

Appendix K

Prototype demonstration of Thermal Design Module for
automated design and temperature calculation of space harness

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Abstract

Design of space harness is based on ECSS-Q-30-11C assuming a thermal balance between heat losses and heat radiation cooling in a worst case environment in spacecraft. A JAVA thermal analyser (Thermal Design Module) was developed and validated for wire temperature prediction for aircraft applications that is extended towards an automatic generation of bundles designs for space. A demonstration of a prototype TDM2.0.1 shows user inputs and output graphs for space harness designs. The TDM supports optimization of harness designs with respect to weight reduction and improved safety.



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Prototype Thermal Design Module for automated designs of space harness

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Contents

- **Electrical wiring design practice in aerospace applications**
- **Why thermal analysis of wiring bundle designs?**
- **Prototype Thermal Design Model (TDM) demonstration**
- **Outlook for space applications**



Why thermal analysis?

- **Typical harness weight in**
 - aircraft (150 seats) > 1500 Kg
 - satellites (Artimes) > 50 Kg (ca 40Kg power + 10Kg data-cable)*

- **Typical cost of wiring**
 - Life cycle cost (per aircraft) > 10.000 Euro/kg
 - Launch cost 12.000-32.000 Euro/Kg (LEO/GEO)

=> For instance a 5% weight reduction of a satellite harness gives a launch cost reduction between 30.000 Euro (LEO) and 80.000 Euro (GEO).

- In 2007 NLR started research for the aircraft industry (Fokker Elmo) to investigate weight reductions and improved safety (structural integrity) of wiring designs by thermal analysis.

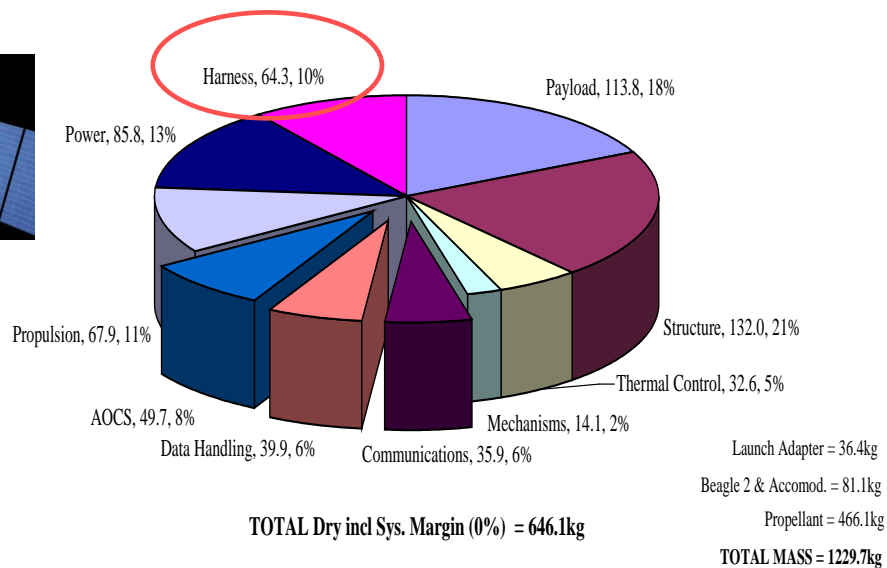
=> On average a 5% temperature elevation increase should save about 5% weight

