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Fibre Optics Evaluation Phase II

Rapid Depressurisation, Vibration, Shock & Thermal Vacuum Testing - Fibre Cable and Connectors

Results & Conclusions

Technical Note 3

Prepared for ESTEC

by Sira Electro-Optics Limited

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CONTENTS

1 INTRODUCTION

This final report concludes the present stage of work undertaken for ESTEC under Contract No. 12299/97/NL/SB(SC) - Identification and Evaluation of Fibre Optics Components – Phase 2. In addition to this final report, sub-titled Technical Note 3: Rapid Depressurisation, Vibration, Shock & Thermal Vacuum Testing – Fibre Cable and Connectors, reference should also be made to the following related documents:

- RD1 Basic Draft Specification (Issue 3) Single Mode Optical Fibre Cable for Use in Space; Environmental Test Procedures. A/1478/00/35, 15 April 2001
- RD2 TN1 – Test Equipment Design Requirements; Data Logging & General Test Facilities. A/1478/00/WP310/001, 5 July 1999.
- RD3 TN2 – Irradiation Test Measurement Results and Conclusions (Issue 3). A/1478/00/36, 16 April 2001

The basic draft specification (RD1) was prepared during the initial stage of a development process to produce a prototype simplex, single-mode, optical fibre cable with connectors, suitable for use in the general space environment and which could be produced by European manufacturers. The tests recommended in this document relate to what are considered to be the basic key environmental conditions.

After further consideration of the way in which actual mission components would be exposed to the space environment during and after launch, it was considered more sensible to leave thermal vacuum testing until last. Furthermore, for practical purposes, vibration (random and power sine) and shock tests were carried out sequentially for each orthogonal axis in turn. The test sequence proposed earlier (Basic Draft Specification – Issue 2) was therefore modified and reissued (RD1 - Basic Draft Specification – Issue 3). Tests were carried out in accordance with the specification unless otherwise reported herein.

Technical Note 1 (RD2) considered relevant standards and the technical literature to enable basic test procedures to be written and suitable test equipment defined. In order to select a suitable fibre, ^{60}Co and proton irradiation testing of selected bare fibres were proposed. Tests performed on associated optical fibre cable covered rapid depressurisation and thermal vacuum testing. Further tests were also proposed for fibre cable with space quality connectors attached; these covered rapid depressurisation, vibration and shock and thermal vacuum testing.

In Technical Note 2 (RD3) reports on the irradiation test measurements made on three commercial, acrylate-buffered, commercial single-mode optical fibres. Here it was concluded that European fibre 267E (code AA 19576G), produced by Plasma Optical Fibre BV, should be incorporated within a space-quality cable manufactured by W.L. Gore & Associates. This new 1.2 mm FLEX-LITE cable was subsequently manufactured under the product code FON 1019.

It was originally planned to include two forms of comparison test cable which incorporated SpecTran fibres; one using an acrylate buffer (similar to that used in the new Sira cable) and one with polyimide/carbon hermetic coatings. Due to problems of fibre breakage, it was necessary to limit comparison with the acrylate form only (see section 1.1).

Technical Note 3 reports on the environmental test work undertaken on the above new cable, together with existing cable manufactured by W.L.Gore which incorporated non-European SpecTran (Lucent) single-mode optical fibre (code FON 1010). Also reported are the results of tests on space quality, AVIM connectors, types D6206-1 and D6206-6 manufactured by Diamond SA, when fitted to the new FON 1019 cable.

1.1 MANUFACTURE OF GORE FLEX-LITE 1.2 MM SIMPLEX CABLE

W.L.Gore & Associates, the manufacturers of FLEX-LITE space-grade single-mode optical fibre cable, were supplied with single-mode fibre type 267E (trace no. AA19576G), manufactured by Plasma Optical Fibre, BV, being the one selected by Sira following an earlier irradiation test programme. Gore were requested to manufacture a new, 1.2 mm, space-grade, simplex cable, using the fibre provided, which they duly did under the new product code FON 1019. Sira were advised by Gore that performance of the new cable should be very similar to their existing range of 1.2 mm simplex products; in particular cable type FON 1010 which incorporates an acrylate-coated fibre manufactured by SpecTran. The performance specification for this fibre cable is reproduced in Appendix I.

With regard to the site of manufacture for the new cable, we were advised by Gore as follows:

> Because of the small number of applications requiring space-qualified components, Gore currently manufactures fiber optic products for space applications only at our plant in Newark, Delaware. At some point in the future, Gore can transfer the technology to manufacture ESA-qualified space fiber-optic products to our plant in Germany. However, current product volumes do not warrant multiple manufacturing sites. The Gore plant in Pleinfeld, Germany, is certainly capable of manufacturing these products, and we have transitioned similar products in the past from the U.S. to Europe to support the European market.

In addition to manufacture and purchase of the new cable, the present project also required purchase of two existing 1.2 mm simplex, single-mode fibre cables; i.e. FON 1010 with acrylate buffer, and type FON 1011 with polyimide and hermetic (carbon) coatings (although the latter cable could not be tested due to fibre failure – see section 1.3.3).

In connection with cable type FON 1011, it is of interest to note that catastrophic failure of polyimide-coated optical fibre cable, manufactured by SpecTran Speciality Optics, for use on the International Space Station (ISS) flight hardware, has also been reported by NASA [1]. The investigation which followed the report is believed to have concluded that the root cause of the defect was hydrofluoric acid etching. Furthermore, whilst the unprocessed fibre had high strength, process steps such as re-spooling appeared to weaken it.

The NASA procurement specification associated with the faulty optical fibre cable was SSQ 21654, “Cable, Single Fiber, Multimode, Space Quality, General Specification for” (Revision B, June 1996). It is maintained by McDonnell Douglas Space Systems Company in Huntington Beach, CA (now part of Boeing). Reference 1 identified ‘significant problems with the specification and indicated that it does not accurately describe the physical characteristics and performance of the cable that is being used and does not adequately define the qualification requirement’. The condition of the specification was not, however, considered to be a leading cause of the cable failure.

1.2 OPTICAL FIBRE CONNECTOR SUPPLY

Swiss company Diamond SA manufacture commercial, off-the-shelf, space-grade AVIM connectors for use with both single and multi-mode optical fibres. These connectors were described in an earlier report, being the subject of test work undertaken by L.J. McMurray, et al, for Goddard Space Flight NASA [2]. An AVIM connector (with protective end cap) coupled to the new FLEX-LITE FON 1019 cable is shown in Figure 1.2-1.

Figure 1.2-1 AVIM D-6206 Single Mode Connector

The commercial literature shows the appropriate connector form to be: AVIM D-6206.1 (see Product Sheet in Appendix II) where the fibre is housed within a robust tungsten carbide ferrule. A dynamic fibre centring process, known as 'active core alignment', is employed in conjunction with SPC end-face polish geometry, to produce repeatable low insertion loss. A MIL-style ratchet, keyed, connector system is used to produce high tolerance to vibration and shock. Connectors may be coupled together using an AVIM D-626 cleanable bulkhead adapter. By dismantling the two-piece adapter (external to the bulkhead) it is possible to access the fixed fibre connector end-face for cleaning purposes.

The performance specification for this form of connector shows an insertion loss of < 0.5dB (0.2 dB typ), and a return loss > 40 dB (50 dB typ). Vibration and shock test performance appear to be commensurate with present requirements. Cyclic operating temperature is given to be between –55°C and +125°C when using appropriate fibre cable. Whilst our present test specification has an upper limit of +150°C, we were advised by Diamond that it may be possible to operate up to this limit as it is believed that the limiting factor is related to performance of the epoxy used (EPO-TEK 353ND) which itself has a continuous operating temperature –50°C and +200°C. We note from the connector performance specification that temperature (and other) acceptance testing was in fact performed by Diamond's customer as part of a DoD Classified Space Program, where the test results were not available for distribution. As a consequence Diamond's otherwise standard Qualification Test Report was not available for AVIM connectors.

Whilst AVIM test connectors type D-6206.1 (tungsten-carbide ferrule) were initially ordered, Sira was informed, during subsequent discussions with Diamond, that a more recently developed version of the connector, type D-6206.6, may be more appropriate for use with the higher temperatures specified for the current tests. This new version of the connector employed a ferrule made from the ceramic zirconia, replacing the standard tungsten-carbide form, and had a slightly modified ferrule insert (see Appendix II). This form of the connector does not yet appear in the commercial literature as a standard item, being under evaluation at the present time.

As a result of the above discussions, Sira supplied Diamond with a sufficient length of Gore cable type FON 1019 with a request to supply eight fibre cable pigtails fitted with AVIM D-6206.6 connectors. In addition, four AVIM D-626 mating adapters were also required to form four complete connector sets. Each connector set was supplied by Diamond in the form of a single cable with a connector at each end (a cut at cable centre would then provide two pigtails). This form of supply was given to be the most appropriate for in-house testing prior to delivery. Unfortunately, a mistake by Diamond resulted in each cable being only four metres long, i.e. half of the correct length (4 m pigtails were specified). Whilst the component form supplied was sufficient to provide two sets of connectors with 4 m pigtails, it was necessary to ask Diamond to complete the original order with additional components. The result of this action was the provision of two additional sets of pigtails of the correct length; however the connector form supplied was type D-6206.1 (tungsten carbide ferrule) and not D-6206.1 (zirconia ferrule).

The outcome of the above was for Sira to undertake specified test measurements using two standard connector sets (DC1, DC2), type D-6206.1, and one special set (DC3), type D-6206.6.

1.3 NOTES RELATING TO TEST MEASUREMENT PROCEDURES

1.3.1 Cladding Mode Stripping

The initial test specification document indicated the need to include a facility for mode-stripping test optical fibres. This was to avoid any error due to measurement of power transported within the fibre cladding material in addition to the true single-mode component within the fibre core. In Technical Note 2 the conditions under which the use of cladding-mode stripping is important were given and justification made for the case of not using mode strippers where long lengths of test fibre were employed.

For some of the present test conditions relatively short lengths of fibre were to be employed and so further investigation into this topic was undertaken. As a first task the fibre manufacturer was asked for comments regarding mode stripping with the following response.

> In principle the fibre is required to operate as a single-mode fibre. This means that the fibre is designed such that only one mode is guided in the core. However to couple light into this one mode is very difficult so at the beginning of the fibre more modes (in the cladding) will be used. If the coating has no mode-stripping features, these modes will also be guided resulting in a multimode fibre. By choosing a coating with a higher refractive index than the cladding material we establish mode stripping at the cladding - coating boundary. By this means the cladding modes are taken out of the cladding, resulting in a single-mode fibre.

From the manufacturers response it appeared that test fibres using acrylate buffers automatically incorporated cladding mode stripping. Some tests were performed however to verify this assertion.

The doped core refractive index of both types of fibre employed was in the region of n = 1.467 (wavelength of 1310 nm); refractive index of the silica cladding was n = 1.447. Total internal reflection (TIR) at the core-cladding interface then dictates the limiting fibre numerical aperture (i.e. $NA = (ncore^2 - nclad^2)^{0.5} = 0.24$; where na = Sinθ, and θ = input cone semi-angle) for single mode operation. Use of an acrylate polymer cladding, with higher index n $\cong$ 1.49, prevents TIR at the cladding/buffer boundary such that normal boundary transmission and (very low) reflection occur governed by the Fresnel equations. Where the acrylate buffer is absent the outer index becomes unity and TIR can then occur for any rays travelling within the cladding medium at an angle greater than, or equal to, the critical angle (now defined by cladding and air refractive indices). Immersion of the bare fibre in an organic oil, with index n > 1.447, is expected to provide mode-stripping similar to that achieved by the acrylate buffer.

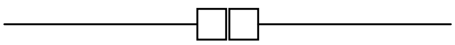
As a practical test case a 1 metre length of FON 1019 cable fibre was prepared, with one end cleaved and inserted into a mechanical splice allowing connection to the fibre-pigtailed, laser diode source. Cable jacket and strength member were then removed from a 15 cm section of fibre at the other end of the cable; 5 cm of acrylate buffer were also removed as usual prior to cleaving. This end of the cable could then be connected to a detector via a second mechanical splice leaving ~ 10 cm of exposed acrylate buffered fibre. The intermediate section of acrylate buffer was next immersed in liquid dichloromethane for a period of one minute, after which the surface was washed with water. Use of dichloromethane is a recommended method for the removal of acrylate buffer, which avoids the need for more aggressive mechanical stripping tools. After treatment the softened buffer may be removed using the fingernails. To act as mode stripper an organic oil, index ~ 1.46, was employed with immersion of the exposed fibre over at least a length of 5 cm.

Throughout the above test, transmitted optical power was monitored using the data-logger, however no change in signal level was apparent. The test was repeated using fibre cable type FON 1010 with the same result. The conclusion from this simple experiment was that for practical test purposes, adequate mode-stripping is provided by the standard acrylate fibre buffer. Therefore no additional mode-stripping techniques were employed during test work.

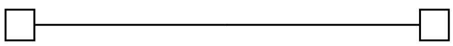
1.3.2 Connector Insertion Loss Measurement

The specification test document required connector pair insertion loss measurements to be made both before and after each test measurement. There are two methods generally proposed for this measurement, dependent upon the form of connectorised cable:

Case a) - the two fibre ends are accessible for attachment to source and detector



Case b) - the fibre ends are inaccessible



The method associated with case a) assumes that the initial length of unbroken fibre cable is available for attachment to light source and detector units after which a transmitted power, P_1, measurement is made. The cable is then broken and the connector set fitted, followed by a second transmitted power measurement, P_2. From these two power measurements insertion loss may be calculated.

Case a) is that associated with the present Sira test configuration, where fibre ends were connected to source and detector via mechanical splices. As it was not possible to attach connector to cable on site an attempt was made to measure insertion loss using a separate unbroken cable for the measurement of P_1. It was found however that the losses associated with each mechanical re-splice were too varied to allow sensible measurements to be made in this way.

Case b) is the situation adopted by the Diamond (see Figure 1.3-1) when measuring insertion loss. Insertion loss measurements made by Diamond on Sira cable fitted with type D-6206.6 connectors are reproduced in Appendix II, items 1 to 8. Using this method it is seen that maximum recorded insertion loss, at wavelength 1310 nm, was 0.2 dB

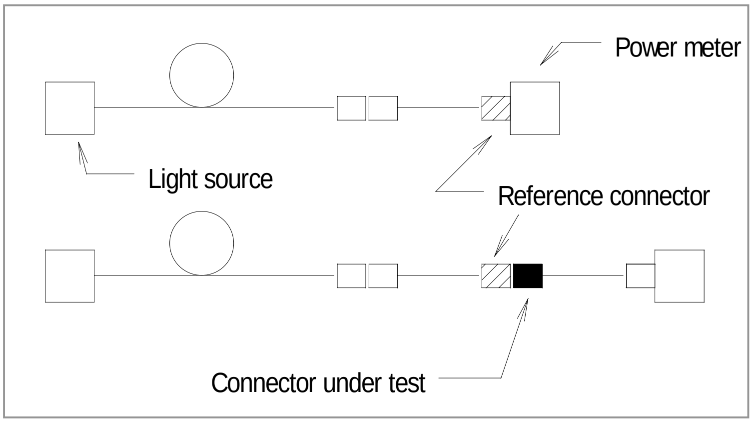


Figure 1.3-1 insertion loss measurement (Diamond SA)

1.3.3 Rapid depressurisation tests

This test was required to determine if exposure to a rapid fall in ambient pressure, from 1 atmosphere to ≤ 10 torr within a period of 5 seconds, affected optical fibre cable transmission. The test equipment employed is shown in Figure 1.3-2. Here a secondary vacuum chamber was connected to the main vacuum chamber via a flexible pipe. Test components could be

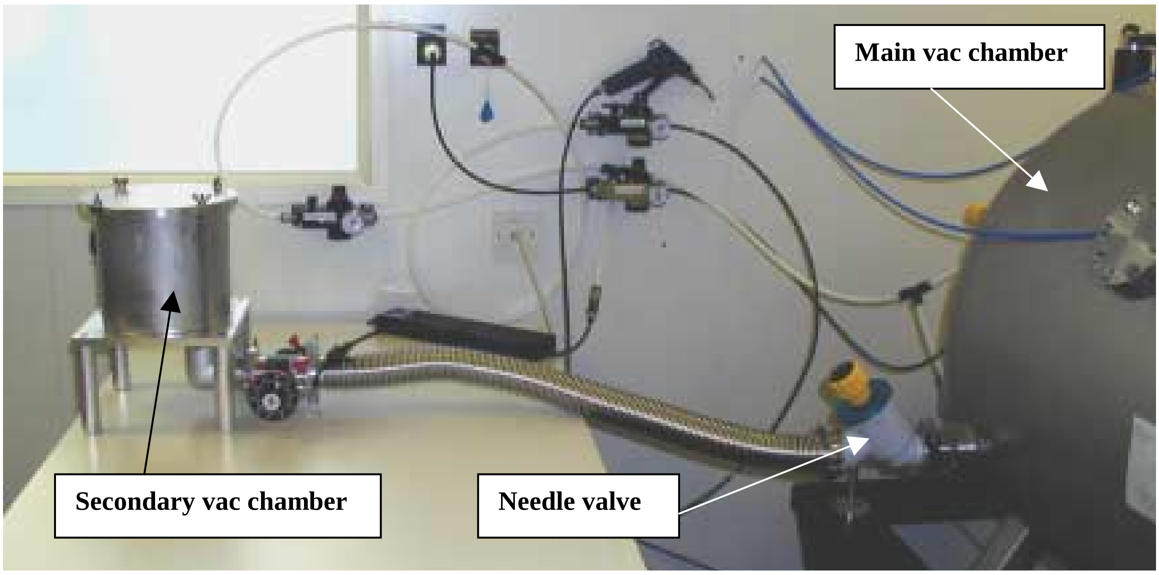


Figure 1.3-2 Rapid Depressurisation Test Set-Up

placed within the secondary chamber via the removable, O-ring-sealed, lid. The maximum volume, V_1, of the secondary chamber (and inter-connection) was determined by the final vacuum requirement, through the relationship, $P_1V_1=P_2V_2$, where V_2 was the combined main- and secondary-chamber volume. P_1 and P_2 represent the initial pressure within the main chamber and pressure after connecting main and secondary chambers respectively.

In order to connect test component fibre cables to the fibre transmission data-logger, the fibres were passed through holes within the lid of the secondary chamber, as shown in Figure 1.3-3. Vacuum sealing was achieved using a clear, flexible, silicone elastomer. An initial test of the vacuum seal was performed, using a short loop (few centimetres) of fibre sealed as described, with no effects upon transmission detected during test depressurisation.

Figure 1.3-3 Secondary Vac Chamber Fibre Feedthrough

The main vacuum chamber was initially pumped down from atmospheric pressure using a diffusion / turbo-molecular drag pump combination. Pressure within the main chamber was monitored using a dual Penning / Piranni gauge. After the desired vacuum was achieved the main chamber could be isolated from the vacuum pumps via an electronically controlled butterfly valve. Rapid depressurisation testing was performed by manually opening the needle valve, connecting the main and secondary chambers, over a period of 5 seconds. For these and other short duration tests the 1310 nm test source was operated in continuous mode and fibre transmission data was logged at intervals of ~ 0.27 sec.

When performing rapid depressurisation tests on fibre cable alone the approach adopted was to wind the required (214 m) length of cable onto a flexible cylindrical former made from metallised, Kapton (polyimide) sheet, thickness 150 μm, secured with adhesive coated Kapton tape, as shown in Figure 1.3-4.

