siraelectro-optics

Sira Electro-Optics Limited, South Hill
Chislehurst, Kent, BR7 5EH, England

Telephone: +44 (0) 20 8467 2636
Fax: +44 (0) 20 8467 6515
Email: info@siraeo.co.uk
Website: www.sira.co.uk
Registered in England No 2248869

Fibre Optics Evaluation Phase II

Irradiation Test Measurement Results and Conclusions

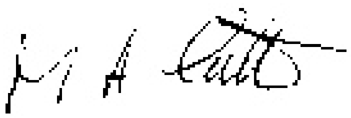
Technical Note 2

Prepared for ESTEC

by Sira Electro-Optics Limited

Sira Reference: A/1478/00/36 issue 3

Authorised by:



Dr M A Cutter
Technology & Developments Manager

16 April 2001

CONTENTS

1. INTRODUCTION TO IRRADIATION TESTS

The current 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 Pirelli, Plasma Optical Fibre and Optical Fibres (Corning). For gamma irradiation, the Cobalt-60 facility at Cranfield University /RMCS, Shrivenham was employed. The proton irradiation source was provided by the Paul Scherrer Institut in Switzerland.

1.1 COBALT 60 GAMMA RAY TESTING

1.1.1 Irradiation Test Source

The Cobalt-60 irradiation test source at RMCS, under the control of Mr Keith Lovell, was in the form of a fixed, 20-pencil, geometry. Due to the fixed nature of the source, dosimetry calculations were based upon earlier, absolute measurements of source variation within the irradiation chamber (see Appendix A) in conjunction with a tertiary calibrated ion-chamber. The date of last formal calibration of the ion-chamber dosimeter was given to be 25 June 1998.

Variation in dosimetry depends upon, a) the half-life state of the source, and b) the distance of the test sample from the source, the dose varying approximately through an inverse square law. RMCS operate a computer controlled facility to calculate the radial source distance required to achieve a given dose rate during a specific test period. Total dose and dose rate are specified by RMCS relative to water. Our initial specification related to Si; consequently the conversion factor: 1 rad (water) ≡ 0.91 rad (Si) applies.

Dose and dose rate accuracy is given by RMCS to be a nominal 5%; additional errors may be associated with errors in set-up geometry (e.g. fibre bobbin radius). We were advised that the use of chemical and crystal dosimeters have been considered, however these can lead to relatively large errors (e.g. 10%-20%). Ion-chambers are the preferred device.

1.1.2 Test Fibre Geometry

All three European test fibres were wound simultaneously upon a polystyrene bobbin, as shown in Figure 1.1.2-1. The complete assembly was mounted upon a rotating turntable and fed with fibres at a slow rate in order to avoid unwanted tension effects. We were advised by RMCS

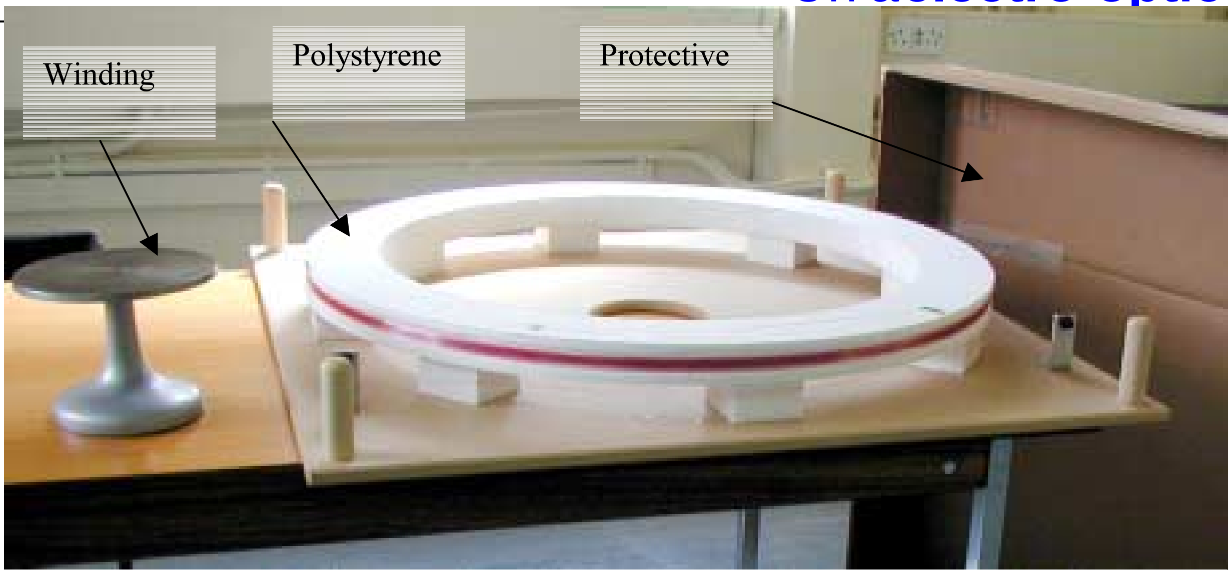


Figure 1.1.2-1 Fibre bobbin with wound fibres

that, in order to achieve a dose rate of 5 rad sec^{-1}, the required fibre bobbin diameter was 96cm. Requirements on permitted fibre height above base plate were also specified. The bobbin material was given to be expanded polystyrene which had a negligible effect upon radiation attenuation (being within the specified dose accuracy). The initial 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. During winding of the test fibres a breakage occurred near the end of winding; the consequence of this was that the exposed length of fibres was reduced to 190m. All fibres were successfully passed through narrow bore tubing, used to protect their 10m passage between irradiation chamber and the data-logger.

In addition to test measurements upon the three European fibres an equal length of SpecTran fibre with hermetic and polyimide coatings was also purchased, for reference purposes, and subsequently wound onto the fibre bobbin described above. This fibre type is particularly fragile, being only 155 micron in diameter as compared with a 250 micron diameter for the acrylate-coated fibres. During the protective tube feed-through process the fibre unfortunately broke necessitating its removal from the fibre bobbin whereupon a further breakage occurred. Whilst the recoiled fibre was irradiated, data-logged transmission could not be performed as immediate facilities for fibre splicing were unavailable (boiling concentrated sulphuric acid is required to remove the polyimide coating). For further discussion see Appendix D1 and D2.

1.1.3 Test Measurement Configuration

Figure 1.1.3-1 shows the fibre bobbin, on MDF base-board, 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. Figure 1.1.3-2

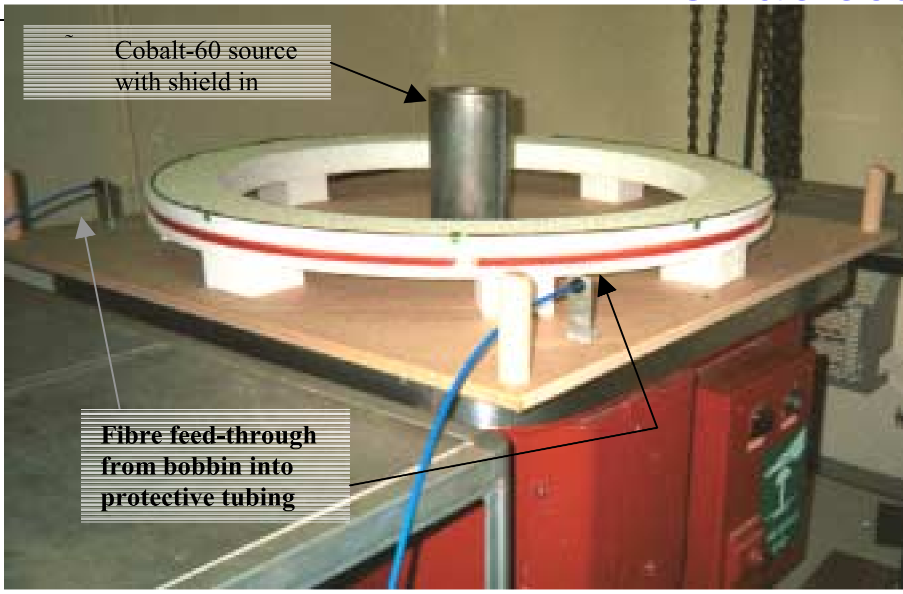


Figure 1.1.3-1 Fibre bobbin positioned within irradiation chamber

shows the method of routing test fibre tails from irradiation chamber to the data-logging hardware.

After passage through to the external data-logger location, fibre tails were connected to the unit in a manner similar to the above. Residual fibre was loosely wrapped around a 200mm diameter mandrel and then passed to the mechanical splice units for connection to, a) the 1x5 optical fibre splitter, and b) the PIN detector diodes. It was originally intended to employ index-matching liquid mode strippers, however the fragility of the fibres (with possible fibre breakage) made the removal of acrylate buffer from intermediate sections of each fibre impractical in the limited test period available (justification for this omission is discussed further in Appendix D3). The three commercial test fibres occupied fibre-splitter paths 3 to 5; a 2m long reference fibre was connected through path 1.

