

Design and qualification of high-power optical interconnects for space applications

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ABSTRACT

This paper consolidates the design rationale, qualification sequence and high-power test evidence for a Mini AVIM® polarization-maintaining Power Solution (PM PS) optical interconnect intended for single-mode operation at 1550 nm in space applications. An initial trial with a standard Mini AVIM® mating adapter failed after only a few minutes at 4 W, +70 °C and approximately 10^{-5} mbar, producing a burned fibre end face. A second trial under the same conditions succeeded after conductive paste was applied, demonstrating that thermal conduction—not optical power alone—controlled interface survival in vacuum. This result motivated the PSt mating adapter, incorporating a rigid WC–Ni sleeve, a venting system and the established AVIM® anti-vibration architecture. The subsequent programme progressed through preliminary characterization, an extensive campaign according to ESCC 3420 chart F4 qualification and ended with high-power/high-temperature step stress, long-duration operation under high vacuum, and power-on thermal cycling. Long-duration exposures comprised 1,000 h at 6 W nominal and +75 °C and 500 h at 5 W nominal and +85 °C. The same specimens were then subjected to three 50-cycle campaigns between –55 °C and +85 °C at 3, 4 and 5 W optical power. No significant degradation of insertion loss, return loss or extinction ratio was observed. The evidence also supported the revision of ESCC 3420 Generic Issue 2 and Detail Issue 6 to include high-power burn-in, a dedicated thermal-vacuum subgroup, the PSt configuration and maximum-power ratings.

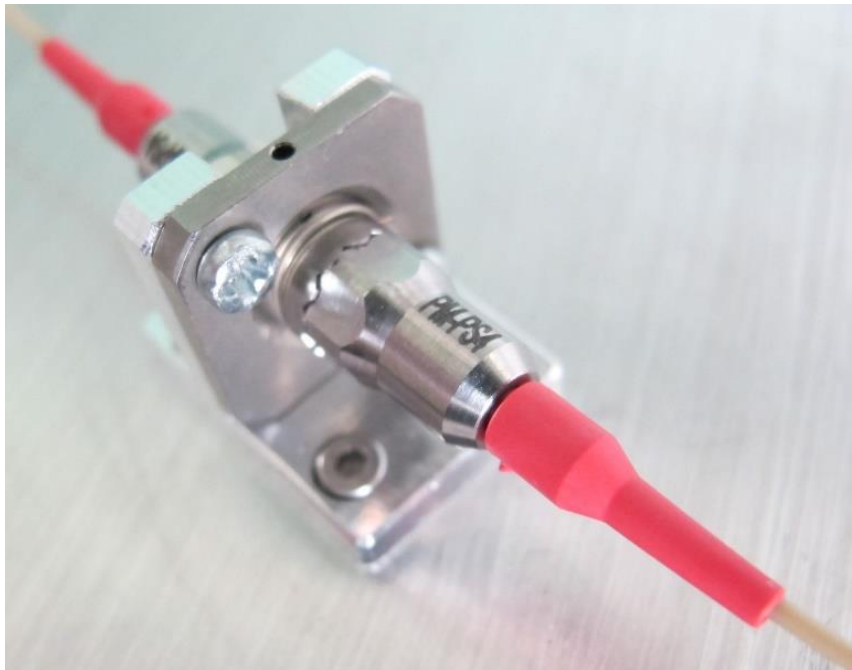


Figure 1. Mini AVIM® PM PS connection assembled with the Mini AVIM® PSt mating adapter and a dedicated fixing jig.
Source: Diamond SA internal

1. INTRODUCTION

High-power fibre-optic interconnects for terrestrial systems are normally able to reject heat generated in the optical interface through a combination of conduction and convection. Under the vacuum conditions relevant to space applications, convection is unavailable and the heat produced at an optical interface must instead be conducted through the ferrule, mating adapter, mounting structure and surrounding hardware. This change in boundary condition is central to the design problem addressed by the reported programme.

The Diamond PS product family was originally developed for high optical power under standard atmospheric conditions. The maximum rating for the established PS technology was up to +85 °C combined with maximum nominal operating power of 6 W. Increased demand for Mini AVIM® components for high power in vacuum applications created the need to verify performance outside that original operating context.

Earlier testing at approximately 10^{-5} mbar, +70 °C and 4 W showed that the original mating-adapter configuration did not provide sufficient heat dissipation. The first trial failed after only a few minutes and the fibre end face burned. A repeated trial under the same vacuum, temperature and output-power conditions succeeded after heat-conducting paste was applied to the connector body. The contrast isolated thermal transport as the decisive design variable: the optical interface could survive when a conductive path was provided, but the paste solution carried an unacceptable contamination concern for routine fibre-optic use.

The objective of the programme summarized here was to establish whether the Mini AVIM® PM PS connector and the purpose-developed PSt mating adapter could retain optical and geometric stability during combined high optical power, high and low temperature, and high-vacuum exposure.

