STUDY ON OPTICAL FIBRE CABLING LOSSES

PHASE 2 - FINAL REPORT

Submitted to

DEPARTMENT OF SUPPLY AND SERVICES

Prepared by

Dr. K. C. KAO

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checked 11/83

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CONTENTS

ACKNOWLEDGEMENTS

The author wishes to express his grateful appreciation to Dr. D.C. Johnson of Communications Research Centre of Canada and Dr. M.A. Dudley of Canada Wire and Cable Company Limited for helpful discussions, to Mr. Y. Takeda and Mr. M. Kawai for their contribution in carrying out experiments and valuable discussions during the course of this investigation, and to Mr. R.J. Sill for his technical assistance. The supply of optical fibre samples from Canada Wire and Cable Company Limited and Hitachi Cable Limited of Japan, and the supply of stainless steel syringes used as fibre connectors from Imperial Surgical Company of Winnipeg, through Mr. Hans Wittmann, are also gratefully acknowledged.

The financial support of the Department of Communications under Contract No. ~~04SU.-36100-6-0341~~ 0SU77-00183 is deeply appreciated.

ABSTRACT

The excess loss, pulse broadening and far-field radiation patterns have been measured with and without bump bends for various types of step-index, graded-index and w-type multi-mode optical fibres. The results show that the fibres with silicone cladding suffer a much less bending loss than those with glass cladding, indicating that silicone plays an important role in screening the core from the external-stress-induced bending. The plastic tubing is more effective than the plastic coating in screening the external-stress-induced bending. An increase in excess loss due to bump bends is always accompanied with a decrease in pulse broadening and in far-field radiation extension. This implies that the excess loss due to bump bends or microbends is the mode-conversion loss.

The experiments on temperature effects, thermal cycling effects, and environment effects reveal that the attenuation loss increases rapidly with decreasing temperature for temperatures lower than -10°C, and the thermal degradation is aggravated as the number of thermal cycles or the exposure duration to environment is increased, if the core and the cladding have different thermal expansion coefficients. The fibres composed of a glass core and a silicone cladding are very temperature-dependent, while those with the core and the cladding made of glass are practically independent of temperature in optical transmission properties. Additional protective plastic coatings or plastic tubings tend to aggravate the temperature effects and the thermal degradation.

Mechanical vibration effects are very small. These effects are not important if pulse code modulation is adopted for signal transmission. However, they may affect the noise level if amplitude modulation is adopted for signal transmission.

For optical fibres composed of a glass core and a silicone cladding, the advantage of low bending loss trades off the disadvantages of large temperature effects and high thermal degradation. The compromising solution is that both the core and the cladding are made of glass with a silicone buffer layer and a nylon jacket to protect the fibre. So far, w-type fibres give almost an optimum performance and merit serious consideration for future use.

STUDY ON OPTICAL FIBRE CABLING LOSSES - PHASE II

I INTRODUCTION

The proposed use of optical glass fibre waveguides for signal transmission in various communication systems has stimulated the intensive study of glass fibre waveguides of various types under diverse operating conditions. These include attenuation losses and pulse dispersion resulting from perturbations of the geometry of the waveguides, mechanical strength and fatigue as functions of temperature and design parameters of the waveguides such as the materials and sizes of the core, the cladding and the protective jacket, and the refractive index profiles. The core radius "a" and the refractive index difference between the core and the cladding "Δ", together with the wavelength of the light "λ" determine whether a fibre is single mode or multimode. For single mode fibres which carry only one mode or only a few modes, the core radius "a" must be small and should be of the order of the wavelength of the transmitting light signal if Δ cannot be made much smaller than 0.01 based on the criterion for single mode operation [Pearson 1976].

$$(2\pi a/\lambda)(2n_o\Delta)^{\frac{1}{2}} \leq 2.4 \qquad (1)$$

where n_o is the refractive index of the core. This type of fibres has been found capable of low attenuation loss and low dispersion and hence large transmission capacity under laboratory conditions. However, these advantages are over-ridden by their high susceptibility to microbending loss, and high splicing and connection losses because of small core radius (less than 10 μm), and the need of a coherent laser source in order to reduce dispersion. Obviously, it is not the transmission capacity alone that determines the type of fibres adopted for a particular system. At present, techniques are not yet available to overcome the difficulty of splicing and connection, it is likely, therefore, that early systems will use multimode low loss fibres with large cores to facilitate splicing and cabling, and reasonably large values of Δ to give a large numerical aperture "NA" or a large light acceptance angle for efficient coupling of the light source to the fibre.

Because of multimodes in nature, a simple step index fibre suffers a very important disadvantage which is that a light pulse injected into the input end of the fibre gradually becomes broadened (or dispersed) as it propagates along the fibre. This tends to distort the signal and to limit the transmission capacity. To overcome this inherent disadvantage, multimode graded index fibres have been developed, in which the refractive index of the core decreases gradually from its maximum value at the center to the value at the periphery equal to the refractive index of the clading which is generally uniform. In this type of fibres, the light rays follow a quasi-helical path rather than a zig-zag path as in the step-index fibre; and because of the graded index, rays that are in lower refractive index regions are travelling faster than those travelling directly along the axis. Theoretically, by profiling the index correctly, all the modes in this type of multimode fibres can be kept in phase, thus the pulse dispersion can be greatly reduced. However, the profile of the refractive index of the graded-index fibres must be accurately controlled to equalize the group delay for all guided modes, or in other words, the fabrication of such fibres requires an exceedingly accurate control system to control the fabricating process.

It should be noted that the singly-clad multimode fibres may be so designed to reduce the number of modes to propagate so as to reduce signal distortion over long distances by decreasing the value of Δ. But this approach has the disadvantage of weak power confinement to the core and high susceptivity to microbending loss. On the other hand, the increase of the value of Δ in order to tighten power confinement will result in a decrease in bandwidth. Of course, it is possible to optimize the choice of a, Δ, λ, N (number of guided modes) and b (bandwidth). However, to overcome the disadvantages of step-index and graded index fibres, the Hitachi Cable Limited has developed so called doubly clad or W-type fibres. This type of fibres has a three layered structure with the intermediate layer called inner cladding having the lowest refractive index, inserted between the core and the outer cladding, and it has the advantages of large cores and moderately wide bandwidths. Recently, Miyagi and Nishida [1977] have proposed a dielectric-tube waveguide with an outer higher index cladding based on a similar principle of W-type fibres, and suggested that a single-mode fibre with a large core and a tight power confinement can be realized by using this type of waveguides.

However, through the research over the past decade, the attenuation losses in all available types of fibres have been reduced to such low levels that they are no longer a prime concern. While further improvement in transmission properties can still be expected, attention at present is focussed on developing optical fibre waveguides with long-term reliability and stability, and strong mechanical strength so that they can withstand considerable stress without breakage in cabling, reeling, handling and installation procedures. For cabling, fibres must have a jacket or coating for protection against abrasion, improvement in resistance to humidity, improvement of the tensile strength needed for cabling, as well as a decrease of the detrimental effects of lateral mechanical stress which results in microbending loss. The microbending or, in general, the bending loss of a fibre depends not only on the parameters such as core radius, cladding thickness, and the value of Δ, but also on the jacket material and its thickness. Chapter 2 of this report will discuss the effects of various fibre parameters on excess loss due to microbending and bending for the three most common types of fibres— step-index, graded index and W-type fibres.

The effects of temperature and thermal cycling on the transmission properties are of extreme importance to fibre applications because such experimental results would help the system designers to determine whether a fibre is suitable for a particular environment and to assess its long-term reliability and stability. Chapter 3 will present some experimental results and discussion about these effects.

Mechanical vibration or dynamic bending causes also additional loss to the fibres. The factors controlling this loss are discussed in Chapter 4. The imperfections of the fibres under investigation due to fabricating processes and damages of the fibres due to thermal cycling and environmental conditioning are discussed in Chapter 5. Conclusions drawn from this investigation are given in Chapter 6. At the end a proposed future plan is also given.

II EFFECTS OF STATIC BENDING ON TRANSMISSION PROPERTIES OF OPTICAL FIBRE WAVEGUIDES

The most important transmission properties of optical fibre waveguides are attenuation and dispersion. The factors affecting these properties are numerous, and one of them is the static bending of the fibre. It is very important to determine the dependence of attenuation loss and dispersion on fibre parameters such as core and outer radius of the fibre, the refractive index profile and the protective jacket material for the design of low-loss and stable fibre cables for practical use. A great deal of theoritical and experimental work have been done on the relation between fibre parameters and transmission properties [a list of important references is given at the end of this report]. However, there is no systematic experimental results along this line available or useful for the design of practical fibre cables.

It is well known that the microbending due to random perturbations of the geometry of multimode optical fibres causes an increase in attenuation loss and a decrease in temporal dispersion [Gardner 1975, Gloge 1975, Keck 1974, Marcuse 1974]. Many investigators have studied and analysed these important phenomena for various types of fibres and under various conditions [Marcuse 1974, Olshansky 1975, Petermann 1976, 1977, Kawakami et al. 1975, 1976; Miyagi and Yip 1977, Jeunhomme and Rousseau 1977, Rousseau and Arnaud 1978]. Although it is generally accepted that the micobending or, in generally, bending loss is basically the mode conversion loss, there are some quantitiative disagreements among theories put forward by several investigators regarding the fibre parameters governing the mode conversion. This may be due to different assumptions used by different investigators for their analyses. Recently, Kawakami and his co-worker [1975, 1976] have predicted, according to their analysis, that the mode conversion loss of a doubly clad (W-type) fibre is much smaller than that of a singly clad (step-index) fibre on the basis of equal beam widths (or sport sizes). However, the analysis of Petermann [1976, 1977] does not agree with this prediction. To resolve this discripancy, more experimental results are necessary. This Chapter will present some new results on bending loss for three major types of multimode optical fibres--step-index, graded-index and W-type fibres, and compare the singly clad (step-index) and the doubly clad (W-type) fibres on the effects of static bending on attentuation loss, pulse broadening and far-field radiation pattern based on equal spot sizes.

2.1 Experimental Techniques

The static bending was formed by placing the fibre over cylindrical steel rods, placing a block elastomer and an aluminum plate on top of the fibre, and then applying a weight to force the fibre to conform to the shape of the rods [Kao 1977, Takeda and Kao 1977]. For all measurements the length of the fibre sample was four meters with both ends cleaved and polished. It should be noted that it is difficult to produce an optical flat fibre end just by cleaving. We first cleaved the fibre end with a diamond cutter, and then inserted the portion with the fibre end into a stainless steel syringe needle whose inside diameter was exactly the same as the outside diameter of the fibre (we had to choose the right size of syringe needles in order to make a good fit). We polished the end first on a very fine sandpaper, and then on a selvyt polishing cloth with Al_2O_3 polishing powder. We can obtain a mirror-like flat surface using this technique. Between the light source and the input end of the fibre a lens was used to focus the light to the input end. The light output at the other end was focussed to a detector. Both ends were mounted on movable fibre holders with micromanipulators which were adjusted to give a maximum light power output at the output end. The excess loss α was determined by the equation.

$$\alpha = 10 \log (P_a/P_b) \qquad (2)$$

where P_a and P_b are, respectively, the light output power at the output end without and with applied static bending.

For measurements of the far-field radiation patterns, a detector was used to scan the radiation field with its pick-up aperture (diameter of 1mm) travelling in a line perpendicular to the fibre axis and located 4 cm from the output end in air as shown in Figure 1. The linear rather than circular scan is adequate if the fibre does not radiate appreciably at angles greater than 15° from the forward direction.

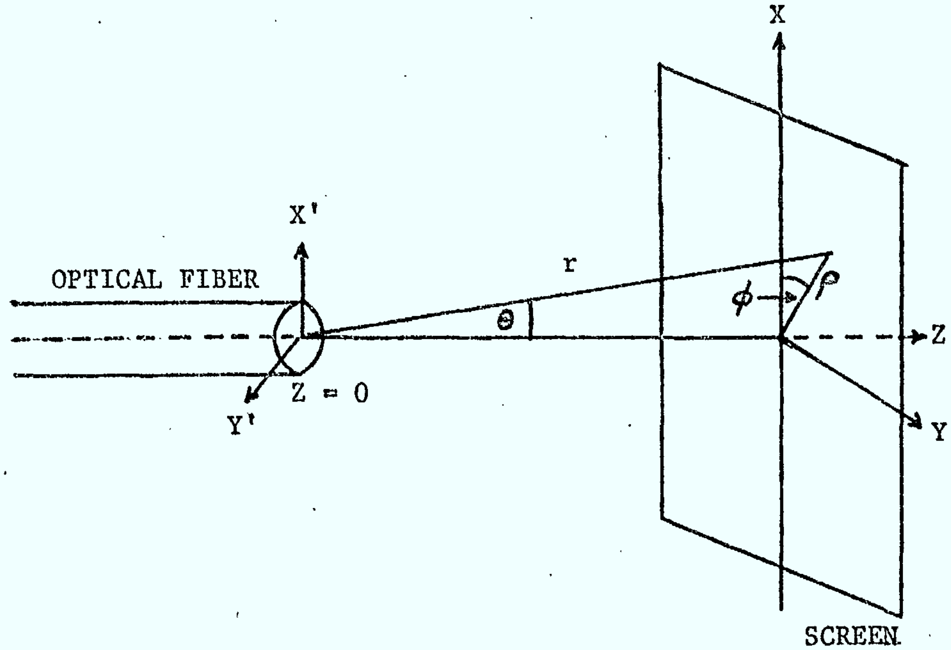


Fig. 1. The arrangement for the measurements of far field radiation patterns from the end of an optical fiber.

For excess loss and far-field radiation measurements the input light used was a monochromatic light of wavelength of 630 nm, while for dispersion measurements a laser light pulse of wavelength of 904 nm and of width of 133.8 ns (measured at the level of 1/e of the peak) was used. The pulse broadening is defined as the difference between the pulse width at the output end with and that without applied static bending.

It should be noted that we chose the wavelength of monochromatic light for all experiments to be 630 nm because this wavelength was calibrated with a Ne-He laser, and that we used a monochromator rather than a Ne-He laser as light source because the former gave a much more stable light intensity. We also used the wavelength of 850 nm occasionally, but for bending loss experiments, the excess loss is practically independent of light wavelength as predicted by existing theories.

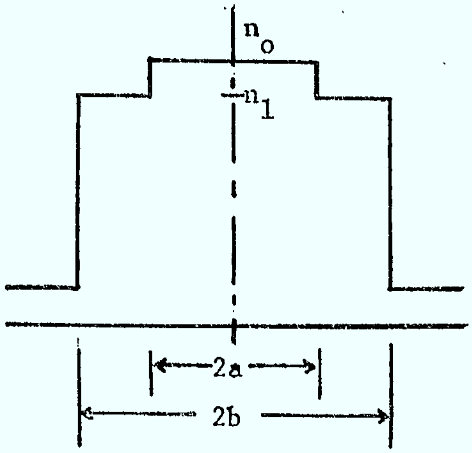
We used EG & G Model 550 Radiometer/Photometer as the detector for static bending excess loss measurements and Motorola MRD 500 PIN photodiodes for far-field radiation pattern and pulse broadening measurements.

2.2 Results and Discussion

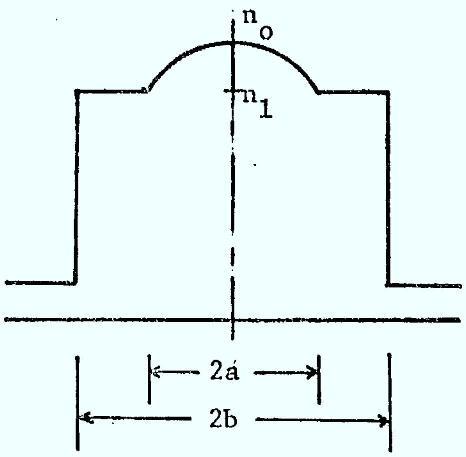
The structures and refractive index profiles of the optical fibres used for this investigation are shown in Figure 2, and some physical parameters of these fibres are given in Table 1. The weight used to produce hump bends was within such a range that it would not cause any mechanical damage to the fibre. For all experiments any change in transmission properties due to the bending returned back to zero when the weight was removed.

Figure 3 shows the excess loss due to hump bends in optical fibres as a function of weight. No measurable excess loss due to two bump bends for diameters of steel rods used to form the bump bends less than 0.1 cm has been detected in optical fibres #1, #2, #3 and #6 [Table 1] within the sensitivity of the detector. These fibres have either a Hytrel or a nylon protective tubing, indicating that the protective tubing does prevent the fibre from being bent. In other words, the tubing reduces the susceptivity of the fibre to external stress applied transversely onto the fibre, thus reducing the possibility of microbending formation during the cabling process. This advantage can be achieved only under the following conditions.

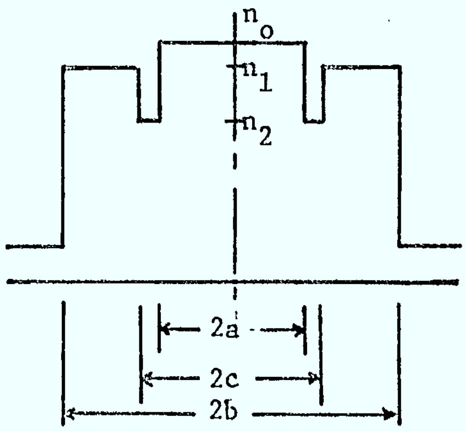
(1) The fibre and the tubing have the same thermal expansion coefficient, so that microbendings cannot be formed due to the change of temperature. This is very important because fibre cables always have a chance to be exposed to outdoor climate on the ground surface before or during the cable-



SINGLY CLAD
(STEP-INDEX)
FIBER



SINGLY CLAD
(GRADED INDEX)
FIBER



DOUBLY CLAD
(W TYPE)
FIBER

Fig. 2. The structures and refractive index profiles of three important types of multimode optical fibers.
n_o - Core refractive index, n_1, n_2 - Cladding refractive index,
a - Core radius, (b - a) - Cladding thickness,
(c - a) - Inner cladding thickness, (b - c) - Outer cladding thickness.

TABLE 1. PHYSICAL PARAMETERS OF OPTICAL FIBRE SAMPLES

ITEM / SAMPLE NO.	INTERNAL CODE	NUMERICAL APERTURE	CORE DIAMETER (μm)	CORE PLUS CLADDING DIAMETER (μm)	OUTER DIAMETER (WITH JACKET)(μm)	JACKET MATERIAL	ATTENUATION AT 850 nm (dB/km)
#1	A-381-#2 Hytrel Tubing	0.37 n_o=1.453 n_1=1.403 (Step-Index)	132* 125 (120-130)	212 *	1080(O.D.) 650(I.D.)	Hytrel	19.3
#2	B-109-#2 Hytrel Tubing	0.37 n_o=1.453 n_1=1.403 (Step-Index)	134* 125 (120-130)	212 *	1040(O.D.) 570(I.D.)	Hytrel	16.4
#3	A-388-#1 Nylon Tubing	0.37 n_o=1.453 n_1=1.403 (Step-Index)	143* 125 (120-130)	219 *	1000-1040(O.D.) 530(I.D.)	Nylon	18.7
#4	A-379-#1 Hytrel Crush Coating	0.38 n_o=1.453 n_1=1.403 (Step-Index)	134* 125 (120-130)	210 *	730	Hytrel	24.8
#5	A-325-#1 PVC Crush Coating	0.32 n_o=1.453 n_1=1.403 (Step-Index)	140* 125 (120-130)	191 *	770	PVC	21.2
#6	Corning 13E Hytrel Tubing	0.22(Fibre) 0.14(Launch) (Graded Index)	62.5 (62.0±0.5)	125 and 132(with thin coating)++	1100(O.D.) 650(I.D.)	Hytrel	10.2
#7	Hitachi W-Type Nylon Coating	Δ_1=0.002 Δ_2=0.007 (W-Index)	60	76 (innerclad) 150 (outerclad)	900	Nylon	5.0

Continued on next page.

TABLE 1. PHYSICAL PARAMETERS OF OPTICAL FIBRE SAMPLES (Continued)

SAMPLE NO. \ ITEM	INTERNAL CODE	NUMERICAL APERTURE	CORE DIAMETER (μm)	CORE PLUS CLADDING DIAMETER (μm)	OUTER DIAMETER (WITH JACKET)(μm)	JACKET MATERIAL	ATTENUATION AT 850 nm (dB/km)
#P1	Glass Cladding EVA Coating	0.19 (Step-Index)	71 ± 1.2	106.7* 108.4 ± 3.8	179.2 ± 24.8	EVA (36.4 ± 11 μm)	19.7
#P2	Glass Cladding EVA + PVC Jacket	0.19 (Step-Index)	71 ± 1.2	109.4* 108.4 ± 3.8	1016 ± 50	EVA(35.4 ± 11 μm) and PVC	18.8
#P3	Silicone Cladding No Coating	0.29 (Step-Index)	97.2* 98	158* 148	158* 148	—	14.7
#P4	Silicone Cladding PVC Jacket	0.29 (Step-Index)	110* 125	160* 161	1016 ± 50	PVC	20.5

Samples: #1 - #5 and #P1 - #P4 Produced by Canada Wire and Cable Co. Ltd.

#6 - Produced by Corning Glass Works of U.S.A.

#7 - Produced by Hitachi Limited of Japan.

$\Delta_1 = (n_o - n_1)/n_o, \Delta_2 = (n_o - n_2)/n_o, n_o$ = core refractive index,

n_1, n_2 = inner and outer cladding refractive index.

$\Delta = (n_o - n_1)/n_o$ for step-index fibers.

++ - Corning graded index fibre has a linear shrinkage of 2.3% and a radial (transverse) shrinkage of 1% after the fibre fabrication process.

* - Measured by means of a microscope at Materials Research Laboratory of the University of Manitoba.

