COVER SHEET

Title: *Cumulative Distribution of Ballistic Impact Failures of Common Twisted-pair Data Cables at Orbital Speeds*

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ABSTRACT

Data wire cable runs are a significant presence on the exterior of the International Space Station (ISS), and continued ISS mission support requires detailed assessment of cables due to micrometeoroid and orbit debris (MMOD) impact. These data wire cables are twisted-pair cables consisting of two 22AWG stranded conductors and fillers inside a tight fitting braided copper shield. The copper shield and its contents are covered with a jacket that has a nominal outer diameter of 3.76mm and beta-cloth tape. The ISS engineering community has identified two loss-of-function mechanisms for these cables: open circuits due to severed conductors within the cable, and short circuits due to contact between conductors or grounded components. As these data cables are low power systems, short circuits are not expected to burn away the contact, so both open and short circuits are considered permanent loss-of-function for the cable. A total of ninety-seven impact experiments have been performed into these cables to develop a statistical model for the failure of these cables to be used in reliability studies. The experimental work has yielded cumulative distribution functions for these cables for steel and aluminum components of the orbital debris environment at representative speeds and impact obliquities.

NOMENCLATURE

d	diameter (mm)
$\bar{d}$	mean diameter (mm)
δd	diameter scale length (mm)
C	failure count
P	probability
S	survivor count
Subscripts	
F	failure
i	impact

INTRODUCTION

The ISS Command and Data Handling (C&DH) system utilizes the MIL-STD-1553 data bus system [1,2] to interconnect its various subsystems such as the Multiplexer De-Multiplexers (MDMs) [3]. The 1553 data bus system is composed of shielded, twisted-pair cables and is doubly redundant. There are 45 MDMs on the ISS with 21 of these MDMs external to the habitable volume. The data buses that service these systems are exposed to the micrometeoroid-orbital debris (MMOD) environment especially in the case of open ISS structures such as the P3 or S3 truss segments like that shown in Fig. 1.

A previous test conducted in 1995 (Test #A2372) resulted in a shorted conductor [4] under an impact from a 0.4mm Al 2017-T4 projectile travelling approximately 7km/s, and has since dominated reliability calculations for the system [5]. Since this early design phase, limited additional research has focused on this cable with heavier shielding [6], and none in the flight-like configuration for the ISS. One purpose of this study is to address the limitations of these early works for the flight-like configuration and to quantify how cable internal geometry affects the critical particle size. In addition, the study has sought to understand if there is a difference in damage to the cable if it is backed by a structural element as compared to an end supported configuration. As can be seen in Fig. 1, both of these configurations are present in a typical cable run through a truss on the ISS. In addition to these objectives, this study also included high density

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particle threats, like steel, in addition to aluminum, and oblique impacts relative to the length of the cable.

Figure 1. An ISS truss with exposed C&DH and power cables as imaged during an Expedition 48 extravehicular activity (EVA) of Commander Jeff Williams and Flight Engineer Kate Rubins [7].

As a result of the multiple objectives and the need to develop cumulative statistic models, this study considered ninety-seven impact experiments performed by the NASA White Sands Test Facility's Remote Hypervelocity Test Laboratory. Coordination between the ISS program and the hypervelocity impact laboratory and target characterization has been performed by NASA Johnson Space Center's Hypervelocity Impact Technology group. This paper presents the findings of this study, along with empirical models that summarize the collected data for the use in reliability assessments of the ISS and other orbital architectures that use similar hardware.

METHODS

The MIL-STD-1553 data cables on ISS structures are both directly supported by structural elements and unsupported runs between them; therefore, both supporting schemes have been considered [8]. This effort used wo types of experimental articles to reflect each scheme with characteristic examples shown in Fig. 2. The cables that are in the experimental articles have come from decommissioned MIL-STD-1553 flight cables provided by the ISS program office's prime contractor, the Boeing Company. The supported configuration, shown in Fig. 2a, consists of cables placed side by side over a 3.175mm aluminum hardback, which is schematically rendered as a cross-section in Fig. 2b. The unsupported configuration, shown in Fig. 2c, consists of cables held in place by a frame separated from a 1mm aluminum witness plate by at least 50mm, which is schematically rendered as a cross-section in Fig. 2d. Cable runs have been doubled or tripled to improve the probability of an impact as there is a small impact aim point uncertainty associated with the aerodynamic effects from the experiments.