2. INTERCONNECT ARCHITECTURE AND QUALIFICATION LOGIC

2.1 Failure-driven thermal redesign

The device used in the initial trials was identified as a Mini AVIM® PM-PS SM1550 APC 4° connector assembled with a standard Mini AVIM® mating adapter. At 4 W output, +70 °C and approximately 10^{-5} mbar, the first test produced a burned end face within minutes. Because the same configuration operated correctly after the addition of conductive paste, the failure was attributed to inadequate heat removal from the mated interface rather than to a general inability of the connector to transmit the power injected.

This comparison established the primary design requirement for the later adapter: heat generated at the fibre-ferrule interface had to be conducted through the adapter and mounting hardware without relying on convection and without introducing a paste close to the end faces. It also defined the logic for the later qualification programme, in which optical power, temperature, pressure, attenuation and physical end-face condition were treated as coupled variables.

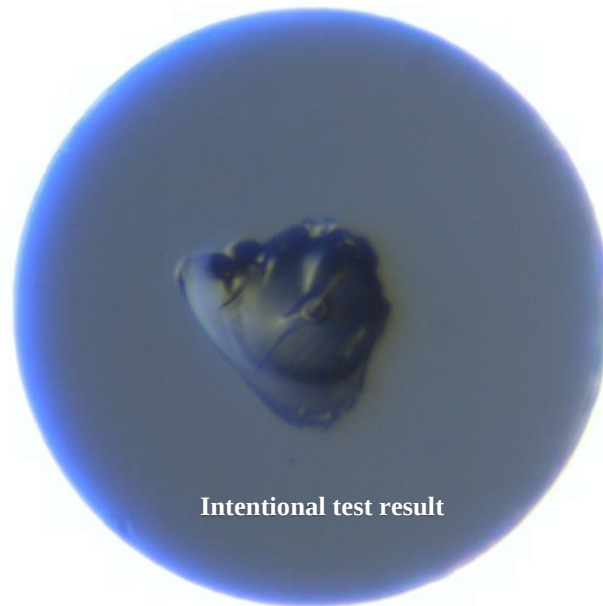


Figure 2. Burned fibre end face observed after the first trial with the standard Mini AVIM® mating adapter at 4 W, +70 °C and approximately 10^{-5} mbar. Source: Diamond SA internal

2.2 From PSm thermal conduction to the PSt space-oriented design

To evaluate alternatives to the thermal conductive paste, a mating adapter design that was considered is the PSm mating adapter in which the conventional floating ceramic sleeve is replaced with a direct ferrule seating hole in a metal block. Its more massive construction improved conduction between the ceramic ferrule and external components. Preliminary test showed promising results: 600+ hours at 6.5W and operating temperature of +75°C and 10^{-3} mbar without noticeable deterioration of the optical functionality. However, the PSm variant had been developed principally for multimode photonics applications and did not retain the standard AVIM® anti-vibration system, creating a limitation for demanding mechanical environments such in space applications.

The PSt mating adapter was developed to preserve the external geometry and anti-vibration features of the standard Mini AVIM® adapter while improving thermal and vacuum compatibility. The design uses a glued-in rigid WC–Ni sleeve with a venting system.

2.3 Five-phase programme

Table 1. Staged characterization and qualification programme reported in the supplied presentation.

Phase	Purpose	Reported outcome
1	Preliminary characterization: mating durability, temperature cycling and vibration.	Completed March 2024 with positive results on 50 samples; venting design updated.
2	Extensive climatic and mechanical characterization following the ESCC 3420 test plan (chart F4).	Completed July 2024 with positive results;
3	Step-stress increase of temperature up to +85 °C and optical power up to 6 W under vacuum.	Completed August/September 2024; operating combinations selected for long-duration tests.
4	Long-term high-power/high-temperature operation under high vacuum.	1,008 h at 6 W/+75 °C and 513 h at 5 W/+85 °C
5	High-power temperature cycling over the full test range under high vacuum.	Three campaigns of 50 cycles at 3, 4 and 5 W; 150 cycles total on the same samples.

Phase 2 included temperature cycling, high-temperature storage, random vibration, mechanical shock, fibre retention, fibre bending, fibre torsion and mating durability according to ESCC 3420 Generic framework (see para. 12.4 chart F4)



Figure 3. Mechanical test arrangement used during Phase 2 for random vibration and mechanical shock. Source: Diamond SA internal

3. EXPERIMENTAL METHOD

3.1 Device under test and optical chain

The high-power tests used Mini AVIM® PM-PS SM1550 APC 4° connectors. Two PM PS interfaces were assembled in series through two PSt mating adapters. Power was injected through the optical chain and measured at an output power meter. A downstream FC/APC PSf connection introduced a nominal 4% dissipation; the effective power at each Mini AVIM® connection was therefore calculated from the measured output power, the downstream dissipation and the measured attenuation of the individual interfaces.

Insertion loss (IL), return loss (RL) and extinction ratio (ER) were measured before and after the relevant test sequences. End-face geometry and visual condition were also examined, with the number of disconnect/reconnect operations kept to the minimum necessary. For the Phase 5 initial and final IL/RL measurements against a reference, a standard Mini AVIM® mating adapter rather than a PSt adapter was used as the reference interface.