Figure 1.1.3-2 Radiation chamber, fibre feed-through

In the original data-logging unit design all components were housed within a 6U Schroff rack unit. During data-logger testing however, significant thermal dependence of signal transmission was discovered when tested using constant relative amplitude signals. Variation in ambient temperature is known to vary laser diode output intensity, however by taking the ratio of test signal and reference signal amplitudes the effect of this variation is removed. This mode of operation is dependent however upon thermal attenuation effects being the same for each signal channel. Operation of the data-logger within Sira's thermally controlled test laboratory (where the thermal-vacuum test equipment is located) provided very good signal data stability. Operation in a standard laboratory environment however, such as that presented by RMCS (external to the irradiation chamber)

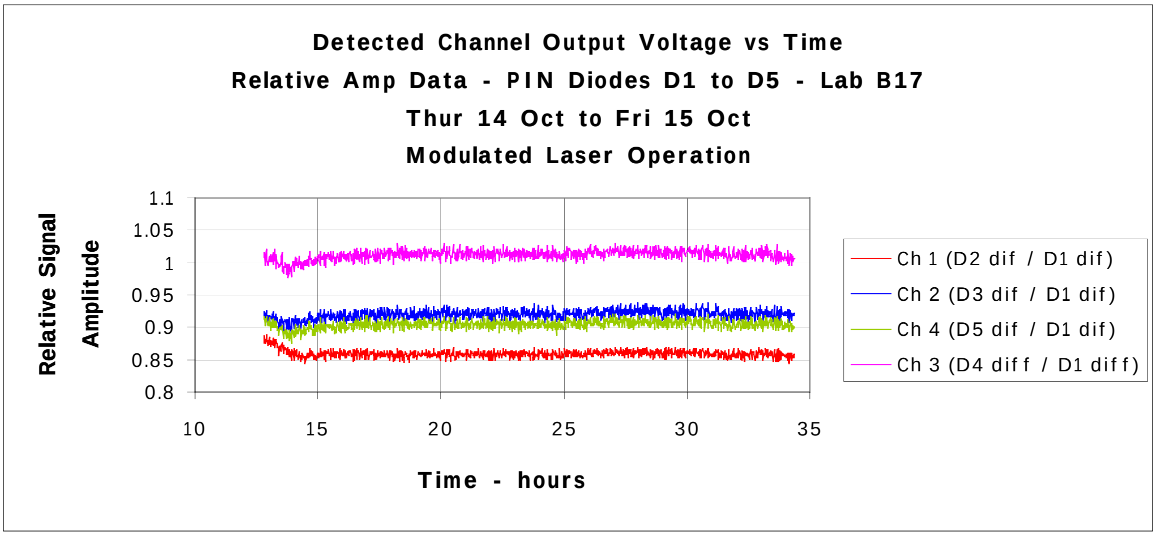


Figure 1.1.3-3 Representative data-logger output under normal laboratory conditions

required that the fibre-splitter be externally housed within a thermally controlled local environment employing a Peltier unit. Trials showed that stability in relative signal intensity was controlled to within a few percent by operating at a mean temperature of ~30±0.5°C. Figure 1.1.3-3 shows representative results of logged output for unperturbed fibres when situated in a normal Sira laboratory (without ambient temperature control). In the above figure relative amplitude values are plotted (with respect to the reference fibre path D1), showing variation in fibre path transmission (principally due to the fibre splitter). For directly comparable results the data are normalised to unity. Time-scale start values represent the actual time when the procedure commenced (i.e. 12.48 PM in the above case). Further discussion is included in Appendix D4.

It may be noted, in relation to the fibre-splitter's temperature sensitivity, that this may have been due to a slight shift in operating wavelength away from the design specified value. Both laser diode and fibre splitter were ordered with central wavelength specified as 1310 nm. The manufacturing tolerance on LD wavelength was ±30 nm with no preselection possible. A supplied LD wavelength of 1324 nm was responsible for operation of the, made to order, fibre-splitter being slightly off centre. Insertion loss measurements made by Sifam Ltd, at both the specified and actual central wavelengths, showed significant variation in attenuation (e.g. path 2 loss increased by 0.93 dB).

In addition to instabilities encountered within the fibre splitter, the use of precision mechanical splice units, filled with index matching gel, provided some further problems. Whilst initial use of the splice provided low loss connections as anticipated, repeated removal and reinsertion of fibres caused a reduction in the volume of index matching gel with associated increase in signal attenuation and instability. The insertion of new index-matching gel did not prove to be a reliable solution to the problem. Where possible new units were employed. Due to the possibility of increased instability, signal transmission measurements through separate 2m lengths of fibre immediately prior to irradiation testing were not performed.

1.2 PROTON TESTING

1.2.1 Irradiation test source

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

In earlier communications with PSI we were advised that the 300 MeV beam geometry would have a gaussian transverse profile and that the maximum dose rate (at PSI's recommended 60 mm diameter) was approximately 3 rad sec^{-1} (Si). As a consequence the requested beam exposure time was 24 hours in order to give a total dose of ~250 krad. From the report obtained from PSI following irradiation we note that a variation in beam geometry enabled a more uniform field to be produced together with an increase in maximum dose rate. As a consequence PSI decided to use this increased dose rate to reduce the exposure duration to less than 10 hours.

1.2.2 Test fibre geometry and measurement configuration

All three European test fibres were wound simultaneously onto a thin-walled (0.5 mm) Al-alloy bobbin (see Appendix D5), as shown in Figure 1.2.2-1, 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. Fibre supplied by Pirelli was easily distinguishable due to its red acrylate buffer. The complete assembly was sealed within a transparent plastic bag prior to dispatch to PSI.

Set-up and exposure to proton irradiation was controlled entirely by PSI personnel, subject to Sira's specification of requirements (Appendix B). Details of experimental set-up, beam set-up, calibration and irradiation, as supplied by PSI, are reproduced in Appendix C. Due to the need to allow residual radioactivity to fall to safe levels an intervening period of approximately six weeks occurred before the assembly was returned to Sira.

Test measurements at Sira were limited to measurement of transmitted signal intensity both before and after irradiation.

Figure 1.2.2-1 Al fibre bobbin with fibres for proton irradiation

2. TEST RESULTS

2.1 COBALT-60, GAMMA IRRADIATION

The polystyrene bobbin with test fibres was located centrally about the Cobalt-60 source axis. Fibres were then fed through to the adjoining laboratory and the fibre protective tubing connected to the data-logger housing. Each fibre type was then appropriately coiled and the ends re-cleaved for insertion into mechanical splice units. A two metre length of reference fibre (Optical Fibres) was already installed. Local temperature control of the fibre splitter was operated to maintain a monitored temperature of approximately 30°C. Some control over ambient room temperature was provided continuously by floor and wall-mounted, thermostatically controlled, fan heaters. Ambient temperature within the irradiation chamber was automatically controlled to be 22.5±0.5°C. The complete system was then allowed to stabilise overnight.

Test measurements were commenced on the morning of 20th Oct 1999, starting with absolute transmission measurement using a UDT radiometer (model S370), with GaAlAs detector head (model 280) fitted with an FC connector adaptor. The laser diode operated at wavelength 1324 nm with drive current modulated at 100Hz. The combination of drive current level and nominal 20dB optical fibre attenuator produced test fibre input power levels close to 1 µW. Attenuation measurement of the fibre attenuator gave 17.3 dB, being within the ±3 dB product specification.

Transmission data for each fibre path was logged automatically at intervals of one minute with real time recorded. More than one data-file was used to record the data. Combined normalised transmission data against exposure time are presented in Figure 2.1-1. The gap in data about the 20 hour point was due to premature termination of the logging process (see Appendix D6). A summary of the radiation-induced attenuation effects is given in Table 2.1-1a.

It is of interest to note that for the first 25 hours the irradiation chamber light was left on (see Appendix D7); after this time the light was switched off. In this context there may be some evidence that an earlier equilibrium situation, between radiation induced attenuation and photo-bleaching effects, may have been re-established due to a reduction in photo-bleaching.

Whilst a general trend in normalised transmission reduction is clear, small local variations are not regarded as meaningful due to the possibility of slight signal modulation due to thermal effects mentioned earlier. From the results of earlier data-logger test measurements using unperturbed fibres (i.e. non-irradiated) fibres an absolute measurement error of ±5% is assumed. Under these conditions there would appear to be little to choose between the fibres tested, which may be expected from their very similar composition.

In addition to the induced effects of gamma radiation on signal attenuation, it is also of interest to note any relaxation in induced attenuation after the radiation source was removed (see Appendix D8). An indication of such an effect is shown in the last 30 minutes of data where removal of the ^{60}Co source produced an increase in normalised transmission. Repeat spot measurement of fibre transmission after a three week interval showed some additional relation had occurred.

2.2 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.

From the results obtained, summarised in Table 2.1-1b (and discussed further in Appendix D9) the total post-irradiation attenuation for each fibre is seen to be slightly higher than for the pre-radiation case. The residual induced attenuation is smaller than for the case of Cobalt-60 irradiation but this may be associated with, i) the smaller maximum radiation dose (i.e. 0.25 Mrad and 0.75 Mrad respectively), and ii) the longer relaxation time following exposure (i.e. 6 weeks and 3 weeks respectively).

It would appear from the results that greater relaxation had occurred in the case of the fibre from Plasma Optical. This was also found to be the case when using Cobalt-60 irradiation.

