Harness Optimization by Improvement of the Derating Standard ECSS-Q-ST-30-11C

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INTRODUCTION

The harness sizing for space applications is driven by derating rules that are specified in international standards. These rules guarantee that the power dissipated due the electrical current will not generate wire temperatures exceeding the maximum acceptable.
ESA supported a study in 2015 on the investigation of European [1], US [2] and Japanese [3] wiring derating standards. This study was conducted by the National Aerospace Laboratory of the Netherlands and Airbus Defence and Space. The outcome of this study was presented in [4]. It showed that the Single Wire Currents and the Bundle Derating factors vary significantly throughout these standards, and that their justifications were ambiguous or not available. Moreover, these sizing rules only cover limited conditions of environment temperatures. These weaknesses lead to misinterpretation, and most of the time overdesign in terms of mass and harness volume, critical factors for spacecraft design. Based on these findings, ESA initiated a second study that was awarded to Airbus Defence and Space and the NLR in 2016. The main goals were:
Phase 1: Single wires

- Re-assess the derating rules for single wires in free vacuum for most of the types of wires and cables used in space applications.
- Extend these rules to a wide range of environment temperatures.

Phase 2: Wires in bundles

- Re-assess the derating rules for wires and cables in bundles for the same range of environment temperatures.
- Evaluate the evolution of the worst case temperature in a partially loaded bundle.
- Promote the use of simulation software to optimize the harness sizing, and define the main requirements related to such tools.

The objective of this study was to verify the derating section 6.32 of ECSS-Q-ST-30-11 (see Annex) related to the sizing rules for wires and cables. The study was successfully completed in 2018 and the results are summarized in this paper. The experiments, modeling and correlations done for Phase 1 are detailed in a dedicated paper [5] and Phase 2 will be presented in a future paper. This paper focusses on the rationale behind the proposed update of the ECSS standard [1] (inputs to a Change Proposal) expecting to deliver significant mass savings between 20-50% on power harness for future space harness designs.

SINGLE WIRES

The conclusion of the previous study [4] was to properly justify the rating of single wires for different environment temperatures in vacuum in two phases. The results of phase 1, investigating the sizing of single wires, is the reference for the Phase 2 investigating the sizing rule for wires in bundles. The approach proposed in phase 1 for single wires was:

- Perform current rating tests on samples of single wires in the NLR's thermal vacuum facility.
- Propose a thermal model for single wires in vacuum
- Compare theoretical model predictions with the test results using the measured physical parameters of the wires.
- Use correlation to determine the emissivity values that cannot otherwise be measured directly.
- Use the thermal model to propose derating rules for single wires covering most of the wire types in a wide range of environment temperatures.

Preparation of the Experiment

Selection of the Samples

The objective was to have the largest coverage of gauges and wire types, however being practical in terms of number of samples. The wires tested covered most of the types and gauges specified in the ECSS-Q-ST-30-11C (copper and aluminum) and ESCC specification related to wire (ESCC detailed specification based on ESCC 3901). Two additional very specific wires were tested as very little information were available concerning their current sizing:

- AWG28 stainless steel conductor (used in cryogenic environments).
- High temperature wire: nickel copper core + Polyether ether ketone (PEEK) dielectric.

The complete list of samples is provided in Table 1.

Table 1. List of the wire sample submitted to the tests

Sample no	Type	Gauge (AWG)	Conductor	Dielectric	Color
1	RE1037 SPC	10	Silver plated Copper	PTFE	White
2	3901/001	12	Silver plated Copper	3 layers Polyimide	Beige
3	3901/001	16	Silver plated Copper	3 layers Polyimide	Brown
4	3901/002	18	Silver plated Copper	2 layers Polyimide	(dark) yellow
5	3901/002	20	Silver plated Copper	2 layers Polyimide	Green
6	3901/002	22	Silver plated Copper	2 layers Polyimide	(dark) red
7	3901/002	24	Silver plated Copper alloy	2 layers Polyimide	Kaki
8	3901/002	26	Silver plated Copper alloy	2 layers Polyimide	Black
9	3901/002	28	Silver plated Copper alloy	2 layers Polyimide	Black
10	Axon HT	12	Nickel Plated Copper	PEEK	Creme
11	Alu AXL1 M 1237	12	Silver plated Aluminum	Crosslinked ETFE	White
12	Alu AXL1 M 1437	14	Silver plated Aluminum	Crosslinked ETFE	White
13	Alu AXL1 M 2019	20	Silver plated Aluminum	Crosslinked ETFE	White
14	3901/012	20	Silver plated Copper	1 layer Fluoropolymer	Red
15	3901/013	20	Silver plated Copper	PTFE+Polyimide	Black
16	3901/018	20	Silver plated Copper	PTFE+Polyimide+PTFE	White (pink)
17	3901/019	20	Silver plated Copper	PTFE+2 layers Polyimide	Natural (light brown)
18	3901019 SS	28	Stainless Steel	PTFE+2 layers Polyimide	Light brown
19	3901/025	20	Silver plated Copper	Fluoropolymer + polyimide	Natural (light brown)

Physical property measurements of the wires

The power dissipation of a single wire in vacuum and the heat exchanges with the environment are directly related to the physical characteristics of the wire. Therefore, the first step was to carefully measure these parameters for all samples. These physical parameters were:

- Mass per meter (kg/m)
- Conductor size (diameter) (mm)
- Insulation thickness (mm)
- Overall external diameter (mm) (±0.1 mm):
- Electrical parameters after calibration test: linear resistance of the wire (mΩ/m) at 20°C and coefficient of temperature (K-1). They are used to measure the conductor temperature as function of wire resistance.
- Temperatures were measured with thermocouples attached the conductor core and to the external surface at three locations along the wire length.

