Document Reference: Final Summary Report

Project: Evaluation of Optic Fibre Cable Assembly

ESA Contract No.:4000101831/10/NL/RA

Title: Summary Report

1. Scope

This report is the summary of all the work carried out during the contract.
This document builds upon the detail provided in TN1, TN2 and TN3. The contract was divided into work packages.

2. Introduction and methodology

The project was broken into 3 tasks, which were then broken into distinct work packages.

Task	Work Package	Description
Task One	WP1100	Critical Review of Requirements
	WP1200	Technology Survey & Selection
Task Two	WP2100	Review of existing standards and specs
	WP2200	Preparation of ETP
Task Three	WP3100	Procurement & Assembly
	WP3200	Evaluation Testing
	WP3300	Result analysis and final Test Report

3. Overview of each Task/Work Package

Task One is the information-gathering phase of the project. The information and industry research was carried out on a number of fronts.

The first work package, WP1100 was designed to gather from space-industry people, information regarding past experience with fibre optics and what their requirements might be looking into the future.

The second work package, WP1200 aimed to gather industry information, about what components might be suitable for space applications.
We spoke to a number of fibre optic connector and cable manufacturers to discuss their space experience and their product range. We also conducted a broad review of various industry sectors who have some experience with fibre optics – and what their experiences have been. By combining this information with information from connector manufacturers, and fibre optic cable manufacturers, it enabled us to build up a good picture of the “state of the art” fibre optic industry.
We then prepared a shortlist of connectors that could be of interest to the European Space Agency, and then we moved from the shortlist to our 2 recommended connector types.

For comparison purposes, we grouped the connectors together under the following subheadings

- Single-fibre standard telecom connectors
- Single-fibre harsh environment & aerospace connectors
- 2 fibre connectors
- Multifibre connectors
- Ribbon fibre connectors

To capture the information, and to compare the connectors, we produced a comparison table.
In this table, we note the following headings for each connector type

Availability
Facility of Assembly
Fibrepulse Capability
Anti-Vibration
Compatibility with various types of fibre (notably 100/140, SM, MM, Angled and Polarisation Maintaining)
Outgassing Data (not much information available)
Mass of the connector system (2 conns plus adapter)
Name of European Supplier

Task Two was concerned with the preparation of an Evaluation Test Plan.

The first work package, WP2100 was based on checking existing specifications (from many sources) to see if there was an industry standard. We also used information from previous tests by ESA and NASA.
By bringing together the end-user requirements, with the capabilities of the test house, we finally came up with an agreed Evaluation Test Plan. This was WP2200.

It was agreed that the following tests would be carried out –

Assembly Tests
Static Side Load
Cable Retention
Torsion
Strength of Coupling
Mating Durability
Temperature Step Stress
Constructional Analysis
Outgassing
Radiation

Task Three included the procurement, assembly, testing and results. In WP3100, we had to identify the components, and procure the agreed quantities. There were many issues in getting the correct cable and jacket to work with the connectors. The assemblies were then built, and shipped to the test-house for testing. We had to identify and procure the necessary test equipment, and this was also sent to the test-house, in Great Yarmouth.

WP3200, the Evaluation Testing took longer than expected (the test-house had a change of ownership in this time).
WP3300 Results Analysis and Final Test Report was delivered to ESA in December 2014.
The detail of the Test Results can be found in the Final Test Report (Document # TN3)

Explanation of each selection criteria

Criteria	Explanation of each topic
Anti-vibration	The connector and assembly need to survive the launch environment
Mass	Lower mass saves on fuel
Materials (Outgassing & Corrosion)	Selection of materials that do not outgas or corrode is recommended, if possible
Availability	We need to be able to get samples of the product
European Source	We would prefer to use a European source, where possible
Known environmental qualifications/ Built to agreed standards	We would prefer that the components are built to agreed standards
Number of contacts	Are there families of connectors that can accommodate various combinations of fibres/contacts
Obsolescence	There needs to be some certainty that these product lines will not be made obsolete
Cost	Cost needs to be considered when all else is equal

Some of these criteria are common when selecting fibre type and cable type.