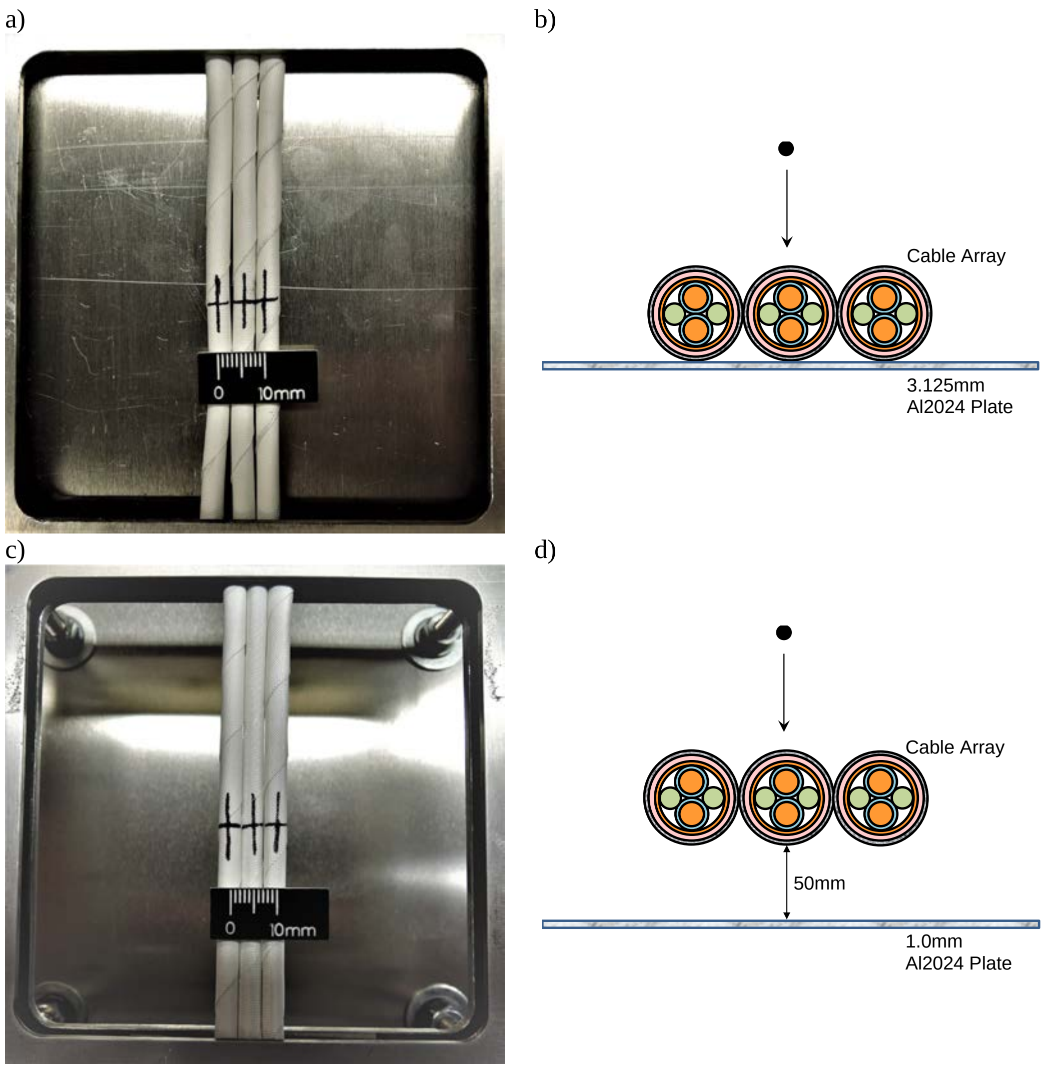

Figure 2. The ISS C&DH cable configurations with hard-backing a) viewed from the front with a b) cross-section schematic and suspended c) viewed from the front with a d) cross-section schematic. Cross-section schematics are not to scale.