Note: it was not possible to accurately measure the infrared emissivity of the dielectric wire surface. This was therefore considered as a parameter to be correlated in the physical model. All details about the measurement procedures and the results have been provided in [5].

Thermal Vacuum Tests

The tests were performed in three batches of 7 wires each using the Harness Derating Test Facility (HDTF) at NLR. The following general test sequence has been conducted for each batch: a current was injected in all samples at an environmental temperature of -50°C, 25°C and 100°C,. The current was manually increased to obtain wire temperature in steps +25°C ±5°C. After each current step, temperature stabilization (steady state) was achieved and the following physical parameters were recorded for each sample:

- Resistance of the wire
- Electrical current injected in the tested wire
- Core temperature
- Dielectric outer surface temperature

A detailed description of the test setup and the test procedure are described in [5].

Fig. 1. Single wire batch located in the Harness Derating Test Facility at NLR

Thermal Model for Single Wire in Vacuum

The thermal model used to correlate the single wire test results is based on the following assumptions:

- The thermal exchanges between the wire and the (vacuum chamber) environment are predominantly based on radiative exchanges.
- The wire is assumed to be of infinite length: the conductive exchanges are considered negligible by the use of stainless steel springs and are not taken into account in the infinite thermal model for single wires. This has been confirmed by analysis.
- Considering that conductive exchanges with the environment (if present) tend to cooldown the wire, this assumption can be seen as a worst case to establish the current rating.

Based on the above assumptions, the following formulae can be used to describe the thermal exchanges in wire:

Radiated power:

$$\mathrm{P_r} = \sigma.\varepsilon.\pi.\mathrm{D.L.}\left(\mathrm{T_{wire}^4} - \mathrm{T_{env}^4}\right) \tag{1}$$

Dissipated power:

$$\mathrm{P_d} = \mathrm{R.L.I^2} \tag{2}$$

Wire resistance:

$$\mathrm{R} = \mathrm{R_{Tref}}(1 + \mathrm{Ct}(\mathrm{T_{conductor}} - \mathrm{T_{ref}})) \tag{3}$$

Where:

P_d:	dissipated power [W]
P_r:	radiated power [W]
L:	length of the wire [m]
D:	wire's external diameter [m]
σ:	Boltzman constant = $5{,}67*10^{-8}$; [Wm-2K-4];
I:	Electrical current [A]
T_{wire}:	Temperature of the external wire surface [K]
$T_{conductor}$:	Temperature of the conductor [K]
T_{env}:	Temperatures of the environment [K].
T_{ref}:	Reference temperature for the resistance [K]
$\boldsymbol{\varepsilon}$:	Thermal Emissivity [-]
R:	Ohmic resistance per unit length at a temperature of T_{wire} [Ω/m]
R_{Tref}:	Ohmic resistance per unit length at T_{ref} [Ω/m]
C_T:	Coefficient of temperature for the wire resistance (related to T_{ref}) [K-1]

When the wire's temperature is stabilized, the dissipated power is equal to the radiated power:

$$\mathrm{P_d} = \mathrm{P_r} \tag{4}$$

Since the temperature gradients between the conductor core and the wire external surface is usually quite small for operational currents it can be assumed that $T_{wire} \sim T_{conductor}$ and the above system of equations gives the Sizing Current:

$$\mathrm{I}_{sw} = \sqrt{\frac{\varepsilon.\mathrm{D}.\pi}{\mathrm{R_{Tref}}}} \times \sqrt{\frac{\sigma(\mathrm{T_{wire}}^4 - \mathrm{T_{env}}^4)}{1 + \mathrm{C_T}(\mathrm{T_{wire}} - \mathrm{T_{ref}})}} \tag{5}$$

With:

I_{SW} = Single wire current for the considered wire gauge [A]

In the above formula, all parameters and variables have been directly measured on the samples before or during the single wires tests except the thermal emissivity.

Typical conservative parameters:

- Emissivity of the wire surface: ε=0.75.
- Coefficient of temperature for the wire resistance:
- C_t=0.00396K-1 for copper
- C_t=0.004 K-1 for aluminum wires.

The above values are given for: T_ref=293.15K.

As an example, Table 2 and Table 3 give a set of physical parameter values for each gauge of wire which are conservative for most of the cables covered by the specifications family ESCC 3901. The minimum value of the diameter is considered because it represents the worst case as it minimizes the radiative surface of the wire, and therefore its cooling capability.