3.2 Test methods and monitored quantities

The measurement and environmental methods used to structure the tests were: insertion-loss measurement by Method B according to IEC 61300-3-4; active attenuation monitoring according to IEC 61300-3-3; optical power handling according to IEC 61300-2-14; and dry-heat exposure according to IEC 61300-2-18. These methods were combined in a serial optical chain containing the two DUT interfaces inside the thermal-vacuum chamber, with the source and output power meter outside the controlled environment.

Insertion loss (IL), return loss (RL) and extinction ratio (ER) were measured before and after the relevant sequences. During powered exposure, attenuation was actively monitored through the output-power trace. Temperature and pressure were recorded by the chamber system. End-face geometry and visual condition were also examined, with the number of disconnect/reconnect operations kept to the minimum necessary.

Methods:

- Insertion loss measurement method B according to IEC 61300-3-4
- Active monitoring of attenuation according to IEC 61300-3-3
- Optical power handling test according to IEC 61300-2-14
- Dry heat test according to IEC 61300-2-18

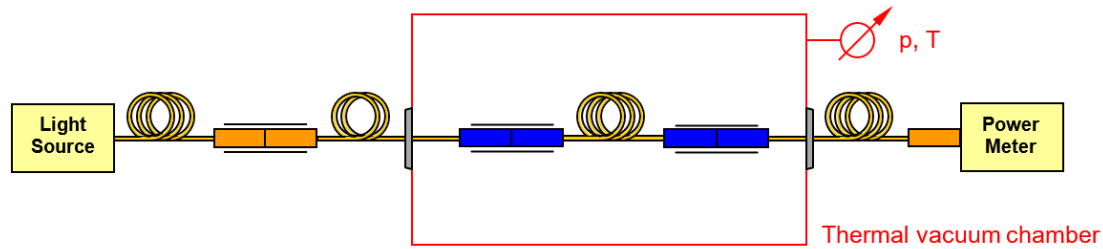


Figure 4. Optical-chain arrangement used for insertion-loss measurement, active attenuation monitoring, optical-power handling and dry-heat testing. Source: Diamond SA internal test report

3.3 Thermal-vacuum chamber and temperature instrumentation

The reported high-power campaigns were conducted in a Nanovac TVC590-650RC thermal-vacuum chamber with a nominal temperature range of $-70\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$, a nominal minimum vacuum level of 1×10^{-6} mbar over that range, a $50\text{ cm} \times 50\text{ cm}$ thermal plate and four type-K temperature sensors. The Phase 4 and Phase 5 campaign are performed at nominal test vacuum of 10^{-7} mbar.

The chamber control temperature was based on the average of two probes, TC1 and TC2, mounted on the two intermediate aluminium plates supporting the specimens. Two additional probes, TC3 and TC4, monitored the square flanges of the two PSt mating adapters. During the long-duration sequence, the difference between the two aluminium plates remained approximately $0.4\text{ }^{\circ}\text{C}$, while the difference between the plates and the adapter flanges remained generally below $1\text{--}1.5\text{ }^{\circ}\text{C}$. Within the spatial resolution of the surface measurements, this stability did not indicate a heat-dissipation bottleneck at the mounting plates or external adapter flange.

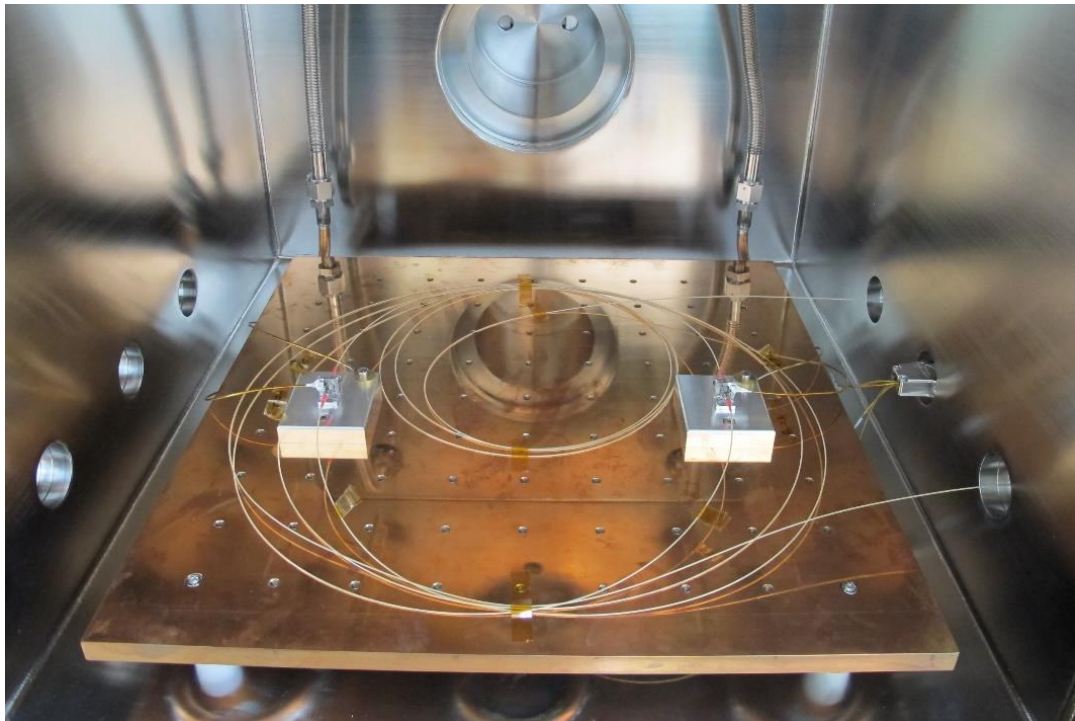


Figure 5. Thermal-vacuum chamber arrangement for the Phase 3–5 test sequences. Source: Diamond SA internal

