



AEROSPACE RECOMMENDED PRACTICE

ARP7987™

Issued

2021-08

Development, Verification, and Validation of a Thermal Model for Determining Current Derating Design Limits of Aerospace Wires and Wire Bundles

RATIONALE

This SAE Aerospace Recommended Practice (ARP) documents the basic guidelines for the development, verification, and validation of a thermal analytical model for determining ampacity and current derating limits of aerospace wires and wire bundles. The document will be updated as new models are developed and new information becomes available.

1. SCOPE

The thermal modeling guidelines and best practices provided in this document are applicable to powered aerospace vehicle wires and wire bundles in thermal environments ranging from -65 to +260 °C (-85 to +500 °F) and pressures ranging from sea level to space vacuum. Currently the ARP only considers steady state and direct current conditions. The effects of wiring terminations and connectors are not addressed. Both can significantly impact the overall current derating and safety margins for a wiring system.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

1. History of the Development of New Current Ratings for Aerospace Wire, Cornelius, R.S., A RayChem Report, circa 1978.
2. A New High Strength Conductor Alloy for Military Wire and Cable Applications, Eng, T., SAE Aerospace Electrical Interconnect System Symposium (AEISS) October 12, 2011, Denver, CO.
3. Thermal analysis of wiring for weight reduction and improved safety, Benthem, R.C. Van, Report No. NLR-TP-2011-469, Oct 2011.
4. Thermal Analysis of Wiring Bundles for Weight Reduction and Improved Safety, Taylor, S., AIAA 2011-5111, National Aerospace Laboratory (NLR), Netherlands, International Conference on Environmental Systems, July 2011.
5. Heat transfer analysis in wire bundles for aerospace vehicles, Rickman, S.L., Proceedings of the 14 International Conference on Simulation and Experiments in Heat Transfer and its Applications (HT 2016), <https://ntrs.nasa.gov/api/citations/20160011474/downloads/20160011474corrected.pdf>.

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2021 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
<http://www.sae.org>

SAE WEB ADDRESS:

Full document details: SAE ARP7987

For more information on this standard, visit
<https://www.sae.org/standards/content/ARP7987/>

Documents
Document Sharing Hub

6. Derating Standards and Thermal Modelling Tools for Space Harness Designs, Benthem, R.C. Van, 45th International Conference on Environmental Systems ICES-2015-59 12-16 July 2015, Bellevue, Washington.
7. Improvement of the Wire Rating Standards based on TV Testing and Thermal Modeling, Malagoli, M., 48th International Conference on Environmental Systems ICES-2018-162.
8. Improvements to Wire Bundle Thermal Modeling for Ampacity Determination, Rickman, S.L., Proceedings of the 3rd World Congress on Mechanical, Chemical, and Material Engineering (MCM'17) Rome, Italy – June 8 – 10, 2017, Paper No. HTFF 102, ISSN: 2369-8136, DOI: 10.11159/htff17.102.
9. Re-Architecting the NASA Wire Derating Approach for Space Flight Applications, Rickman, S.L., NASA/TM-2018-220114, Nov 2018.
10. Harness Optimization by Improvement of the Derating Standard ECSS-Q-ST-30-11C, Malagoli, M., 9-12 October 2018, ESA/ESTEC, Noordwijk, The Netherlands.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR6540 Fundamentals in Wire Selection and Sizing for Aerospace Applications

AS22759 Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy

AS50881 Wiring Aerospace Vehicle

2.1.2 NEMA Publications

Available from National Electrical Manufacturers Association, 1300 North 17th Street, Suite 900, Arlington, VA 22209, Tel: 703-841-3200, www.nema.org.

WC27500 American National Standard for Aerospace and Industrial Electrical Cable

2.2 Definitions

ACCURACY: The degree of closeness of measurements of a quantity to that quantity's true value.

AMPACITY: The maximum amount of current that a wire or wire bundle can safely carry.

AXIAL CONDUCTION: Heat transfer along the length of a wire or wire bundle.

CONVECTION: The transfer of heat by the circulation or movement of the heated parts of a liquid or gas.

CORRELATION: Fine-tuning of model parameters to minimize differences between model predictions and measurements for a test range, especially before putting it into widespread use or practice.

DESIGN MARGIN: The additional performance capability above required standard basic system parameters that may be specified by a system designer to compensate for uncertainties.