Table 2. Parameters for Copper and Copper Alloy wires

Wire Size (AWG)	28	26	24	22	20	18	16	14	12	10	8	4	0
Resistance at 20°C (mOhm/m)	242	148	105	50.9	32.2	20.6	14.3	10.1	6.03	3.9	2.38	0.91	0.38
Min diameter (mm)	0.6	0.7	0.8	1	1.2	1.45	1.77	2.07	2.68	(*)	(*)	(*)	(*)

(*) These gauges are not available in ESCC3901 family.

Table 3. Parameters for Aluminum wires

Wire Size (AWG)	22	20	18	16	14	12	10	8
Resistance at 20°C (mOhm/m)	92	52	33	23	17	10.3	6.4	3.6
Min diameter (mm)	0.88	1.13	1.38	1.73	2.1	2.7	3.45	4.85

Correlation of the Model with the Test Results

All of the test configurations have been simulated using [5] and the measured physical parameters of the wire. The thermal model simulations correlate very well with the test results (an example is shown on Fig. 2), with a value of emissivity that was estimated between 0.85 and 0.95 depending on the sample. These values were as expected based on characterizations performed earlier by Airbus Defence and Space on polyimide and FEP thin layers. Additional experimentations (not included in this paper) could help to characterize more accurately the surface emissivity of the different wires.

Fig. 2. shows an example of the good matching between the model and the test results

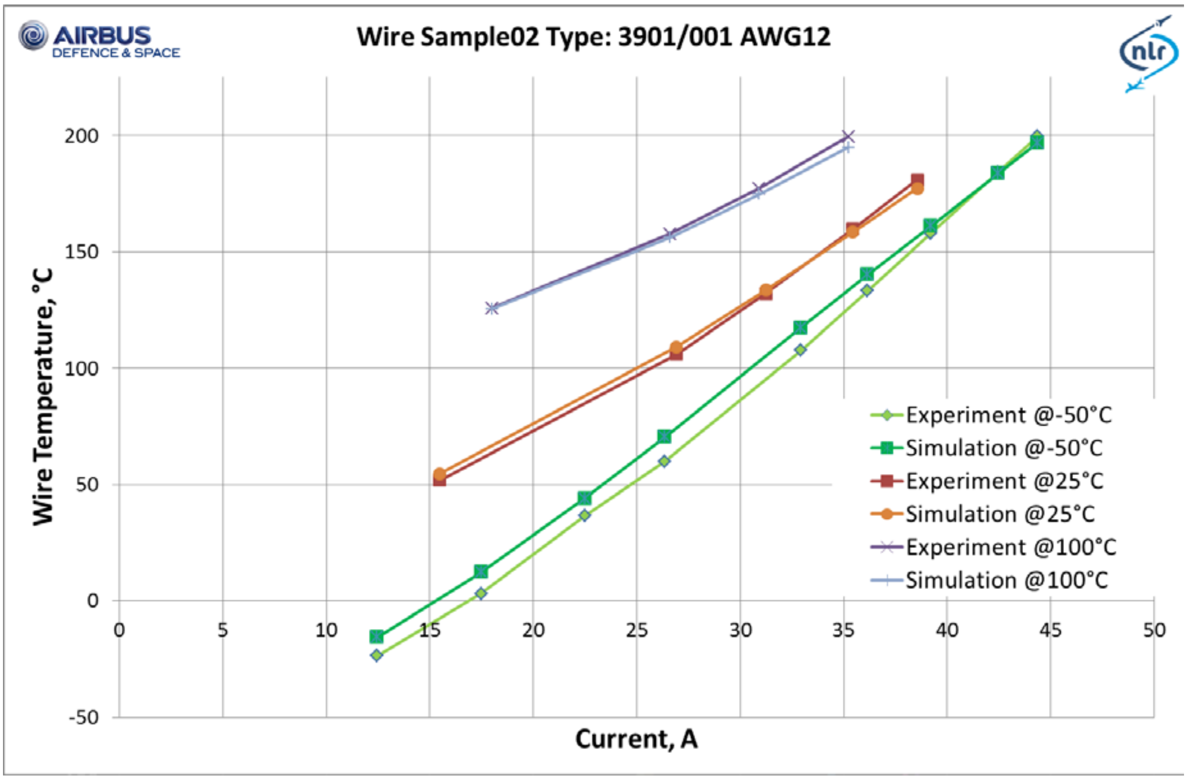

Fig. 2. Model prediction and the test results for a single wire in vacuum,
at three different environment temperatures

Conclusion for Single Wires Sizing Rules

We conclude that the thermal model based on radiative thermal exchanges defined in (5) is a worst case representation (predicted temperature are slightly higher than measured) of the physical behavior observed during the single wire tests. It covers a wide range of environment temperatures, types and gauges of wires. This model will therefore be part of the proposed update of the derating rules, as it will be presented.