2.3 GENERAL COMMENT

For the above test results a normalised transmission measurement error of ±5% is ascribed for ^{60}Co irradiation, principally being due to thermal effects within the fibre splitter and mechanical splice units. Small amplitude, higher frequency signal noise may be ascribed to

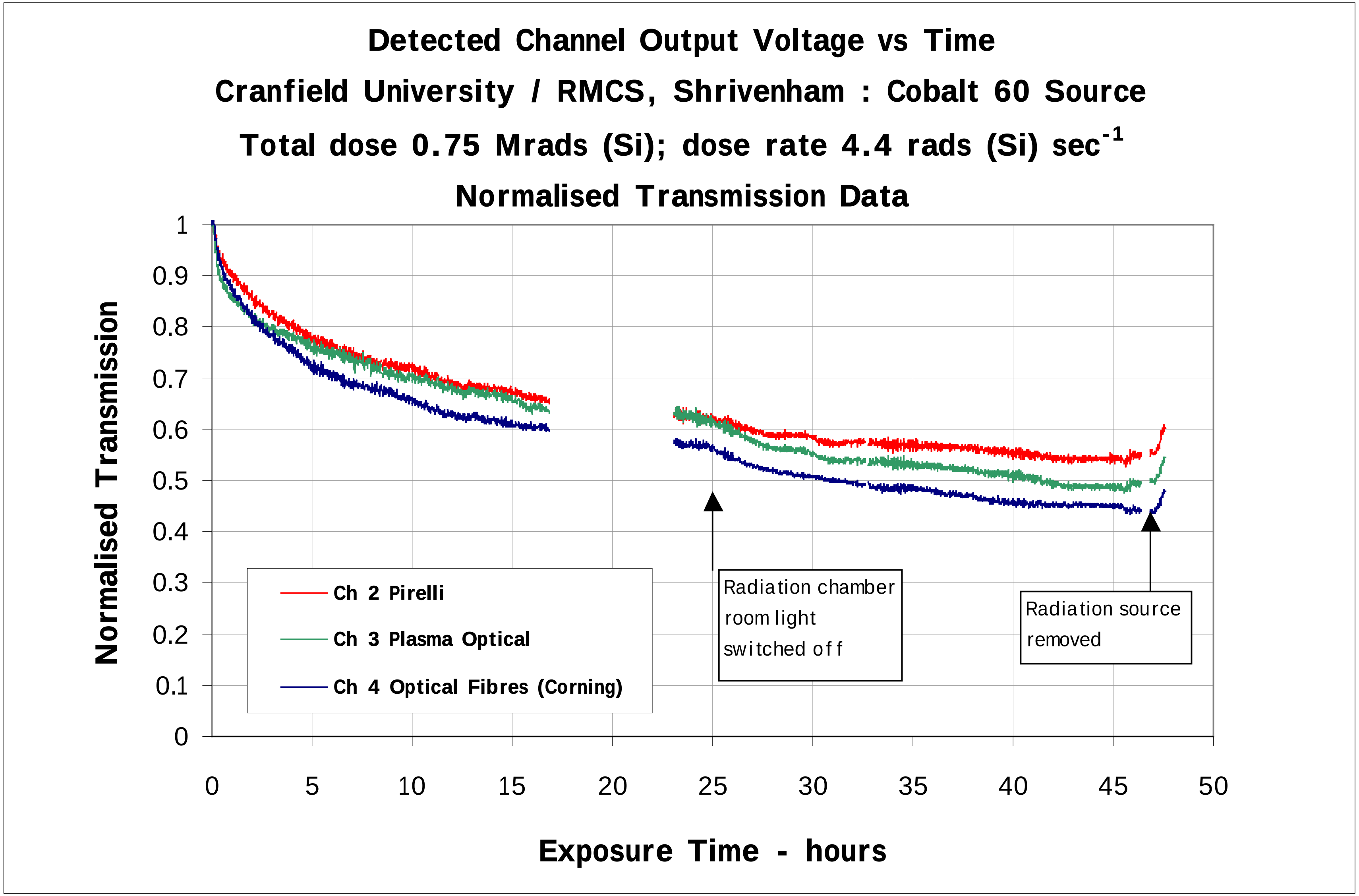


Figure 2.1-1 Data-logger results showing normalised transmission against Cobalt-60 source exposure time

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 2.1-1a 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 -

Fibre	Pre exposure			Post exposure*			Induced attenuation*	
	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 2.1-1b Summary data for proton irradiation tests)

electronic noise on the square-wave drive signal which was applied to the laser diode power driver unit (Oxford Optronix). During data acquisition periods, at 1 minute intervals, sampling of 80 points per 100 Hz modulation cycle over 10 cycles was performed. Each data point was acquired sequentially from each analogue detector input; i.e. the first data points were acquired from each PIN detector input in turn, followed by subsequent data points in a similar manner. Data measurements were separated in software into square-wave peak and trough regions, followed by calculation of the mean peak and trough signal voltages and consequent signal amplitudes. Calculation of the ratio between test and reference fibre signal amplitudes provided the relative signal amplitude. Normalised transmission was obtained by applying a constant normalisation factor to the data for each data channel, calculated at the commencement of fibre irradiation.

A detailed explanation of the local changes observed for each fibre during and post ^{60}Co irradiation is not viable, such changes being largely due to system thermal effects. A possible effect of photo-bleaching was also postulated but not substantiated. It is considered that the lack of such information in no way invalidates the conclusions drawn as each of the three candidate fibres were similarly affected. It is also suggested that the acquisition of such detailed information should be directed towards subsequent test measurements which involve the complete fibre cable structure. This argument applies equally to the results of proton irradiation.

3. FIBRE SELECTION FOR CABLE MANUFACTURE

From the test results obtained it is concluded that all three European commercial optical fibres tested have 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 is 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 is 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, at this stage, only one fibre type can be incorporated within the proposed new GoreTex cable we recommend that the fibre supplied by Plasma Optical Fibres be employed.

4. CONCLUSION

It is considered that any of the three commercial fibre types selected here would be suitable, in terms of radiation induced attenuation performance, for further performance evaluation testing when incorporated within a space-quality GoreTex cable. For purposes of the present contract it is proposed that Plasma Optical fibre, type 267E (code AA 19576G) be employed.

APPENDIX A - RMCS DOSIMETRY CERTIFICATION

Department of Materials and
Medical Sciences
Centre for Materials Science and Engineering

Cranfield UNIVERSITY

Cranfield University
RMCS, Shrivenham, Swindon
SN6 8LA, UK
Fax +44 (0) 1793 785772
Switchboard +44 (0) 1793 782551
Department +44 (0) 1793 785433
tel (direct) 01793 785237
fax(direct) 01793 785774
email: lovell@rmcs.cranfield.ac.uk

25 October 1999

SIRA Electro-Optics Ltd
South Hill
Chislehurst
Kent
BR7 5EH

JJ THOMSON IRRADIATION LABORATORY

COBALT 60 GAMMA FACILITY

CERTIFICATE OF IRRADIATION

This is to certify that the undermentioned samples have been irradiated in this facility to total doses and at the dose rate as described below.

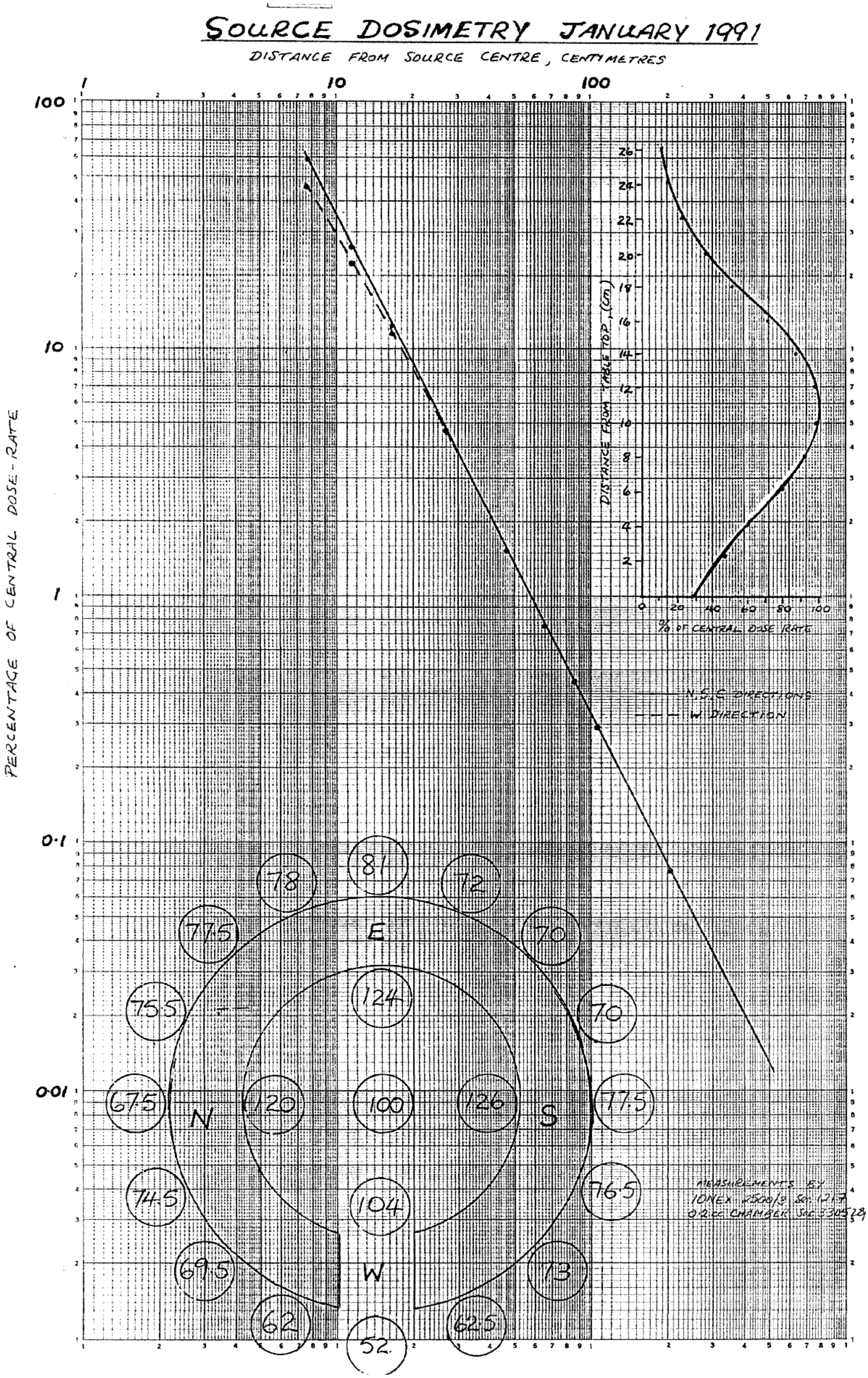
Sample Identification	Dose Rate (rads sec^{-1})	Irradiation Time (hours)	Total Dose ((rads),(water))
1. Plasma Optical Fibre,.Prod. code 267E, Lot no. AA 19576G.	4.86	47.0	8.22×10^5
2. Corning Optical Fibre, Prod. code SMF-28,P5001, Lot no. 272053809812	4.86	47.0	8.22×10^5
3. Pirelli Cables, Prod. Code SM13DA08, Lot no. L0152A3110	4.86	47.0	8.22×10^5
4. Spectran, Prod. code SMT-A1310J, Lot no. CD 0251XC	4.86	47.0	8.22×10^5

Dosimetry was by PTW-Unidos Dosemeter and Ion Chamber calibrated and traceable to German National Standards. Calibration Certificate Number 983308, 25 June 1998.

