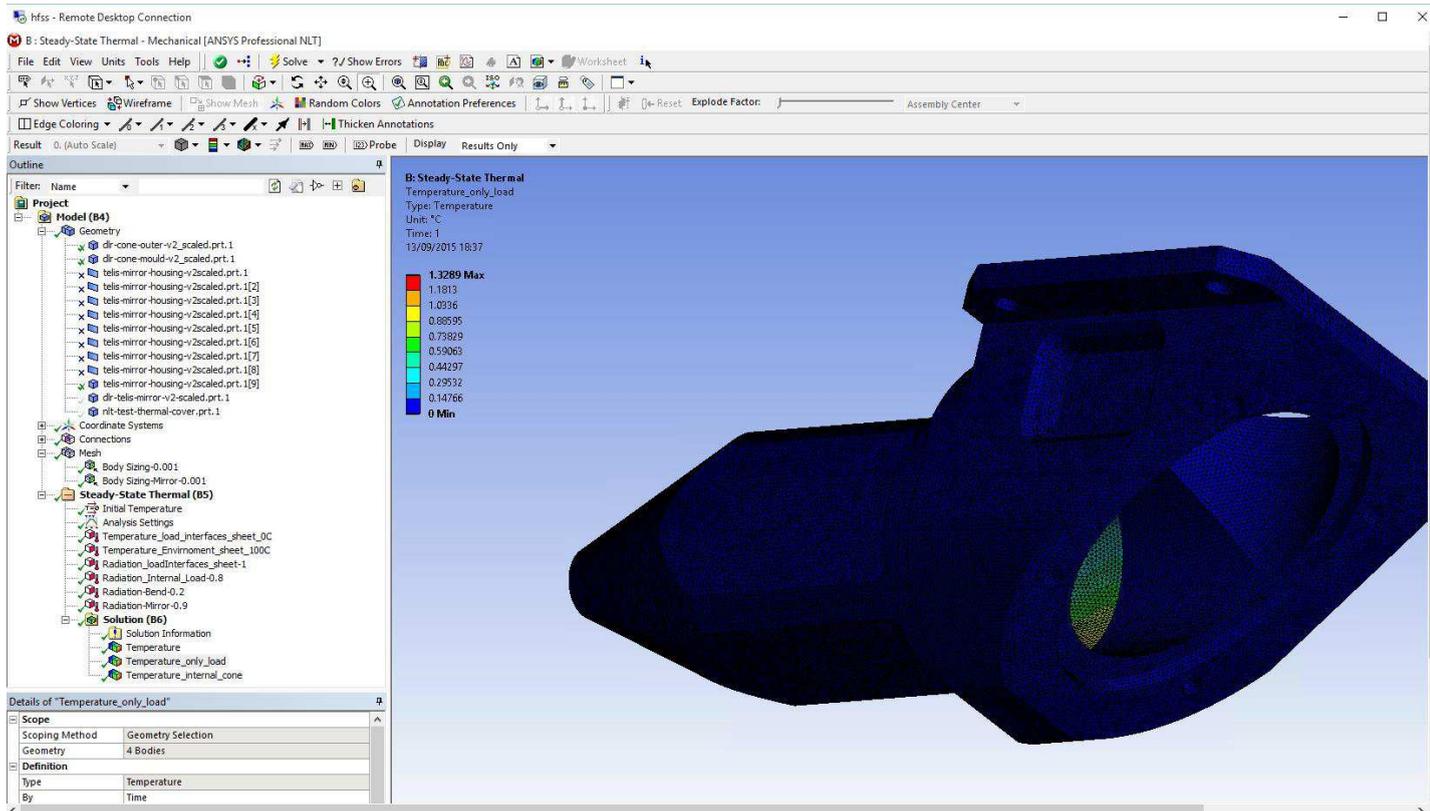
The external surfaces are ignored in this calculation - as if they were covered by perfect MLI.

For simplicity the load interface (the flat aperture at the entrance to the 90 degree bend) is set (i.e. forced to) to 0C and the loading surface - covering this aperture - is set to 100 C

Note the radiation exchange, and therefore the settling temperatures, are non-linear functions of the difference in temperature.

Meshing Tet. size is set to 1mm.

