# Low Dose Failures of Hardened DC-DC Power Converters*

J. Lehman, C. Yui, B. G. Rax, T. F. Miyahira, M. Weideman, P. Schrock, G. M. Swift and A. H. Johnston
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

## I. Introduction

Box-level total dose testing of the FOG (Fiber Optic Gyro) by IXSEA at ESA's Gammabeam Facility were abruptly terminated at 8krad(Si) due to catastrophic failure (complete shutdown). This was unexpected because all components within the gyro were supposedly radiation tolerant. Further testing showed that the components responsible for the failure were two DC-DC converters, manufactured by Interpoint, that stopped regulating shortly before shutdown. The 28F/KR series of power converters are designed to be radiation hardened to levels of 100 krad(Si). This paper summarizes diagnostic test results for the converters to determine the underlying cause of the unexpected failure at low levels of radiation.

Power converter tests are difficult to interpret because the failure level depends on the conditions used for testing and electrical characterization. The specific load conditions that are applied during irradiation have little effect on converter degradation as long as bias voltages are applied and the converter is operating with a suitable heat sink. However, the voltage and load conditions have a large effect on how one defines failure for these devices when they are tested after irradiation. These converters can be used with input voltages from 16 to 40 volts. The first indication of degradation occurs when the converter can no longer regulate when low input voltages are used in combination with high load conditions. The interplay between loading conditions and the voltage required for failure is potentially confusing, and makes it difficult to compare results from different tests. However, our evaluation of the load dependence has shown that the failure level depends only on the total load, not the way that it is distributed between the two outputs on dual versions of the converter. Heating of the converter may also play a role in the failure level and recovery. Finally, the dose rate and type of irradiation (proton versus gamma ray) may also affect results (1).

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## II. Device Description

The 28F/28K devices are DC-DC dual output converters manufactured by Interpoint. These are hybrid devices, and they can be manufactured with different types of internal components which makes it more difficult to ensure that radiation test data actually applies to the specific parts used in an actual space program. Key design features of these devices are as follows:

1. They use a TCS4426 MOSFET driver that had been radiation tested as an individual component, but nevertheless is suspected to be the internal component that causes the converters to fail at levels well below the 100 krad(Si) level guaranteed by the manufacturer;
2. They use a special hardened optocoupler in order to improve their radiation hardness to proton damage; and
3. They also use hardened power MOSFETs in the output stage.

The samples were procured from the same lot used by the Genesis and Jason programs and the test conditions used to evaluate them were based on applications in those two spacecraft.

## III. Experimental Details

### *A. Overall Description*

A series of special tests was done on the converters, including proton testing, collimated X-ray testing of individual components in a working module, gamma ray irradiation at various dose rates, and interleaved irradiation and anneal cycles. Total dose irradiations were performed using the JPL cobalt-60 high and low dose rate facilities. The bias conditions during irradiation used a fixed load condition of 87% of maximum; 1.4A load on the positive output and 0.7A on the negative output, with an input voltage of 28V. Input and output voltages and currents were monitored throughout irradiation. Special heat sinks were attached to the modules to reduce heating and Pb-Al shields were used to eliminate low-energy scattered gamma rays. Proton testing was done at the University of California-Davis using the same procedures and comparable dose rates.

Prior to our testing, Interpoint identified the TSC4426 MOSFET as the likely internal component involved in the converter's failure from special probe tests of converters that no longer functioned after radiation testing. Figure 1 shows a photograph of the converter, along with the location of the MOSFET driver chip.

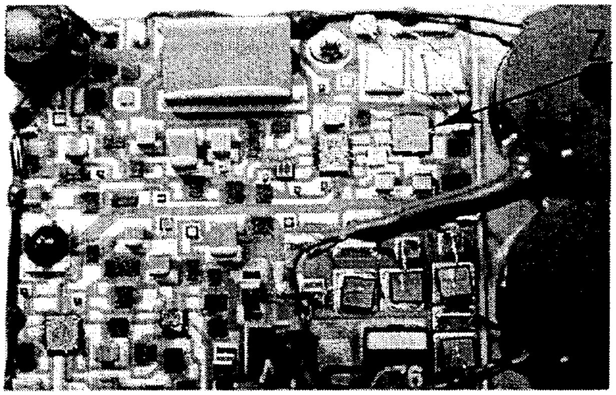

Figure 1: Interpoint DC-DC Power Converter. The arrow points to the location of the MOSFET driver.