WIRES IN BUNDLES

When a wire loaded with an electrical current is located in a bundle, its temperature tends to be higher than if it was alone. The main reason is that the other wires block the view factor to the environment, reducing the radiative cooling, which is predominant in vacuum. The contact conduction and the radiative exchanges between the wires shall therefore be taken into account to predict the temperature of a wire in a bundle. This temperature also depends on the location of the wire in the bundle and the electrical current running in all of the other wires. Therefore, the electrical current that can be allowed in the wire within a bundle shall be derated compared to rated current for a single wire in vacuum.
The aim of this study was to evaluate a corrective factor to define the derated current of a wire in a bundle compared to the single wire rating current, then to compare it to the specifications in the European derating standard [1] and propose an update of the standard in case needed. The approach proposed for harness bundles was very similar to the one used for single wires:

- Perform experiments on samples of bundles in the NLR's thermal vacuum facility.
- Use a thermal model for bundles and thermal simulation software developed by Airbus Defence and Space to simulate all of the test cases and compare theoretical values obtained with the model with the test results.
- Correlate the model with the test results.
- Use the thermal model to propose derating factors for bundles covering various numbers of wires, wires types, thermal environments, and load cases.

Preparation of the Experiments

Selection of the Samples
The bundles samples have been carefully defined to be able to evaluate one by one the effect of each major parameter, as:

- The number of wires in the bundle
- The gauge of the wires
- The current load
- The location of the loaded wires within the bundle: several current groups have been radially implemented, from "Current Group 1" in the center to "Current Group 3" at the surface of the bundle.

The complete list of samples is provided in Table 4.

Table 4. List of the bundles submitted to the tests

Bundle	**Number of wires**	**Standard**	**Current group #1 (center)**	**Current group #2 (middle)**	**Current group #3 (outer)**
1	6	3901/002	2 x AWG20	4 x AWG20	N/A
2 (with connector)	14	3901/002	14 x AWG20	N/A	N/A
3	14	3901/002	4 x AWG20	10 x AWG20	N/A
4	60	3901/002	6 x AWG20	24 x AWG20	30 x AWG20
5	100	3901/002	14 x AWG20	36 x AWG20	50 x AWG20
6	200	3901/002	14 x AWG20	86 x AWG20	100 x AWG2
7	30	3901/002	8 x AWG26	22 x AWG12	N/A
8	30	3901/002	22 x AWG26	8 x AWG12	N/A

Instrumentation
Fig. 3 shows an example of instrumentation drawings for one of the cable bundles.

The following general guidelines have been used for the instrumentation:

- Bundles are attached with stainless steel springs to be able to cope with a cable elongation due to temperature and to minimize thermal conduction to the environment.
- Sense wires are used to measure the voltage on the tested current group (see dark green line on Fig. 3).
- The current supply wires are used to inject the current in the tested current groups. The gage is compatible with the injected current (see purple lines on Fig. 3).
- The current into each current group is determined by measuring the voltage over a calibrated shunt resistor.
- Thermocouples are used to ensure the temperature measurement (see red lines on Fig. 3).
- A guard heater is used to minimize the temperature gradient over the bundle (see light green lines in on Fig. 3), simulating (semi)-infinite bundle lengths.
- TC limiter is used for safety to make sure that the temperature will not reach a too high value (see orange lines on Fig. 3).