Here's a screenshot of the calculation



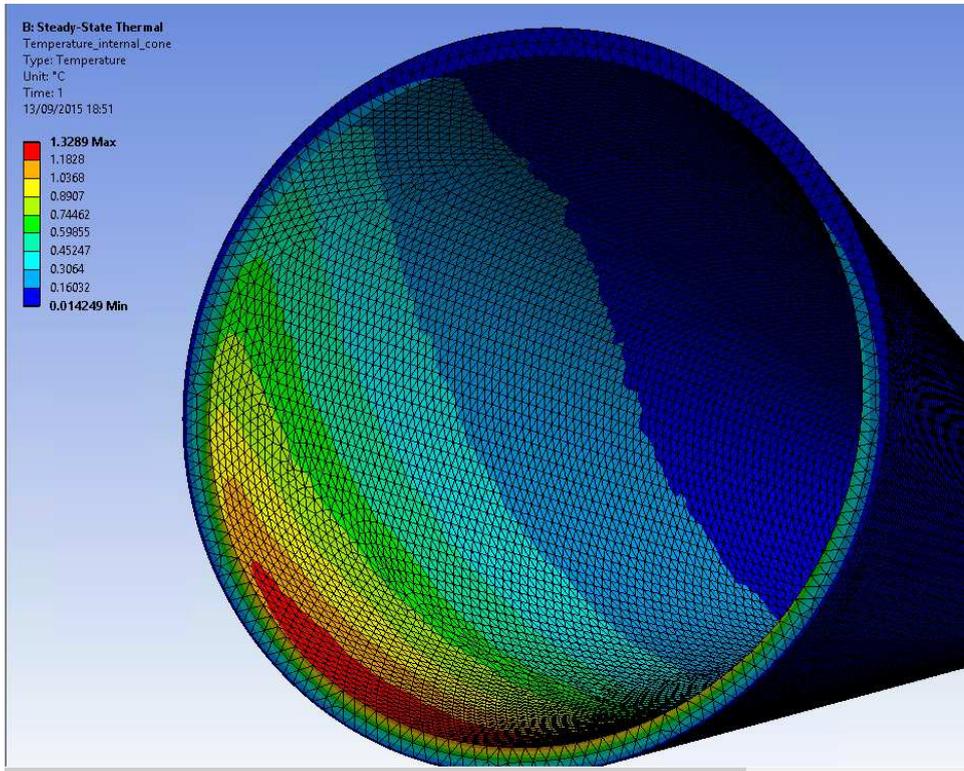
The temperature of the whole body, with the mirror removed to allow one to see inside the structure. And here's the data-tree to set the calculation up.

- Project
 - Model (B4)
 - Geometry
 - dlr-cone-outer-v2_scaled.prt.1
 - dlr-cone-mould-v2_scaled.prt.1
 - telis-mirror-housing-v2scaled.prt.1
 - telis-mirror-housing-v2scaled.prt.1[2]
 - telis-mirror-housing-v2scaled.prt.1[3]
 - telis-mirror-housing-v2scaled.prt.1[4]
 - telis-mirror-housing-v2scaled.prt.1[5]
 - telis-mirror-housing-v2scaled.prt.1[6]
 - telis-mirror-housing-v2scaled.prt.1[7]
 - telis-mirror-housing-v2scaled.prt.1[8]
 - telis-mirror-housing-v2scaled.prt.1[9]
 - dlr-telis-mirror-v2-scaled.prt.1
 - nlt-test-thermal-cover.prt.1
 - Coordinate Systems
 - Global Coordinate System
 - Connections
 - Contacts
 - Contact Region 16
 - Bonded - dlr-cone-outer-v2_scaled.prt.1 To dlr-cone-mould-v2_scaled.prt.1
 - Bonded - telis-mirror-housing-v2scaled.prt.1[9] To dlr-cone-outer-v2_scaled.prt.1
 - Mesh
 - Body Sizing-0.001
 - Body Sizing-Mirror-0.001
 - Steady-State Thermal (B5)
 - Initial Temperature
 - Analysis Settings
 - Temperature_load_interfaces_sheet_0C
 - Temperature_Environment_sheet_100C
 - Radiation_loadInterfaces_sheet-1
 - Radiation_Internal_Load-0.8
 - Radiation-Bend-0.2
 - Radiation-Mirror-0.9
 - Solution (B6)
 - Solution Information
 - Temperature
 - Temperature_only_load
 - Temperature_internal_cone

6. NLT analysis - results

Here's the temperature on the surface of the cone – noting that the forcing temperature of the sheet above the input is 100 C higher. Note that the 1.3C is the maximum increase, and this peak is at the cone edge and is not where (input beam dependent) beam will get absorbed.

