Derating Standards and Thermal Modelling Tools for Space Harness Designs

Presented at 45th International Conference on Environmental Systems (ICES) 12-16 July 2015, Seattle, USA

Customer

National Aerospace Laboratory NLR

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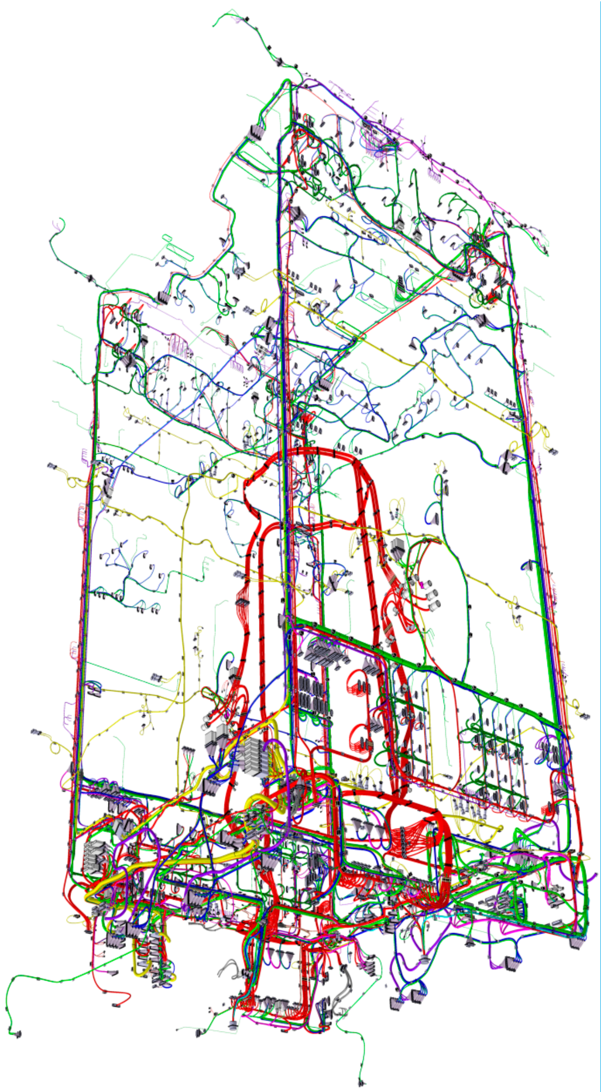

High solution picture of a space harness design of a telecommunication satellite (Airbus-DS)

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EXECUTIVE SUMMARY

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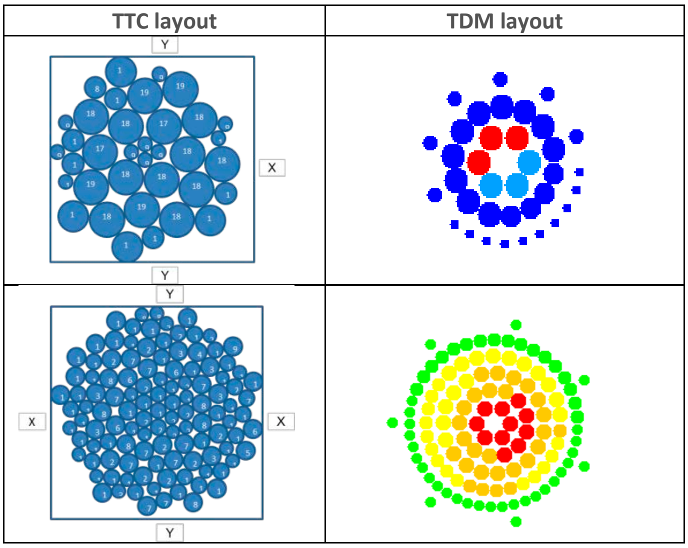

FExample of cross-sectional analyses of two harness designs using thermal modelling tools TTC (Airbus DS) and TDM (NLR)

Problem area

Due to an increasing complexity, mass and volume of electrical harnesses in aerospace systems, wiring can be considered as a subsystem in itself that requires dedicated analyses and optimization. Since the 50s, harness design is basically driven by derating rules based on the current of a free wire at its maximum temperature, an approach that is over-conservative for many modern spacecraft.

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This report is based on a presentation held at the 45th International Conference on Environmental Systems (ICES) July, 12-16 2015, Bellevue, Washington, Seattle, USA.

