Using Commercial off-the-shelf (COTS) Fuses in Vacuum

Derrick A. Early[1]
Chesapeake Aerospace LLC, Manteo, North Carolina, 27954
and
Alexander Krimchansky[2]
NASA Goddard Spaceflight Center, Greenbelt, Maryland, 20771

I. Introduction

IN the summer of 2015 during thermal vacuum testing of the Geostationary Operational Environmental Satellite-R series (GOES-R) observatory, a heater circuit that was part of the ground support equipment in the vacuum chamber developed an electrical short. The current flow through the short melted and vaporized approximately a meter of 14 gauge polytetrafluoroethylene (PTFE) insulated twisted pair copper wire. The test event was treated as a mishap, and an independent team investigated the failure. The mishap investigation team found as a contributing root cause that the test set up lacked sufficient circuit protection, and for future testing of the next three GOES-R observatories, they recommended the use of fusing or circuit interruption to protect the heater circuit wires [1]. In response to this recommendation, the GOES-R flight project traded two fusing options. One option was to locate the fuses for the wires inside the vacuum chamber, and the other was to locate the fuses external to the chamber. To support fusing inside the vacuum chamber, developmental testing of Commercial off-the-shelf (COTS) fuses was initiated. Based on the heater circuit design, the testing focused on fusing 9 amps (A) at 250 volts direct current (VDC) in both soft, ~130 Pa (1 torr), and hard, < 30 mPa ($2 \cdot 10^{-4}$ torr), vacuum conditions. If the selected fuses do not open a shorted circuit, then the test heater wires could vaporize again and cause another contamination event. If the fuses open below the required 9 amps, then the spacecraft thermal vacuum testing campaign will be interrupted to open the chamber to replace test heater fuses.

[1] Mission Systems Engineer, MS 417.0, Goddard Spaceflight Center, Greenbelt, MD, 20771, derrick.a.early@nasa.gov.
[2] Systems Manager, MS 417.0, Goddard Spaceflight Center, Greenbelt, MD 20771, alexander.krimchansky@nasa.gov.

II.Fuse Selection

As a result of conversations with Mr. Jeff Montgomery of AEM, Inc., a supplier of GOES-R flight fuses [2], the project selected the Solar Protection Fuse (SPF) series by LittelFuse®. This fuse series has amperage ratings from 1 to 30 A, and a voltage rating of 1000 VDC [3]. To obtain the 1000 VDC rating, the fuse body is filled with silica sand. The silica sand arc suppression is an important feature, since air filled FM08 fuses can arc at 50 VDC or above when the internal pressure is between 130 to 200 Pa (1 to 1.5 torr) [3, 4].

III.Fuse Testing

In order to determine the feasibility of using COTS fuses in vacuum, a series of tests was conducted, and the tests are described below.

A. Do the fuses leak?

The fuses were not hermetically sealed, so they were expected to leak. If the fuses leaked slowly, the testing would require long wait periods while the fuses vented to vacuum. In prior testing [4], the fuse bodies were cut to allow the fuse body to vent more rapidly.

In order to determine if the fuses leak, gross leak testing of two SPF 10 amp fuses was conducted as described in MIL-STD-883K for a perfluorocarbon gross leak test [5]. For this gross leak test, the detector fluid used was Galden ® HT-90 with a boiling point of 90 C, and the indicator fluid was Galden ® DO-2 with a boiling point of 175 C. First, the fuse was placed in a beaker inside a vacuum chamber. After evacuating the chamber, the beaker was filled with the detector fluid and then the chamber was pressurized to four atmospheres at room temperature for four hours to drive the detector fluid into the part. The chamber was vented back to atmosphere, and the detector fluid filled beaker containing the fuse was removed. Immediately after removing the fuse from the beaker, the fuse was placed into a vat of the indicator fluid heated to 125 C, and a video was recorded of the detector vapor releasing from the fuse. Fig. 1 contains a frame from this video showing that the fuse has a steady stream of gas bubbles rising from both of its end caps. Both fuses failed the gross leak test; therefore, we assumed that the fuses were vented and that the internal pressure of the fuse was approximately equal to the chamber pressure.

