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Executive Summary of the Final Report

Identification and Evaluation of Fibre Optic Components

ESA contract no. 12299/97/NL/SB(SC)

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EUROPEAN SPACE AGENCY
CONTRACT REPORT

The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organisation that prepared it.

Contents

1 INTRODUCTION

This final summary report concludes the present stage of work undertaken by Sira Electro-Optics Ltd for ESTEC under Contract No. 12299/97/NL/SB(SC) - ***Identification and Evaluation of Fibre Optics Components – Phases 2 and 3***. The work follows on from an earlier Phase 1 contract, No AO/1-3170/NL/SB, where consideration was given to the availability of commercial, space quality, components, which employed optical fibre technology.

1.1 PHASE 1 - AVAILABILITY OF COMMERCIAL FIBRE-OPTIC, SPACE QUALITY, COMPONENTS

The work performed in Phase 1 undertook a general review of the availability of commercial fibre-based components which were intended specifically for use under space environment conditions and, where these were available, what national or international standards had been applied. The result of this review showed that there were effectively no off-the-shelf components available which did not require the end user to perform extensive evaluation test measurements.

One specific area of development however, being undertaken in the USA by workers at NASA's Goddard Space Flight Center in collaboration with US industry, related to the provision of multimode optical fibre cable primarily in relation to the application of fibre optic data busses to the space environment. A key direction of this work was towards increasing maximum bit data rate. Future requirements indicated that it would be necessary to employ the greater bandwidth capability of single-mode fibre. As there was no direct evidence of work being undertaken, either in the US or Europe, to standardise the supply of space-qualified single mode optical fibre cable with connectors, and because fibre cable is a fundamental component within many optical fibre systems, it was proposed that single mode fibres should form the basis of the work undertaken in Phases 2 and 3.

1.2 PHASE 2 - IDENTIFICATION AND EVALUATION OF FIBRE OPTICS COMPONENTS

The work undertaken in Phase 2 was directed first towards evaluation and final selection of identified standard single-mode optical fibres of European origin through exposure to ionising radiation. This was followed by environmental test measurements to assess the selected optical fibre when incorporated within commercially available, space-quality cable fitted with space-quality connectors.

1.3 PHASE 3 – PREPARATION OF ESA/SCC DOUMENTATION

The work performed in Phase 3 was undertaken to provide a suite of ESA/SCC documents, which detailed the route to qualification and procurement of the above and similar space qualified optical fibre cable.

1.4 REFERENCE DOCUMENTS

For details of Phase 2 work, reference should 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
- RD4 TN3 – Rapid Depressurisation, Vibration, Shock & Thermal Vacuum Testing – Fibre Cable and Connectors (Issue 2). A/1478/00/TN3, 15 June 2001

For details of Phase 3 work, reference should be made to the following:

- RD5 Single Mode Simplex Optical Fibre Cable Assemblies – ESA/SCC Generic Specification, Draft 5
- RD6 Requirements for Capability Approval of Optical Fibre Cable Assemblies – ESA/SCC Basic Specification, Draft 5
- RD7 Evaluation Test Programme for Optical Fibre Cable Assemblies – ESA/SCC Basic Specification, Draft 5
- RD8 Single Mode Simplex Optical Fibre Cable Assemblies Based On Type XXXX – ESA/SCC Detail Specification, Draft 5
- RD9 Terms, Definitions, Abbreviations, Symbols and Units for Optical Fibre Cable Assemblies – ESA/SCC Basic Specification, Draft 5

2 PHASE 2 - OPTICAL FIBRE SELECTION AND IRRADIATION TEST MEASUREMENTS

The initial requirement was to irradiate standard, commercial, single-mode, bare optical fibres using both gamma ray and proton test sources and, from the resulting information on induced attenuation effects, select one fibre type for inclusion within a space-quality fibre cable structure.

Three commercial, double acrylate-buffered, single mode fibres were earlier identified, being manufactured in Europe by Plasma Optical Fibre, Optical Fibres (Corning) and Pirelli. Fibre construction was in the form of germanium-doped silica core (diameter ~9 µm) and silica cladding (diameter 125 µm); the acrylic outer layer diameter was 250 µm.