Figure 1.3-4 Test Cable On Flexible Former

Figure 1.3-5 Mounting Base-Plate For Testing Optical Fibre Connectors

Whilst the cable winding procedure was in principle straightforward, a problem occurred when processing cable FON 1011 (SpecTran fibre with polyimide and hermetic coatings). A number of loops of fibre became separated from the Kapton former making it necessary to rewind part of the cable back onto its original spool, before reloading it back onto the Kapton cylinder. This process, although time consuming, appeared to be undertaken satisfactorily. However subsequent transmission tests prior to rapid depressurisation indicated that one or more fibre breakages had occurred as no signal transmission could be obtained. The test cable was subsequently checked by G.N.Nettest (formerly York Technology), using time-domain reflectometry equipment, where more than one break was apparent. The positions of these breaks could not, however, be detected satisfactorily. We were therefore forced to abandon further test work using this cable type (it will also be remembered that polyimide-coated fibre breakage occurred during a winding stage in preparation for ^{60}Co irradiation tests).

In addition to rapid depressurisation testing of fibre cable, the same tests were also performed on fibre cables coupled using connectors manufactured by Diamond SA. Here a connector mounting-plate was employed, seated on a raised base as shown in Figure 1.3-5, to which three detachable mating adapters were fitted. After attaching the fibre connectors, fibre pigtails were routed via vacuum feed-through seals as before. Care was taken to avoid micro-bend loss effects by maximising cable bend radii. During initial testing it was seen to be important to attach connectors using the recommended torque values. Figure 1.3-6 shows a typical response when connectors were secured using 'finger pressure' only.

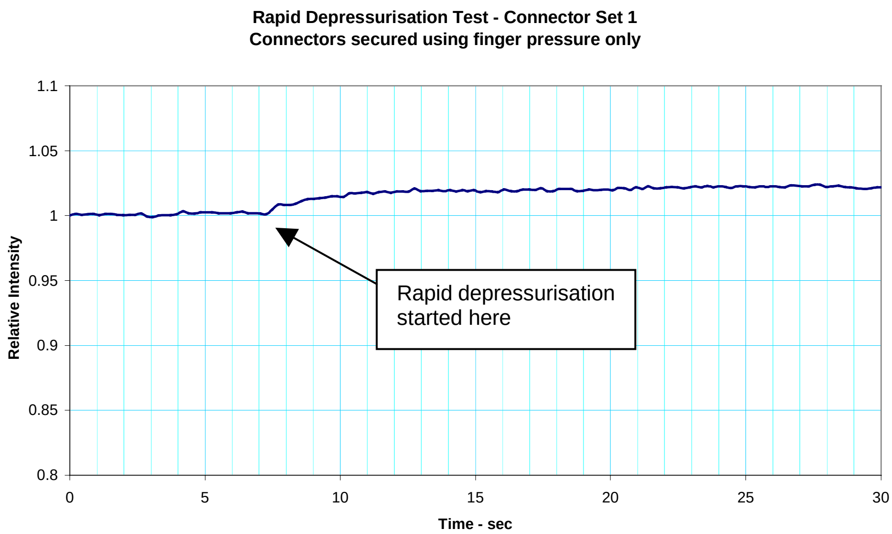


Figure 1.3-6 Rapid Depressurisation - Incorrect Connector Torque Settings

1.4 VIBRATION AND SHOCK TESTS

Sinusoidal and random vibration, and shock tests, were performed on connectorised cable with the vibration/shock axis along each of three orthogonal axes. Sira's computer controlled vibrator (shaker) test system employed is shown in Figure 1.4-1, with vibration axis vertical.

Figure 1.4-1 Sira Vibrator System

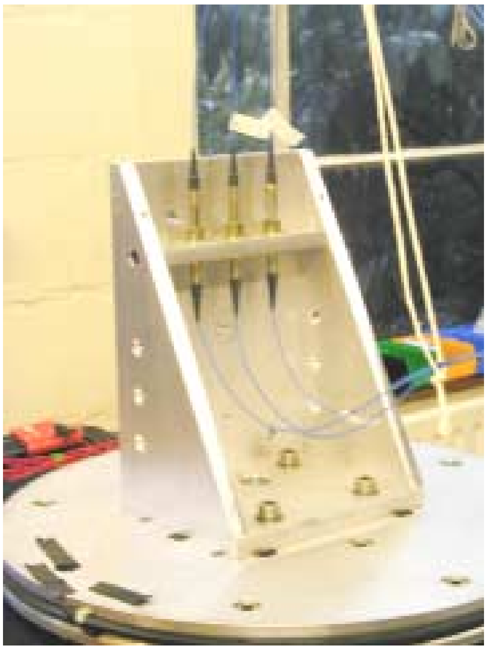


Figure 1.4-2 Connector Mounting Arrangement

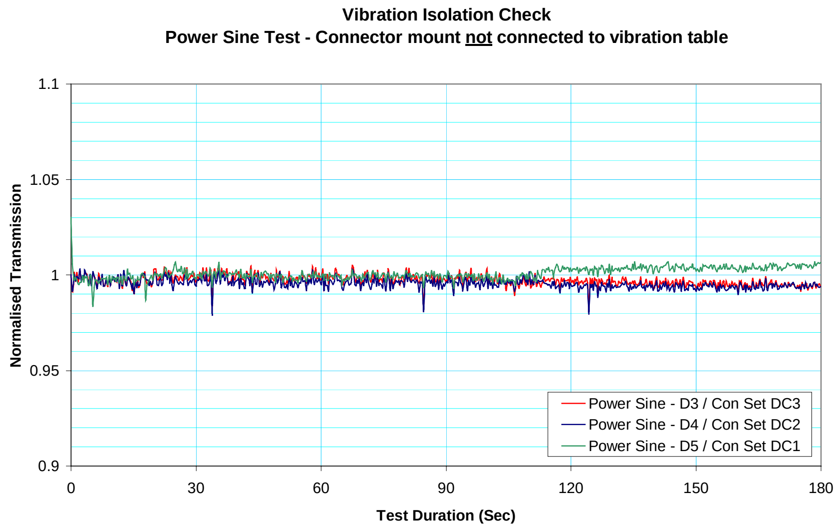
The fibre connector base plate described earlier was again used on which was mounted the three detachable mating adapters as supplied by Diamond. This base-plate was mounted rigidly to a triangular frame, as detailed in Figure 1.4-2, which in turn was rigidly mounted to the shaker platform with the prescribed torque setting (10 Nm). A torque wrench was also used when securing connectors to their mounting adaptor (0.3 Nm) and also when assembling the demountable mating adaptor components (1.0 Nm). Accelerometers were mounted upon the shaker platform for control and measurement purposes.

The vibration axis designated for the arrangement shown in Figure 1.4-2 (small rectangular face mounting) was the Z-axis. Vibration along the orthogonal X-axis was achieved by attaching the large rectangular face of the triangular frame to the shaker base-plate. In order to vibration test along the final Y-axis, the basic Z-axis configuration was employed with the fibre connector base plate attached to the triangular frame at 90 degrees to that shown. In this case the fibre cables passed through holes within the triangular frame wall.

The test sequence for power sine and random vibration was to commence transmission data-logging just prior to starting the vibrator sequence which had a duration of 2.5 minutes. In the case of shock testing the data-logger was first started, after which 5 pre-shocks were employed to establish the correct vibration control profile, followed by the 3 specified test shocks with 1 second intervals.

For each test case, fibres were supported flexibly using overhead lines such that no unintentional vibration effects were transferred during the test sequences. In addition anti-vibration measures were employed to isolate the fibre transmission data-logger from the laboratory bench and floor. Additional acoustic shielding was also employed to isolate the data-logger from air-borne vibration.

The data given in Figure 1.4-3 show the results obtained when the test was performed with connectors disconnected from the vibration assembly (i.e. the triangular frame with connectors attached was supported by laboratory personnel). From these data it would appear that the isolation achieved was satisfactory.



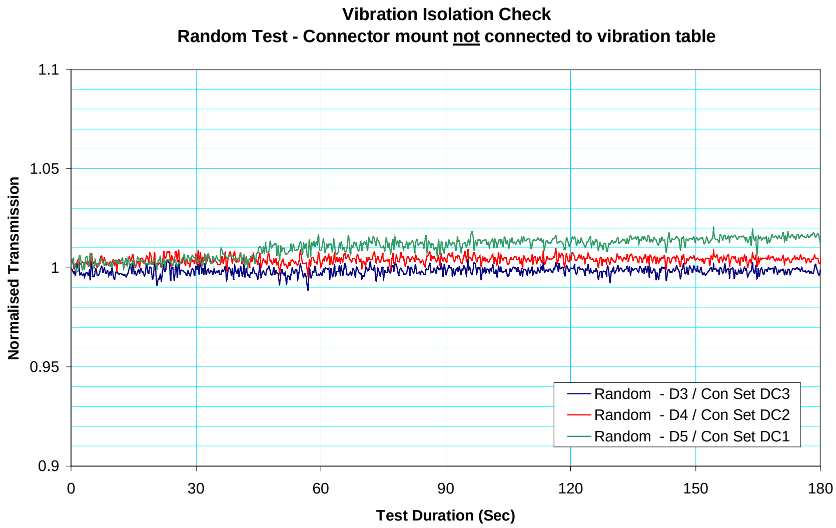


Figure 1.4-3 Vibration Isolation Testing

1.5 THERMAL VACUUM TESTS

Thermal vacuum testing was performed on optical fibre cables and on short lengths of cable joined using cable connectors and mating adapter. Test components were exposed to cyclical variation in temperature over the range –50°C to +150°C and an initial vacuum pressure of ~10^{-5} torr. The general thermal vacuum test facility is shown in Figure 1.5-1 below.

Figure 1.5-1 Thermal vacuum test facility

1.5.1 Thermal control system

When using the original Sira thermal control system, heating and cooling of the thermal-vacuum chamber was achieved solely through the use of a temperature-controlled, silicone-based, thermal fluid which circulated around the test system. An external heat-exchange mechanism was employed to pump fluid into, and out of, the vacuum chamber system via sealed copper tubing. Within the chamber a looped tube configuration was welded to an aluminium base-plate which was in close contact with the test piece. Thermal fluid was also passed around enclosing shroud and door spaces. Using the original system, temperature control over the range ~ –50°C to ~ +70°C could be achieved. For the present tests, however, it was a requirement to achieve a thermal range covering –50°C to +150°C, which was not possible using the thermal fluid alone.

For the present test work, thermal fluid flowed within a network of tubing located on the inner face of an aluminium fibre-cable support cylinder (see Figure 1.5-4), similar to the original test facility. In addition a number of symmetrically positioned resistive elements were also employed (with heating effect proportional to I^2R, where I is current and R resistance) to provide heating over the range +70°C to +150°C.

In order to measure temperature of the test component for control purposes, a standard two-wire platinum resistance thermometer (PRT) was connected to the aluminium support cylinder, using thermally conducting vacuum grade epoxy. A second, calibrated, 4-wire, PRT was also similarly attached. Output from the calibrated PRT was connected to the fibre component optical transmission data-logger to enable simultaneous optical transmission / system temperature measurements to be made.

Whilst it initially appeared straight-forward to undertake the modifications required to the existing thermal control hardware and computer software (Eurotherm IPS), it was subsequently found that significant modifications were actually required in order to achieve the desired thermal control profile. In the final version a dual loop control system was employed as follows. During the heating phase of each cycle, thermal fluid passed only through the chamber shroud and door spaces, its temperature being raised to a maximum of 70°C at 0.9°C min^{-1}. Within the test chamber only resistive heating was employed to raise the temperature to the maximum required value (+150°C or +85°C) again at 0.9°C min^{-1} (use of thermal fluid within the high temperature region causes liquid cavitation effects leading to rapid pump failure). Maximum temperature was maintained for 30 minutes after which time all resistive heating was removed and the test component allowed to cool by conductive and radiative effects only (controlled cooling via the thermal fluid not being possible in this region). When the test system temperature had fallen to +70°C thermal fluid was then allowed into the test chamber; simultaneously, controlled fluid cooling commenced to take the complete test chamber temperature down to the minimum required value (–50°C). Thirty minutes after the minimum set temperature had been reached the control valve was closed to prevent further fluid flow around the test piece during the subsequent 'resistive-heating' phase of the new cycle.

It can be seen from Figure 1.5-2 that maximum and minimum temperatures recorded were generally slightly in excess (e.g. ~ +160°C and ~ –56°C) of the specified requirements.

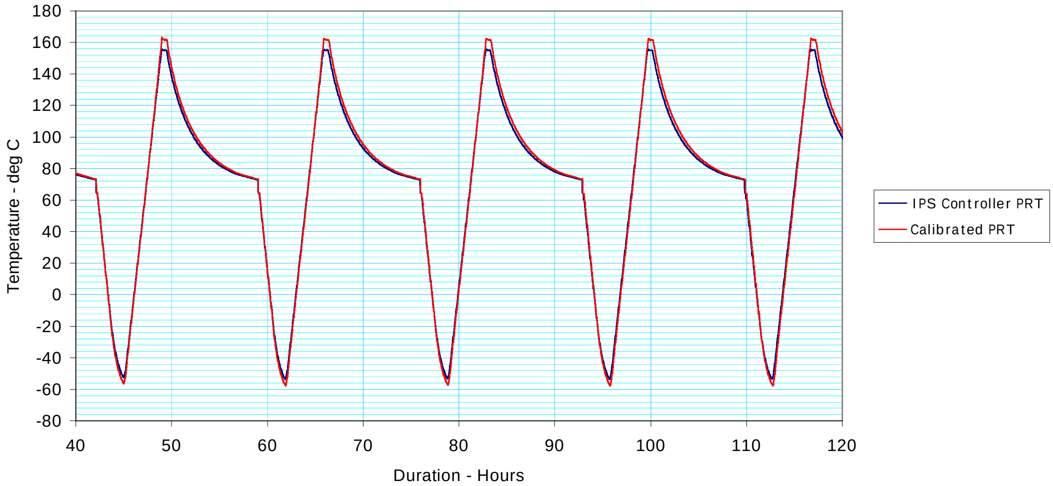


Figure 1.5-2 Typical thermal control cycles

Fibre cables were passed into, and out of, the vacuum chamber via holes located within a removable flange plate, as shown in Figure 1.5-3. As in the case of rapid-depressurisation measurement vacuum sealing was achieved using a clear, flexible, silicone elastomer. In the test specification document it was suggested that the protective cable layers be removed before passing the fibre through the vacuum feed-through. During preliminary tests however the very high probability of fibre breakage at this interface made it necessary to consider passing the complete cable. As no deleterious effects could be found, either upon fibre transmission or vacuum level, this was the approach adopted.

As an additional precaution, to avoid any thermally induced effects at the vacuum feed-through interface, the flange plate was held nominally at ambient temperature. This was done by incorporating cooling channels within the plate, to allow mains supply water to be passed continuously through it (without direct fibre contact). Transmission tests performed using a small loop of fibre cable at the vacuum feed-through did not, as expected, show any signal modulation (due to the interface) throughout the test temperature range.

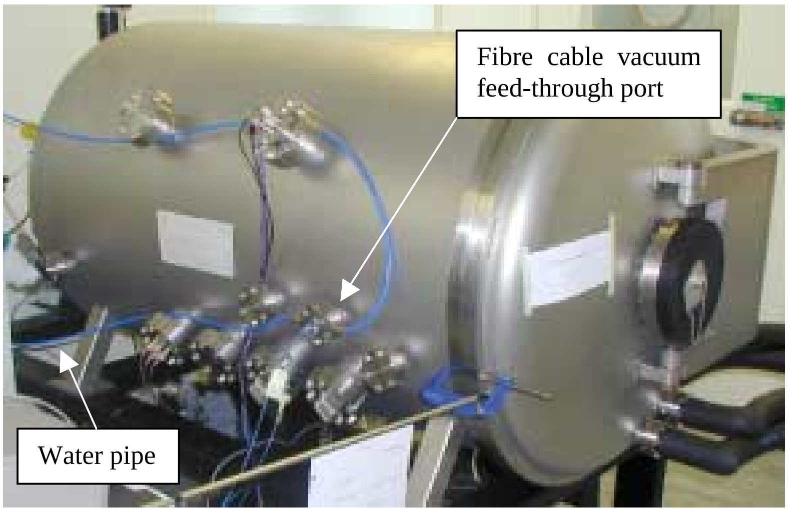


Figure 1.5-3 Sira's thermal-vacuum chamber, showing fibre feed-through vacuum seal

1.5.2 Optical fibre cable – thermal vacuum cycling

Thermal vacuum testing was performed on two 200 m lengths of, acrylate buffered, optical fibre cable (cable types FON 1019 and FON 1010). As discussed earlier, the cable incorporating polyimide coated fibre was unavailable for testing. Both test cables were wound simultaneously upon a rigid aluminium cylinder, with length 250 mm and external diameter 130 mm, as shown in Figure 1.5-4. Using this arrangement the cable winding depth was approximately 5 layers. In order to ensure optimum contact between cable and cylindrical support surface, whilst avoiding introduction of cable stress due to cylinder expansion at high temperatures, cable winding was undertaken using a predetermined thickness of removable shims.

The position of the cylindrical fibre cable test support when mounted within the vacuum chamber is shown in Figure 1.5-5.

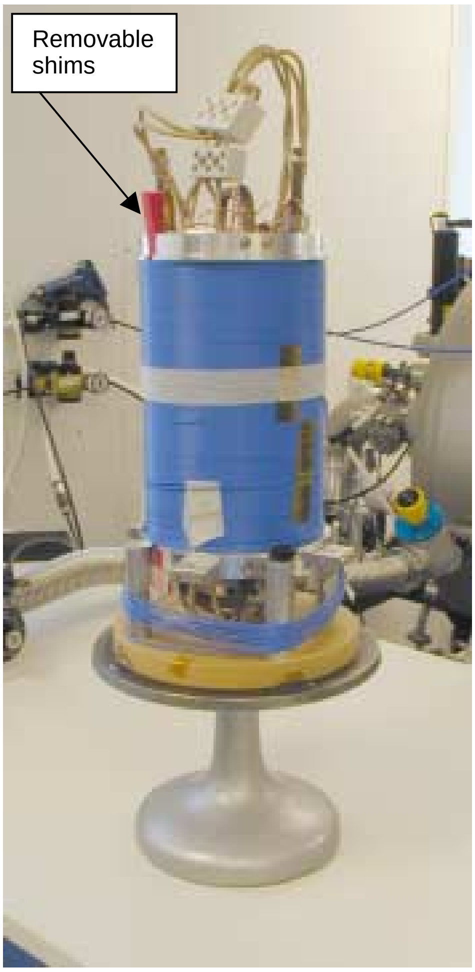


Figure 1.5-4 Test Fibre Cables Wound On Aluminium Cylinder Support

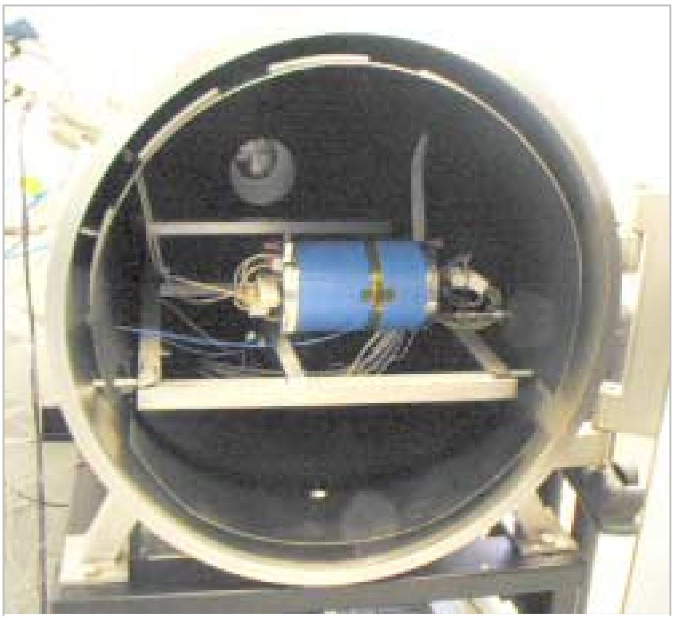


Figure 1.5-5 Cable Support Cylinder Mounted Within Sira's Thermal-Vacuum Chamber

1.5.3 Optical Fibre Connectors – Thermal Vacuum Cycling

Thermal vacuum testing was also performed on three sets of Diamond AVIM optical fibre cable connectors, attached to short lengths of cable type FON 1019 and coupled using Diamond mating adapters. As noted earlier a torque wrench was employed when securing connector components. Torque settings used were those recommended by the connector manufacturer.

