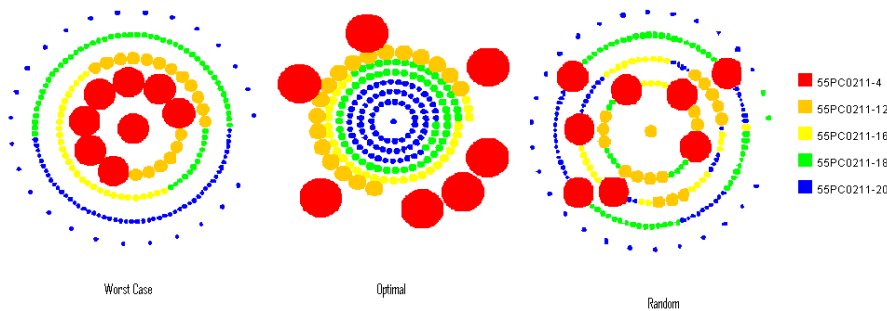




Executive summary

Thermal analysis of wiring for weight reduction and improved safety

Requirements review and validation of wire bundle model inside enclosure



Problem area

In SAE AS50881 wire (conductor) sizing is based on heat losses due to the electrical resistance (when carrying a constant duty current) and the maximum allowed temperature of a free wire cooled by ambient air convection. The maximum free wire current in ambient air is derated for altitude, number of wires in a bundle, load conditions and air temperature. It is not a trivial matter to ensure that the end design conforms to the design assumptions in such an integrated system hence it is speculated that over-conservative derating factors are typically part of the system design e.g. at the maximum air temperature, lowest pressure derating factors are usually taken by the equipment suppliers e.g. at the maximum air temperature, lowest pressure and largest bundle size under a maximum load. Poor cooling conditions such as an

elevated air temperature due to neighbouring bundles and/or limited convection due to structural enclosures are not considered. Also heat radiation is not taken into account. It is therefore to be expected that application of SAE-AS50881 for aircraft bundle designs or ECSS-Q30-11A⁵ leads to significant uncertainties in actual wire temperatures or aerospace applications. Beside heavy harness designs this could lead to unacceptable high bundle temperatures with respect to sensitive wire/cable content or structural parts subject to temperature limitations.

Description of work

The concept of thermal analysis was demonstrated with the construction of a Thermal Design Model (TDM) predicting wire temperatures in bundles. Better knowledge of the wire temperature leads to improve

Report no.

NLR-TP-2011-469

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Report classification

UNCLASSIFIED

Date

October 2011

Knowledge area(s)

Avionicatechnologie
Ruimtevaartinfrastructuur en
-payloads

Descriptor(s)

Thermal Analysis
Wire Design Optimization
SAE-AS50881
ECSS-Q-30-11A

bundle design in terms of weight and safety. Several configurations of 14 mm to 16 mm diameter wiring bundle samples were tested under representative air temperatures between -55°C to +70°C and pressure conditions between 120 mBar to 1 Bar (50.000 feet to sea level).

Results and conclusions

Evaluation revealed a temperature prediction accuracy of +/-19°C (@ 150°C) related to modelling and manufacturing uncertainties.

Extension of the validation range of the TDM1.0 for 5-35 mm bundles in aircraft enclosures, other environmental conditions such as vacuum (space) or low pressure CO2 (Mars) and axial heat leak predictions is under investigation for space applications.

Applicability

Design optimization of wiring bundle designs for aerospace applications.



NLR-TP-2011-469

Thermal analysis of wiring for weight reduction and improved safety

Requirements review and validation of wire bundle model inside enclosure

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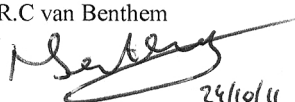

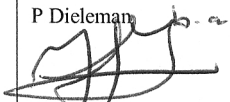
This report is based on a presentation held at the AIAA/ICES Conference, Portland, Oregon, USA, 18-21 July 2011.

"This report has been reviewed by Ruel A. (Tony) Overfelt, Reed Professor of Mechanical Engineering, Auburn University, and two other session attendees prior to the AIAA conference."

The contents of this report may be cited on condition that full credit is given to NLR and the authors.

Customer	Netherlands Agency for Aerospace Programmes (NIVR)
Contract number	59919N
Owner	NLR
Division NLR	Aerospace Systems and Applications
Distribution	Unlimited
Classification of title	Unclassified
	October 2011

Approved by:

Author R.C van Benthem  24/10/11	Reviewer J van Es 	Managing department P Dieleman  24/10/11
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Summary

The concept of thermal analysis was demonstrated with the construction of a Thermal Design Model (TDM) predicting wire temperatures in bundles. Better knowledge of the wire temperature leads to improve bundle design in terms of weight and safety. Several configurations of 14 mm to 16 mm diameter wiring bundle samples were tested under representative air temperatures between -55°C to $+70^{\circ}\text{C}$ and pressure conditions between 120 mBar to 1 Bar (50.000 feet to sea level). Evaluation revealed a temperature prediction accuracy of $\pm 19^{\circ}\text{C}$ (@ 150°C) related to modelling and manufacturing uncertainties.

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Nomenclature

A_e	= wire external surface area $\pi D_e L$	m^2
A_b	= bundle external surface	m^2
c_D	= heat flux by air conduction	W/m^2
C_D	= heat transfer coefficient cylinder	W/K per meter
D_e	= external wire diameter $D_i + 2t$	m
D_i	= internal (conductor core) diameter	m
F	= view factor (for IR radiation)	-
h	= heat flux by air convection	W/m^2
I	= (design) current	Amp
L	= wire length	m
M_D	= wire mass	Kg
Nu_D	= Nusselt Number	-
P	= transported Power	W
Q_c	= wire cooling	W
Q_h	= wire heating	W
r	= heat flux by IR radiation	W/m^2
R	= wire resistance	Ohm
t	= insulation thickness	m
ΔT	= temperature difference wire and air	K
ΔV	= voltage drop	Volt
$\sigma(T_1^4 - T_2^4)$	= IR radiation transfer $\sim 4\sigma T^3 \Delta T$	W/m^2
β	= air expansion coefficient	K^{-1}
ε	= IR emission coefficient	-
λ	= air conduction	W/mK
σ	= Stephan Boltzmann = $5.67 \cdot 10^{-8}$	$W/m^2 K^4$
ρ	= material density	Kg/m^3
ρ_e	= specific conductor resistance	Ohm.m
ν	= kinematic viscosity	cm^2/s
μ	= contact conduction	$W/m^2 K$



Abbreviations

AWG	=	American Wire Gauge
FEM	=	Finite Element Model
IR	=	Infra Red
TDM	=	Thermal Design Module
NIST	=	National Institute for Standards and Technology
NLR	=	National Aerospace Laboratory, The Netherlands

1 Introduction

Mass figures for wiring bundles required for distribution of electrical power and data for aerospace applications, are difficult to obtain. A typical commercial aircraft with 150 seats may contain over 1500kg of installed wiring harnesses, whereas commercial satellites could have 50kg of wiring on board. Life cycle cost for an aircraft, or launch costs for a satellite, could go up to >10.000 Euro's per kilogram of wiring. Significant effort has been applied in the aerospace industry for a reduction of the weight of wires and cables through application of aluminum rather than copper as conductor material. Application of light weight dielectric materials and high voltage designs also contribute to a reduction of the bundle weight. However, not many electrical engineers realize that the weight of power bundles is related to a thermal equilibrium. Wiring in bundles produce significant amounts of heat when transporting a current (due to the electrical resistance of its wires) and need sufficient cooling to control its temperature. Since cooling is only available at the outer surface of a wire by means of natural convection and infrared heat radiation, the temperature of a wire (Figure 1) is controlled by sizing-up the conductor core D_i , controlling heat losses per meter and cooling area, at the cost of an increased weight. Optimizing on voltage drop ($\Delta V=IR$) across a piece of wire transporting a current I and power ($P =IV$) is often used by some aircraft manufactures to reduce weight. However, voltage drop design only limits *the total heat loss of a wire*, hence the limiting factor for the current - especially for short wire lengths- is also thermal. Now-a-days electrical engineers in the aerospace industry around the world use the selection rules from SAE AS50881⁶ or ECSS-30-11A⁵ when designing wiring bundles for aircraft and space applications. However the recommended design rules follow the successive series of MIL-W-5088s are basically unchanged since the early 50s. The selection rules are based on a *thermal balance* between the *heat losses* due to its electrical resistance of a wire and *cooling* by natural convection and heat radiation. This results in a *free wire current* for which the *maximum allowed temperature* (T_{max}) of a single free copper wire in ambient air is given. Although several parameters contribute to the heating and cooling of a wire the free wire current I_{fwc} is mainly related to the conductor size D_i , the temperature elevation above ambient ΔT and the air pressure P_a . whereas the heat loss is related to design parameters such as material properties, sizing and operating current, external cooling of a wire is related to its local environment e.g. its application:

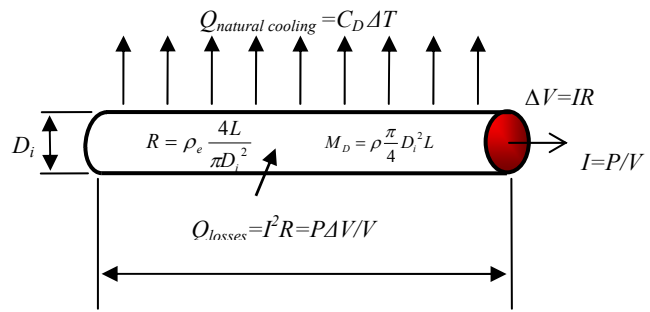


Figure 1 Heating and cooling conditions for a piece of wire

especially for short wire lengths- is also thermal. Now-a-days electrical engineers in the aerospace industry around the world use the selection rules from SAE AS50881⁶ or ECSS-30-11A⁵ when designing wiring bundles for aircraft and space applications. However the recommended design rules follow the successive series of MIL-W-5088s are basically unchanged since the early 50s. The selection rules are based on a *thermal balance* between the *heat losses* due to its electrical resistance of a wire and *cooling* by natural convection and heat radiation. This results in a *free wire current* for which the *maximum allowed temperature* (T_{max}) of a single free copper wire in ambient air is given. Although several parameters contribute to the heating and cooling of a wire the free wire current I_{fwc} is mainly related to the conductor size D_i , the temperature elevation above ambient ΔT and the air pressure P_a . whereas the heat loss is related to design parameters such as material properties, sizing and operating current, external cooling of a wire is related to its local environment e.g. its application:

$$I_{fwc} = F(D_i, D_e, \rho_e, \varepsilon, \Delta T, P_a) \tag{1}$$

With ρ_e is the specific electrical resistance, ε the emission coefficient, and D_e the external diameter due to dielectric insulation. To understand the implication of the thermal equilibrium with respect to the wiring weight in Table 1 below an example is given for the *free wire currents* allowed by the standards for a 120°C wire in a 70°C environment ($\Delta T=50^\circ C$), under several pressure conditions.



Wire Gauge (AWG)	Core diameter mm	Wire weight kg/km	Free Wire Current [Amp]		
			SAE- AS50881 ⁶		ECSS-Q-30- 11A ⁵
			Ambient Air @ 1 Bar	60.000 feet @ 0.072 Bar	Vacuum @ 0 Bar
24	0.59	2.7	7.5	5.6	3.5
20	0.97	6.8	13.5	10.5	7.5
16	1.45	14.6	20	15.6	13
12	2.18	31.3	36	28.1	25
8	3.85	90.0	75	58.5	45
4	6.35	215	132	103	81

120°C wire and 70°C environment (ΔT=50°C)

Table 1 Wire properties related to size and free wire current for a single copper wire as recommended by the aeronautical standards

The American Wire Gauge (AWG)^{9,10} diameter is calculated by applying the formula $D(\text{AWG})=0.127 \cdot 92^{((36-\text{AWG})/39)}$ mm. This means that the American Wire Gauge every 6 gauge decrease gives a doubling of the wire diameter, hence every 3 gauges doubles the weight. For instance an industrial application in ambient air at sea level uses a single AWG 20 wire to carry a current of 13.5 Amps. For a wire inside an aircraft flying at 60.000 feet, transporting the same current, an AWG 18 (2 steps) is needed– which is about 75% heavier. A spacecraft (vacuum) needs an AWG 16 wire (4 steps) - which is more than 100% heavier. - at the same current. This example illustrates that the application has a significant impact on bundle weight. Another way to prevent overheating of wiring is to reduce the allowed current. The standards therefore recommend a ‘current derating factor’ *d* on the *free wire current* to compensate for a temperature increase related to its environmental conditions.

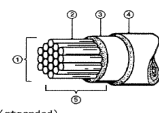
$$I_d = I_{fwc} \cdot d \tag{2}$$

However, as illustrated above, ‘current derating’ effectively means ‘increase wire size & weight’. Especially the high derating factors recommended for wires in bundles result in a significant weight increase of bundles. Clearly for applications where weight is an issue estimation of the current derating factors should therefore be as accurate as possible.

For practical reasons wires are usually routed together in bundles. The standards recommend derating factors for core material, altitude, number of wires in a bundle and load conditions. (See also section II 2.2) Since cooling of a wire in a bundle is largely blocked by its neighboring wires, bundles are thermally worst case. The current derating factor for a wire in a bundle could be as low as 0.1 corresponding to 16 gauges (example AWG 20 -> 4) resulting in a ca 64 times weight increase. For weight optimization it may be better (however unpractical) to split large bundles, keeping the number of wires per bundle low hence limiting the derating factors. Since the maximum current is related to its application, manufactures, specify the maximum wire temperature (rating). The wire rating (Table 2) is related to conductor plating and the applied dielectric insulation.

T_{max} °C	Insulator Type(s)	Conductor and plating
135	Fluoropolymer, FEP, PVF2	Tin coated copper
150	Fluoropolymer, extruded ETFE Polytetrafluorethylene/polyimide Cross linked polyalkene	Tin coated copper
200	Fluoropolymer, TFE and TFE coated glass, FEP, Fluorocarbon polyimide	Silver coated copper
260	Fluoropolymer, extruded TFE	Nickel coated copper

Non-shielded cable single core
Class II



1. Conductor (stranded)
2. Wire
3. Insulation *1
4. Core
5. Jacket

FIG. 4

Note: *1 Example with extruded fluoropolymer

Table 2 Wire ratings for several wires types as specified in SAE-AS50881⁶

With increasing weight and complexity of wiring bundles in aerospace applications, the need is felt to get a better understanding of the thermal conditions and related current derating for wiring bundles, for optimization of the bundle weight and to prevent overheating. Environmental cooling is limited by neighboring bundles, application of insulating braids, routing through poorly ventilated channels and the use of composite structural materials which are not considered in the standards at all. This justifies thermal modeling of the local conditions of wiring bundles beyond the assumptions in the aeronautical standards. This paper investigates the physical background of the wiring selection rules in section II and proposes a Thermal Mathematical Method (TMM) comparing the results with the aeronautical standards in section III. This led to the construction of a Thermal Design Module (TDM) that generates a thermal model of wires in a bundle. In this stage the focus was the modeling of the heat transfer of a bundle and wire configuration. The TDM is partly validated by testing of six 15-17 mm bundle samples inside a temperature controlled low pressure facility simulating enclosure condition. The test results are described in section IV. The work on the TDM is continuing by extending its validation range for bundles between 5-35 mm and towards more complex enclosures interactions estimated with Finite Element Analysis (FEM).

2 Requirements review

Starting point for the aerospace standards is the cooling conditions of a single wire provided at the outer surface by natural convection in ambient (sea level) air. For space applications without air, cooling of a wire is reduced to heat radiation. When cooling is limited, for instance at high altitudes or due to neighboring wires in a bundle, the temperature of a wire increases and current derating factors should be applied e.g. to prevent overheating at the cost of a increased weight. For SAE AS50881⁶ the maximum free wire current is derated for altitude, number of wires in a bundle, load conditions and air temperature. In ECSS-Q-30-11A⁷ only the number of wires at a 100% load is taken into account for derating the currents.