Signed:

K Lovell

K V LOVELL
Radiation Facility Manager


SOURCE DOSIMETRY JANUARY 1991
DISTANCE FROM SOURCE CENTRE, CENTIMETRES
PERCENTAGE OF CENTRAL DOSE-RATE
DISTANCE FROM TABLE TOP, (cm)
% OF CENTRAL DOSE RATE
N.S.E DIRECTIONS
W. DIRECTION
MEASUREMENTS BY
IONEX 2500/3 Sr. 1217
0.2cc CHAMBER Sr. 330528
E
N
S
W
81
78
72
77.5
70
124
75.5
70
67.5
120
100
126
77.5
74.5
104
76.5
69.5
73
62
52
62.5

APPENDIX B - PSI - SPECIFICATION OF REQUIREMENTS

Sira Fibre Optic TRP Contract No. 12299/97/NL/(SB(SC)); A/1478/00

Proton Irradiation of Single Mode Optical Fibres at PSI

1. Introduction

Three different, acrylate coated silica, single mode optical fibres, wound upon an aluminium bobbin are to be exposed to proton irradiation, at the Paul Scherrer Institut, Switzerland, during the period 24^{th} – 26^{th} September 1999. Prior to the dispatch of the wound fibre bobbin to PSI, Sira will measure the transmission of each fibre at a wavelength of 1320 nm. PSI are only required to position the supplied fibre bobbin within the proton beam, as described below. PSI shall return the exposed fibre bobbin to Sira when the exposed fibre bobbin is considered safe to handle by Sira personnel. At the present time Sira assumes this period to be 2 weeks following exposure. Upon return to Sira, fibre transmission measurements will again be performed to determine which of the three fibre samples has undergone the lowest irradiation-induced transmission loss.

2. Details of the Fibre Bobbin and Test Fibres

Three, 200 m lengths of single mode optical fibre will be wound around a thin-walled, aluminium bobbin. A drawing of the bobbin and test fibres is shown in Figure 1.1 below. It will be seen that the bobbin has an outer diameter of 60 mm and an axial length of 50 mm. The three fibres will be wound simultaneously onto the bobbin in order to ensure that each fibre receives the same exposure. Each fibre has an outer diameter of 0.25 mm and therefore the final fibre layer thickness is expected to be approximately 4 mm.

Fibres will have cleaved ends, i.e. no connectors are used. It is assumed that it will be necessary to produce new cleaved fibre ends, following irradiation and return to Sira, and therefore no special cleanliness procedures (to avoid fibre end contamination) are required. One of the three fibres has a red acrylate buffer; the other two will be identified at each end by the use of a suitable coloured paint material. It is important that this identification be retained in order that we may continue to clearly differentiate between the three different fibre samples. Fibres will be prevented from unwinding from the bobbin by the use of small sections of adhesive tape.

3. Proton Exposure Requirements

The exposure conditions required are as follows:

bobbin size:	60 mm outer diameter
bobbin axial length:	50 mm
bobbin material:	aluminium
bobbin position:	centred axially about proton beam having gaussian transverse profile
proton beam energy:	300 MeV
dose rate:	$\geq$ 3 rad sec^{-1}

exposure duration:	24 hours
total dose:	approximately 250 krad

A discussion of the perceived exposure conditions is given in Appendix 1

4. Test Procedure

The mounted test sample fibres should first be positioned correctly within the test chamber. It is assumed that the fibre bobbin will be mounted coaxial with the proton beam and that no additional shielding of the test samples will occur. The test sample should then be preconditioned at the proposed measurement temperature (20±5 degC) for a period of one hour prior to exposure to the proton source. During exposure suitable dose monitoring equipment should be employed as appropriate. Ambient temperature variation should also be recorded continuously during the exposure period.

Following exposure the test fibre samples shall be removed from the test chamber and stored in a safe location, for a period determined by PSI, before return to Sira. A record of the storage conditions should also be provided.

It would be of assistance to Sira if the following information could be provided along with the exposed fibre samples:

- description of proton source
- description of dosimeter(s) used
- description of proton beam detection and recording apparatus
- date of latest calibration of test equipment
- dose rate and total dose (with measured or estimated total dose variation)
- test temperature and temperature variation
- ambient lighting conditions

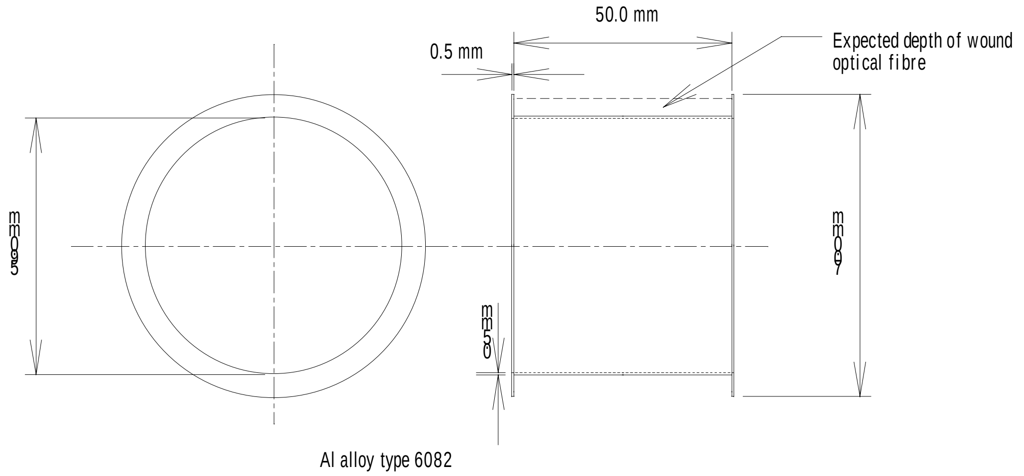


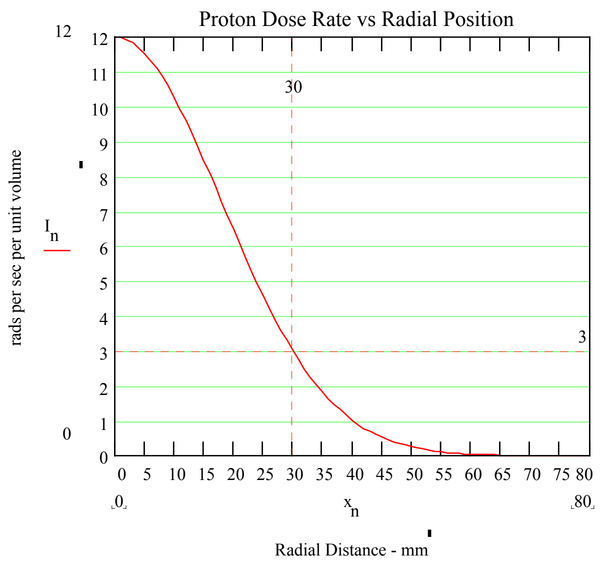
Figure 1-1 Aluminium Bobbin Fibre Holder

Appendix 1 – Consideration of Perceived Exposure Conditions

The irradiation dose achieved when using a proton source is dependent upon the proton beam incident energy, E (in MeV) and the beam fluence, F (protons cm^{-2}). Tables giving such data have been produced by Biersack and Ziegler. Stopping distances for given input beam energies are also given, being related to the test material density. For a proton beam with energy 300 MeV, incident upon a typical boro-silicate glass, dose = $4.81x10^{-11}$ krads x F ; whereas dose rate = $4.81x10^{-2}$ x Flux, where flux has the units fluence per sec. From PSI graphical data we see that, at a beam energy of 300MeV, the flux is approximately $2.5x10^{8}$ protons cm^{-2} sec^{-1}. Hence dose rate (at beam centre) is calculated to be approximately 12 rad sec^{-1}.

Dose rate will vary, however, both along and transverse to the proton beam. In the along beam direction (where the fibre bobbin is assumed to be coaxial with the beam), the dose rate will vary due to absorption. At 300 MeV, the loss rate is given to be 0.774 MeV mm^{-1}, with an associated total stopping distance of 234.6 mm. At lower beam energies the dose rate increases and the stopping distance decreases. From a simplistic calculation, based upon the above loss rate, the beam is seen to decrease in energy to approximately 260MeV over the length of the fibre bobbin (50 mm). At this beam energy the dose rate is given to be $5.21x10^{-11}$ krads x F, or 13 rad sec^{-1}.

Due to the proton beam possessing a Gaussian transverse profile, beam flux will also decrease accordingly. We are advised by PSI that a fibre bobbin diameter of 60 mm is appropriate for the proposed tests, where the initial dose rate for a 300MeV beam has decreased to approximately 3 rad sec^{-1}. On the basis of employing three, 200 metre, lengths of 0.25 mm outer diameter single mode fibre, wound around a 60 mm diameter bobbin of axial length 50 mm, a simplistic calculation indicates an increase in wound fibre radius of approximately 4 mm will occur. From a consideration of the Gaussian beam profile, it would appear that the dose rate experienced at inner and outer radii will vary by approximately 33%. Whilst dose rate variation occurring between fibres wound sequentially could be taken into account theoretically, it is considered more appropriate to wind all three fibres *simultaneously*, whereupon each will be exposed to the same dose rate variation.