Component Selection

Single-fibre connector

The physical dimensional parameters of telecoms connectors are controlled by IEC standards and the performance is controlled by Telcordia GR-326 and EIA-455. However, those connectors manufactured with plastic components and housings are not controlled by any standard with reference to out-gassing in a vacuum. As long as the connector meets the IEC and EIA specifications this material choice is open to the manufacturer’s discretion. Without this control on the material used with respect to outgassing, any testing would be useless as there would be no control over material changes.
Of the three most widely used telecom connectors (SC,FC,LC) the SC and LC both have plastic housings as standard. The FC is normally nickel-plated brass.

However, the FC is a screw-on connector and would need secondary fixing to guarantee there is no demating during vibrations. At the very least, there would need to be some control as to the torque used to tighten the coupling nut which is only designed for hand-tightening.
Both the SC and LC have push-pull mating mechanisms which should perform well during vibration. Of these two connectors, the LC is available with a metal housing from Molex (LC2+) and is also half the size of the SC. Taking the above observations into account, it was decided to select the LC2+ from Molex for further evaluation, meeting the following criteria:

1. No uncontrolled plastic housings
2. Small mass and footprint
3. Push-pull latching mechanism
4. High temperature strain-relief boot available

Multi-fibre connector

There were many multi-fibre connectors available but most were harsh-environment connectors which were bulky and heavy. Continuing the desire to use low-cost, off-the-shelf and high density telecom connectors, it was decided to select the USConec MTP 12 fibre connector for evaluation.
As there was a desire to evaluate both singlemode and multimode fibres it was agreed that pairing the multi-fibre connector with the singlemode fibre would provide the more difficult test condition particularly concerning alignment, as there are twelve fibres aligned together.

Fibre cable

A preliminary temperature cycling test on standard telecom grade cables proved the unsuitability of these cables for high temperature use. They are only rated for 80°C and all showed signs of melting and shrinkage. However, in keeping with the plan to use off-the-shelf solutions which would not be as vulnerable to obsolescence, it was decided to use standard telecom fibres overjacketed with high temperature cable jackets.
It was decided to use Carlisle Group for the jacketing. The fibres would be Corning OM4 and SMF-28e for the Multimode and Singlemode fibres respectively.

Component selection conclusion

There were two fibre optic cable assemblies chosen for further evaluation:

a) LC2+ patchcord on 1.8mm OM4 multimode fibre cable

b) MTP-12 fibre patchcord on 3.8mm Jacket with 12x SMF-28e fibres.

LC2+

MTP

4. Testing

After much discussion, the following were the agreed tests. These were carried out for Multimode and Singlemode.

Constructional Analysis (ETP 6.1)
Temperature Step Stress (ETP 6.2)
Static Side Load (ETP 6.3)
Cable Retention (ETP 6.4)
Torsion (ETP 6.5)
Strength of Coupling (ETP 6.6)
Mechanical Shock (ETP 6.7)
Random Vibration (ETP 6.8)
Temperature Cycling (ETP 6.9)
Outgassing (ETP 6.10)
Radiation (ETP 6.11)
Mating Durability (ETP 6.12)
Cable Storage Life (ETP 6.13)

This summary report should be read in conjunction with the Final Test Report to avoid loss of context.

4.1 Multimode Tests

4.1.1 Constructional Analysis (ETP 6.1)

Data to be supplied by ESTEC

4.1.2 Temperature Step Stress (ETP 6.2)

The samples performed within acceptable limits throughout the test from +167°C to -70°C. There was no visible damage after testing to the connector, strain relief boot or cable. Performance was better at the lower temperatures. The T_{max} multimode samples performed within acceptable levels up to +167°C. Up to +180°C the samples were outside the insertion loss limits set but were still functional at approx. +0.50dB and +0.70dB at 850nm and 1300nm respectively

4.1.3 Static Side Load (ETP 6.3)

The samples performed within limits while undergoing a static load up to 4N and 7N.
The losses increased as the load increased but showed no sign of permanent damage until there was catastrophic failure at 60N.

4.1.4 Cable Retention (ETP 6.4)

The samples performed within acceptable limits up to approx. 70N load. This demonstrates that the crimp was performing its function well up until complete failure. As with the side load test, the hardness of the jacket may have resulted in less crimp force on the cable strength members as the connector can perform better on softer cables or by applying some epoxy to the strength members before crimping.

4.1.5 Torsion (ETP 6.5)

The samples suffered catastrophic failure at 37N and 46N. As with the cable retention test, the samples performed within limits up to the failure point which consisted of 25 twists at each 1N step up to that point. It is felt that the torsion results may be improved by modifying the crimp technique.