A reconstructed, CT-radiograph of a cross-section of an actual experimental specimen is shown in Fig. 3 with the major components of the cable called out. The radiograph has been obtained using North Star Imaging software and a NASA Johnson Space Center custom system that uses a Hamamatsu 150kV Microfocus L8121-03 source with a PerkinElmer XRD 1621detector.

The 1553 data bus twisted-pair cable, consists of two 22 AWG stranded conductors with nominal diameters of 0.76mm, covered with polytetrafluoroethylene (PTFE) insulation such that the nominal diameter of the finished basic wire is 1.32mm. The wires are twisted, along with two 0.889mm diameter fillers inside a tight fitting braided copper shield (through-thickness areal density of 0.034g/cm^2) and covered with a fluorinated ethylene propylene (FEP) jacket having a nominal outer diameter of 3.76mm.

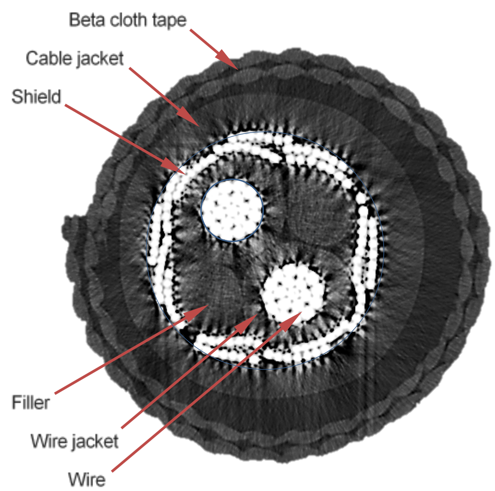

Figure 3. Cross-section image of the ISS C&DH twisted-pair cable from a CT scan of an experimental article.

To match the on-orbit configuration the wire has been wrapped with 25.4mm wide strips of beta-cloth tape (areal density 0.029g/cm^2) using a 50% overwrap. The 50% overwrap means that the cable has two layers of beta-cloth over its length; although, in the actual experimental article setup, the coverage is sometimes slightly higher. The 50% overwrap specification requires that each twist overlap the previous layer by 12.7mm perpendicular to the length of the wrap strip.

RESULTS

Typical results of four experiments that resulted in a short of the twisted-pair data cables are given in Fig. 4 for normal to the cable and 45° to normal to the cable. The impact obliquity is relative to the plane that contains the length of the cable and the cross-product of the projectile impact vector and the cable axis (vertical in Fig. 2a and 2c). This study has considered both spherical aluminum and steel projectiles at impact speeds of 7.0±0.3km/s [8].

Figure 4 includes an optical micrograph and the corresponding CT-radiograph of HITF15035 in Fig. 4a and Fig. 4b, respectively. As can be seen in Fig. 4a, much of the shielding has been exposed by the impact event, and that the shielding came into contact with one of the conductors resulting in a short as seen in Fig. 4b. This condition resulted from an impact of a 0.6 mm Al2017 spherical projectile at 7.25km/s. What can also be seen from this pair of images is that the final condition of the internal, cable-components is only easily seen from the CT-radiograph, so only when CT-radiographs are obtained are impact locations known with certainty. CT-radiographs have not been obtained for all ninety-seven experiments due to the volume of work and the complexity of CT-radiography; however, optical microscopy with continuity and short-circuit measurements are sufficient for determining loss-of-function.