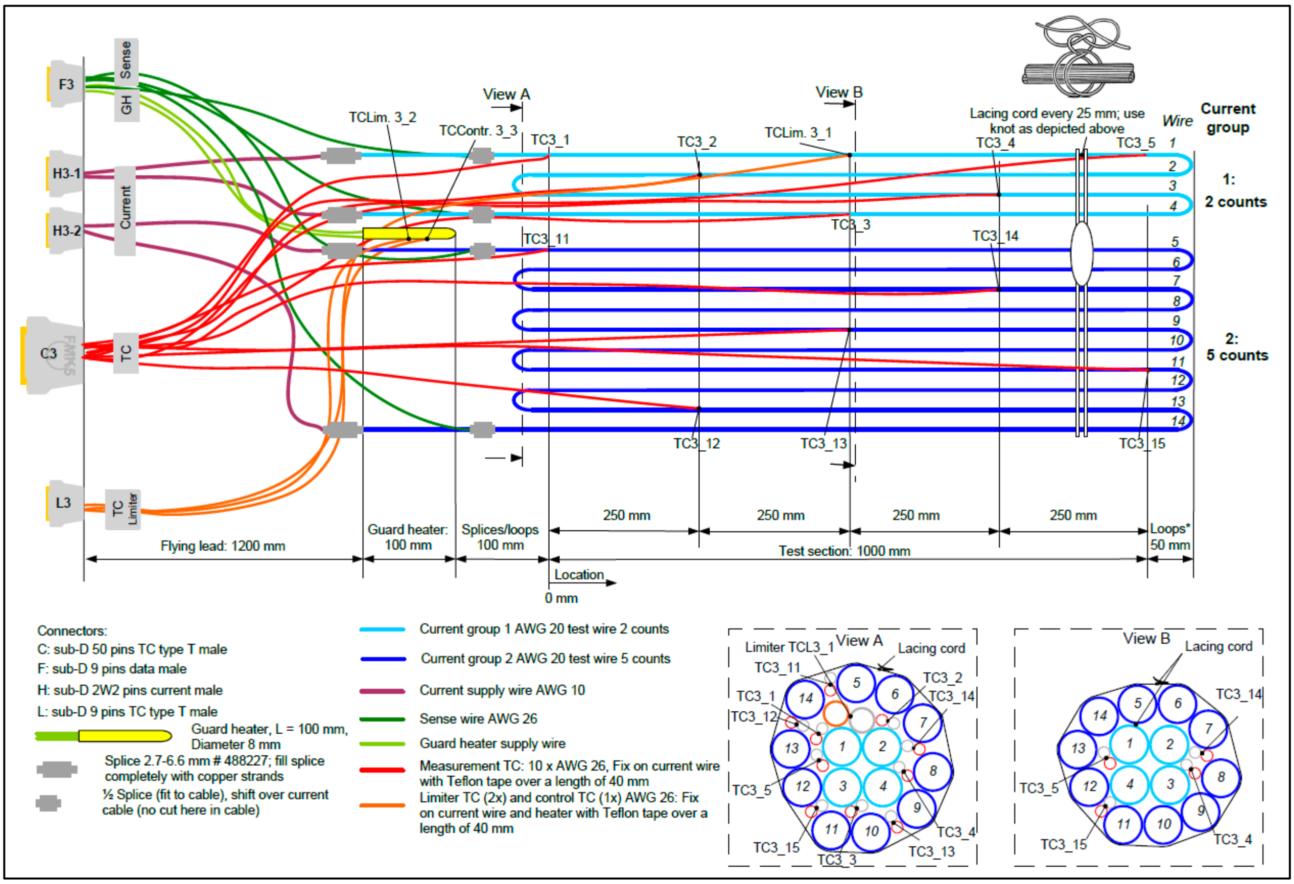

Fig. 3. Definition and Instrumentation of the Bundle 3

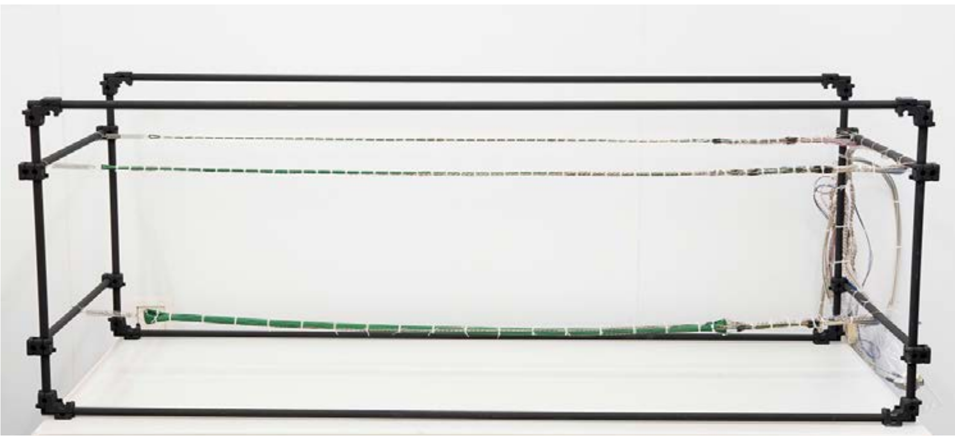

Fig. 4. Actual setup of a cable bundle batch

Test in vacuum

The test sequence was done as follows:

1. Setup the shroud (environment) temperature to -50 °C, 25 °C or 100 °C according to the test plan.
2 Increase the current step by step in order to have the average temperature of each cable bundle (all current groups averaged) equal to the target temperature ±5 °C.

Wait for the stabilization of the temperature. The variation of temperature should be <1 °C per hour.

Measure the physical parameters for each Current Group:

- Electrical measurements
  - Resistance of the current group [Ohm]
  - Electrical current [A] injected in the current group
  - Power dissipation in the current group [W]
- Thermal measurements
  - Bundle Current Group temperatures

Correlation of the Model with the Test Results

All test configurations have been simulated using the Airbus DS simulation software “Thermal Tool for Cables” (TTC) presented in [5]. The correlation was quite good, nevertheless the algorithm has been enhanced to better take into account the variation of the thermal conductivity within the bundle with respect to the size of the bundle. The fine tuning of all parameters was done in such a way that the simulation always remains slightly worst case compared to the test results, to make sure that a positive margin remains. This resulted in a good correlation for all bundles in all conditions, as illustrated in Fig. 5: this chart shows for each of the test condition (x axis) the maximum and minimum temperatures measured within the bundle nr. 5 (red lines), the maximum and minimum temperatures from the simulation (blue lines), the environment temperature (yellow line) and the electrical current in the wires for the different current groups (three lines at the bottom, y axis on right side).