EMISSIVITY: The ratio of the energy radiated by an object at a given absolute temperature to the energy emitted by a perfect radiator, or 'black body' at the same absolute temperature.

LABORATORY TESTING: The process of performing physical measurements on samples using a dedicated test facility.

MONTE CARLO EXPERIMENTS: A broad class of computational algorithms that rely on repeated random sampling to obtain numerical results. The underlying concept is to use randomness to solve problems that might be deterministic in principle.

TEMPERATURE COEFFICIENT OF RESISTANCE (α): The fractional change in electrical resistance per unit temperature.

THERMAL CONTACT CONDUCTION: Heat transferred by direct contact between two objects.

THERMAL RADIATION: Heat transferred via electromagnetic radiation in accordance with the Stefan-Boltzmann Law.

UNCERTAINTIES: Variations in the numerical and physical parameters that affect model outcomes.

VALIDATION: The process of determining if a model accurately represents the real-world application of the intended system to be evaluated.

VERIFICATION: The process of determining that a model meets the mathematical description of the intended system to be evaluated.

3. BACKGROUND

Design of wiring for aerospace vehicles relies on an understanding of “ampacity,” which refers to the current carrying capacity of insulated wires, individually or in wire bundles. Designers rely on standards such as AS50881 to de-rate allowable current flow to prevent exceeding wire temperature limits due to resistive heat dissipation within the wires or wire bundles. A more extensive discussion on the principles for selecting a wire size for an aerospace application using AS50881 is given in AIR6540. Laboratory testing, as identified in AS50881, has shown that most derating curves are conservative. The curves were developed using data from multiple aircraft companies, and worst-case values were typically used when determining conductor temperatures, ambient temperatures and current levels [1]. However, laboratory tests have shown adding shielding and jacketing and placing wire bundles in enclosures can significantly raise internal bundle temperatures, imposing a risk of overheating, a situation that is not addressed in the standards. These limitations can be overcome by using thermal modeling which has also been shown to enhance the mass optimization and safety of aircraft wire bundles [3,7,10]. Thermal modeling is also expected to become an important tool in developing, verifying, and validating all-electric aircraft wiring systems.

4. INTRODUCTION

AS50881 current derating curves are presented as generalized single wire sizes and simple wire bundles based on the current rating of the wire construction and ambient conditions [1]. In some cases, the curves can under-report conductor temperatures given specific bundle configurations and harness jacketing [3]. Published curves do not consider proximity to other wire harnesses or structure, different wire insulations and thicknesses, use of shielding and jacketing, protective coverings impact of enclosures, connectors, or if wiring is in a conduit [3,4]. The impact of these factors has typically been addressed by the Original Equipment Manufacturers (OEMs) and is rarely made available to outside organizations since it has been considered proprietary data. Although thermal models can successfully simulate wire bundles, an ongoing effort for refinements and verification by testing is needed to address the above factors and conditions. Modeling that has been validated with representative single wires and wire bundles through laboratory testing can allow for a more accurate representation of wiring systems when compared to using published and generalized current rating curves and derating factors [9]. Accurate thermal modeling of wire bundles has the potential to improve safety and reliability and reduce the weight and size of wiring used on aerospace systems [10]. Published papers and government studies have shown thermal modeling can effectively reproduce the current derating curves given in AS50881 [3 through 10]. At this time, the aerospace community is primarily interested in a model that can reproduce the AS50881 curves plus the ability to consider factors not accounted for in the AS50881 curves.

Two studies on modeling and testing served as the foundation for this ARP. First, the U.S. Government report included in the reference section [9] provides detailed guidance on developing a thermal model, building a test apparatus for verification, and building and instrumenting wire bundles to validate the model. Extensive comparisons between model results, measurements of wire bundles, and how these results compare with AS50881 current derating curves are also included in the report and NASA published papers [5,8,9]. Second, the Netherlands Aerospace Center (NLR) in cooperation with Airbus Defense and Space has also published detailed results on testing and developing a thermal model for wire bundles for the European Space Agency (ESA). NLR has also developed thermal models for aircraft applications with Fokker [4]. The European thermal modeling work includes a test apparatus description, model results compared with test results and published design standards, and the thermal impact of shielding, jacketing and enclosures [3,4,6,7,10]. Several publicly available references have been included in this document and should be reviewed before developing or using a thermal model to establish wire bundle current derating requirements for a specific application [3,4,5,6,7,8,9,10].