For gamma irradiation tests, the Cobalt-60 facility at Cranfield University /RMCS, Shrivenham was employed. The proton irradiation source was provided by the Paul Scherrer Institut in Switzerland.

2.1 GAMMA IRRADIATION TESTS

For gamma irradiation all three European test fibres were wound simultaneously upon a polystyrene bobbin, as shown in Figure 2.1-1. The complete assembly was mounted upon a rotating turntable and fed with fibres at a slow rate in order to avoid unwanted tension effects. The required bobbin diameter was 96 cm in order to achieve a dose rate of ~5 rad sec-1. The bobbin material was expanded polystyrene, which had a negligible effect upon radiation attenuation (being within the specified dose accuracy). The test length (~200m) of each fibre type was required to have additional 10m input and output ‘tails’ to enable feed-through to the adjoining laboratory where data-logging hardware was located.

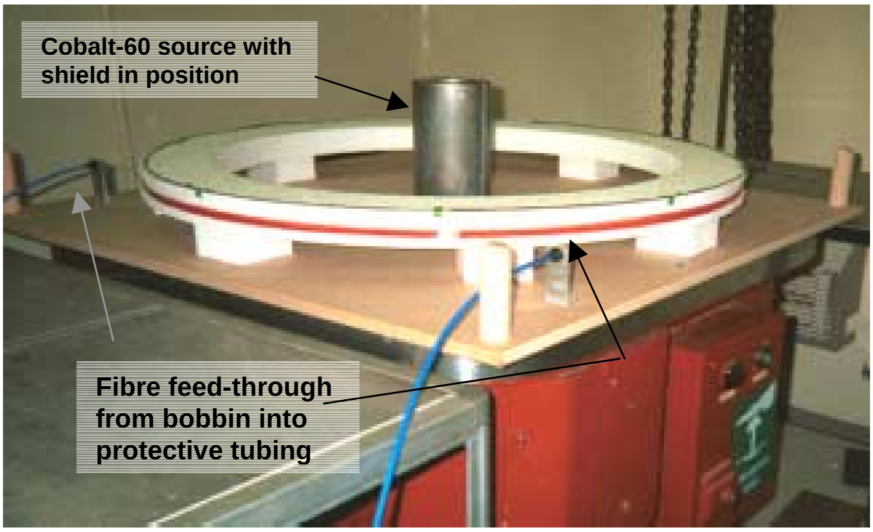

Figure 2.1-1 - Fibre bobbin positioned within irradiation chamber

Figure 2.1-1 also shows the fibre bobbin mounted centrally about the 20-pencil, Cobalt-60 source. Room illumination was by way of a ceiling mounted, fluorescent lamp, which could be switched from outside of the sealed chamber. Ambient temperature was thermostatically controlled to lie between 22°C – 23°C. When the chamber door was sealed the radiation source cover could be lowered allowing fibre irradiation to commence. Transmission data for each fibre path was logged automatically at intervals of one minute. The total dose achieved was ~ 0.75 Mrads (Si) over a continuous period of 47 hours.

The layout of the purpose-built data-logger is shown schematically in Figure 2.1-2. Here a fibre coupled laser diode package, operating at wavelength 1310 nm, was coupled into the three test fibres and one short length (2 m) reference fibre, using a fibre splitter, patch cords and mechanical splices. Each of the four fibres was connected to separate InGaAs PIN photodiode detectors. The laser diode source was modulated at 100 Hz with 50% duty cycle and had a mean output power of 1.5 mW. A requirement for transmitted power within each test fibre of ≤ 1 μW during irradiation testing was achieved using an inline attenuator.

A summary of the radiation-induced attenuation effects is given in Table 2.1-1.