Description of work

The paper reviews the derating standards as used in the space industry throughout the world and alternatively evaluates the use of two independently developed software tools for thermal analysis of harness bundle designs. The NASA, ESA and JAXA derating standards use the single wire current as defined in MIL- STD-975L, however the environment (40°C or 70°C) and maximum wire temperature (120°C or 200°C) are ambiguously defined. Also the worst case environmental conditions, allowed temperature gradients between bundle and environment and derating related to the bundle configuration (e.g. number of wires and load) differs significantly between the agencies that could lead to different wire sizing in Japan, the US and Europe for the same electrical functionality. Rather than applying the coarse derating rules from the aerospace standards that should be applied indiscriminately for the whole harness, thermal modelling takes into account local environmental conditions. Thermal analysis of space harness designs could lead to smaller gauging and bend radii, a lower mass for bundles and connectors, miniaturisation of electrical interfaces, robustness for modifications and improved reliability and safety.

Results and conclusions

The paper evaluates two independently developed software tools TTC (Airbus-DS) and TDM (NLR) for thermal analysis of wiring bundles showing similar predicted wire temperatures for two space harness examples. It is recommended to verify and update the aerospace derating standards by defining temperature criteria rather than current derating rules and allow the use of validated thermal models for space harness design optimization.

Applicability

Space harness design improvements.

Derating Standards and Thermal Modelling Tools for Space Harness Designs

Presented at 45th International Conference on Environmental Systems (ICES) 12-16 July 2015, Seatlle, USA

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Customer

National Aerospace Laboratory NLR

August 2015

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Summary

Due to an increasing complexity, mass and volume of electrical harnesses in aerospace systems, wiring can be considered as a subsystem in itself that requires dedicated analyses and optimization. Since the 50s, harness design is basically driven by derating rules based on the current of a free wire at its maximum temperature, an approach that is over-conservative for many modern spacecraft. The paper reviews the derating standards as used in the space industry throughout the world and alternatively evaluates the use of two independently developed software tools for thermal analysis of harness bundle designs. The NASA, ESA and JAXA derating standards use the single wire current as defined in MIL- STD-975L, however the environment (40°C or 70°C) and maximum wire temperature (120°C or 200°C) are ambiguously defined. Also the worst case environmental conditions, allowed temperature gradients between bundle and environment and derating related to the bundle configuration (e.g. number of wires and load) differs significantly between the agencies that could lead to different wire sizing in Japan, the US and Europe for the same electrical functionality. Rather than applying the coarse derating rules from the aerospace standards that should be applied indiscriminately for the whole harness, thermal modelling takes into account local environmental conditions. Thermal analysis of space harness designs could lead to smaller gauging and bend radii, a lower mass for bundles and connectors, miniaturisation of electrical interfaces, robustness for modifications and improved reliability and safety. The paper evaluates two independently developed software tools TTC (Airbus-DS) and TDM (NLR) for thermal analysis of wiring bundles showing similar predicted wire temperatures for two space harness examples. It is recommended to verify and update the aerospace derating standards by defining temperature criteria rather than current derating rules and allow the use of validated thermal models for space harness design optimization.

Contents

Nomenclature

I_d	=	Design current of a wire	[Amps]
I_{fwc}	=	*Free Wire Current* in ambient air	[Amps]
K	=	Derating factor	[-]
N	=	Number of wires in a bundle	[-]
ΔT	=	Temperature difference of a wire with its environment	[^{o}C]
MLI	=	Multi -Layer Insulation	
SLI	=	Single Layer Insulation	

I. Introduction

Currently electrical engineers in the aerospace industry around the world use *derating* rules from SAE AS50881[3] or ECSS-ST-Q-30-11C[1] when designing wiring bundles for aircraft and space systems without consideration about their validity and hidden margins. Since the assumptions used to establish these rules are ill defined it could be worthwhile to verify these independently.

The *derating* rules in the standards are in fact a combination of the *Single Wire Current (*i.e. the *Wire Rating)* and subsequently a *derating factor* to be applied indiscriminately for the whole harness. However the *Single Wire Currents* (Table 1) and the *Bundle Derating* (Section II) are ambiguously defined throughout the standards leading to misinterpretation. For instance the environmental temperature and the allowed temperature rises are not defined except in MIL-STD-975M[8] stating a maximum wire temperature of 200°C however without any reference. The best match with the *current rating* in Table 1 was obtained from NASA TM-102179[11] (Section A) with measurement in 93°C vacuum for ΔT=33°C and ΔT=55°C. Also the derating factors for the number of wires in a bundle vary significantly between the standards that have been investigated.