2.1 Thermal equilibrium

Both SAE AS50881⁶ and ECSS-30-11A⁵ take the current versus temperature of a single free copper wire as the starting point for the wire section rules. The heat loss Q_h of a wire section L when transporting a current I is related to the specific electrical resistance of the conductor material ρ_e and its cross-section $\frac{1}{4}\pi D_i^2$ according to Ohm's law:

$$Q_h = I^2 R = I^2 \rho_e \frac{4L}{\pi D_i^2} \quad (3)$$

From this function it is evident that the heat loss of a wire with a fixed length L can be reduced by using a material with a low specific resistance ρ_e (such as copper or aluminum) or by enlarging the conductor diameter D_i at the cost of a weight increase.

$$M_D = \rho \frac{\pi}{4} D_i^2 L \quad (4)$$

Although the density of Copper is relatively high it is the preferred conductor material in most cases due to its low specific resistance. Aluminum which has a somewhat higher specific resistance which is compensated by a increasing the core diameter and is applied in the aerospace industry for its lower density resulting in lighter bundles, however at the cost of an increased volume. The heat flux $\Phi_h = Q_h/A_i$ across the outer surface of a wire ($A_i = \pi D_i L$) is a function of D_i^3 with:

$$\Phi_h = \frac{Q_h}{A_i} = \frac{4I^2 \rho_e}{\pi^2 D_i^3} \quad (5)$$

The cooling of a wire is provided at its outer surface ($A_e = \pi D_e L$) limited by natural convection of air ($h = \lambda Nu_D / D_e$) and Infrared (IR) radiation ($r \sim \epsilon \sigma (T_s^4 - T_a^4)$), T_s the temperature of the outer surface of a wire and T_a the air or enclosure temperature. See also section C for more details. Since air is transparent for IR radiation for short distances as found in enclosures these two contributions add up for the overall heat transfer coefficient C_D of a wire. The temperature elevation ($\Delta T = T_s - T_a$) of the wire with respect to its ambient is then defined by:

$$Q_c = A_e (h + r) \Delta T = C_D \Delta T \quad (6)$$

For space applications, in the absence of air $h=0$ and wire cooling is provided by heat radiation only. The overall cooling flux c_D can be written as $c_D = h + r$ in W/m^2K or $C_D = \pi D_e L c_D$ which is a function of the wire external surface area. The free wire current (I_{fwc}), the final temperature elevation of a wire above ambient (ΔT) is found when there is an equilibrium between the heat losses and the available cooling thus $Q_h = Q_c$ which is optimized by selecting the conductor diameter D_i . Note that the external diameter D_e of a finished wire is slightly larger than the conductor diameter D_i due to insulation thickness. For the calculation it has been assumed that $D_e = D_i + 2t \sim D_i$ and that ΔT does not vary along the wire length L .

$$\Delta T = \frac{4\rho_e I_{fwc}^2}{\pi^2 D_i^2 D_e C_D} = k_D I_{fwc}^2 \approx \frac{\Phi_h}{C_D} \quad (7)$$

The temperature elevation is the ratio between the heat flux at the outer surface and the heat transfer coefficient. The heat transfer coefficient C_D of a cylindrical body (a wire or bundle) in free air or inside an enclosure is calculated in section 2.3 using air properties as function of temperature and pressure. When C_D is implemented in a Thermal Mathematical Model (TMM) this shows ΔT versus the current for a free copper wire in 20°C ambient air. The TMM produces straight lines for each wire size (Figure 2) when plotting ΔT versus I on a log-log scale. When including both convection as well as heat radiation the calculation fits well with SAE AS508815 (Figure 3). When excluding convection, the TMM calculations also matches with the currents provided by ECSS-Q-30-11A5 under vacuum conditions (see Figure 4). Small deviations indicate that possibly insulation thickness variation is considered in ECSS-Q-30-11A5. Conclusion is that function (7) produces results comparable with the standards.

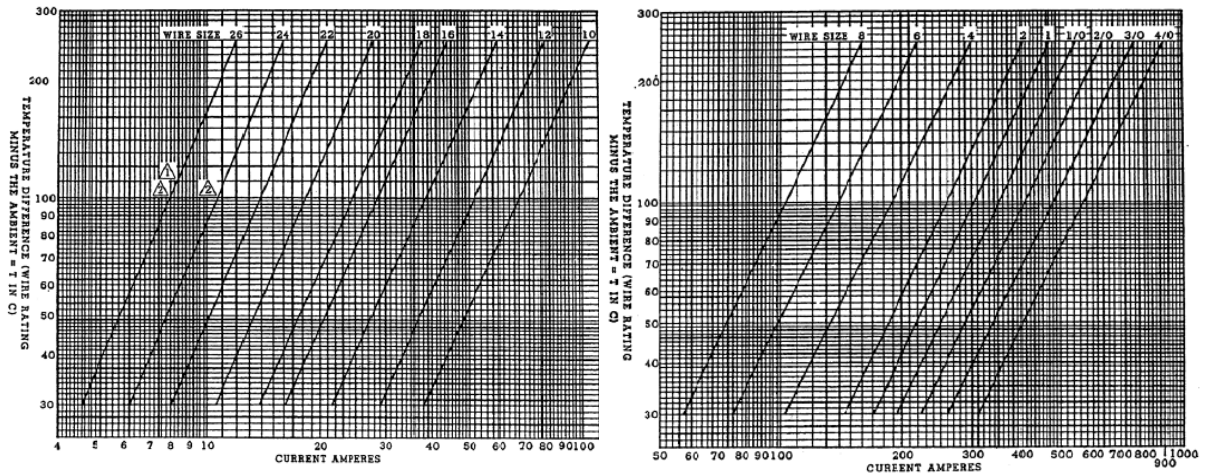


Figure 2 Temperature difference as function of the current for a single free copper wire in ambient air as specified in SAE-AS50881⁶ in the range of wire size 26 up to size 4/0

For ECSS-Q-30-11A a similar graph (Figure 3) is constructed for a free wire in 20°C environment only radiating heat. The result is slightly fitted to match the currents as found in the specifications for $\Delta T=50^{\circ}\text{C}$. In SAE AS50881 the ambient temperature is set as high as possible (worst case) to determine the maximum current and from that point current derating factors are given for the core material (e.g. copper or aluminum), air pressure, number of wires in a bundle and load. However, other conditions affecting external cooling such as braiding, neighboring bundles or (local) enclosure (materials) are not addressed. Note that *derating* the free wire current to level off the wire temperature is done at the cost of an increased bundle weight.

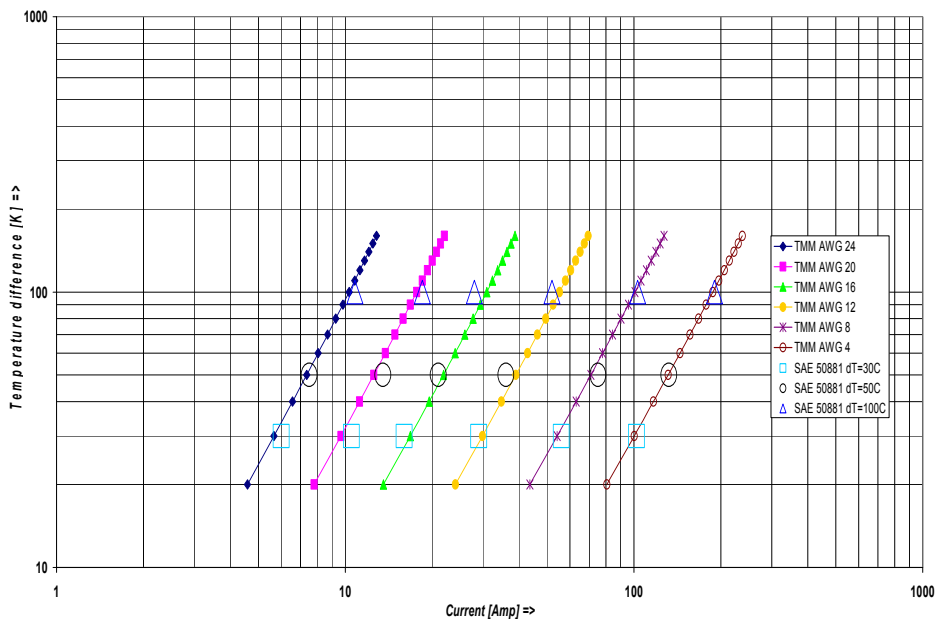


Figure 3 Predicted temperature elevation versus current using TMM for a single free copper wire as function of wire size 24 up to size 4 compared with SAE AS50881⁶