Test connector assemblies were thermally coupled to the temperature controlled support cylinder via rigidly attached aluminium mounting lugs. At low test temperatures both the walls of the thermal chamber and support cylinder were maintained at the same temperature due to use of thermal control fluid. At high temperatures the maximum thermal chamber wall temperature was +70°C and therefore a temperature gradient existed in this case. In order to maintain optimum thermal control of the test connector assembly, test connectors were shielded using reflective thermal blanket material as shown in Figure 1.5-6. [Use of this material was not considered feasible during earlier fibre cable tests due to the need to maintain an effective radiative path between test component and chamber wall; i.e. to enable passive cooling to take place (from +150°C down to +70°C) within a practicable timescale. In retrospect, for fibre cable testing, a more efficient mounting scheme may have been to locate test cables in the space between rigidly attached inner and outer cylinders].

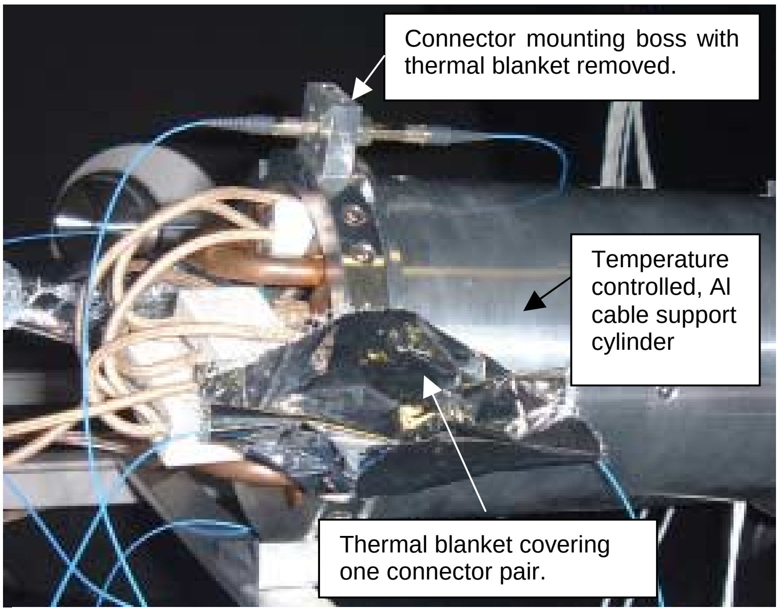


Figure 1.5-6 Connector Test Mount Configuration

2. TEST RESULTS

A report on the results of each test performed is given below. Key test data obtained are summarised in Tables 2.1-1 to 2.5-1 and Figures 2.1-1 to 2.5-6.

Whilst it was not possible to measure connector insertion loss at Sira, the results obtained by Diamond for the four sets of connectors, type AVIM D-6206.6 (zirconia ferrules), supplied initially (in the form of patch-cords but with the wrong cable length) are given in Appendix II. It is seen that, for these connectors, the maximum measured insertion loss (items no.1 to 8) was 0.18 dB at wavelength 1310 nm.

Measurement of optical fibre cable diameter was made using a micrometer with digital readout (resolution ~1μm). The material to be checked was found to be too soft to use the micrometer's ratcheted torque limiter and so a microscope with back-lighting was used to detect contact visually. Wall thickness measurement was attempted by viewing cut sections, using a microscope with x40 objective and calibrated graticule (25 μm/ div), to an estimated accuracy of ± 15 μm.

Inspection of optical fibre connectors and mating adaptors was undertaken using a low power Wild (x6 to x40) microscope. An unused set of connectors and mating adaptor were employed for comparison purposes.

2.1 OPTICAL FIBRE CABLE – RAPID DEPRESSURISATION

Purpose: To determine performance of optical fibre cable when subjected to a rapid pressure fall from 1 atmosphere to 10 torr or less.

Test Data Summary: See Table 2.1 and Figure 2.1-1.

Comments: Rapid depressurisation had no discernible effect, in terms of optical transmission or dimensionality, on either cable tested.

2.2 OPTICAL FIBRE CONNECTORS – RAPID DEPRESSURISATION

Purpose: To determine how exposure to a rapid fall in pressure, from 1 atmosphere to 10 torr or less, affects the performance of a connector pair used to terminate specified optical fibre cable.

Test Data Summary: See Table 2.2 and Figures 2.2-1.

Comments: When connectors were connected using the recommended torque settings, rapid depressurisation had no discernible effect, in terms of optical transmission or dimensionality, on any of the items tested.

2.3 OPTICAL FIBRE CONNECTORS – VIBRATION AND SHOCK

Purpose: To determine the effects of vibration and shock, at predominant frequency ranges and magnitudes that may be encountered during use, on the performance of a connector pair used to terminate specified optical fibre cable.

Test Data Summary: See Table 2.3, Figures 2.3-1 to 2.3-9 and Appendix III

Comments: From the result of relative optical transmission measurements, only connector set DC1 (tungsten-carbide ferrule) showed any significant attenuation effects, where the maximum attenuation measured was 0.18 dB. This is to be compared with the manufacturer's specification for maximum permitted change in optical transmittance; i.e. ≤ 0.4 dB.

All three connector pairs and mating adaptors were inspected for vibration damage using the Wild microscope. No obvious damage due to vibration was observed; specifically there was no swarf build-up or fretting; also no sign of 'hammering' type impact damage. Some minor contamination was evident however. All connector ferrule end faces had very fine surface scratches, but these could also be seen on the unused samples. The used samples appeared to have acquired some additional digs and scratches, possibly due to the effects of handling. The worst scratch mark defect was found on connector A from set DC1.

2.4 OPTICAL FIBRE CABLE – THERMAL VACUUM CYCLING

Purpose: To determine the ability of optical fibre cable to operate in vacuum with varying temperature.

Test Data Summary: See Table 2.4 and Figures 2.4-1 to 2.4-2.

Comments: The existing (FON 1010) and new (FON 1019) optical fibre cables were both tested simultaneously under vacuum. A total of 10 thermal cycles were applied over the lower test band (–50°C to +85°C) and 20 cycles applied over the higher test band (–50°C to +150°C), with a delay of approximately 24 hours between the two. The result of thermal-vacuum cycling showed no significant effect upon optical transmission for either cable type within a signal noise level of ~ 0.13 dB.

Both fibre cables were removed from the thermal vacuum chamber by severing the cable at the vacuum feed-through, providing un-cycled fibre tails for comparison purposes. For both cable types approximately 10 m was removed from the aluminium support cylinder. Measurement of the FON 1010 cable diameter (nominal specification 1.2 ± 0.075 mm) showed some ovality; i.e. 1.09 mm to 1.13 mm (tested cable), 1.10 mm to 1.17 mm (external comparison cable). Also, for the tested cable, the outer jacket wall thickness was 175μm and inner jacket diameter was 624 μm to 629 μm. This is to be compared with a specified inner jacket diameter of 610 ± 50 μm. For the new cable, type FON 1019, the same cable measurements showed: diameter 1.03 mm to 1.12 mm (tested cable), 1.06 mm to 1.15 mm (external comparison cable); outer jacket test cable wall thickness 175 μm and inner jacket diameter 511 μm to 640 μm.

2.5 OPTICAL FIBRE CONNECTORS – THERMAL VACUUM CYCLING

Purpose: To determine how exposure to vacuum and temperature cycling affects the performance of a connector pair used to terminate specified optical fibre cable.

Test Data Summary: See Table 2.5 and Figures 2.5-1 to 2.5-6.

Comments: The same three sets of AVIM connectors (DC1 to DC3), and associated mating adaptors, were each tested simultaneously under vacuum. A total of 20 thermal cycles were applied first over the lower test band (–50°C to +85°C), with a delay after the first 10 cycles of ~ 30 hrs. An unavoidable delay of 10 days then occurred after which a further 3 cycles were applied at the lower test band followed by 10 cycles over the higher test band (–50°C to +150°C).

The result of thermal-vacuum cycling showed a very significant effect upon optical transmission for each of the standard connector sets, type D-6206.1, with tungsten carbide ferrules. Optical transmission was seen to fall drastically at low temperature, with transmission for one connector set falling to zero during a number of test cycles. Transmission was seen to recover, however, close to its original value when the temperature was again raised. This action was repeated for each of the 33 test cycles applied. In the case of connector set DC3, with zirconia ferrules, only a slight fall in optical transmission occurred during the low temperature part of each cycle.

The results given in Figure 2.5-1 show normalised optical transmission for each connector set, relative to the data-logger reference fibre, over the first 20 thermal cycles. The associated test temperature profile has also been included with the correct timescale; note that the vertical temperature scale is relative only. Figure 2.5-2 gives data just for connector set DC3 (zirconia ferrules). From a least square fit to this data the average transmission is 0.964 with minimum recorded transmission of 0.910 (i.e. 0.25 dB).

Small sections of missing data were due to failure of the data-logging computer; this did not affect performance of the thermal cycling control computer. Thermal cycle data for the first 20 cycles is given in Figure 2.5-3 where temperatures measured using calibrated and control system PRT's are overlaid. Figure 2.5-4 shows a section of the worst case performance in greater detail. Here both temperature and optical transmission data were recorded at 1 minute intervals.

Figures 2.5-5 and 2.5-6 show similar data for thermal cycles covering the higher temperature band. It was decided to include approximately three initial cycles at the lower temperature band, due to the interim delay of 10 days (with system remaining under vacuum during this time), in order to determine if performance was similar to that which occurred during the earlier test. From Figure 2.5-5 it can be seen that similar performance was obtained. We also note that a sudden drop in transmission did not occur at the third cycle minima as the control program was switched to that for the higher band before the critical temperature was reached.

In order to obtain quantitative information relating to the onset of rapid transmission loss for connector sets DC1 and DC2 the transmission data were examined and estimations made of the temperatures at which onset and recovery of signal loss occurred for each transmission 'trough'. The result obtained for the first 23, lower temperature, Band-A cycles is given in Figure 2.5-7. From this it would appear that after some initial oscillation, the onset temperature stabilised in the region of –37.5°C (DC1) and –40°C (DC2) during the first 20 continuous cycles. The temperature at which loss onset first occurred was found to be approximately –43°C (DC1) and –55°C (DC2).

Figure 2.5-8 shows the result extended to include the higher temperature, Band-B, cycles. From consideration of Figure 2.5-5, showing optical transmission over Band-B, it would appear that operation at the higher temperature has widened each 'trough', indicating that loss onset and recovery should occur at higher temperatures. This effect is apparently accompanied by a smaller maximum attenuation.

The precise reason for the above performance of connector sets with tungsten carbide ferrules is unclear (but see comments below), however we should note the work undertaken by L.J. McMurray(ref), at Lockheed Martin Astronautics, when assessing Diamond single-mode, single fibre connectors for NASA applications. In this paper very similar connectors to those used here, with tungsten carbide ferrules and designated type 6108, were tested. It is reported that the connector supplier performed the thermal cycling tests, utilizing the specified cable, epoxy and termination procedures, over the temperature range –40°C to +100°C. Under this lower specification no significant attenuation effects were reported (we also note that the specification of requirements for the performance of single fibre connectors gave the required thermal characteristics as 10 cycles from –30°C to +100°C). This might be considered consistent with the results of the present test work where the onset of transmission losses first occurred at temperatures below –40°C.

All three connector pairs and mating adaptors were again inspected for damage due to the thermal cycling process, with the following results.

Connector set DC1: For connector part A the highly polished end of the plug insert was found to be slightly sub-flush (~ 25 μm) with respect to the outer barrel and there was slight exudation of epoxy at the interface. In places some epoxy could be seen standing very slightly proud of the outer barrel. These subtle features were not noted during earlier inspection prior to thermal cycling. The cluster of scratches seen on the connector mating surface appeared to be the same as before thermal cycling. In the case of connector part B, no significant effects were obvious. The appearance of small scratches on the mating end-face appeared to be unchanged. Examination of the mating adaptor showed some shiny particles on the inner bore which could be swarf or plating, possibly produced whilst using the torque wrench. Some evidence also of plating loss, through an etching effect, on the outside of the adaptor at one end. No obvious thermal effects upon any part of the fibre cables were found.

Connector set DC2: For connector part A, very similar characteristics to that found in set 1, with possibly slightly more potting material breaking up (through glass transition effect). For connector part B, the polished insert is more nearly flush than the previous three connectors examined, however the exudation of epoxy makes a precise assessment difficult. An additional surface dig was also noted on the mating surface. Examination of the mating adapter shows good condition, with fewer particulates than seen on the adapter for connector set 1. Again no obvious thermal effects upon any part of the fibre cables were found.

Connector set DC3: Connectors within this set had a completely different ferrule structure to that found within sets DC1 and DC2; i.e. connectors within DC3 possessed a ferrule with a 'top-hat' shaped insert located within a ceramic (zirconia) barrel. The other 'standard' connectors employed a simple cylindrical insert within a tungsten carbide barrel. For connector part A (set DC3) there were no obvious effects due to thermal cycling. There was a slight possibility of minor changes to the epoxy fillet but the appearance was very similar to the unused set of D-6206.6 connectors. For connector part B, the condition of the mating face was very similar to that of part A. Similarly the mating adapter was in good condition and no obvious thermal effects upon any part of the fibre cables were found.

2.6 CONCLUDING SUMMARY

In Part 1 of the current project, single mode optical fibre cable with acylate buffer, principally for use at wavelength 1310 nm, was purchased from three commercial suppliers, namely:

- Plasma Optical Fibre, BV ; Product Code: 267E, MCSM DLPC7
- Corning Optical Fibres, UK ; Product Code: SMF-28, CPC6, Spec P5002
- Pirelli Cables, UK ; Product Code: Standard VAD single mode fibre

The above optical fibres were radiation tested, using both ^{60}Co gamma and proton irradiation, and all found to have acceptable levels of radiation induced attenuation. In the case of ^{60}Co irradiation, a total dose of 0.75 Mrads (Si) at a dose rate of 4.4 rads (Si) sec^{-1} produced a maximum attenuation of 16 dB km^{-1}.

The optical fibre manufactured by Plasma Optical Fibre was subsequently chosen for incorporation within a 1.2 mm simplex FLEX-LITE single mode fibre cable, to be manufactured by W.L. Gore & Associates, under the new product code FON 1019. A sample length of this cable was then subjected by Sira to thermal vacuum cycling, over the temperature range –50°C to +150°C and rapid depressurisation testing. An associated, environmental test induced attenuation of < 0.13 dB over a test cable length of 200 m equates to < 0.65 dB km^{-1}. A post-test visual inspection of the cable showed no signs of test induced deterioration.

It is to be noted that an existing cable manufactured by W.L Gore (FON 1010), with the same construction as FON 1019, but using an acylate-buffered single mode fibre manufactured by SpecTran (Lucent), has a recommended operating temperature range of –50°C to +100°C. Furthermore the associated Gore test specification document dictates a maximum test temperature of +85°C for temperature induced attenuation measurements. Whilst the present test measurements showed acceptable performance at temperatures up to +150°C it is considered sensible to exercise care when considering long term use of the cable within an environment with temperatures exceeding +100°C.

In order to make efficient use of the new cable, space compatible, low loss, single mode fibre connectors, produced by Diamond SA, type AVIM D-6206.n SM PC, were attached to lengths of FON 1019 cable (note that n = 1 or 6 depending upon the specific version concerned – see discussion below). Performance evaluation testing covered thermal vacuum cycling, over the above cable test range, vibration and shock, and rapid depressurisation.

In addition to the catalogue standard, space-compatible, connector design form, type AVIM D-6206.1, which uses a ferrule manufactured from tungsten carbide, a new design form, type AVIM D-6206.6, which uses a zirconia ferrule was also tested.

For rapid depressurisation measurements the effects of pressure change were found to be very small; i.e. attenuation ≤ –0.084 dB, where the negative sign indicates an increase in transmission.

The results of vibration and shock testing again showed small but slightly larger attenuation values. Here the largest attenuation, 0.18 dB, was associated with a standard connector set with tungsten carbide ferrules. From a consideration of the literature produced by NASA laboratories the general opinion is that a suitable space grade single mode connector should be capable of an initial insertion loss of ≤ 0.5 dB per mated pair, with insertion loss increasing to ≤ 0.7 dB after exposure to the environment. Insertion loss measurements made by Diamond on supplied test connectors, type D-6206.6, together with Diamond's commercial literature on standard connector forms (type D-6206.1), show that the initial insertion loss requirement can easily be achieved. The result of Sira's connector vibration and shock tests also indicate that the given maximum insertion loss after exposure to the environment is equally possible.

The results which gave greatest cause for concern were associated with thermal vacuum testing of connectors. Whilst the standard connector (D-6206.1) catalogue performance specification shows an operating range of –50°C to +125°C, very severe degradation in optical transmission (including zero transmission) occurred at lower temperatures. From test measurements made at Sira the onset of transmission loss was estimated to occur at temperatures below –40°C. Transmission was seen to recover almost completely when temperature was raised, however the point of onset for transmission loss for subsequent cycles was somewhat variable, being particularly affected when the connector set was also exposed to high temperatures (i.e. ~ +150°C in the present case).

In contrast to the above, performance of the new test connectors (type D-6206.6), with zirconia ferrules and new design of ferrule insert, were seen to be essentially unaffected by the thermal test conditions used. Whilst only one set of the new form of test connectors were included in our tests, it would appear that this form must be the preferred choice. As an aside we are also advised by Diamond that NASA have also recently accepted this fact.

From consideration of the above we are able to specify a space-grade, single mode, optical fibre cable with connectors, for use principally at wavelength 1310 nm. Furthermore we have the potential for all components to be manufactured within Europe given sufficient demand.

2.7 RECOMMENDED FUTURE ACTIONS

From consideration of the test work undertaken, in combination with technical information taken from the technical literature, it is recommended that formal ESA/SCC documentation be produced for the performance specification and manufacture of single mode optical fibre cable, operating at 1310 nm. The cable should incorporate an acrylate-buffered fibre type 267E manufactured by Plasma Optical Fibre BV, and the FLEX-LITE cable structure should (initially) be manufactured by W.L. Gore & Associates under the product code FON 1019. The new specifications relating to space compatible cable manufacture should also include documentation relating to qualification and acceptance testing.

We note here that since beginning the current project work fibre type 267E has been superseded by an improved, almost identical, single mode fibre type 268E. From communications with the manufacturer we believe that the changes made to the fibre will not affect its performance in the current application (see fax document Appendix D).