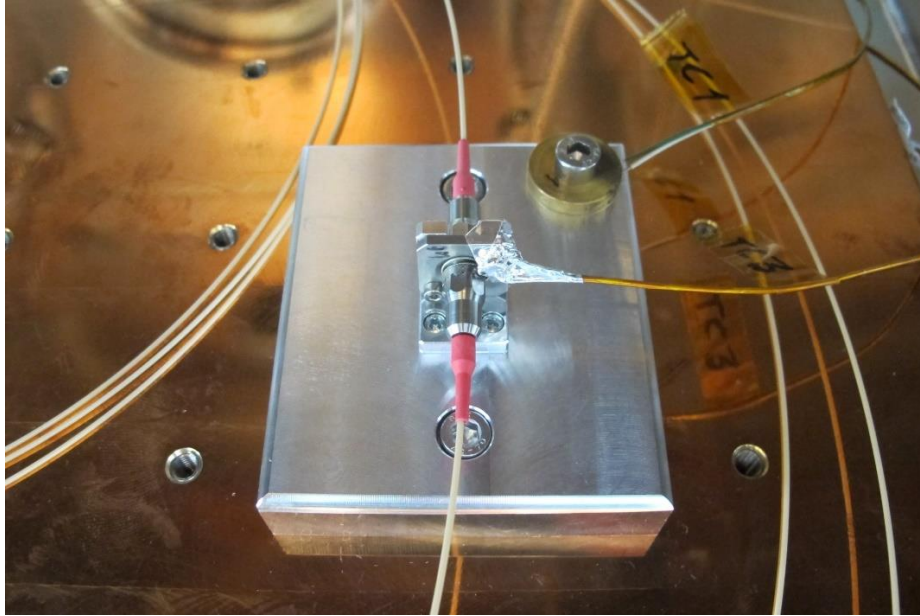


Figure 6. Detail of one PSt assembly mounted on an intermediate aluminium block, with a temperature sensor attached on the adapter flange. Source: Diamond SA internal

3.4 Stress profiles and monitoring criteria

Table 2. Quantitative stress conditions and effective connection powers extracted from the Diamond SA internal test reports.

Campaign	Nominal condition	Duration / cycles	Effective power: connection 1	Effective power: connection 2
Phase 4A	6 W; +75 °C, 10-7 mbar	1,008 h	6.95–7.12 W	6.53–6.69 W
Phase 4B	5 W; +85 °C, 10-7 mbar	513 h	5.82–5.89 W	5.47–5.54 W
Phase 5A	3 W; –55/+85 °C, 10-7 mbar	50 cycles; ≈350 h	≈3.3–3.5 W	≈3.1–3.3 W
Phase 5B	4 W; –55/+85 °C, 10-7 mbar	50 cycles; ≈350 h	≈4.4–4.6 W	≈4.2–4.4 W
Phase 5C	5 W; –55/+85 °C, 10-7 mbar	50 cycles; ≈350 h	≈5.6–5.8 W	≈5.3–5.5 W

For each Phase 5 campaign, the temperature profile extended from +85 °C to –55 °C, with a one-hour dwell at each extreme and heating and cooling ramps of 1 °C/min. Fifty cycles required approximately 350 h. Two preliminary sequences of five and four cycles at 3 W were used to verify the test setup; these preliminary cycles were not included in the detailed reported campaign results.

Continuous power monitoring served both as a performance trace and as protection against a developing interface failure. A reduction below the laser threshold could indicate an increase in attenuation caused, for example, by fibre recession. Such degradation can precede local burning and a self-propelled fibre-fuse event. This monitoring logic was therefore essential to limiting the consequences of a possible high-power interface failure.

4. RESULTS

4.1 Long-duration operation at the power and temperature limits

The first long-duration exposure operated for 1,008 h at a nominal 6 W output and +75 °C. The measured output power remained between 5.92 and 6.06 W, corresponding to effective power ranges of 6.95–7.12 W at connection 1 and 6.53–6.69 W at connection 2 after accounting for the downstream FC/APC PSf dissipation and interface attenuation. No anomalous optical behaviour was reported during the test or in the final measurements.

The second long-duration exposure targeted 5 W nominal and +85 °C and accumulated 513 h. Output power was 4.96–5.02 W, corresponding to effective powers of 5.82–5.89 W and 5.47–5.54 W at connections 1 and 2, respectively. The test stopped because a software malfunction in the laser-monitoring system triggered a laser shutdown. The DUT did not show anomalous behavior and didn't report any failure. Dismantling the chamber was nevertheless necessary to determine the cause and to perform the optical checks.

Across both long-duration exposures, the before/after IL, RL and ER results did not indicate significant degradation.