5. THERMAL MODELING VERIFICATION BEST PRACTICES

The following thermal modeling verification approaches have been shown to be effective for modeling the thermal response of wires and wire bundles under varying environmental conditions.

5.1 Single Wire Thermal Analysis

Model input requires detailed wire properties since this will impact thermal model accuracy. Published reports have shown finished (insulated) wire sizes must be measured since specification values provide a broad range and the actual wire diameters are typically at or near the specification minimums for both the conductor and finished wire diameters [7,8,9,10]. Resistance values also need to be measured since the specification provides a maximum resistance and not a minimum. Note that the conductor plating and alloy types such as ultra-high strength, high strength, and regular copper affect resistance measurements. Data required for thermal modeling and testing are listed in the sections below.

5.1.1 Single Wire Thermal Model Parameters

- Wire gauge.
- Conductor alloy.
- Measured wire diameter (insulation and conductor).
- Measured wire length.
- Conductor electrical resistance per unit length, measured at a reference temperature (usually 20 °C [68 °F]). If a measured value is not factored into the modeling, the analysis may yield incorrect results.
- Temperature coefficient of resistance (α) with value(s) over the expected wire operating temperature range of the wire conductor. This must be incorporated into the model if it will be used to predict current ampacity over the operational temperature range of a wire or wire bundle. Typically, each conductor alloy will have a different α . A description of how to calculate α is given in Appendix A.
- Insulation material (by layer) and average thickness of each layer.
- Thermal conductivity of each insulation constituent layer.
- Wire insulation radiative properties (infrared emissivity and infrared transmissivity). These properties may vary with temperature.

5.1.2 Environmental/Test Parameters

- Heat transfer parameters such as compartment geometry, compartment emissivity, and convection (forced and/or natural) should be evaluated.
- Wire-termination temperatures (i.e., as a boundary condition for the model) for each test condition.
- Current, duty cycle, and voltage across the wire for each test condition.
- Environment gas composition and pressure for each test condition for cases where atmosphere is present. For modeling single wires in a compartment, define any enclosure impacts on the model and wiring under evaluation; consider the impact of air flow and the atmosphere in an enclosure. Acceleration due to gravity (i.e., one-g, micro-gravity, etc.) influences on natural convection in cases where a surrounding atmosphere is present.

5.1.3 Other Considerations

- The wire can be considered cylindrical in shape and of infinite extent by assuming a long length for the wire. However, if a wire is assumed to be of finite length, the effect of end terminations must be evaluated.
- A sensitivity analysis should be conducted on input parameters.
- Techniques such as Monte Carlo analysis can be used to show the thermal impact of manufacturing variations between qualified vendors, variances in wiring properties or uncertainties in environmental parameters [9].
- The model should include thermal radiation exchange with the compartment/environment and convective exchange if an atmosphere is present.
- Conducting tests using aged wiring should also be considered so the wiring resistance remains stable throughout testing. Testing has shown over a 14% permanent increase in resistance for a silver-plated high strength conductor when aged for 1000 hours at its rated temperature [2]. Resistance increases will be different depending on the plating and alloy type.

5.2 Wire Bundle Thermal Analysis

A wire bundle thermal model may be thought of as a network of heat transfer paths between adjacent conductors considering the effects of insulation, thermal contact conductance, thermal radiation, and heat transfer through any interstitial gas, if present. Heat transfer to and from the wire bundle is through thermal radiation and, either convection or gas conduction if an atmosphere is present. For sufficiently long wire bundles, the effects of end terminations or connectors may be neglected.

The thermal impact of the wire insulation and shielding can be represented as a thermal conductor of a wire node to its environment. Wire to wire heat transfer should be based on properties of the insulation such as emissivity and infrared transmissivity of materials, thickness, thermal conductivity, contact with surrounding wires, gas conduction between wires (if an atmosphere is present), shields, and enclosure materials as these respond differently to heating and cooling. The model should incorporate the effects of external air convection (if atmosphere is present) and thermal radiation at the outer surface of the bundle. Gas conduction inside the bundle should also be considered in terrestrial applications. For steady state conditions there may be a small difference between individual wires under terrestrial conditions while under vacuum there could be significant differences. Current models assume thermal radiation and convection are evenly distributed over the wires located at the bundle's perimeter. A notional schematic representation of a segment of a typical bundle thermal network model is given in Figure 1 [9].