4.1.6 Strength of Coupling (ETP 6.6)

A plastic coupling adaptor was used, as it is believed this would provide the worst case. The coupling out-survived the connectors in all cases, with the connectors failing due to fibre retention, consistent with the fibre retention result of 70N. Again the samples performed within acceptable limits up to the complete failure. There was no damage to the connector body or latching mechanism.

4.1.7 Mechanical Shock (ETP 6.7)

There was no resultant damage or performance reduction on any sample.

4.1.8 Random Vibration (ETP 6.8)

Tests were performed up to 40g RMS. There was no resultant damage or performance reduction on any sample.

4.1.9 Temperature Cycling (ETP 6.9)

As with the temperature step stress test, the performance of the assemblies was better at lower temperatures. The range of 0.30dB-0.70dB at 850nm and 0.25dB-1.0dB at 1300nm was repeated throughout all the cycles with no permanent damage caused after the test. Again, the higher losses at the high temperatures and at the 1300nm wavelength indicate that there was bending caused by jacket shrinkage.

4.1.10 Outgassing (ETP 6.10)

Data to be supplied by ESTEC

4.1.11 Radiation (ETP 6.11)

103m of fibre was subjected to a total dose of 1,1Mrad over an eleven day period. Insertion loss increased almost immediately upon exposure, with 80% of the total loss occurring within the first day of exposure. There then appeared to be a saturation point whereby further increases in dose resulted in only a gradual increase in insertion loss. However, the loss was still increasing by the final day so it is unclear how long the losses would have increased if testing continued.

The losses at 850nm were almost double the values at 1300nm. There was no effect on return loss.

The total loss over the 103m length was 3.8dB and 2.1dB at 850nm and 1300nm respectively. This is the equivalent of increasing the loss by only 0.04dB/m and 0.02dB/m in the fibre.

The cable was retested 1 week post exposure and had recovered to actual loss of 0.02dB.

4.1.12 Mating Durability (ETP 6.12)

The samples were mated and unmated 500 times with cleaning when required which was about every 50 matings. After 500 matings losses for the two samples increased by 0.06dB and 0.02dB. There was some minor damage to the fibre endface around the core but performance remained well within acceptable levels. A higher curing temperature may address the issue if necessary and results from the temperature stress test demonstrate that the fibre could be cured at a higher temperature if required without stressing the fibre.

4.1.13 Cable Storage Life (ETP 6.13)

The cables tested unmated showed no visible or optical difference between before and after test. The cables tested in the mated position (two fibres pressed together) had acceptable scuffing on the ferrule, but fibre and performance remained unchanged.There was no visible damage to any component.

4.2 Singlemode Tests

4.2.1 Constructional Analysis (ETP 6.1)

Data to be supplied by ESTEC

4.2.2 Temperature Step Stress (ETP 6.2)

The results of the temperature stress test clearly show that the ultimate performance at both temperature extremes is a function of the termination procedure.

The first sample performed very well at temperatures down to -70°C but poorly at temperatures up to 180°C. The second sample was the polar opposite, performing poorly at low temperatures but very well at high temperatures up to 180°C. There was no damage to either connector (excluding the strain-relief boot, which melted) or the fibre endfaces. The difference appears to be how much the components can expand and contract without putting stress on the fibre and this can be the result of what state the fibres are in when they are fixed to the connector. If the fibres are under a small tensile stress when unmated at room temperature they will perform well at low temperatures but poorly at high temperatures. If, however, the fibres are compressed, the opposite occurs. Return loss was not an issue with either sample. The test demonstrates that the assembly can function at both temperature extremes, but the termination process needs tight control. The samples were built using twelve individual fibres inserted loosely into the cable jacket. Both ends were then ribbonised for insertion into the connector. This was done to reduce the layers of material covering the fibres along their length. However, it is not possible to be fully confident of the route each fibre takes inside the tube and there may be some twisting or micro-bending occurring.

It is therefore recommended that pre-ribbonised fibre be used. It would then be not as difficult to control the stresses on all the fibres at termination. Every assembly should be subjected to one temperature cycle (-40°C to +140°C) to confirm the performance at each extreme.