4.2 End-face and geometric observations

Visual inspection did not reveal tangible deterioration of the ferrule end-face quality. A slight flattening of the titanium insert at the ferrule face was observed after high-temperature exposure; a behavior identified as typical of earlier Diamond product characterizations. One Mini AVIM® PM PS connector changed from approximately 20 nm fibre protrusion to approximately 80 nm recession, corresponding to an approximately 100 nm shift.

The magnitude and timing of this isolated recession were not judged critical in light of the accumulated exposure and the stable optical results. The report proposes that this type of change likely occurs during the initial minutes or hours of exposure as the contacting interface reaches a geometric equilibrium. This interpretation is supported indirectly by the later cycling campaign: after the preceding high-temperature tests, only small variations around the established geometry were seen, with no systematic further fibre recession.

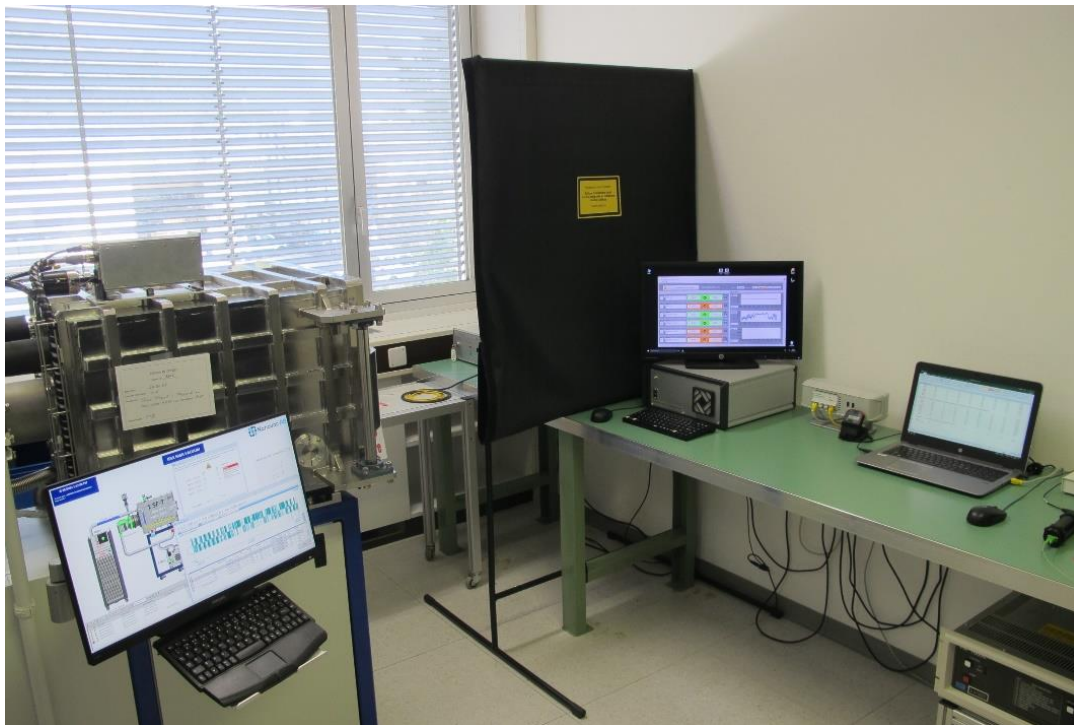


Figure 7. Complete test-equipment layout used to control the thermal-vacuum environment and monitor the optical chain.
Source: Diamond SA internal

4.3 High-power thermal cycling

The Phase 5 sequence applied 150 temperature cycles to the same interconnected samples already used in the preceding high-power and high-temperature phases. The three 50-cycle campaigns used nominal output powers of 3, 4 and 5 W. The measured output ranges were 2.89–3.05 W, 3.87–4.05 W and 4.88–5.09 W, respectively. Calculated effective powers at the two Mini AVIM® connections were consequently higher than the output-meter set points, as summarized in Table 2.

No anomalous behaviour was observed during any of the three campaigns. Final IL, RL and ER measurements showed no significant degradation relative to the initial measurements. The visual assessment did not identify tangible end-face degradation. A further slight tendency toward titanium-insert flattening remained visible after the high power and high temperature testing, but the fiber geometry exhibited small non-systematic variations rather than progressive recession, consistent with the specimens having already reached a mechanical equilibrium during the earlier exposures.

Within a representative sixteenth cycle from each campaign, the total IL variation over the two Mini AVIM® PM PS connections was approximately 0.2 dB and was similar at all three optical power levels. The larger change occurred between ambient temperature and $-55\text{ }^{\circ}\text{C}$; the chamber regulation produced temperature oscillations of approximately $5\text{ }^{\circ}\text{C}$ under high-vacuum and low-temperature conditions (Figure 8). Those variation directly affected the output power with variations about 0.01 dB that was considered negligible.