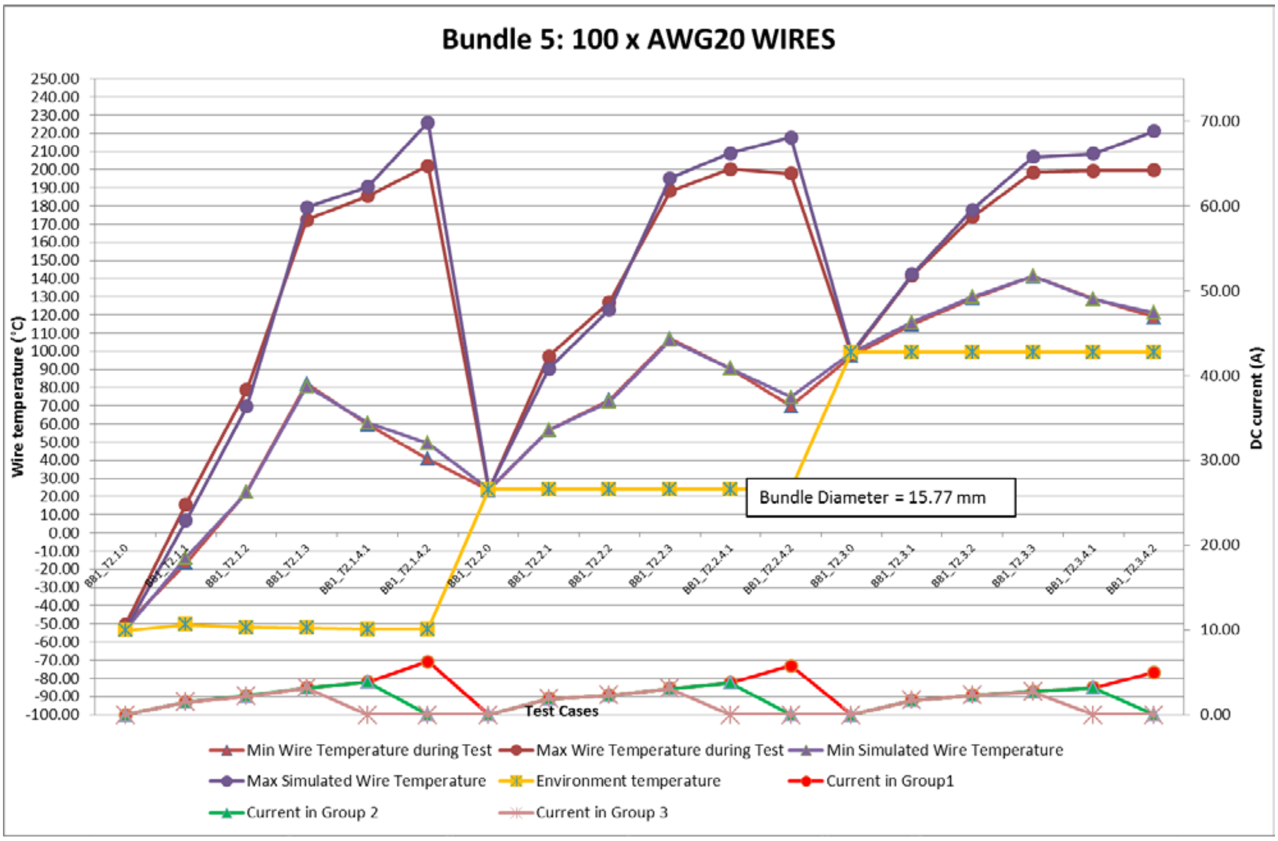

Fig. 5. Comparison of Simulated and Measured Extremum Temperatures for Bundle 5.

Identification of Derating Factors for bundles Based on Simulation

After correlation, the simulation software TTC was used for different types of bundles in various conditions to determine sizing rules for bundle with respect to single wire ratings. The approach was to identify K(N), a function of the number of wires in the bundle. The derating of the Single Wire current for bundles (I_{BW}) with N wires shall be calculated as:

$$I_{BW} = I_{SW} \times K(N) \tag{6}$$

With I_{SW} the rated current for single wire from (5) considering given D, T_{wire}, and T_{env} (see section “Single Wire” before).Three types of simulations have been performed for correlation of the TTC:

- All wires fully loaded, single gauge
- All wires fully loaded, mixed gauge
- Only the wires in the center of the bundles being fully loaded, the external wires being passive.

After correlation, hundreds of cases were simulated varying:

- The gauges (i.e. D).
- The environment temperatures (T_{env}).
- The targeted maximum wire temperatures (T_{wire},).

An example of the simulation results is plotted in Fig. 6

Fully Loaded Bundles

The main finding was that, as long as the bundle is fully loaded, the function K(N) is quite independent of T_{wire}, and T_{env}. A small influence of the wires gauge is noticed: worst case (highest derating) being for large gauges. Fig. 6 shows that the difference between the two blue curves (gauge 26 and gauge 12 wires derating factors) is small. This means that the ratio between the current in a single wire and the current in the same wire in the center of a bundle to reach the same temperature depends, at the first order, on the number of wires in the bundle only. For bundles made of mixed gauges, the simulation showed that the K(N) function remains valid with the larger gauges as worst case. This allows a single table of worst case K factors for different sizes of bundles, which shall be applicable for all gauges and environment temperatures. This table is provided in the next section, and is reflected in Fig. 6. The comparison with the European Standard [1] is plotted in the same figure (red curve) and shows that for bundles between 5 and 25 wires, gauge optimization can be obtained thanks to a lower bundle derating factor. This optimization can can be cumulated with the one resulting from the model (5) proposed for single wires.

Table 5. Derating factor K(N) for Fully Loaded Bundles.

