Appendix D

TMRT
A thermal model reduction tool

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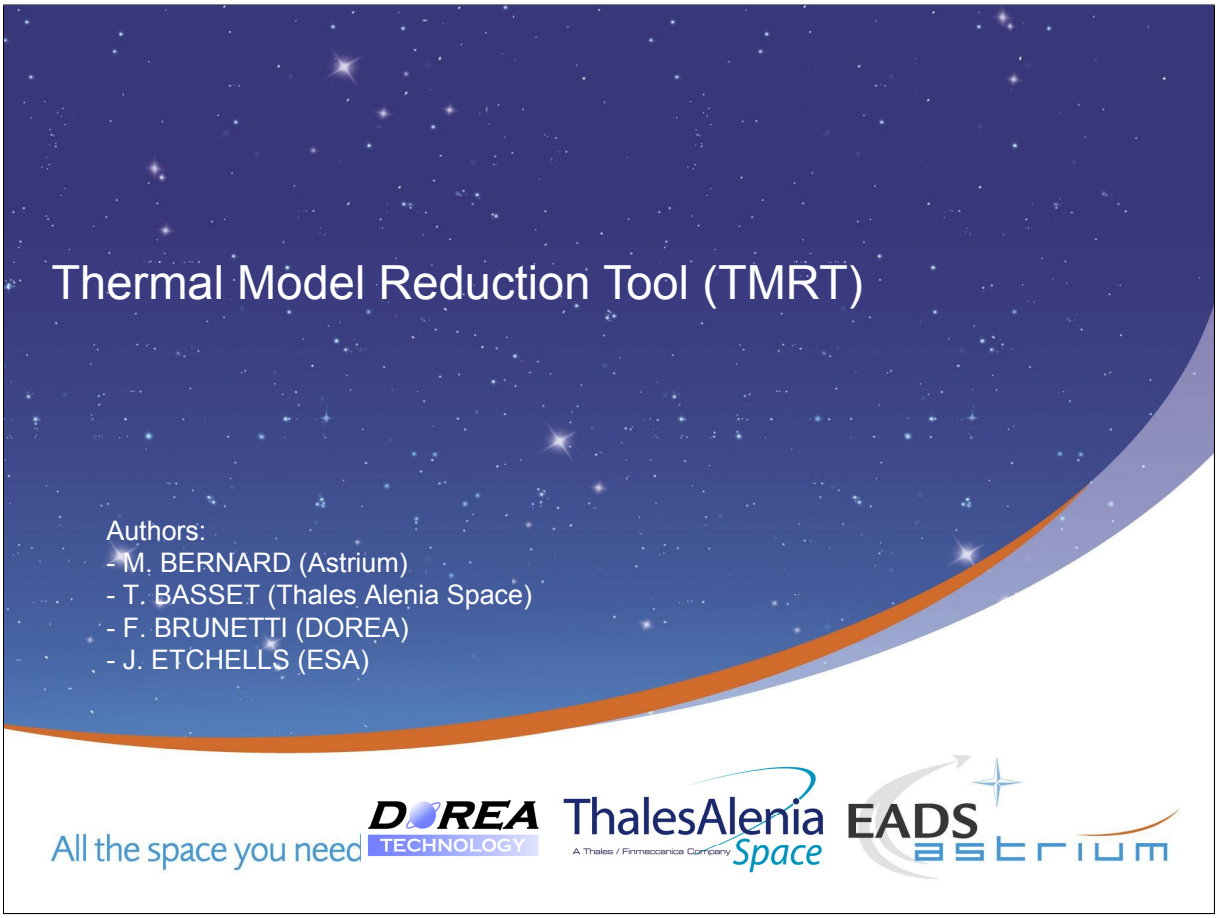
Abstract

TMRT is a software performing thermal model reductions, based on equivalent conductance matrices. It gathers the experience and knowhow of both THALES ALENIA SPACE and ASTRIUM in this domain. The presentation will first introduce the theory of the reduction method. Then, a demonstration will be made and used to show the advantages of the TMRT reduction method.