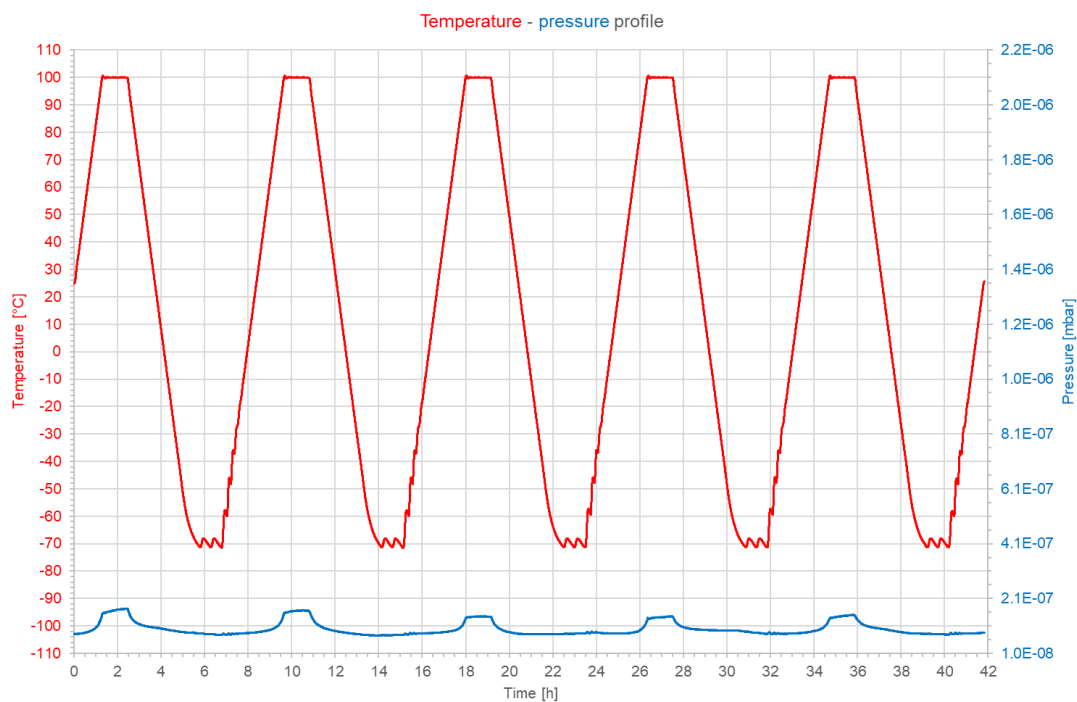


Figure 8. Representative chamber temperature and vacuum profiles for cycling with $1\text{ }^{\circ}\text{C}/\text{min}$ ramps. Source: Diamond SA internal

5. DISCUSSION

5.1 Demonstrated operating combinations

The available results support stable operation of the tested Mini AVIM® PM PS/PSt configuration at two limiting long-duration combinations: 6 W nominal with a maximum temperature of +75 °C, and 5 W nominal with a maximum temperature of +85 °C. They also support stable operation during repeated thermal excursions from –55 °C to +85 °C at nominal powers up to 5 W for the tested interfaces. In each case, the calculated power incident on the individual Mini AVIM® connections exceeded the output-meter nominal value, providing a modest margin relative to the stated set point.

The evidence should nevertheless be interpreted as configuration-specific. The effective powers depend on the attenuation of the two tested connections, reported at approximately 0.2 dB per connection during Phase 5. This is not necessarily representative of either a typical or a worst-case product: typical losses can be up to 0.4 dB and a 97% value up to 0.8 dB for the product family. Because absorbed power and local heating are coupled to interface loss, deployment limits cannot be separated from actual connection quality.

5.2 Maximum-power envelope derived from the test programme

The two successful long-duration conditions are used to create a temperature-dependent maximum-power envelope for the PM PS/PSt configuration: 6 W up to +75 °C and 5 W at +85 °C. This envelope support 6 W operation when the maximum temperature is limited to +75 °C and 5 W operation at the full +85 °C product-temperature limit.

The envelope must be interpreted together with the measured interface loss. The successful samples had connection attenuation around 0.2 dB. Consequently, the rating curve is a tested configuration envelope rather than a universal guarantee for every possible end-face condition, loss value or mounting arrangement.

5.3 Cumulative stress and absence of progressive degradation

The two detailed long-duration tests accumulated 1,521 h, and the three cycling campaigns added approximately 1,050 h. Thus, the documented Phase 4 and Phase 5 exposures alone represent approximately 2,571 h on the same connection chain, in addition to step-stress work and preliminary cycling. This cumulative use is important: Phase 5 was not performed on new specimens, but on interfaces that had already experienced the preceding high-power vacuum programme.

The lack of significant IL, RL or ER degradation after this sequence, together with the absence of systematic fibre recession during later cycling, indicates that the minor geometric changes did not develop into a progressive failure mode within the tested exposure. The stable differences between the mounting plates and the PSt flanges also support the intended conduction path at the external hardware level. The measurements cannot localize every internal thermal resistance, but they provide no surface-temperature evidence of a dominant bottleneck in the aluminium supports or flange region.

5.4 Controls and limitations

Several controls remain central to translating the test outcome into a flight-relevant operating envelope. First, the end faces must remain clean; the source material notes a greater tendency for particle formation with the PSt configuration and therefore a risk of early end-face degradation after reconnection. Second, the number of mating operations should remain controlled, as was done during the programme. Third, actual interface attenuation must be measured and included in thermal-power assessments rather than relying only on source output power.