Fig. 1 Littelfuse SPF 10 amp fuse gross leak test showing a steady stream of gas bubbles at the interface of the fuse body and metal caps.

B. Will the fuses clear in vacuum?

In order to test if the fuses would clear in a vacuum, the test set was wired as illustrated in Fig. 2. The power supply, PS, used was a Sorensen SGI250-120 capable of providing 250 VDC and 120 A. The resistive loads, R1 and R2, were a Megger Torkel 840 and 860 respectively. Both of the loads could handle the 250 VDC; however, at that voltage they could only carry 55 A. As a result, we used the two loads in parallel for the higher amperage test cases. The current probe, CP, was a Fluke i310s. The probe uses a Hall effect sensor allowing the measurement of current without breaking the circuit. The data recorder used was an Oros OR36 with a sample rate of up to 40 kHz. The switches, S1 through S6, were Siemens' HNF364 safety switches rated for 200 A and 600 V. Unfortunately, the switches were fairly large (76 cm high, 39 cm wide, and 16 cm deep); however, they were more cost effective compared to other options considered. In order to support the large switches, we had to fabricate a support structure consuming some lab floor space. Switch, S6, was used to verify the desired current was achieved prior to running the current through a fuse in vacuum.

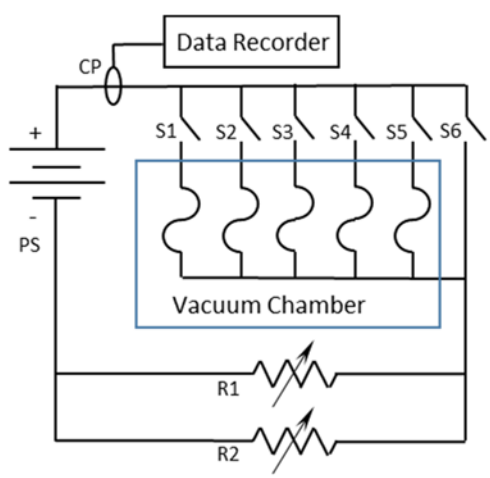

Fig. 2 Fuse test schematic.

Fig. 3 plots the results of the SPF 10 amp fuse testing for ambient pressure, soft, and hard vacuum conditions. The current ratio on the ordinate axis is the ratio of the applied current over the rated current of the fuse. The clear times in vacuum were typically shorter than at ambient pressure. Also under hard vacuum, the fuses cleared at currents lower than the rated current of the fuse. This is consistent with the 50% derating of fuses described in [6]. The five fuses for the point plotted to the right of 10^5 seconds survived 6 days at ambient pressure with the rated current of 10 amps. The dashed line in Fig. 3 shows the required 9 amps needed for the heater circuits. Since the SPF 10 amp fuses cleared below that line under a hard vacuum, the subsequent testing moved on to higher rated fuses.

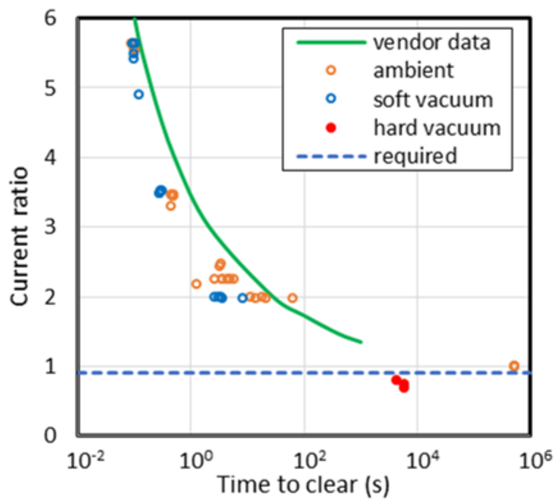

Fig. 3 Littelfuse SPF 10 amp fuse clearing times; comparing vendor data (green line) with ambient (orange circles), soft vacuum (blue circles), hard vacuum data (red dots), and the requirement (dashed line).

For longer duration testing, greater than 4 hours, the test set was rewired to place the fuses in series as illustrated in Fig. 4. This allowed for simultaneous testing of five fuses at a time with the same current flowing through each fuse. When one fuse failed, the test was terminated. This configuration was helpful, since all the fuses needed to pass the longer durations.