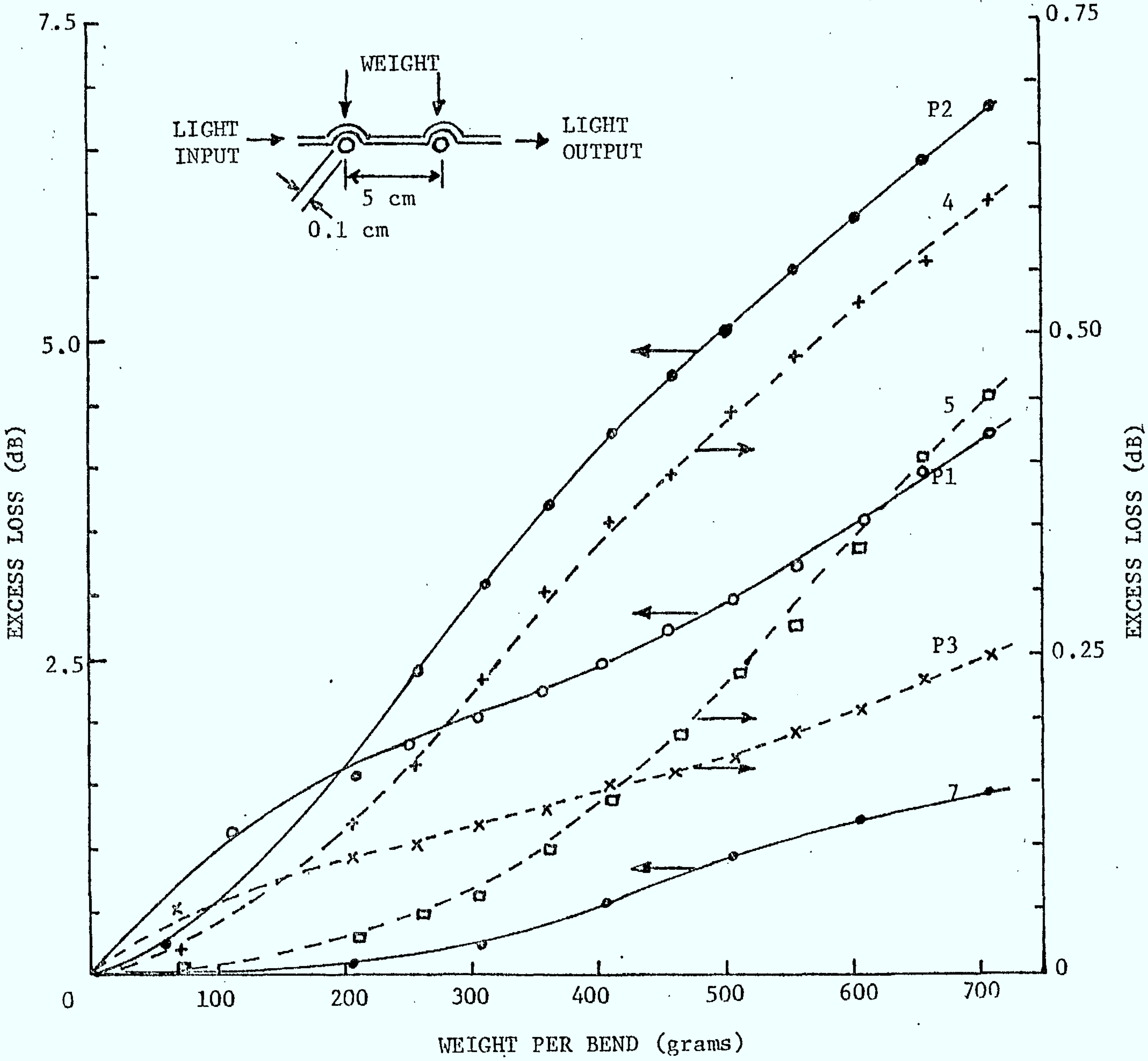


Fig. 3. Excess loss due to bump bends in optical fibers as a function of applied weight. P1- glass cladding with EVA coating, P2- glass cladding with EVA coating and PVC jacket, P3- silicone cladding without coating, 4- silicone cladding with Hytrel crush coating, 5- silicone cladding with PVC crush coating, 7 - glass cladding with nylon jacket (W-type from Hitachi).

installation process, particularly in winter climate in North America.

(2) If the fibre and the tubing have different thermal expansion coefficients, the fibre cables must be kept within an allowed range of temperatures at which microbendings would not be formed. Fibres with a protective tubing are very sensitive to low temperatures—lower than normal room temperature and this will be discussed in Chapter III.

Of the six fibres in Figure 3, the fibres with glass cladding suffer a much higher excess loss due to bump bends than those with silicone cladding. This may be due to the fact that it is easier to force a fibre with a stiff glass cladding to conform to the shape of the bump than to force a fibre with an elastic silicone cladding (by comparing fibre samples #P1 with #P3, and samples #P2 with #5). These results are consistent with the microbending loss results reported earlier [Kao 1977].

The excess loss due to bump bends in fibre sample #P4 (not shown in Figure 3) is of about the same order as that in fibre sample #P1, but is about ten times larger than that in sample #5. In terms of core diameter, cladding and protective jacket-materials, sample #P4 is very similar to sample #5. Therefore, the large difference in excess loss between these two samples must be due to the following factors: (i) the numerical aperture of sample #P4 is smaller than that of sample #5, (ii) the interface between the silicone cladding and the PVC jacket is microscopically more irregular in sample #P4 than in sample #5 if the microscopic irregularities in the interface between the core and the silicone cladding are assumed to be about the same in both samples.

The PVC jacket provides a screening effect to protect the fibre from microbending due to external transverse stress. In general, the bending loss increases with increasing diameter of the steel rods used for producing bump bends (or with increasing effective bump height). For microbends or bump bends produced by the steel rods of diameters less than 0.03 cm, the fibres with a PVC jacket suffer a much less bending loss than those without a PVC jacket, and also the thicker the jacket material, the smaller is the bending loss provided that the other parameters are identical. This trend is consistent with the theory [Gloge 1975, Olshansky 1975]. However, for bump bends produced by the steel rods of diameters larger than 0.06 cm, this trend in some cases is reversed. For example, the excess loss due to two bump bends by the rods of diameter of 0.1 cm in fibre sample #P2 (glass cladding with a PVC jacket on top of an EVA coating) is larger than that in sample #P1 (glass cladding without a PVC jacket) for applied weights larger than 200 grams, but smaller than that in sample #P1 for applied weights less than 200 grams as shown in Figure 3. At low weights the PVC jacket acts effectively to screen the fibre from bending, but at large weights the weight not only forces the fibre to conform to the shape of the cylindrical rods of a relatively larger diameter, but also induces microbends around the rods possibly due to irregularities at the interface between the cladding and the PVC jacket.

In Figure 3 all fibres are of singly clad (step-index) fibres except fibre sample #7 which is of doubly clad (w-type) fibre. These two types of fibres are different in their structures. It is therefore important to compare these two types of fibres based on their response to applied bump bends. First, we present the results of excess loss and pulse broadening due to bump bends in the w-type fibre in Figure 4. This figure shows that the excess loss due to bump bends increases with increasing applied weight and increasing number of bends as expected. All curves tend to reach a saturation if the weight is continued to increase to such a value that the fibre becomes more or less completely conformable to the shape of the rods. The trend of the excess loss is consistent with the decrease of the light pulse width as the applied weight is increased as shown in Figure 4. This implies that with bump bends a number of high guided modes have been coverted to higher order modes and a number of high-order modes to leaky modes and filtered out. The rate of increase in excess loss diminishes as the number of bends is increased, and it is also expected that the excess loss will approach to a saturation value if the number of bends is continued to increase. A bump bend can be thought of as a high order mode filter. If there is a series of bump bends, the first bend suppresses the efficiency of the second bend, and the second bend suppresses the efficiency of the subsequent bends in their filtering action.

The comparison of the excess loss and the pulse broadening

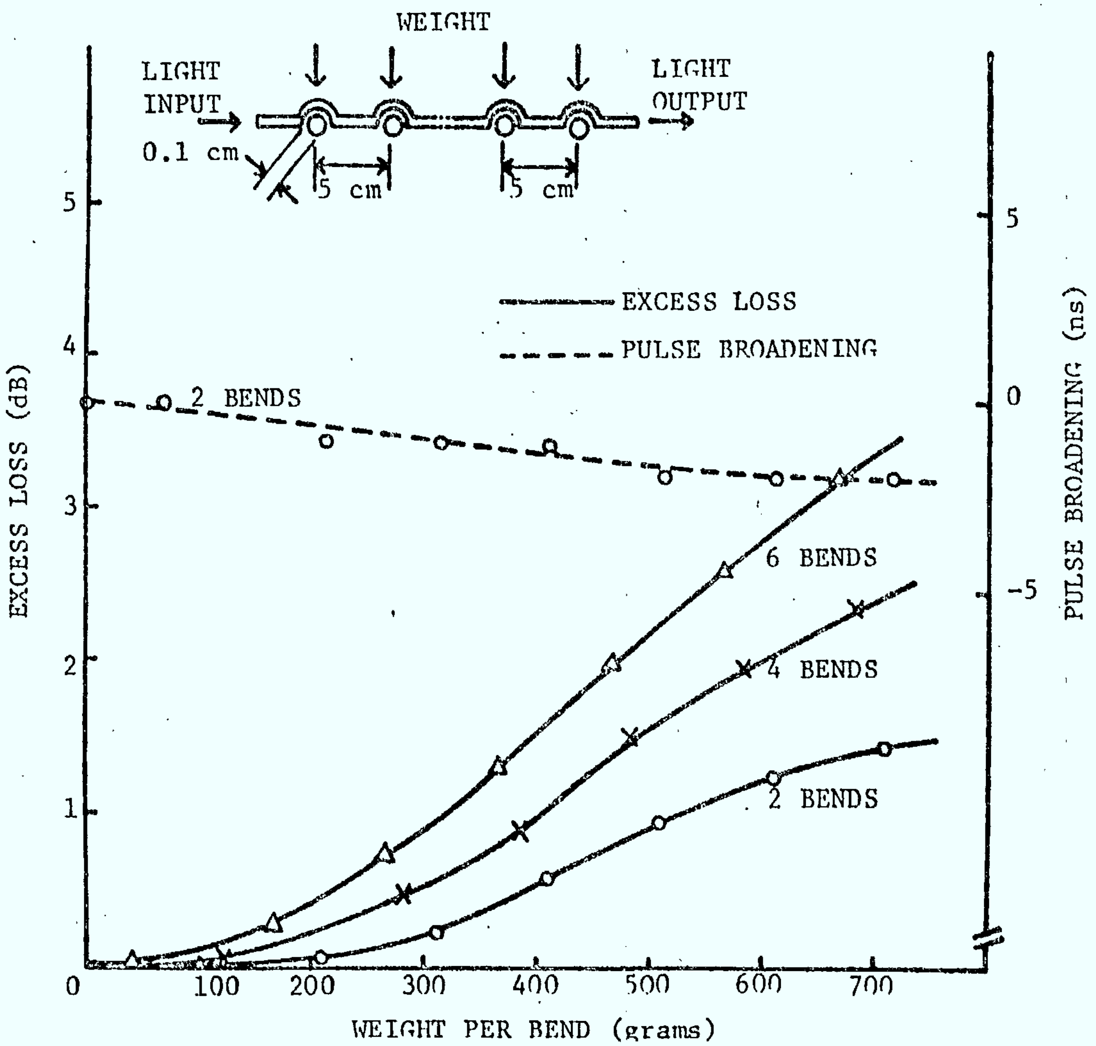


Fig. 4. Excess loss and pulse broadening due to bump bends in the doubly clad (W-type) optical fiber as functions of applied weight.

between the w-type and the step-index fibres is shown in Figure 5. We choose fibre sample #P1 to compare with the w-type fibre because both have glass claddings. However, to compare these two types of fibres, it is necesary to choose some common parameters as a basis. In here we choose the characteristic spot size r_o defined by [Kawakami et al. 1975, 1976]

$$2r_o = \pi\ a/u \tag{3}$$

as the basis for this comparison, where u is determined by the following equation

$$\begin{aligned} v &= u/\cos u \\ &= [1-(n_1/n_o)^2]^{\frac{1}{2}} n_o k_o a \end{aligned} \tag{4}$$

in which $k_o = 2\pi/\lambda$, λ is the wavelength of the light, and other constants are defined in Figure 2. For the two fibres under investigation, the refractive-index difference between the core and the cladding for the step-index type is $\Delta = (n_o-n_1)/n_o \simeq 0.008$ (based on $n_o = 1.5$) and the effective Δ for the w-type is 0.007. The slight difference in Δ does not make a great difference in u between the two fibres provided that a is the same. The main parameter which makes these two fibres differ in spot size is the radius of the core. Since the values of a are, respectively, 35 μm and 30 μm for the step-index and the w-type fibres, we have to adjust the excess loss for the step-index type before comparison. The microbending loss for multimode waveguides is given by [Olshansky 1975].

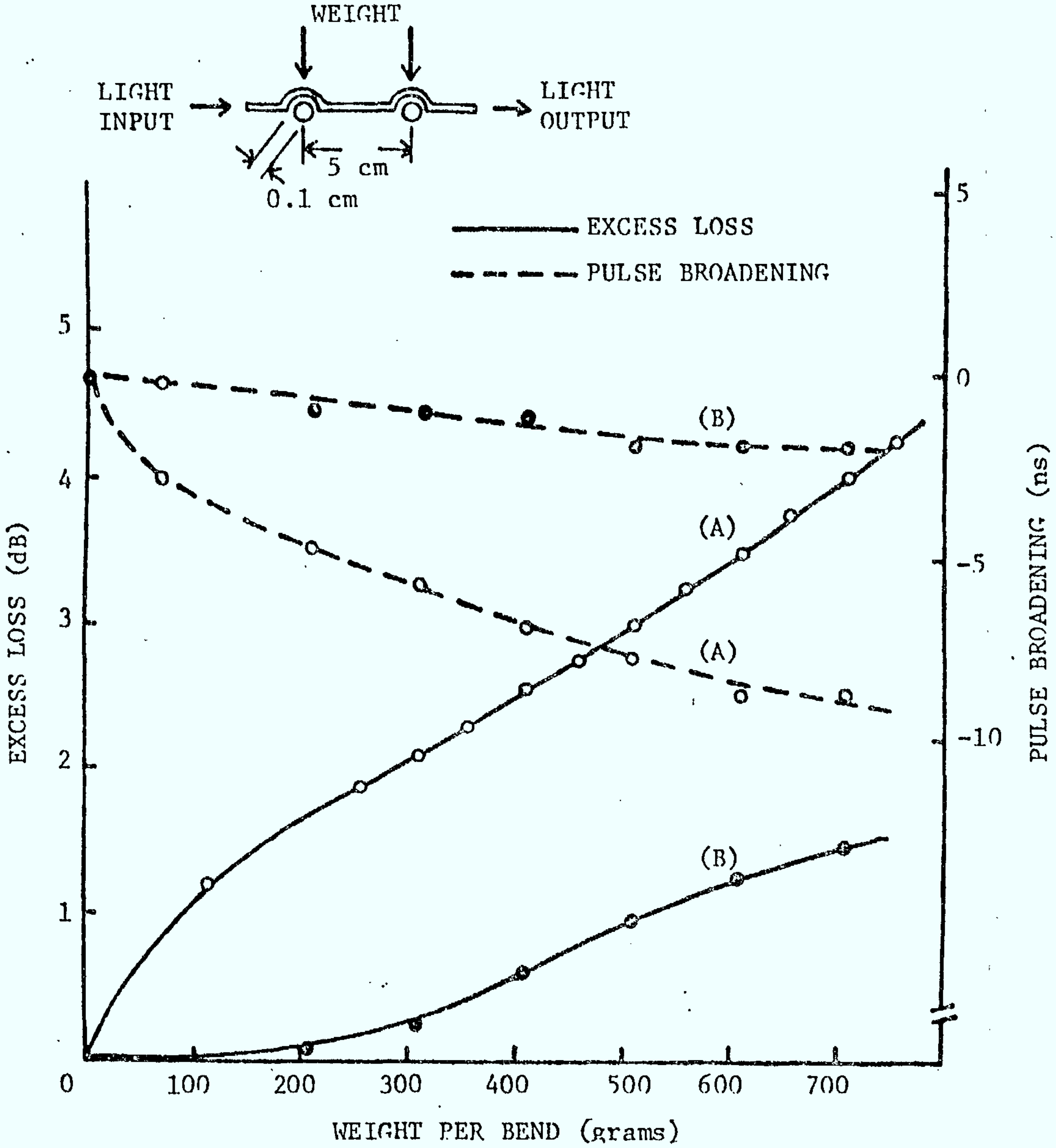


Fig. 5. Excess loss and pulse broadening due to two bump bends in the fiber as functions of applied weight:(A) Single clad (step-index) fiber and (B) Doubly clad (W-type) fiber.

$$\alpha = (C/\Delta) \ (a^2/\Delta)^p \qquad (5)$$

where C is a parameter depending on the refractive index profile and p lies between 0 and 2. By choosing $p = 1$, then α is proportional to $(a/\Delta)^2$. To find the equivalent excess loss for the step-index type corresponding to $a = 30\ \mu m$ and $\Delta = 0.007$ (corresponding to the same spot size of the w-type), we have to multiply the excess loss for the step-index type (Figure 5) by a factor of $(30/35)^2\ (0.008/0.007)^2 = 0.96$. It can be seen that on the basis of equal spot size, the w-type fibre is superior to the step-index type in the tolerance to micro-bending. Our experimental results support the theoretical predictions of Kawakami and his coworkers [1975, 1976] and Mayagi and Yip [1977], and agree with the experimental work of Tanaka et al. [1977].

In Figure 6 are also shown the far-field radiation patterns of the step-index and the w-type fibres. It can be seen that in the w-type fibre the major radiation is confined within the angles of 5° indicating that the guided modes are well confined within the core region. Unlike the step-index fibre in which the extension of the far-field radiation decreases with increasing degree of bending (i.e., with increasing weight), there is only a negligibly small change caused by the increase of weight in the w-type fibre, indicating that the number of guided modes is much less or the mode spacing is much wider in the w-type than in the step-index fibres. This inherent advantage of the w-type fibre can be considered due mainly to the outer cladding with a refractive index higher than that of the inner cladding.

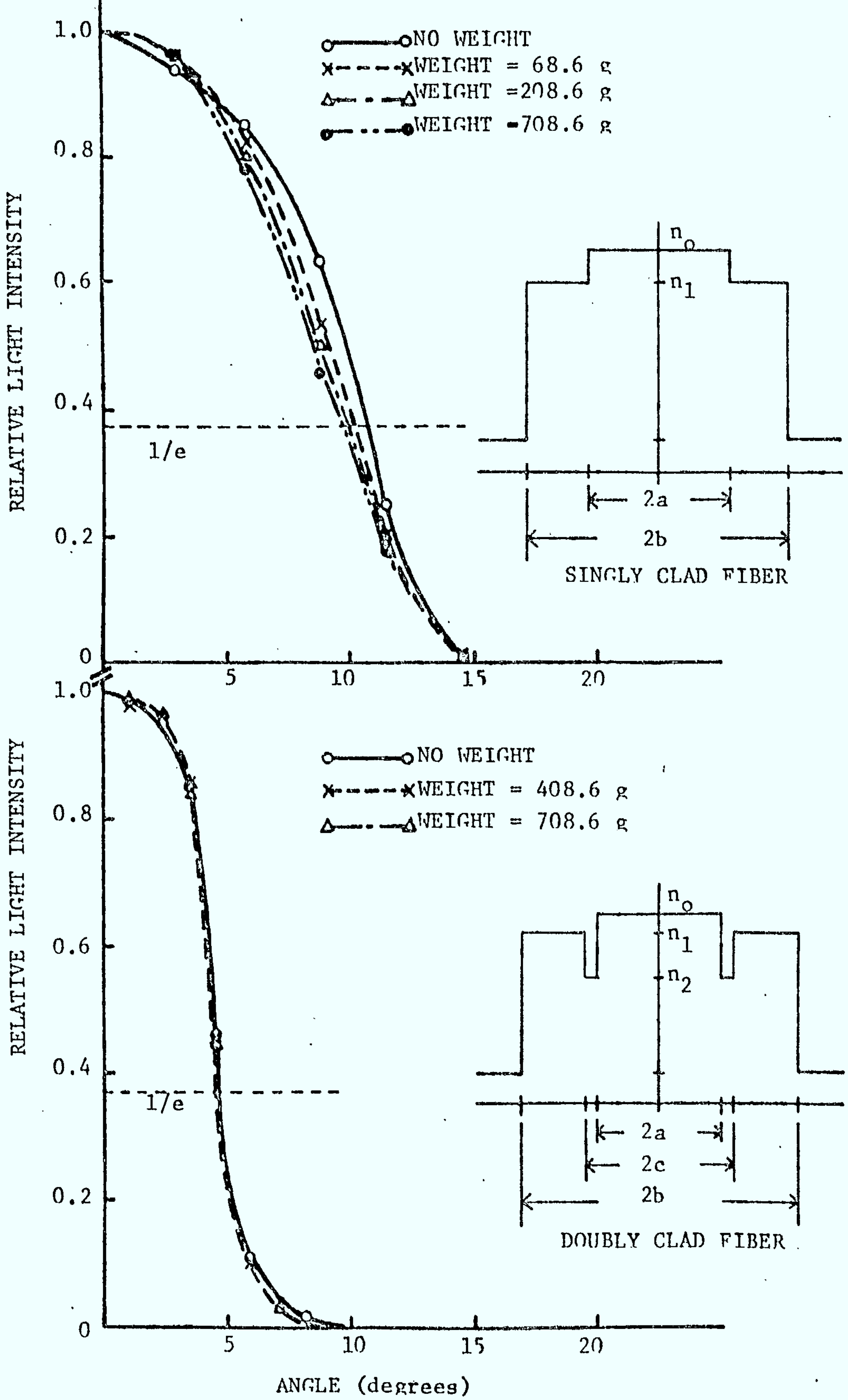


Fig. 6. Far field radiation patterns of output light from the fiber with two bump bends. Steel rod diameter = 0.1 cm; Bend separation = 5.0 cm. (A) Single clad fiber: $n_o[2(n_o - n_1)/n_o]^{1/2} = 0.19$; 2a = 71 μm; 2b = 108.4 μm; Overall diameter = 179.2 μm with an EVA coating. (B) Doubly clad fiber: $(n_o - n_1)/n_o = 0.002$; $(n_o - n_2)/n_o = 0.007$; 2a = 60 μm; 2b = 150 μm; 2c = 76 μm; Overall diameter = 900 μm with a Nylon jacket.