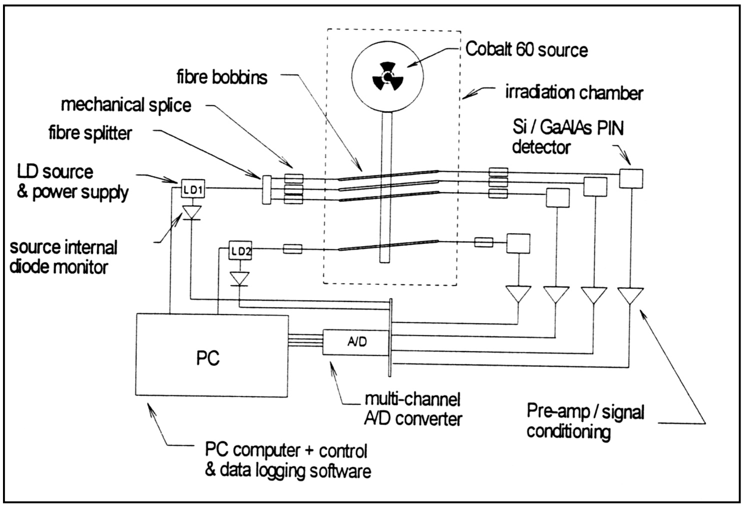

Figure 2.1- 2 – Schematic data-logger configuration

2.2 PROTON IRRADIATION TESTS

Proton irradiation was provided by the Proton Irradiation Facility (PIF) at the Paul Scherrer Institut, Switzerland. The proton beam was produced by a 590 MeV Ring accelerator; an electrostatic beam splitter deflected between 1 and 20 microAmp of the beam current into the NA-hall. After the PIREX target station, the beam passed through a set of exchangeable copper-graphite blocks (primary degrader), reducing its energy and intensity, and was then guided to the NA2 (PIF) area where the present test irradiation was performed.

All three European test fibres were wound simultaneously onto a thin-walled (0.5 mm) Al-alloy bobbin as shown in Figure 2.2-1, with inner fibre diameter 60 mm and axial length 50 mm. The fibre-layer thickness was less than 5 mm. Trailing input/output fibre ends, used for connection to mechanical splice units, were secured using plastic tape. Tape was also used to clearly distinguish between test fibres supplied by Plasma Optical and Optical Fibres (Corning). Fibre supplied by Pirelli was easily distinguishable due to its red acrylate buffer.

Figure 2.2-1 Fibre bobbin with fibres for proton irradiation

Transmission measurements were made, using the laser diode operating at a wavelength of 1324 nm in continuous

(CW) mode, for each of the three commercial fibres both before and after irradiation. Transmission measurements were also made at the same time using a 2 m length of reference fibre. Additional, mechanically induced, attenuation due to winding fibre on a relatively small bobbin diameter (60 mm) was noted. The results obtained are summarised in Table 2.2-1.

2.3 FIBRE SELECTION FOR CABLE MANUFACTURE

From the test results obtained it was concluded that all three European commercial optical fibres tested had similar performance in terms of induced attenuation when irradiated with Cobalt-60 gamma rays and energetic protons. Maximum gamma ray induced attenuation at a wavelength of 1324 nm was in the region of 0.02 dB m^{-1}. For a 1 km fibre this is equivalent to 20 dB attenuation, i.e. a factor 1/100.

From consideration of all potential errors associated with transmission measurement none of the fibres tested was considered to have a significant performance margin. Whilst the Pirelli fibre appeared to give better performance during Cobalt-60 irradiation (and the red coloured acrylate buffer proved to be a distinct advantage during fibre handling), the relaxation characteristics of the Plasma Optical fibre appeared to be better under both gamma and proton irradiation.

As only one fibre type was required for incorporation within the new GoreTex cable it was recommended that the fibre supplied by Plasma Optical Fibres be employed. It was noted however that any of the three commercial fibre types selected would be suitable, in terms of radiation induced attenuation performance, for further performance evaluation testing when incorporated within a space-quality GoreTex cable.

3 PHASE 2 - 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 in the above 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 the US company SpecTran.

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 two existing Gore 1.2 mm simplex, single-mode fibre cables were also purchased for use in test measurements; 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, which occurred during a cable winding procedure).