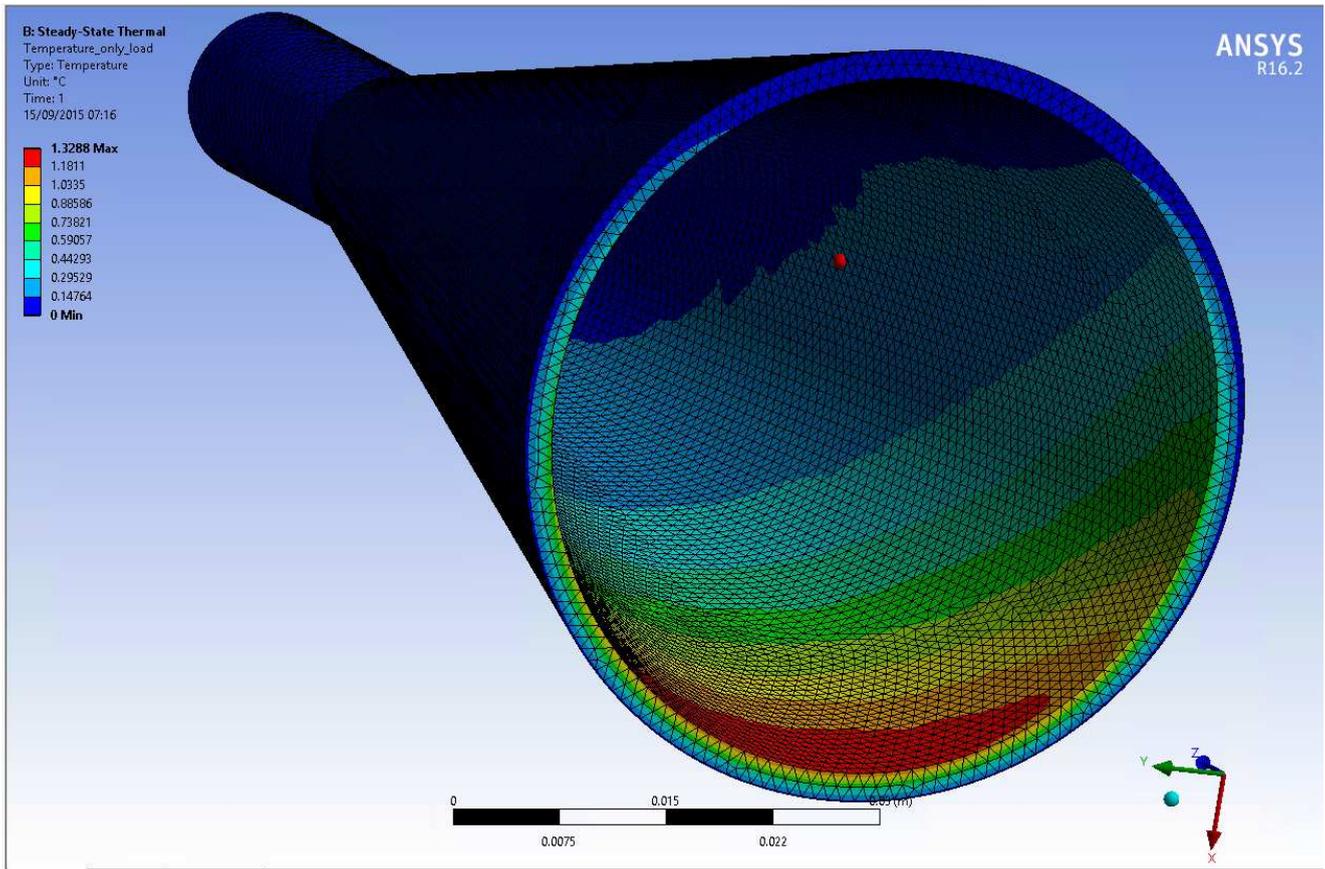
The structure is therefore performing in the way one hoped:



Effect of reflections from the 90 bend structure, with a 100C different environment temperature.