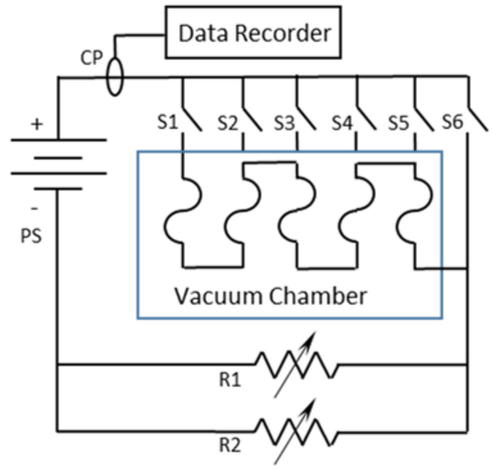

Fig. 4 Fuse test schematic with fuses in series.

Further testing on SPF 12, 15 and 20 amp fuses were conducted. Figs. 5 and 6 plot the results for the SPF 12 and 15 amp fuses. Both of these fuses failed to meet the requirement of 9 amps. Finally, the SPF 20 amp fuse did meet the test requirement by conducting 9 amps for 4.9 days under hard vacuum with elevated fuse body temperatures between 110 and 125 C. Anything longer than a day was considered a success. Therefore, the SPF 20 amp fuse met the 9 amp requirement, and the result is consistent with the 50% derating recommended in [6] for vacuum conditions.

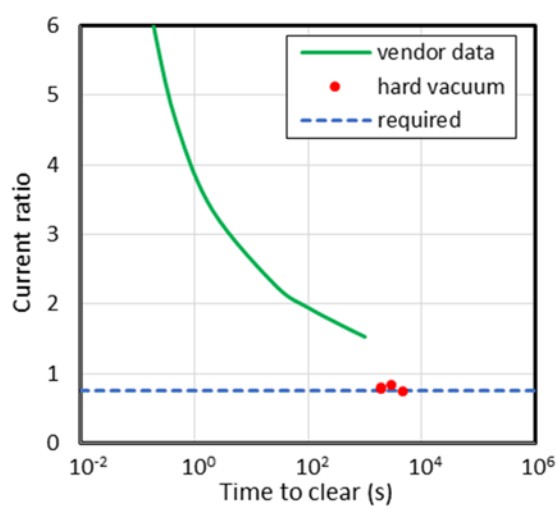

Fig. 5 Littelfuse SPF 12 amp fuse clearing times; comparing vendor data (green line) with hard vacuum data (red dots) and the requirement (dashed line).

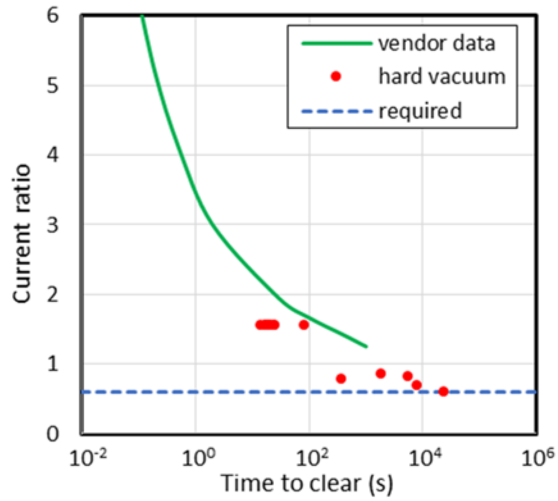

Fig. 6 Littelfuse SPF 15 amp fuse clearing times; comparing vendor data (green line) with hard vacuum data (red dots) and the requirement (dashed line).

C. Will the fuses arc in vacuum?

Since none of the testing below 60 amps indicated any sustained arc, the maximum current available was provided to the fuses by removing the loads R1 and R2 from the circuit as illustrated in Fig. 7. Figs. 8, and 9 plot the current traces for multiple fuses. The hard vacuum traces in Fig. 8 do not show any evidence of arcing; however, the soft vacuum, 16 to 19 mPa (1.2×10^{-4} to 1.4×10^{-4} torr), traces in Fig. 9 show that two fuses sustained an arc for about 1.8 ms.