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.

4 PHASE 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 4-1.

The commercial literature shows the appropriate connector form to be: AVIM D-6206.1 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.

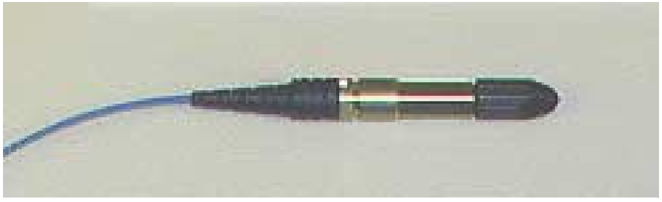

Figure 4-1 AVIM D-6206 Single Mode Connector

The performance specification for this form of connector shows an insertion loss of < 0.5dB (0.2 dB typical), and a return loss > 40 dB (50 dB typical). Vibration and shock test performance specifications were commensurate with the requirements defined in the evaluation programme. Cyclic operating temperature is specified as between –55°C and +125°C when using appropriate fibre cable. Whilst the proposed test specification had an upper limit of +150°C, Sira

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.

were advised by Diamond that it should 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, should be more appropriate for use with the higher temperatures specified for the proposed tests. This new version of the connector employs a ferrule made from the ceramic zirconia, replacing the standard tungsten-carbide form, and has a slightly modified ferrule insert. This form of the connector did not, at that time, appear in the commercial literature as a standard item, as it was undergoing evaluation testing.

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 (although it was subsequently discovered that the additional connectors supplied were of 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.

5 PHASE 2 - OPTICAL FIBRE CABLE TEST MEASUREMENTS

The following key test measurements were performed on a number of fibre cable samples both with and without fibre connectors fitted:

- Rapid depressurisation
- Vibration and shock
- Thermal vacuum cycling

5.1 RAPID DEPRESSURISATION TESTS

This test was required to determine if exposure to a rapid fall in ambient pressure, from 1 atmosphere to $\leq$ 10 torr within a period of 5 seconds, affected optical fibre cable transmission. The test equipment employed is shown in Figure 5.1-1. Here a secondary vacuum chamber was connected to the main vacuum chamber via a flexible pipe. Test components could be 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. Vacuum sealing was

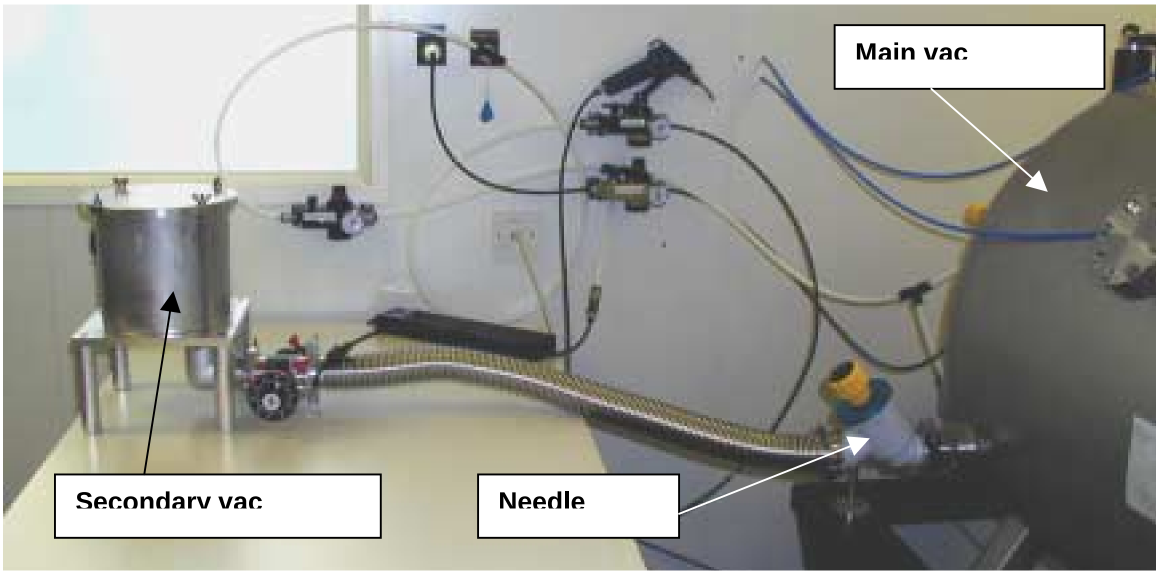

Figure 5.1-1 - Rapid Depressurisation Test Set-Up

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.