Count Of Wires (N)	1	2	3	4	5	6	7	8	9	10	15	25	50	100	200	300
Bundle Derating Factor K(N)	1	0.9	0.81	0.76	0.71	0.66	0.62	0.6	0.59	0.57	0.49	0.4	0.29	0.21	0.15	0.12

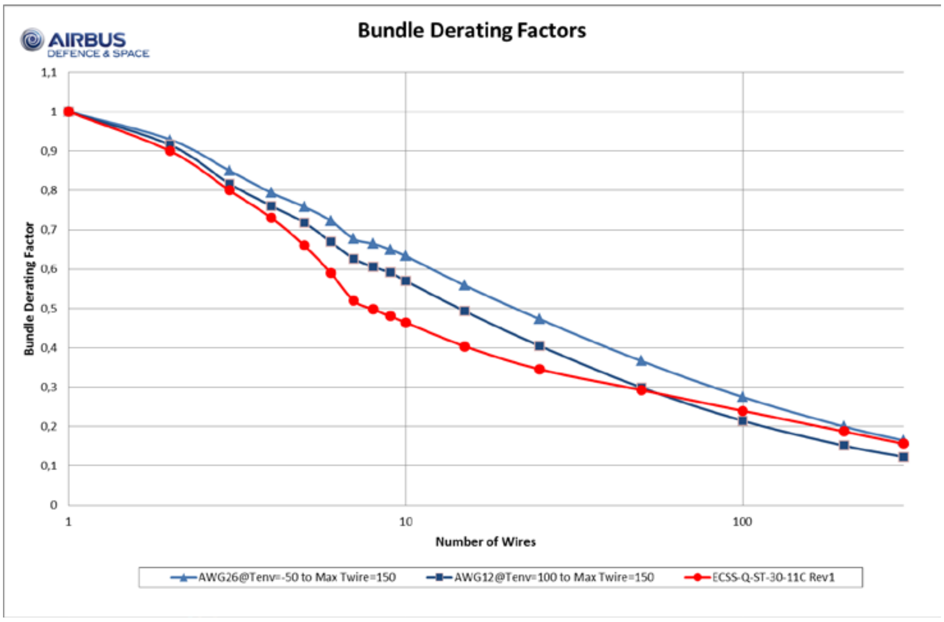

Fig. 6. K(N) values for fully loaded bundles: simulation (larger and smaller gauges) compared to ECSS Standard (logarithmic scale).

Partially Loaded Bundles

Equation (6) defines I_{BW} as the maximum current allowed in the wires for a fully loaded bundle (each one of the wires are loaded with the maximum current). If some of the wires in the bundle are not powered, the average temperature of the bundle will drop. This could allow increasing the current in the active wires compared to I_{BW} by a certain factor: (6) can then be replaced by:

$$I_{BW} = I_{SW} \times K(N) \times L \quad (7)$$

With L being an additional coefficient ≥ 1 reflecting the increase of current allowed in the partially loaded bundle, keeping the temperature of each wire below a given limit. The simulations show that the additional coefficient is depending on several parameters:

- The number of wires in the bundle.
- The ratio of passive wires compared to the active ones.
- The radial location of the active and passive wires within the bundle.

The simulations show that it is virtually impossible to define L which is applicable for all configurations of loaded and unloaded wires within an arbitrary bundle. Dedicated thermal simulations are requested for each bundle configuration and load distribution. Nevertheless, based on the simulation results, a worst case value of L is proposed depending on the percentage of loaded wires in the bundle, assuming that:

- The loaded wires are radially located in the center of the bundle.
- The number of wires in the bundle is less than 300.

These values are listed in Table 6.

Table 6. Additional factor for partially loaded bundles.

Percentage of loaded wires	Less than 25%	Above 25% and less than 50%	More than 50%
L	1.2	1.1	1

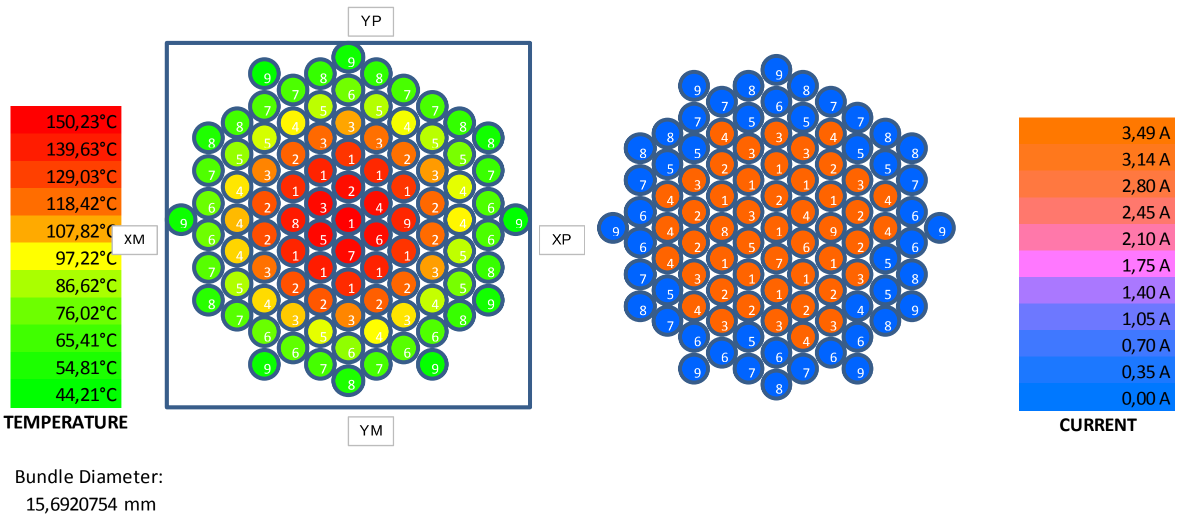

Fig. 7. Example of thermal simulation result with loaded wires in the center and passive wires at the surface

