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ATTENUATION MEASUREMENTS ON DEFORMED OPTICAL FIBERS

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Contents

Attenuation Measurements on Deformed Optical Fibers

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Attenuation measurements were made on several different optical fibers subjected to bending, tension, twisting, and overlapping. The measurements were performed with an optical time-domain reflectometer which gives a partial separation between the various contributions to the measured deformation loss. The graded- and step-index multimode fibers had a variety of different dimensions and coatings. The results of bending attenuation are compared with models and other reported experimental loss data. Based on the results of the present experiments, an empirical model has been derived which permits a prediction of the smallest bend radius consistent with a given allowed attenuation.

Keywords: attenuation; bending attenuation; bending loss; light guides; optical fibers; optical fiber waveguides

1. Introduction

From a system designer's point of view, optical attenuation is one of the most important parameters which characterize lightguides. In addition to the intrinsic sources of loss in the transmission medium, additional losses can be induced by environmental perturbations. The purpose of the present report is to investigate, for a few representative multimode fibers, the magnitude of the excess loss associated with fiber deformations produced by bending, tension, twisting, and overlapping of uncabled fibers. In some situations

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encountered in optical fiber systems, losses due to these effects may be unavoidable because of space constraints in the device layout, or they may be inherent in the construction of certain fiber sensors and mode filters. We are concerned here with losses arising from severe distortions of the optical axis which occur over very limited lengths of fiber (a few meters).

In the present work we have used an optical time-domain reflectometer (OTDR) to measure fiber loss [1]. While the sensitivity is not as great as that of some other experimental techniques, OTDR methods are unique in allowing for loss to be measured as a function of distance along the test fiber. For example, we can distinguish between losses originating from bending and overlapping loss, which are localized effects, and tension and twisting losses which are distributed over extended intervals of the fiber.

Four different kinds of multimode fiber were examined for deformation-induced attenuation. The results obtained for bending attenuation are compared with the values of a computed model. Since the bending attenuation measured here agrees only qualitatively with the theoretical predictions, we have derived an empirical model which relates the minimum curvature radius consistent with a specified loss per loop of fiber. We do not deal here with the case of a long fiber wrapped on a drum but mainly with deformation of a section of a long fiber and its contribution to the total fiber attenuation.

2. Background

In this section we will briefly review the two main sources of extrinsic loss occuring in installed optical fiber systems. These are curvature loss and microbending loss. They will be present to some extent in every application of fibers as a result of uncontrollable environmental disturbances. Although both of these effects have their origin in deviations of the fiber axis from a straight line, the underlying physical mechanisms are different in the two cases. Under the conditions encountered in the great majority of installed systems, the excess losses due to these effects can be controlled to the point that they are not troublesome. Only in situations involving bends with a small radius of curvature, or unusual tension in conjunction with rough surfaces, does the system designer need to be concerned with these induced losses.

2.1 Curvature Loss

When light propagates in a multimode waveguide whose axis is characterized by a constant radius of curvature, some of the guided energy is lost to forward scattering. The loss mechanism can be described from several points of view. One physical picture involves a wavefront confined to a curved trajectory. Due to this geometry, the phase front on the outside of the arc must travel farther than on a straight section of the guide. At some critical radius the phase velocity must exceed the velocity of light in the medium, and, since this is not physically possible, the light is no longer guided and must be radiated away. Another physical picture which has been invoked uses a potential well to describe guidance. Bends can be interpreted in terms of a conformal mapping of this potential, resulting in a quantum-mechanical tunneling effect. Finally, curvature loss can be predicted from the conventional geometrical optics methods of ray tracing. These simple concepts provide the basis for a number of detailed theories on curvature loss. The more important mode theories have been discussed in recent review papers [2,3], and the geometrical ray theories have been described in references [4] and [5]. We will give here only a very brief outline of some of these results, as discussed by Olshansky [3].