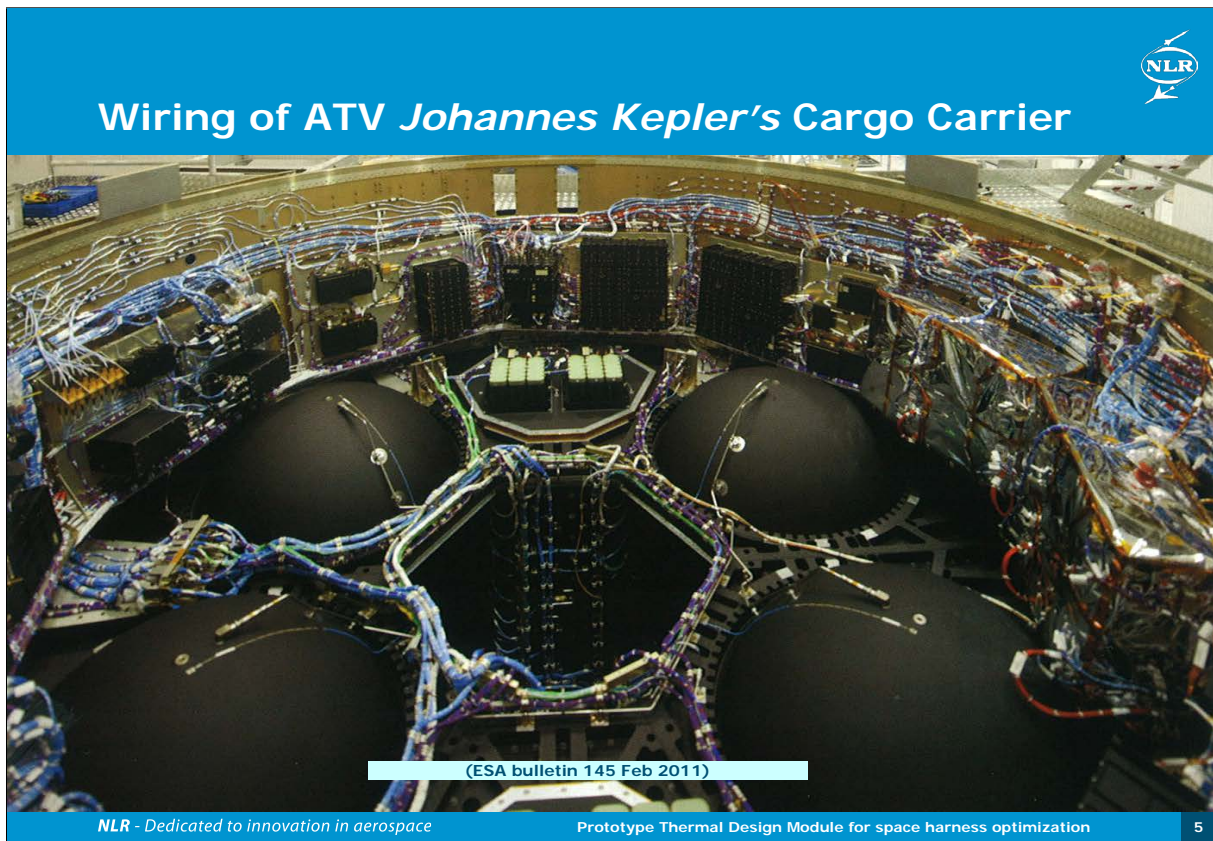
- **Extension towards space applications?**

* Workshop on Spacecraft Data Systems, 5-7 May 2003, ESTEC, Noordwijk, rodder.magness@esa.int



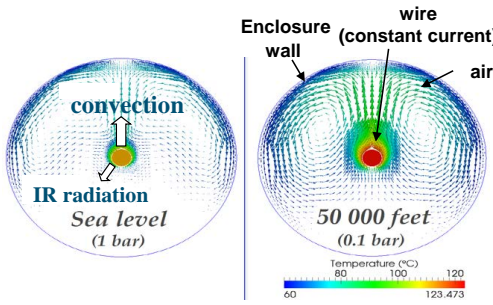
Harness weight in space systems





Harness design requirements


- Wires sizing in the aeronautical standards is based on a thermal equilibrium between heat loss (I^2R) and natural cooling of a wire segment.
- Cooling is provided by air convection & conduction, heat radiation and axial conduction.



The figure consists of two circular diagrams illustrating thermal analysis. The left diagram is labeled 'convection' and 'IR radiation' and is set at 'Sea level (1 bar)'. It shows a central wire with a green-to-yellow gradient, indicating a temperature profile. The right diagram is labeled 'Enclosure wall', 'wire (constant current)', and 'air', and is set at '50 000 feet (0.1 bar)'. It shows a similar wire but with a more pronounced red-to-yellow gradient, indicating higher temperatures. A color scale at the bottom indicates temperature in degrees Celsius, ranging from 60 to 120, with a maximum value of 123.473.