On the basis of experimental results on pulse broadening and far-field radiation patterns, we can conclude that the excess loss due to microbending and, in general, bending is due to mode-conversion loss. From the above results, we should consider the following points in order to reduce microbeing or bending losses.

(1) Small core diameter "a". If "a" can not be made small from the splicing difficulty point of view, the ratio of a/Δ must be kept as small as possible. In most multi-mode fibres the bending loss is in proportion to $(a/\Delta)^3$ rather than $(a/\Delta)^2$ [Naruse et al. 1977].

(2) Large numerical aperture. This means large value of Δ . This is necessary if "a" cannot be made small.

(3) Elastic cladding. From bending loss point of view, an elastic cladding would give a less bending loss than a glass cladding. It should be noted that silicone may not be the best material to be chosen for cladding because its thermal expansion coefficient is larger than that of the glass. The thermal expansion effect is not important for temperatures higher than 0°C because silicone is elastic at high temperatures. But it would be very important at low temperatures (below 0°C), at which silicone becomes stiff and may cause microcracks or microbendings. This will be discussed in Chapter III. If there is no suitable elastic material with about the

same thermal expansion coefficient as the glass and suitable for cladding. We would like to suggest to use glass cladding with an elastic protective jacket.

(4) Doubly cladding. There is an inherent advantage of the w-type over the step-index type because the former has double cladding which provides less guided modes and tighter confinement guided modes within the core region, thus reducing the mode-conversion loss.

111 EFFECTS OF TEMPERATURE, THERMAL CYCLING AND WINNIPEG ENVIRONMENT ON TRANSMISSION PROPERTIES OF OPTICAL FIBRE WAVEGUIDES

In future, optical fibre cables for optical communications may be buried underground to a depth of about 3 meters or deeper below the ground surface inside a conduit in which the temperatures may vary within the range of -1°C to 25°C all the year round. However, unless special precautions are taken during storage and shipment, the fibre cables may have to be exposed to the actual climate (at temperatures as low as -50°C) during cable installation or shipment, particularly in winter time in North America. Thus temperature, thermal cycling and actual environment tests on fibres are of great importance to system engineers who are responsible for the design and the performance of the whole communication system, and also to manufacturers who supply fibre cables for particular systems to be operated at particular climates and environments. This chapter is to present some results on the effects of temperature, thermal cycling and Winnipeg environment on the attenuation loss of optical fibre waveguides.

3.1 Effects of Temperature

To avoid any possible microbending formation due to external stress, the fibre was not wound on a smooth glass drum as the method used in the previous report [Kao 1977]. This time, we placed the fibre of about 8 meters loosely in circular form of diameter of 25 cm on a wooden plate which was then placed inside a thermostatically controlled chamber.

The temperature range used for this investigation was from -50°C to +50°C.

For all fibres listed in Table 1, the excess loss is practically unchanged for temperatures between +10°C and +50°C as shown in Figures 7 and 8. The excess loss is drawn in dB per 10 meters of fibre with the temperature of 20°C as the reference temperature so that it is easy to compare the temperature effects among different fibres. We now summarize the temperature effect results as follows:

(A) Fibre #P1 practically suffers no excess loss for the temperature range from -50°C to 50°C. This is due to the fact that in this fibre both the core and the cladding are made of glass which is not sensitive to temperature in this temperature range. There is no stress developed between the core and the cladding because both have about the same thermal expansion coefficient. Although the EVA material may have a thermal expansion coefficient higher than the glass, the EVA material is more elastic than the glass even at low temperatures. Thus a change in the temperature may induce a longitudinal stress to the fibre in the direction parallel to the fibre axis, but the longitudinal stress alone would not cause excess attenuation loss in the fibre. Of course, the longitudinal stress may cause microbreaks between the cladding and the EVA coating along the fibre, but such microbreaks occur at the outer cladding surface which should not affect the loss. However, a change in temperature may also induce a transverse stress to the fibre in the direction perpendicular to the fibre axis. This stress depends on the thickness of the coating, the difference in thermal

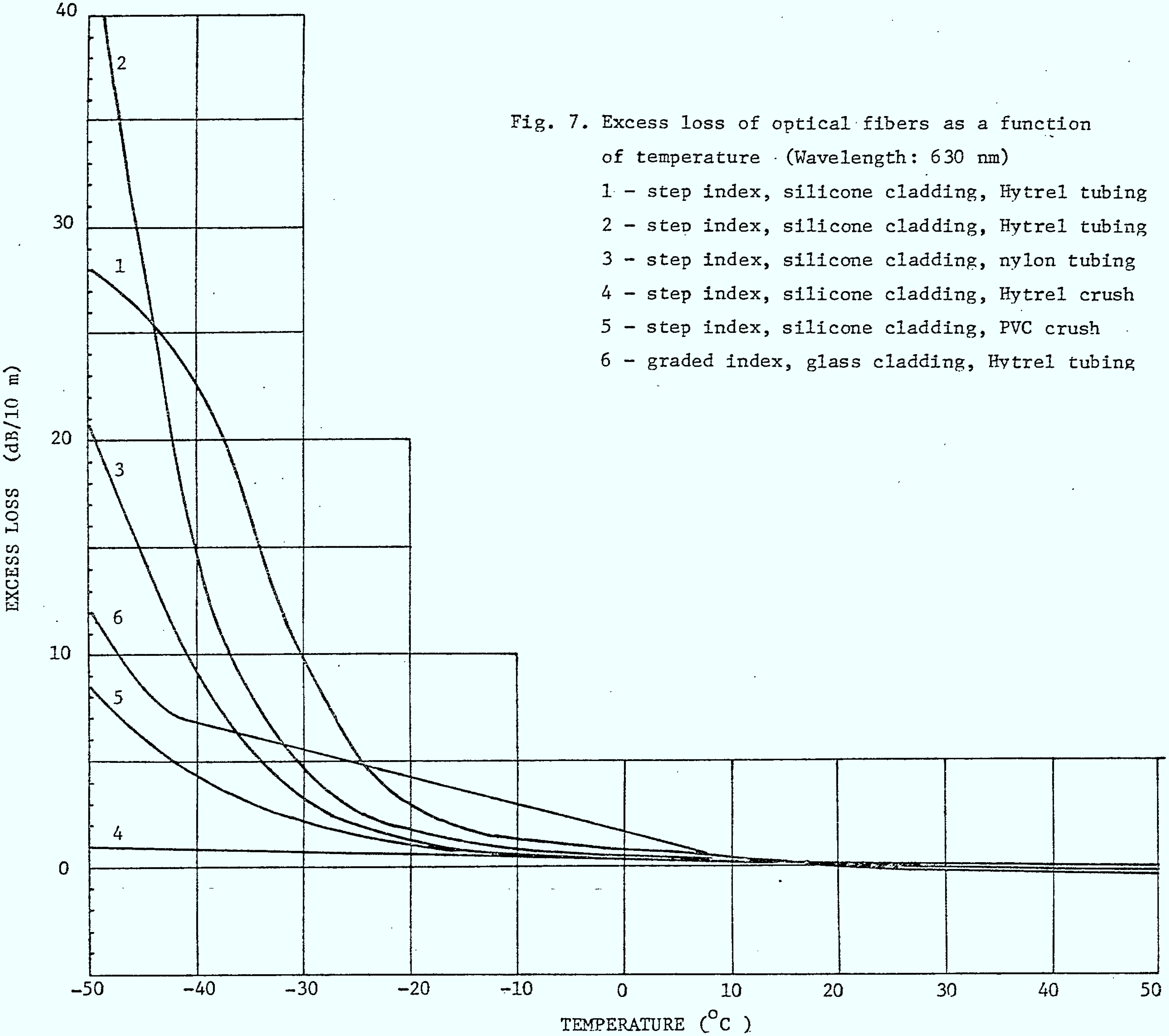


Fig. 7. Excess loss of optical fibers as a function of temperature (Wavelength: 630 nm)

1 - step index, silicone cladding, Hytrel tubing

2 - step index, silicone cladding, Hytrel tubing

3 - step index, silicone cladding, nylon tubing

4 - step index, silicone cladding, Hytrel crush

5 - step index, silicone cladding, PVC crush

6 - graded index, glass cladding, Hytrel tubing

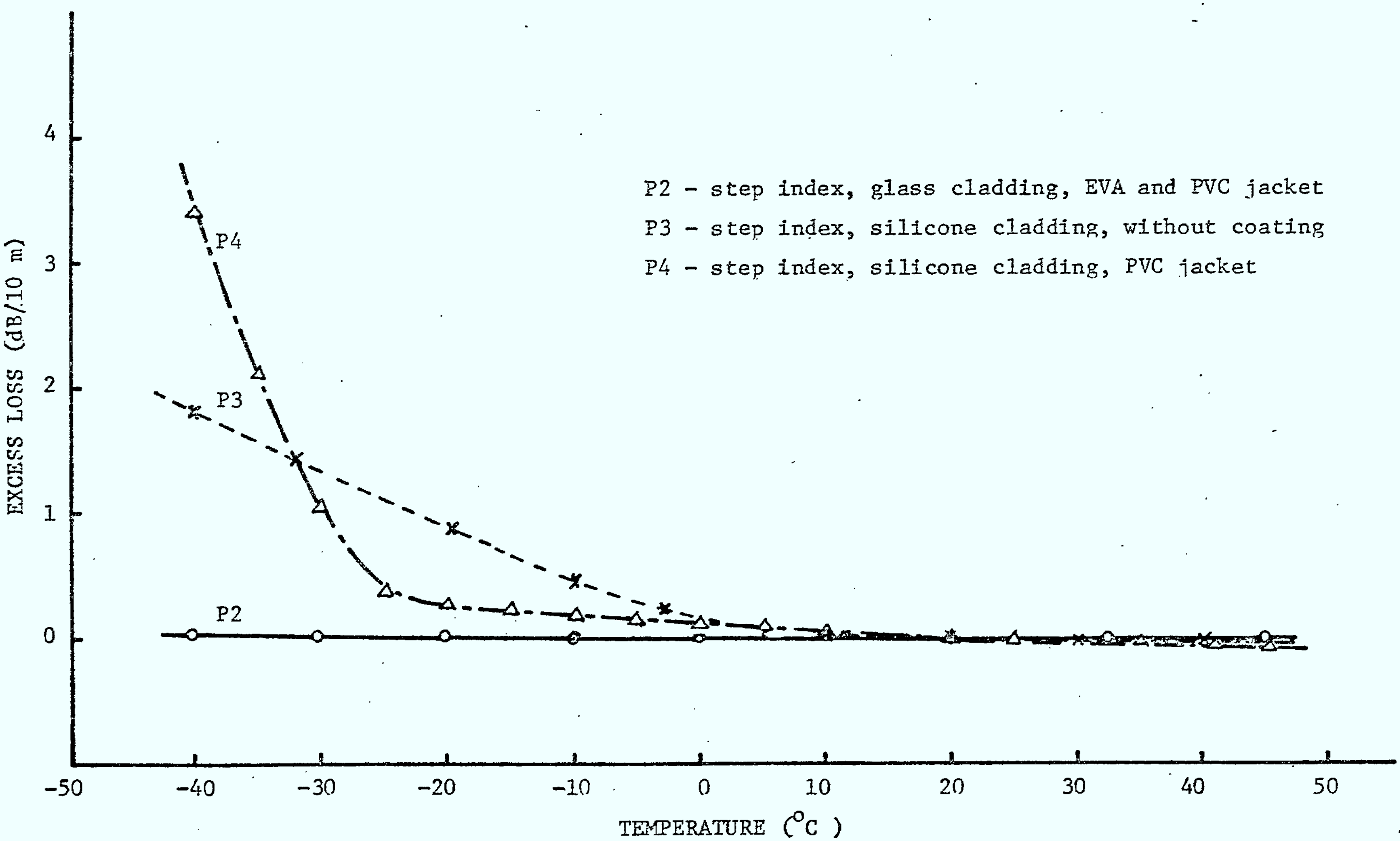


Fig. 8. Excess loss of optical fibers as a function of temperature (Wavelength: 630 nm)

expansion coefficient between the glass and the coating (EVA in the case here), and the stiffness of the coating. For Fibre #P1, the thickness of EVA coating is small, therefore the transverse stress induced by temperature is small and this may be the reason why no excess loss was observed for this fibre over the temperature range from -50°C to 50°C.

(B) Fibre #7, like Fibre #P1, practically suffers no excess loss for the temperature range from -50°C to 50°C. This fibre has a nylon jacket whose thermal expansion coefficient is higher than that of the glass. We would expect that the temperature-induced transverse stress may cause microbendings in the way shown in Figure 9. However, there are at least three reasons which may explain why this fibre is not sensitive to temperature in the temperature range under investigation:

(i) The nylon is still quite soft even at -50°C as compared with the glass.

(ii) Even if there are bends produced by the temperature-induced transverse stress, the radius of curvature of the bends would be large. The bending loss due to this type of bends is proportional to exp $(-R/R_o)$, where R_o is a constant and R is the curvature radius [Kao 1977]. If R is larger than a few millimeters, the bending loss is not significant. However, such a bend may create many microbends within the bend due to uneven outer surface of the glass cladding and uneven inner surface of the nylon jacket coupled with non-uniform distribution of stress distribution around the bend. W-type fibres can

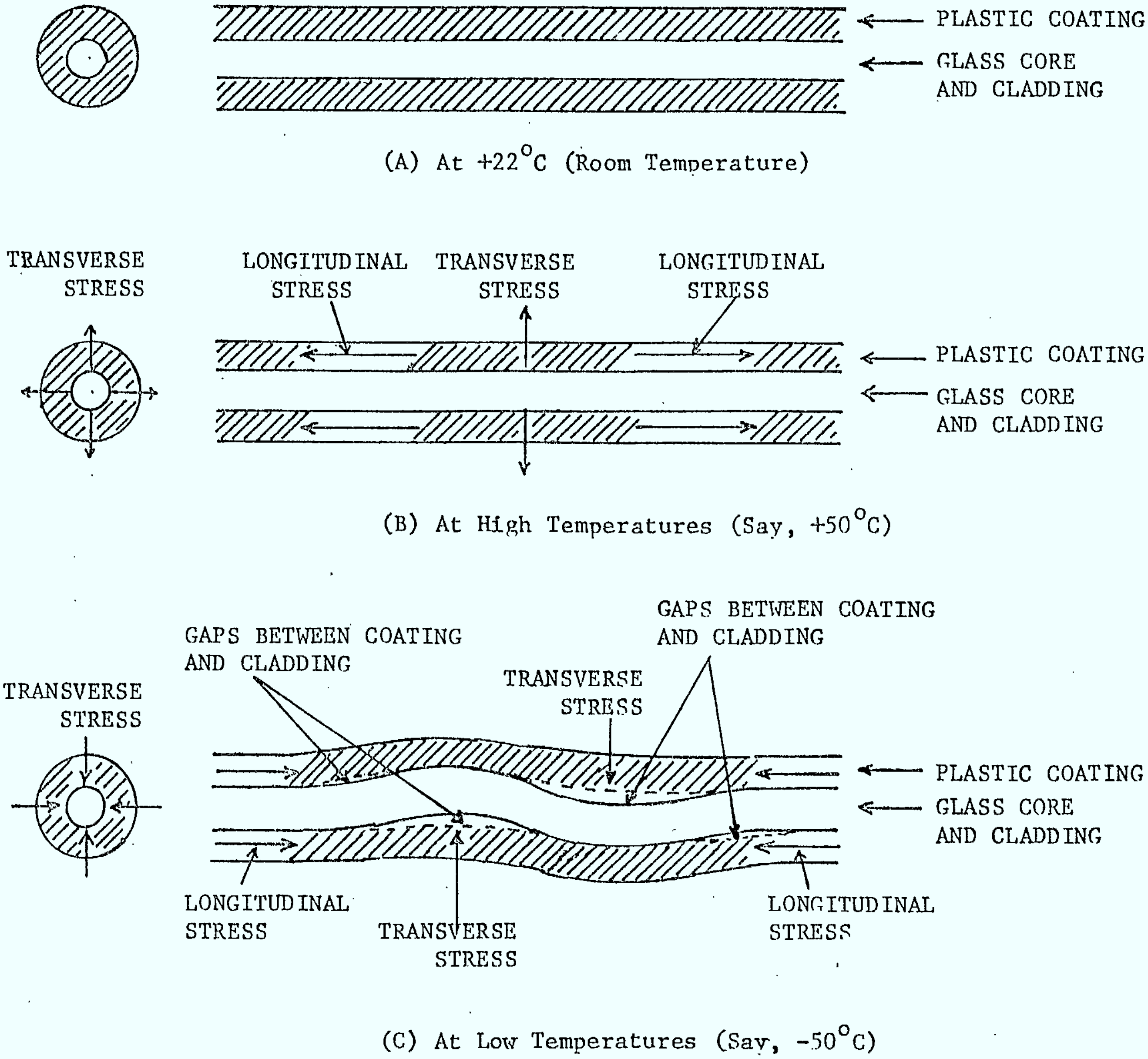


Fig. 9. Illustrating the effects of stresses induced by the change of temperature in an optical fiber composed of a glass core, a glass cladding and a plastic coating. The thermal expansion coefficient of the plastic coating is higher than that of the glass.

tolerate sharper microbends than step-index fibres as has been explained in Chapter 2 because they have an outer cladding with a higher refractive index to reduce the mode-conversion loss.

(iii) Even if the temperature-induced stress may cause microbreaks between the outer-cladding surface and the nylon jacket, such microbreaks should not significantly affect the loss.

(C) Fibre #P2 is similar to Fibre #P1 except that Fibre #P2 has a PVC jacket. It is obvious that the PVC jacket brings a small excess loss in attenuation at low temperatures as shown in Figure 8. The excess loss is very small and may be unimportant. The main cause of this excess loss may be attributed to the mechanism given in reason (ii) of (B) above. In w-type fibres the jacket material is nylon, while in Fibre #P2 it is PVC. The microbends formed around the bend shown in Figure 9(C)are the main cause of the excess loss and not the bend itself. This finding is consistent with the results on the effects of bump bends shown in Figure 3. At higher weights, Fibre #P2 suffers a higher excess loss than Fibre #P1 due to bump bends produced by steel rods of diameter of 0.1 cm. All these results indicate that microbends produced around a large bend are due to unsmooth or uneven interfaces between the cladding and the EVA coating, and between the EVA coating and the PVC jacket. In fact the EVA coating in Fibres #P1 and #P2 is very uneven. According to the data supplied from the manufacturer, the thickness of the EVA coating varies from the extreme 24.4 μm to the extreme 46.4 μm (35.4 ±11 μm). Such a thickness variation is not important if there is no PVC jacket (e.g., Fibre #P1) but it is very important if a PVC jacket is added on top of the EVA coating (e.g., Fibre #P2). The PVC jacket creates an transverse stress due to the change of temperature or large bump bends, which modulates the straightness of the glass fibre according to the non-uniformity of the EVA coating or, in general, to the roughness of the interface between the EVA coating and the PVC jacket.

(D) Fibres #P1, #P2 and #7 have both the core and the cladding made of glass, so as fibre itself there is no constraint in stress because both the core and the cladding have about the same thermal expansion coefficient and the same Young's modulus. This leads to the fact that the attenuation loss of these fibres is insensitive to temperature changes.. Of course, an added buffer layer and an added protective jacket may introduce indirectly a transverse stress onto the fibre making this type of fibre slightly dependent on temperature as has been discussed in (C) above. Fibre #P3 is quite different, its cladding is made of silicone which has a much larger thermal expansion coefficient (or smaller Young's modulus) than the glass core (see Table 2). There are at least two possible effects associated with silicone cladding.

(i) At temperatures higher than 0°C silicone is reasonably soft and elastic, both the longitudinal and the transverse stresses induced by temperature change to higher temperatures should not affect the attenuation loss. However, at temperatures lower than 0°C silicone becomes less elastic. The contraction of the silicone cladding, particularly at temperatures lower than -30°C, may create a very high transverse stress, causing microbreaks or microcracks

TABLE 2. THERMAL EXPANSION COEFFICIENTS OF SOME MATERIALS USED IN OPTICAL FIBRES*

MATERIAL	THERMAL EXPANSION COEFFICIENT($^{o}C^{-1}$)	REMARKS
Glass	5.5×10^{-7}	
Silicone	1.0×10^{-3}	Plastic clad silicone (PCS) which has a linear shrinkage of 1% after the fibre fabrication process
PVC	1.0×10^{-4}	
Nylon	8.0×10^{-5}	
Hytrel	2.1×10^{-4}	Dupont Polyester
EVA	-	EVA has a linear shrinkage of 2.3% after the fibre fabrication process.