Most multimode fibers can support several hundred modes. The maximum number of modes N is given approximately by the relation

$$N = \frac{g}{g + 2} (ka)^2 n_1 \Delta \tag{2-1}$$

with the usual notation that k is the propagation constant, a the core radius, and g the index profile parameter [5]. The relative refractive index difference Δ may be approximated as

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{2-2}$$

where n_1 is the index of refraction on the core axis, and n_2 is the cladding index. A convenient parameter for describing attenuation effects is the mode group number m, which refers to all of the $LP_{\mu\nu}$ modes with the indices μ and ν such that

$$m = 2\mu + \nu + 1. \tag{2-3}$$

The maximum mode group number M is related to the total number of modes N by the relation

$$M = \sqrt{N}. \tag{2-4}$$

The lightguide attenuation γ, in inverse meters, may then be put in terms of these parameters as follows

$$\gamma = 4n_1 k\Delta[1 - (\frac{m}{M})^2]\exp\{\frac{2}{3}n_1 k(2\Delta)^{3/2}R[1 - (\frac{m}{M})^2 - \frac{q}{R\Delta}]^{3/2}\} \tag{2-5}$$

where R is the bend is radius of curvature. It is seen that the curvature loss depends critically on the mode group number and may be completely insignificant for small m and, at the same time, very large for m larger than some some threshold value. The principal result of a bend on a waveguide therefore is to rapidly dissipate the power associated with a certain set of higher modes while leaving the remaining modes virtually undisturbed. We also see that the loss effects are more pronounced for lightguides with small Δ (or small numerical aperture) and large core radius. It can also be shown that a parabolic-index fiber will exhibit twice the curvature loss of a step-index fiber with the same Δ and a. Most of the mode theories appearing in the literature are in qualitative agreement with these conclusions. In our present applications, the quantitative predictions of these bending-loss mode theories are of limited interest since it is known that they do not adequately describe the effect of rapid bend changes which occur over short distances [6]. This deficiency has been confirmed by Agarwal and Unrau [7]. Another weakness of these theories, at least from the point of view of experimentalists, is that the loss equations are couched in terms of variables which are usually not known and cannot be readily obtained.

The ray-path derivations of curvature loss [4] assume that every ray in the bent waveguide is a leaky ray. For our purposes a leaky ray may be defined as a ray which would not be totally internally reflected but for the fact that the waveguide core cross section is curved (quite apart from any bend). The term "leaky" may thus be synonymous with weakly bound. In this model light may be lost from simple principles of refraction. Some of the results of this theory will be shown later in connection with our experimental data, but for our present purposes we merely point out that the predictions exhibit the same characteristic behavior discussed above for the mode theories. That is, there is a rapid power loss in a transition region commencing at the bend, followed by a steady-state region of the fiber where the higher-order modes have been extinguished. Computer-generated results have been put in graphical form, which makes for a convenient comparison with experiment. It should be emphasized however that the reported geometric-optics models assume a steady-state modal distribution of energy impinging on the bend region of the fiber, a condition not realized in the present work. Also, the effect of leaky rays in the unperturbed input section is neglected. It is known, for example, that typically about 10 percent of the launched energy in a fiber may be attributed to leaky modes [8], and some of these modes are present even for kilometer lengths of fiber.

Figure 1 demonstrates the approximate magnitude of multimode-fiber curvature losses. This figure is adapted from the work of Le Noane [9].

2.2 Microbending Loss

There is one other important source of extrinsic loss which can occur when fibers are cabled or deployed in environments where the fiber comes into contact with rough surfaces. This is the phenomenon of microbending [10], and it will occur in any lightguide in which the optical axis is periodically or randomly displaced in a direction perpendicular to the direction of propagation. Typically, the optical axis distortion amplitude is a few micrometers, and the distortion period along the length of the fiber is on the order of millimeters. The irregularities in the axis of the guiding structure cause coupling of energy between the modes in a multimode fiber. Some of the propagating energy will be coupled into nonguided radiation modes, an effect which produces an additional loss. Due to the importance of microbending in long lengths of installed cable, a great deal of attention has been devoted to the design of coatings and cable structures which minimize this effect. For example, it is common practice to coat the fiber with a hard outer shell in conjunction with a soft compliant inner buffer to reduce this type of excess loss.