(Oofelie: Multiphysics, Open Engineering)

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Current derating in ECSS-Q-30-11C

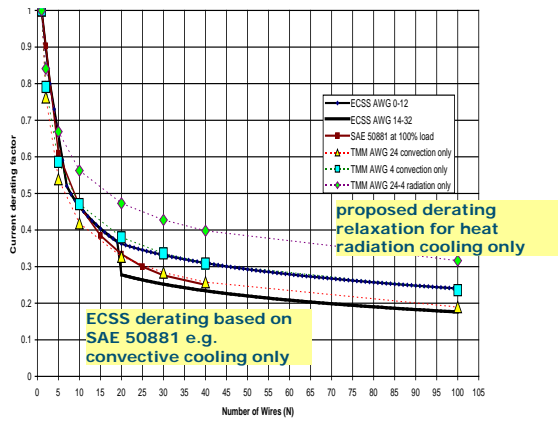
Parameters	Load ratio or limit														
Voltage	50 %														
Wire size (AWG)	32	30	28	26	24	22	20	18	16	14	12	10	8	6	4
Maximum current Cu (I) (A) *	1,2	1,3	1,5	2,5	3,5	5	7,5	10	13	17	25	32	45	60	81
Maximum current Al (I) (A) *						4	6	8	10,4	13,6	18,4	25,6	36		
Wire surface temperature	Manufacturer's maximum rating Tmax: 50°C.														

* The derating on current for bundles with N wires is calculated as follows:
 $IBW = ISW \times K$ for ambient temperature of 40°C.


Number of wires (N)	Wires AWG 14 to AWG 32		Wires AWG 0 to AWG 12	
	K		K	
$1 < N \leq 3$	1,1	$(0,1 \times N)$	$1 < N \leq 3$	$1,1 - (0,1 \times N)$
$3 < N \leq 7$	1,01	$(0,07 \times N)$	$3 < N \leq 7$	$1,01 - (0,07 \times N)$
$7 < N \leq 19$	0,81	$[0,15 \times \ln(N)]$	$7 < N \leq 52$	$0,81 - [0,15 \times \ln(N)]$
$19 < N \leq 331$	0,59	$[0,076 \times \ln(N)]$	$52 < N \leq 331$	$0,467 - [0,0632 \times \ln(N)]$

Isw: maximum current for an individual wire in a bundle.
 Ibw: maximum current for a single wire as given in the derating table above.
 ln: Natural log.

In case of wires in cold redundancy or wires non used in the same bundle (one with current, the other without current) the number of wires to take into account is calculated as follows: N equivalent bundle = N wire with current + 0,5 x N wire without current with IBW which shall not overpass ISW.



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7



Development of Thermal Design Module

- **Development of Thermal Design Module for thermal analysis of wiring in aircraft to investigate potential weight saving and safety risks:**
 - TDM1.0 validated in 2009 for 15-16 mm bundles in a 200mm cylindrical enclosure (Fokker Elmo)
 - TDM2.0 validated in 2011 for 5-35 mm bundles in 4" aircraft enclosures (Fokker Elmo)

- **Investigation of extension towards space applications by switching 'off' convective and conductive heat transfer.**

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8

Thermal Design Model (TDM)

TDM 2.0 features:


- Java matrix solver
- Wire size properties & design currents (load cases)
- Bundle configuration with or without braid
- 2D Heat Transfer coefficient calculation
- Continuous (steady state) temperature prediction per wire
- Wire size iteration

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Thermal Design Model (TDM) prototype demo

Additional post processing step added for automated bundle design based on design currents and derating factors

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Thermal Design Module demonstration (0)


Example design...