In addition to formal documentation relating to cable manufacture, additional ESA/SCC documentation should also be produced for the performance, manufacture and qualification/acceptance testing of space compatible AVIM connectors, type D-6206.6, used in combination with AVIM mating adapter type D-626.

Optical Fibre Cable Measurements - Rapid Depressurisation:				
Cable type & test code	FON 1010 (C3)		FON 1019 (C1)	
Fibre manufacturer	SpecTran (Lucent)		Plasma Optical	
Cable length	214 m		214 m	
Cable support mechanism	110 mm dia flex. cyl / 150um metal. Kapton sheet			
Main chamber initial pressure (torr)	~ 1.0×10^{-6}		~ 1.0×10^{-6}	
Final pressure (torr)	4.5 torr		3.3 torr	
Duration of pressure fall	~ 5 sec		~ 5 sec	
	pre-test	post-test	pre-test	post-test
Absolute power transmission (uW)	262	262	190	191
Attenuation (dB)	~ 0 dB		~ 0 dB	

TABLE 2.1 OPTICAL FIBRE CABLES – RAPID DEPRESSURISATION TESTING

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Optical Fibre Connector Measurements - Rapid Depressurisation:

Connector pair type & test code	AVIM D-6206.1 (DC1)		AVIM D-6206.1 (DC2)		AVIM D-6206.6 (DC3)	
Connector ferrule material	Tungsten-carbide		Tungsten-carbide		Zirconia	
Cable type	FON 1019					
Fibre manufacturer	Plasma Optical					
Cable length within vac chamber [1]	~ 1.0 m					
Cable/connectors support mechanism	see report section 1.6					
Connector torque (Nm)	0.3					
Mating adaptor torque (Nm) [2]	1.0					
Main chamber initial pressure (torr)	~ 1.0×10^{-6}		~ 1.0×10^{-6}		~ 1.0×10^{-6}	
Minimum pressure (torr)	3.1		3.8		3.5	
Duration of pressure fall	~ 5 sec					
	pre-test	post-test	pre-test	post-test	pre-test	post-test
Abs power transmission - ref fib (uW)	358	357	361	340	353	351
Abs power transmission - test con (uW)	210	212	201	193	246	246
Attenuation during test (dB) [3]	-0.053		-0.084		-0.025	
Connector pair insertion loss [4]	-		-		-	

[1] Distance between connector & vac feed-through port

[2] Refers to removable section which allows connector cleaning

[3] Neg value implies gain

[4] See report section 1.3-2

TABLE 2.2 OPTICAL FIBRE CONNECTORS – RAPID DEPRESSURISATION TESTING

Optical Fibre Connector Measurements - Vibration & Shock:

Connector pair type & test code	AVIM D-6206.1 (DC1)			AVIM D-6206.1 (DC2)			AVIM D-6206.6 (DC3)		
Connector ferrule material	Tungsten-carbide			Tungsten-carbide			Zirconia		
Cable type	FLEX-LITE FON 1019								
Fibre manufacturer	Plasma Optical Fibre								
Vibration axes [1]	Z	X	Y	Z	X	Y	Z	X	Y
Pre-test absolute power transmission (uW) [2]	220 (333)	219 (334)	216 (332)	182 (333)	183 (334)	185 (332)	203 (333)	203 (334)	206 (332)
Post-test absolute power transmission (uW)	214 (335)	216 (336)	213 (331)	183 (335)	184 (336)	183 (331)	203 (335)	201 (336)	206 (331)
Final attenuation (dB) [3]	0.125	0.065	0.053	-0.012	-0.005	0.038	0.014	0.068	-0.014
Peak attenuation during test period (dB) [4]	0.180	0.180	0.130						

[1] Tests performed in axis order: z, x, y

[2] Values in parenthesis represent reference fibre transmission

[3] Based upon radiometric power transmission measurements

[4] Based upon continuous data-log

Notes -Tests performed in the order: Power Sine vibration, Random vibration, Shock

a) Tests performed in the order: Power Sine vibration, Random vibration, Shock

b) Duration of Sine & Random vibn tests: 2.5 min

c) Shock testing: initial 5 setup shocks followed by 3 specified shocks

TABLE 2.3 OPTICAL FIBRE CONNECTORS – VIBRATION AND SHOCK TESTING

Optical Fibre Cable Measurements - Thermal Vacuum Cycling:

Cable type & test code	FON 1010 (C3)		FON 1019 (C1)	
Fibre manufacturer	SpecTran (Lucent)		Plasma Optical	
Cable length	200 m		200 m	
Cable support mechanism	Al cylinder, dia = 130 mm, length = 250 mm			
Initial vacuum chamber pressure	9.0×10^{-6} torr			
Pre-test absolute power transmission (uW) [1]	206	(358)	215	(358)
Test Condition A	Temperaturel range -50C to +85C [4] (10 cycles)			
Peak attenuation during test period (dB)	see note 2			
Test Condition B	Temperaturel range -50C to +150C [5] (20 cycles)			
Peak attenuation during test period (dB) [2]	see note 2			
Post-test absolute power transmission (uW) [1]	204	(354)	214	(354)
Final attenuation (dB) [3]	0.006		-0.018	
Final vacuum chamber pressure	4.6×10^{-3} torr			

[1] Values in parenthesis represent reference fibre transmission

[2] Data-logger results show maximum variation (~ 0.18 dB) to be within signal noise level

[3] Based upon pre- and post-test radiometric power transmission measurement

[4] Actual min and max temperatures recorded were: -56 deg C, +91 deg C

[5] Actual min and max temperatures recorded were: -56 deg C, +159 deg C

Notes -

a) Tests were performed in the order: Test condition A, Test Condition B

TABLE 2.4 OPTICAL FIBRE CABLE – THERMAL VACUUM CYCLING TESTS

Optical Fibre Connector Measurements - Thermal Vacuum Cycling:

Connector pair type & test code	AVIM D-6206.1 (DC1)		AVIM D-6206.1 (DC2)		AVIM D-6206.6 (DC3)	
Connector ferrule material	Tungsten-carbide		Tungsten-carbide		Zirconia	
Cable type	FON 1019					
Fibre manufacturer	Plasma Optical					
Cable length within vac chamber [1]	~ 1 m					
Connector support mechanism	See report section 1.4					
Initial vacuum chamber pressure	$2.8\text{x}10^{-5}$ torr					
Band A - min/max temps recorded	-58C/+89C					
Band A - number of cycles applied	23					
Band B - min/max temps recorded	-58C/+163C					
Band B - number of cycles applied	10					
	pre-test	post-test	pre-test	post-test	pre-test	post-test
Absolute power transmission (uW) [2]	293 (338)	227 (338)	182 (338)	172 (338)	206 (338)	212 (338)
Final attenuation (dB) [3]	1.11		0.25		-0.12	
Peak attenuation during test period (dB) [4]	See report section 2.5					

[1] Distance between connector & vac feed-through port

[2] Values in parenthesis represent reference fibre transmission

[3] Based upon pre- and post-test radiometric power transmission measurement (post-test measurements made ~ 72 hours after cessation of thermal cycling)

[4] Very significant attenuation found for connector type D-6206.1 (tungsten carbide ferrule) at low temperature

Notes -

a) Temperature bands were applied in the order given

TABLE 2.5 OPTICAL FIBRE CONNECTORS – THERMAL VACUUM CYCLING TESTS

3. DRAFT SPECIFICATION - CABLE & CONNECTORS

The following preliminary draft specifications are based upon test work undertaken at Sira, manufacturers component specification sheets and technical literature published by NASA laboratories. It has been assumed, at least in the initial case, that the optical fibre cable will be manufactured by W.L. Gore & Associates; the single mode optical fibre connectors will be manufactured, and attached to Gore cable, by Diamond SA.

Also note that the following specifications relate principally to standards operating under the American National Standards Institute (ANSI). It will be the task of a following work phase to direct such references to equivalent standards under the control of the International Organisation for Standardisation (ISO) or the International Electrotechnical committee (IEC).

The precise methods for qualification and acceptance testing are outside the scope of the brief draft documents given here and will be covered in a subsequent work phase. During this later phase careful attention will be paid to relevant documents which are expected to include equivalent ESA/SCC basic component specifications and NASA specification SSQ 21654, “Cable, Single Fiber, Multimode, Space Quality, General Specification for”.

3.1 OPTICAL FIBRE CABLE

1.0 SCOPE This specification establishes requirements for a single optical fibre (“simplex”) cable. The part number is FON1019. The cable consists of a single-mode optical fibre, a layer of expanded PTFE, a thin layer of FEP, braided Aramid yarn for a strength member and FEP outside jacketing. The fibre cable may be used in a temperature range of –55° C to 100° C continuous operational, at a wavelength of 1300 nm.

2.0 APPLICABLE DOCUMENTS The following documents form a part of this specification to the extent specified herein.

SPECIFICATIONS

EIA/TIA-455-A	Standard Test Procedure for Fibre Optics. Cables. Transducers, Sensors, Connecting and Terminating Devices and Other Fibre Optic Components
EIA/TIA-455-3A (FOTP-3)	Procedure To Measure Temperature Cycling Effects on Optical Fibre Cable and Other Passive Components
EIA/TIA-455-11A (FOTP- 11)	Vibration Test Procedure for Fibre Optic Connecting Devices and Cables
EIA/TIA-455-33A (FOTP-33)	Fibre Optic Cable Tensile Loading and Bending Test
EIA/TIA-455-37A (FOTP-37)	Low or High Temperature Bend Test for Fibre Optic Cable
EIA/TIA-455-61 (FOTP-61)	Measurement of Fibre or Cable Attenuation Using an Optical Time Domain Reflectometer (OTDR)
EIA/TIA-455-171(FOTP-171)	Attenuation by Substitution Measurement for Short-Length Multimode Graded-Index and Single-mode Optical Fibre Cable Assemblies

3.0 REQUIREMENTS Cables furnished to this specification shall meet the requirements specified herein.

3.1 Design and Construction Only virgin material shall be used in the fabrication of cable assemblies.

3.1.1 Cable construction shall be as specified herein.

3.1.1.1 Fibre The optical fibre shall be single-mode fibre having a mode field diameter of 9.3 m ± 0.5 m. The cladding diameter shall be 125 m ± 2 m. The attenuation at 1310 nm shall be ≤ 0.4 dB/km. The numerical aperture shall be 0.24 ± 0.02. The cladding non-circularity shall be ≤ 2 %. The core/cladding concentricity error shall be ≤ 1 m.

3.1.1.2 Coating/Primary Buffer The fibre coating shall be UV cured acrylate with a diameter of 245 m ± 10 m. The coating concentricity error shall be ≤ 12.5 m.

3.1.1.3 Secondary Buffer Material The secondary buffer shall be tape-wrapped, expanded polytetrafluoroethylene (PTFE) conforming to the requirements of MIL-C-17, Type F-6.

3.1.1.4 Inner Jacket shall be extruded fluorocarbon material conforming to MIL-C-17, Type IX, tinted blue. The diameter shall be 0.024” ± 0.002” (610 m ± 50 m).

3.1.1.5 Strength Member The strength member shall be a braid of aramid yarn.

3.1.1.6 Outer Jacket Jacket shall be extruded fluorocarbon material conforming to MIL-C-17, Type IX, tinted blue. The diameter shall be 0.046” ± 0.003” (1.2 mm ± 75 m).

3.2 Workmanship Finished cable shall conform to the requirements specified herein. Non-conforming cable shall not be shipped.

3.3 Visual Inspection All aspects of material and construction shall be visually examined. The cable outer surface shall be smooth (free from lumps, kinks, abrasions, pitted or pocked surfaces).

4.0 QUALITY ASSURANCE PROVISIONS - TBD

4.1 Quality Assurance Verification - TBD

4.2 Performance

4.2.1 Attenuation The attenuation of the optical fibre cable shall be determined in accordance with test procedure FOTP-61 of EIA/TIA-455-61. If the length of cable is less than 200 meters, attenuation shall be determined in accordance with test procedure FOTP-171 of EIA/TIA-455-171. This measurement shall be done at 1310 ± 20 nm and must be less than 1.4 dB/km.

4.2.2 Temperature Induced Attenuation The attenuation due to temperature shall be measured per FOTP-3 of EIA/TIA-455-3A. At least 5 fibre cables will be tested in accordance with EIA-455-3A Test condition C, the length of the cable inside the chamber shall be 50m. The minimum test temperature shall be –55° C. The maximum test temperature shall be +100° C. The number of cycles shall be 10. The rate of change of temperature shall be less than 1°C /min. The induced loss due to temperature shall be no more than 0.1 dB/50 m during testing and no more than 0.05 dB/50 m after the test.

4.2.3 Vibration Induced Attenuation The attenuation due to vibration shall be measured per EIA/TIA-455-11A. The test duration shall be 3 minutes in each orthogonal axes. Optical conformance tests shall be performed on all functional channels. The induced loss shall be no more than ± 0.05 dB/50m after vibration.

4.2.4 Geometrical Measurements The outside diameter of the cable and the buffer layers are to be measured using an in-line process. The outer diameter of the overall cable shall be 1.168 ± 0.076 mm.

4.2.5 Weight The cable shall have a nominal weight of 1.5 g/m. The actual weight shall be within ± 10 % of the nominal value.

4.2.6 Cable Tensile Strength The cable jacket shall be tested for tensile strength in accordance with FOTP-33 per EIA-455-33A. The tensile strength shall be no less than 66 kg.

4.2.7 Temperature Cycling and Bend Induced Attenuation The attenuation of the bend in temperature shall be measured per EIA/TIA-455-37A. With the following modifications: The sample shall be tested in a thermal cycling environment of –55° C to 100° C; and the optical fibre cable shall be wrapped 4 times around a mandrel of 35 mm diameter. The reference data shall be the room temperature data before temperature cycling. The cable shall not experience more than 0.10 dB/50 m during testing and no more than 0.05 dB/50m after testing.

4.3 Traceability Records shall be kept by the supplier showing all significant manufacturing processes, procedures, and inspection steps that have been performed. Records shall indicate the date of the operation and the stamp of the individual performing the operation, and shall relate the finished product to the specific production lot. Assembly serial numbers shall be the key to the records, and shall allow trace-ability to raw materials. Records shall be retained by the supplier for a minimum of three (3) years.

4.4 Certificate of Compliance A Certificate of Compliance, signed by a supplier Quality Representative, which guarantees that fibre optic cable has been tested in accordance with this specification and meets the requirements herein and as specified by the procuring activity shall be provided with each shipment of cable.

3.2 OPTICAL FIBRE CONNECTORS

Specific details of the Qualification Test Report for Diamond AVIM connectors were not available from the manufacturer, Diamond SA. Work undertaken by NASA GSFC [2], using the same type of connector, has however produced a preliminary specification document and its general application in the current context is considered below. It is believed that the connectors used during the current test work are able to meet the given specification.

3.2.1 Specification of Requirements for Single Fibre S/M Connectors

CHARACTERISTIC	REQUIREMENT	COMMENTS
Cleanability	Connector mated to adapter must be cleanable from the unmated side (without demating)	Modular method of spacecraft fabrication.
Repeatable loss measurements. APC polish capability.	Keyed plug and receptacle	
Mating torque	Wrench flats on plugs. Anti-vibration coupling mechanism.	Assure repeatability. Ensure vibration and shock resistance.
Materials	Limitations on ferromagnetic materials, use of pure tin plating, dissimilar metals in intimate contact, lubricants and polymeric materials which outgas in vacuum.	Typical requirements for all space usage components.
Initial insertion loss	0.5 dB per mated pair of connectors maximum with single mode fibre at 1310 nm.	Necessitates active alignment ferrules.
Insertion loss after environmental exposure	0.7 dB per mated pair of connectors maximum, but no more than 0.4 dB change from initial measurement.	
Return loss	45 dB minimum radiused physical contact (PC) polished connectors. 55 dB minimum for angled physical contact (APC) polished connectors.	
Thermal cycling	10 cycles from –50°C to +100°C. EIA/TIA-455-3A Condition C.	
Temperature life	240 hours at +100°C. EIA/TIA –455-4B.	Qualification only.
Tensile load	80 N minimum. EIA/TIA-455-6B Method 1.	At this point, cable design begins to exert effect on maximum sustainable tensile load.
Vibration	46.4 G rms 3 minutes in each of three orthogonal axes.	Qualification only. Test method does not ensure system operation during vibration.
Shock	2000 G peak, frequency range 100 – 10,000 Hz.	Qualification only. Pyro shock type test. Test method does not ensure system operation during system operation during shock exposure.
Mating durability	500 cycles. EIA/TIA-455-21A	

APPENDIX I – FIBRE OPTIC CABLE DOCUMENTATION (GORE & PLASMA OPTICAL FIBRE)

APPENDIX 1(A) – PLASMA OPTICAL FIBRE DATASHEET; FIBRE TYPE 267E

APPENDIX 1(B) – W L GORE FLEX-LITE AEROSPACE FIBER OPTIC CABLES

APPENDIX 1(C) – W L GORE FLEX-LITE CABLE FON 1010 SPECIFICATION DOCUMENT

Creative Technologies
Worldwide

Specification for

Fiber Optic Cable (Bulk)

FON1010

W. L. Gore & Associates, Inc.
1901 Barksdale Road
P. O. Box 9236
Newark, DE 19714-9236
(302) 368-3700 FSCM: 65474

1.0 SCOPE This specification establishes requirements for a single optical fiber ("simplex") cable. The part number is FON1010. The cable consists of a single-mode optical fiber, a layer of expanded PTFE, a thin layer of FEP, braided Aramid yarn for a strength member and FEP outside jacketing. The optical fiber cable may be used in a temperature range of –55° C to 85° C continuous operational at a wavelength of 1300 nm.

2.0 APPLICABLE DOCUMENTS The following documents form a part of this specification to the extent specified herein.

SPECIFICATIONS

EIA/TIA-455-A	Standard Test Procedure for Fiber Optics. Cables. Transducers, Sensors, Connecting and Terminating Devices and Other Fiber Optic Components
EIA/TIA-455-3A (FOTP-3)	Procedure To Measure Temperature Cycling Effects on Optical Fiber Cable and Other Passive Components
EIA/TIA-455-11A (FOTP- 11)	Vibration Test Procedure for Fiber Optic Connecting Devices and Cables
EIA/TIA-455-33A (FOTP-33)	Fiber Optic Cable Tensile Loading and Bending Test
EIA/TIA-455-37A (FOTP-37)	Low or High Temperature Bend Test for Fiber Optic Cable
EIA/TIA-455-61 (FOTP-61)	Measurement of Fiber or Cable Attenuation Using an Optical Time Domain Reflectometer (OTDR)
EIA/TIA-455-171 (FOTP-171)	Attenuation by Substitution Measurement for Short-Length Multimode Graded-Index and Single-mode Optical Fiber Cable Assemblies

3.0 REQUIREMENTS Cables furnished to this specification shall meet the requirements specified herein.

3.1 Design and Construction Only virgin material shall be used in the fabrication of cable assemblies.

3.1.1 Cable construction shall be as specified herein.

3.1.1.3 Fiber The optical fiber shall be single-mode fiber having a core diameter of 9.3 µm ± 0.5 µm. The cladding diameter shall be 125 µm ± 2 µm. The attenuation at 1300 nm shall be ≤ 1.4 dB/km. The numerical aperture shall be 0.11 ± 0.02. The cladding non-circularity shall be ≤ 2 %. The core/cladding concentricity error shall be ≤ 1 µm.