Multimode optical fibers having a parabolic index profile are particularly sensitive to periodic distortions that have spatial wavelengths λ centered around the value

$$\lambda_r = \frac{2\pi a}{(2\Delta)^{1/2}}. \qquad (2\text{-}6)$$

The resonant effect as a function of λ is due to the fact that, in a graded-index fiber, all mode groups are separated by the same difference in propagation constant and therefore are coupled by the same spatial interaction. This relation has been established both theoretically and experimentally [10]. By contrast, a single periodicity cannot couple all the mode groups in a step-index fiber, and significant excess loss occurs for all spatial wavelengths satisfying the relation

$$\lambda < \frac{\pi a}{\Delta^{1/2}}. \qquad (2\text{-}7)$$

The dependence of microbending loss on fiber propagation parameters has been investigated by a number of authors [11,12]. Keck [13] gives the following relation for the excess attenuation γ

$$\gamma = \frac{K\, d_1^{\,A}}{(N.A.)^{B}\, d_2 C} \qquad (2\text{-}8)$$

where d_1 is the core diameter, d_2 is the outside diameter of the cladding, N.A. is the numerical aperture, and K is a constant whose value depends on the type of fiber; for a loose-tube structure $0 < K < 0.03$, for a tight-tube $0.05 < K < 0.1$, and for high strength fibers $40 < K < 80$. The additional constants are given as: $A = 3.7$, $B = 7.4$, and $C = 5.2$.

The magnitude of the microband loss for a particular fiber can be measured by winding the fiber under constant tension onto a drum which has a known surface roughness [10,14]. The transmitted power loss associated with a single microbend has been investigated by Rourke [14] using OTDR methods.

A certain amount of excess attenuation can also occur from long-period bending with spatial wavelengths of several centimeters. Periodic bends of this sort are common in certain cable structures, and they produce what is usually referred to as macrobending losses [16]. This is really nothing more than a form of microbending. Unfortunately, the term "macrobending" is sometimes used to refer to the continuous curvature loss discussed in section 2.1 which arises from a different physical mechanism.

There was no intention to specifically address the measurement of microbending effects in the experimental phase of the present work. However, this mechanism is involved in the losses observed with the tension and overlapping experiments discussed in section 4.

3. OTDR Attenuation Methods

Optical attenuation in lightguides is often measured by the cutback method [16]. This approach involves measuring the optical power emerging from the distal end of the test fiber. The fiber is then cut a meter or so from the launch end and the output power is again recorded. Loss is inferred from the ratio of these two power levels. The insertion-loss method is similar except that the reference power is measured through a separate short length of fiber identical to the test fiber. The optical time-domain reflectometer does not have the potential sensitivity or accuracy which characterize these other two techniques. However, it is convenient, requires only one end of the fiber, is nondestructive and has the advantage of being able to spatially resolve loss regions. With the instruments used in the present work, the limit of spatial resolution was about 1 m.

The value of the measured attenuation in multimode waveguides depends to a considerable extent on the input launching conditions. This is a result of the fact that each mode group in general has its own loss value. In the present series of experiments, overfilled conditions were used. That is, all guided-mode groups were equally excited. Since the OTDR instrument uses oil for refractive index matching, it also operates as a mode stripper [16] and no additional mode stripping was required. The attenuation coefficient of the undisturbed fiber is almost constant and independent of the length of the fiber tested with the OTDR.