Gauge	Number of cables	ECSS max current [Amp]	ECSS Derating	Design current [Amp]
4	2	81	0.24	19.4
12	4	25		6.0
16	6	13		6.2
18	14	10	0.48	4.8
20	18	7.5		3.6
Total	44			

Design Current = Maximum current x derating

Calculation Current = Design Current x Load-factor

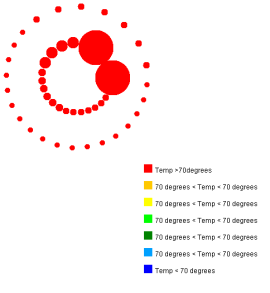
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11



Thermal Design Module demonstration (1)

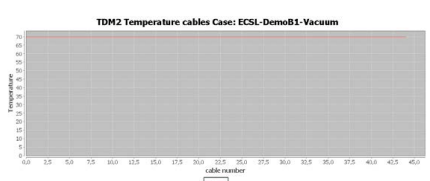
Example design with all load-factors = 0 (no load)

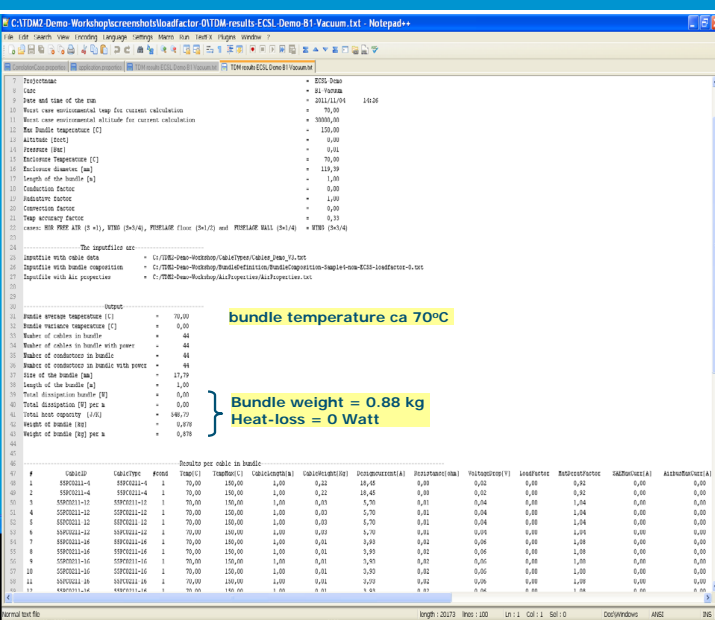
$T_{amb} = 70^{\circ}\text{C}$, $P = 0 \text{ BAR}$, $L = 1 \text{ m}$




bundle temperature ca 70°C

Bundle weight = 0.88 kg
Heat-loss = 0 Watt





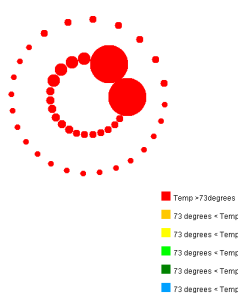
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12



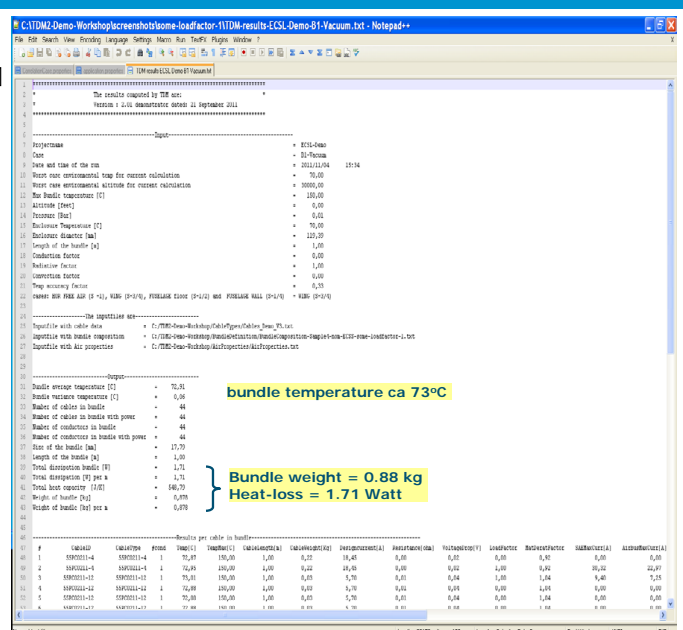
Thermal Design Module demonstration (2)