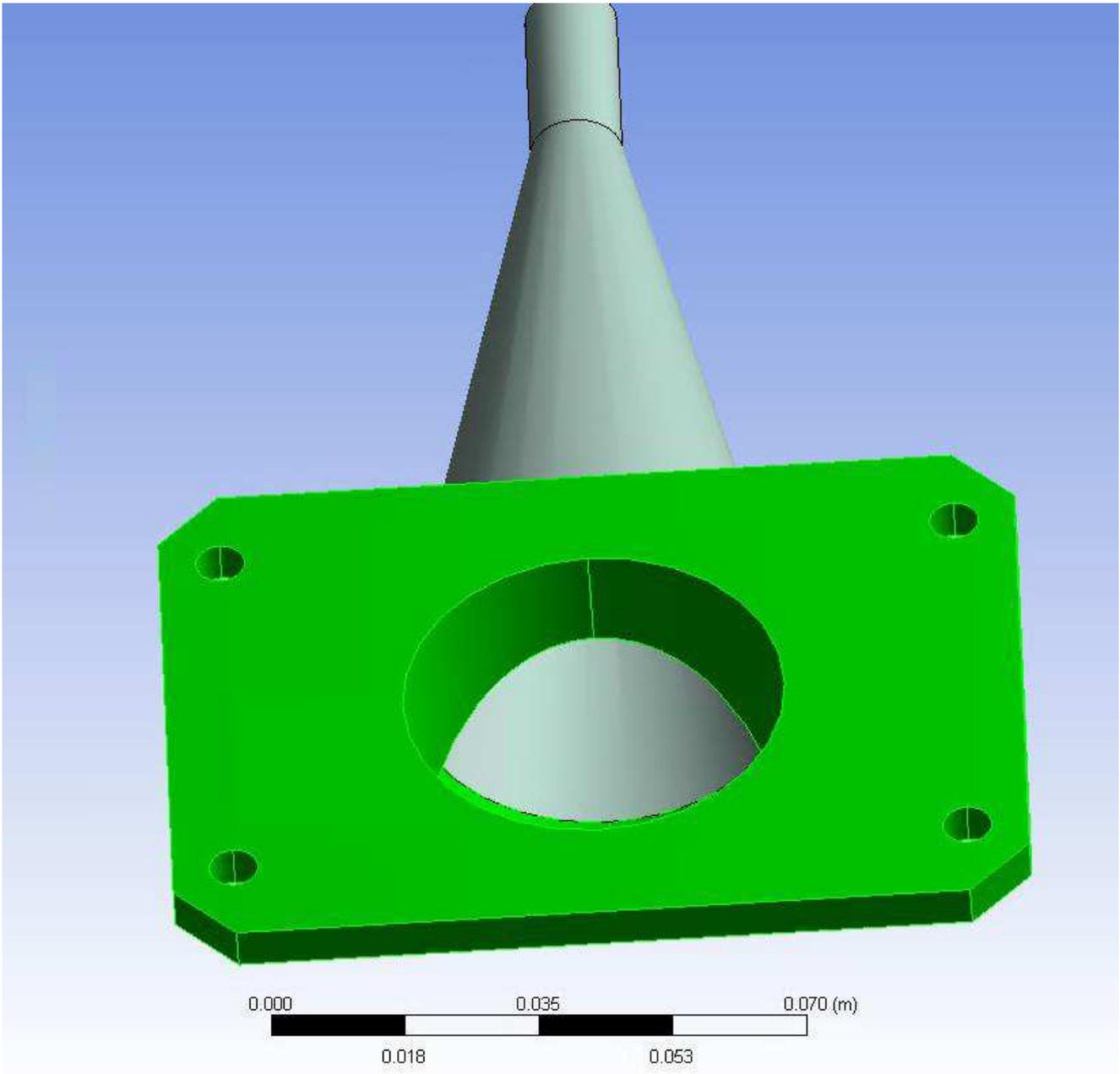
The model was re-run with the internal parts of the 90 bend structure set to an emissivity of 1. Any radiation landing on this from the hot driving surface will be fully absorbed, and not contribute directly to the rise of the inner parts of the cone.

Below is the temperature distribution on the inner cone. The distribution has changed very little, arguing that the hot area (albeit only 1.3C higher) comes from a direct view of the external hot body.



As seen here.

One might therefore hope to get good thermal results from this (unheated) cone - given that the environment is not 100C hotter.



The geometry, showing that the cone is visible from the exit aperture.