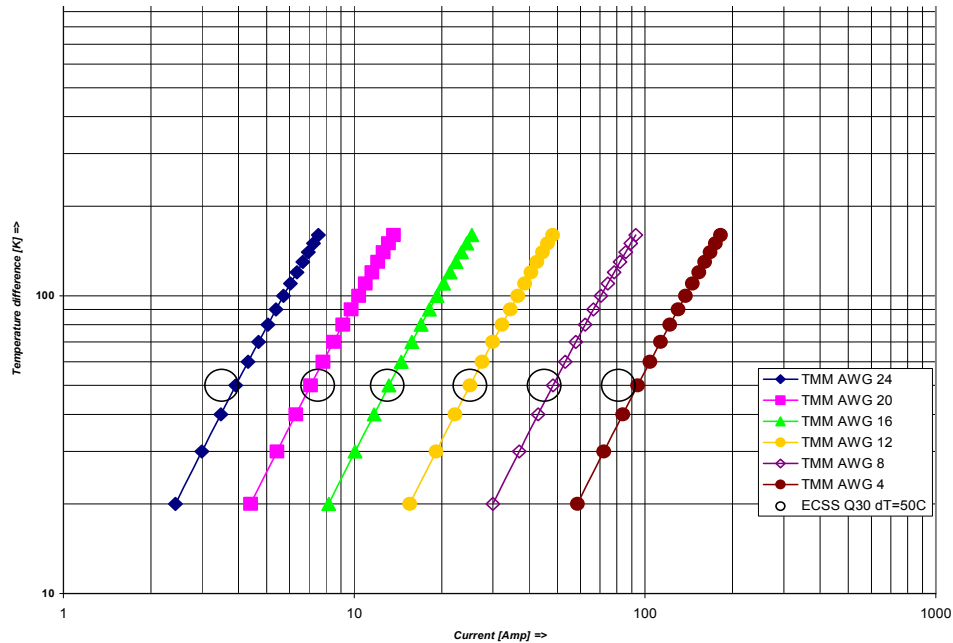


Figure 4 Predicted temperature elevation versus current using TMM for a single free copper wire as function of wire size 24 up to size 4 compared with ECSS-Q-30-11A⁵

2.2 Current derating factors

Application of current derating factors are recommended in the standards to prevent overheating of wires. Because the *free wire current* is calculated for a single copper wire in ambient air, worst case derating factors in SAE-AS50881⁶ must be applied for:

- Aluminum conductor ($d_1 = 0.8$) \rightarrow ratio of the specific resistances of copper and aluminum ρ_{cu}/ρ_{al}
- Altitude ($d_2 = 1-0.7$) \rightarrow See also altitude derating factor calculated with TMM (Figure 5) for convection and heat radiation for wire size 4 and 24.
- Multiple wires & load cases in bundles ($d_3 = 1-0.25$) \rightarrow See Figure 6 and bundle derating factors calculated with TMM (Figure 8)

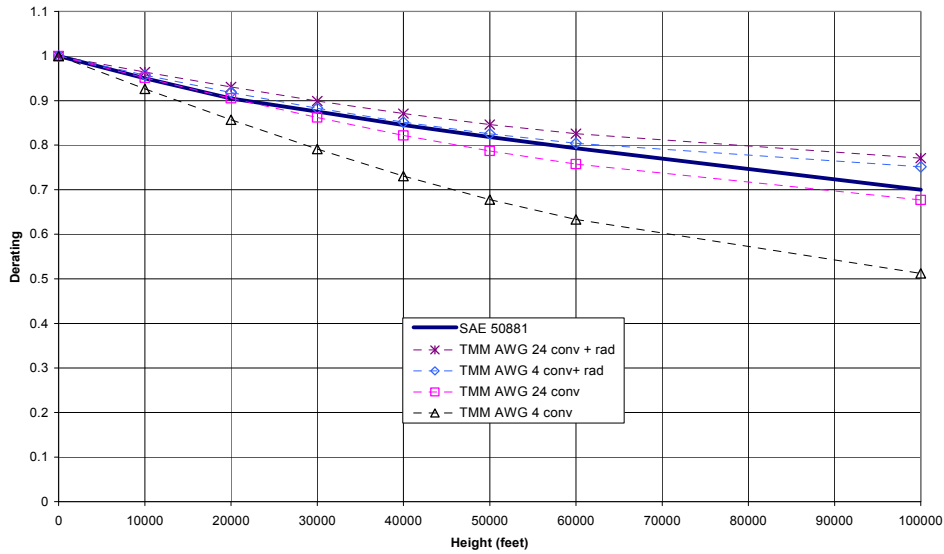


Figure 5 Current derating factor as function of altitude in SAE-AS50881⁶ (solid line) compared with TMM predicted for wire size 4 and 24 using convective cooling with and without heat radiation

The overall derating is defined as: $d = d_1 \times d_2 \times d_3$. The design current for the selection of a wire is then defined as: $I_{design} = d I_{fwc}$. For example the derating factor for a wire inside a bundle with >33 wires is $0.8 \times 0.85 \times 0.26 = 0.17$, for an aluminum conductor ($d_1 = 0.8$) at a worst case altitude of 40,000 feet ($d_2 = 0.85$) and a 100% load ($d_3 = 0.26$). This indicates that for 33 or more wires in a bundle, with a 100% load, a current derating factor of 0.26 must be applied. Note that in this example the bundle composition gives the largest contribution to the derating factor. When a wire in air is allowed to carry 100A, it can carry 26A when applied in a bundle with 33 or more wires at a 100% load. The derating levels off to about 0.24 (@100%load) for 33 wires or more. The requirements for space are fully comparable with SAE-AS50881⁶, however ECSS-30-Q-11A⁵ assumes a worst case 100% load and has ‘split’ has been made between size 0-12 and size 14-32 resulting in derating factors between 0.32-0.25 for 33 or more wires. In section D an analysis is done to calculate the bundle derating factor from the ratio between the sum of the heat transfers of its wires related to overall heat transfer of a bundle.

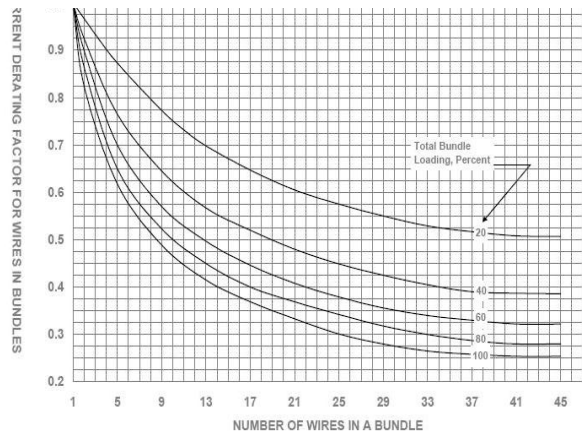


Figure 6 Current derating factor for

2.3 Heat transfer of bundles in free air and cylindrical enclosure

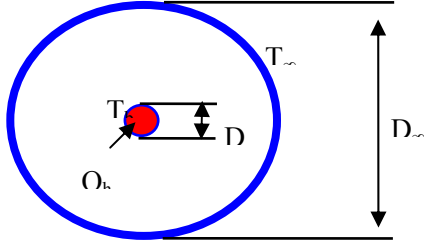


Figure 7 Bundle in enclosure

The heat transfer coefficient of a bundle can be estimated using empirical functions for convection, conduction and IR radiation of a bundle in free air or inside a cylindrical enclosure which have been validated by test. For more complex enclosure conditions C_D is evaluated using Finite Element Modeling (FEM). For a general approach of the heat transfer coefficient C_D assume a isothermal heated cylindrical object (e.g. a bundle) with length L meter and size D in free air ($D_{\infty} \rightarrow \infty$) or inside an (cylindrical) enclosure size D_{∞} . See Figure 7. The final

temperature elevation of a bundle above ambient is found when there is an equilibrium between heating and cooling conditions. The heat dissipation is the sum of the heat loss of N wires in a bundle.

$$Q_c = C_D \Delta T = Q_h = \sum_{n=1}^N i_n^2 R_n \quad (8)$$

With $\Delta T = T_{\infty} - T_b$ is the temperature difference between the (external surface of) the bundle and the enclosure. C_D is the overall heat transfer coefficient of the bundle which is the sum of air convection and IR radiation to the enclosure. The heat transfer coefficient C_D is a function of the averaged air temperature $T_{avr} = (T_b + T_{\infty})/2$ and bundle size that can be evaluated *per meter* bundle length by taking $L = 1m$.

$$C_D(\bar{T}) = \pi L D \left(\frac{\lambda}{D} Nu_D + 4 \varepsilon_{eff} \sigma \bar{T}^3 F \right) \quad (9)$$

The Nusselt number Nu_D is the ratio between convective and conductive heat flow, a dimensionless number >1 reflecting convective properties of air related to bundle diameter D and also includes cylindrical enclosure diameter D_{∞} . The convection heat exchange of an isothermal horizontal cylindrical shaped body in free air can be written according to:

$$Nu_D = \left\{ 0.6 + \frac{0.387 Ra_D^{1/6}}{\left[1 + (0.559 / Pr)^{9/16} \right]^{4/27}} \right\} \quad (10)$$

(Free convection for horizontal cylinder, $10^5 < Ra_D < 1012$, Churchill and Chu (1975)1)