Example design with a few cables load-factor = 1 (partial load)

$T_{env} = 70^{\circ}\text{C}, P = 0 \text{ BAR}, L = 1 \text{ m}$



■ Temp = 73 degrees
■ 73 degrees = Temp = 73 degrees
■ 73 degrees = Temp = 73 degrees
■ 73 degrees = Temp = 73 degrees
■ 73 degrees = Temp = 73 degrees




bundle temperature ca 73°C

Bundle weight = 0.88 kg
Heat-loss = 1.71 Watt

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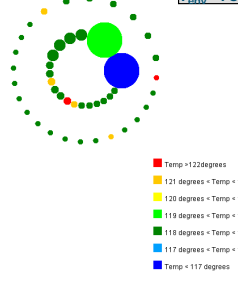
13



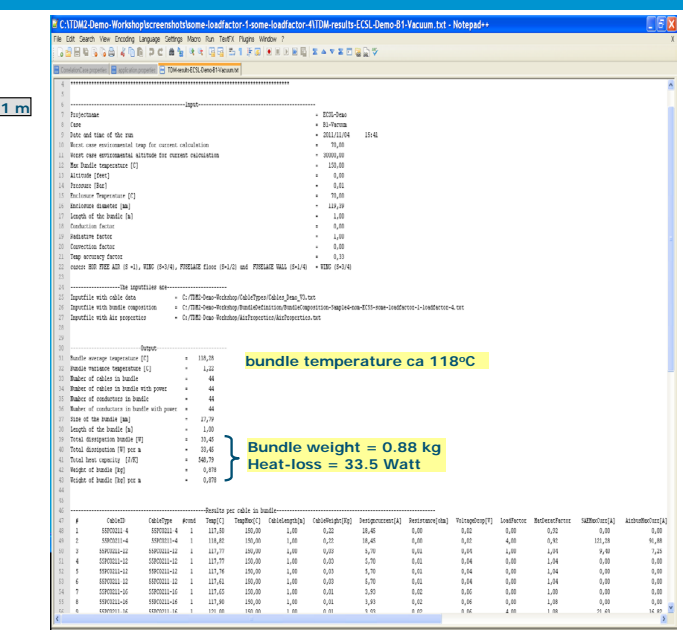
Thermal Design Module demonstration (3)

Example design + most cables load-factor = 1 but a few with load-factor = 4 (partial overload)

$T_{env} = 70^{\circ}\text{C}, P = 0 \text{ BAR}, L = 1 \text{ m}$



■ Temp = 122 degrees
■ 121 degrees = Temp = 122 degrees
■ 120 degrees = Temp = 121 degrees
■ 119 degrees = Temp = 120 degrees
■ 118 degrees = Temp = 119 degrees
■ 117 degrees = Temp = 118 degrees



bundle temperature ca 118°C

Bundle weight = 0.88 kg
Heat-loss = 33.5 Watt

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14

Thermal Design Module demonstration (4)

Example design (full load)

$T_{env} = 70^{\circ}\text{C}, P = 0 \text{ BAR}, L = 1 \text{ m}$

- Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- 87 degrees + Temp = 87 degrees
- Temp = 86 degrees

TDM2 Temperature cables Case: ECLS-Demo01-Vacuum

bundle temperature ca 86°C

Bundle weight = 0.88 kg
Heat-loss = 10.3 Watt

Results per cable in bundle														
#	CableID	CableType	Power	Temp[C]	TempMax[C]	CableLength[m]	CableResistance[Ohm]	Resistance[Ohm]	Resistance[Ohm]	VoltsDrop[V]	LossFactor	HeatLossFactor	HeatLoss[Watt]	AccHeat[Watt]
1	SPP0211-4	SPP0211-4	1	86,19	150,00	1,00	0,22	10,40	0,00	0,00	0,00	0,00	0,00	0,00
2	SPP0211-4	SPP0211-4	1	86,39	150,00	1,00	0,22	10,40	0,00	0,00	0,00	0,00	0,00	0,00
3	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
4	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
5	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
6	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
7	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
8	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
9	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25
10	SPP0211-12	SPP0211-12	1	86,52	150,00	1,00	0,03	0,70	0,01	0,04	1,00	1,04	9,40	7,25