Besides the surprisingly ambiguous definition in the standards, this coarse approach also does not respect local environmental constrains for modern aerospace harness to their full extent[10]. For example narrow or insulated enclosures, the use of structural composite materials with low thermal conductance, solar radiation and hot surfaces are fully neglected in the standards leaving this for the judgment of the harness engineers. This situation leads to large uncertainties and potential failures for harness designs with respect to the actual wire temperatures in aerospace systems. It is considered that experimental verification of the *derating* rules and thermal analysis of harness designs could lead to a relaxation/optimization of electrical systems which in turn could:

- Save a significant mass of both the harness and connectors
- Facilitate spacecraft integration with smaller diameters and lower bend radii wiring
- Support miniaturization of electrical interfaces
- Improve design robustness for modifications
- Improve reliability and safety

In **Section II,** the *derating* standards and reference reports[1-9,11] as used in the aeronautical industry have been reviewed and compared. In **Section III,** two in-house developed thermal mathematical tools (TTC[12] and TDM[13]) are compared for the calculation of harness temperatures. In **Section IV,** the conclusions and outlook for improvements are listed.

	MIL-STD-975M[8]	**EEE-INST-002[2]**	**JERG-2-212[5]**	**ECSS-Q-ST-30-11C[1]**	**NASA TM-102179[11] (Section A)**	
Environment temperature	70°C	70°C	70°C	40°C	93°C	93°C
Maximum wire temperature	200°C	Unspecified	Unspecified	Unspecified	126°C	148°C
Temperature rise ΔT above ambient	Unspecified	-	-	-	33°C	55°C
Wire size /AWG						
30	1.3	1.3	1.3	1.3		
28	1.8	1.8	1.8	1.5		
26	2.5	2.5	2.5	2.5	2.7	
24	3.0	3.0	3.3	3.5	3.7	
22	4.5	4.5	4.5	5.0	5.1	
20	6.5	6.5	6.5	7.5	6.9	
18	9.2	9.2	9.2	10	9.1	
16	13.0	13.0	13	13		14
14	19.0	19.0	19	17		18
12	25.0	25.0	25	25		25
10	33.0	33.0	33	32		33
8	44.0	44.0	44	45	44	
6	60.0	60.0	60	60	62	
4	81.0	81.0	81	81	81	

Table 1 Comparison of the Single Wire Current *(rating) [Amp] in vacuum as defined in several derating standards*

II. Review of Derating Standards

The standards and reference reports[1-9,11] as used in the aeronautical industry have been reviewed and compared with respect to the *rating* and *derating* rules for wires and bundles with a focus on experimental verification and thermal analysis and assumptions. Figure 1 indicates how the investigated derating standards relate to each other with an overview of the derating as function of the number wires in a bundle (N). A very coarse bundle derating requirements of K=0.5 (for N>15) in EEE-INST[2]/MIL-STD[8] is replaced in ECSS[1] with the derating as function of the number of wires (N) with split for N>19 for AWG 12 and larger or by test results (JERG[5]) for bundles. The DOD[6] and SMC[4] refer to AS50881[3] for wire sizing but this is only valid for aircraft and not for space applications. For the ECSS-ST[1] bundle derating requirements trace back to calculations and tests performed by Matra Marconi Space[9] and Airbus Defense & Space[7]. JAXA[5] performed tests on AWG20 composed harnesses with power to signal line ratios of 1:9 and 3:7 and wrapped in MLI or SLI.