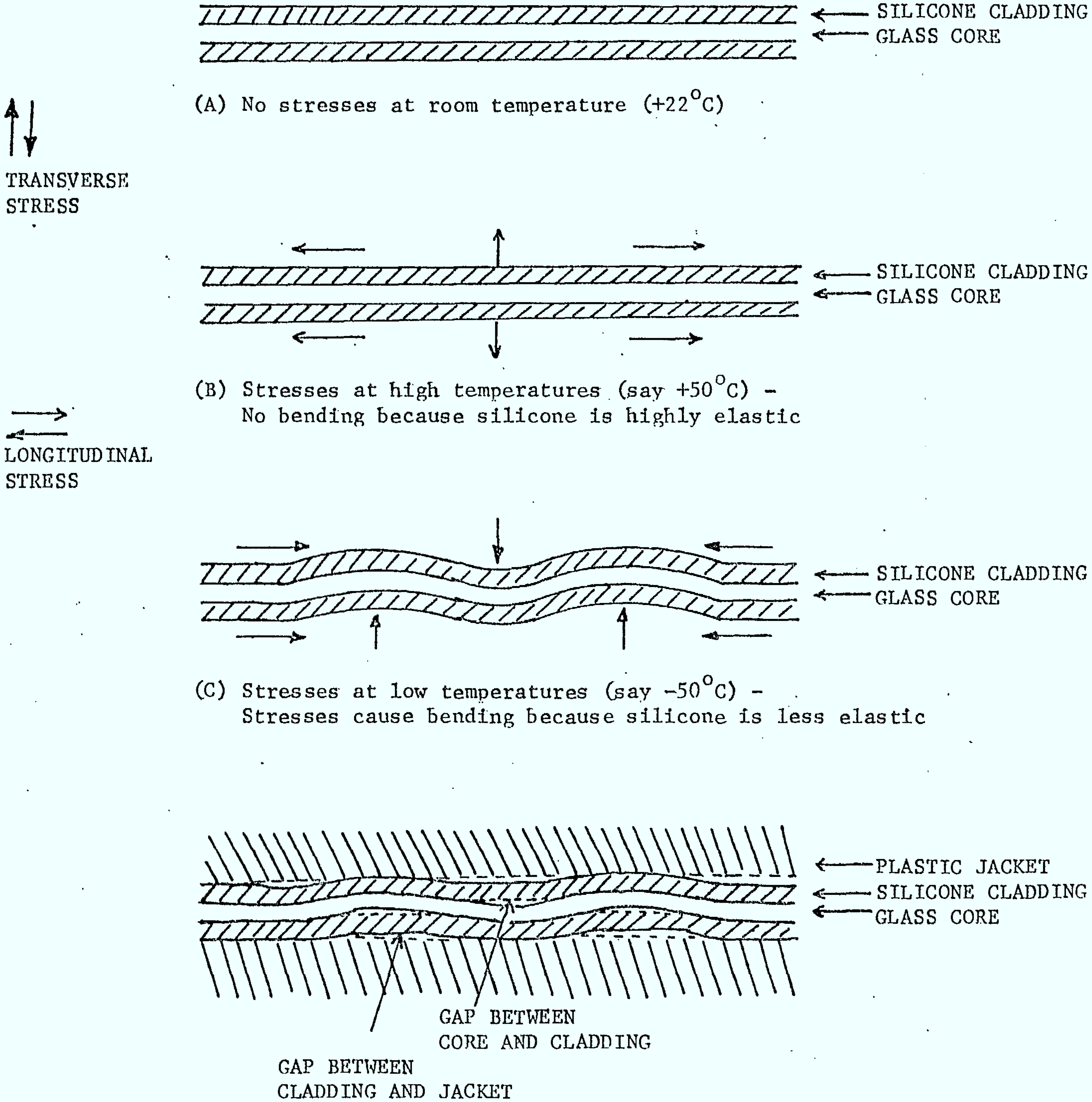
* Courtesy of Mr. P. Scadding of Canada Wire Fibre Optics.

as shown in Figure 10. These microbreaks or microcracks which occur in the interface between the core and the cladding, are far more detrimental to optical transmission properties of the fibre than those occurring at the outer cladding surface as described in (C) or shown in figure 9. This explains why the excess loss is so high at low temperatures. It should be noted that this change in excess loss due to the decrease in temperature is reversible. This means that when the temperature is increased from -50°C to room temperature, the excess loss decreases to the original value at room temperature (zero excess loss as a reference). This phenomenon implies that the transverse stress may not be strong enough to produce microbreaks between the core and the cladding, though it is strong enough to produce microbendings as shown in Figure 10.

(ii) A decrease in temperature may also result in an increase in refractive index of silicone because it is known that the permittivity of silicone starts to increase rapidly with decreasing temperature for temperatures lower than 0°C. This means that the value of Δ decreases with decreasing temperature, and this may be one of the important factors to cause the rapid increase in excess loss with decreasing temperature for Fibre #P3. Of course, this change is of a reversible nature.

The effects described in (i) and (ii) explain well the temperature dependence of excess loss for Fibre #P3.

(E) Fibre #5 is similar to Fibre #P4. Both have a PVC jacket. Fibre #4 is also similar to Fibre #P4 except that Fibre #4 has a Hytrel



(A) No stresses at room temperature (+22°C)

(B) Stresses at high temperatures (say +50°C) - No bending because silicone is highly elastic

(C) Stresses at low temperatures (say -50°C) - Stresses cause bending because silicone is less elastic

(D) Plastic jacket coupled with silicone cladding cause microbreaking of bonds in interfaces at low temperatures (say -50°C)

Fig. 10. Illustrating the effects of stresses induced by the change of temperature in an optical fiber composed of a glass core and a silicone cladding.

jacket instead. So we can discuss the results of these three fibres together. In general, the jacketing process brings excess loss in attenuation. This may be due mainly to the formation of microbends caused by differential cooling and dissimilarity in thermal expension coefficients during the jacketing process. It is expected that there are imperfections in the interface between the silicone cladding and the plastic jacket. Such imperfections include small bubbles, non-uniformity in adhesion between the two materials, etc. Again, at temperatures higher than 0°C both the silicone cladding and the plastic jacket are elastic and should not have any significant temperature effects on attenuation loss. However, at low temperatures (lower than 0°C), the situation is quite different. The contraction of the PVC jacket may give rise to microbreaks not only along the interface between the silicone cladding and the PVC jacket, but also possibly between the glass core and the silicone cladding as shown in Figure 10. We could not detect the imperfections in the interface between the glass core and the silicone cladding, but we found that after the exposure of Fibre #5 to thermal cycling for about 200 cycles between -50°C and 50°C, the fibre could be easily separated from the PVC jacket in some sections (PVC crush coating looked like a tubing), indicating that the adhesion between the silicone cladding and the PVC coating completely disappeared after long exposure to thermal cycling. This may be interpreted as due to the microbreaks caused by low-temperature-induced transverse stress. This also explains why silicone cladding fibres with a plastic jacket have a much stronger temperature dependence of excess loss than those without a plastic jacket (compare Fibres #4, #5 and #P4 with Fibre #P3).

(F) Fibres #1, #2, #3, and #6 have a loose plastic tubing to protect the fibre. These fibres suffer an even much higher excess loss at low temperatures than those with a plastic crush coating. The plastic tubing has a much higher thermal expansion coefficient than the glass, and thus at low temperatures the fibre inside the tubing will form a kind of serpentine bends as shown in Figure 11. Furthermore, each of such bends is touching the inner wall of the tubing. If the inner wall is rough, the low-temperature-induced stress will also force the fibre to conform to the roughness of the inner wall to create microbending. In fact, the fibre is quite eccentric, i.e., the centre of the core is not the centre of the fibre as shown in Figure 12. If the thin cladding side is touching the rough inner wall surface of the tubing, the situation would be much worse. This means that the susceptibility to microbending is higher. We have also measured the pulse broadening as a function of temperature. Figure 13 shows that the pulse broadening decreases with decreasing temperature indicating that the higher excess loss at lower temperatures is due to the mode-conversion loss caused by the low-temperature induced bending.

3.2 Effects of Thermal Cycling

Thermal cycling tests can be used to evaluate the following properties:

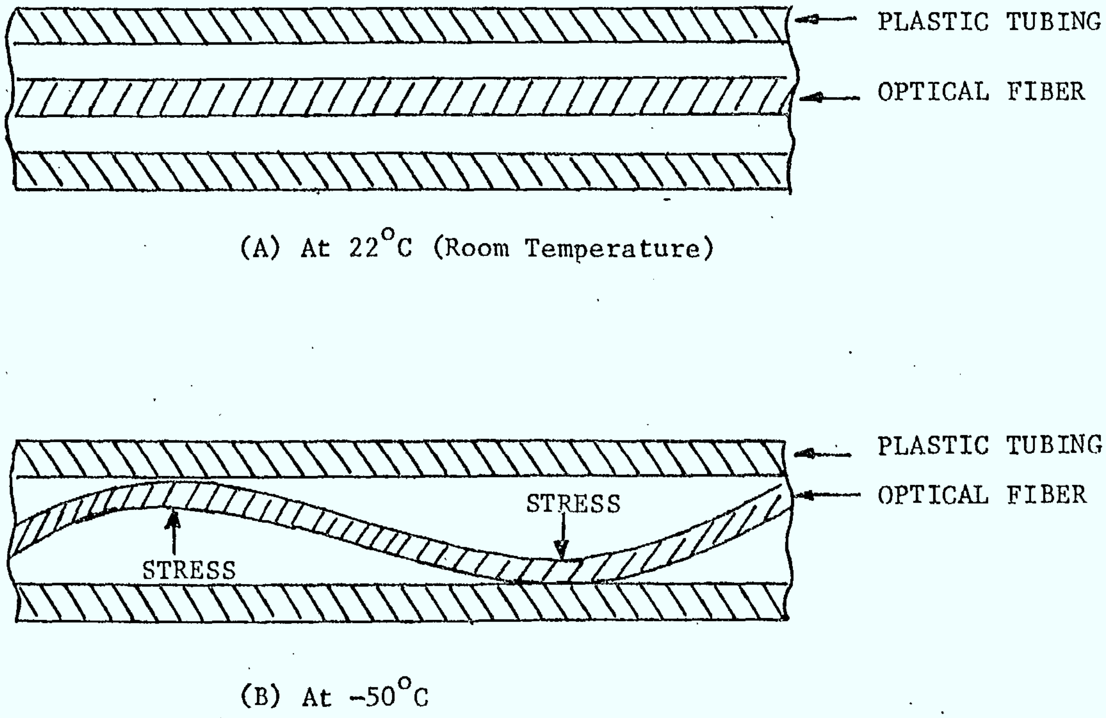


Fig. 11. The fiber bending inside the plastic tubing due to the dissimlarity in the thermal expansion coefficient between the fiber and the tubing.

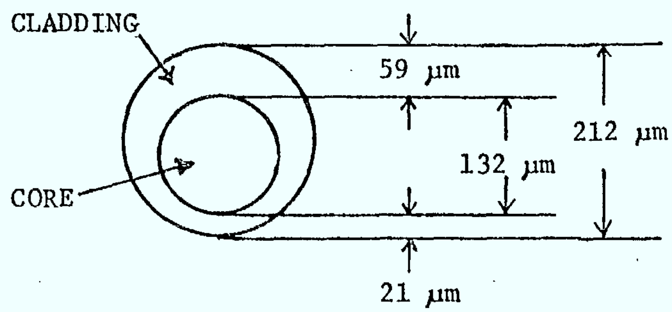


Fig. 12. A typical example of the eccentricity of Fiber #1 (silicone cladding with a Hytrel tubing) - The center of the core different from the center of the fiber.

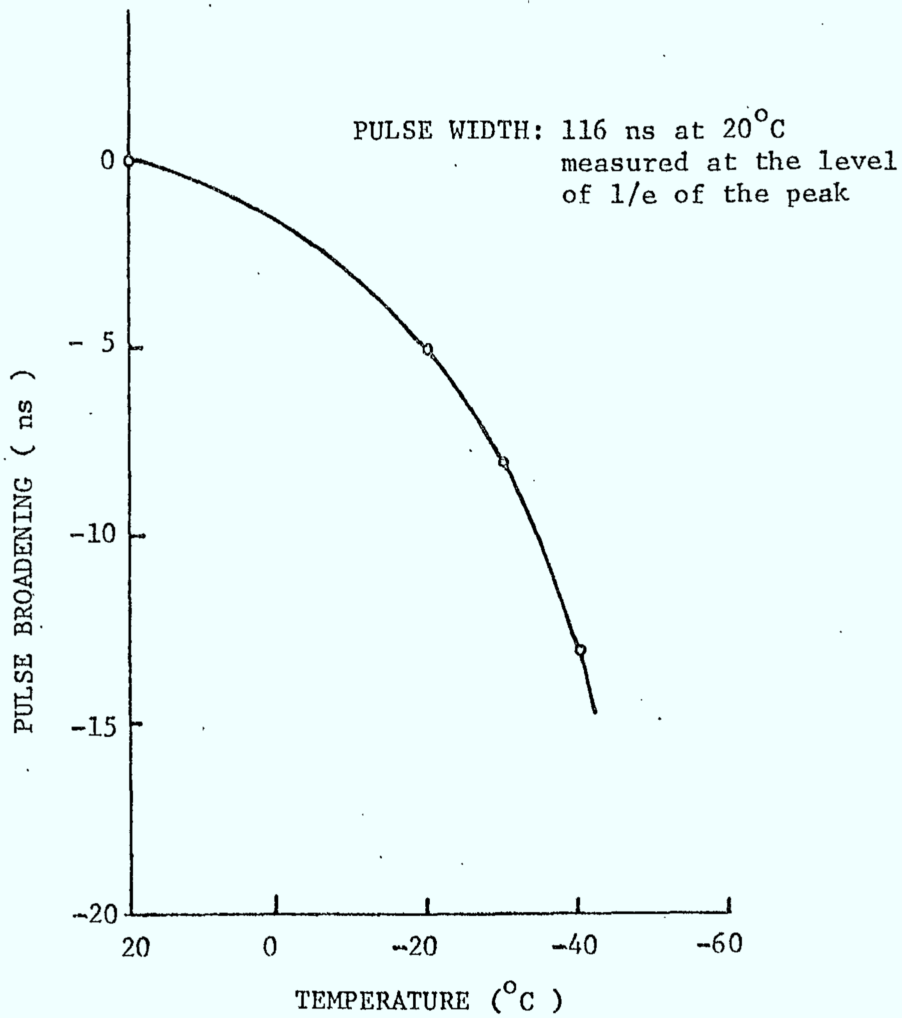


Fig. 13. Pulse broadening due to the decrease in temperature in Fiber # 2 silicone cladding with Hytrel tubing.

(i) The dimensional changes resulting from thermal expansion (or contraction) are of a reversible nature provided that such changes would not cause secondary effects such as microcracks or microbreaks. The changes resulting from polymeric shrinkback are of an irreversible nature. The measurement of temperature dependence of the optical transmission properties alone is not sufficient to distinguish such changes because irreversible changes depend on thermal history and not on temperature alone as time is required for such changes to occur. Thermal cycling tests can reveal the chemical instability of the materials, particularly the plastic materials used for buffering or jacketing the fibre.

(ii) Thermal cycling may affect the bonding between two different materials, such as between the silicone cladding and the PVC jacket. Thermal cycling is equivalent to alternating stress. In the positive half cycle the fibre is stressed in one direction, and in the negative half cycle, it is stressed in the opposite direction. A long-duration thermal cycling may lead to the fatigue of the fibre cable. Of course, this effect depends on the peak-to-peak temperature and the frequency of thermal cycling. Again, this effect can be assessed through the thermal history and not by temperature dependence alone.

(iii) By adjusting the peak-to-peak temperature and thermal cycling frequency, thermal cycling tests can be used to assess the lifetime of the fibre.

At first we used a deep freezer and super-anti-freeze fluid together with a pump and a temperature-controller to make a thermal-cycling chamber. This chamber could provide a minimum temperature of -25°C and a continuous thermal cycling at one cycle per two hours with the temperature variation of +50°C→ -25°C→+50°C. We did use this chamber for some thermal cycling tests on some optical fibres. Later, we found that this chamber was not suitable for thermal cycling tests because the temperature cannot be made lower than -25°C. Fortunately, we found an old environment chamber. After repairing, this chamber works well and provides automatically controlled thermal cycling. The time required for one complete thermal cycle depends on the peak-to-peak temperature chosen. For example, if the peak-to-peak temperature is from -40°C to +40°C, it is one thermal cycle per two hours; and if the peak-to-peak temperature is from -50°C to +50°C, it becomes one thermal cycle per three hours. The variation of temperature with time during one thermal cycle for the peak-to-peak temperature from -50°C to +50°C is shown in Figure 14 (reproduced from a strip-recorder chart which records the temperature in the chamber regularly through a thermocouple inside the chamber). We first used the peak-to-peak temperature of -40°C +40°C for our tests and after 80 thermal cycles, we changed the peak-to-peak temperature to -50°C→ +50°C because we thought the latter condition is more severe and better for our testing purposes.

For thermal cycling tests, 40 meters of the fibre were wound loosely on a glass cylinder of diameter of 12.5 cm. Before winding, the glass cylinder was covered with a very soft towel to ensure [similar to that shown in Figure 29] that no additional microbends would be produced

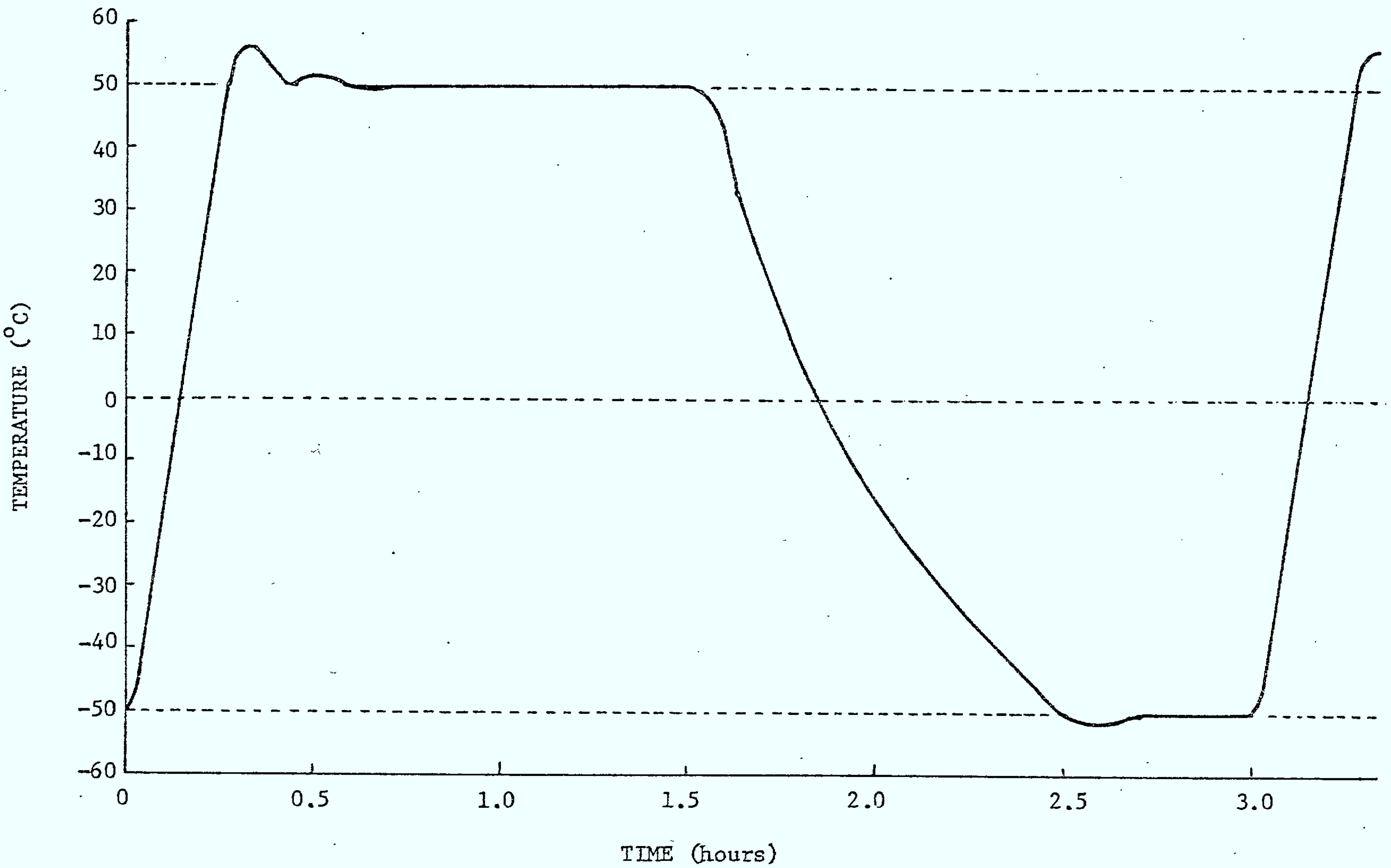


Fig. 14. Variation of temperature with time during one thermal cycle.

in this case. From Figure 14, it can be seen that we have ample time to make excess loss measurements at +50°C and -50°C during a thermal cycle, but for +22°C, we had to switch off the chamber when the temperature at +50°C started to fall, and to keep it off for about 45 minutes which was normally sufficient for the fibre to settle to 22°C. After the measurements at 22°C the chamber was then switched on again for thermal cycling. We measured the excess loss at +50°C and -50°C twice a day but, at 22°C, only once a day. For excess loss measurements, we focused a monochromatic light to the ends of 9 fibre samples bound together as a bundle, and fixed one PIN diode at the other end of each fibre sample as a detector. At the input end, we have a short piece of fibre used as a reference fibre and kept at room temperature for checking the input light level. For each measurement, we first checked the input light level and to make sure that the input light level was constant for all measurements. The thermal cycling results are summarized as follows:

(A) Fibres #P1 and #P2 were not included in the tests because these two samples were used up for other experiments. We would like very much to compare these fibres (glass cladding fibres) with those with silicone cladding. However, we hope to include step-index fibres with glass cladding in our future thermal cycling tests.

(B) The results of Fibre #6 (Corning 13E graded index fibre with a Hytrel tubing) are not included in this section because this fibre suddenly ceased to respond after about 20 thermal cycles. We did not find the cause yet because the search of the cause would disturb the whole measuring system. However, we plan to repeat the tests on this fibre in the future.

(C) Figure 15 shows the excess loss as a function of number of thermal cycles for Fibre #1 (A-381-#2 silicone cladding with a Hytrel tubing). For this fibre, the transmission properties were seriously degraded by thermal cycling. After about 80 cycles this fibre ceased to respond. We believe that long-duration-thermal cycling leads to thermal degradation of the bonding between the glass and the silicone and may also result in microbreaks or microcracks in the core. The fibres with a plastic tubing have much poorer transmission properties than those with a plastic crush coating at low temperatures (particularly at temperatures lower than -20°C), indicating that the fibre itself might have been partially damaged during the tubing-fabrication process. Low temperature measurements exhibits this effect of such damages, and thermal cycling tests aggravate this effect—possibly by further aggravating the damages around the weakest regions in the fibre.