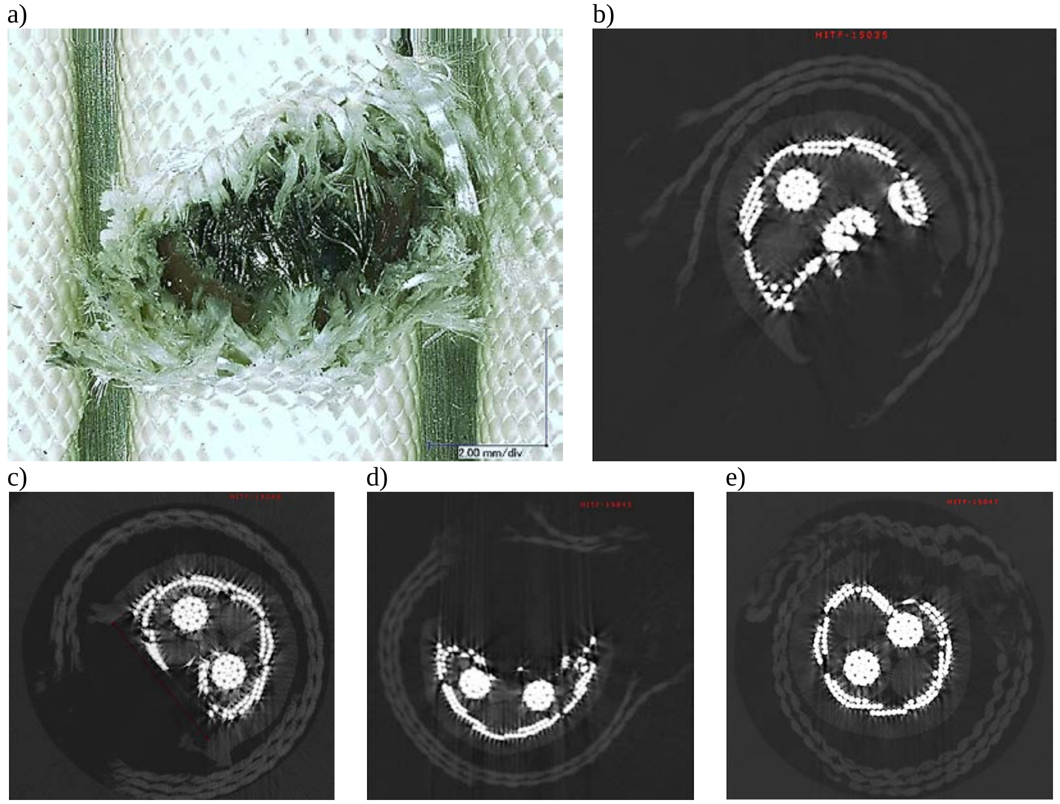

Figure 4. Typical impact results at 7 km/s for ISS C&DH cables including a) an optical micrograph from HITF15035 (a 0.6 mm Al2017 projectile) and b) a CT cross-sectional image of HITF15035. Additional CT cross-sectional images of c) HITF15040 (a 0.6 mm Al projectile), d) HITF15043 (a 0.44 mm SS440C projectile), and e) HITF150447 (a 0.44 mm SS440C projectile).

During the full course of this study, both types of failure modes (shorts and open circuits) have been observed in the hypervelocity experiments; however, the smallest particles that result in permanent, loss-of-function of the cable generally result from short circuits before open circuits. Other representative short circuits from additional aluminum and steel impacts are shown in Fig. 4c through Fig. 4e.

DISCUSSION

Due to the non-uniformity of internal materials, a pronounced variability for the outcome has occurred with the same particle size resulting in both closed and short circuits depending on the impact conditions. To illustrate this, the count of particles that resulted in an intact cable for a given particle size bin is shown in Fig. 5 as an orange bar for each impact condition. Similarly, the count of particles that resulted in a failure, short or open conductor, for a given particle bin are shown as a stacked blue bar. The combined height of the two bars is the total number of impacts considered for a given impact condition, and this total count includes all of the experiments performed under this study as well as the experiments documented in Ref. 4. As can be seen, the count of intact results generally decreases with impact particle size, and the count of failed results generally increases with impact particle size.