APPENDIX C – PSI - PROTON IRRADIATION REPORT

Proton Irradiation of the Optical Fibres for Sira

Irradiation place and date

The test was conducted in the NA2 area in the PIF target station. Irradiation started on 1 October at 18:00 and finished on 2 October at ca 12:00.

Experimental set-up

After general preparation of the area and test set-up check, the calibration detector was located on the position of the Optical Fibre Bobbing. The fibre and calibration detector were aligned at the beam axis center using a laser. The calibration detector was a plastic scintillator of 8 mm 2 area. The rest of the setup consisted of iron square collimator (72 x 72 mm 2), wire chamber and two ionization chambers. The chambers were located upstream of the collimator and in front of the irradiated sample respectively. The relation between the beam-flux at the sample and the current read-out from the chambers were determined using plastic detector during calibration run.

Beam Set-up

Standard 304 MeV set-up was chosen from the disk-set database for the beam line magnets. The final energy at the target was equal to 301.8 MeV. The beam was centered and defocused using wire chamber located in front of the sample/calibration detector. The beam field was flat over the whole area of the collimator opening (72 x 72 mm 2).

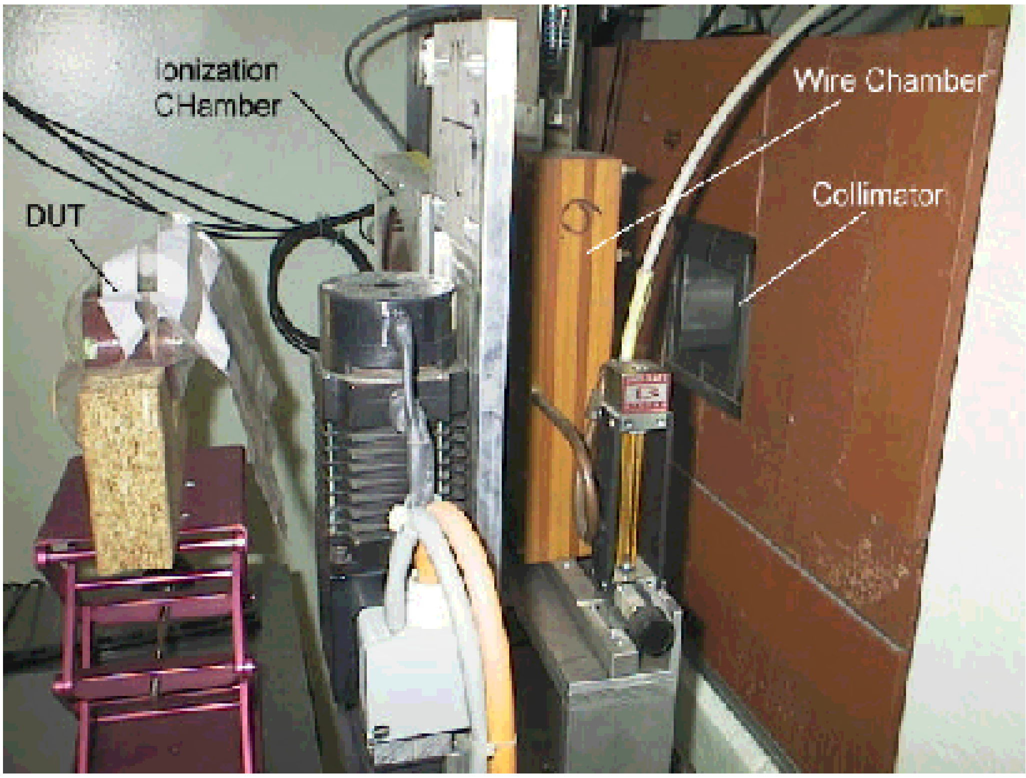
Calibration

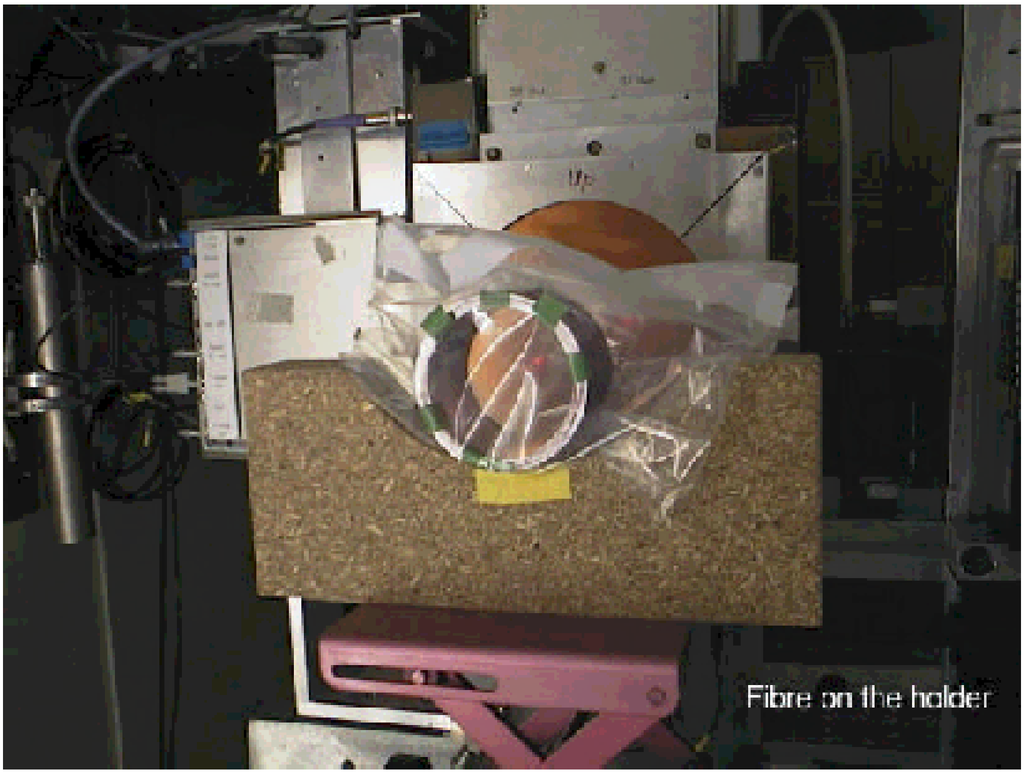
The plastic detector (8 mm 2 area) was used to measure to measure the proton flux at the sample position and determine calibration factors for two ionization chambers. After calibration, the plastic was replaced by the irradiated sample. The chambers were used to monitor the beam during irradiation of the Optical Fibre. Beam intensity during calibration was kept on lower level (few hundred thousands counts per second in the plastic) to minimize dead time and pile-ups errors. Beam field shape was checked for both low and high current intensity.

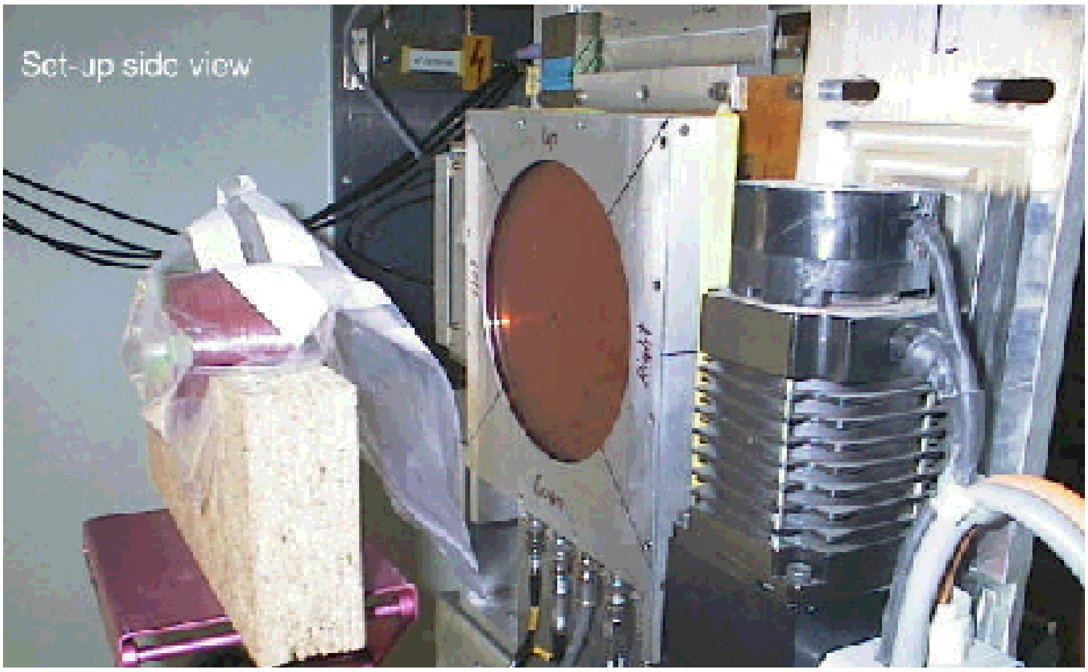
Irradiation

Optical Fibre sample was located on the wooden bench and centered on the beam axis using laser beam. The sample was permanently kept in the plastic bag also during proton exposures. The irradiation of the sample started at 1:20 am and finished at 11:18 am. The beam flux was kept on the level of $1.52 \cdot 10^{8}$ protons/sec/cm^2 and total dose was equal to 250 krad(Si). Beam profiles were periodically checked during the test using the wire chamber. (As the dose rate was equal to ca. 7 rad/sec the whole irradiation was completed within ca. 10 hours. It was possible due to low beam intensity degradation by another parasitic experiment PIREX running upstream of PIF.)

Beam intensity during the test run was also monitored using the pen-writer – see copy from the logbook. The beam intensity over the whole run was kept stable within less than 10%. There were ca. 18 short (1-2 min) breaks in beam during the test due to cyclotron security system.