3.1.1.4 Coating/Primary Buffer The fiber coating shall be UV acrylate with a diameter of 250 µm ± 15 µm. The coating concentricity shall be ≥ 70 %.

3.1.1.7 Secondary Buffer Material The secondary buffer shall be tape-wrapped, expanded polytetrafluoroethylene (PTFE) conforming to the requirements of MIL-C-17, Type F-6.

3.1.1.8 Inner Jacket Jacket shall be extruded fluorocarbon material conforming to MIL-C-17, Type IX, tinted blue. The diameter shall be 0.024” ± 0.002” (610 µm ± 50 µm).

3.1.1.9 Strength Member The strength member shall be a braid of aramid yarn.

3.1.1.10 Outer Jacket Jacket shall be extruded fluorocarbon material conforming to MIL-C-17, Type IX, tinted blue. The diameter shall be 0.046” ± 0.003” (1.2 mm ± 75µm).

3.2 Workmanship Finished cable shall conform to the requirements specified herein. Non-conforming cable shall not be shipped.

3.3 Visual Inspection All aspects of material and construction shall be visually examined. The cable outer surface shall be smooth (free from lumps, kinks, abrasions, pitted or pocked surfaces).

4.0 QUALITY ASSURANCE PROVISIONS The quality assurance provisions of MIL-I-45208 shall apply with exceptions and additions as specified herein. All inspections and tests shall be conducted by Gore at a Gore facility or at an outside test facility. The supplier shall allow reasonable procuring activity access to the quality control and test facilities for source inspection purposes. All documentation not considered proprietary by the supplier shall be available for review at the supplier's facility.

4.1 Quality Assurance Verification Quality assurance will be verified by:

A. Acceptance Inspection - 100% inspection of all product

B. Qualification -When specified by the procuring activity.

4.1.1 Acceptance Inspection Prior to shipment, all cable shall be subjected to, and successfully pass, the following tests:

Attenuation per FOTP-61
Diameter
Visual Inspection

4.1.2 Acceptance Inspection Report Acceptance inspection reports for each shipment lot shall be certified by a responsible supplier Quality Assurance Representative. The report shall be available for review at the supplier's facility, upon request. Successful completion of the acceptance inspection for each cable assembly shall be indicated by completion of a supplier Certificate of Compliance (4.4) and submitted to the procuring activity with the shipment lot.

4.1.3 Qualification Qualification, when requested shall be in accordance with this specification in part or whole, and by procuring activity requirements.

4.1.4 Qualification Methods Qualification may be satisfied either by similarity, analysis or by actual testing as agreed upon by the procuring activity and Gore.

4.3 Performance

4.2.1 Attenuation The attenuation of the optical fiber cable shall be determined in accordance with test procedure FOTP-61 of EIA/TIA-455-61. If the length of cable is less than 200 meters, attenuation shall be determined in accordance with test procedure FOTP-171 of EIA/TIA-455-171. This measurement shall be done at 1310 ± 20 nm and must be less than 1.4 dB/km.

4.2.2 Temperature Induced Attenuation The attenuation due to temperature shall be measured per FOTP-3 of EIA/TIA-455-3A. At least 5 fiber cables will be tested in accordance with EIA-455-3A Test condition C, the length of the cable inside the chamber shall be 50m. The minimum test temperature shall be –55° C. The maximum test temperature shall be +85° C. The number of cycles shall be 10. The ramp up temperature shall be at a minimum of 20° C per hour. The induced loss due to temperature shall be no more than 0.1 dB/50 m during testing and no more than 0.05 dB/50 m after the test.

4.2.3 Vibration Induced Attenuation The attenuation due to vibration shall be measured per EIA/TIA-455-11A. The test duration shall be 3 minutes in each orthogonal axes. Optical conformance tests shall be performed on all functional channels. The induced loss shall be no more than ± 0.05 dB/50m after vibration.

4.2.6 Geometrical Measurements The outside diameter of the cable and the buffer layers are to be measured using an in-line process. The outer diameter of the overall cable shall be 0.046 ± 0.003 inches.

4.2.7 Weight The cable shall have a nominal weight of 1.5 g/m. The actual weight shall be within ± 10 % of the nominal value.

4.2.6 Cable Tensile Strength The cable jacket shall be tested for tensile strength in accordance with FOTP-33 per EIA-455-33A. The tensile strength shall be no less than 30 lb.

4.2.7 Temperature Cycling and Bend Induced Attenuation The attenuation of the bend in temperature shall be measured per EIA/TIA-455-37A. With the following modifications: The sample shall be tested in a thermal cycling environment of –55° C to 85° C; and the optical fiber cable shall be wrapped 4 times around a mandrel of 35 mm diameter. The reference data shall be the room temperature data before temperature cycling. The cable shall not experience more than 0.10 dB/50 m during testing and no more than 0.05 dB/50m after testing.

4.3 Traceability Records shall be kept by the supplier showing all significant manufacturing processes, procedures, and inspection steps that have been performed. Records shall indicate the date of the operation and the stamp of the individual performing the operation, and shall relate the finished product to the specific production lot. Assembly serial numbers shall be the key to the records, and shall allow trace-ability to raw materials. Records shall be retained by the supplier for a minimum of three (3) years.

4.4 Certificate of Compliance A Certificate of Compliance, signed by a supplier Quality Representative, which guarantees that fiber optic cable has been tested in accordance with this specification and meets the requirements herein and as specified by the procuring activity shall be provided with each shipment of cable.

5.0 PREPARATION FOR DELIVERY

5.1 Packaging Continuous lengths of cable shall be individually packaged on spools. The spools shall then be packed in boxes and voids shall be filled with shock-absorbent material to prevent damage. Shipping containers may contain multiple spools.

5.2 Labeling Each cable spool shall be labeled or tagged to indicate the customer's part number or Gore part number, as applicable.

6.0 NOTES

6.1 Qualification when required must be specified by the procuring activity at the time of request for quote or proposal.

APPENDIX 1(D) – PLASMA OPTICAL FIBRE – RECENTLY INTRODUCED UPGRADE FIBRE TYPE 268E

APPENDIX II – OPTICAL FIBRE AVIM CONNECTOR DOCUMENTATION (DIAMOND SA)

APPENDIX II(A) – DIAMOND AVIM STANDARD CONNECTOR (D-6206.1) DATA SHEETS

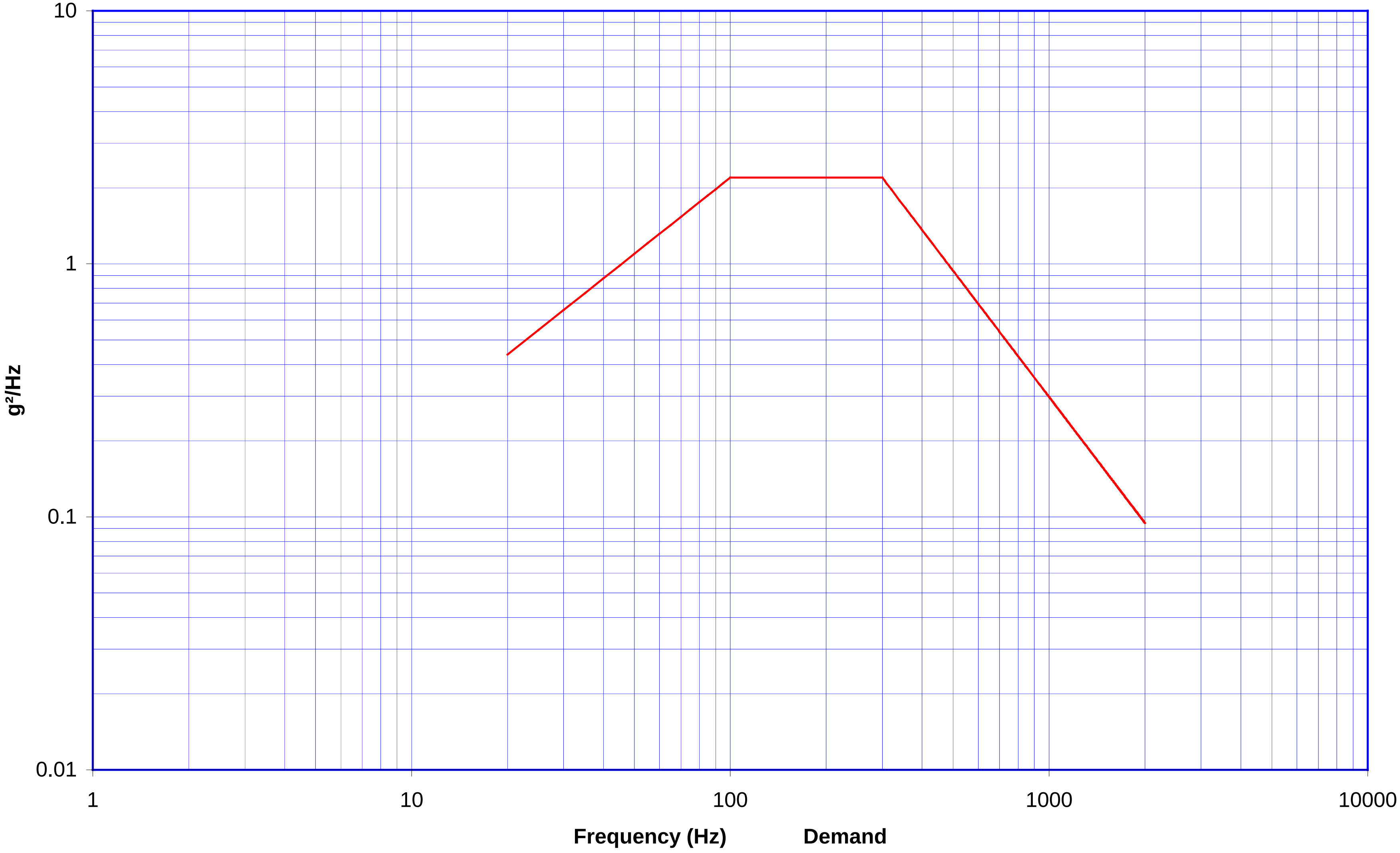
APPENDIX II(B) – DIAMOND AVIM CONNECTOR (NEW DESIGN FROM D-6206.6) AND MATING ADAPTOR D-626

APPENDIX II(C) - MEASUREMENTS PERFORMED BY DIAMOND SA ON ORIGINAL 8 AVIM CONNECTORS (TYPE D-6206.6)

APPENDIX III – VIBRATION AND SHOCK, CONTROL & PERFORMANCE DATA

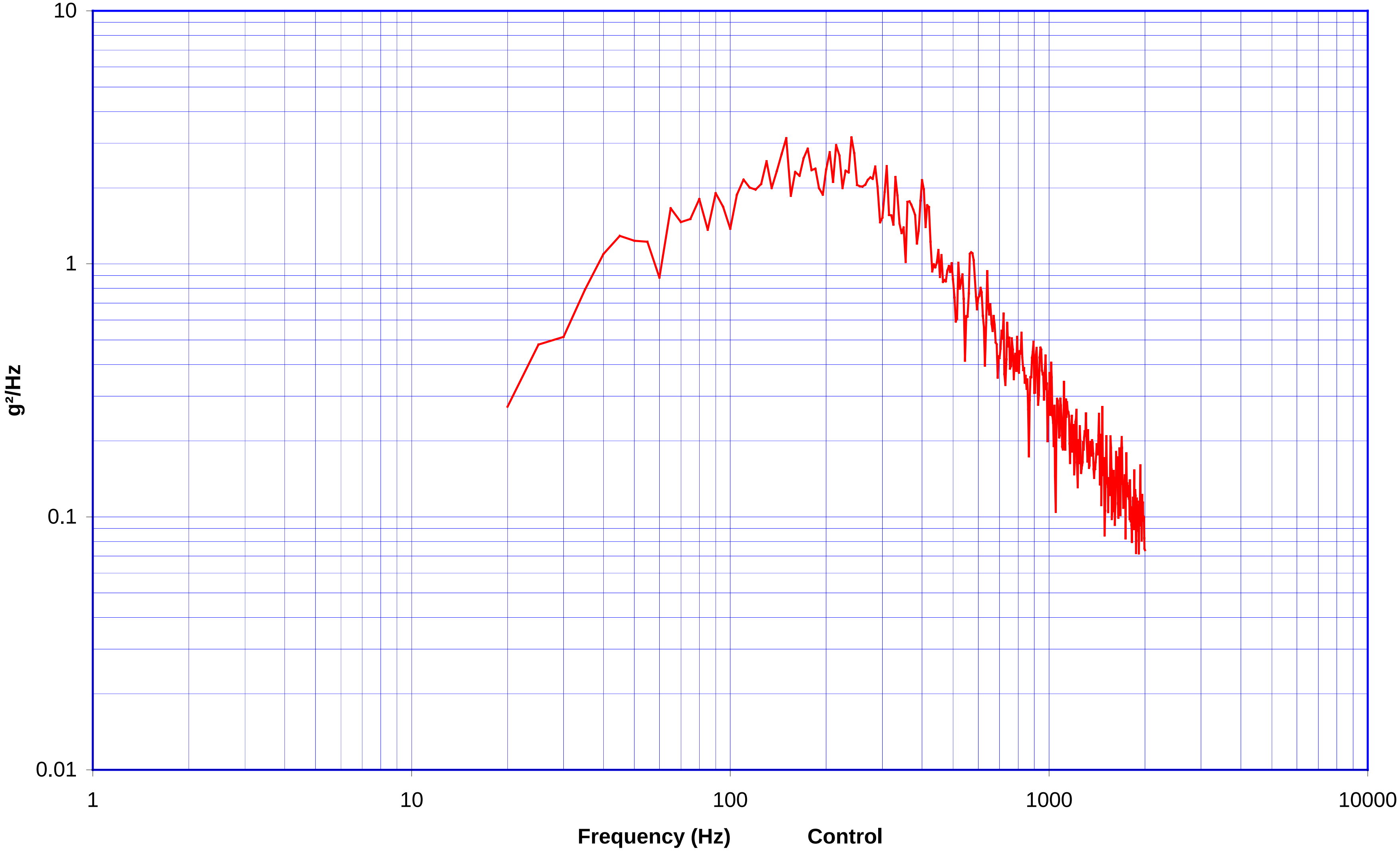
ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: X AXIS - DEMAND
g(rms) : 35.4

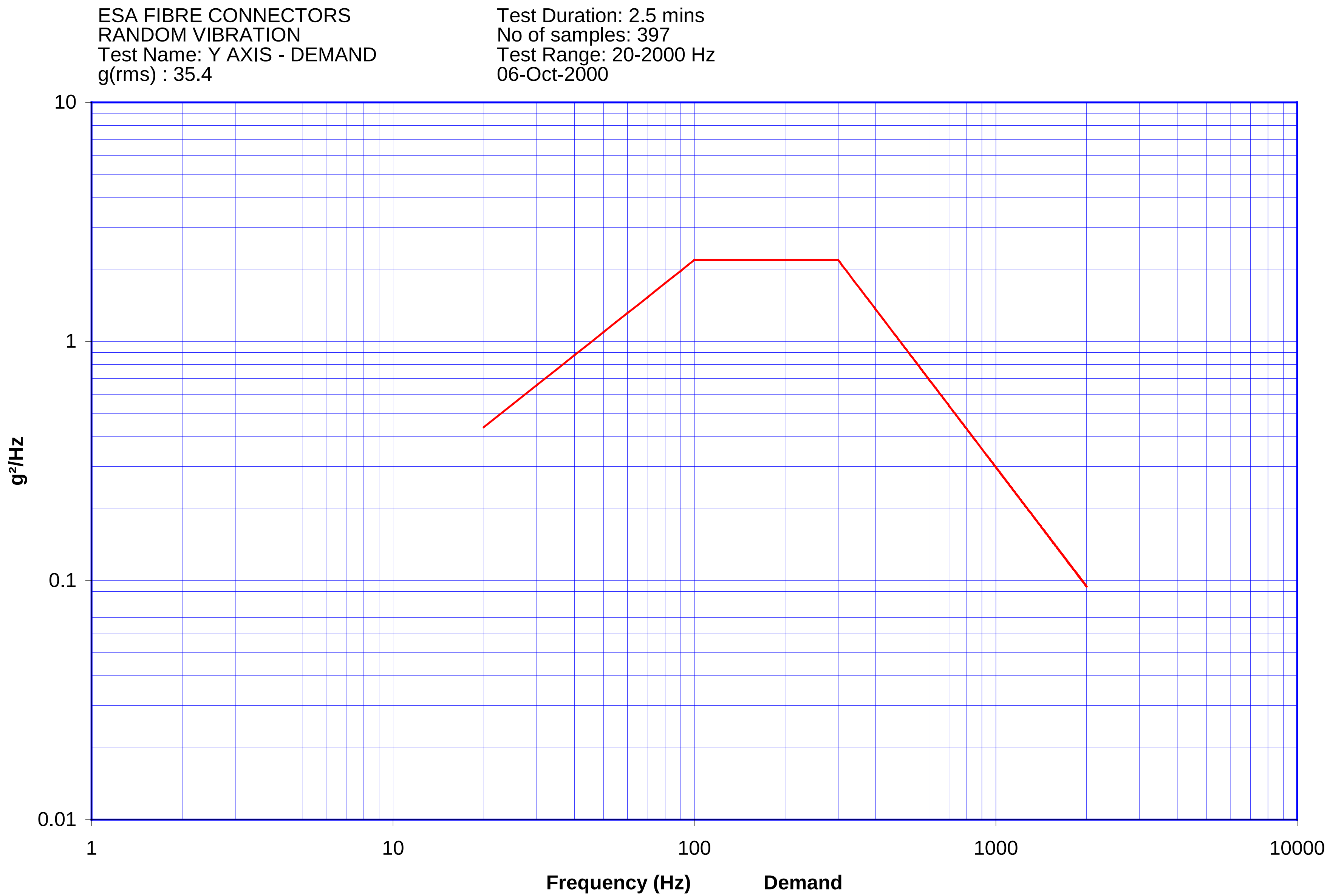
Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
05-Oct-2000



ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: X AXIS - CONTROL
g(rms) : 35.37

Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
05-Oct-2000

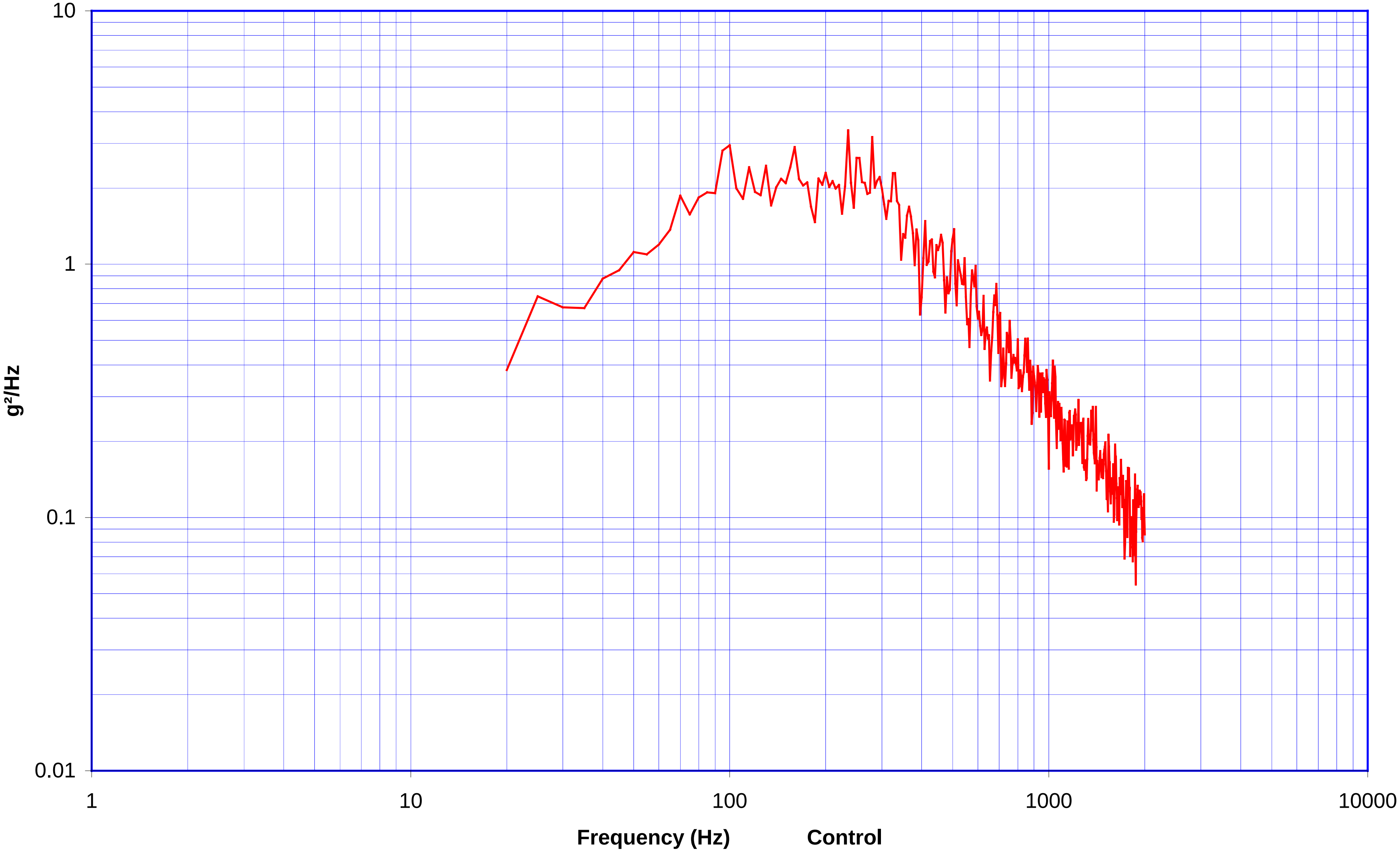




ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: Y AXIS - DEMAND
g(rms) : 35.4
Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
06-Oct-2000
10
1
0.1
0.01
g²/Hz
1
10
100
1000
10000
Frequency (Hz)
Demand

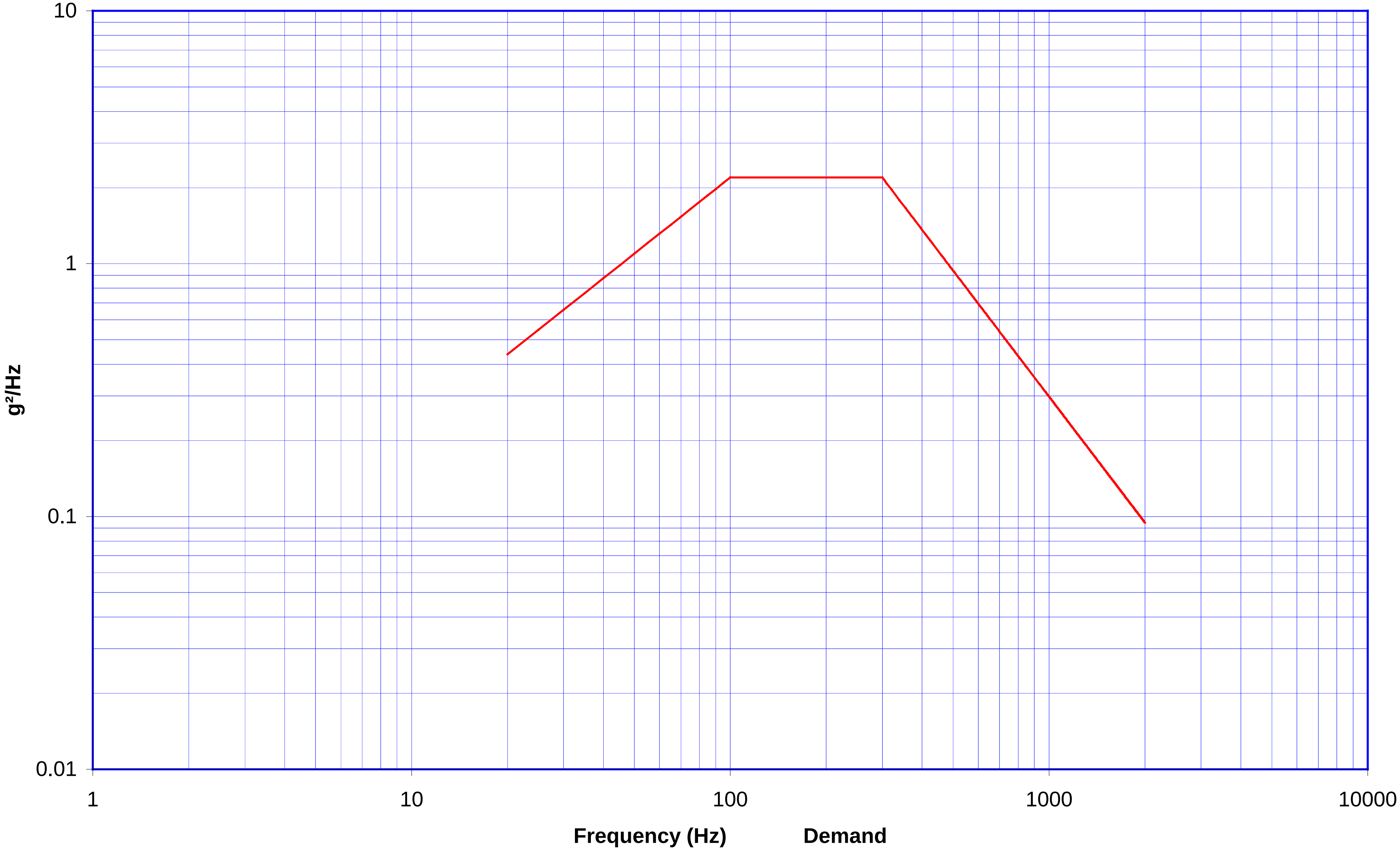
ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: Y AXIS - CONTROL
g(rms) : 34.88

Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
06-Oct-2000



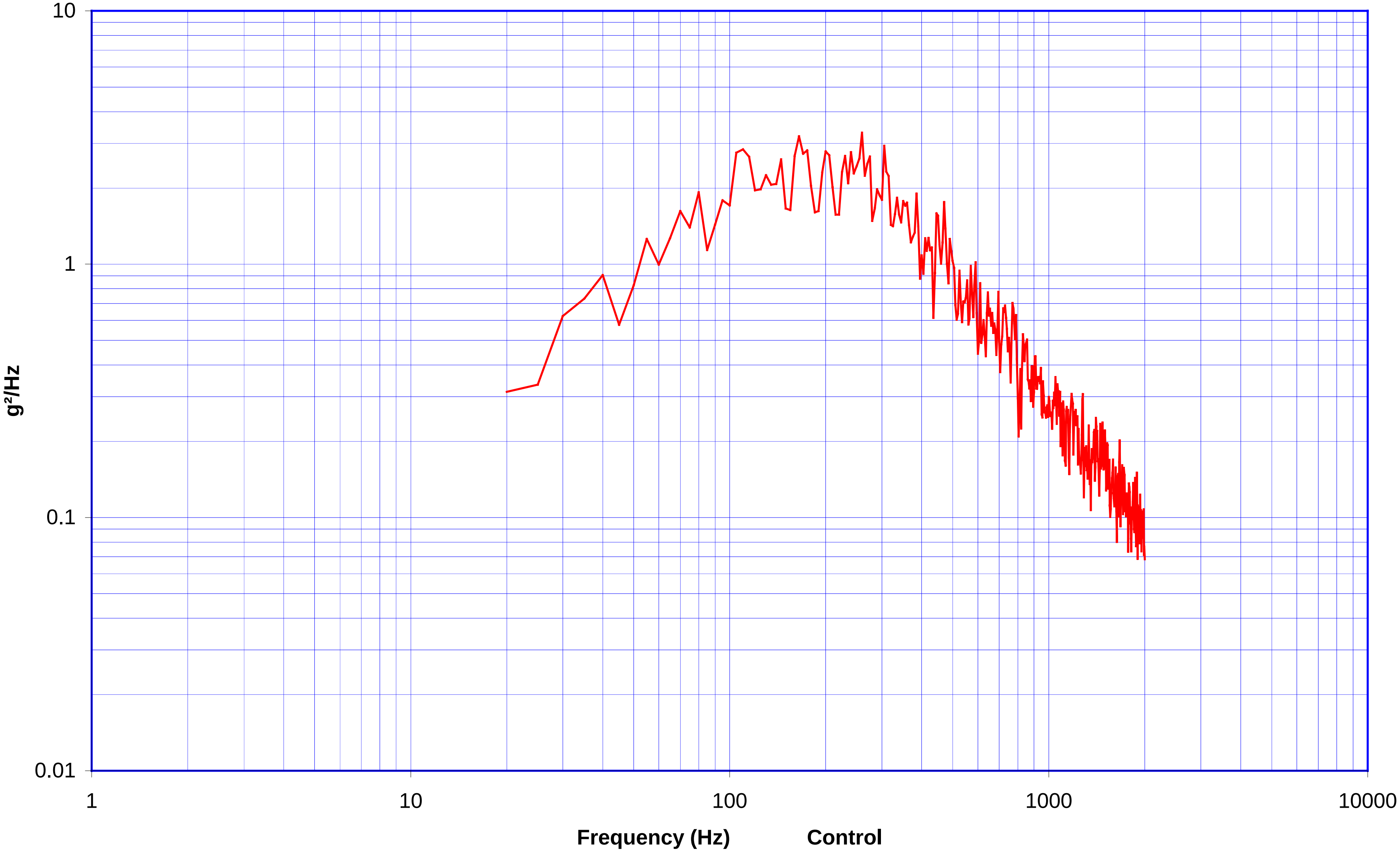
ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: Z AXIS - DEMAND
g(rms) : 35.4

Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
05-Oct-2000



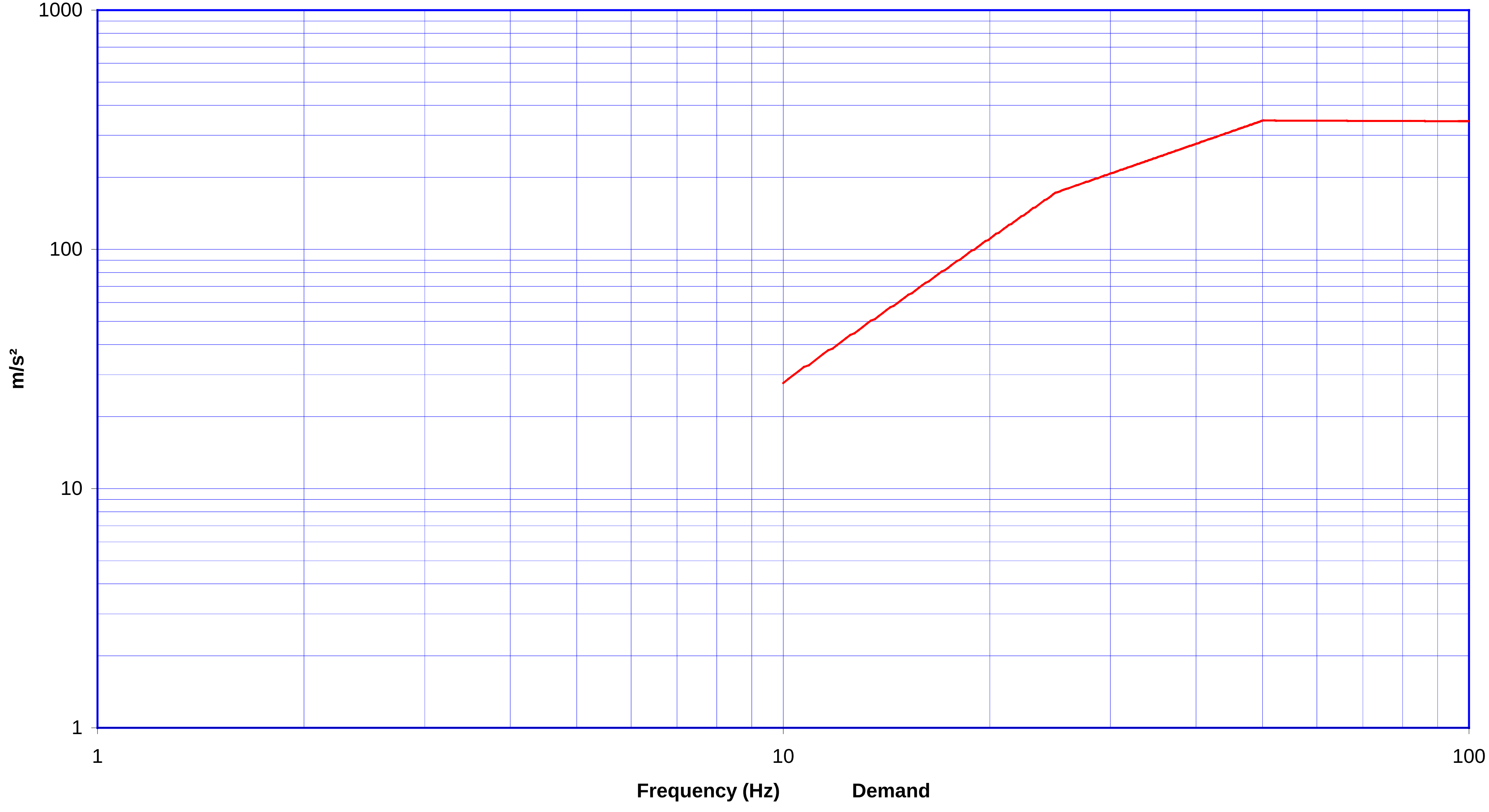
ESA FIBRE CONNECTORS
RANDOM VIBRATION
Test Name: Z AXIS - CONTROL
g(rms) : 35.25

Test Duration: 2.5 mins
No of samples: 397
Test Range: 20-2000 Hz
05-Oct-2000



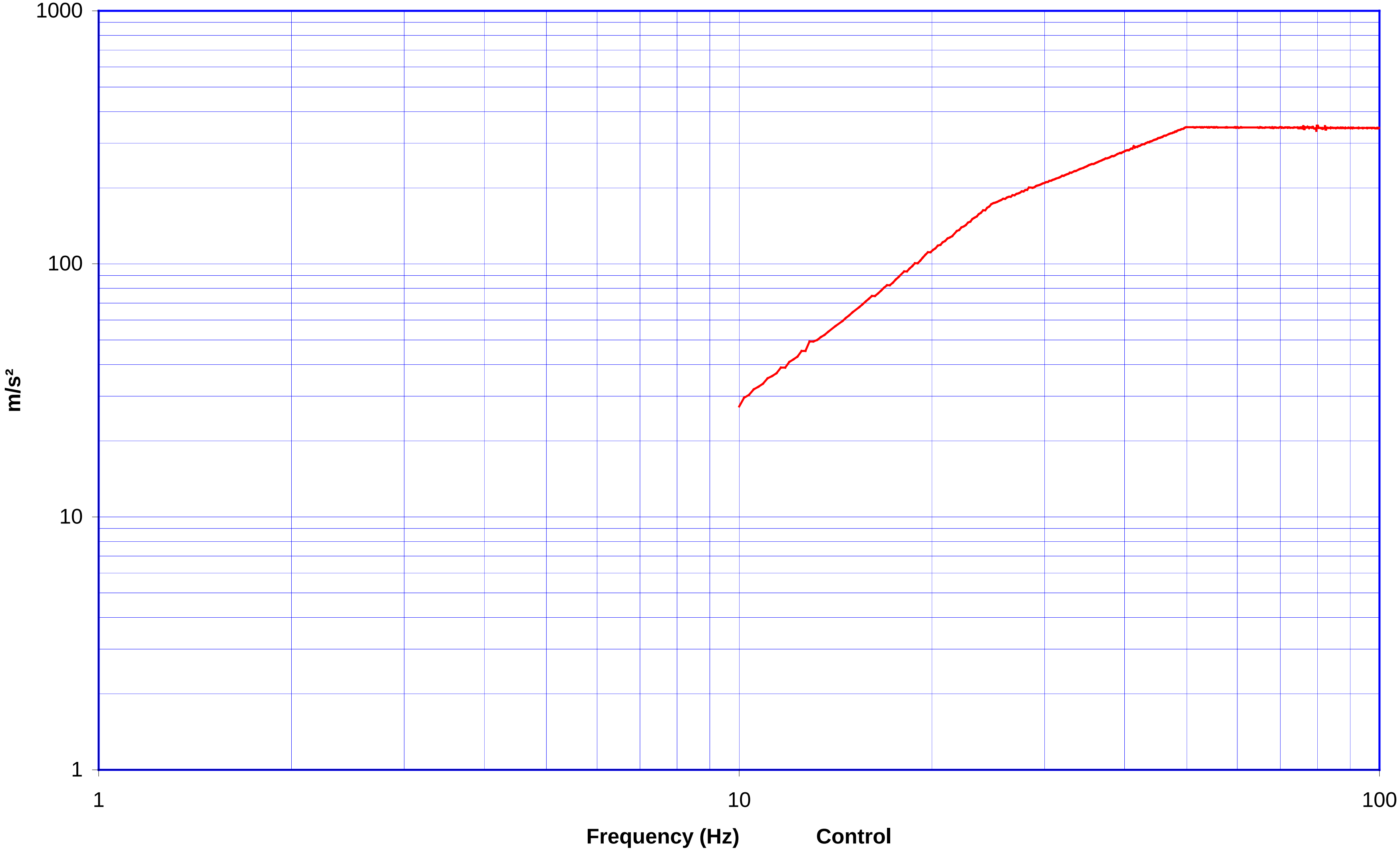
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: X AXIS - DEMAND
g(rms) : 35