Thermal Model Reduction Tool (TMRT)
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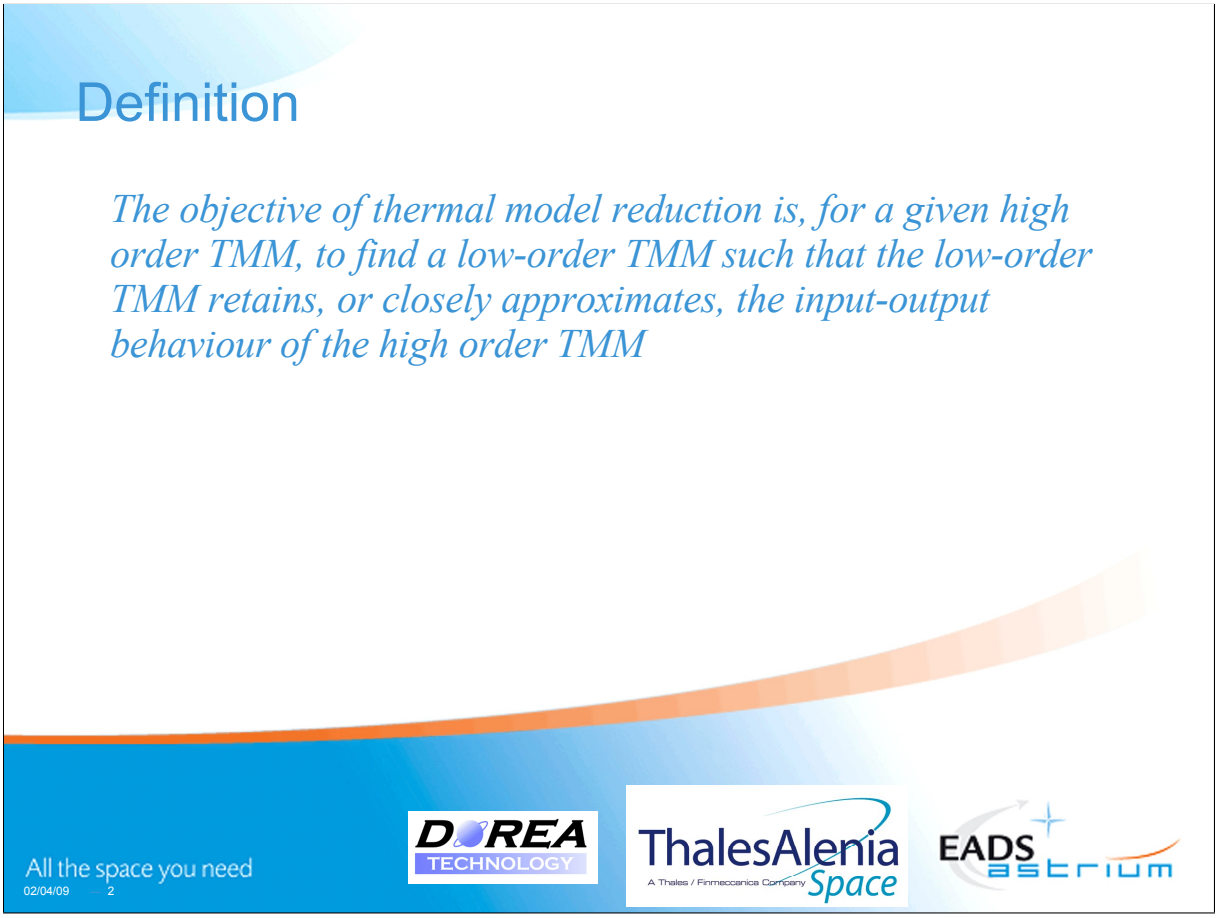
Definition
The objective of thermal model reduction is, for a given high order TMM, to find a low-order TMM such that the low-order TMM retains, or closely approximates, the input-output behaviour of the high order TMM
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Presentation Summary

- Project General Presentation
- Reduction Theory
- Software functionalities
- Demonstration
- Conclusion

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1 – Project General Presentation

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TMRT Project: Objectives

- Similar Conductive matrix reduction method in use at TAS & ASTRIUM ⇒ existing in-house tools:
  - Tools used for reduction of satellites, P/L, S/S, electronic units…
  - Efficiency of the tools proven (in use for many years).
- Methodology may be used by subsystem supplier to deliver more accurate reduced model for more accurate S/C model.
- In-house tool could not be commercialized as is.
- ESA, CNES, TAS & ASTRIUM wanted to get a single standard tool for distribution to thermal community.

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TMRT Project: Major specifications

- Compatibility with usual European thermal solvers:
  - CORATHERM, ESATAN and THERMISOL.
- Compatibility with TAS & ASTRIUM thermal analysis workflows.
- Maintain TAS & ASTRIUM tool functionalities:
  - Temperature recovery for nodes eliminated during TMM reduction.
  - Reduction of nodes with dissipation.
  - Summation of radiative couplings.
  - Reduction of already reduced models.
  - Maximum TMM size: 50000 nodes with CPU time objective.
- New functionality: reduction of capacitance matrix.