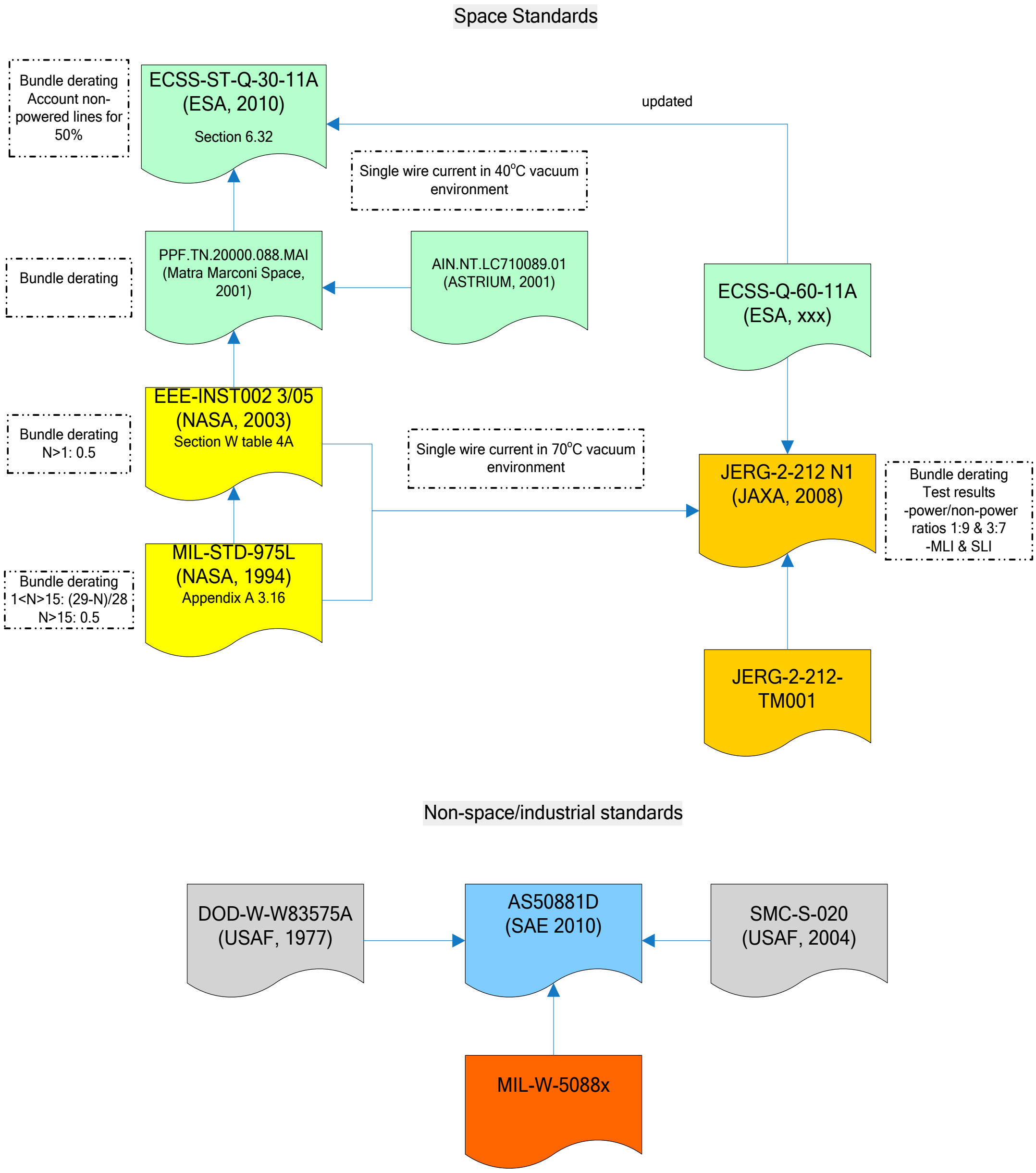


Figure 1 Relations between space and non- space derating standards. Wire and environmental temperatures and bundle derating are ambiguously defined. Between brackets are the organizations that apply these standards

A. Wire rating: Single Wire Current

For all standards the *Single Wire Current* or *Wire Rating* for wires in vacuum trace back to EEE-INST002[2] and MIL-STD-975M[8]. The wire temperature rise *ΔT* should be related to the gage (wire size) and the applied current. The *Single Wire Current* is based on the maximum allowed temperature rise *ΔT* in vacuum i.e. cooled by heat radiation due to its electrical resistance when transporting a current. See Figure 2 for the rise curves for AWG 0/1-26 for single free wires in 93°C (200°F) vacuum as translated to degrees Celsius from NASA TM-102179[11] for the STS orbiter with a reference to measurements done by Rockwell International (1976) and NASA (1968-1989). The best match with the *free wire currents* (Table 1) was obtained for ΔT=33°C (60°F) for AWG 4-8 and AWG 20-26 and ΔT= 55°C (100°F) for AWG 10-18. This irregularity urges for further investigation about the indisputable basis of the derating standards.