4.2.3 Static Side Load (ETP 6.3)

Fig. 3 (Sample 1)

Fig. 4 (Sample 2)

Another limitation of ribbonising the ends of single fibres is that the two fibres at the extremities are less supported than those of pre-ribbonised fibres.

The first test sample failed after 3N sideload on the cyan fibre (fig. 3 channel 12). It appears that the fibre separated from the other fibres being held with ribbon tape. All other channels remained okay until channel 9 failed after an audible crack was heard at 12N. The other channels failed between 16N-20N but were still functional up to 35N.

Total failure at 35N occurred when the guide pins split through the connector ferrule as shown (fig 5). The return loss remained within acceptable limits throughout the test.

Fig. 5 (Sample 1)

The second sample had very good performance on all channels right up to failure at 34N. All fibres remained secured in the ribbon. (fig. 4)

The physical limit of the component appears to be at the 34N level and sample 2 demonstrates that a properly ribbonised assembly will survive up to that point.

4.2.4 Cable Retention (ETP 6.4)

The two samples failed at 70N and 80N. There was a 180sec. dwell after every 10N while the samples were held under strain. As with the torsion result, the sample where the Kevlar did not break performed better. On the 70N sample the Kevlar was still held inside the crimp sleeve (fig. 6) but had broken further down. There was no
obvious reason for the difference albeit only 10N.
Both crimps were compressed the same to 5.6mm and both seemed to have the same amount and distribution of Kevlar inside the crimp sleeve. There was no epoxy used on the Kevlar, which would increase its strength. As the strength of coupling failed at 65N there would be little to gain from trying to increase the cable retention value.

Fig. 6

4.2.5 Torsion (ETP 6.5)

Sample 1 failed at 42N and had >50% loss after 50N. Sample 2 failed at 73N but remained functional up to 87N. As with the cable retention test, the poorer result occurred when the Kevlar broke, but in this case the better performing sample 2 had a small amount of epoxy placed on the Kevlar before crimping. On sample 1 the fibres remained inside the connector and the cable broke along its length.

4.2.6 Strength of Coupling (ETP 6.6)

The test failed at 65N where the fibres became disengaged from the mated fibres.

4.2.7 Mechanical Shock (ETP 6.7)

There was no damage to any fibres. Three cores of one sample showed slightly high insertion loss in one direction only. There was no visible reason for this and may be just a mating anomaly.

4.2.8 Random Vibration (ETP 6.8)

There was minor pitting on one fibre core and this core plus its adjacent core showed slightly higher insertion loss of 0.60dB and 0.57dB respectively.
One core of the second sample had some damage but all cores remained within acceptable performance levels.

4.2.9 Temperature Cycling (ETP 6.9)

Both samples suffered high loss at low temperatures returning to acceptable loss at the high temperature until eventually suffering catastrophic failure during the test. Analysis of the samples show no damage to the fibres inside the connector.
The breakages were occurring along the fibre length. Removal of the outer jacket at the breakages revealed that the 250µm coating on the SMF-28e fibres had melted away (fig. 8). The fibres were covered with an oily, thick substance along their length. As the fibres were individually inserted loose into the jacket, their route could not be controlled and they may have become intertwined. Because the fibres were loose inside the tubing they were able to accommodate the extra bending at higher temperatures but during contraction at lower temperatures may

have suffered micro-bending and ultimately breakages due to the loss of jacketing support because of melting. As with the findings from other tests, it is concluded that loosely inserting single fibres into a jacket is not suitable for harsh environment applications.All 4 ends suffered reduced protrusion after the test. All still had protrusion, however, with the lowest at 0.7mm. The samples were cured at a maximum temperature of s110°C. There may be a case for increasing this.

4.2.10 Outgassing (ETP 6.10)

Data to be supplied by ESTEC

4.2.11 Radiation (ETP 6.11)

100m of Singlemode SMF-28e fibre was subjected to a total dose of 1,1Mrad over an eleven day period. Losses in the cable increased over this time by 1.2dB at 1310nm and 1.7dB at 1550nm.

Half the final loss occurred with the first two days of exposure for both wavelengths. Return losses improved consistent with increased attenuation in the fibre. While the increase in loss continually dropped over the course of the test, it had not leveled off by the end of the test. The effective loss that would increase in a 3m cable assembly would be only 0.04dB and 0.05dB at 1310nm and 1550nm respectively.