(D) Figures 16 and 17 show the excess loss as a function of number of thermal cycles for fibre #2 (B-109-#2 silicone cladding with a Hytrel tubing) and Fibre #3 (A-388-#1 silicone cladding with a nylon tubing), respectively. The effects of thermal cycling on these two fibres are similar to that on Fibre #1. The difference is only in the degree of suffering thermal degradation by thermal cycling. It can be seen that after 400 thermal cycles the excess loss of both fibres tends to increase permanently as the number of thermal cycles is increased. The tests are continuing, but we predict that these two fibres will end up the same fate as Fibre #1 and cease to transmit light. The degradation

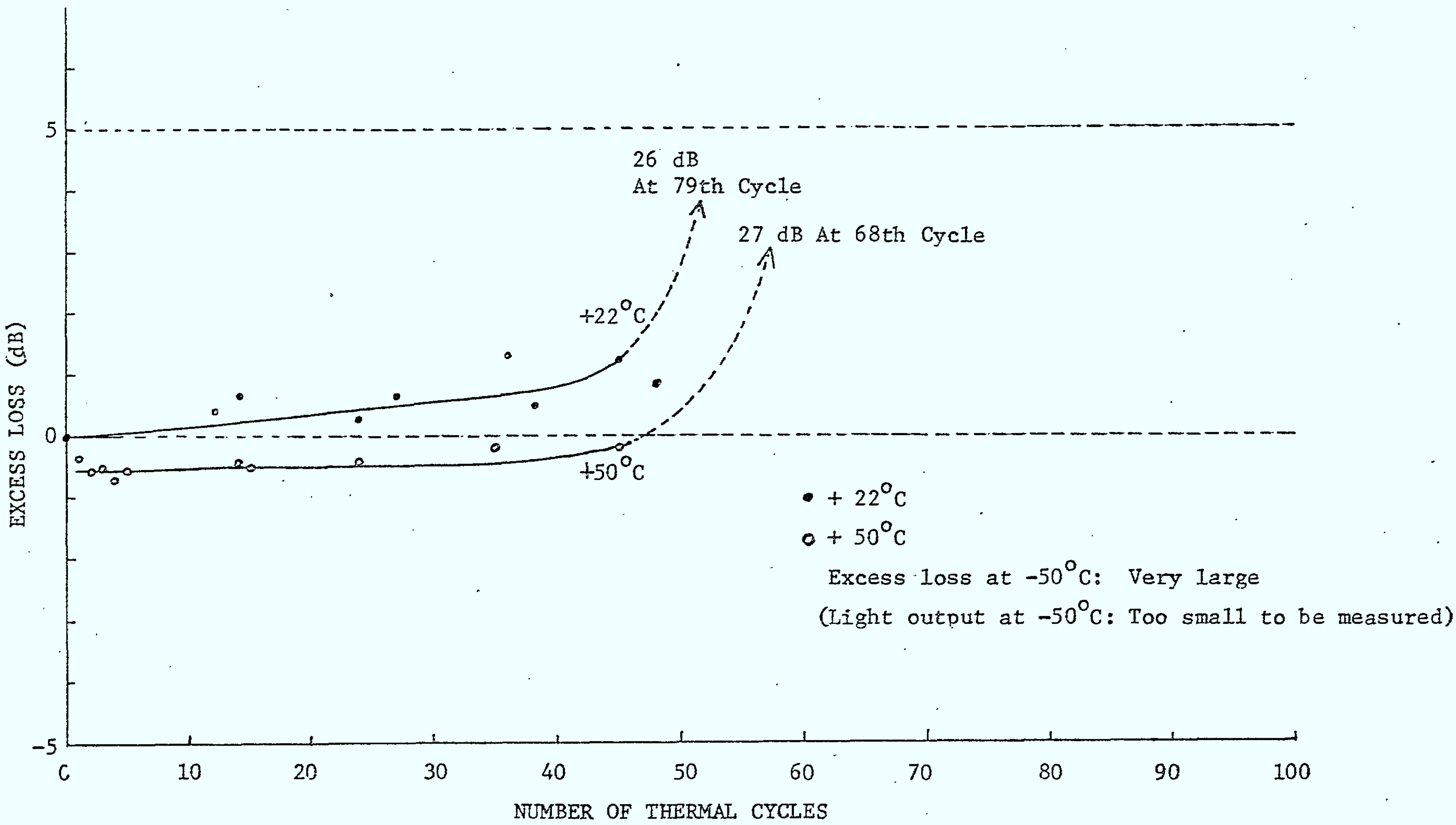


Fig. 15. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #1 (A-381-#2 silicone cladding with a Hytrel tubing).

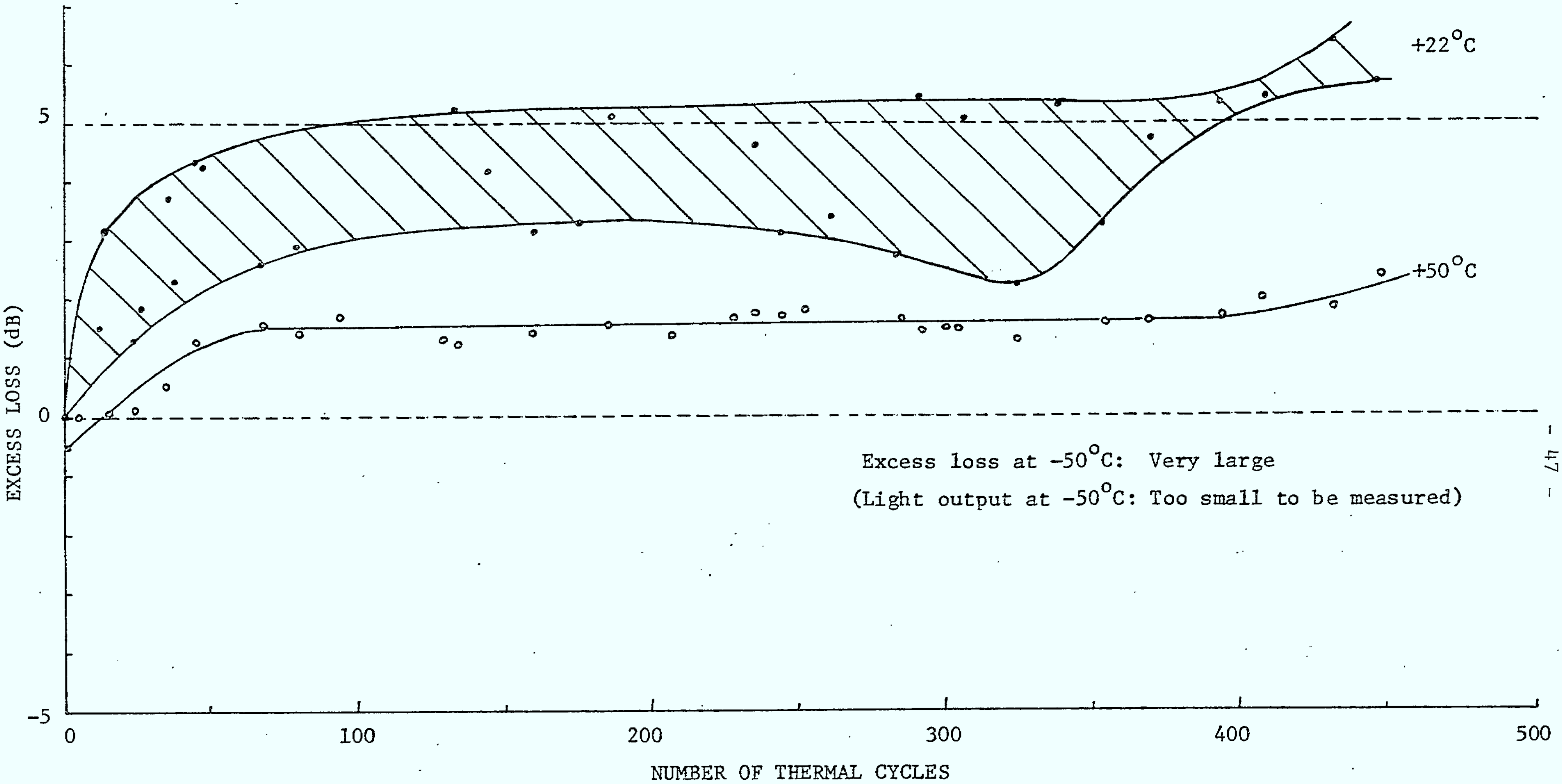


Fig. 16. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #2 (B-109-#2 silicone cladding with a Hytrel tubing).

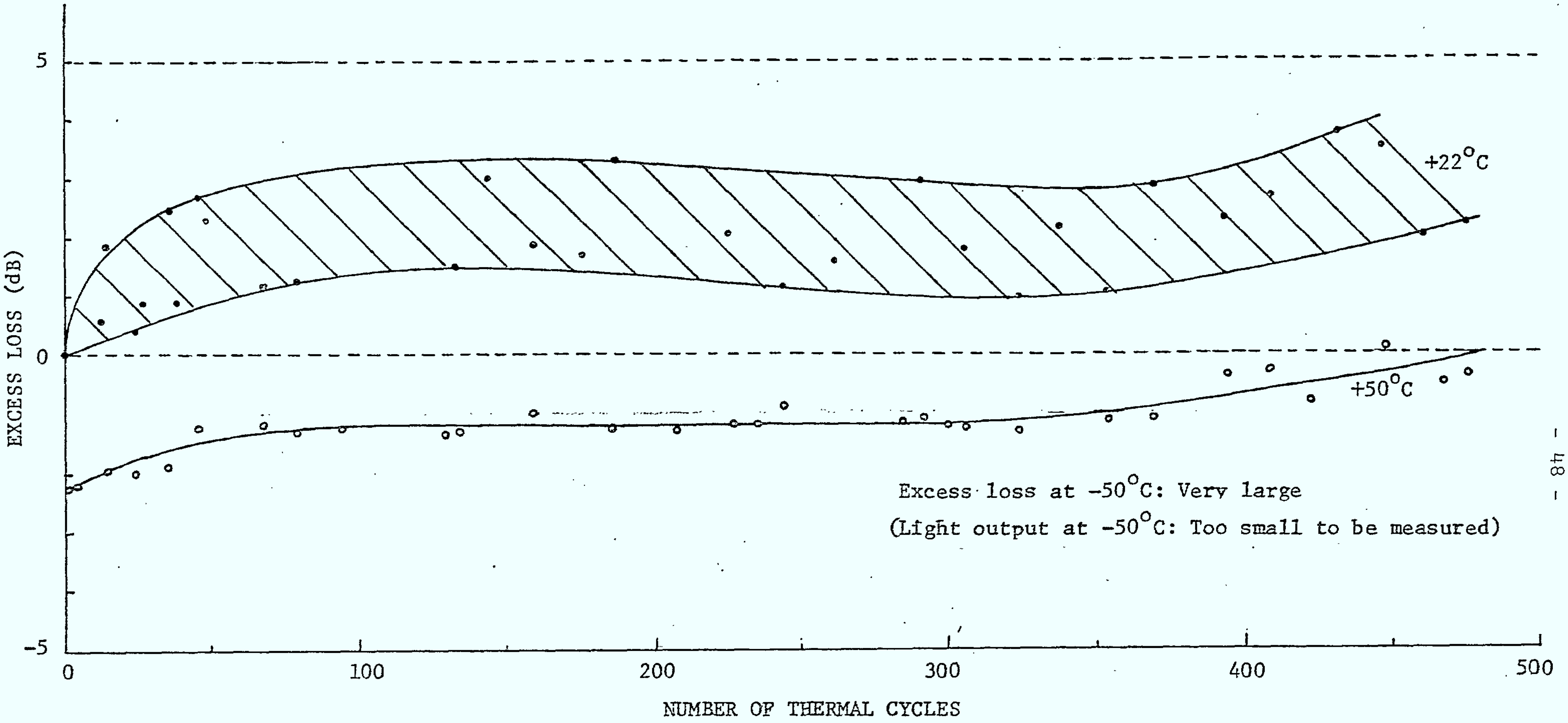


Fig. 17. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #3 (A-388-#1 silicone cladding with a nylon tubing).

in transmission properties after prolonged exposure to thermal cycling is permanent and irreversible. This indicates that serious damages due to thermal cycling had occurred in these fibres with a plastic tubing.

(C) Fibres #4 (silicone cladding with a Hytrel coating) and #5 (silicone cladding with a PVC coating) have similar characteristics on the excess loss as a function of number of thermal cycles as shown in Figures 18 and 19. Although the excess loss at +22°C and at +50°C does not show clearly the degradation, the excess loss at -50°C definitely increases permanently as the number of thermal cycles is increased. The tests are continuing, more results will be reported later. However, Fibre #5 is more lossy than Fibre #4 at low temperatures, and the thermal degradation rate for these two fibres with a plastic crush coating is much slower than those with a plastic protective tubing.

(D) Figure 20 shows the variation of excess loss measured at 20°C and 50°C for Fibre #P3 (silicone cladding without coating) with the number of thermal cycles. The excess loss at -50°C is very large. For this fibre, the loss at 20°C and 50°C goes up gradually from 350 cycles to the peak at 400 cycles, and then goes back to the original value. We could not explain this peak of excess loss occurring at 400 cycles. However, the tests are continuing. More thermal cycling results about this fibre will be reported later.

(E) Fibre #P4 is similar to Fibre #5 in structure, but the thermal cycling behaviour of Fibre #P4 is quite irregular as shown in Figure 21. Within the first 80 thermal cycles the excess loss measured at +22°C and +50°C decreases

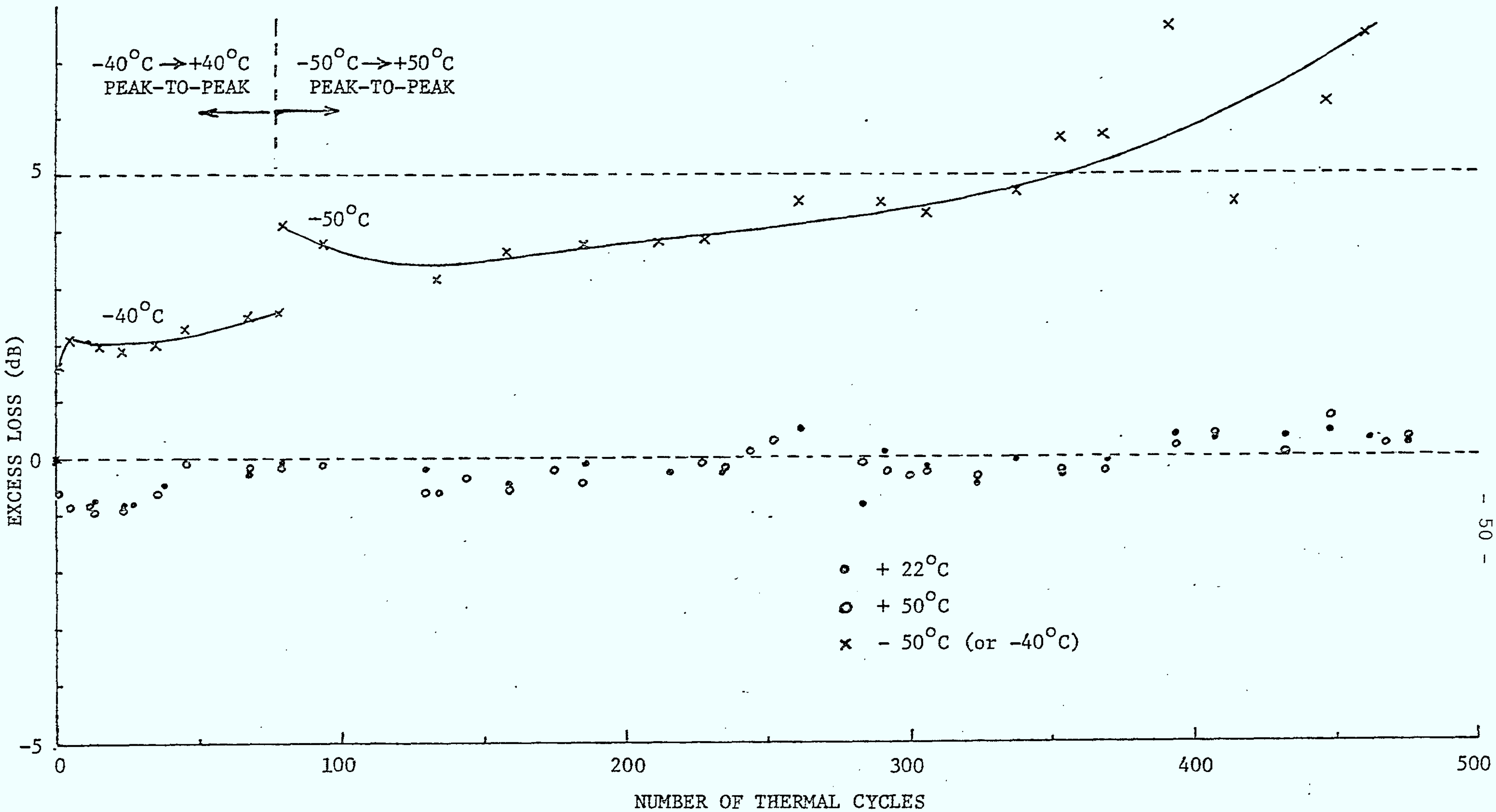


Fig. 18. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #4 (A-379-#1 Silicone cladding with a Hytrel crush coating).

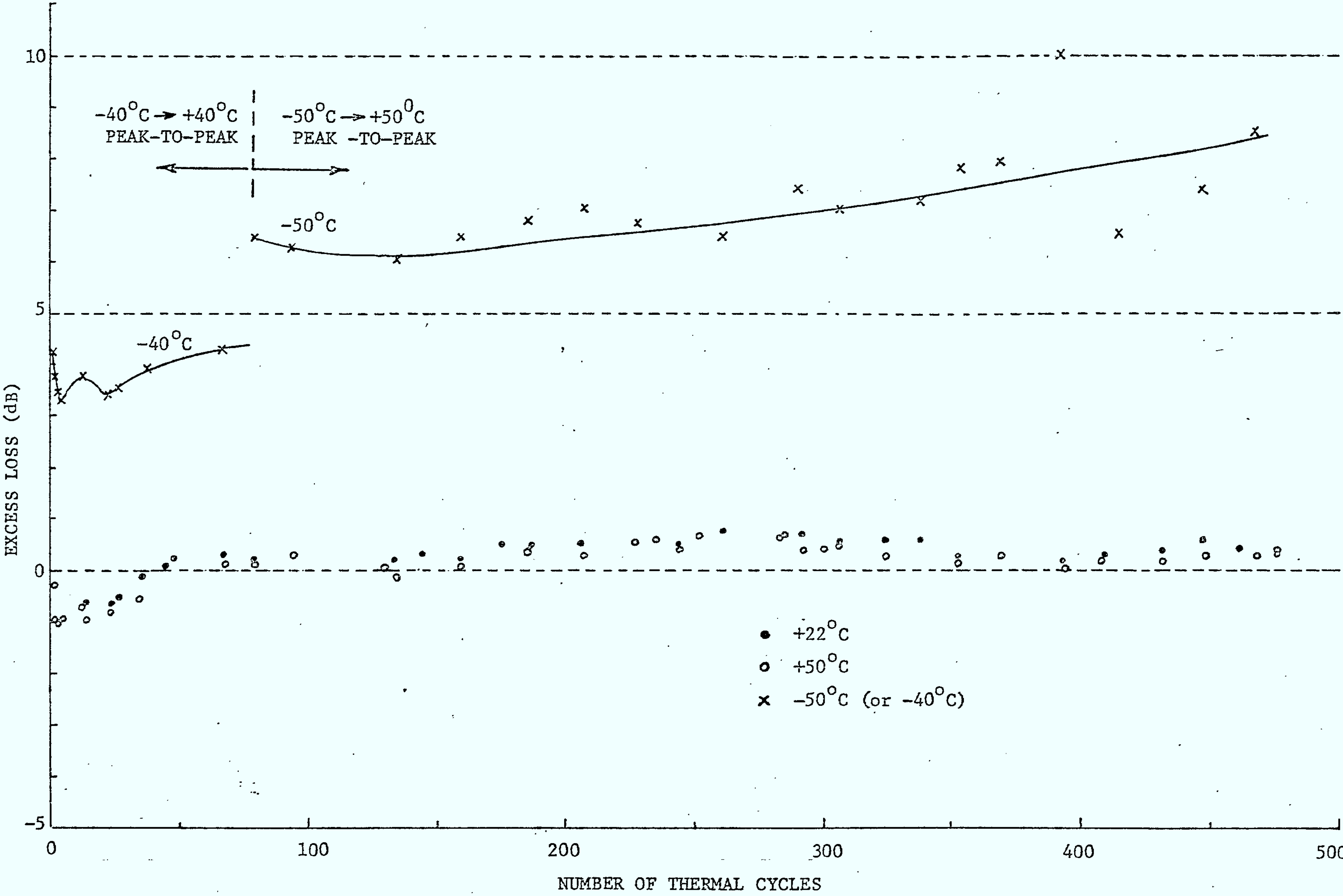


Fig. 19. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #5 (A-325-#1 silicone cladding with a PVC crush coating).