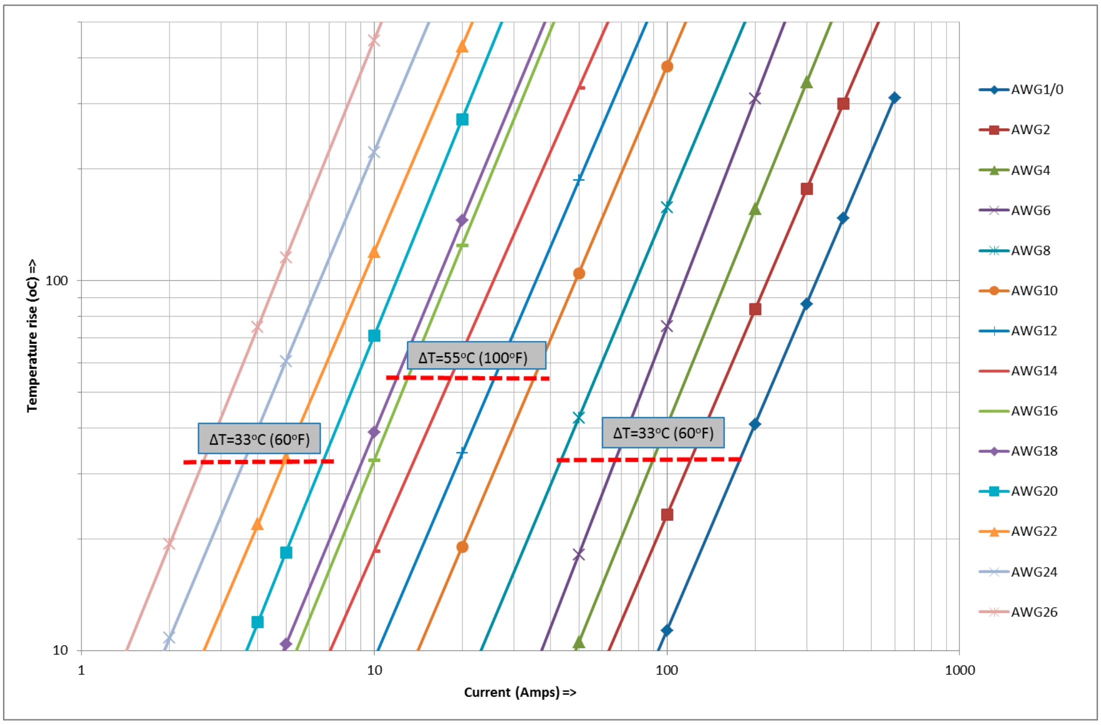


Figure 2 Free wire currents in 93°C (200°F) vacuum translated to degree Celsius from AWG 1/0-26 (NASA TM-102179[11]). Best match with the current rating in Table 1 is found for ΔT=33°C (60°F) for AWG 4-8, 20-26 and ΔT=55°C (100°F) for AWG 10-18

The *Free Wire Current* or *Wire Rating* for space applications is reduced ('derated') with about 60% with respect to single free wire sea-level air currents as defined in AS50881[3], for equal gage and temperature difference, due to the absence of convective cooling. The design current (I_d) is calculated from: $I_d = I_{fwc} * K$ defining the wire gage to select. The total derating (K) is a number between 0-1 for altitude (for aircraft wiring systems), the number of wires (N) and load conditions in bundles for aeronautical systems[3].

B. Bundle derating

Since the bundle *derating* in the standards is based on simplifications and a limited number of test cases they can hardly be compared due to significant differences in the environmental conditions such as temperature and pressure and bundle configurations such as the number of wires and gages and load cases. The bundle derating usually increases with the number of wires and increasing loads. See Figure 3 for an overview of the bundle derating factors versus the number of wires (N) of the investigated standards. JAXA[5] derating is significantly less severe (~0.3-0.4) for fully loaded bundles and for 3:7 and 1:9 bundles compared with ECSS[1], however more severe for insulated bundles wrapped in MLI which is not accounted for in the ECSS[1].