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Thermal Design Module demonstration (5)

Example design (full load)

length cables = 4 [m]

$T_{env} = 70^{\circ}\text{C}, P = 0 \text{ BAR}, L = 4 \text{ m}$

- Temp = 88degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- 89 degrees + Temp = 89 degrees
- Temp = 88 degrees


TDM2 Temperature cables Case: ECLS-Demo01-Vacuum

bundle temperature ca 88°C

Bundle weight = 3.51 kg
Heat-loss = 41.2 Watt

Results per cable in bundle														
#	CableID	CableType	Power	Temp[C]	TempMax[C]	CableLength[m]	CableResistance[Ohm]	Resistance[Ohm]	Resistance[Ohm]	VoltsDrop[V]	LossFactor	HeatLossFactor	HeatLoss[Watt]	AccHeat[Watt]
1	SPP0211-4	SPP0211-4	1	86,48	150,00	4,00	0,88	40,60	0,00	0,00	0,00	0,00	0,00	0,00
2	SPP0211-4	SPP0211-4	1	86,48	150,00	4,00	0,88	40,60	0,00	0,00	0,00	0,00	0,00	0,00
3	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
4	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
5	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
6	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
7	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
8	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
9	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25
10	SPP0211-12	SPP0211-12	1	86,57	150,00	4,00	0,12	5,70	0,03	0,25	1,00	1,04	9,40	7,25

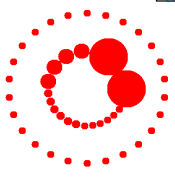
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Thermal Design Module demonstration (7)

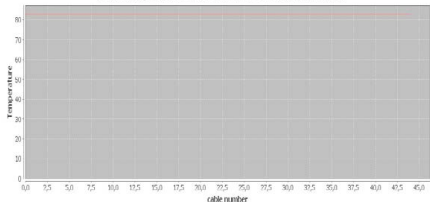
Fixed current design (gauging calculated using ECSS)

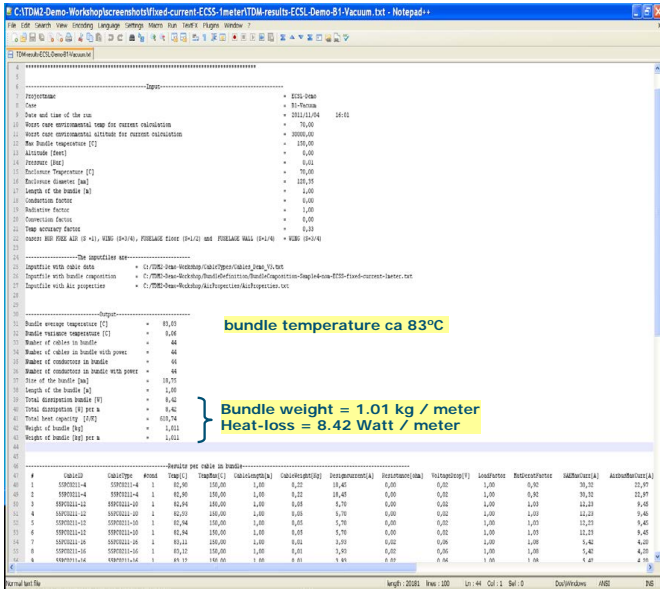
$T_{env} = 70^{\circ}\text{C}, P=0 \text{ BAR}, L=1 \text{ m}$



- Temp >93degrees
- 93 degrees < Temp < 93 degrees
- 93 degrees < Temp < 93 degrees
- 93 degrees < Temp < 93 degrees
- 93 degrees < Temp < 93 degrees
- 93 degrees < Temp < 93 degrees
- Temp < 93 degrees