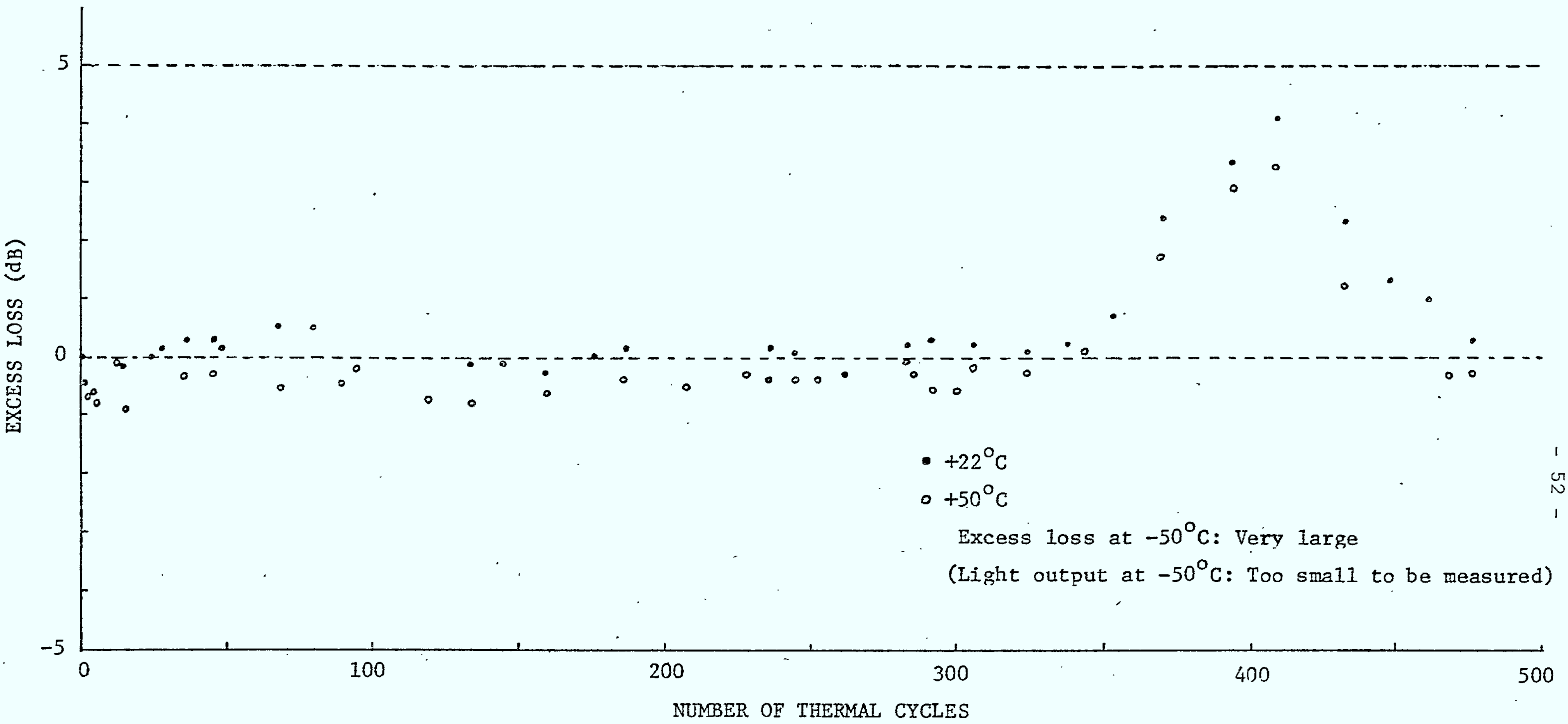


Fig. 20. Excess loss due to thermal cycling with the peak-to-peak temperature of $-50^{\circ}C \rightarrow +50^{\circ}C$ at one cycle per three hours for Fiber #P3 (Silicone cladding without coating).

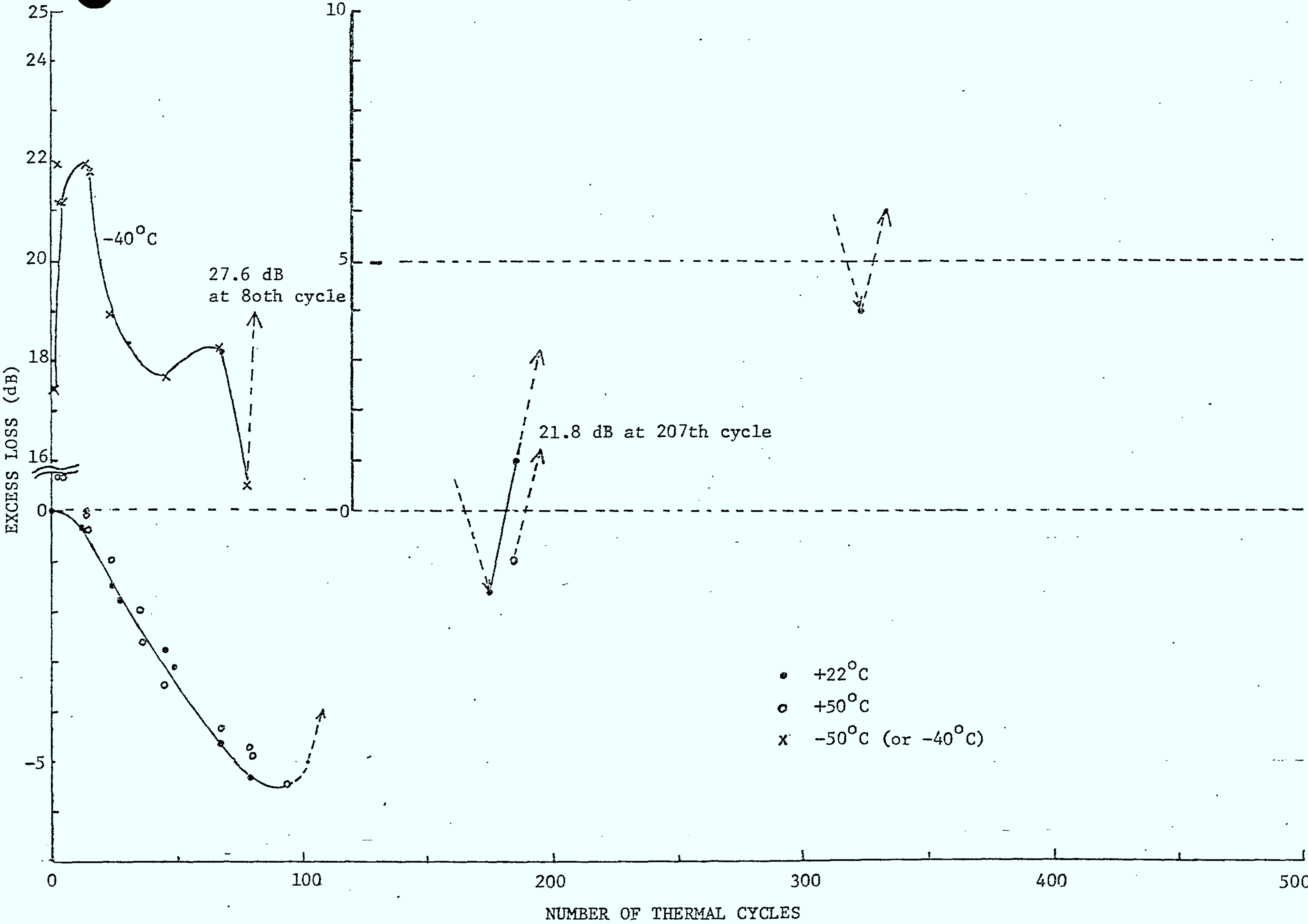


Fig. 21. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber # P4 (Silicone cladding with a PVC coating).

with increasing number of thermal cycles. Within 80 cycles the peak-to-peak temperature was -40°C → +40°C, and after 80 cycles the peak-to-peak temperature was changed to -50°C → +50°C. After this change, the excess loss at -50°C was too large (or the output signal was too small) to be measured, but the excess loss at +22°C and +50°C was still decreasing. Up to about 100 cycles, the excess loss suddenly jumped to a very high value and after 320 cycles the excess loss became so high that our measuring instrument could not measure it. The results indicate a serious thermal degradation developing continuously inside the fibre due to extended duration of thermal cycling.

(F) Fibre #7 (w-type with a nylon jacket) remains extremely stable after a long duration of thermal cycling as shown in Figure 22. At +22°c and +50°C the excess loss is practically unchanged as the number of thermal cycles is increased. At -50°C there are several small peaks occurring in the thermal cycling history. The first peak occurred at about 90 cycles, the second peak at about 250 cycles and the third peak at about 400 cycles. In this fibre both the core and the cladding are made of glass, and the jacket is made of nylon. We believe that the weak area which may suffer thermal degradation is the bonding between the outer cladding surface and the inner nylon-jacket surface. The small peaks in excess loss appearing and disappearing in the thermal cycling history may be associated with thermal degrading and healing processes. However, the w-type fibre is the best of all fibres under investigation in terms of microbending or bending losses, temperature and thermal cycling effects.

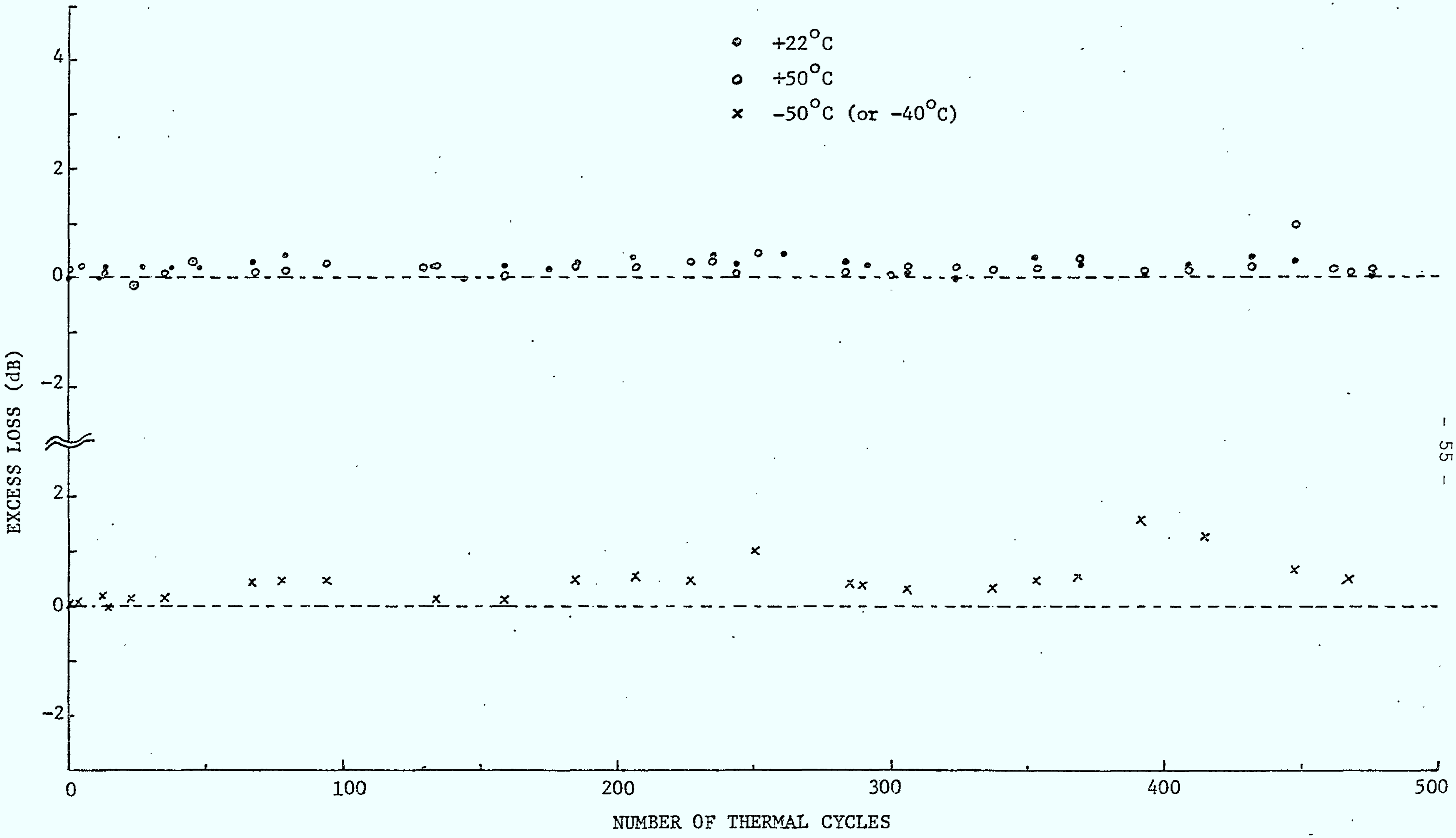


Fig. 22. Excess loss due to thermal cycling with the peak-to-peak temperature of -50°C → +50°C at one cycle per three hours for Fiber #7 (W-type with a nylon jacket).

3.3 Effects of Winnipeg Environment

It is extremely important to know the transmission properties of the fibre in an actual environment of the district in which an optical communication system is planned for the future. For this reason we decided to carry out a simple experiment to measure the excess loss of the fibres in an actual Winnipeg environment.

The optical fibres under investigation were installed in a copper tubing of about 2.5 cm in diameter, which extended from a small laboratory in the attic to the roof of the Engineering Building of the University of Manitoba [see Figure 23]. The total length of each fibre is about 40 meters. Since Fibres #7 (w-type), #P1, #P2, #P3 and #P4 were used up for other experiments, the fibres included in this Winnipeg environment tests were Fibres #1, #2, #3, #4, #5 and #6. We used the same techniques adopted for thermal cycling tests, except that the light source is not a monochromator, but a white light lamp with a filter to produce a peak light output at the wavelength of 630 nm. The six fibre samples were bundled and with their input ends located close to the filter output. We also used a short-piece of reference fibre kept at room temperature to check the input light level in the same manner as described in Section 3.2. We used a strip recorder to measure the outdoor temperature and also compared our records with the temperature records supplied by Winnipeg Weather Information Centre. The temperature records from two different sources are slightly different. Also, the outdoor temperature measured was not exactly the same temperature inside the copper tubing, so we estimated that the temperature given in

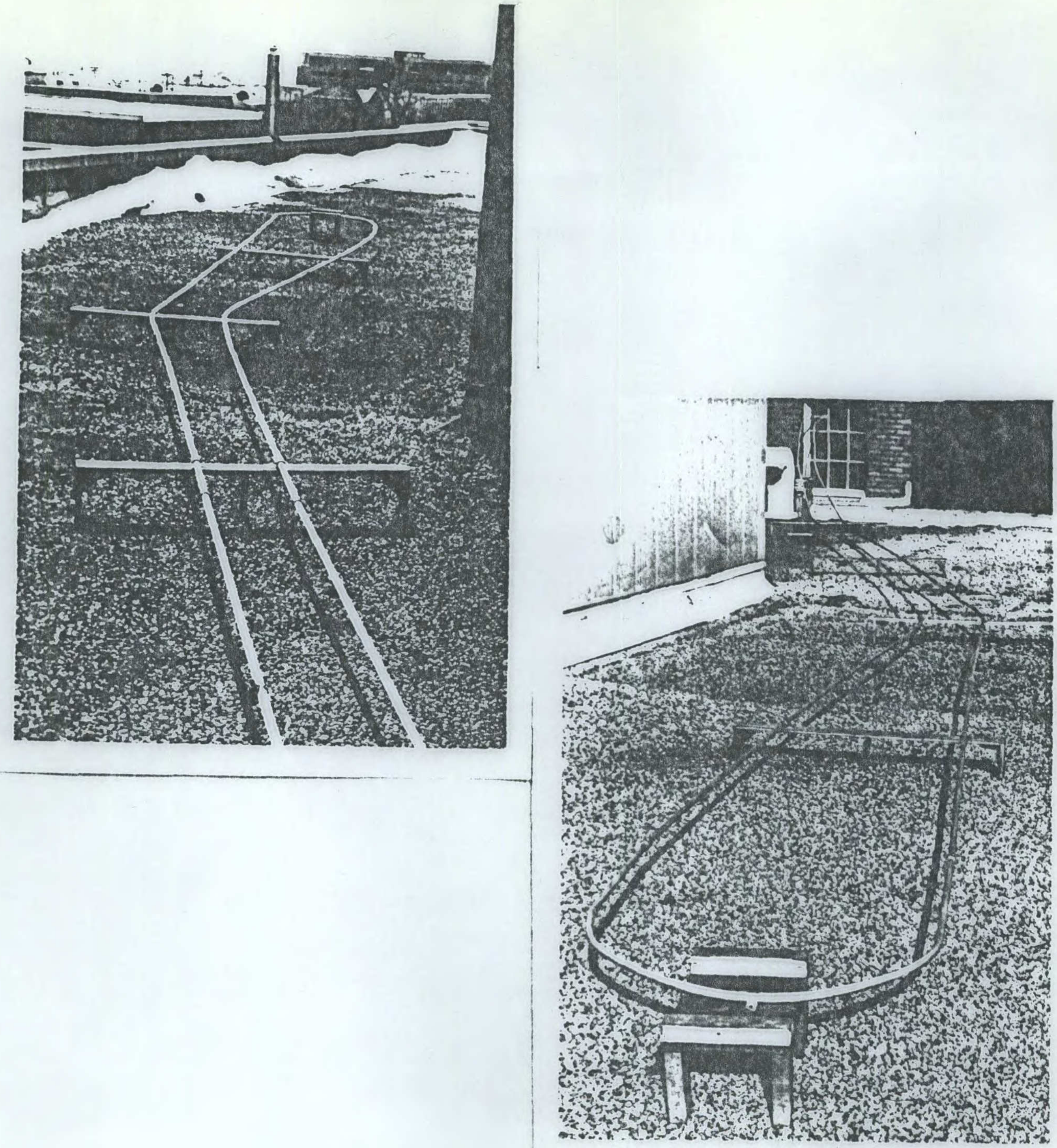


Fig. 23. Installation of optical fibers inside a copper tubing in the roof of the engineering building of the University of Manitoba.

Figure 24 may involve an error of ± 3°C.

We started the tests on February 3, 1978, the first set of excess loss data was measured on that day at -18.5°C and therefore, this set of loss data was used as reference data. Unlike the thermal cycling tests for which we used the loss data at room temperature as reference data, for environment tests, we used the loss data at -18.5°C as reference data because we had to install the fibres outdoors before carrying out measurements.

Figure 24 shows the variation of excess loss with days. During the period of 50 days the temperature variation is between -10°C and -27°C. The tests are continuing. We would like to wait till summer before discussing these results.

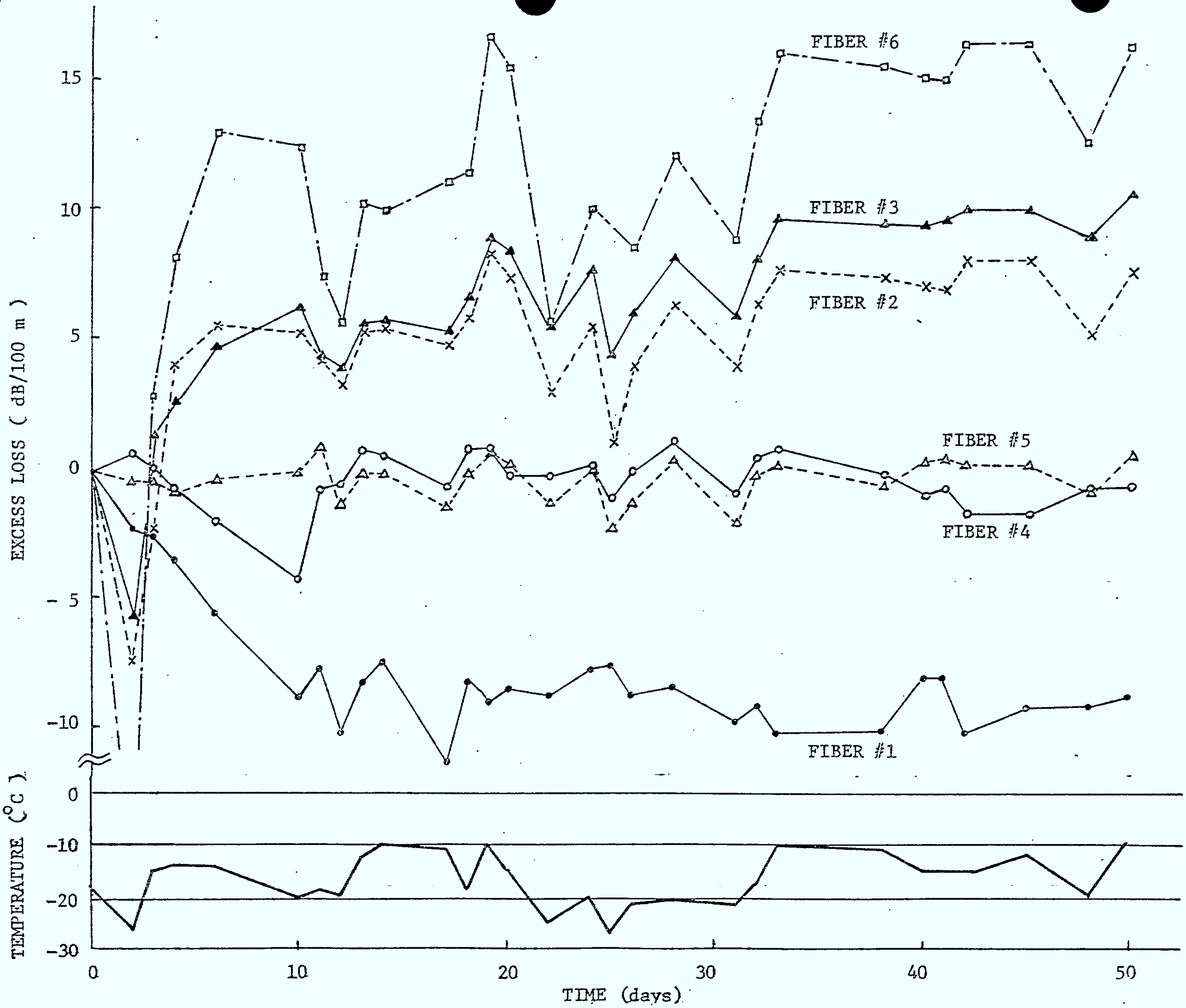


Fig. 24. Excess loss as a function of period of time measured in Winnipeg environment

IV EFFECTS OF MECHANICAL VIBRATIONS

Several investigators [Nelson et al. 1977, Nishida et al. 1977] have studied the vibration-induced attenuation loss in optical fibres. So far, data about the effects of mechanical vibrations are very scarce in the literature. Kansai Electric Power Company, Inc. and Nippon Electric Company Limited of Japan had recently installed an experimental optical fibre cable containing 4 SELFOC fibres and 8 quad-conductors for studies of the effects of environmental conditions on transmission properties. The total length of the cable was 2.05 km including 1.5 km aerially installed portion and a 0.3 km vertically installed portion inside of a building. Total loss of each fibre was 23 db (11.22 db/km in average). They observed the temperature effect, but no vibration effect caused by the wind up to the wind speed of 10 meters per second. In their experiments the vibrational spatial wavelengths are very large and hence the radii of the wind-induced bending are large though the vibrational amplitudes are large, thus such a bending would not cause mode conversion. Obviously, such a wind-induced vibration may create a problem of mechanical breakage of fibres inside the cable installed aerially. However, Nelson et.al.[1977] have observed light intensity modulation of several percent resulting from mechanical vibration of the fibre of amplitudes less than the fibre diameter, and found that the modulation amplitude increases with increasing vibra-ational amplitude. They have attributed this phenomenon to modulated bending loss. They placed a fibre in a U shaped configuration with two end-supports fixed to rigid mounts by epoxy, the radius of curvature at the centre of the U shaped bend was about 3 cm. The vibration was produced by an accoustically vibrated membrane attached to the centre of the U shaped bend. They have also found that the modulation intensity depends on the position of the vibration-excitation point. This implies that the bending loss has an oscillatory dependence on the radius of curvature. So far, the available theories on bending loss do not reveal such an oscillatory dependence. Nelson et al. [1977] have also observed such an oscillatory dependence of static bending loss on the radius of a circular loop made in the fibre between two end-supports and attributed this phenomenon to a curvature-induced parametric coupling between core modes and modes of the whole fibre, which introduces a coupling length— the distance needed for complete exchange of energy from core to whole fibre modes and vice versa. Energy may be coupled back into the core to cause the oscillatory dependence if the coupling distance is less than the inverse loss coefficient of whole-fibre modes caused by outside surface scattering.