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 laser diode 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 5.1-2.

Figure 5.1-2 - Test Cable On Flexible Former

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 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 (we also note that polyimide-coated fibre breakage occurred during a winding stage in preparation for ^{60}Co irradiation tests – see also section 3).

Figure 5.1-3 - Mounting Base-Plate For Testing Optical Fibre Connectors

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 5.1-3, 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.

5.2 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 5.2-1, with vibration axis vertical.

Figure 5.2-1 - Sira Vibrator System

The fibre connector base plate 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 shown in Figure 5.2-1, 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 (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 test values employed, for each of three orthogonal axes, were:

a) Power Sine Vibration

Frequency Hz	Sweep rate: 2 Oct. / min Duration: 1 sweep up
10 – 25	14 mm pk-pk
25 – 50	1.1 m/s
50 - 100	35 g

b) Random Vibration

Frequency Hz	PSD $g^2\ Hz^{-1}$	Overall g (rms)
20 - 100	+3 dB/Oct.	
100 - 300	2.2	35.4
300 - 2000	–5 dB/Oct.	

c) Shock

Half sine shock pulse of duration 0.5 msec and magnitude 150g

5.3 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 5.3-1 below.

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.

Figure 5.3-1 - Thermal Vacuum Test Facility

It can be seen from Figure 5.3-2 that maximum and minimum temperatures recorded were generally slightly in excess of the specified requirements (i.e. ~ +160°C and ~ –56°C).

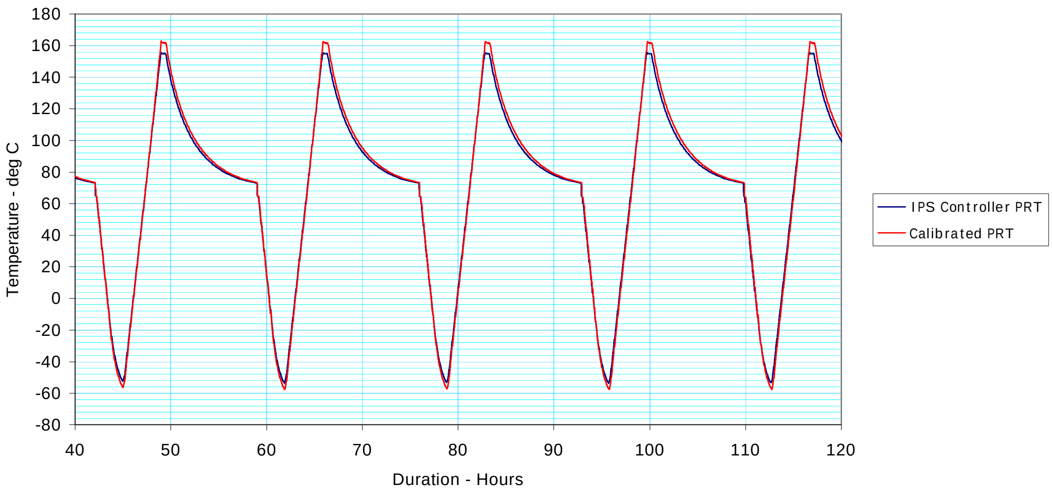

Figure 5.3-2 – Typical Thermal Control Cycles

5.3.1 Optical fibre cable – thermal vacuum cycling

Fibre cables were passed into, and out of, the vacuum chamber via holes located within a removable flange plate. As in the case of rapid-depressurisation measurement vacuum sealing was achieved using a clear, flexible, silicone elastomer. 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).