The convective heat exchange of a cylindrical shaped body inside an enclosure can be written according to Raithby and Hollands¹ as:

$$Nu_D = \frac{1}{\pi} \left[\frac{2.425}{1 + \left(\frac{D}{D_{\infty}} \right)^{3/5}} \right]^{5/4} \left(\frac{Pr Ra_D}{0.861 + Pr} \right)^{1/4} \quad (11)$$

(Convection in cylindrical enclosure, $Ra_D < 10^7$, Raithby and Hollands¹)



With Reynolds Number $Ra_D = g\beta(T_b - T_\infty)D^3/\nu^2 P_r$ and $P_r(\text{Prandtl})=0.707$ for air. Air properties β (thermal expansion) and ν (kinetic viscosity) as function of pressure and temperature are taken from NIST⁸. At low pressures the contribution of convection is poor and $Nu_D=1$ (air conduction only) until the boundary layer δ becomes larger than the available space e.g. $\delta < (D_\infty - D)/2$ in that case $Nu_D = 1/\ln(D_\infty/D)$. In vacuum $Nu_D=0$, leaving heat radiation doing the cooling. $F=1$ is the geometrical view factor for IR radiation between the bundle and the enclosure which assumes and unblocked view to the enclosure. Note that due to the relatively small temperature differences between the bundle and the enclosure ($T_b \sim T_\infty$), IR radiation can be linearized by taken T^3 at the averaged temperature using:

$$\sigma(T_b^4 - T_\infty^4) = \sigma(T_b^2 + T_\infty^2)(T_b + T_\infty)(T_b - T_\infty) \approx 4\sigma\bar{T}^3 \Delta T \tag{12}$$

The effective emission coefficient becomes:

$$\epsilon_{eff} = \frac{1}{\left(\frac{1}{\epsilon_b} - \frac{A_b}{A_\infty} \left(\frac{1}{\epsilon_\infty} - 1 \right) \right)} \tag{13}$$

When assuming $\epsilon_b \sim 1$ and $\epsilon_\infty \sim 1$ an effective emission coefficient ($\epsilon_{eff}=1$) was chosen as a starting point for the calculation. For free air $A_\infty \rightarrow \infty$. Below the heat transfer coefficient C_D for a $L=1$ meter bundle at 120°C in free air (Table 4) and inside a 200 mm cylindrical enclosure at 70°C (Table 4) is calculated using the above functions. For a 200 mm enclosure minor deviations in heat transfer with respect to free air situation is found. However for improved thermal analysis the deviations in heat transfer should be included for bundles inside enclosures.

Bundle Size mm	Ambient 1 Bar	50.000 feet 0,116 Bar	Vacuum
5	0.40	0.23	0.14
10	0.69	0.42	0.29
15	0.95	0.61	0.43
20	1.20	0.79	0.58
25	1.43	0.96	0.72
30	1.65	1.13	0.86
35	1.87	1.30	1.01

Table 3 Heat transfer coefficient CD (W/K) for a cylindrical object ($L=1m$) at 120°C in free air at 70°C

Bundle Size mm	Ambient 1 Bar	50.000 feet 0,116 Bar	Vacuum
5	0.36	0.25	0.14
10	0.63	0.43	0.29
15	0.89	0.61	0.43
20	1.14	0.79	0.58
25	1.39	0.96	0.72
30	1.64	1.13	0.86
35	1.88	1.31	1.01

Table 4 Heat transfer coefficient C_D (W/K) for a cylindrical object ($L=1m$) at $120^\circ C$ in a 200 mm enclosure at $70^\circ C$

2.4 Estimation of current derating factor for multiple wires in a bundle

Assume N equally sized wires size D_i in a bundle. When assuming a good packing of these wires the bundle diameter D_B becomes approximately:

$$D_B = \sqrt{N} D_i \quad (14)$$

The thermal equilibrium is found when the total heat losses of all wires in the bundle (including a current derating factor d) should be in thermal equilibrium with the overall bundle cooling.

$$Q_h = \sum_{n=1}^N (d i_n)^2 R_n = d^2 \sum_{n=1}^N i_n^2 R_n = d^2 \sum_{n=1}^N C_i \Delta T = C_B \Delta T \quad (15)$$

The current derating factor d for a wire in a bundle is calculated from ratio between the sum of the heat transfer coefficient of all the wires and the overall heat transfer coefficient of the bundle assuming an equal temperature difference.

$$d = \sqrt{\frac{C_B}{\sum_{n=1}^N C_i}} \quad (16)$$

The above estimation of the derating factor for all wires in a bundle gives a good match with SAE-AS50881⁶ for a 100% load case, the smallest sizes and assuming convection only. See the TMM AWG 24 line (triangle) in Figure 8. Since radiation cooling is not considered this is worst case. Also it is found that derating factors in ECSS-Q-30-11A⁵ (black line) neglect radiation cooling (TMM AWG24-4 radiation only - tilted square). The 'size split' for >20 wires only makes sense when assuming convective cooling only. It looks like that deration factors of SAE-SA50881⁶ are copied into ECSS-Q-30-11A⁵ which in fact is too worst case under vacuum. Since for space applications the current is already significantly derated up to 50% for vacuum conditions additional bundle deration leads to an increase in weight.

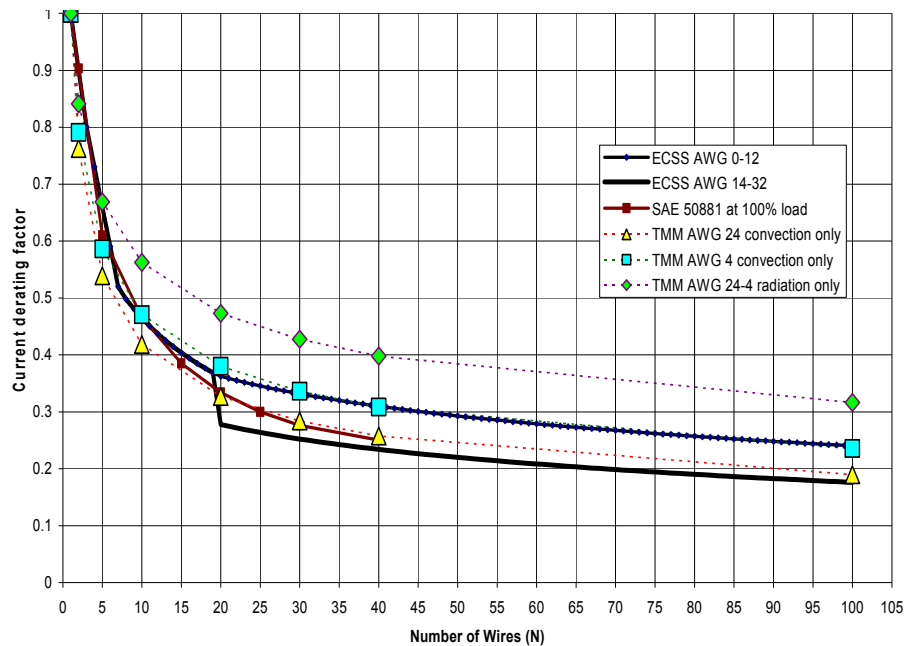


Figure 8 Current derating as calculated with TMM in air and vacuum compared with SAE-AS50881⁶ and ECSS Q-30-11A⁵

Conclusion is that since heat radiation looks like to be neglected in both SAE-AS50881⁶ and ECSS-Q-30-11A⁵ the recommended current derating factor for wires in bundles is most likely too worst case, leading to an increase in bundle weight. A detailed thermal analysis of an actual bundle design is therefore recommended to investigate if a weight saving is possible when including heat radiation cooling.

3 Thermal Analysis

Since a bundle in an aircraft enclosure is surrounded by a pocket of air most of its heat generated is transported in radial direction due to natural convection, air conduction and heat radiation. Cooling by conduction in axial/length direction (via the wire cores) and by air ventilation is very limited and therefore neglected for the worst case analysis. Note that the generated heat by a bundle is finally absorbed in the surrounding aircraft structure. The enclosure temperature is related to the balance between the absorbed and conducted heat to the thermal mass of the aircraft. The final temperature of a bundle with respect to the enclosure (air) temperature stabilizes by having a thermal balance between the (time averaged) heating and cooling contributions. The heat balance for a bundle segment in aircraft is therefore:

$$Q_{\text{heat-dissipation}} = Q_{\text{natural-convection}} + Q_{\text{IR-radiation}} = Q_{\text{absorbed-enclosure}} + Q_{\text{ventilation}} + Q_{\text{axial}} \quad (17)$$

Worst case, cooling by axial conduction or ventilation is usually neglected. At high altitudes e.g. low pressure conditions, the contribution of natural convection reduces significantly, leaving heat radiation and air conduction to do the cooling of a bundle. See Figure 9 below for an example calculation of the air's velocity field around a bundle of 16mm diameter due to

natural convection dissipating 50W *per meter* inside a 60°C cylindrical enclosure (ID=200mm) as function bundle temperature and pressure conditions. The result is that the bundle temperature increases from 112°C ($\Delta T=52^{\circ}\text{C}$) to 123°C ($\Delta T=63^{\circ}\text{C}$) when transporting the same currents for aircraft flying in low pressure air at an altitude of 50.000 feet.