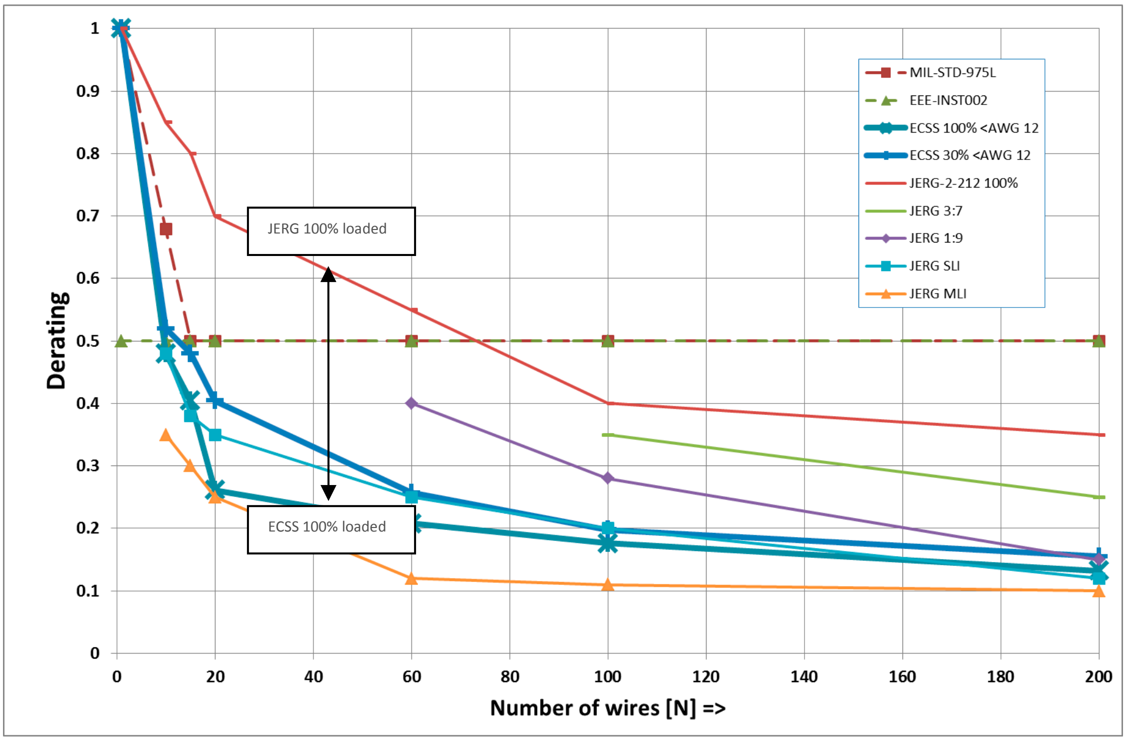


Figure 3 Comparison of the bundle derating versus number of wires (N) for several standards. JERG[5] derating is less severe (~0.3-0.4) for 100% loaded bundles compared with ECSS[1] except for bundles wrapped in MLI

III. Thermal Modeling Tools Evaluation

Urged by new design constraints that could not be resolved by the indiscriminate application of the coarse derating rules in the derating standards both NLR and Airbus Defense & Space have independently developed software tools to compute the actual temperature of wires within bundles under specific loads and environment conditions.

C. Thermal Tool for Cables (TTC) - Airbus Defense & Space

This TTC[12] is aimed to compute the temperature within a bundle of wires in a Space environment. The bundle is constituted of wires which are modeled as metallic conductors surrounded by dielectric material. The harness is supposed to be in a balanced thermal environment, delimited by a rectangular border, with each face i of the border at temperature T_i, $i \in \{+Y, -X, -Y, +X\}$. An optional circular layer of Kapton can be added around the harness. Knowing electrical properties of the wires and the thermal properties of dielectrics, the software determines the temperatures of the whole system (conductors, dielectrics, Kapton).

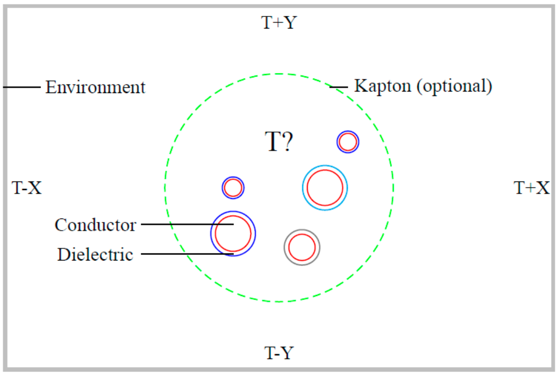


Figure 4 TTC model assumptions

The following model assumptions were made for the TTC:

1. Wires are supposed to be cylinders of infinite length with a common symmetry axis, so that the 3D problem is equivalent to a 2D problem.
2. Temperature is homogeneous within in the wires.
3. Temperature is homogeneous at the surface of dielectrics.
4. Conductive coupling GL between each wire and its dielectric.
5. Radiative coupling GR between each wires and the environment (or Kapton).
6. Optional solar power is received by the surface of the dielectric.
7. Areal conductive resistance of 45 $W/m^2/K$ based on experiments and proportional to the field of view between two touching cables.
8. Temperatures are obtained by solving thermal steady state equations.