Figure 5.3-3 – Cable Support Cylinder in Thermal Vacuum Chamber

Thermal vacuum testing was performed on two 200 m lengths of, acrylate buffered, optical fibre cable (cable types FON1019 and FON 1010). Both test cables were wound simultaneously upon a rigid aluminium cylinder, with length 250 mm and external diameter 130 mm, as shown in Figure 5.3-3. 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.

5.3.2 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. [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].

6 PHASE 2 - OPTICAL FIBRE CABLE TEST RESULTS

A report on the results of each test performed is given below. Key test data obtained are summarised in a separate document RD4.

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 document RD4 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.

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.

6.1 OPTICAL FIBRE CABLE – RAPID DEPRESSURISATION

Objective: 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, document RD4

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

6.2 OPTICAL FIBRE CONNECTORS – RAPID DEPRESSURISATION

Objective: 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, document RD4.

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.

6.3 OPTICAL FIBRE CONNECTORS – VIBRATION AND SHOCK

Objective: 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, document RD4

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. $\leq$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, however, evident. 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.

6.4 OPTICAL FIBRE CABLE – THERMAL VACUUM CYCLING

Objective: 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, document RD4.

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 fibre types. 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.

6.5 OPTICAL FIBRE CONNECTORS – THERMAL VACUUM CYCLING

Objective: 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, document RD4.

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 over the lower test band 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 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. From a least square fit to this (DC3) data the average transmission was 0.964 with minimum recorded transmission of 0.910 (i.e. 0.25 dB).

The data obtained for thermal cycles covering the higher temperature band was similar to the above; i.e. a significant loss in transmission at the lower temperatures in the case of tungsten carbide ferrules, with little effect upon transmission in the case of zirconia ferrules.

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 from examination of the lower temperature band data, indicated that after some initial oscillation, the onset temperature stabilised in the region of –37.5°C (DC1) and –40°C (DC2). The temperature at which loss onset first occurred was found to be approximately –43°C (DC1) and –55°C (DC2).

Consideration of transmission loss was also extended to include the higher temperature, band data. In this case, subsequent operation at the higher temperature was seen to widen each 'trough', accompanied by a smaller maximum attenuation.

The precise reason for the above performance of connector sets with tungsten carbide ferrules was unclear (but see comments below), however we should note the work undertaken by L.J. McMurray(ref 2), 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 was 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. No obvious signs of damage were evident.

7 PHASE 2 - EVALUATION TESTING - CONCLUDING SUMMARY

Single mode optical fibre cable with acylate buffer, principally for use at wavelength 1310 nm, were 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

(Note: 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 Appendix D, document RD4)).

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 that 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.

8 PHASE 3 - ESA/SCC DOCUMENTATION: SINGLE MODE SIMPLEX OPTICAL FIBRE CABLE ASSEMBLIES

Draft ESA/SCC documentation was prepared for single mode simplex optical fibre cable assemblies. The documents prepared were: a Basic Specification for Capability Approval, an Evaluation Test Programme, a Generic Specification, a Detail Specification and a document of terms, definitions, abbreviations, symbols and units used in the other documents.

The Basic Specification for Capability Approval of simplex optical fibre cable assemblies (with, or without, connectors) outlines the requirements for the definition of the Capability Domain and its boundaries, the evaluation of a Capability Domain, Capability Approval Testing and cable assembly type approval testing.

The Evaluation Test Programme establishes the procedure to be followed in the evaluation of the capabilities of optical fibre cable assemblies as required for space applications and to anticipate, as far as possible, behaviour during qualification testing. The test programme described sets out to over-stress specific characteristics of the optical fibre cable and connectors with a view to the detection of possible failure modes. A constructional analysis is also described for detection of any design and construction defects which may affect reliability and to facilitate failure analysis activities.

The Generic specification defines the general requirements for the qualification approval, capability approval, procurement, including lot acceptance, and delivery of optical fibre cable assemblies. This specification contains the appropriate inspection and test schedules and also specifies the data documentation requirements.