Finally, the programme is a characterization of a specific connector, adapter, loss state, mounting arrangement and optical chain. The results do not by themselves establish universal limits for every PM PS connection or for the emerging PS+ technology. They do, however, provide a coherent experimental basis for defining application-specific derating, screening and monitoring rules.

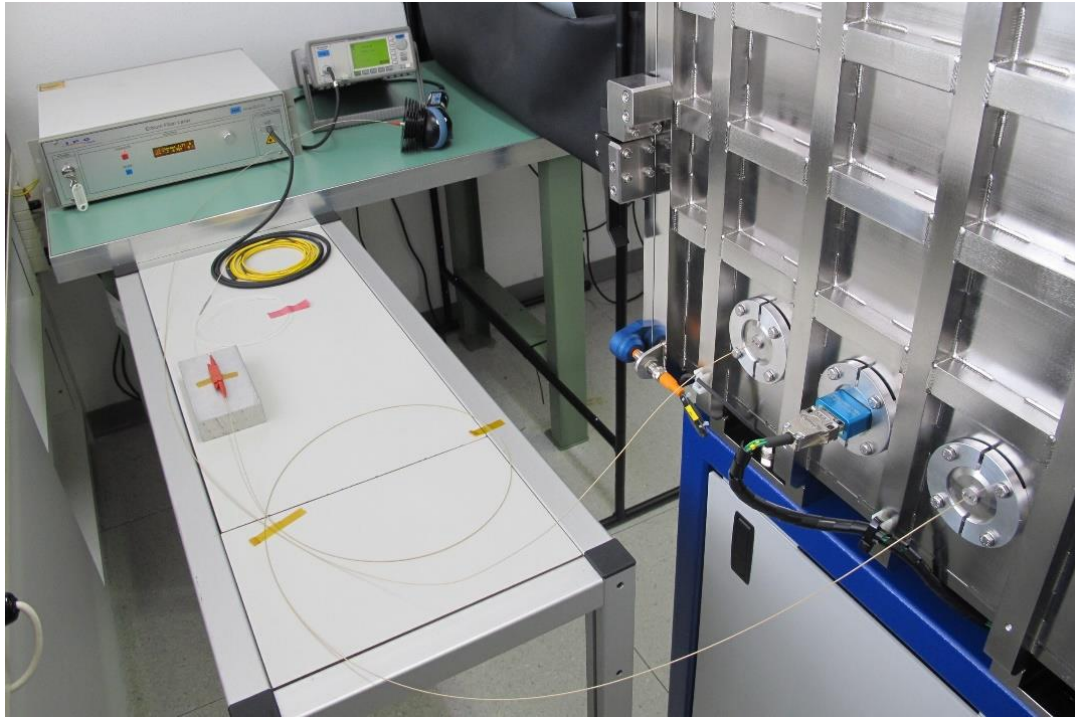


Figure 9. Optical equipment and fibre routing outside the thermal-vacuum chamber. Source: Diamond SA internal

6. TRANSLATION INTO THE ESCC 3420 FRAMEWORK

The evaluation program was used to formulate changes into ESCC 3420 Generic Issue 2, and ESCC 3420/001 Detail Issue 6 published in February 2026 for high-power space-grade variants

6.1 Proposed high-power burn-in for screening

The modification in the Generic Issue 2 screening includes a high-power burn-in to 100% of manufactured High Power Space Grade products (variant 07 only, paragraph 1.4.2 ESCC 3420 detail specification). The high-power burn-in specifies 30 min at nominal power, at room temperature, with optical end-face visual inspection before and after the powered exposure. The screening sequence also places initial and final parameter-drift measurements around the burn-in and repeats room-temperature optical and geometrical measurements after the final visual inspection.

6.2 Proposed high-power qualification subgroup

A dedicated high-power subgroup is proposed for the high-power qualification batch (variant 07 only, paragraph 1.4.2 ESCC 3420 detail specification). The programme comprises at least 500 h at each of two power levels, for a total of 1,000 h, at the maximum temperatures defined for the configuration in the Detail specification and at a pressure below 10^{-5} mbar. Insertion loss is monitored throughout the thermal-vacuum exposure. The proposed qualification flow identifies this activity as High-Power Thermal Vacuum, ESCC 3420 Generic issue 2 paragraph 8.19.