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
05-Oct-2000



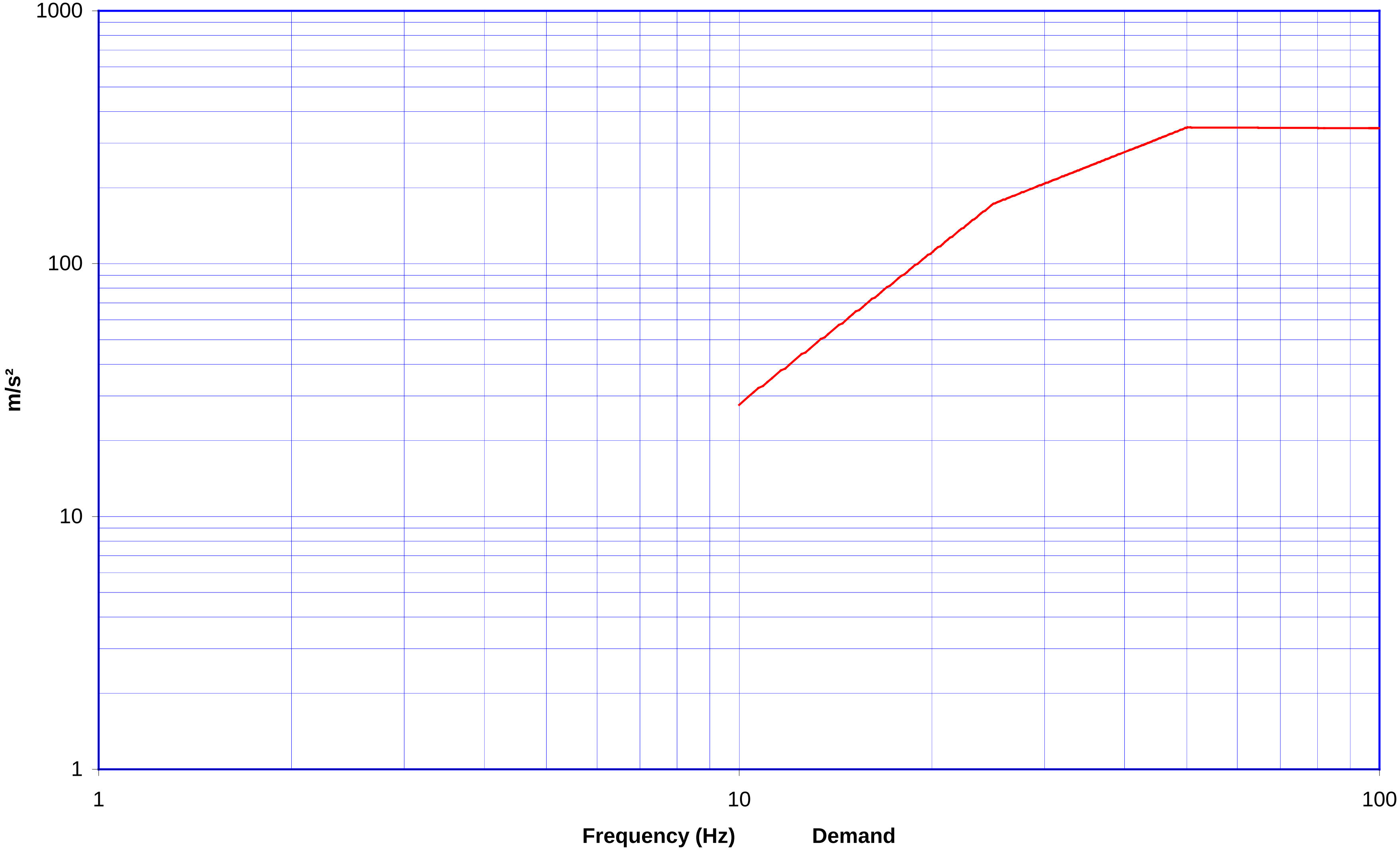
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: X AXIS -
g(rms) : 35.071

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
05-Oct-2000



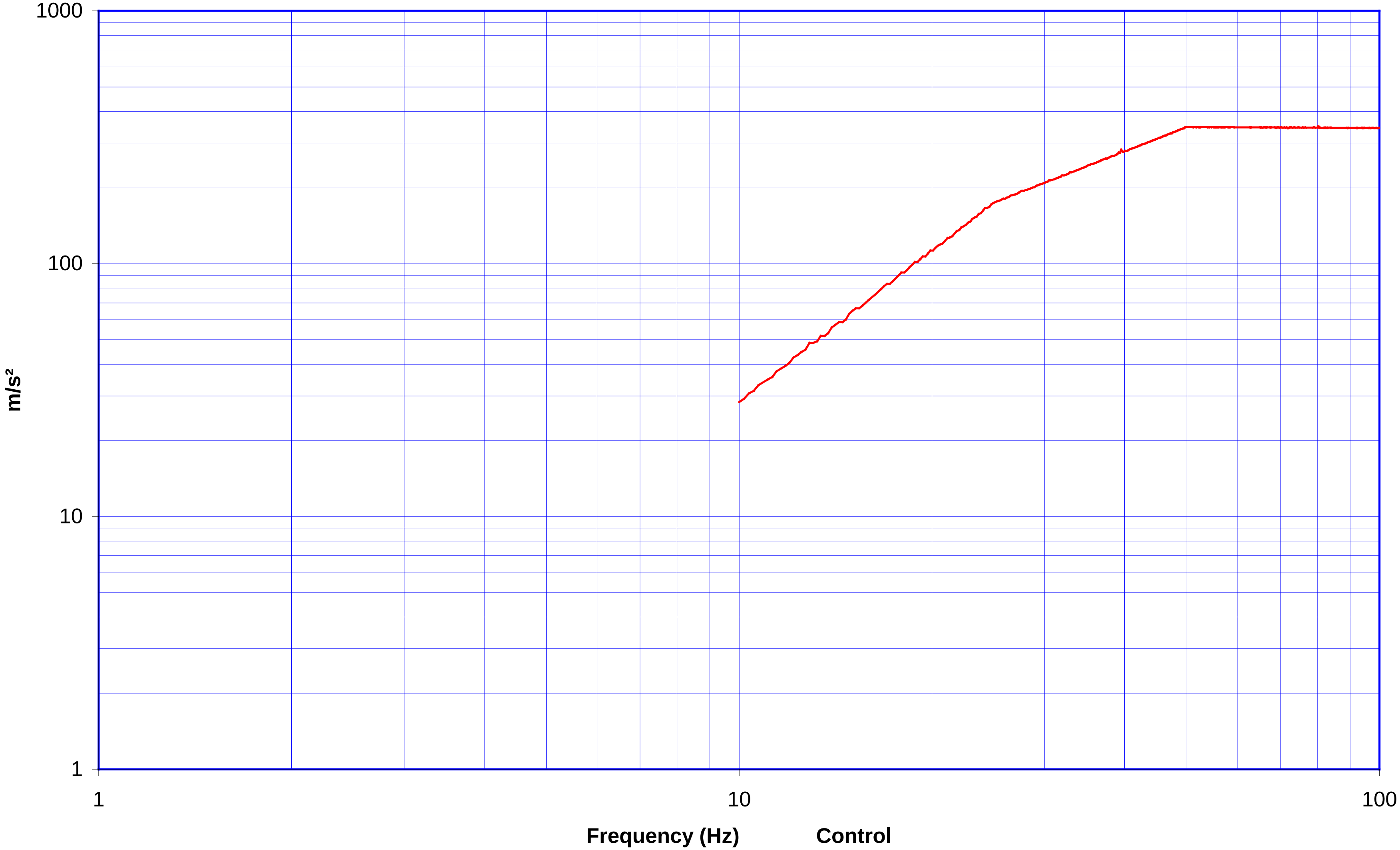
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: Y AXIS - DEMAND
g(rms): 35

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
06-Oct-2000



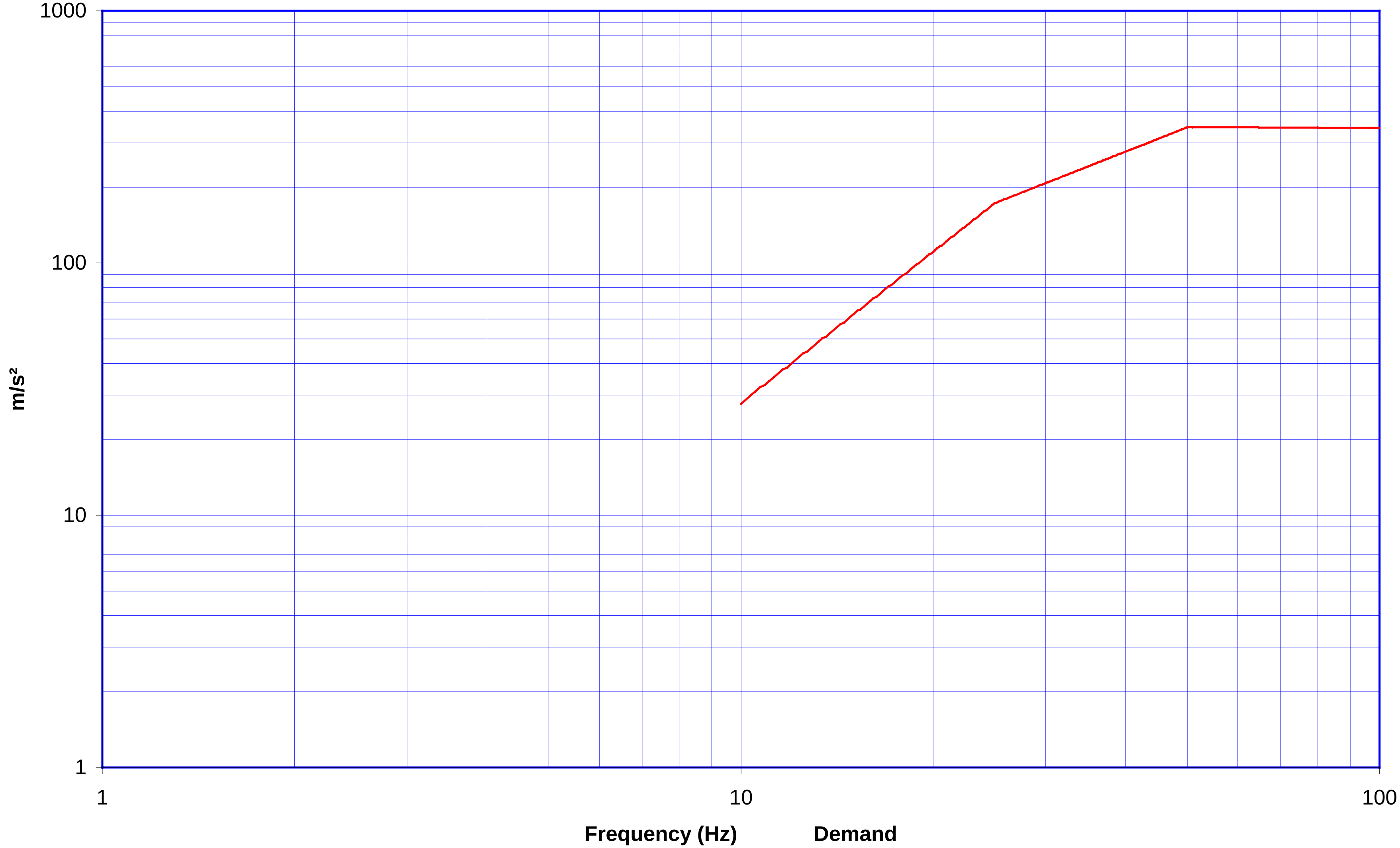
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: Y AXIS - CONTROL
g(rms) : 35.087

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
06-Oct-2000



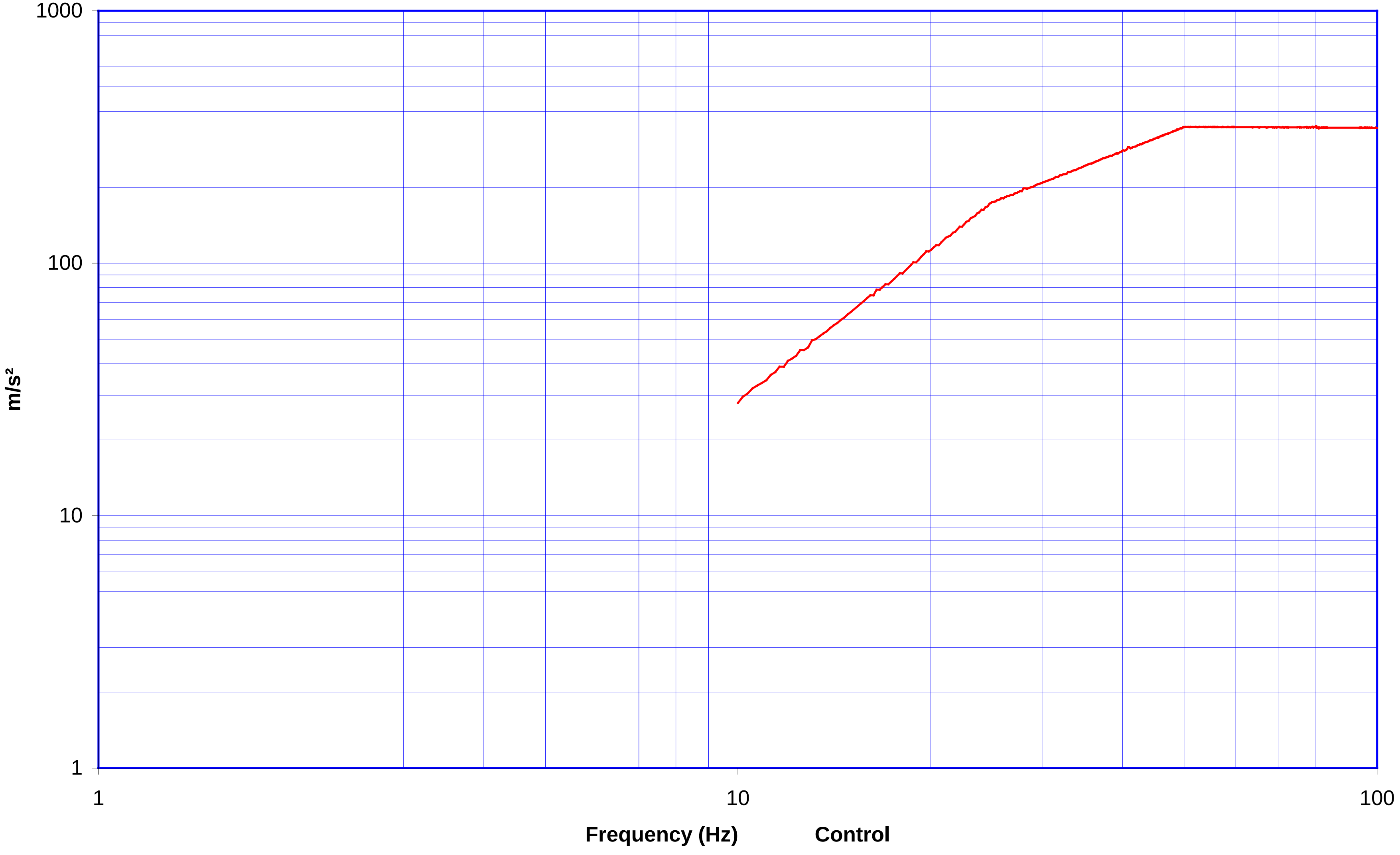
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: Z AXIS - DEMAND
g(rms) : 35

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
05-Oct-2000



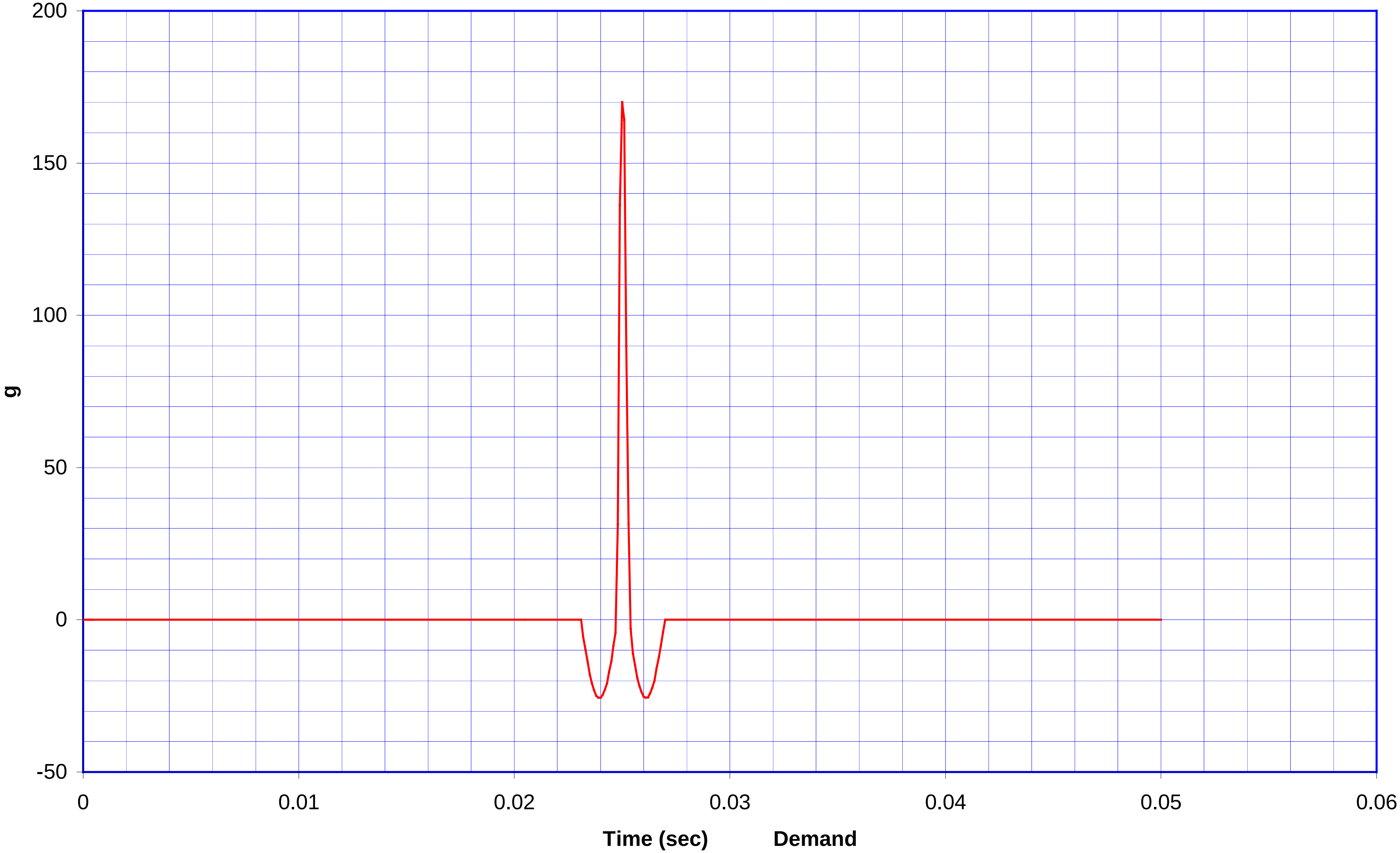
ESA FIBRE CONNECTORS
POWER SINE VIBRATION
Test Name: Z AXIS - CONTROL
g(rms) : 35.059