Ionization
CHamber
Wire Chamber
Collimator
DUT


Fibre on the holder



>PIFM data acquisition log file: PIFM_015.LOG

>PIFM started: Fri Oct 01 01:04:39 1999

Target : 01 , Run : 001
Comment: optical fibres - SIRA
>   Run Started: Fri Oct 01 01:19:22 1999
                                          Stopped: Fri Oct 01 11:18:06 1999

>Beam Energy = 304.0 [MeV]   <@Splitter> = 13.399 [uA]
>Energy@Target = 301.8 [MeV],   Alu Degrader = 0.0 [mm], LET(for Si) = 6.642 [MeV/cm]

>Sample Position: X = 0.0 [mm] ,   Y = 0.0 [mm]

>Run_Time = 35926 [sec]   (rel. 0.449)   Preset = 80000
Fluence = 5.472e+12 [p/cm2]   (rel. 1.000)   Preset = 5.472e+12
Dose = 2.500e+05 [rad]   (rel. 1.000)   Preset = 2.500e+05

<Flux> = 1.523e+08 [p/cm2/sec] ,   <Dose-rate> = 6.959e+00 [rad/sec]

># Scaler	Counts	Rate	Cal.Factor
0 @Sample	1.05e+07	2.93e+02	5.19e+05
1 NA2-Beam	1.82e+07	5.07e+02	3.46e+05
2 Monitor 2	0.00e+00	0.00e+00	1.00e+00
3 Splitter	4.81e+08	1.34e+04	
4 User/SEU	0.00e+00	0.00e+00	

(Target 01 - Total collected dose = 2.500e+05 [rad])

>PIFM stopped: Fri Oct 01 19:42:17 1999

APPENDIX D - FURTHER ISSUES RELATING TO TEST MEASUREMENTS

D1 Data salvage options following SpecTran fibre breakage

A basic problem faced with measurement of the irradiated lengths of SpecTran fibre (believed to be three at the present time) is the need to cleave fibre ends with the associated requirement to remove polyimide coatings. Initial trials using boiling sulphuric acid proved to be successful although it is not an easy task. In addition a disadvantage of using several short lengths of fibre for measurement is that losses associated with the mechanical splices are present in each case. Enquiries were made through colleagues at Imperial College London, regarding the possibility of fusion splicing fibre sections together (using a dynamic alignment technique for minimal splice loss). Whilst this can be done there is still a requirement to remove polyimide before splicing can take place. We therefore have the option to remove the polyimide layer from the ends of each fibre section and either measure the transmission of each section separately or join fibre sections together and measure the single fibre length produced. It is considered that the latter option is preferable.

The alternative option adopted was to make use of published data relating to the attenuation effects of ^{60}Co irradiation on SpecTran fibre. Test results, including those obtained by Goddard Space Flight Center/Swales Aerospace, are reviewed in Appendix E.

D2 Polyimide-coated fibre fragility and impact upon ease of use

From present experience the acrylate-coated fibres were found to be somewhat more robust during handling, compared with the polyimide-coated fibre. This was in part due to more effective buffering by the soft plastic coating but also due to the larger overall diameter making handling easier. In particular the red-coloured acrylate of the Pirelli fibre made handling appear easier due to its greater visibility. Both acrylate and polyimide-coated fibres were relatively strong under bending and controlled tension. Sudden tensioning of either fibre type (due to an involuntary movement coupled with (almost) fibre invisibility) could, very easily, cause the fibre to break. The particular problem with polyimide fibre, again, is the difficulty of buffer removal, required before splicing can be performed. From the evidence gained of sample cabled fibre however, a very robust and visible product is presented which, it is expected, can easily be handled (e.g. coiled) with little risk of breakage.

It should also be noted here that investigations performed for NASA by Goddard Space Flight Center (GSFC) into space compatible (principally multi-mode) optical fibre and cable were, initially, directed towards use of polyimide-coated fibres due to their enhanced thermal and radiation hardness properties. For space flight applications however GSFC prohibit the use of mechanical stripping and use of boiling sulphuric acid chemical stripping is considered unnecessarily problematic and hazardous. Recent work has therefore been directed towards the use of acrylate coated fibre which may easily be stripped using methylene chloride solution, being similar to paint stripper.

D3 Omission of cladding-mode strippers

The omission of a cladding-mode stripper under the measurement conditions employed should not cause significant measurement error for the following reasons. Where absolute measurement of signal attenuation is required (using the insertion-loss method) the loss associated with a small length (e.g. 1-2 m) of fibre is first measured using fixed coupled beam input and output geometry. The short length of fibre is then replaced by the (significantly) longer fibre under test. The difference in attenuation effectively gives the loss due to the longer length of test fibre, but does include any variation in splice connection efficiency.

The use of a cladding-mode stripper is important under three conditions, i) the method of focused input beam coupling places a significant amount of energy into the cladding region, ii) short lengths of test fibre are to be measured, and iii) absolute attenuation measurement is required.

Where a significant length of single mode test fibre is involved (e.g. 200 m) it is believed that the percentage of any initial cladding mode energy reaching the fibre output will be minimal. Furthermore the use of a pigtailed (single-mode fibre) laser-diode source is expected to be efficient in placing most of the output power into the fibre core. Unintentional transfer of energy from core to cladding may occur at a splice interface but this again is expected to be small using high precision mechanical splices.

From a consideration of the fibre output power measurements made it would appear that, assuming an expected fibre attenuation loss of around 2% (based upon typical 0.35 dBkm^{-1} loss and 200 m), a small amount of cladding mode energy was in fact introduced at fibre input. Whilst this would be important if we were making absolute attenuation measurements it is considered insignificant in connection with the radiation-induced attenuation being measured, as in this case only output signal levels are employed which have propagated only by way of the fibre core.

D4 Further discussion on residual data-logger signal instability

Whilst temperature control was employed for the data given in Figure 1.1.3-3, and re-plotted in Figure D4-a), the temperature data-log was not saved. Consequently an associated temperature plot is unavailable. Similar measurements were performed however a day earlier and for these measurements the temperature log is available. Both relative transmission and temperature log plots are given in Figures D4-b and D4-c below. In these plots a scale was employed starting at the time when the procedure commenced (12:48 PM on 14th Oct 99 for Figure D4-a) and continuing in hours until test completion (10:22 AM on 15th Oct 99, approximately 22 hours later).

The dips seen at the start of testing in Figure D4-a are attributed to a variation in the (dual) mechanical spice efficiency within the reference fibre path (thus affecting each of the test channels against which reference is made). In the second test case (Figures D4-b and D4-c) a more marked variation is seen to occur, due to this effect, within test fibre 4 path (channel 3) only. Such effects were seen to occur due to a combination of sudden temperature change and loss of index-matching fluid following several re-insertions of the fibre into its splice unit. Replacement of the mechanical splice units in fibre 4 test path was seen to be effective in the subsequent test measurement (Fig D4-a) however this result necessitated subsequent replacement of the reference fibre mechanical splice units.

One reason for the sudden small change in ambient temperature was seen to be associated with closing of the laboratory door after leaving following commencement of a test period, and subsequent re-entry to the laboratory just prior to test completion. This effect was found to be most pronounced when the temperature difference between laboratory and adjoining corridor was greatest. The least effect occurred when the door to the laboratory was left open. Such sudden small temperature swings were avoided during data acquisition at RMCS.

Precautions were taken to overcome possible variation in relative signal amplitude measurement when performed under different ambient temperature conditions. A relative amplitude measurement system was initially adopted to overcome the effects of variation in laser diode power output. By feeding each fibre with the same source, and comparing signal transmission through an unperturbed reference fibre housed within the data-logger with that measured for each irradiated fibre, any thermally induced change in laser diode intensity will be cancelled out. It should be noted however that the laser diode was in fact also incorporated within the environmental cavity within which the splitter was housed. Both fibre-splitter and laser diode source were controlled in temperature to within ±0.3 °C.

In the case of perturbation effects associated with the mechanical splice units and variation in ambient temperature, it is true that their use in an environment with significantly different temperature profile could result in perturbation effects different to those examined above. We endeavoured however to maintain a laboratory environment at RMCS very similar to that experienced at Sira and would expect the test conditions to be acceptable.

D5 Fibre bobbin design and proton irradiation energy

A question was raised concerning the reasons for selection of aluminium as the material for manufacture of the fibre bobbin required for proton irradiation of fibres. From consideration of the technical literature the use of an aluminium support structure for test fibres is believed to be common. Furthermore the proposed use of this material was set out in Technical Note 1, Section 2.2.2 Proton Source Exposure Requirements.

The proposed proton energy to be used (300MeV) was specified in the Environmental Test Procedures (ETP) document. I have no record of communications from ESA relating to bobbin material and/or proton energy selection. Records show that an e-mail was received (7th Jun 99, 05:00 PM) regarding the ETP document which included the following statement: ‘Otherwise the document appears to be fine although I await a response from Ali Mohammadzadeh on the radiation part of it’. In the same communication an annex was requested which resulted in document issue 2. A subsequent communication (1st Jul 99, 14:07) accepted the complete document.