4.2.12 Mating Durability (ETP 6.12)

Up to 400 matings, the insertion loss remained at a surprisingly consistent value, considering there were 12 singlemode fibres being aligned. Insertion loss remained within acceptable levels but constant cleaning (every 10 matings) of the endfaces was required to achieve this and to prevent damage to the fibres. After approximately 460 matings the springs on the connector housing were noticeably weaker but they don't appear to be involved in the mating mechanism.

There was no damage to the fibres.

4.2.13 Cable Storage Life (ETP 6.13)

There was no visible damage to any component after the test. Fibre endfaces remained clear with acceptable protrusion. Insertion loss remained within acceptable levels.

5. Outcomes

Multimode OM4 LC2+

Mechanical: The connector proved to be very durable. None of the tests resulted in any damage to the connector or the strain-relief boot. The mating clip was undamaged even after the destructive tests. The crimp sleeve is a little light, but it is only holding a 1.8mm cable.
The cable jacket is attached to the connector body by splitting the jacket and crimping the split ends. A 1.8mm jacket held this way will not survive much twisting, as shown by the torsion test. However the cable was functional up to 40N under 180° twisting and 70N of pull when not twisted. Static side loads appear to be the only weakness at 4N and 7N. A drop of epoxy on the Kevlar would probably be of benefit here.
The assemblies had no issue with mechanical shock or vibration.

Environmental: All the components from connector, fibre, strain relief boot and cable survived -70°C and +180°C without any damage. The assembly returned to normal after the test. During the test the cable assembly remained within acceptable performance levels from -70°C to +150°C and was only slightly outside these levels at +180°C. Pre-conditioning the cable would better the performance at the high temperatures.
The 1Mrad radiation exposure resulted in a 20dB/km increased loss in the OM4 fibre.
The cable was standard fibre. This would equate to 0.20dB for a 10m assembly or 0.10dB per end.
The OM4 fibre has a bandwidth of >4GHz.Km and over short lengths would be comparable to singlemode with regard to bandwidth.

Overall, the assembly performed very well, and with the changes mentioned should be a very good choice for space applications. The LC2+ could also be considered for singlemode applications.

Singlemode MTP/APC 12 Fibre

Mechanical: The connector coupling survived 65N and the other mechanical tests were above this except for static side load which would appear to be limited to 12N.
However the process of ribbonising the fibres at the end of the cable appears to be a weakness.
There was minor damage to one core after vibration to 40grms and slight increase in loss for a couple of channels.

Repeated matings produced very consistent performance demonstrating very good alignment mechanisms.

Environmental: The temperature step stress test demonstrates that the assembly can perform at -70°C and +180°C. However due to the method of inserting individual fibres into a loose jacket neither assembly performed at both extremes.
The problem was further confirmed with fibre breakages during temperature cycling which were not near the connectors. This turned out to be caused by the 250µm coating melting away from the fibres. Standard telecom cable jackets were eliminated from consideration due to melting.
It appears that using a high temperature over-jacket does not protect the standard 250µm coating on telecoms fibre and they are, thus, unsuitable for high temperature applications.
Corning now have a mid-temp (180°C) acrylate-based fibre coating available: SMA-C
The strain-relief boot is not suitable for temperatures above 140°C as there was melting and brittleness. The internal fibre boot showed minor signs of melting also. There was no damage to the cable jacket.
Exposure to 1.1Mrad radiation resulted in increased loss of 1.2dB which equates to 0.12dB increased loss in a 10m assembly.
Overall, the process of ribbonising individual fibres may be unsuitable for harsh environment applications, however an issue only appeared on one sample during the static side load test. Using pre-ribbonised fibre would address the static side-load issue and make termination easer to control. It would also address the temperature cycling failure in conjunction with pre-conditioning of the jacket.
Although the jacket showed no signs of damage, it is stiff and heavy and may have increased the stress on the connector during vibration testing. It could be feasible to use ribbonised fibre without a jacket at all.
The MTP looks like a very good connector but the cabling needs to be addressed.

Other benefits of the program undertaken.

- Test equipment sourced which allows Fibrepulse to properly direct any future testing and to use local test houses.
- Valuable experience gained regarding the tests required and better ways to implement testing programs.
- Environmental chamber sourced to allow Fibrepulse to run preliminary tests, process checks and production tests.