Sweep Rate: 2 oct/min
No of samples: 501
Test Range: 10-100 Hz
05-Oct-2000



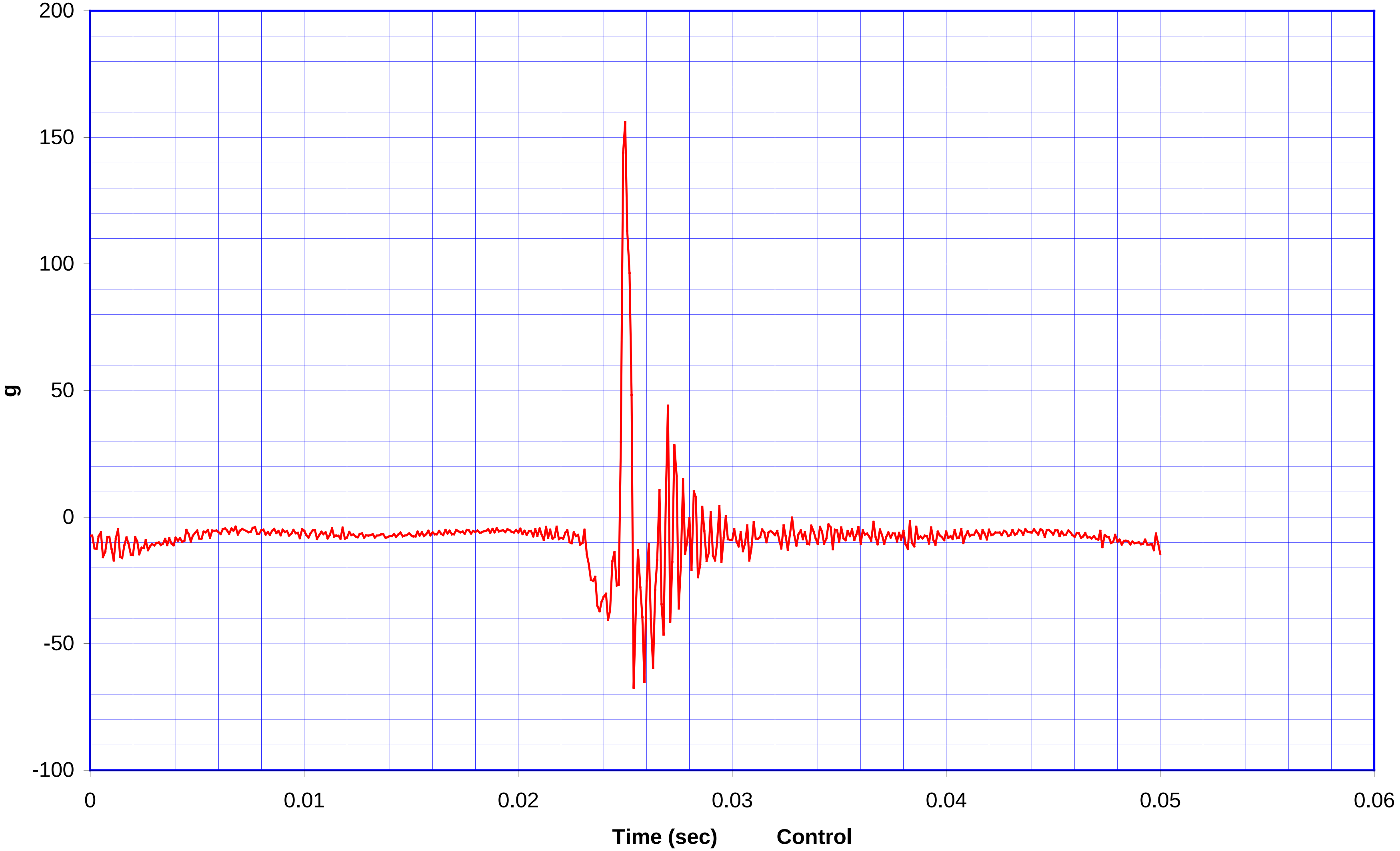
ESA FIBRE CONNECTORS
SHOCK VIBRATION
Test Name: X AXIS - DEMAND
Max g : 169.996

Sweep Rate: --------
No of samples: 502
Test Range: 150 g over 0.5
05-Oct-2000



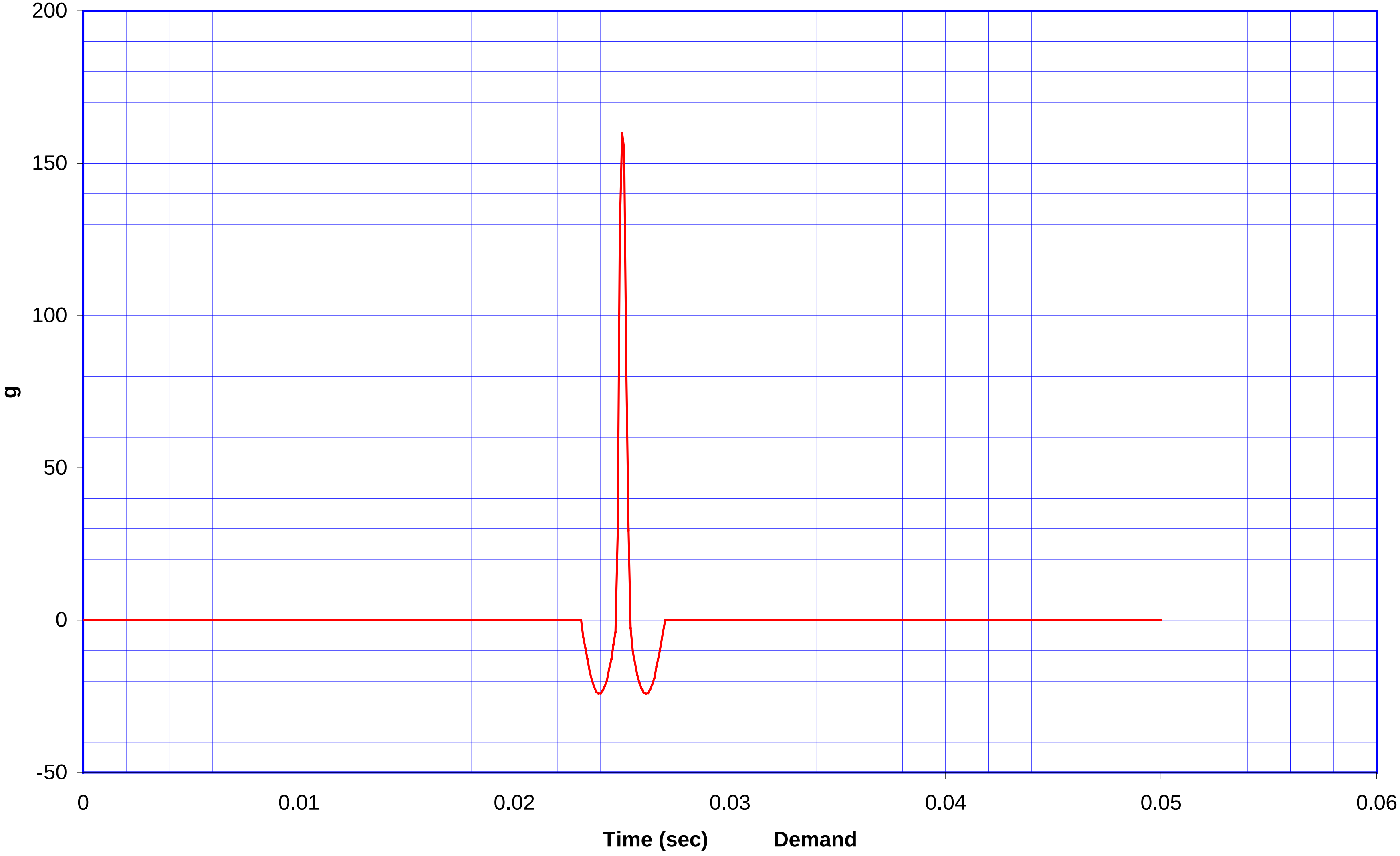
SHOCK VIBRATION
Test Name: X AXIS - CONTROL
Max g : 156.16

Sweep Rate: -------
No of samples: 502
Test Range: 150 g over 0.5
05-Oct-2000



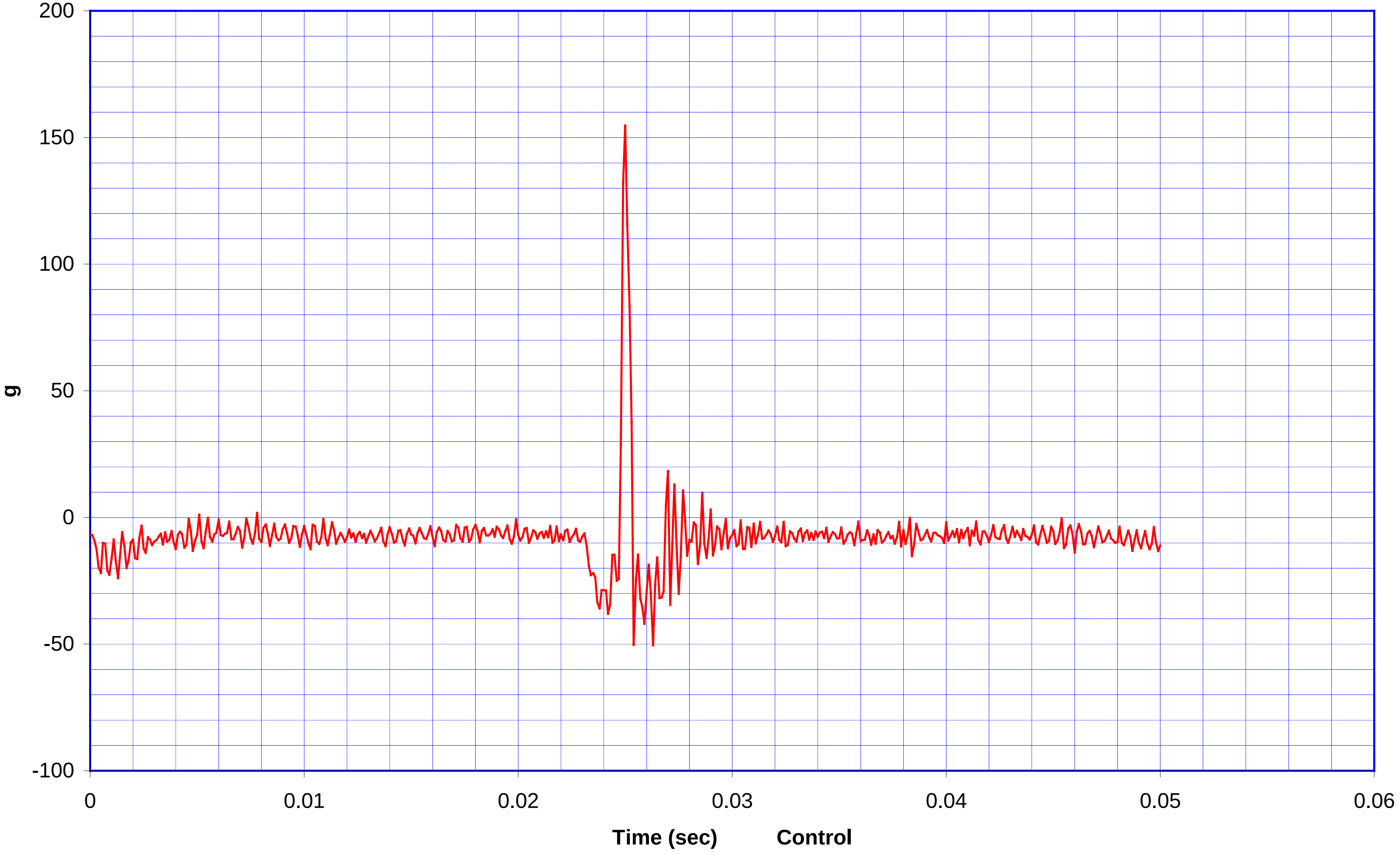
ESA FIBRE CONNECTORS
SHOCK VIBRATION
Test Name: Y AXIS - DEMAND
Max g : 160

Sweep Rate: -------
No of samples: 502
Test Range: 150 g over 0.5
06-Oct-2000



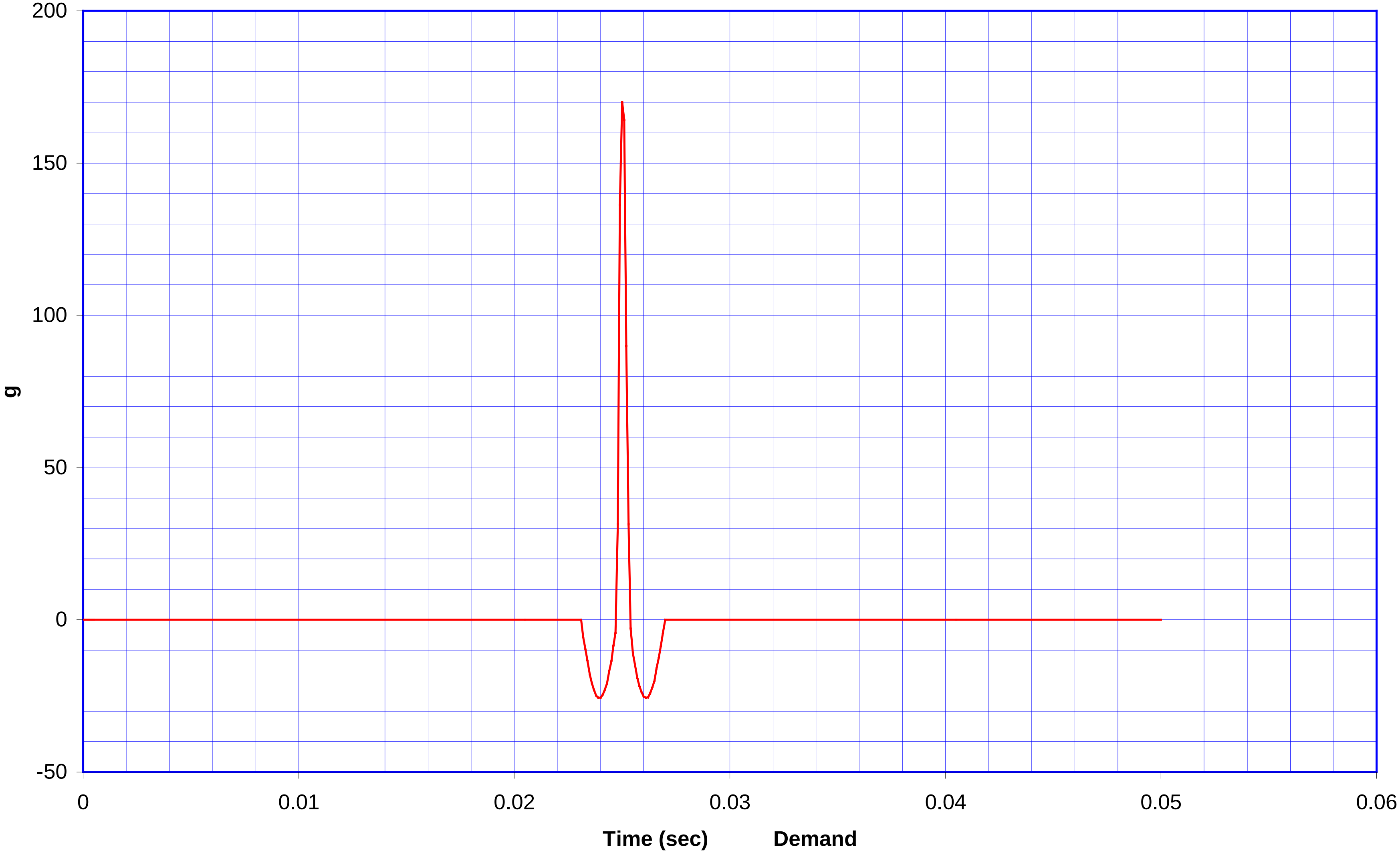
ESA FIBRE CONNECTORS
SHOCK VIBRATION
Test Name: Y AXIS - CONTROL
Max g : 154.68

Sweep Rate: -------
No of samples: 502
Test Range: 150 g over 0.5
06-Oct-2000



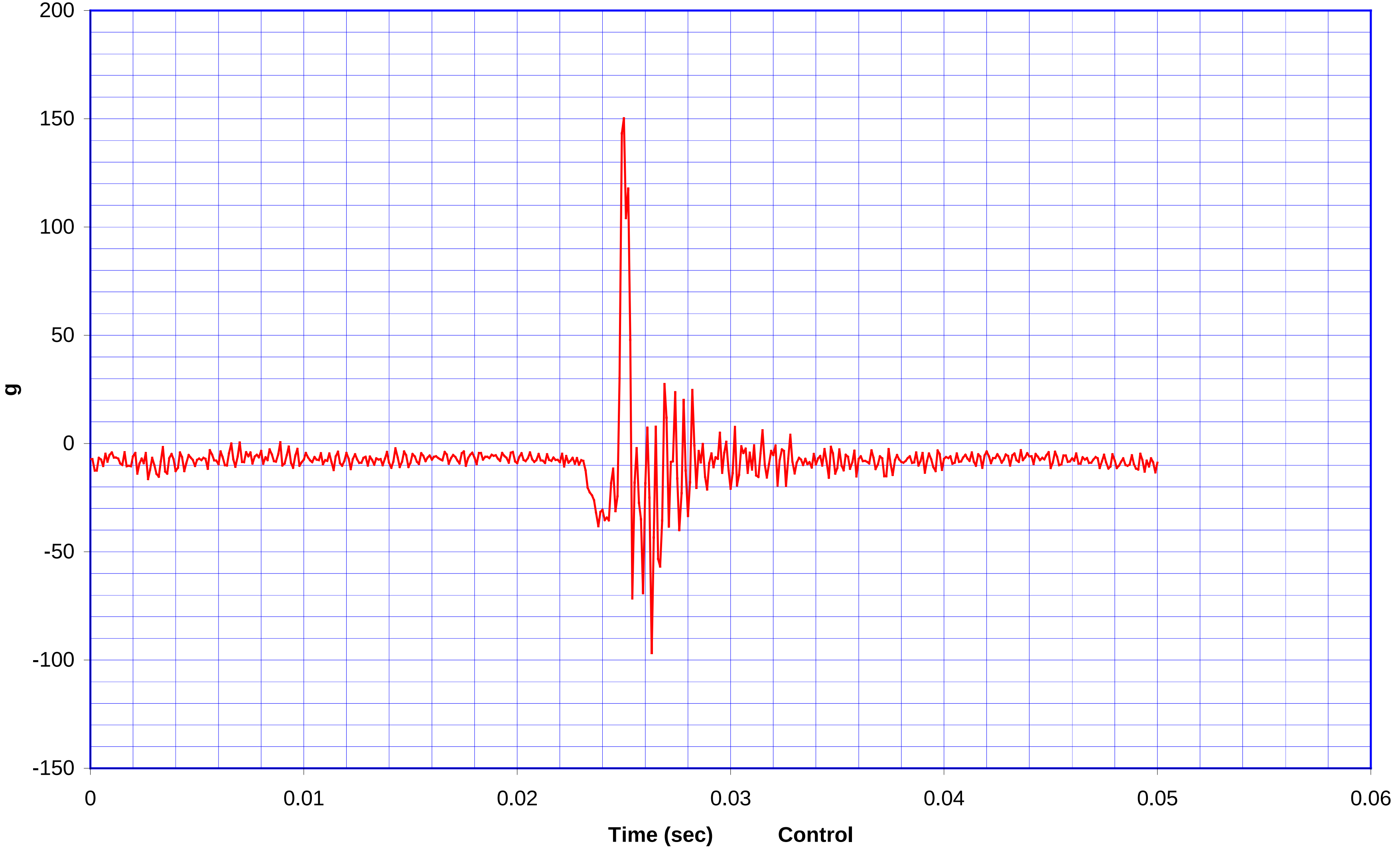
ESA FIBRE CONNECTORS
SHOCK VIBRATION
Test Name: Z AXIS
Max g : 169.996

Sweep Rate: -------
No of samples: 502
Test Range: 150 g over 0.5
05-Oct-2000



ESA FIBRE CONNECTORS
SHOCK VIBRATION
Test Name: Z AXIS - CONTROL
Max g : 150.195

Sweep Rate: -------
No of samples: 502
Test Range: 150 g over 0.5
05-Oct-2000



References:

1 ISS Fiber Optic Failure Investigation – Root Cause Report, August 1, 2000
NASA GSFC Report, Sponsored by NASA JSC and the Boeing Company.

2 Tests and Results of Active Alignment Fiber Optic Connectors for Space Usage, Lisa J. McMurray, SPIE Vol 2811, pp 264-275, 1996.