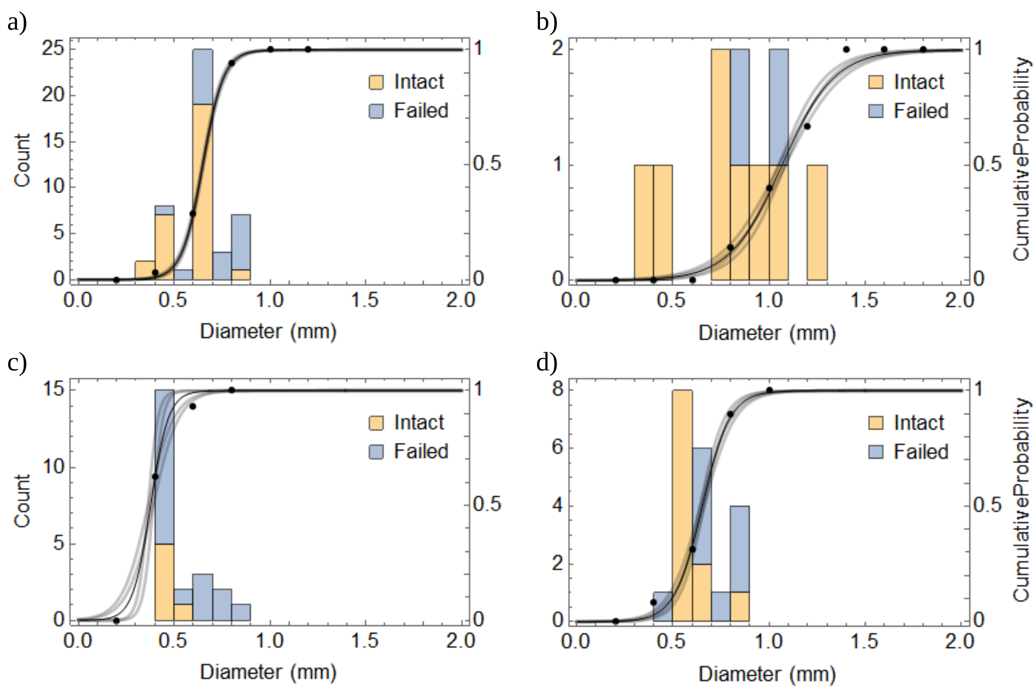

Figure 5. The ISS C&DH cable statistical analysis for 7 km/s impacts of spherical Al2017 a) at normal incidence and b) 45° to normal, and spherical SS440C c) at normal and d) 45° to normal. The plots show the cumulative count and probability of failure as a function of projectile diameter.

A total of twenty-five impact experiments using a 0.6 mm Al2017 at 7 km/s normal to the cable have been performed to understand the influence of the mounting system. Of these twenty-five impact experiments, nine of the experiments have been performed in a supported, hard-backed, configuration, and sixteen have been performed in an unsupported, suspended, configuration. Of the nine supported experiments, only one of the experiments resulted in a failed cable; whereas, of the sixteen unsupported experiments, five of the experiments resulted in a failed cable. As such, the probability of failing the cable is approximately three times higher for the unsupported cable as compared to the supported cable; although, implicit in this observation is the assumption that neither configuration experienced biased impact conditions (i.e. variance in impact speed and location is random over the set of experiments).

For the fifteen impact experiments using a 0.44 mm SS440C at 7 km/s normal to the cable, five supported experiments resulted in three failed cables. This failure rate is similar to the ten unsupported experiments with seven failed cables. As the mounting observations of steel didn't reverse the findings with aluminum, subsequent experiments focused on the unsupported cable configuration; however, the mounting architecture continued to be explored at lower resolution for other impact conditions.