The testing techniques described in the Evaluation Test Programme and the Generic specification are based on published procedures and Sira experience from previous phases of optical fibre evaluation. Published methods referenced include IEC optical and environmental tests, and ESA/SCC flammability test methods.

The Detail Specification gives the physical and optical characteristics, test and inspection data for optical fibre cable assemblies. The values given are based upon the specific components and manufacturers identified in Phase 2.

Irradiated Fibre Transmission Measurements:

a) Cranfield University; RMCS, Shrivenham

Cobalt 60 Gamma Irradiation Tests

Total dose	0.822	Mrads($H_2$0)	0.75	Mrads(Si)
Dose rate	4.86	rads sec^{-1}	4.4	rads(Si) sec^{-1}
Source type	^{60}Co		20 pencil fixed geometry, symmetrical	
Source accuracy	+/-5.0	%		
Dosimeter			tertiary calibrated ion chamber traceable to Nat Std	
Ambient temp	22.5+/-0.5	deg C	controlled	
Exposure duration	47.0	hours	continuous	
Fibre length	190.0	m	additional 10m tails; all 3 fibres wound simultaneously	
Bobbin diameter	960.0	mm		
Bobbin axial length	25.0	mm		
Bobbin material			expanded polystyrene (negligible loss)	
Laser diode wavelen	1324	nm		
PIN diode detectors			GaAlAs	
Radiometer			UDT; GaAlAs detector head; Responsivity 0.9058 A/W)	

Transmission Data:	using LD with attenuator -							
	Data-logged period*				Post exposure**			
	(LD modulation freq: 100 Hz)				(LD operated CW)			
Fibre	Int (micW)	Rel T	dB	dB m^{-1}	Int (micW)	Rel T	dB	dB m^{-1}
2m Ref fibre***	2.7	-	-		3.3	-	-	-
Pirelli	2.2	0.544	2.64	0.014	2.1	0.63	2.01	0.011
Plasma Optical	2.0	0.489	3.11	0.016	2.3	0.68	1.65	0.009
Optical Fibres	2.5	0.449	3.48	0.018	2.2	0.66	1.81	0.010

* mean attenuation in 4 hour period just before source removed

** after delay period of 3 weeks following exposure

*** Ref fibre not irradiated

Signal intensity for data-logged period is calculated from mean of pre- and post-exposure measurements using radiometer

Table 2.1-1 Summary data for Cobalt-60 irradiation tests

b) PSI, Switzerland

Proton Irradiation Tests

Total dose	0.25	Mrad (Si)	
Beam energy	301.8	MeV	
Flux	1.52×10^{8}	p sec^{-1} cm^{-2}	
Dose rate	7	rads sec^{-1}	
Source type			590 MeV Ring-accelerator with electro-static beam splitting
Source accuracy	10	%	
Dosimeter			plastic scintillator / ionization chamber(s) combination
Ambient temp	-		
Exposure duration	10	hours	(18, 1-2 min breaks)
Fibre length	200	m	including tails; all 3 fibres wound simultaneously
Bobbin diameter	60	mm	
Bobbin axial length	50	mm	
Bobbin material			0.5 mm wall thickness alluminium alloy
Laser diode wavelen	1324	nm	
PIN diode detectors			GaAlAs
Radiometer			UDT; GaAlAs detector head; Responsivity 0.9058 A/W)

Transmission Data: using CW LD with attenuator -

	Pre exposure			Post exposure*			Induced attenuation*	
Fibre	Int (micW)	Rel T	dB	Int (micW)	Rel T	dB	dB	dB m^{-1}
2m ref fibre**	3.36	-	-	3.32	-	-	-	-
Pirelli	2.62	0.78	1.08	2.15	0.65	1.89	0.80	0.0040
Plasma Optical	2.68	0.80	0.98	2.57	0.78	1.10	0.12	0.0006
Optical Fibres	2.73	0.81	0.91	2.26	0.68	1.66	0.75	0.0037

* after safety delay period of 6 weeks following exposure

** test fibre not irradiated

Table 2.2-1 Summary data for proton irradiation tests