Diagnostic tests done at JPL included tests with collimated 10-keV X-rays, which irradiated only the TSC4426 device within the converter, as well as cobalt-60 tests of individual TSC4426 MOSFET drivers from the same lot used in the converters.

Tests were also done on power converter hybrids to determine how the failure level depended on dose rate, load, and temperature. Annealing experiments were also done on some of the converters.

*B. Electrical Tests*

Two series of electrical tests were performed on the converters before and after irradiation:

1. Load Performance with Fixed Input Voltage
   Input voltage held at each of three voltages (16, 28, and 40V) while varying the positive load from 10 to 100% in combination with varying the negative load from 0 to 90%.
2. Input Voltage Ramp Test with Fixed Output Load Conditions
   Load conditions held at each of three currents (50%, 75%, and 100% with a "2/3", "1/3" split between the positive and negative outputs) while ramping the input voltage up and down between 16 to 40V.

The operational requirements of the converter can be understood by examining how the duty cycle of the converter depends on (Vin, Iload) conditions over the specified operating region. Various operating contours are shown in Figure 2. When the minimum input voltage increases because of radiation damage, the converter will no longer operate when the specific input voltage and load conditions exceed the minimum input voltage of degraded converters. Note the first radiation failure is expected at Vin=16V and Iload = 0.24A. Also note there is normally about 2V of hysteresis; that is, for a given load regulation will continue until the input voltage is about 2V lower (when ramping voltage down) than at the onset of regulation when ramping voltage up[4].

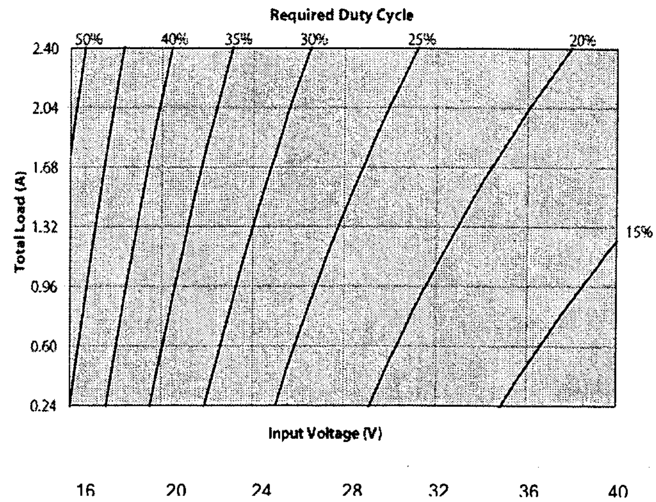


Figure 2: Duty Cycle Contours for the Converters

In many cases converters were subject to special conditions that varied from test to test in order to determine whether operational changes could compensate for the extreme radiation sensitivity. These included unbiased tests to a certain radiation level, followed by biased tests to higher levels; testing converters containing new lots TSC4426 MOSFET drivers; testing converters that had been "reworked" by the manufacturer prior to radiation testing with a different MOSFET driver, the TSC4429; and tests with collimated X-rays. Annealing tests were also done on several converters after irradiation. All tests confirmed the same failure mode and were consistent with each other.

## IV. Test Results

Eleven standard converters from the same lot were tested, along with several modified converters. The modified units included one with a new lot of the TSC4426 MOSFET driver, two containing unhardened optocouplers, and four where the TSC4426 was replaced with a TSC4429 MOSFET driver. The parts with the TSC4429 had been assembled with soft optocouplers. Results for the eleven standard converters are shown in Table 1. There is some indication that tests at low dose rate increased the radiation failure level slightly (perhaps as much as 20%), but the variability between units that were tested under common conditions does not allow any conclusive statement about the effects of dose rate on failure level.