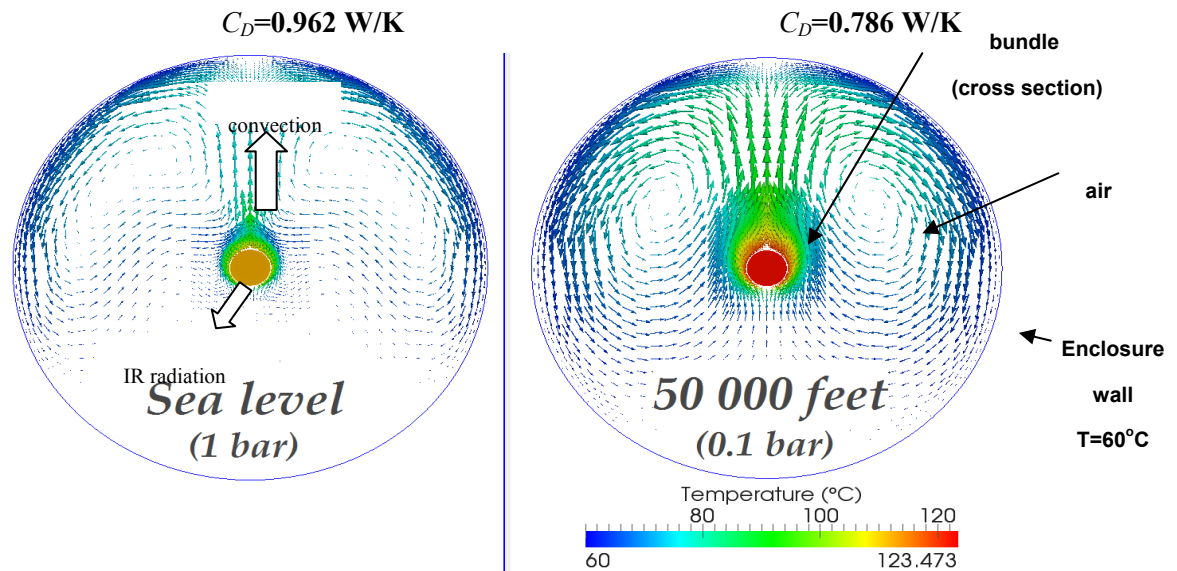


Figure 9 Example calculation (FEM) of natural air convection as function of pressure on the temperature of a 16mm bundle inside a 200mm enclosure (velocity arrows colored with temperature field, Oofelie:Multiphysics, Open Engineering)

3.1 Bundle modeling

A bundle is defined as a collection of wires. A mixed (power + data) harness design has been considered as starting point for the modeling which is possible for current below 15 Amps. A typical mixed bundle has more than 100 wires per bundle of which are:

- ca 35% AWG 24
- ca 40% AWG 22
- 25% < AWG 22

Ca 65% of the large wires (<AWG 22) carry a current and the remaining small > AWG 22 'passive' wires are ca 35% for data transmission. Clearly, the size, currents, number of cores in wire, the position of a wire in a bundle, fixtures and supports, air temperature and pressure determines the wire core temperature. For instance a wire in the centre of a bundle is hardly cooled since it is in close contact with surrounding wires limiting cooling whereas a wire along the perimeter is directly cooled by air convection. Thermal modeling of wires in a bundle therefore should take into account:

- Wire type, dimensions and number of cores (e.g. AWG size, single, double, triple, quad).
- Insulation, shielding and jacket thickness (thermal resistance).
- Wire core (conductor diameter and material).
- Current (DC, AC, heat losses).
- Bundle configuration e.g. contact conduction with neighboring wires or air convection at the bundle perimeter.
- Environmental conditions (air temperature, pressure, enclosure).

A major point of concern for the modeling is that the wire position inside a bundle is fluctuating e.g. changes along the length of a bundle due to the manufacturing process. For instance a wire starting in the centre of a bundle can be at the perimeter several meters down the line. The above factors require general assumptions about the wire environment inside a bundle. Each wire is represented by a single thermal node with a radial heat transfer to its local environment.

- A cylindrical shape of cores, wires, bundles and enclosures.
- Electrical resistance as function of temperature.
- Radial heat losses only, axial conduction, bundle supports and fixtures are neglected.
- Small temperature difference exists between wires in a bundle.
- Wires are mainly cooled by 'contact' conduction; internal convection and heat radiation is neglected
- Mutual contact conduction between the wires is related to their 'contact angles'.
- Each wire is modeled as a single node; no internal temperature gradients due to the high specific thermal conduction of the conductor material all cores carry the same current.
- The influence of the ETFE insulation and shielding is represented by a thermal resistance of a wire node to its environment.
- A fixed wire distribution assumed e.g. each bundle configuration requires a new calculation
- External air convection and heat radiation at the outer surface of the bundle is evenly distributed over the wires located at the bundles perimeter.
- The influence of braiding can be included by an additional node representing the braid of a bundle.

3.2 Thermal Design Module (TDM) Software

The Thermal Design Model (TDM) is a NxN nodes matrix solver (see Figure 10) that is implemented in a software application. It is a standalone application developed in Java. The main advantage of the development in the Java language is that the application is platform independent and it only needs a java runtime environment (jre 1.5 or higher). The TDM software needs the following three input files:

- *Wire database file.* File with information about the individual wires as provided by the manufacturer. Per wire the following information is used: The wire type number, the wire-type (twisted shielded, twisted shielded triple, twisted triple, twisted pair and single wire are the types that are supported by the TDM software), the conduction-outer-diameter [mm], the wire-outer-diameter [mm], the wire-outer-diameter [mm], the wire-size [mm], the number-of-leads and the jacket-thickness [mm].
- *Bundle composition file.* This file contains the wires of which the bundle is composed, including the design currents [A]. The configuration is defined by the user. See figure 11 for the three preset configurations.

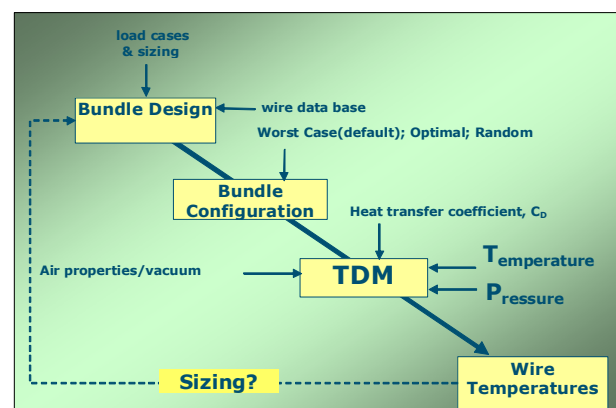


Figure 10 Thermal Design Module to predict wire temperatures in a bundle

- *Air-properties file.* This file contains the following values: Altitude [feet], Air Temperature [°C], Pressure [MPa], Density [Kg/m³] Thermal condition [mW/mK], Kinematic viscosity [cm²/s], Prandtl Volume-expansivity [1/K]. The values have been generated using NIST⁸ information.