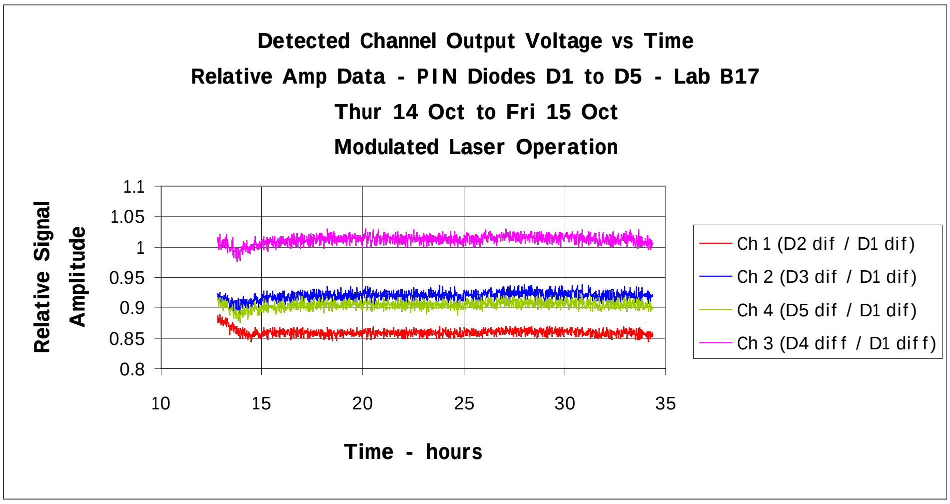


Figure D4-a

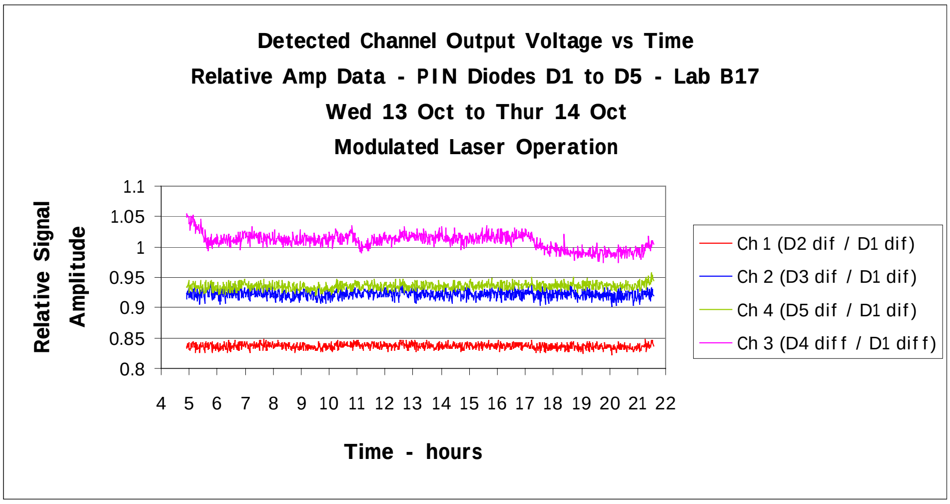


Figure D4-b

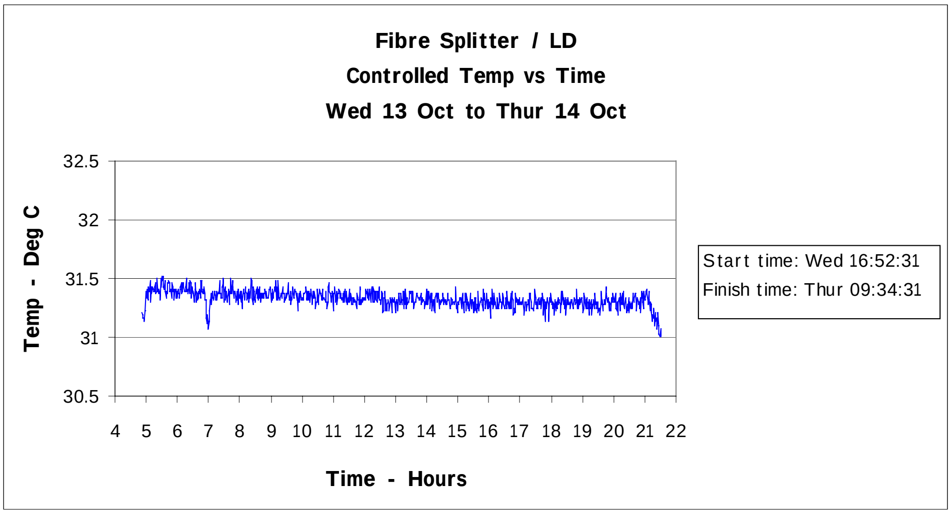


Figure D4-c

Proton beam energy was referred to in the ETP document where it was seen that selection of higher energies result in greater dose uniformity through an increase in stopping distance. In the present case it was the axial length (50 mm) of fibre material in combination with proton energy which determined maximum beam attenuation. The situation was somewhat confused through early discussions with PSI, where it was believed that only a limited beam diameter was available, hence necessitating the axial length used.

In hindsight it may have been a more appropriate option to employ a larger fibre bobbin diameter and to expose using a lower proton beam energy. In this case, whilst beam attenuation would have been greater and stopping distances smaller, the larger beam diameter would have allowed a smaller ‘axial’ depth of fibres to be used.. Use of lower proton energy may be expected to produce lower induced radioactivity, however the true situation requires clarification. This option would be explored fully were subsequent proton irradiation test work to be undertaken.

As an aside, Sira contacted Dr Wojtek Hajdas at PSI asking for comments regarding the reasons for the six-week delay after exposure, where the specification of requirements given to them before testing stated the expectation of a two week delay. Their reply was as follows, ‘Unfortunately the sample was too active for its shipment after 2 weeks only’.

D6 Hiatus occurring in ^{60}Co data-logging test results

The data-logging software implemented wrote acquired data with time-stamping , at 1 minute intervals, to a Microsoft NotePad text file. On rare occasions a software error was seen to be invoked when the text file was perceived to be full (i.e. unable to accept more data). In the case referred to this error occurred overnight and could not immediately be corrected. Whilst the data file was not actually full the software error caused cessation of the data-logging program. The only impact upon the test procedure was the removal of laser diode signal modulation, resulting in ~50% increase in laser diode mean power over the error period. The gap in logged data shown in Section 2.1, Figure 2.1-1, indicates the period during which the software error occurred. The program was restarted, with full recovery of functionality (including laser diode modulation) immediately after error discovery.

D7 ^{60}Co chamber illumination and photo-bleaching effects

It was not our original intention to leave the irradiation chamber light switched on during the test period. The fact that it had not been switched off was not discovered by the source controller (Keith Lovell) until after irradiation had commenced. Under the given circumstances the approach decided upon was to switch the light off after approximately 24 hours and to observe any associated effects.

D8 Post ^{60}Co irradiation, attenuation recovery measurements

Test specification No.1 Optical Fibre – Ionising Irradiation: Cobalt 60, only required monitoring of fibre transmission for a fifteen minute period after the irradiation source had been removed. In reality a 45 minute period was logged. Whilst it may be of interest to observe the relaxation period in more detail it was not considered a requirement to perform such measurements at the present stage of fibre cable development.

The key point of interest at this stage of development is considered to be the maximum attenuation introduced; historical evidence in the technical literature has shown that some optical fibre dopants can lead to significant attenuation effects. More detailed measurements on radiation response and annealing effects should be considered with regard to the cabled fibre, particularly as it likely that (as discussed in the Phase I report) possible out-gassing effects associated with the acrylate layers (not to mention significantly improved ruggedisation) make it more attractive to employ fibre in the cabled form, where the additional layers ameliorate the out-gassing problem.

In addition to the above, small attenuation changes associated with variation in fibre micro-strain caused through transportation of the fibre test system following disassembly after irradiation with subsequent reassembly at Sira, together with possible effects associated with mechanical splice loss variation (e.g. caused by thermally induced loss of index matching gel over time), can degrade the value of measurements undertaken over an extended period.

<u>Measurement temperature</u> - The Sira laboratory temperature was approximately the same as that experienced within the RMCS laboratory. The fibre splitter / laser diode controlled thermal environment employed the same Peltier system current settings as used during RMCS irradiation tests, controlling temperature to a mean of 28.95 °C, with maximum excursion 0.65°C.

Earlier tests have shown that the condition of the mechanical splices and variation in local temperature can vary measured relative transmission by the order of a few percent about the mean. This was assumed to be the case for the post irradiation measurements. It should also be noted that it was necessary to re-cleave each fibre end due to system disassembly for transport following irradiation. Furthermore new Amp mechanical splices were used for these post-irradiation measurements.

D9 Post proton irradiation, attenuation recovery measurements

Reasons for limited recovery measurement detail are believed to have been covered in the preceding discussions presented in sections D5 and D8 above.

With regard to the temperature at which pre- and post-proton-irradiation transmission measurements were performed, the Sira laboratory temperature was subject to standard central heating control (~22 °C). The measurement situation employed for pre- and post-irradiated fibres used a single fibre splitter channel together with two new mechanical splices. Initially a 2 m length of reference fibre and UDT detector was used to measure cw laser diode coupled input power. The reference fibre was then replaced by each, re-cleaved, test fibre in turn and the transmitted power remeasured. From these measurements it may be seen that part of the transmission losses may be associated with the act of fibre bending on a small diameter support (60 mm); residual, radiation-induced transmission loss was determined from the difference in overall pre- and post-irradiation attenuation measurements.

APPENDIX E - PUBLISHED TECHNICAL LITERATURE ON IRRADIATION TESTING OF SPECTRAN FIBRES

1. Optical fibres in the adverse space environment: A critical assessment of optical fibres for the space station, R.S.Greenwell, Science & Engineering Assoc., C.E.Barnes, JPL, D.R.Biswas, SpecTran Corp: SPIE Vol 1314, pp 100-104, 1990.

This paper examined the suitability of radiation hardened (polyimide-coated), hermetically sealed, multi-mode, graded-index SpecTran fibre, type SR-328H as a candidate for use in the proposed US Space Station. Attenuation and recovery measurements, for ^{60}Co irradiation, were made using a source wavelength at 1300 nm and temperature extremes of –150°C to +150°C. As expected induced attenuation was highest at the lowest temperature, relaxation effects increasing with increased temperature.

Using a dose rate of 1300 rad min^{-1} (Si) (approximately 22 rad sec^{-1}), after a total dose of 10 krad the induced attenuation was approximately 1 dB km^{-1} at 72°C, 2 dB km^{-1} at 22°C and 20 dB km^{-1} at –30°C. At the lowest temperature, removal of the radiation source caused attenuation to relax to 6dB in a time of approximately 1 hour.