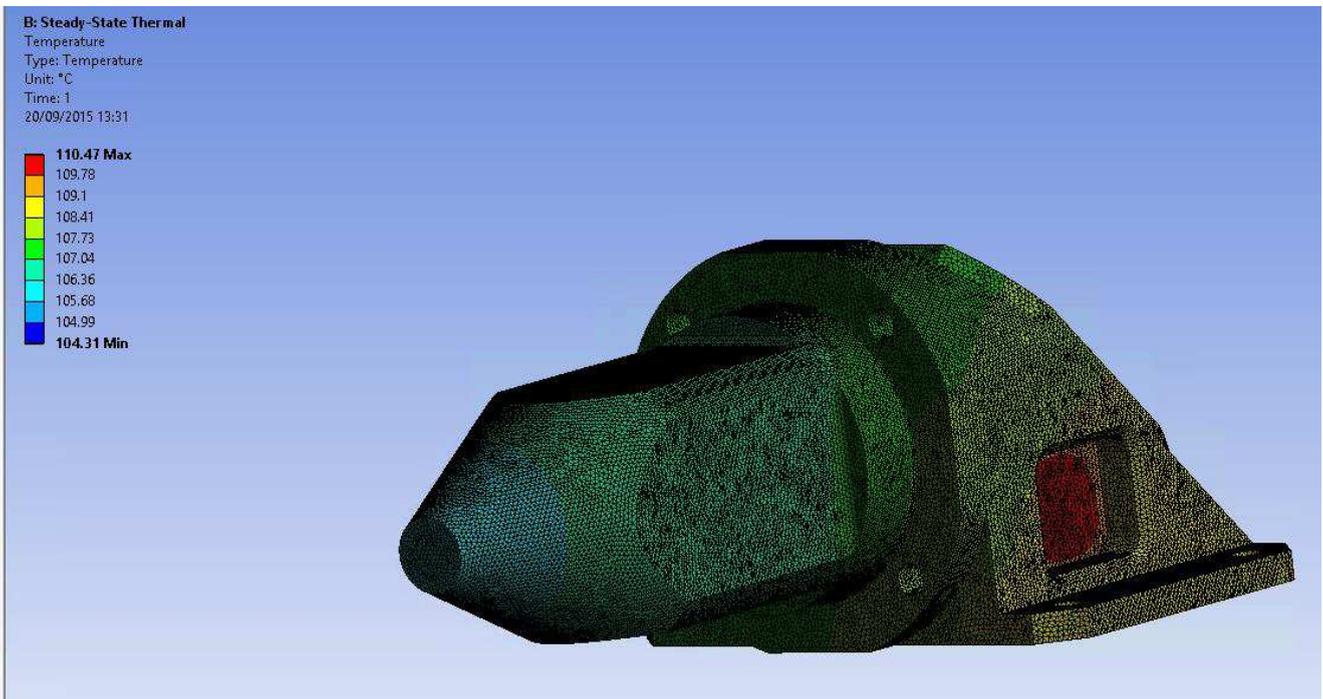
Determination of heater power required

We now try a model with heaters on both sides of the 90 degree mirror bend. We place heaters of (for modelling purposes) 5W on one side, 15W on the other side, in cut-outs (see image below - red is the hot area, of course).

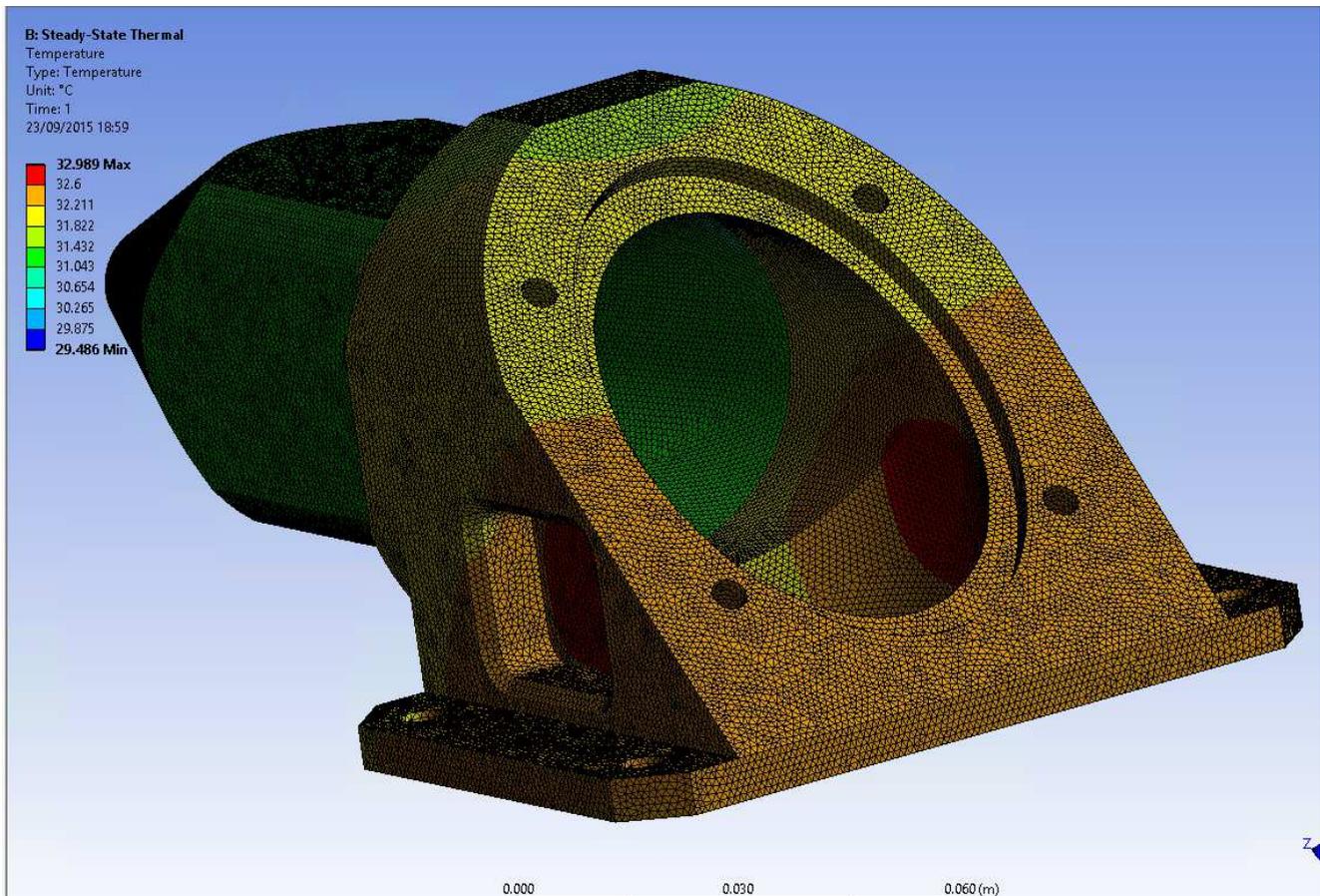
This is in vacuum only - no convection: the external ambient environment is set to 0C, with the external surfaces having a surface emissivity 0.2 - see table below.