Table 1. Test Results for the Eleven Standard Converters

| S/N | FAILURE DOSE (KRAD(SI)) | DOSE RATE (RAD(SI)/SEC) |
|---|---|---|
| 188 | 3.9 | 2.78 |
| 13 | 12 | 2.78 |
| 14 | 5.0 at 16V<br>5.6 at 28V<br>6.5 at 40V | 2.3<br>(63-MeV protons) |
| 1 | 5.0 at 16V<br>5.0 at 28V | 2.3<br>(63-MeV protons) |
| 23 | 5.0 | 2.78 |
| 9* | 5.2 | 2.78 |
| 33 | 9.4 | 2.78 |
| 35** | 6.3 | 0.0066 |
| 34** | 8.7 | 0.0066 |
| 10 | 5.0 at 16V<br>5.4 at 28V<br>6.2 at 40V | 2.78 |
| 31 | 5.9 at 16V<br>7.3 at 28V<br>7.7 at 40V | 2.78 |

*Unit 9is an SMHFDF/MR, all others converters are SMHF2805D/KR types.
**Devices 34 and 35were tested at 93% maximum load instead of an 87% load.

It was further determined that the low failure levels occurred because the TSC4426 was unable to provide the required pulse duty cycle after ionization damage. Typically the input current of the converter decreased slightly just before the output voltage started to exceed specification limits. Internal probe measurements showed that the output waveform of the MOSFET driver, after irradiation, became severely truncated and failed to follow the input waveform (inputs and outputs are complementary). Figure 3 shows an oscilloscope trace of a normal module. The waveforms depict the input and output of TSC4426 MOSFET driver. The first, third, and fifth peaks are inputs, the second and fourth are outputs. The operation of the converter requires a wider output pulse from the driver for low input voltage and high load conditions, and that is the condition where failures first occur.

Figure 4 shows the same waveforms for a converter on the threshold of failure (load condition 0.24 A). The trailing edge of the output waveform starts to collapse prematurely. At still higher radiation levels only very narrow spike occurs at the output and the converter is completely non-functional.

A MOSFET driver with a slightly different design, the TSC4429 does not exhibit the unusual failure mode of the TSC4426. Additional converters were obtained that used the TSC4429 rather than the TSC4426 (however, they contained unhardened optocouplers). When those converters were tested with gamma ray irradiation they continued to operate over all conditions at levels in excess of 50krad(Si). However, with proton irradiation, they failed below 10krad(Si) because of the soft optocoupler. Those results are summarized in Table 2. (No converters were available containing TSC4429 MOSFETs with hard optocouplers.)

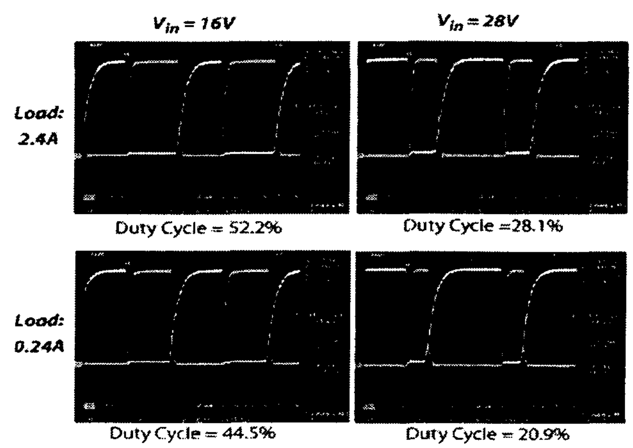


Figure 3. Internal Waveforms of a Normal DC-DC Power Converter.

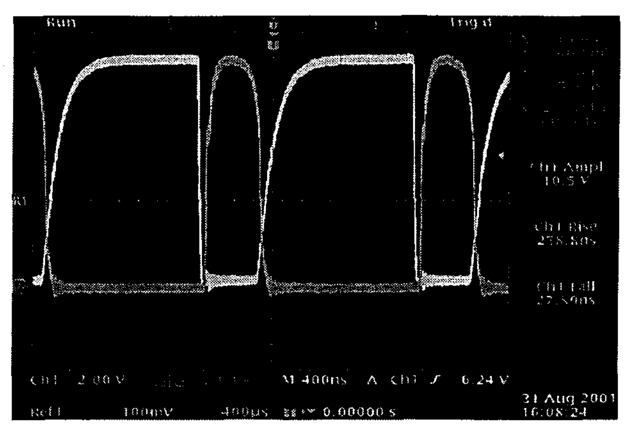


Figure 4. TSC4426 MOSFET Driver Input and Output Waveforms of a DC-DC Power Converter at the Onset of Failure.

Annealing did provide partial recovery when the converters were biased after radiation, both at room temperature and under heating with faster recovery seen after heating. Table 3 shows the annealing conditions along with the incremental total dose required for converter failure when the converters were subjected to an additional irradiation after annealing.