However, the modulated bending loss due to mechanical vibration may not be important to optical fibre transmission systems using digital pulse-code-modulation for signal communications, but could be a source of interference to systems employing amplitude (or light intensity) modulation for signal communications.

Mechanical vibrations may be easily induced in optical fibre cables installed underground by longitudinal mechanical waves generated by cars, trains, or even jet aeroplanes and transmitted from the ground surface to the cables underground. Furthermore, mechanical vibrations in aircrafts would cause vibrations in fibre cables installed inside, or engine vibrations in factories would definitely cause vibrations in fibre cables installed nearby. For this reason, we felt that it would be worth carrying out further investigation of the possible effects of vibrations.

4.1 Experimental Techniques

We used two methods to produce vibrations in optical fibres. With method (A) the fibre was epoxied to three pistons (or to one or two pistons depending on the number of vibrational modes produced) with two end-supports epoxied to rigid mounts as shown in Figure 25. The pistons were driven by a speed-controlled motor so that the vibrational amplitude d, frequency f and spatial wavelength L could be varied by adjusting the length of the fibre between pistons, and the speed of the motor. With this technique the maximum vibrational frequency is limited to 80 Hz. With method (B), the fibre was epoxied carefully to a piano wire. The two ends of the wire were clamped rigidly at two supports, so that the tension of the wire can be adjusted. The resonant frequency of the wire is given by [Strutt, 1945].

$$f = \pi(R/4L_t^2)(E/\zeta)\ (n + \frac{3}{2})^2 \qquad (6)$$

where n = 0, 1, 2, ... is the mode number which is equal to the

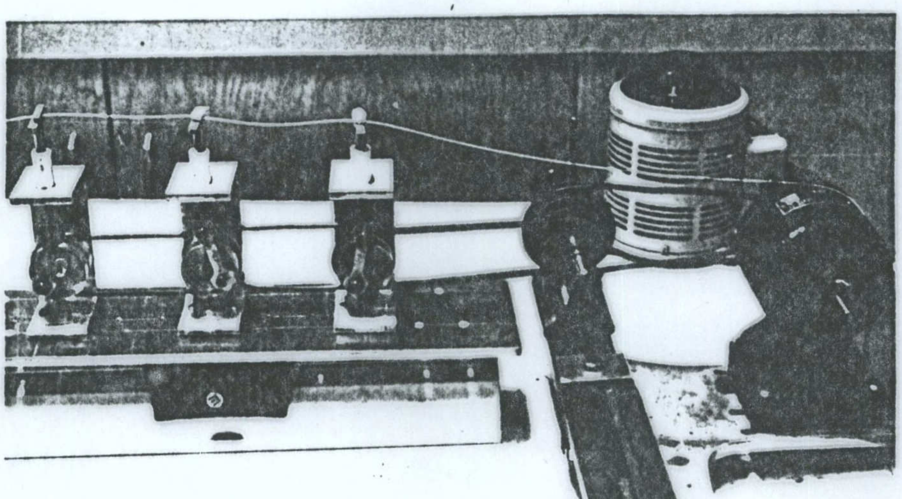


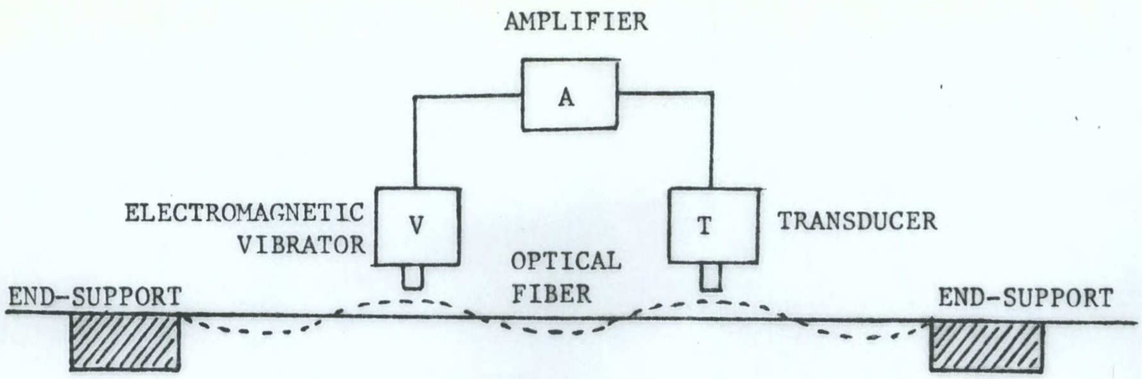
Fig. 25. Method (A) for producing vibrations in optical fibers

number of nodes excluding the end points; R is the crossection, L_t is the total length between two end supports, E is the Young's modulus and ζ is the mass density of the wire with the attached optical fibre. The set-up of this method is shown in Figure 26.

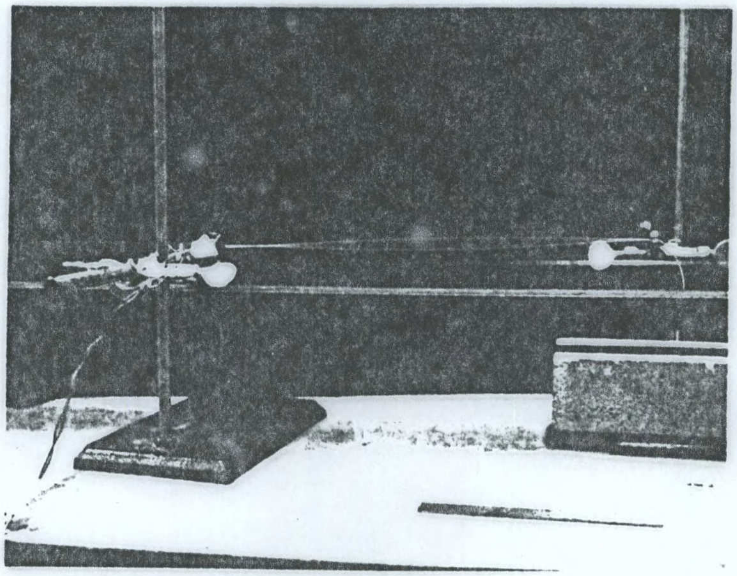
For all measurements, the length of the fibre used was four meters and the excess loss was measured using the same techniques described in Section 2.1.

4.2. Results and Discussion

The excess loss caused by vibrations is very small. No detectable excess loss was observed if the 4-meter fibre with two ends rigidly fixed was made to vibrate randomly. However, with method (A) to produce vibrations, we observed the effects of vibrations. Figure 27 shows that the excess loss increases with increasing vibrational amplitude and frequency, but with decreasing spatial wavelength. For two adjacent vibrations the excess loss for the case with the two vibrations in the same spatial phase (two peaks occur at the same phase simultaneously) as shown in case D is higher than that with the two vibrations in the opposite spatial phase as shown in case C of Figure 28. All of phenomena may be attributed to the mode-coupling effects. The results shown in Figures 27 and 28 are for fibre No. #P1 (glass core and glass cladding with only thin EVA coating). For fibres with a thick protective jacket the vibration effect was so small that our measuring system was not sensitive enough to detect it.



Schematic Diagram



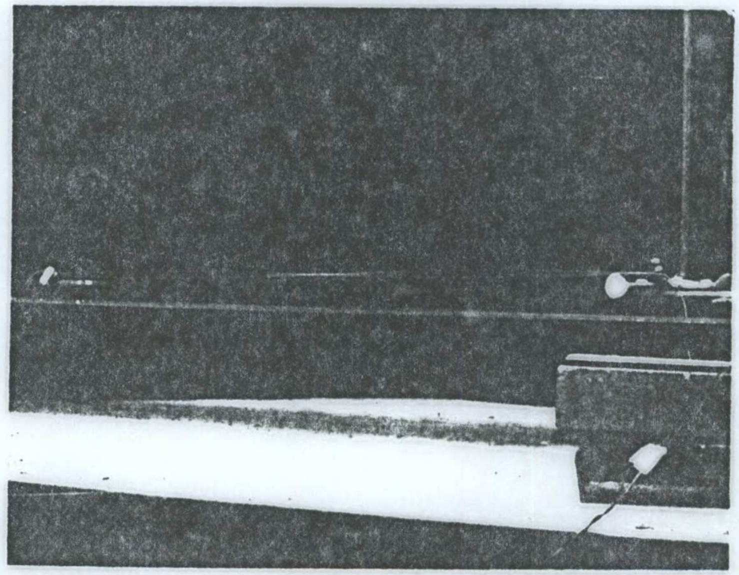


Fig. 26. Method (B) for producing vibrations in optical fibers

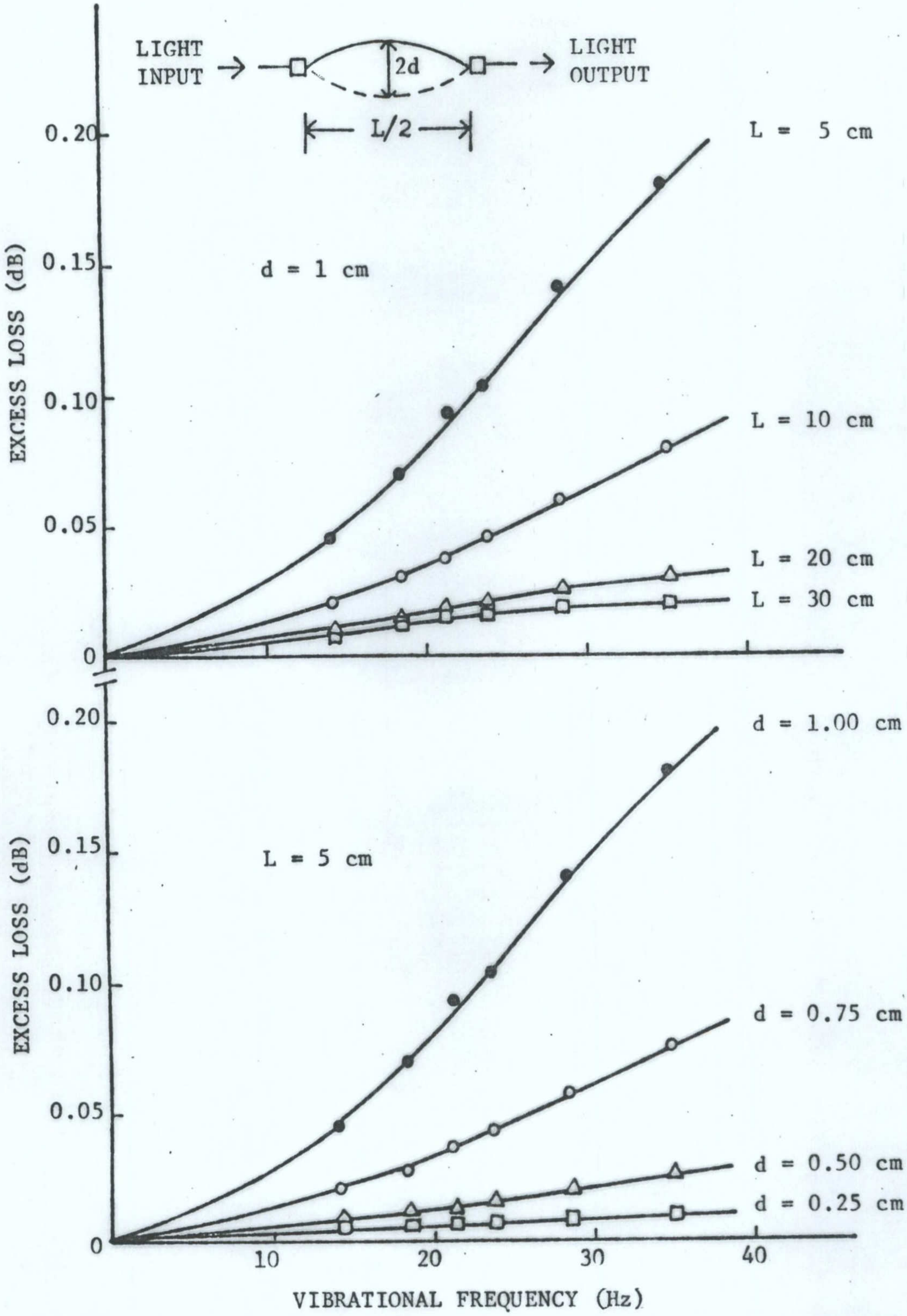


Fig. 27. Excess loss caused by mechanical vibrations in the fiber (Fiber #P1, glass cladding with EVA coating only)

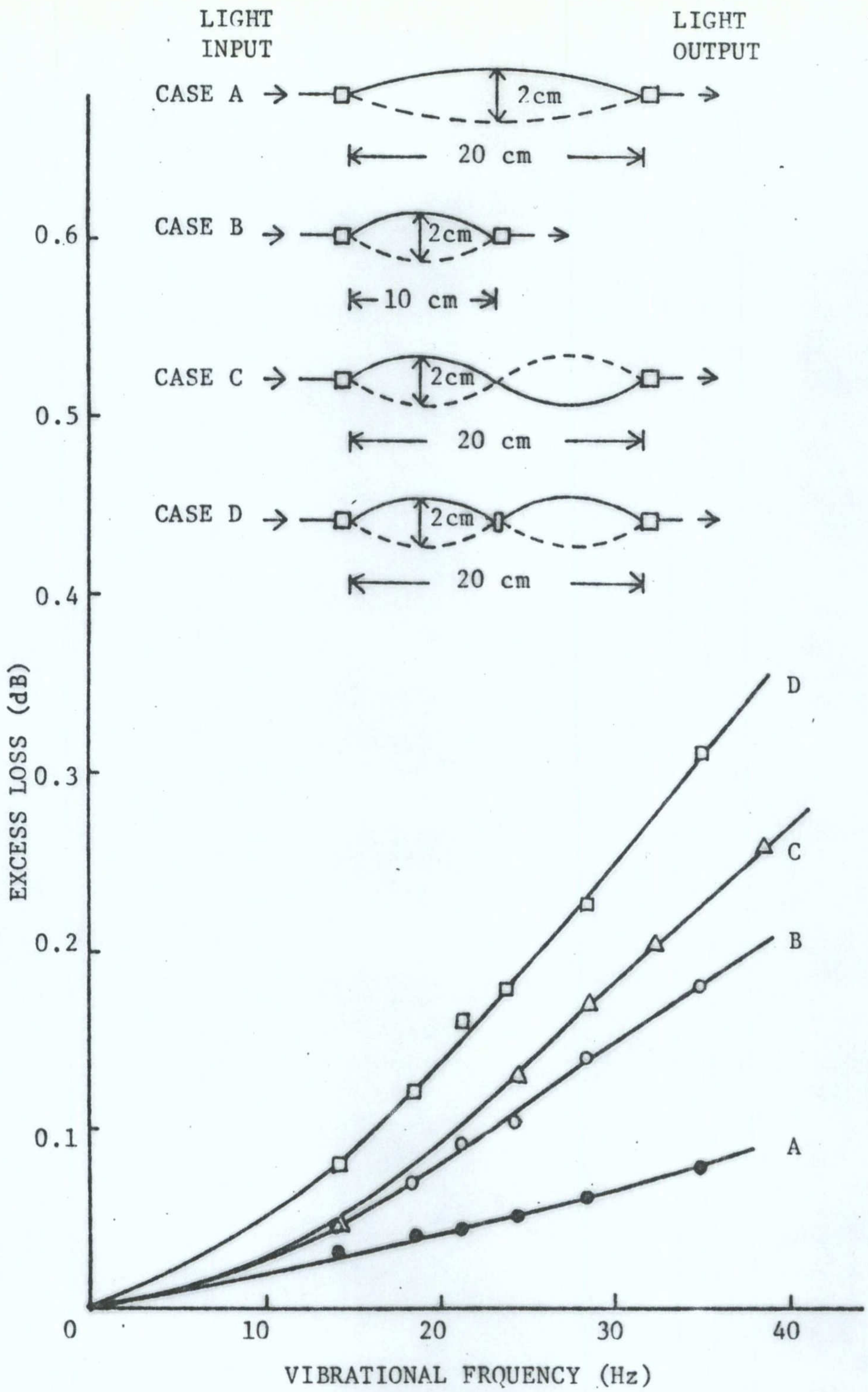


Fig.28. Excess loss caused by mechanical vibrations in the fiber for four cases. (Fiber # Fl, glass cladding with EVA coating only).

However, our results on dynamic bending are in qualitative agreement with those reported by Davies and kingsley [1974, 1975] who have reported that, using an accoustic transducer to modulate the longitudinal or diametric stress of a short section of the fibre to provide optical phase modulation, the mode-conversion loss increases with increasing the number of modes in the fibre. Our results also agree well with the existing theories on bending loss. For static bending, several investigators [Zeidler et al.1976, Tokuda et al.1977] have reported that the excess loss α due to mode conversion in a series of sinusoidel serpentine bends increases with increasing amplitude d of the bend and increasing number of bends following approximately the empirical law

$$\alpha = b_1 d^{b2} \qquad (7)$$

where b   is in the range of 3 to 4, and b depends on the periodic length (spatial wavelength), the number of bends, and the numerical aperture of the fibre. The basic difference between static and dynamic bendings may be that for the latter the amplitude d varies periodically with time. Thus, it is expected that the integrated excess loss for dynamic bending is smaller than that for static bending. The phenomenon that the excess loss for case D is larger than that for case C as shown in Figure 28 may be due to the fact that for case D there is a fixed support in the centre which may cause additional bending loss at this point. however, it is also possible that this phenomenon is associated with the findings of Nelson et al.[1977] about the oscillatory dependence of the transmitted light intensity on the radius of curvature. It may be related to the coupling distance required for complete exchange of energy from the core to the whole fibre modes. This implies that under certain conditions some energy may be coupled back into the core, thus reducing the excess loss.

For practical mechanical vibrations the vibrational amplitude may be very small (e.g., less than 100 μm) but both the vibrational frequency and the number of spatial wavelengths along the fibre may be very large (e.g. larger than 1 kHz). In order to further study the vibration effects, we have constructed a new excitation source [Method (B) in Figure 26]to produce vibrations of frequencies higher than 1 kHz. Because of small vibrational amplitudes (less than 0.25 cm), we did not detect any significant change in transmitted light intensity due to such vibrations, partly because our present detection system is not sensitive and accurate enough to detect small signals, for example less than 5 percent of change in light intensity. However, the experiments did show changes in transmitted light intensity due to vibrations though the changes are small. We plan now to build a better detection system in order to measure such small changes. In our laboratory we can only make a small section of a fibre to vibrate in frequencies higher than 100 Hz. It is possible that the vibration over a long length of fibre cannot be assessed by extrapolating the results obtained over a short length of fibre because of the oscillatory nature of dynamic bending effects. To investigate the vibration effects over a long length of a fibre, it may be necessary to resort to a field test by placing a fibre in or nearby a true vibrating system which employ optical fibre as signal transmission medium.

V MICROSCOPIC OBSERVATION OF IMPERFECTIONS IN OPTICAL FIBRE SAMPLES

In order to find out what kind of damages would be caused by long-duration exposure of the fibre samples to thermal cycling, we placed six fibre samples (#1 to #6), each of 4 meters in length, in circular form (about 12.5 cm in diameter) on a wooden plate which was placed inside the thermal cycling chamber. For testing the effects of Winnipeg environment, we wound the six fibres, each of 4 meters in length, on a glass cylindrical drum of diameter of 12.5 cm. Before winding, the glass drum was covered with a very soft towel as a cushion to ensure that no additional effect due to microbending would be produced in this case. This glass drum with fibre samples was placed inside a large tin box as shown in Figure 29. This box was covered lightly with a metal lid and then put in the roof of the Engineering Building of the University of Manitoba for long-duration exposure to the Winnipeg environment.

After 40 days of exposure of these fibre samples to thermal cycling and the Winnipeg environment, we took them out and examined the possible damages in these samples under an electron scanning microscope. We first focused a strong light beam through a lens from a He-Ne laser to one end of the fibre, and then located the light spots along the fibre. A typical light spot in Fibre #5 is shown in Figure 30. We considered the light spots as the indication of the damaged portions, so we cut such portions out and removed the plastic coating by burning it off over a burner, or by immersing it in chloroform or acetone.