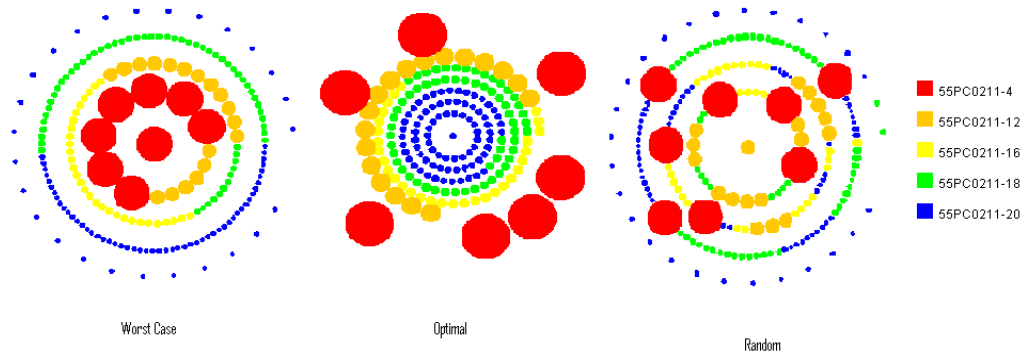


Figure 11 TDM Bundle configurations: (1) Worst Case (default), (2) Optimal or (3) Random

Next to the input-files the following user input is required: altitude, enclosure-temperature, enclosure-diameter and the bundle-diameter for the calculation of the heat transfer coefficient C_D . The TDM1.0 software distributes the cables of the bundle according to a worst case configuration, which means that cables with largest weight and currents are in the centre of the bundle and cables with smallest weight and lowest currents are at the outside of the bundle. It was found during the testing of the samples that the worst case configuration gives the highest wire temperatures compared to the 'as manufactured' (random) case. The TDM software uses a radial approach for the calculation of the heat transfer coefficient of a bundle and computes the

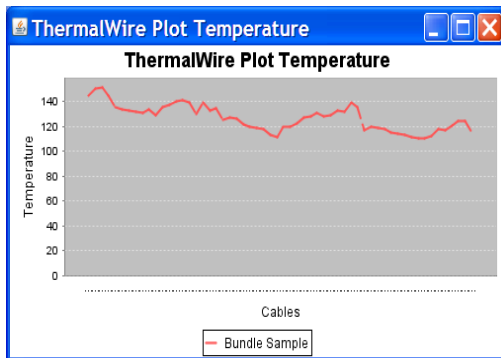


Figure 12 TDM output plot of wires temperatures in a bundle

mutual contact conduction of each wire based on contact angles and bundle configuration. TDM computes for each wire the dissipation P_i and its temperature T_i . The predictions are provided in a file or plot (Figure 12). The TDM version 1.0 is validated for worst case, optimal and random bundle configurations, enclosure dimension 200 ± 40 mm, bundle sizes 16 ± 2 mm, 40 to 100 wires and a absolute temperature accuracy of $\pm 20^\circ\text{C}$ at 150°C related to modeling and manufacturing uncertainties.

4 Test Evaluation

The Thermal Design Model version 1.0 was validated using 6 samples (Figure 13 and Table 5) of a typical mixed aircraft wiring bundle design statistically equivalent with respect to composition and sizing with a bundle in typical aircraft. Note that modern separation rules do not allow mixing of power and data wire anymore, but this has no influence on the model validation. Two main series of samples were tested:

- A series using a standard design (bundle diameter ca 16 mm)
- B series using a reduced design (bundle diameter ca 14 mm)

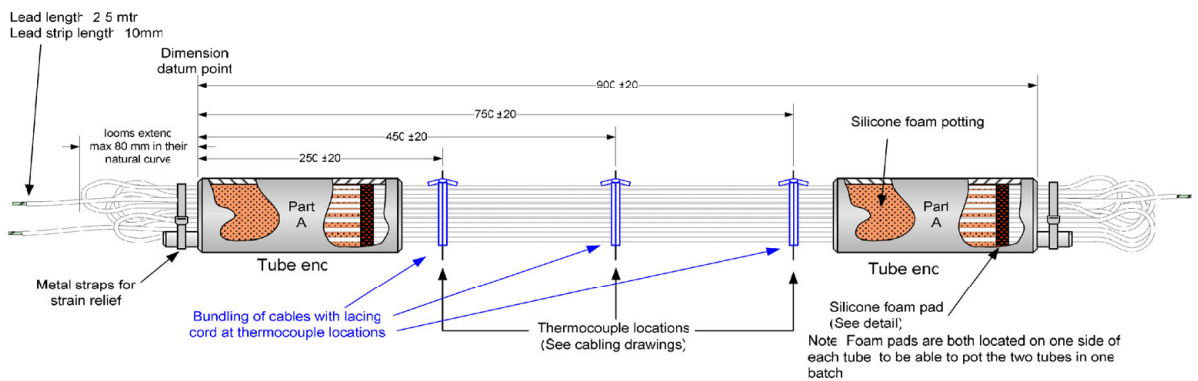


Figure 13 Sample layout

For each series three wire configurations (Table 6) with respect to the distributions of power (current carrying) and data (no/low current) wires were constructed, resulting in a (small) difference in the convection properties:

- “1” Worst case (power wires inside, data wires outside)
- “2” Optimal (data wires inside, power wires outside)
- “3” Random (manufacturing practice)

The wire temperatures are measured using thermocouples at the left, centre and right position attached to the wires (for all wire size at least three) located in that particular cross-section. Note that the terms "Optimal" and "Random" were used prior to the testing. It was an unexpected result that the random configuration gave a 6 á 7°C lower averaged bundle temperature than "Optimal". See also Figure 15. A possible explanation is that the random case spreads out its heat in all directions either by convection or conduction to surrounding wires. In the optimal configuration only wires at the surface loose heat, resulting in higher bundle temperatures.

Sample no	Bundle Diameter [mm]	Bundle Configuration
A1	17	Worst Case
A2	17	Optimal
A3	17	Random
B1	15	Worst Case
B2	15	Optimal
B3	15	Random

Table 5 Samples used for the validation of the TDM

4.1 Wire sizes

See Table 6 for the definition of the test sample wiring and currents. The wires inside each sample are defined in 4 power lines carrying a current and 2 passive data lines.

Line	Sample A series	Sample B series	Number of wires	Type Raychem SPEC55 ⁷
Power 1	AWG 12	AWG 14	1	Wire, twisted triplet, tin plated, light weight insulation
Power 2	AWG 16	AWG 20	3	Wire, twisted shielded jacketed triplet, tin plated, light weight insulation
Power 3	AWG 20	AWG 22	5	Wire, tin plated, light weight insulation
Power 4	AWG 22	AWG 24	7	Wire, twisted pair, tin plated, light weight insulation
Data 1	AWG 22	AWG 24	13	Wire, twisted shielded jacketed pair, high strength copper, tin plated, light weight insulation
Data 2	AWG 24	AWG 24	29	Wire, high strength copper, silver plated, light weight insulation
			57	

Table 6 Wire & current definition for the samples

4.2 Test cases

The above combinations resulted in the construction of the six bundles: A1, A2, A3, B1, B2, and B3. Each bundle was tested under three environmental conditions (hot, nominal and cold) ranging from -50°C to +60°C and 0.1 Bar to 1 Bar. The pressure and temperature ranges were chosen for correlation of the air convection properties at sea level and 50.000 feet:

Test Case	Environment Temperature [oC]	Air Pressure [Bar]
Hot	60	0.1
Nominal	15	0.7
Cold	-50	1

Table 7 Test conditions used for the validation of the TDM

4.3 Test Facility

The following set-up (*Figure 14*) is used for the bundle tests.

- The sample bundles were placed in a pressure controlled cylindrical tube (ID=200 mm) with sealed flanges to allow testing in low pressure environments.
- The large tube was placed in a temperature controlled chamber.
- The cylinder temperature is measured using several thermocouples.
- The averaged bundle temperature is measured using several thermocouples located in the centre cross-section of the sample.

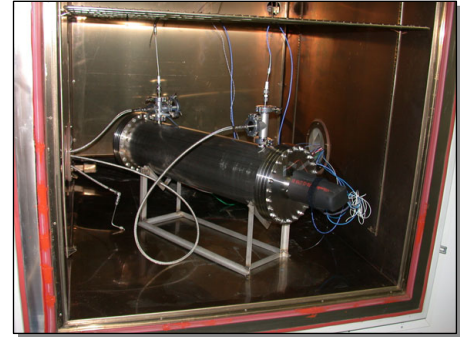


Figure 14 Photograph of the test facility in the climate chamber

4.4 Test Results

It was been assumed that the *averaged surface temperature* of a bundle equals the *averaged wire temperature*. The effective heat transfer C_{eff} ($= P/dT$) between the bundle and the enclosure (cylinder wall) is calculated from the total dissipation per meter of the bundle and the temperature difference dT between the averaged bundle and the enclosure (facility wall) temperature. Note the bundle configuration has a slight effect on the averaged bundle temperature. As can be seen in *Figure 15* were the average bundle temperature is plotted for sample A1, A2 and A3 in the hot case. The max temperature difference in the bundle averaged temperature between the bundle configurations is in the order of 12°C. Interestingly the 'random' configuration gives the lowest averaged bundle temperature even better than the 'optimal' configuration. The 'worst case' configuration gives indeed the highest temperature of +12°C above