Surface Material	Emissivity Coefficient - ϵ -
Aluminum Foil	0.04
Aluminum Commercial Sheet	0.09
Aluminum Heavily Oxidized	0.2 - 0.31
Aluminum Highly Polished	0.039 - 0.057

The no-convective outcome is that the structure warms up to about 100C, with a variation of 6C, across the structure.



If the heater power is reduced to 5 W a side and the emissivity of the surface increased to 0.8, the temperature increase drops to 30C and – although there are variations across the whole structure, the external cone structure (where the PRT’s are) and the inner cone are the same colour in the image below and therefore well within 0.5C



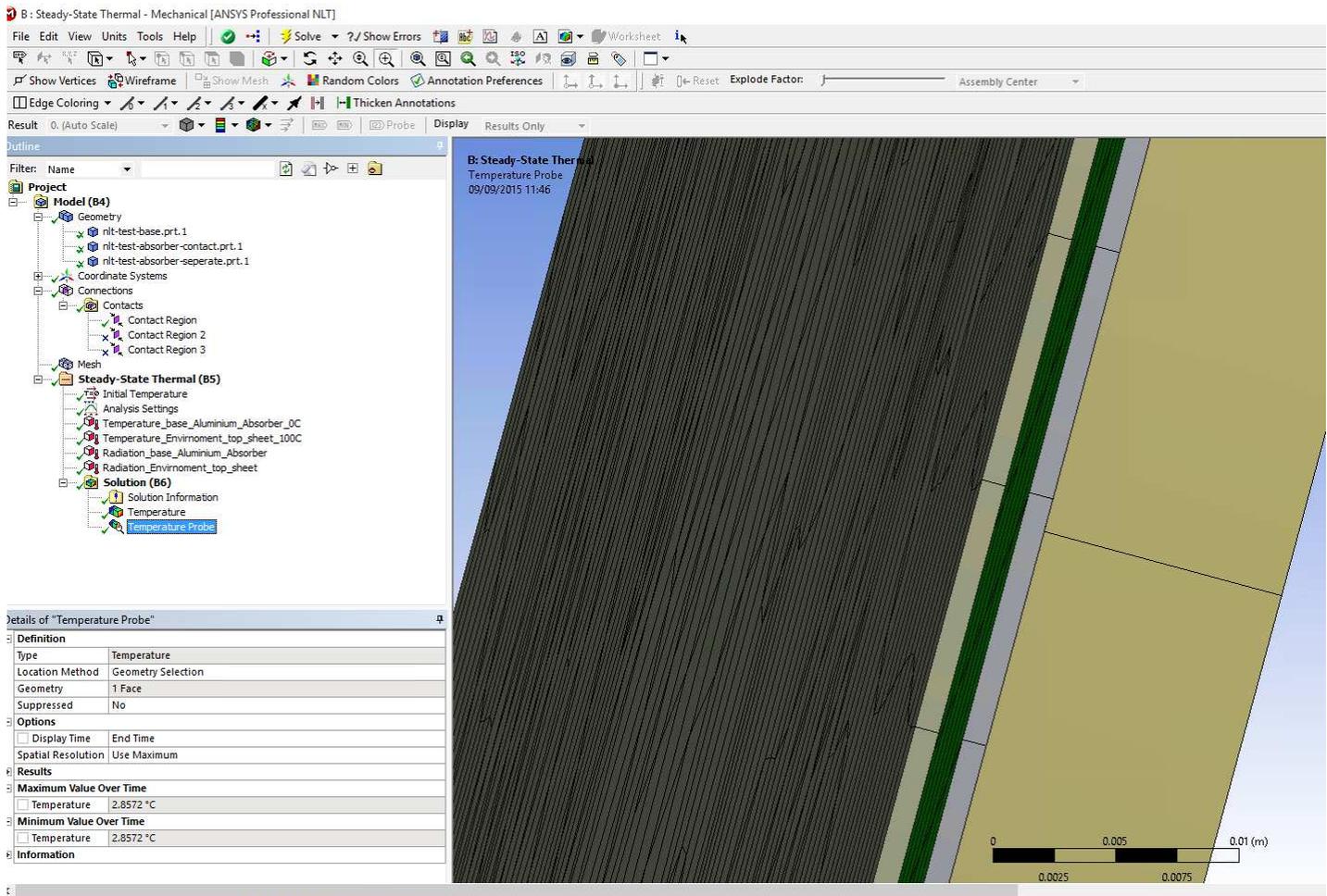
We conclude that two 3.7 W heaters (The nearest Minco devices available) will be quite sufficient.