As the motivation of this work has been to not only identify configuration dependence but to also develop probabilistic models for use in assessments, a model for the functional dependence of probability of failure based on particle size, material and obliquity has been developed. To this end, the cumulative failure count to a given particle diameter has been divided by the total cumulative survival count of experiments to arrive at a failure probability given by,

$$P_F = \frac{C}{C+S}, \quad (1)$$

where C and S are the cumulative count of failures from smallest particle bin to the largest and survivors from largest particle bin to the smallest, respectively. As the cumulative count of failure goes to zero for small particle diameters, this failure probability goes to zero for small particles. Similarly, the cumulative count of survivors goes to zero for large particle diameters; hence, the failure probability goes to unity for large particles.

This failure probability is also shown in Fig. 5 as the data points, and they correspond to the secondary ordinate. To model this failure probability, a nonlinear regression to a logistic function with the independent variable of diameter, d, has been performed. The failure probability, P_F, is given by:

$$P_F[d] = \frac{1}{Exp\left[-\left(\frac{d-\bar{d}}{\delta d}\right)\right]+1}. \quad (2)$$

The two fitting parameters are the diameter at 50% probability of failure, $\bar{d}$, and a diameter scale length, δd. The values for these coefficients for the two projectile materials and the two impact obliquities considered are given in Table I. The mean standard error for the coefficients based on the quality of fit is included with the best fit parameters. This model is also shown on Fig. 5 with the best fit curve and associated uncertainty estimates. As this model is a fit, it approaches the two limits of probability for small and large particles and never fully reaches them.

TABLE I. STATISTICAL MODEL COEFFICIENTS

Material	θ_i **(°)**	$\bar{d}$ **(mm)**	δd **(mm)**
Al2017	0	0.6494±0.0037	0.0546±0.0032
Al2017	45	1.067±0.017	0.135±0.015
SS440C	0	0.377±0.013	0.047±0.021
SS440C	45	0.652±0.010	0.0720±0.0088

As the normal aluminum impact experiments had a large data set, the uncertainty associated with the parameters are low; conversely, the smaller data set for the oblique aluminum impact experiments resulted in a larger model spread. Owing to the limits of the dataset, the normal impact steel and oblique aluminum models are extrapolated outside of the dataset, which results in additional systematic uncertainty.

CONCLUSIONS

The ISS C&DH cable runs are a significant presence on the exterior of the International Space Station (ISS), and as such, these components are affected by the external environments including MMOD. Moreover, as the cables are of a universal architecture, they have a broader presence in many other satellites and vehicles and are of a more general interest for other MMOD analyses. For these reasons, these 1553 cables have been studied in detail and summarized herein.

This work revisited some of the early reliability engineering assessments for the ISS C&DH cable runs. To this end, a total of ninety-seven impact experiments have been performed to develop a statistical model for future analysis of this component. Using the data that has been obtained thus far for the ISS program, this work has yielded cumulative distribution functions for these cables for steel and aluminum components of the orbital debris environment at a representative impact speed and obliquities for ISS operation. It has been found that while during the design phase a failure due to shorting occurred for a 0.4mm particle, a much more exhaustive look shows that more than a 50% larger particle is needed to achieve a 50% failure probability. This demonstrates that it is likely that the cables are more robust than was initially assumed during the vehicle design [5]. Additionally, it has been considered and found that an unsupported cable has a higher probability of failing than a supported cable, and as such, the majority of the obtained data from this study used that configuration. While the scope of the experimental work is significant and touched many areas of concern for the cable's continued operation, some impact conditions have been left unexplored. Most notable among the dataset insufficiencies is the lack of observations to check the impact speed dependence on the performance of the cable.

In spite of the large set of impact experiments, the breadth of variability in a cable and the many factors in the MMOD environment definition leaves room for further exploration. Among the possibilities are impact speed variation and extending impact obliquity assessments. Additionally, as it is likely that other impacting materials and shapes are needed for full reliability assessments, these parameters have received limited variation here and may need to be explored in more depth.

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