TDM2 Temperature cables Case: ECLS-DemoB1-Vacuum






bundle temperature ca 83°C

Bundle weight = 1.01 kg / meter
Heat-loss = 8.42 Watt / meter

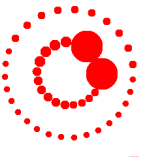
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Thermal Design Module demonstration (8)

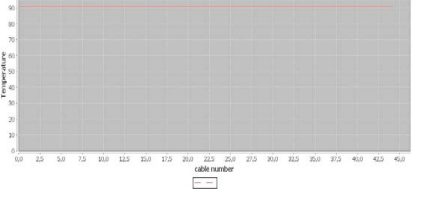
Fixed current design optimization (gauging calculated with derating relaxation with respect to ECSS)

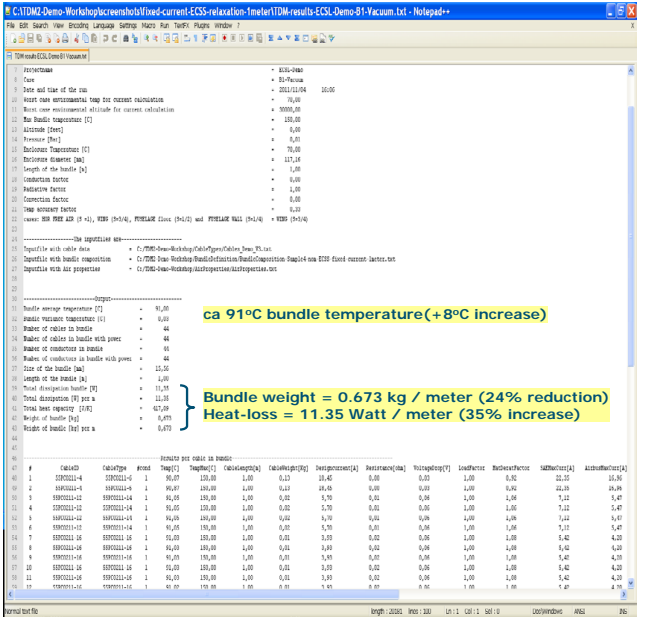
$T_{env} = 70^{\circ}\text{C}, P=0 \text{ BAR}, L=1 \text{ m}$



- Temp >91degrees
- 91 degrees < Temp < 91 degrees
- 91 degrees < Temp < 91 degrees
- 91 degrees < Temp < 91 degrees
- 91 degrees < Temp < 91 degrees
- 91 degrees < Temp < 91 degrees
- 91 degrees < Temp < 91 degrees
- Temp < 91 degrees

TDM2 Temperature cables Case: ECLS-DemoB1-Vacuum





ca 91°C bundle temperature (+8°C increase)

Bundle weight = 0.673 kg / meter (24% reduction)
Heat-loss = 11.35 Watt / meter (35% increase)

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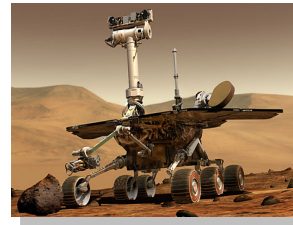


Prototype Thermal Design Module

- **Outlook for space applications:**
 - Space harness weight reduction by derating relaxation e.g. allow a higher wire temperature with respect to ECSS (see also *ESA ITT 6839*, 22/07/2011, *Evaluation and qualification of high temperature cable*)
 - Validation tests for vacuum or low pressures conditions (CO₂, Mars)
 - Space harness design optimization tool for CDF
 - Investigation of S/C structural integrity
 - Axial heat conduction prediction (heat leak minimization)

⇒ **Space harness examples needed to investigate potential of the TDM**

⇒ **Questions??**



Acknowledgements

- **The research on the thermal analysis of aircraft wiring was sponsored by the Dutch Aeronautical Institute, Fokker Elmo and the National Aerospace Laboratory**
- **NLR was responsible for the development of the Thermal Design Module and the validation testing**



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