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TMRT Project: Team

- Benefit from existing applications: *EQUIVAL application (TAS) as root for TMRT development.*

⇒TAS supported by DOREA for tool development.

- ASTRIUM for tool specification & validation (Prime contractor).
- GSTP program ⇒ monitored by ESA and supported by CNES.

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2 – Reduction Theory

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TMRT Theory: Matrix Equations

- Thermal System Heat Equation:

$$[C_{DD}]\{T_D\} + \{Q_D\} + \{P_D\} - [M_{DD}]\left\{\frac{\partial T_D}{\partial t}\right\} = \{0\}$$

- 3 kinds of nodes in detailed model:
  - K = kept nodes.
  - S = suppressed nodes (only if not radiative).
  - G = grouped nodes G defining average nodes A.

$$\begin{bmatrix} C_{KK} & C_{KS} & C_{KG} \\ C_{SK} & C_{SS} & C_{SG} \\ C_{GK} & C_{GS} & C_{GG} \end{bmatrix} \begin{Bmatrix} T_K \\ T_S \\ T_G \end{Bmatrix} + \begin{Bmatrix} Q_K \\ Q_S \\ Q_G \end{Bmatrix} + \begin{Bmatrix} P_K \\ 0 \\ P_G \end{Bmatrix} - \begin{bmatrix} M_{KK} & 0 & 0 \\ 0 & M_{SS} & 0 \\ 0 & 0 & M_{GG} \end{bmatrix} \begin{Bmatrix} \frac{\partial T_K}{\partial t} \\ \frac{\partial T_S}{\partial t} \\ \frac{\partial T_G}{\partial t} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

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TMRT Theory: Matrix Equations

- Average Node Definition TA:
  - $T_A = \sum_G a_{AG} T_G$
  - a_{AG} = area/capacitance ratio of node G vs node A.
- Physical hypothesis: *Fluxes, radiative exchanges or convective exchanges proportional to node area.*
  - $P_G = a_{GA} P_A$

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TMRT Theory: Matrix Equations

- Equivalent equations:
  - Reduced system heat equation:

$$\left[C'_{RR}\right]\begin{Bmatrix}T_K\\T_A\end{Bmatrix}+\left[PwD_{RD}\right]\begin{Bmatrix}Q_K\\Q_S\\Q_R\end{Bmatrix}+\begin{Bmatrix}P_K\\P_A\end{Bmatrix}-\left[M'_{RR}\right]\begin{Bmatrix}\frac{\partial T_K}{\partial t}\\\frac{\partial T_A}{\partial t}\end{Bmatrix}=\{0\}$$

  - Temperature recovery equation:

$$\begin{Bmatrix}T_S\\T_G\end{Bmatrix}\approx\left[TRt_{MR}\right]\begin{Bmatrix}T_K\\T_A\end{Bmatrix}+\left[TRq_{MM}\right]\begin{Bmatrix}Q_S\\Q_G\end{Bmatrix}$$

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TMRT Theory: Radiative Approximation

- Error for radiative exchanges is a second order:

$$\sum_G a_{AG}T_G^4=\sum_j a_{AG}\left(T_A+\Delta T_G\right)^4$$

=1 =0

$$\sum_G a_{AG}T_G^4=T_A^4\sum_G a_{AG}+4T_A^3\sum_G a_{AG}\Delta T_G+6T_A^2\sum_G a_{AG}\Delta T_G^2+..$$

$$\sum_G a_{AG}T_G^4\approx T_A^4+6T_A^2\sum_G a_{AG}\Delta T_G^2$$

Proportional to radiative fluxes for detailed model

Proportional to radiative fluxes for Reduced model

Relative error is a second order

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TMRT Theory: Capacitance Approximation

- Equivalent Capacitance Matrix:
  - This matrix is a full matrix.
  - For use in usual solvers, it is “made diagonal” by summation of the terms of a line on the diagonal term.
  - Better than manual distribution.

- Resulting Approximation:
  - $$\sum_j \left(M_{i,j} \frac{\partial T_j}{\partial t} \right) \approx \sum_j \left(M_{i,j} \right) \frac{\partial T_i}{\partial t}$$
  - $M_{i,j}$ factors are more important for j nodes that are conductively close to node i.