This system of equation is then solved using an improved Newton-Raphson algorithm. Tests have been conducted in a vacuum chamber to correlate the simulation results with experimental results and determine the value of conductive coupling between the wires.

D. Thermal Design Module (TDM) - NLR

The TDM[13] was developed and validated by testing for the thermal analysis of wiring bundle in aircraft inside a 4" x 4" enclosure with adiabatic side walls (no heat transfer see Figure 5) to investigate potential weight saving and safety risks. 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.

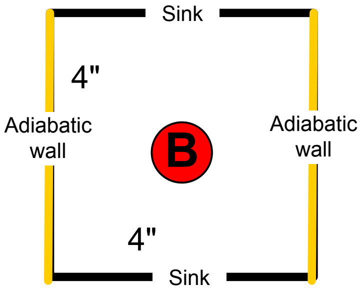


Figure 5 TDM Enclosure Conditions

The TDM simulations were prepared for space (vacuum) applications by switching ‘off’ convective and conductive heat transfer. A solution is obtained in 5 steps by:

1. Building bundle configuration is taken from an input file (N wires) including current loads.
2. Areal contact conduction of 1000 $W/m^2/K$ assumed between contacting wires.
3. Radiative coupling between the bundle of N wires (or braid) and the environment (sink temperature)
4. Convective coupling is switched off (i.e. vacuum) for space applications.
5. Electrical power dissipated in the N wires is calculated from the current and electrical resistances.
6. Wire temperatures by solving the steady state equations by N x N Matrix conversion and parameter iteration.
7. Model assumption have been verified for a range of bundles with diameters between 5 mm to 35 mm having 20-200 (partly loaded) wires with and without braid inside a representative enclosure

E. TTC and TDM Model Comparison

The main differences between the model tools are:

1. TDM models the axial conduction along the wires whereas TCC is a 2D simulation assuming an infinite length.
2. The areal contact conduction within the bundle is taken into account, but the value of the coupling factor was determined based on tests performed on samples of space harnesses in vacuum for TTC whereas the tests were performed on aircraft bundles at different altitudes for TDM. The resulting parameters significantly differ: 45W/m²K for TTC compared to 1000W/m²K for TDM.
3. TTC and TDM can both generate a worst case layout of the bundle's section using the list of wires. However, TTC takes into account the gage and the current in each wire whereas TDM only considers the wire gage and therefore TDM locates the largest wires in the center of the bundle, which is normally a worst case if all wires are fully loaded with their rated currents.

Two real–life examples of space harness designs and corresponding environmental cases were selected in Table 2 Bundle samples I & II used for comparison of the thermal model tools in Table 2. These samples are typical for bundles found in a (Sample I) commercial and (Sample II) scientific satellites. The worst case layouts automatically generated by TTC and TDM for samples I and II are shown in Table 2.

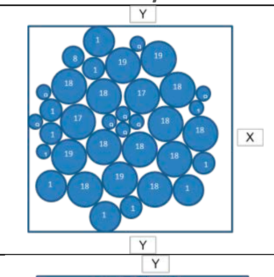
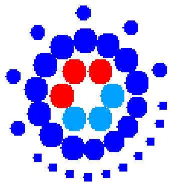
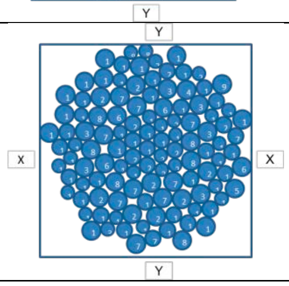
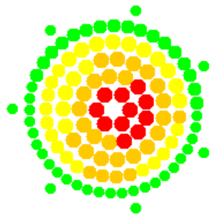
Sample	Application	Characteristics	TTC layout	TDM layout
I	Commercial – Telecom	- 36 wires - Mix of gages: AWG28-22-24-16. - Environment: 60°C - DC current: unequally loaded. From 0.01 to 3.5 Amps		
II	Scientific – Observation	- 116 wires - Mix of gages: AWG 18-22-20 - Environment: 30°C - DC current: unequally loaded. From 0.24 to 1.93 Amps		

Table 2 Bundle samples I & II used for comparison of the thermal model tools

Table 3 hereafter summarizes the temperature results as obtained with the software tools on the samples I and II.