2. Survivability of optical fibres in space, E.J.Friebele, M.E.Gingerich and D.L.Griscom, Optical Sciences Division, NRL: SPIE, Vol 1791 pp 177-188, 1992.

Investigations were carried out by these workers again based upon the potential application of Ge-doped silica core fibres for use in a space environment, including those manufactured by SpecTran. In this case however both gamma and proton irradiation sources were employed to assess attenuation effects on single and multi-mode fibres at 1300 nm. A significant outcome of their work was that (for ^{60}Co γ-rays and 60MeV protons) "it can be concluded with high confidence that high energy proton exposures do not induce significantly greater incremental loss than γ-rays".

3. Extrapolating radiation-induced loss measurements in optical fibres from the laboratory to real world environments, E.J.Friebele, M.E.Gingerich and D.L.Griscom, Optical Sciences Division, NRL: 4th Biennial Department of Defense Fibre Optics and Photonics Conference, March 22-24, 1994

This paper presents the basis for an 'extrapolation method' whereby, given two sets of attenuation measurements using different dose rates, coefficients of the expression $A(D) = C_0\,\Theta^{(1-f)/n}\,D^f$ may be determined to enable recalculation of fibre attenuation A, at new dose rate Θ and total dose D. This approach was employed by Ott in the following reference (4).

4. Fibre optic cable assemblies for space flight II: thermal and radiation effects, Melanie N. Ott, GSFC / Swales Aerospace: SPIE Vol.3440, pp 37-46, 1998.

In this paper Ott examines (among other things) irradiation testing of a germanium-doped, multi-mode, graded-index, hermetic acrylate-coated, SpecTran fibre, type BF0544. As usual a ^{60}Co radiation source was employed. Attenuation measurements were carried out at 1300 nm using transmitted power in the region of 10 µW. The test fibre length was 100 m, being wound on a 6-inch diameter spool. The effects of two different dose rates, 34 rad min^{-1} and 50 rad min^{-1}, were examined. The close spacing of dose rates used was not through choice but was dictated by source limitations. Total dosage was restricted to 200 krad, this being considered adequate to represent mission exposure. Logged data are shown in Figures E4-1 and E4-2 with extrapolated data calculated on the basis of Ref. (3) above.

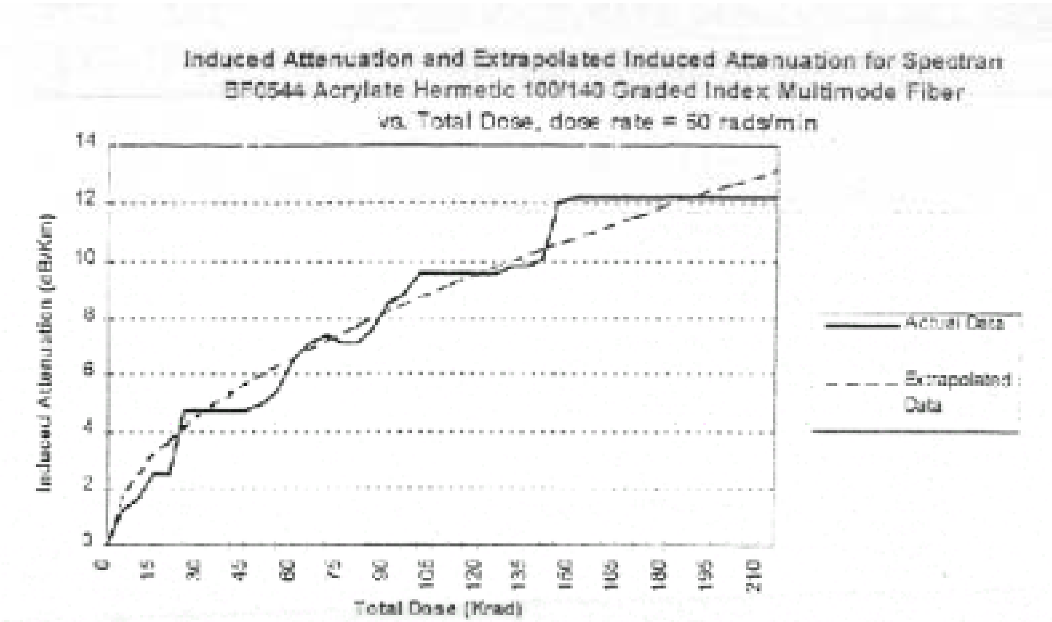


Figure E4-1

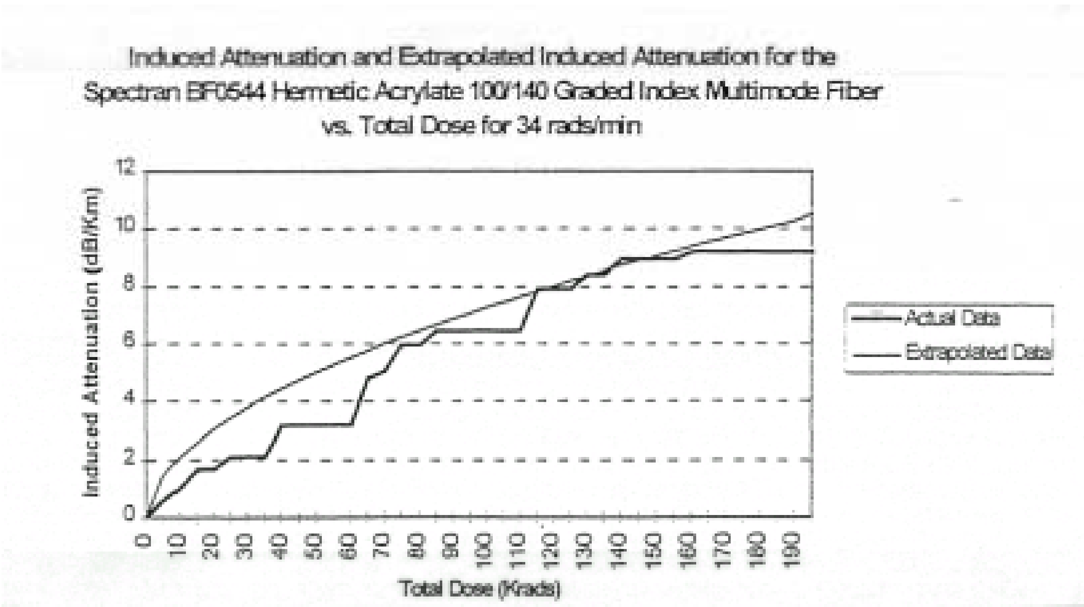
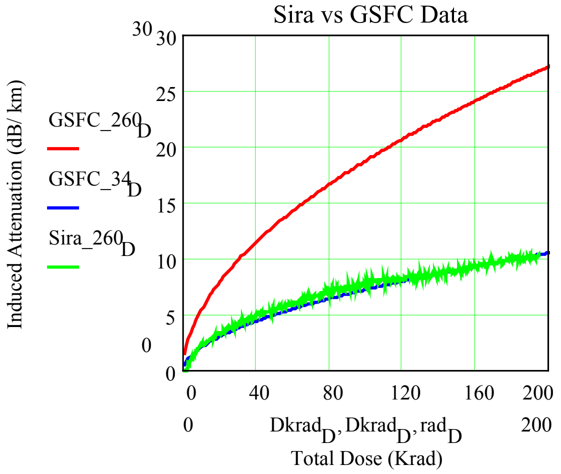
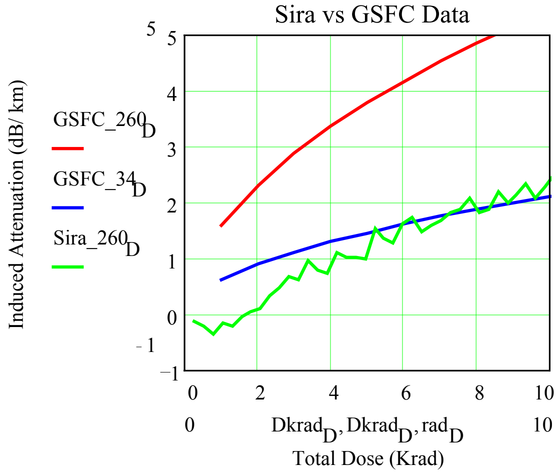


Figure E4-2

The same equation coefficients given in Ref.(4) were used by Sira to determine extrapolated attenuation using an irradiation dose rate (260 rad min^{-1}) equal to that used in recent tests performed at RMCS. These data are plotted in Figures E4-3 and E4-4 along with measured Sira





data for the highest attenuation case.

Figure E4-3 **Figure E4-4**

From consideration of Figure E4-3 it is seen that actual attenuation measured by Sira is significantly less than the extrapolated value. This is consistent with the findings obtained by Ott where calculations performed using higher dose rates were also reported to vary significantly from actual attenuation produced. It is of interest to note however, with regard to Sira's test measurements, that there is very close agreement with GSFC data obtained using 34 rad min^{-1} dose rate. The reason for the disparity between extrapolated and actual dose rate performance is unclear. However what does appear evident is that measured radiation induced attenuation characteristics for the new Sira fibre is comparable with that obtained using a broadly equivalent SpecTran acrylate fibre.

Figure E4-4 replots the data in Figure E4-3 up to a reduced total dose of 10 krad. This may then be compared with the results given in Ref (1) which considered radiation hard polyimide-coated SpecTran fibre and a dose rate of 1300 rad min^{-1}. At an ambient temperature of 22°C attenuation was quoted to be 2dB km^{-1} for 10 krad total dose; Sira acrylate fibre measurements, for radiation dose rate 260 rad min^{-1} and total dose 10 krad, show a worst case attenuation of approximately 2.4 dB km^{-1}.