7. NLT Validation

We need to have confidence both in the accuracy of the NLT software, but also in our correct usage of it.

We constructed a very simple mode of a 1Metre round Al plate, with 1mm thick CR110 with a conductivity of $0.27 \text{ W M}^{-1} \text{ K}^{-1}$ and a matching “radiation” plate 1mm away from it. Both the CR110 and the radiation plate have an emissivity set as 1. The plate diameter to spacing ratio of 100:1 is expected to be large enough to ignore edge effects.

Setting the back of the CR110 to 0 C and the radiation plate face which points at the CR110 at 100 C, we asked NLT to predict the surface temperature of the CR110:



NLT gives 2.8572C

Looking at a direct solution: We need to balance heat flowing through the CRS110 1mm layer against the difference in radiative loading - i.e. the difference in radiative energy received and transmitted. To first order, to calculate DeltaT

Conductivity flow = Radiative loading

$$\text{Area } \Delta T \cdot 0.27 \text{ W M}^{-1} \text{ K}^{-1} / 0.001 \text{ M} = \text{Area} \times 5.67 \cdot 10^{-8} \text{ W M}^{-2} \text{ K}^{-4} (373.15 \text{ K}^4 - 273.15 \text{ K}^4)$$

$$\Delta T = 5.6 \cdot 10^{-8} \text{ W M}^{-2} \text{ K}^{-4} (373.15 \text{ K}^4 - 273.15 \text{ K}^4) * 0.001 \text{ M} / 0.27 \text{ W M}^{-1} \text{ K}^{-1}$$

Iterating this with the surface temperature in a spreadsheet, to correct for the adjusted radiative temperature (this is a non-linear problem) of the CR110 surface we get

1			
2			
3			
4			
5			
6	Sefan-Boltzman constant	5.6704E-08	
7	T1	373.15	
8	T2 base	273.15	
9	Delta T	2.852867	
10	T2 combination	276.002867	
11	Thickness	0.001	
12	Conductivity	0.27	
13			
14			
15			
16	DeltaT		2.853053
17			
18			

Giving 2.853C: Taking this from 2.8572C we get 0.004C
So the difference is 0.14%, a very acceptable result....

8. APPENDIX



**MODEL 0118MF
HIGH RELIABILITY
SURFACE TEMPERATURE SENSOR**

- > Small Size
- > High Reliability
- > Linear Output
- > Wide Temperature Range
- > Recommended for Space Vehicles



DESCRIPTION

Model 0118MF is a general purpose surface temperature sensor designed to measure temperatures in the range of -269°C to +400°C. The sensing element is made of pure platinum encapsulated in ceramic insulation. This sensor is intended for demanding applications where precision, accuracy, and long-term stability are critical requirements. The space heritage of the 0118MF can be traced to the early 1960's.

SPECIFICATIONS

Temperature Range: -269°C to +400°C

Resistance (0°C): 10 to 5000 ohms

Interchangeability

	0°C Resistance Tolerance	0°C Error
Standard	±1.0%	2.56°C
Optional	±0.5%	1.28°C
Optional	±0.25%	0.64°C
Optional	±0.1%	0.26°C

Nominal Alpha: 0.00389Ω/Ω°C from 0°C to 100°C

Resistance-Temperature Relationship

See tables on back page. Interchangeability error limits over the temperature range will follow this equation:

$$\text{Error } ^\circ\text{C} = \pm(0^\circ\text{C error} + (A \cdot |T|)) \text{ at temperature } T$$

TABLE 1. A Values

Temperature Range	Interchangeability Options			
	1%	0.5%	0.25%	0.1%
-240°C to 0°C	-0.009	-0.004	-0.001	0.0005
0°C to +400°C	0.0131	0.0076	0.0046	0.0031

SPECIFICATIONS (continued)

Calibration

Each sensor is calibrated at 0°C. To establish a sensor specific R vs T table, optional multi-point calibrations are available. All calibration temperatures are traceable to NIST.

Insulation Resistance

10 megohms minimum with 100 VDC applied.

Thermal Hysteresis

0.1% maximum of temperature span encountered between readings.

Stability

0.03% maximum change in R₀ per 1000 hours at +400°C air.

Time Constant

0.6 seconds in oil flowing at 3 fps.

Repeatability

The sensor will shift ≤0.1°C at 0°C when exposed to 20 temperature shocks from liquid nitrogen to +150°C air.