Table 2: DC-DC converters containing TSC4429 replacement MOSFET along with soft optocoupler. The soft optocoupler caused the devices to fail at much lower levels when they were irradiated with protons.

| S/N* | FAILURE DOSE [KRAD(SI)] | DOSE RATE (RAD(SI)/ SEC) | RADIATION SOURCE |
|---|---|---|---|
| 30 | 9.57 | 11 | 63-MeV Protons |
| 32 | >100 | 42 | Cobalt 60 gamma ray |
| 38 | 9.47 | 11 | 63-MeV Protons |
| 39 | 53.6 | 50 | Cobalt 60 gamma ray |

Table 3: Annealing Effects on DC-DC Converters

| S/N | Annealing Conditions | Hours Annealed | Post Anneal Failure Dose (krad(Si)) |
|---|---|---|---|
| 13 | RT | 118 | 2.0 |
| 23 | 60C | 336 | 6.4 |
| 9 | 60C | 336 | 7.0 |
| 10 | 100C | 211 | 5.2 |
| 35 | 65C during irradiation | n/a | n/a |
| 34 | 65C during irradiation | n/a | n/a |

## V. SUMMARY AND CONCLUSIONS

Several different radiation tests were done on the SMHF-series of Interpoint power converters to determine their failure characteristics, and to verify that the unexpected failures at low total dose levels were really due to radiation damage. For converters that were tested with Cobalt-60 gamma rays using normal heat sinking (an important detail), failures occurred at total dose levels between 3.9 and 12 krad(Si) for several different devices. The mean failure level under these conditions was 6.8 krad(Si). There is some indication that tests at lower dose rates -- 2 rad(Si)/m compared to 167 rad(Si)/m -- raises the failure level by about 20%. That is a very small difference considering the amount of time required to irradiate the devices under these conditions. It raises the distinct possibility that these devices may not anneal very much during actual conditions in space.

Proton tests of the entire converter with 63 MeV protons show a mean difference of about 30% between the mean failure level of converters that were tested with gamma rays. That difference is consistent with the expected difference in charge recombination for thick oxides, such as the field oxide of CMOS devices. However, the median energy of the proton spectrum for the Jason mission, a high-inclination earth orbiting mission at 1338 km, is about 120 MeV. Thus, there may be less difference between proton damage in the actual environment than observed in the laboratory tests at lower proton energy. It is also possible that degradation of other components within the converter may contribute to the failure mechanism. Diagnostic tests with 10-keV X-rays show that degradation of discrete transistors also affect converter operation.

Tests of the TSC4426 MOSFET drivers have shown that failure in the converters is the result of a very unusual failure mode in those CMOS devices that cannot be easily explained. This failure mode was not observed when TSC4426s was tested at the component level by a different radiation test laboratory and is only evident when specific tests are done on the TCS4426 devices that replicate the switching and load conditions within the power converters. The failure may be due to either gate threshold shift or field oxide leakage, and is strongly affected by temperature. Radiation test results and diagnostic tests of those components will be included in the final paper.

Finally, it should be noted that Interpoint was extremely helpful in providing converters for radiation testing, and no longer uses the TCS4426 driver circuits in their converters. The latest versions of their 28F/KR converters do not exhibit the unusual low dose failures that appear to have been caused by a very unusual response mode in the older TCS4426 MOSFET drivers.

## REFERENCES:


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(Routed to Susan for Ann)



To: Ann Bussone <Ann.K.Bussone@jpl.nasa.gov>, S Kayali <Sammy.A.Kayali@jpl.nasa.gov>
From: Scott Bowdan <Scott.E.Bowdan@jpl.nasa.gov>
Subject: Agreements
Cc: Linda J Worrel <Linda.J.Worrel@jpl.nasa.gov>, Mary O'Brien <Marysue.Obrien@jpl.nasa.gov>, David E Fulton <David.E.Fulton@jpl.nasa.gov>, Clarise A Okwach <Clarise.A.Okwach@jpl.nasa.gov>, Kathleen A Lynn <Kathleen.A.Lynn@jpl.nasa.gov>, susan.gray@caltech.edu
Bcc:
Attached:

Ann and Sammy,

I apologize for my delay in getting these notes to you about the agreements we reached in our meeting on Feb. 22.

We agreed to the following:

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- For limited distribution, clearance through Document Review is not required. However, the following requirements apply:
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