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3 – Software Functionalities

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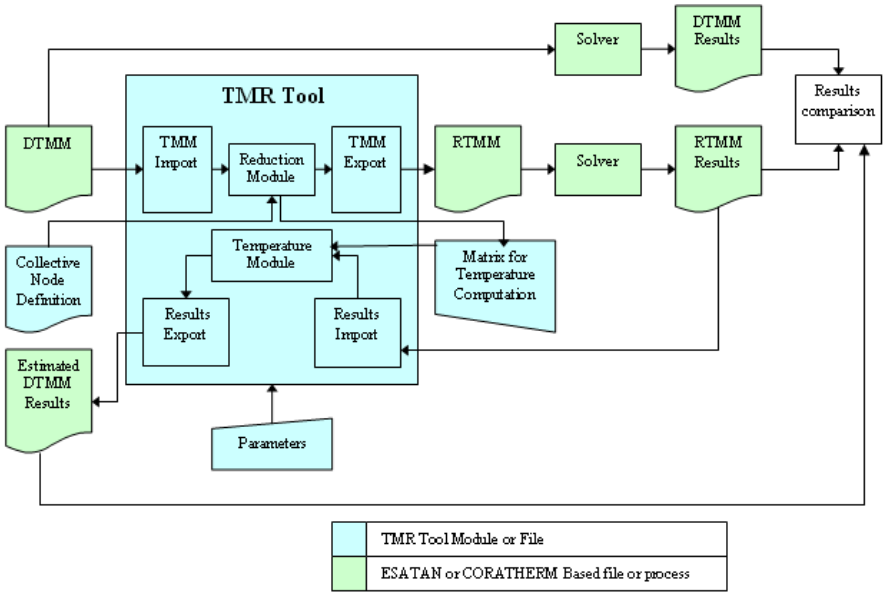
TMRT Functionalities: Logic Diagram



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TMRT Functionalities: Reduction

- Reduced model conductive coupling list computed by:
  - Building the original system conductance matrix from its conductive coupling list.
  - Importing the reduction definition.
  - Computing the equivalent conductance matrix.
  - Building the reduced model conductive coupling list from the equivalent conductance matrix.
- Reduced model radiative coupling list computed by summation of detailed model radiative couplings.

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TMRT Functionalities: Reduction

- Reduced model capacitances computed using either:
  - The equivalent capacitance matrix (made diagonal).
  - The user defined affectation of Suppressed and Grouped nodes capacitances to Kept and Average nodes.
- Power distribution performed by:
  - Keeping dissipative Suppressed and Grouped nodes as inactive nodes with their dissipated power declaration.
  - Adding power distribution lines to the reduced model.

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TMRT Functionalities: Temperature Recovery

- Import of reduced model temperature results including dissipative Suppressed and Grouped nodes powers
- Use of temperature recovery equation.
- Export of computed Suppressed and Grouped temperatures.

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TMRT Functionalities: Filters

- The matrices generated by TMRT are full matrices. Then, even if the number of nodes has been reduced, the number of couplings may have increased in greater proportion.
- Therefore, TMRT can filter the insignificant terms in the matrices in order to really have a reduced model (the filtering threshold is set by the user).
- The user can filter the conductance list, the power distribution factors and the temperature recovery factors.

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TMRT Functionalities: Formats

- TMRT is capable of handling both CORATHERM and ESATAN/THERMISOL (with some restrictions) thermal model formats.
- Input format and output format may be different:
  - CORATHERM → CORATHERM.
  - ESATAN/THERMISOL → ESATAN/THERMISOL.
  - CORATHERM → ESATAN/THERMISOL.
  - ESATAN/THERMISOL → CORATHERM.

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TMRT Functionalities: Post-process Nodes

- Recomputed Average (RA): Computing the average temperature for a group of nodes of the original thermal model.
- Conductive Exchange (CE): Computing the power conductively exchanged between 2 groups of nodes of the original thermal model.
- Computation performed during temperature recovery.