Self-Heating

46mW with a temperature rise of <1°C in oil flowing at 3 fps at 25°C ±5°C.

Vibration

MIL-STD-810C, Method 514.2, Procedure V, Level U & AP.

Compatibility

Any fluid or environment that is compatible with platinum and a metal oxide ceramic.

Humidity

Model 0118MF is not susceptible to moisture absorption in moderate humidity atmospheres if the leads are suitably protected.

Sensor Weight

0.35 grams maximum

MODEL 0118MF HIGH RELIABILITY SURFACE TEMPERATURE SENSOR

SPECIFICATIONS (continued)

Lead Configurations

The model 0118MF comes with 1.5" platinum leads and is available in two, three and four wire configurations.

Lead Wire Extensions

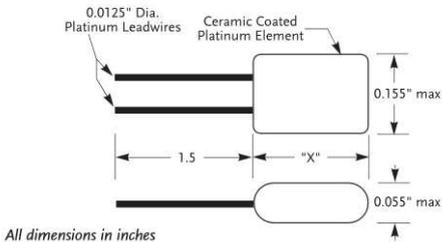
Lead wire extensions meeting various industry requirements are available. Please see Price List 2339 for details.

Identification

The sensor body is marked with the serial number. The shipping container is labeled with the following information:

Model 0118MF _____
 Serial Number _____
 Date Code _____

CONFIGURATION DRAWING



Length "X" = 0.155" max. for ice-point resistances of 500Ω or less.
 = 0.450" max. for ice-point resistances of greater than 500Ω up to 2000Ω.

Temperature (°C)	Resistance-Temperature Relationship Table			
	100Ω	500Ω	1000Ω	2000Ω
-260.00	0.24	1.25	2.25	5.41
-240.00	2.53	12.67	25.14	50.43
-220.00	8.92	44.62	89.08	179.50
-200.00	17.22	86.10	172.07	345.62
-180.00	25.90	129.50	258.92	519.40
-160.00	34.54	172.64	345.24	692.06
-140.00	43.04	215.14	430.25	862.06
-120.00	51.42	257.03	514.06	1029.62
-100.00	59.69	298.43	596.86	1195.12
-80.00	67.89	339.41	678.84	1358.89
-60.00	76.01	380.03	760.09	1521.16
-40.00	84.07	420.33	840.67	1682.04
-20.00	92.06	460.31	920.63	1841.64
0.00	100.00	500.00	1000.00	2000.00
20.00	107.87	539.36	1078.62	2157.23
40.00	115.69	578.49	1156.79	2313.56
60.00	123.47	617.39	1234.53	2468.99
80.00	131.21	656.05	1311.83	2623.54
100.00	138.90	694.50	1388.70	2777.20
120.00	146.55	732.72	1465.14	2929.98
140.00	154.15	770.71	1541.15	3081.88
160.00	161.71	808.48	1616.74	3232.92
180.00	169.22	846.03	1691.89	3383.08
200.00	176.69	883.36	1766.64	3532.38
220.00	184.12	920.46	1840.96	3680.82
240.00	191.51	957.34	1914.85	3828.40
260.00	198.85	994.01	1988.33	3975.12
280.00	206.15	1030.46	2061.39	4120.98
300.00	213.40	1066.68	2134.03	4265.98
320.00	220.61	1102.68	2206.24	4410.12
340.00	227.78	1138.47	2278.04	4553.40
360.00	234.91	1174.03	2349.42	4695.82
380.00	241.99	1209.37	2420.37	4837.38
400.00	249.03	1244.49	2490.91	4978.07

ORDERING INFORMATION: MODEL 0118MF SURFACE TEMPERATURE SENSOR

CODE	R ₀ - ICE POINT RESISTANCE OPTIONS
100-2000	100, 500, 1000 and 2000 ohm (consult factory for other R ₀ values)
CODE	LEADWIRE CONFIGURATION
A	2 Wire - 1.5" Platinum
B	3 Wire - 1.5" Platinum
C	4 Wire - 1.5" Platinum
CODE	R ₀ INTERCHANGEABILITY
Blank	±1.0%
A	±0.5%
B	±0.25%
C	±0.1

TYPICAL MODEL NUMBER: 0118MF 100 A



Sensor Systems
 Goodrich Corporation
 1256 Trapp Road
 Eagan, MN 55121-1282
 USA
 Tel: 651 681 8900
 Fax: 651 681 8991

www.aerospace.goodrich.com

FOR ADDITIONAL INFORMATION

To learn more about the Model 0118MF High Reliability Surface Temperature Sensor, call Goodrich at 651 681 8900.

4014 LIT 03/02
 © Rosemount Aerospace Inc., 2002
 Printed in the USA

The Goodrich name, logotype and symbol are trademarks of Goodrich Corporation.