12.4 CHART F4 - QUALIFICATION, PERIODIC TESTING AND LOT VALIDATION TESTING

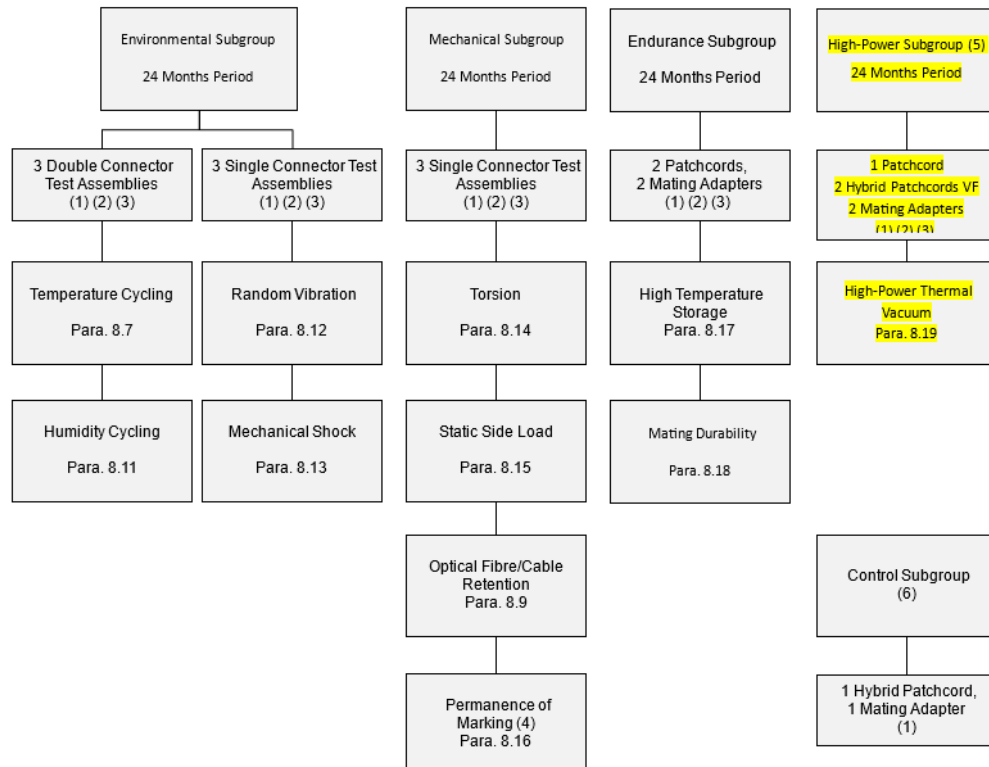


Figure 10. Proposed High-Power Subgroup within the ESCC 3420 Generic Issue 2 qualification flow, including the High-Power Thermal Vacuum test. Source: ESCC Generic Specification issue 6, Chart F4

6.3 Detail specification and approval status

The corresponding Detail Issue 6 adds the Mini AVIM® PSt configuration (variant 07, paragraph 1.4.2) and updates the maximum ratings based on the evaluation program. Formal implementation of the high-power solution in the ESCC 3420 was adopted in February 2026.

7. CONCLUSIONS

A purpose-developed Mini AVIM® PSt mating adapter enabled the established Mini AVIM® PM PS connector platform to be evaluated under the combined thermal, vacuum, optical-power and mechanical conditions relevant to space use. Its rigid WC–Ni sleeve, venting arrangement and retained anti-vibration architecture addressed limitations identified in earlier adapter concepts while preserving the Mini AVIM® form factor.

The staged programme converted an initial failure into a defined engineering solution. A standard adapter produced end-face burning within minutes at 4 W/+70 °C in vacuum; providing a conductive path prevented recurrence, and the PSt adapter then delivered stable long-duration and cycling performance without the contamination exposure associated with paste. The detailed evidence includes 1,008 h at 6 W/+75 °C, 513 h at 5 W/+85 °C, and 150 powered cycles between –55 °C and +85 °C at 3, 4 and 5 W. No significant degradation of IL, RL or ER and no tangible end-face damage were observed after the PSt campaigns. Minor insert flattening and an isolated approximately 100 nm fibre recession did not produce a measurable functional decline over the reported cumulative exposure.

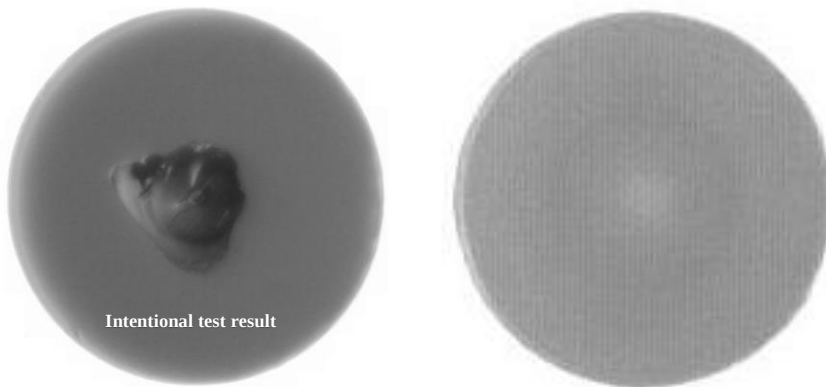


Figure 11. On the left: burned front face of a Mini-AVIM with standard mating interface within minutes at 4 W/+70°C in vacuum, on the right: front face of a Mini-AVIM after 2500h+ at high power and in vacuum condition mated with a PSt mating adapter.

For the tested samples and loss state, the results substantiate the suitability of the PM PS/PSt interconnect for demanding 1550 nm space-photonic applications within the evaluated combinations. Final application limits should remain tied to measured interface attenuation, cleanliness and reconnection control, verified thermal conduction, and robust power-monitoring and interlock behaviour.

REFERENCES

- [1] Diamond SA Testing Laboratory, Diamond SA internal report, “High optical power handling at high temperature in vacuum conditions”;
- [2] Diamond SA Testing Laboratory, Diamond SA internal report, “High optical power handling during temperature cycling in vacuum conditions”;