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4 – Demonstration

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TMRT Demonstration

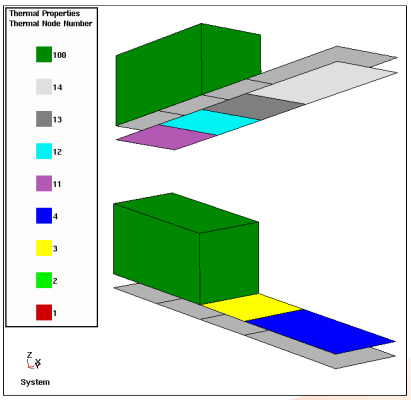
- Original model:

```
$NODES
 D   1 = 'Panel 01   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 0.000D+0;
 D   2 = 'Panel 02   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 1.0D+0, QR= 1.0D+1, QS= 0.000D+0;
 D   3 = 'Panel 02   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 0.0D+0, QR= 2.0D+1, QS= 0.000D+0;
 D   4 = 'Panel 03   ', T=0.0D0, C= 2.628D+1, A=2.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 0.000D+0;
 D  11 = 'Panel 04   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 5.670D-1;
 D  12 = 'Panel 05   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 5.670D-1;
 D  13 = 'Panel 05   ', T=0.0D0, C= 1.314D+1, A=1.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 5.670D-1;
 D  14 = 'Panel 06   ', T=0.0D0, C= 2.628D+1, A=2.0D-2, QI= 0.0D+0, QR= 0.0D+0, QS= 1.134D+0;
 D 100 = 'Component  ', T=0.0D0, C= 8.000D+2, A=8.0D-2, QI= 1.0D+0, QR= 0.0D+0, QS= 0.000D+0;

 B 999 = 'Space      ', T=-269.0D0;

$CONDUCTORS
# NIDA Couplings:
GL(  1,  2) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+1.0D-1);
GL(  2,  3) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+1.0D-1);
GL(  3,  4) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+2.0D-1);
GL( 11, 12) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+1.0D-1);
GL( 12, 13) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+1.0D-1);
GL( 13, 14) = 8.909*1.0D-1*0.0075*2.0/(1.0D-1+2.0D-1);
GL(  1, 11) = 1.801*1.0D-1*1.0D-1/0.015;
GL(  2, 12) = 1.801*1.0D-1*1.0D-1/0.015;
GL(  3, 13) = 1.801*1.0D-1*1.0D-1/0.015;
GL(  4, 14) = 1.801*1.0D-1*2.0D-1/0.015;
#Component Couplings:
GL(100,  1) = 1.0D-1*1.0D-1*4000.0;
GL(100,  2) = 1.0D-1*1.0D-1*4000.0;
#Space Couplings:
GR( 11,999) = 7.730E-03;
GR( 12,999) = 7.730E-03;
GR( 13,999) = 7.730E-03;
GR( 14,999) = 1.546E-02;

$CONSTANTS
$INTEGER
 HEATER=0;
$CONTROL
 STEFAN=5.6686D-08;
 RELXCA=1.0D-04;
 MAXOP=2000;
 DTIME1=60.0D0;
 DTMIN=60.0D0;
 DTMAX=60.0D0;
 TIME0=0.0D0;
 TIMEND=3600.0D0;
 OUTINT=60.0D0;
$INITIAL
       QI100 =   1.00D0
       QI2   =   1.00D0
$VARIABLES1
       CALL THRMST(T100,30.0D0,25.0D0,HEATER)
       QR2    = 10.0*HEATER
       QR3    = 20.0*HEATER
```