CONCLUSION

This paper proposes an upgrade of the rating and derating rules for wires and cables in free vacuum that are defined in the European standard [1]. The proposed rules are based on the results of a dedicated ESA study started in 2016 and conducted by Airbus Defence and Space and the NLR. The new rules improve the precision of the wire's thermal model. In addition, they allow taking into account the environment temperature and the exact physical characteristics of the wires. In most cases a mass and volume reduction of harness bundles is to be expected. Mass savings in the range 20% to 50% could be expected on power bundles depending of the use cases. The assumptions for application of the new rating and derating rules are more clearly defined and shall be thoroughly checked by the harness engineers.

In addition to the new single wires and bundle (de)rating rules, it is proposed to allow thermal simulations for harness sizing based on worst case wire temperatures. The mathematical model and simulation tools should comply with the specified criteria. This approach permits specific harness configurations and dedicated design optimizations.

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AUTHORS

Marc Malagoli's current position is Space Harness Expert within the Engineering & Integration Department in Airbus Defence and Space. He has 28 years of experience in space industry in the field of electrical systems design and data management for various space applications: Ariane 5 development, more than 60 different satellites (telecom, observation, scientific and new constellations), as Electrical Architect, Harness Team Manager, or for Expert support and R&D. He was awarded a Black Belt on an Airbus Lean Engineering Program. He has a master Degree in Electricity and Automation from ENSEIHT High School in Toulouse, France.

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Yoann Allewaert has been in the position of Harness Design Manager for Mechanical Design Office of Airbus Defence and Space Toulouse for three years. He also worked in the aeronautic industry as a Quality and Harness integration and innovation engineer during two years and a half . He was also responsible of developing electronic products in the automotive industry during one year.

Annex

Current Derating Requirement for Wires and Cables

Fig. 8 and Fig. 9 give a snapshot of the derating rules in the European Standard [1] for wires and cables as they are today.

ECSS-Q-ST-30-11C Rev 1
4 October 2011

6.32 Wires and cables - family-group code: 13-01 to 13-03

6.32.1 General

No general clause.

6.32.2 Derating

a. Parameters of Wires and cables from family-group code 13-01 to 13-03 shall be derated as per Table 6-37.

b. The derating on current for bundles (I_{BW}) with N wires shall be calculated as $I_{BW} = I_{SW} \times K$, with I_{SW} the derated current for single wire and K as per Table 6-38.

c. In case of wires in cold redundancy or wires non used in the same bundle (some with current, others without current) the number of wires to take into account is calculated as follows: N equivalent bundle = N wires with current + 0,5 x N wires without current with I_{BW} which shall not overpass I_{SW}.

Table 6-37: Derating of parameters for Wires and cables family-group code 13-01 to 13-03

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 for single wire Cu (I_{SW}) (A) [a]	1,2	1,3	1,5	2,5	3,5	5	7,5	10	13	17	25	32	45	60	81
Maximum current for single wire Al (I_{SW}) (A) [a]						4	6	8	10,4	13,6	18,4	25,6	36		
Wire surface temperature	Manufacturer's maximum rating Tmax -50 °C.														
[a] for ambient temperature of 40 °C.															

Fig. 8. Derating rules for Single Wires in Free Vacuum as per [1]

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Table 6-38: Bundle factor K for calculation of the derated current for each individual wire in bundles of N wires

Wires AWG 12 to AWG 32		Wires AWG 0 to AWG 10	
Number of wires (N)	K	Number of wires (N)	K
$1 < N \leq 3$	$1{,}1 - (0{,}1 \times N)$	$1 < N \leq 3$	$1{,}1 - (0{,}1 \times N)$
$3 < N \leq 7$	$1{,}01 - (0{,}07 \times N)$	$3 < N \leq 7$	$1{,}01 - (0{,}07 \times N)$
$7 < N \leq 19$	$0{,}81 - [0{,}15 \times \ln(N)]$	$7 < N \leq 52$	$0{,}81 - [0{,}15 \times \ln(N)]$
$19 < N \leq 331$	$0{,}59 - [0{,}076 \times \ln(N)]$	$52 < N \leq 331$	$0{,}467 - [0{,}0632 \times \ln(N)]$
I_{BW}: maximum current for an individual wire in a bundle.			
I_{SW}: maximum current for a single wire as given in the derating Table 6-37.			
ln: Natural log.			

6.32.3 Additional requirements not related to derating

No additional requirement.

Fig. 9. Derating rules for Wires in Bundles as per [1]