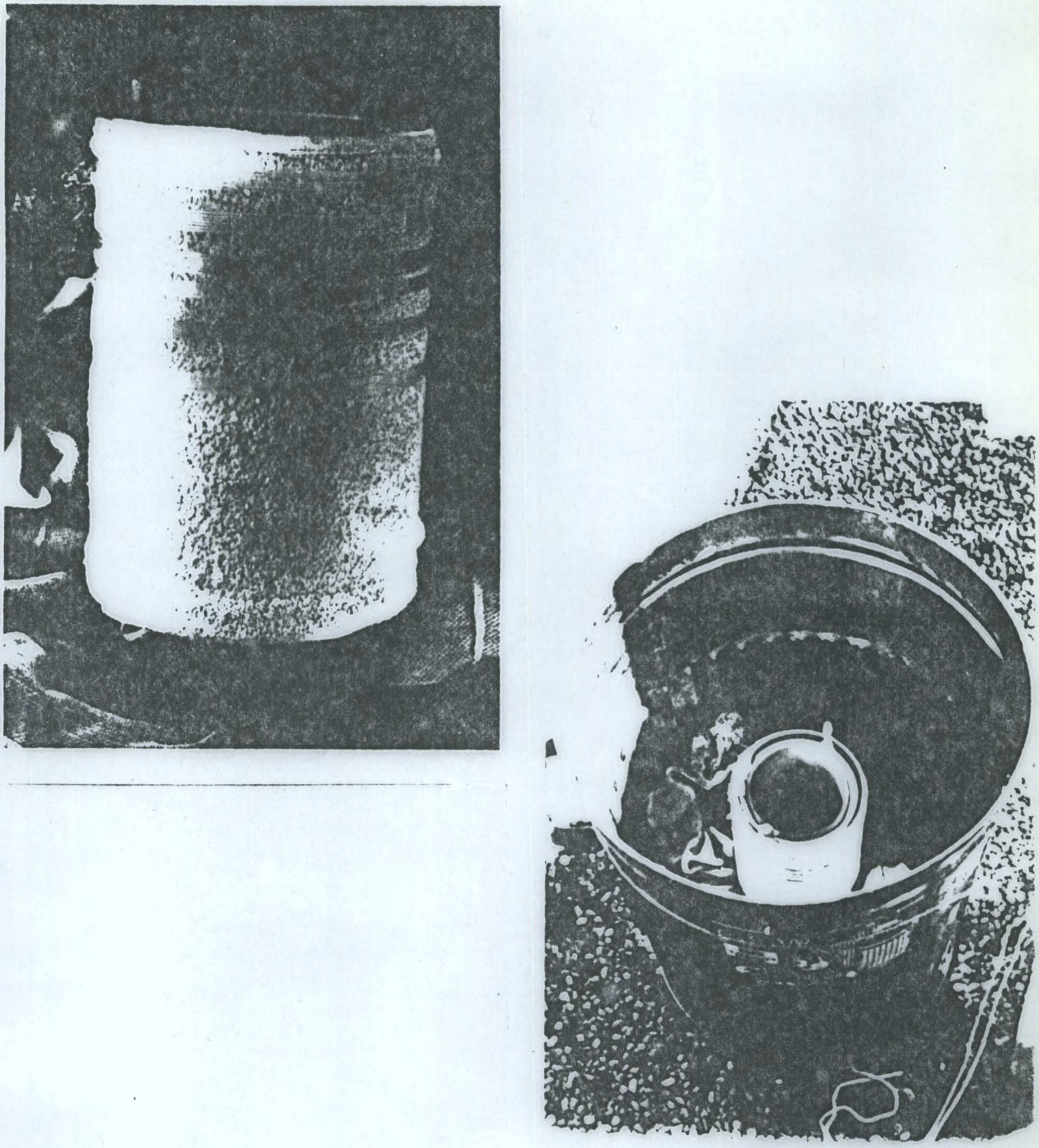


Fig. 29. Glass drum covered with a soft towel as a cushion and optical fiber samples wound loosely on the cushion surface for envioronmental tests.

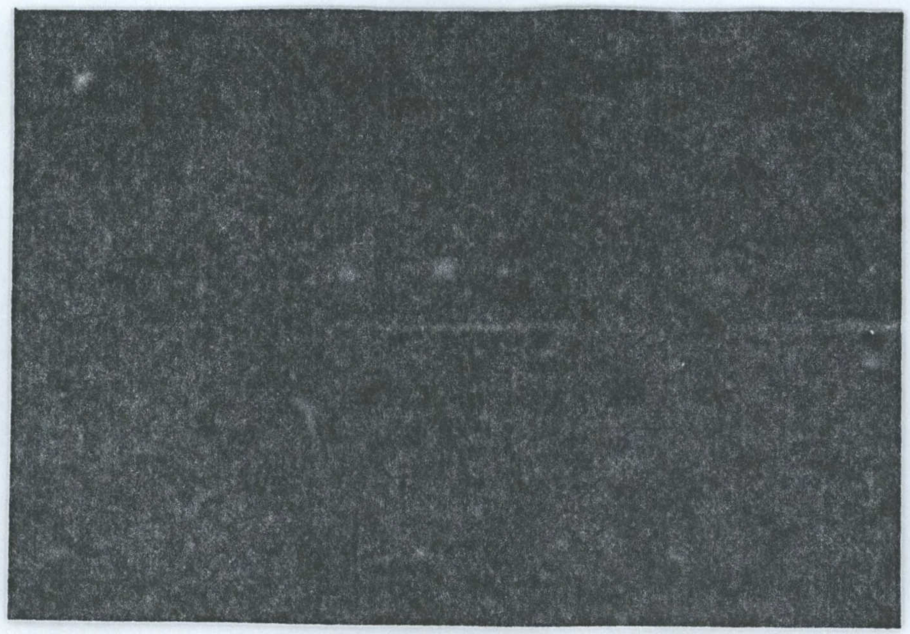


Fig. 30. A typical light spot appearing in Fiber #5
(Silicone cladding with a PVC coating)

It should be noted that glass is a hard material, and thus a concave and convex irregularities on the glass core surfaces must result from the manufacturing processes and not from the exposure to thermal cycling or to the Winnipeg environment. In fact, we observed no damages on the core surfaces of many portions which showed leaky light spots. We believe that light spots are the indication of imperfections but the imperfections may not occur on the core surface. It is most likely that the imperfections due to thermal degradation occur in silicone cladding and in plastic coating, and particularly in the interface between the glass core and the silicone cladding, and that between the silicone cladding and the plastic coating. Imperfections of this kind are difficult to determine using a scanning electron microscope. The stresses induced by the change of temperature (particularly at low temperatures) may cause the following imperfections.

(a) Microbreaking of bonds in the interface between two materials with two different thermal expansion coefficients.

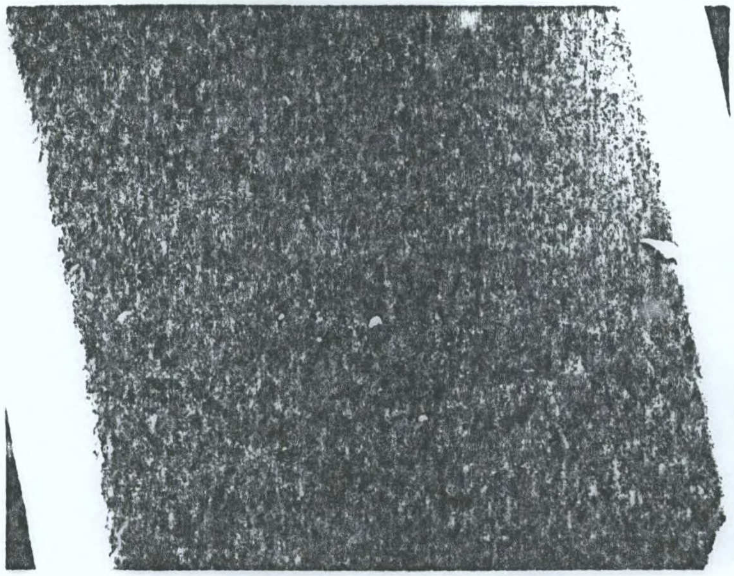
(b) The increase in refractive index with decreasing temperature for silicone and other plastic materials.

(c) At low temperatures (say -50°C) both silicone and plastic materials would become so stiff that thermal contraction due to the lowering of the temperature may cause microcracking of the glass core.

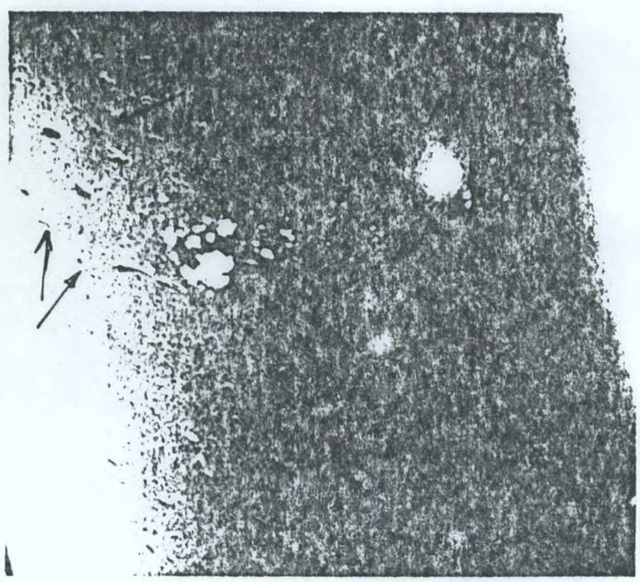
It is most likely that the thermal degradation of Fibres #1 -

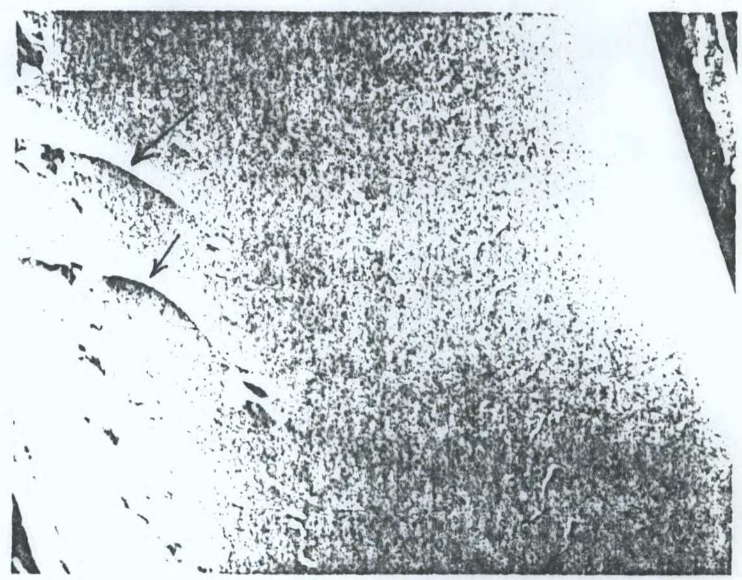
#5 might result from one or more of the above thermally induced imperfections. Microscope can be used to observe imperfection (c), but not imperfections (a) and (b). Perhaps a backscattered light technique or a scattering pattern technique has to be used to study imperfections (a) and (b),

However, some serious imperfections on the core surfaces are shown in Figures 31 - 33. It should be noted that although the microcracks observed were on the samples after either thermal cycling or exposure to outdoor environment, there is no direct proof that they resulted from thermal degradation. They could also be the original imperfections produced during the manufacturing processes.



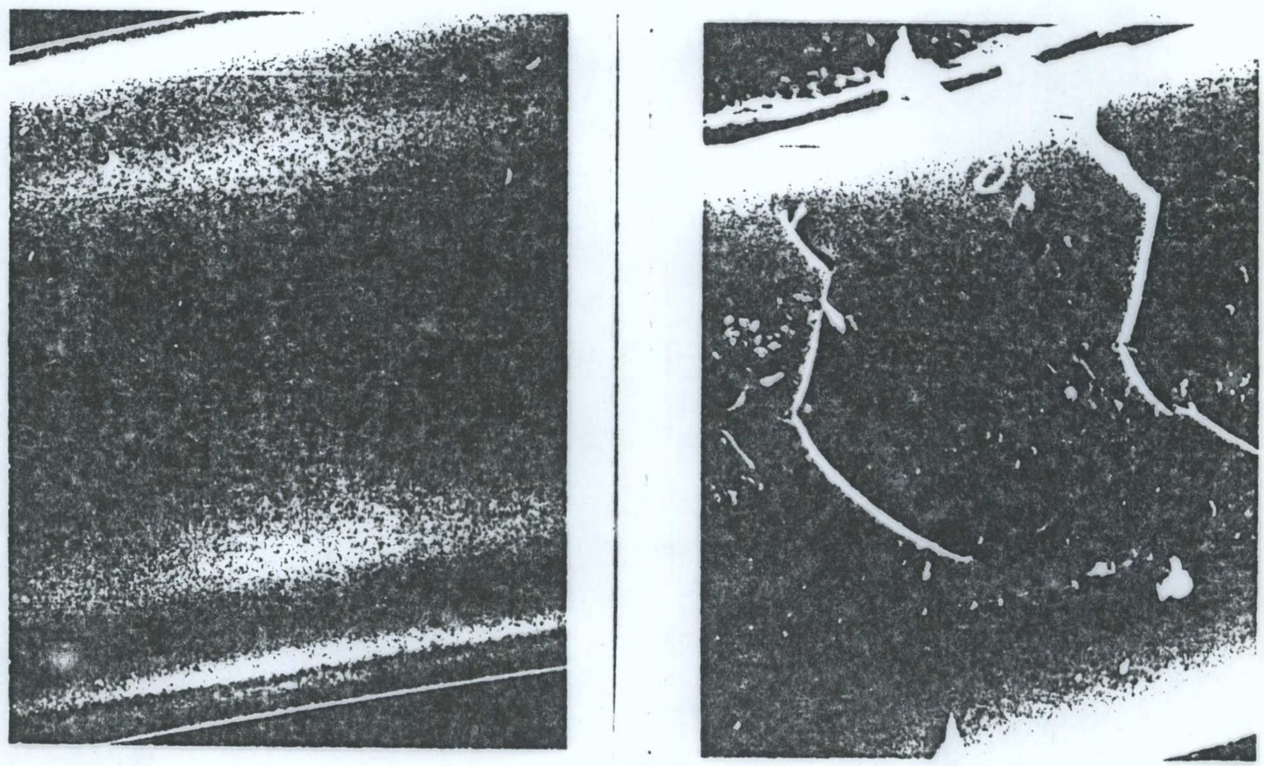
(A) NO IMPERFECTIONS





(B) IRREGULARITIES ON CORE SURFACE (C) MICROCRACKS ON CORE SURFACE

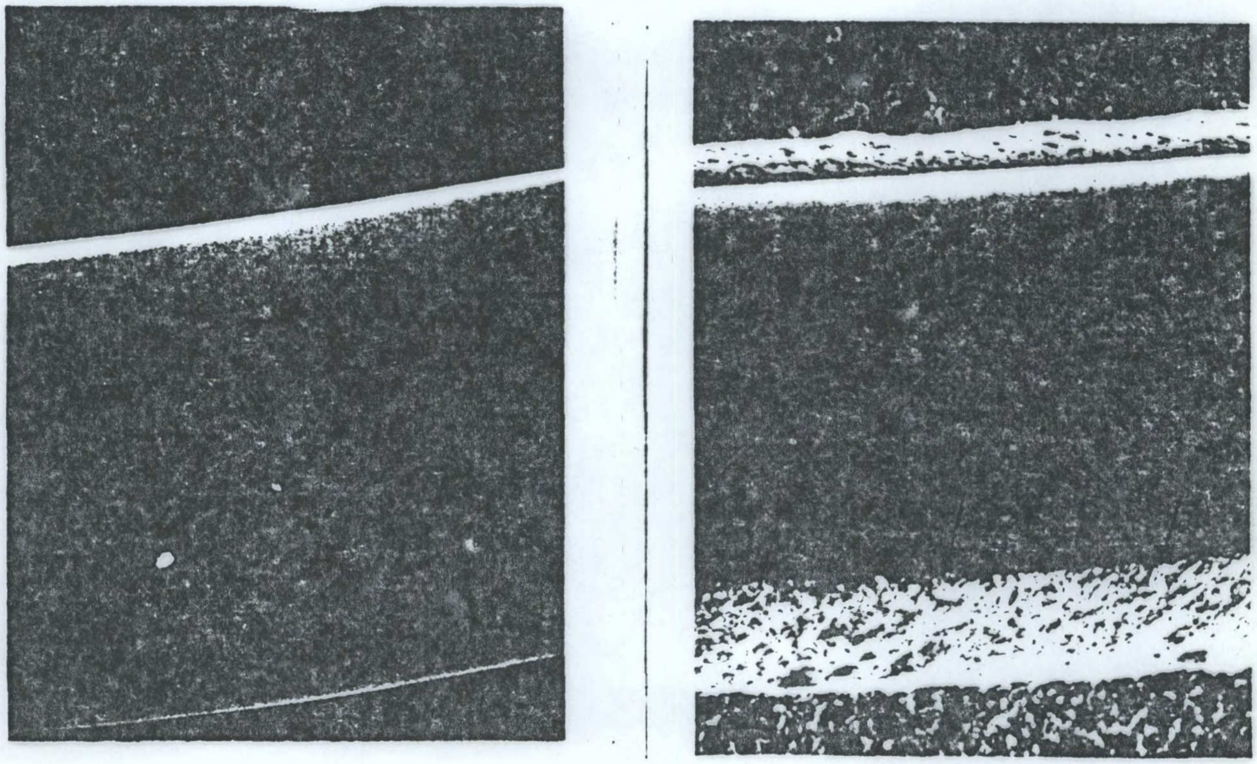
Fig. 31. Scanning electron microscope pictures of the core surface of Fiber #3 (A-388-#1 Silicone cladding with a nylon tubing). (A) A portion of the core surface without imperfections, (B) A portion of the core surface from the sample after thermal cycling, (C) A portion of the core surface from the sample after exposure to outdoor environment. Magnification: X 490.



(A) NO IMPERFECTIONS

(B) MICROCRACKS ON CORE SURFACE

Fig. 32. Scanning electron microscope pictures of the core surface of Fiber #5 (A-325-#1 Silicone cladding with a PVC crush coating). (A) A portion of the core surface without imperfections, (B) A portion of the core surface from the sample after thermal cycling (with intense light spot). Magnification: X 490.



(A) NO IMPERFECTIONS

(B) SERIOUS DAMAGES ALONG A STRIP ON THE CORE SURFACE

Fig. 33. Scanning electron microscope pictures of the core surface of Fiber #6 (Corning 13E with a Hytrel tubing). (A) A portion of the core surface without imperfections, (B) A portion of the core surface from the sample after exposure to outdoor environment. Magnification: X 490.

VI CONCLUSIONS

On the basis of the experimental study of the attenuation loss in various types of optical fibres presented in previous chapters, we draw the following conclusions:

(i) The thermal cycling or the exposure to actual environment of an optical fibre composed of different materials for the core, the cladding and the protective jacket (different thermal expansion coefficients) may lead to the opening of gaps in the bonds between the core and the cladding (e.g.,between the glass core and the silicone cladding), and between the cladding and the jacket (e.g., between the silicone cladding and the PVC jacket), and may also cause microcracking of the glass core, resulting in a very large attenuation loss. To avoid these effects, both the core and the cladding must have approximately the same thermal expansion coefficients. This means that they must be made of similar materials (e.g., glass) with a slight difference in refractive index.

(ii) The plastic tubing for protecting the optical fibre is not recommended because (a) it introduces additional bends to the fibre inside the tubing due to thermally induced stresses, and (b) it allows the environmental atmosphere to enter the tubing, including moisture, which is harmful to the fibre in terms of chemical reactions. To protect the fibre, it is suggested to coat a silicone layer as a buffer layer on the outer surface of the glass cladding and to add a nylon jacket on top of it to protect the fibre from the external environment. Glass, silicone and nylon have a strong adhesion to bond each other.

(iii) Mechanical vibration effects are very small and are not significant if pulse code modulation is adopted for signal transmission. However, they may affect the noise level if amplitude modulation is adopted for signal transmission.

(iv) The w-type fibre is superior to the step-index fibre in terms of attenuation loss based on equal spot size. This may be due to the outer cladding with a refractive index higher than that of the inner cladding. The w-type fibre under investigation is composed of a glass core, double glass claddings and a nylon jacket. This fibre gives almost an optimum performance in bending loss, temperature, thermal cycling and Winnipeg environment effects. It is strongly proposed that this fibre be considered for future use.

FUTURE PLAN

In view of the fact that experimental data about the long-term thermal cycling effects on the attenuation loss and other properties of optical fibres are very scarce in the literature, and yet, they are of extreme importance to industrial applications; we propose that the present experiments on thermal cycling effects and environment effects be continued for one more year. In addition to these, we also propose to study further the effect of dynamic bending (mechanical vibration) because this effect is not fully understood. Since we do not have facilities to fabricate optical fibres and have only limited facilities to carry out experiments, we would like to modify the original program for Phase III to the following program in order to complete this project.

(1) THERMAL CYCLING EFFECTS

To investigate the long-term thermal cycling effects on transmission properties and damages of various types of optical fibres using our existing environment-controlled chamber which can provide continued thermal cycling at one cycle per 3 hours from -50°C to +50°C or at one cycle per 4 hours from -60°C to +60°C. We shall use light-emitting diodes (LED) rather than monochromators as light sources, and use PIN diodes as detectors so that one LED and one PIN diode are required for each fibre. This seems to be the most economical way for experiments involving a large number of optical fibres. We shall also examine microscopically the damages of the optical fibres due to thermal cycling using a high-power microscope. It is hoped that this thermal cycling test will include optical fibres manufactured from various companies such as from Canada Wire and Cable Company Limited, Corning Glass Works, Hitachi Cable Limited and General Cable Corporation. General Cable Corporation has agreed to supply samples of their new optical fibres for our studies of the thermal cycling effects and we plan to write to various companies for samples for this test.

(2) WINNIPEG ENVIRONMENT EFFECTS

We shall repeat the experiments described in (1) under the actual environmental condition in Winnipeg. We shall put the optical fibre samples in a copper tubing and expose them outdoors.

(3) MECHANICAL VIBRATION EFFECTS

Our preliminary results indicate that the changes in transmission properties of optical fibres due to mechanical vibrations are very small. We shall build a low-noise and highly sensitive detector to measure such changes. The purpose of this investigation is to find out whether small amplitude but high frequency mechanical vibrations can be tolerated in the optical fibre communication systems.

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