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TMRT Demonstration

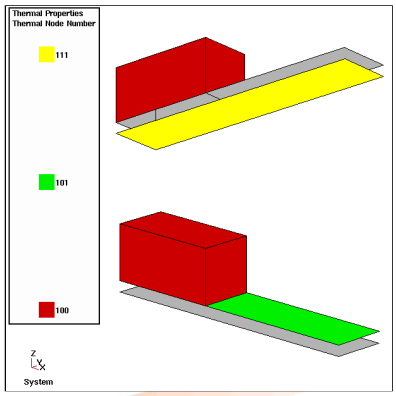
- Reduction:

```
$SUPPRESSED
1 100
$Q
2 100
3
$NREC
3
4
#
$AVERAGE
CAPACITANCES
$101
3 1
4 1
$102
11 1
12 1
13 1
14 1
#
$RA
AREAS
$1001
11  1
12  1
$1002
13  1
14  1
#
$CE
$2001
$GROUP1
1
2
$GROUP2
11
12
$2002
$GROUP1
11
12
$GROUP2
13
14
```

```
$NODES
# Nodes definition
#################################################################################
#                                RTHM Nodes                                     #
#################################################################################
 D 100 = 'Component  ', T=0.0D+0, C= 8.26280D+2, A= 8.0D-2, QI= 1.98626296E+0, QR= 1.76001575E+1, QS= 0.000D+0;
 D 101 = 'Average 1  ', T=0.0D+0, C= 3.94200D+1, A= 3.0D-2, QI=-1.58672864E-2, QR= 1.18715444E+1, QS= 0.000D+0;
 D 111 = 'Average 2  ', T=0.0D+0, C= 6.57000D+1, A= 5.0D-2, QI= 2.96043265E-2, QR= 5.28298062E-1, QS= 2.835D+0;
#
#################################################################################
# Former DTMH Q Nodes With Internal/Heating Power: Used For Power Distribution #
#################################################################################
 X   2 = 'Panel 02   ', T=0.0D+0, C= 1.314D+1, A= 1.0D-2, QI= 1.00000000D+0, QR= 1.00000000D+1, QS= 0.000D+0;
 X   3 = 'Panel 02   ', T=0.0D+0, C= 1.314D+1, A= 1.0D-2, QI= 0.00000000D+0, QR= 2.00000000D+1, QS= 0.000D+0;
#
#################################################################################
#                              Boundary Nodes                                   #
#################################################################################
 B 999 = 'Space      ', T=-269.0D0;

$CONDUCTORS
#
# Linear couplings ie conductive or convective couplings
GL(100,101) =-1.34484776D+0;
GL(100,111) = 2.37054531D+0;
GL(101,111) = 3.56163215D+0;
#
# Radiative couplings
GR(111,999) = 3.86500000D-2;

$INITIAL
       QI100 =   1.0D0
       QI2   =   1.0D0
#
#################################################################################
#                    Former DTMH Q Nodes Internal Power Distribution            #
#################################################################################
       QI100 =  9.86262960D-1*QI2+QI100
       QI101 = -1.58672864D-2*QI2
       QI111 =  2.96043265D-2*QI2
$VARIABLES1
       CALL THRMST(T100,30.0D0,25.0D0,HEATER)
       QR2    = 10.0*HEATER
       QR3    = 20.0*HEATER
#
#################################################################################
#                    Former DTMH Q Nodes Heating Power Distribution             #
#################################################################################
       QR100 =  9.86262960D-1*QR2+3.86876397D-1*QR3
       QR101 = -1.58672864D-2*QR2+6.01510863D-1*QR3
       QR111 =  2.96043265D-2*QR2+1.16127399D-2*QR3
```



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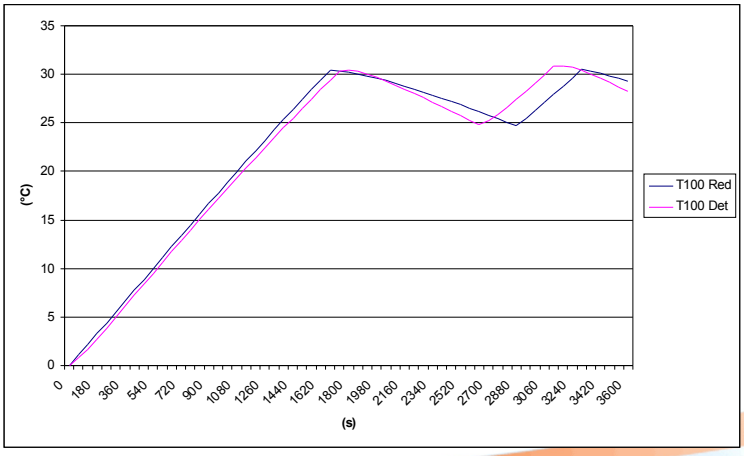
TMRT Demonstration

- Unit Temperature Response Comparison:



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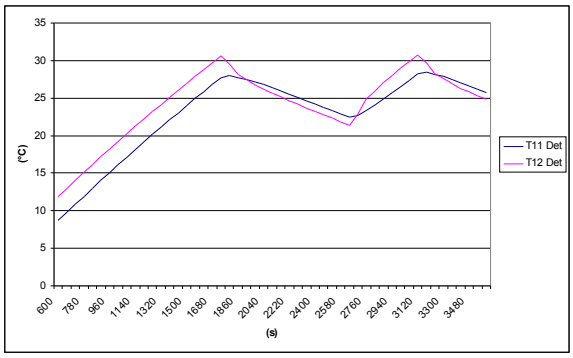
TMRT Demonstration

- Temperature Recovery:



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5 – Conclusion

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Conclusion

- Present Situation: End of software validation
- For huge models, special attention is needed for reasonable CPU time duration (software optimised for LINUX 64bits)
- Commercialization: Q4 2009 with dedicated documentation :
  - Theoretical manual explaining theory based on rigorous mathematical demonstration.
  - User's manual.

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