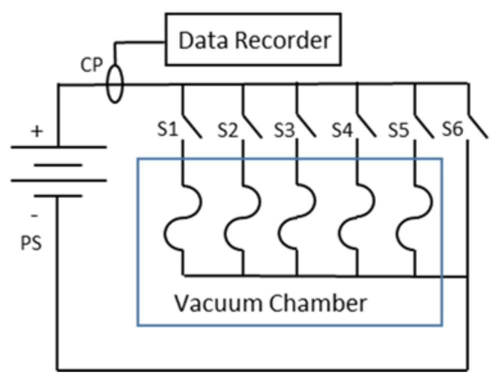

Fig. 7 Fuse test schematic for high current.

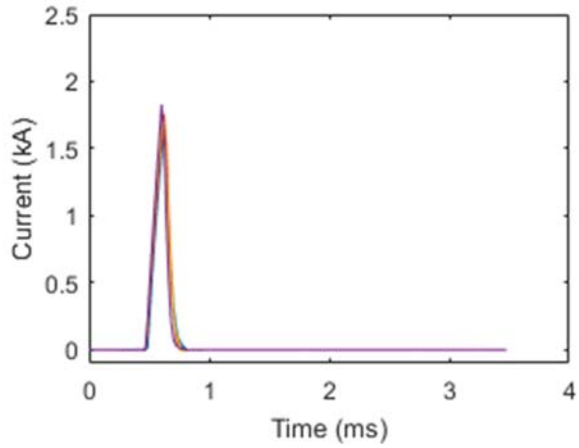

Fig. 8 Littelfuse SPF 15 amp; high current with hard vacuum; 5 fuses.

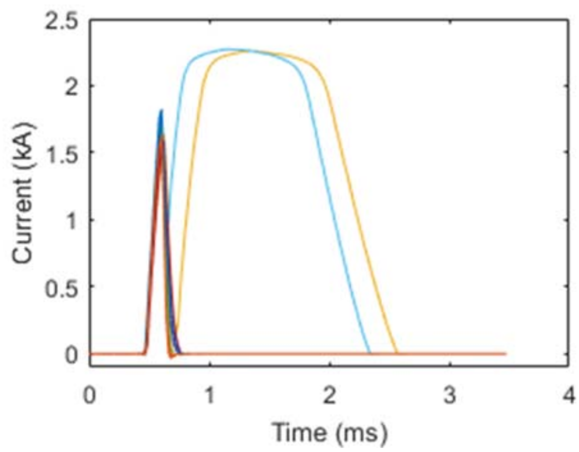

Fig. 9 Littelfuse SPF 15 amp; high current with soft vacuum; 8 fuses.

D. Do the fuses outgas when they clear?

In order to determine if the fuses outgas when they clear, the fuse block terminals were insulated with polyimide tape as shown in Fig. 10. Then aluminum foil was draped over the fuses as shown in Fig. 11. The mass of the foil prior to the test was 1.33926 g. After pulling a vacuum and clearing all five fuses, the mass of the foil was 1.33949, so the foil gained 230 µg of mass. A control test was performed without clearing the fuses, and the foil lost 10 µg of mass. The Fig. 7 schematic without the resistive loads was used for this gravimetric testing.

Fig. 10 Fuse block insulation.

Fig. 11 Aluminum foil draped over fuse block.

IV.Conclusion

Based on the testing reported here, commercial off the shelf fuses can be used for circuit protection in vacuum. In soft vacuum conditions with a pressure of 16 to 19 mPa, a short duration arc can be sustained for about 1.8 ms when a fuse carries high currents above 1 kA. While in vacuum, the fuses should be derated by 50% per [6], and they have some outgassing when they clear. When current flows through the fuse, the heat generated will require dissipation; otherwise, the fuse rating will be reduced further. Due to the outgassing, observed arcing, and lack of access to replace failed fuses during thermal vacuum testing, the project decided to locate the fuses external to the vacuum chamber for future test campaigns.

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