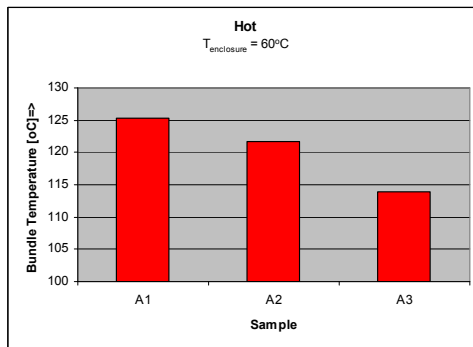


Figure 15 Average bundle temperature as measured for the A samples during the hot case

'random'. An explanation is that in the random case wires loose their heat in all directions either by convection or conduction to surrounding wires evenly spreading out heat, whereas in the optimal case only heat rejection towards the external surface is possible. Since the worst case bundle configuration gives the highest wires temperatures this is taken as the default case for wire temperature prediction in TDM1.0. A small difference of ca 8-14% in the averaged overall conduction (*Figure 15*) is found between the sample configurations 1, 2 and 3 of both the series A and B. As expected by its ca 12% smaller surface area the reduced bundles ("B") give a ca 12% lower heat transfer value compared to the nominal ("B") samples. Within the error margins the sample measurements and TMM predictions correspond very well (see *Table 8*) except for sample A3. The overall measurement accuracy is estimated using an error of $\pm 5^\circ\text{C}$ for the measurement of the temperature difference between the

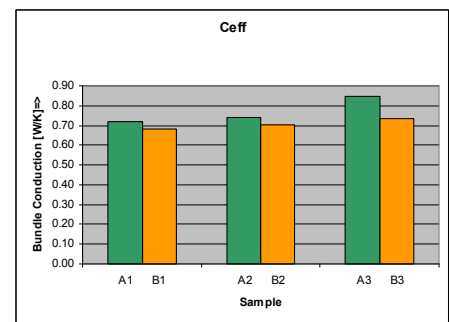


Figure 16 Hot case heat transfer coefficient C_D as measured for samples A&B

bundle and the facility and a heat dissipation measurement error of $\pm 1W$. The estimated calculation accuracy (± 0.05) is related to the uncertainty in the measurement of the bundle diameter ($\pm 0.5-1mm$) and overall bundle surface temperature ($\pm 5-10^{\circ}C$). A3 has a heat transfer coefficient which is slightly higher than measured & predicted for sample A1 and A3 in all cases. This could be related to a deviation in bundle diameter and/or random variations in the bundle surface temperature.

	Hot		Nominal		Cold	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
Sample	+/-0.15	+/-0.05	+/-0.15	+/-0.05	+/-0.15	+/-0.05
A1	0.742	0.712	0.739	0.754	0.676	0.661
A2	0.749	0.698	0.746	0.743	0.716	0.643
A3	0.838	0.678	0.872	0.719	0.815	0.623
B1	0.652	0.529	0.721	0.809	0.666	0.687
B2	0.670	0.597	0.753	0.759	0.692	0.672
B3	0.683	0.592	0.785	0.748	0.731	0.657

Table 8 Measured and predicted heat transfer coefficient [W/K] for the sample bundles inside a 200 mm enclosure

Since the focus of sample test was on the internal temperature distribution, the bundle diameters and corresponding heat transfer coefficients only slightly varied. It is therefore recommended to extend the validation range by testing larger and smaller sized bundles and also to include enclosure size variations.

4.5 Model accuracy

When including the calculation of the bundle's heat transfer the TDM1.0 predicts the wire temperature with a temperature variations of $\pm 10.3^{\circ}C$ between similar wires, related to the radial position. Also the temperature difference between the averaged predicted and averaged measured wire temperatures is about $\pm 8.2^{\circ}C$. Conclusion is that the worst case accuracy of TDM1 is $\pm 18.5^{\circ}C$ to predict a wire temperature, related to both the bundle manufacturing (e.g. varying radial position) and modelling accuracy.

$$\delta T_{TDM1} = \delta T_{\text{manufacturing}} + \delta T_{\text{modelling}} = \pm |10.3^{\circ}C| \pm |8.2^{\circ}C| = \pm 18.5^{\circ}C$$

Since this is a *worst case estimation of the accuracy* it is more convenient to use a *relative accuracy* related to the *temperature elevation* ΔT between the wire and ambient temperature. With this approach the prediction accuracy of the model improves when the temperature elevation reduces and worsens when the temperature elevation increases. For TDM1.0 this is defined as $\delta T_{TDM1} = \Delta T / 60 * 20$ (or $\Delta T * \epsilon$ with $\epsilon = 1/3$), meaning that for a temperature elevation of $60^{\circ}C$ the TDM prediction accuracy is $\pm 20^{\circ}C$ and for a wire temperature elevation of $30^{\circ}C$ above ambient the prediction accuracy becomes $\pm 10^{\circ}C$. It is therefore recommended to use the relative accuracy related to the temperature elevation rather than a worst case accuracy for future validation of the TDM.

5 Conclusion

In this paper it is investigated that the physical background of wire selection rules in the aeronautical standards are based on a thermal equilibrium which is fully understood by thermal modelling in a TMM. Application of current derating factors to reduce wire temperature leads to a significant increase in bundle weight. Since not all local factors limiting bundle cooling are considered in the standards, this could lead to overheating of bundle or structural parts or to over weight designs. Because heat radiation cooling is neglected in both SAE-AS50881⁶ and ECSS-Q-30-11A⁷ the recommended current derating factor for wires in bundles is most likely too worst case, leading to an unnecessary increase in bundle weight. A detailed thermal analysis is recommended to investigate if a weight saving is possible when including heat radiation cooling.

A generic Thermal Design Model (TDM) was constructed to predict wire temperatures inside bundles for three preset configurations. It appeared that the overall heat transfer coefficient C_D of a bundle to its enclosure due to air convection and heat radiation at outer surface should be taken into account when calculating wire temperatures. Bundle heat transfer coefficients can be approximated using empirical functions for convection and heat radiation in free air or inside cylindrical enclosures. For more complex enclosure conditions the heat transfer can also be estimated with FEM analysis. The TDM1.0 was validated with 2x3 representative samples (14-16 mm) and was found to have a worst case accuracy of $\pm 18.5^\circ\text{C}$ for the tested range. This is the sum of the uncertainty in the modelling and the inherent uncertainty of the variable radial position of a wire inside a bundle due to bundle manufacturing. TDM1.0 is now validated for:

- a generation of a worst case (default), optimal or random bundle configuration
- enclosure dimensions: 200 ± 40 mm
- bundle sizes : 16 ± 2 mm
- 40 to 100 wires (extrapolated from test results)
- worst case accuracy $\pm 19^\circ\text{C}$ (modeling uncertainty + manufacturing variations)
- a temperature range between : -55°C and 60°C
- a pressure range between 0.1 Bar and 1 Bar.

Since the accuracy and range of the TDM1.0 was too limited for practical use, work is continuing extending the validation range to 5-35 mm diameter bundles and several enclosures. A focus on the conditions found for the largest bundle segments in aircraft for the Fuselage and the Wing is recommended. Proposed improvements of the thermal analysis for aerospace applications are:

- Implementation of more representative enclosure conditions using FEM
- Implementation of bundle braids
- Implementation of heat capacities & load profiles for power critical bundle designs
- Implementation of axial heat leaks for delicate bundle designs
- Implementation of vacuum or low pressure conditions (e.g. CO_2 atmosphere on Mars) for space bundle designs
- 10% less current derating is possible, saving bundle weight for space applications
- Use a relative accuracy related to the temperature elevation ΔT of $\pm \delta = \Delta T / 3$ (e.g. $\pm 20^\circ\text{C}$ at 120°C).

When the TDM is extended towards more complex environmental conditions an improved prediction of the thermal interaction between bundles and structural parts for aerospace applications is possible. By using thermal analysis in the design phase, derating factors and wire gauging can be optimized beyond the limitations of the aeronautical standards. Life cycle cost (or launch cost) reduction with respect to the harness weight and improved safety are to be expected

Acknowledgments

The investigation of the thermal requirements for aircraft wiring was initiated by Fokker Elmo and sponsored by the Dutch Aeronautical Institute. Fokker Elmo was responsible for the bundle design and installation requirements and for the manufacturing of the samples. NLR was responsible for the requirements review, the construction of the thermal model and evaluation of the validation testing. Open Engineering provided the FEM analysis for the prediction of the bundle heat transfer coefficients inside enclosures.

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Air properties

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