		Temperature		
Sample	**Thermal Model**	*Averaged*	*Minimum*	*Maximum*
I	TTC	83.3 °C	78.3 °C	89.5 °C
	TDM	85.2 °C	85.0 °C	86.9 °C
II	TTC	47.2 °C	41.3 °C	55.1 °C
	TDM	47.0 °C	46.0°C	48,8°C

Table 3 Sample I & II Temperatures computed by TTC and TDM

Conclusion

The results in Table 3 show a very good correlation on the average temperatures computed by both tools: the difference is less than 2°C for sample I and 1°C for sample II. This confirms the validity of the models and the algorithms, as assessed through tests performed to validate both the tools but improvements are possible. For instance the temperature gradient within the bundle appears to be higher with the TTC than the TDM. This is due to a significant difference in the (partly verified) areal contact conduction of 45 $W/m^2/K$ (TTC) versus 1000 $W/m^2/K$ (TDM), and the differences in the bundle layouts performed by both tools.

Additional investigation and tests should improve the understanding of the areal contact conduction and the temperature gradient inside the bundle as well as the predominant factors and parameters driving the thermal exchanges within the bundle.

IV. Conclusions & Outlook

The standards review showed that the agencies NASA, ESA and JAXA use the same *single wire rating* as in MIL-STD-975M[8] but the specified environmental (40°C or 70°C) and maximum wire temperature conditions are ambiguous and do not match with measurements in NASA TM-102179[11]. The applied *bundle derating* differs significantly between the agencies because they based on their own analysis or test results. ECSS[1] derating standard is conservative compared to other international standards. Experimental verification of the *wire rating* and *bundle derating* is therefore recommended.

The comparison of the in-house developed software tools TTC (Airbus-DS) and TDM (NLR) for two cases showed that the predicted averaged bundle temperature is similar. This proves that the use of thermal modelling tools for harness temperature analysis could be valuable in the design phase. A deviation is found for the temperature gradients inside the bundle due to a significant difference in the applied contact conductance between adjacent wires. An experimental verification of the thermal model parameters is recommended to improve the model accuracy.

An update of the harness derating requirements could improve design practices and potentially save weight and costs for space harness systems. A thorough re-assessment by experiments & analysis of both the single wire currents as well as the bundle derating factors for the most common configurations of bundles & environments in actual space applications is recommended. Derating factors in the ECSS[1] could most likely be relaxed for large bundles given the large differences with measurements results from JAXA[5]. With experimental verification of the derating standards and allowing thermal analysis for prediction of the bundle temperatures significant mass savings for harness designs are to be expected. Safety improvements are to be expected with additional derating factors for applications with braids, shields, local confinements or heat sources wherever applicable.

Acknowledgments

The study on the investigation of wiring derating standard has been initiated and financially supported by ESA. The TDM was developed under governmental support in association with the Aircraft Harness Manufacturer Fokker Elmo. The TCC was independently developed by Airbus Defense & Space.

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Standards

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[10] Roel van Benthem, Wubbo de Grave, Fennanda Doctor, Simon Taylor, Kees Nuyten, Pierre-Alexis Jacques Dit Routier "Thermal Analysis Of Wiring Bundles For Weight Reduction And Improved Safety", American Institute of Aeronautics and Astronautics, *41st International Conference on Environmental Systems*, 17 - 21 July 2011, Portland, Oregon, AIAA 2011-5111

Specifications

[11] Technical Memorandum 102179 (NASA 1991) "Selection of Wires and Circuit Protective Devices for STS Orbiter Vehicle Payload Electrical Circuits"

Software

[12] Thermal Design Module (TDM), NLR, in-house developed tool for thermal analysis of aircraft harnesses.

[13]Thermal Tool for Cables (TTC), Airbus-DS, in-house developed tool for thermal analysis of space harnesses.

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