4. Curvature Loss Measurements

For loss measurements with the OTDR the test fiber was wound under a minimum of tension onto two spools. The diameter of each spool was about 15 cm. The spools were wrapped with soft padding in order to minimize the effects of microbending. The controlled bending was done on a short section of fiber between the two spools and close to the middle of the fiber. Whenever possible, about 1 km total length of fiber was used for the measurements, although the bending attenuation was independent of the length of the test fiber. Since the OTDR is capable of measuring local loss, the effects of downstream mode coupling on the transmitted power could be neglected, and the loss of a single or at most a few turns could be measured directly.

Four optical fibers were tested for bending attenuation. Their specifications are given in table 1 [17]. Graded-index fibers with both large and small numerical apertures and one large core diameter step-index fiber were examined. Each of the fibers had a different coating.

Table 1. Type and specifications of test fibers.*

	Fiber number			
	1	2	3	4
Manufacturer	Corning double window GI	Ensign-Bickford SI	ITT GI	Fiber B GI
Core/cladding/ coating diameters [μm]	49/125/240	116/127.5/-	55/125/500	50/125/210
Coating	Scpc	Plastic	Hytrel-s	--
N.A.	0.21	0.27	0.25	0.16
Attenuation [μm]-[dB/km]	0.85-2.3 1.3-0.7	0.85-7.7	0.85-5 1.06-3	-- --
BW [μm]-[MHz/km]	0.85-608 1.3-853	-- --	-- --	-- --
Dispersion	--	--	1 ns/km	--
Screen tested	0.35 GN/m^2	--	0.347 GN/m^2	--
Bending radius (min)	--	--	5 mm	--

*See reference [17].

4.1 Results and Discussion

The results of the attenuation measurements presented here are for very few wraps. They provide the basis for a method to measure local attenuation [19]. The usual way to measure attenuation is to measure it over a 1 km length of fiber wrapped on a spool. Under the last condition the attenuation reaches saturation and becomes nonlinear (attenuation versus the number of wraps). The method proposed here will enable (a) derivation of the exact diameter mode filter, (b) estimation of the minimum spool-core diameter, and (c) determination of the minimum bend radius allowed at corners.

The experimental model seems to be equally valid for graded-index and step-index fibers as long as the measured attenuation values are far from saturation.

Examples of curvature loss obtained from the OTDR measurements are shown in figure 2. Measurements were made on two fibers changing two parameters: the radius of the bends and the number of turns. The experimental loss values varied between 0.1 and 10 dB.

When the attenuation due to a single turn is high (about 1 dB), additional turns add only slightly to the overall attenuation. However, for low attenuation values per turn (about 0.1 dB), additional turns increase the overall attenuation in proportion to the number of turns. These results are qualitatively in agreement with the theories discussed in section 2.1 which predict a steady-state attenuation once the higher order modes are removed. The experimental data in figures 3 through 6 indicate that, as long as the curvature loss is far removed from the steady-state value, the logarithm of the loss in decibels is a nearly linear function of the diameter of the bend. This is true for all the different fibers and for different numbers of turns. With a linear dependence of this sort, and with simple interpolation procedures, it is possible to determine the minimum bend diameter corresponding to a given attenuation per turn. The straight line obtained when the logarithm of the loss in decibels is plotted as a function of R forms the basis for a promising method for estimating curvature loss as long as the steady-state region is avoided.

An effort was also made to quantitatively compare these results to the theoretical predictions of Love and Snyder [4]. The theoretical and experimental points are shown in figures 7 and 8. Numerical values of the step-index fibers exhibit a worse fit than those observed from the graded-index fibers, although only very few calculated data can be fitted into the figure. In both cases, the rather striking lack of agreement indicates that the theory is not satisfactory for accurate prediction of curvature loss for the kinds of fibers and in the regime studied here. As we have discussed previously, this may be due in part to a difference between the assumed mode distributions in the theoretical model and those obtained under our laboratory conditions. This discrepancy might justify the introduction of the proposed experimental model.

5. Tension Loss Measurements

Many optical fibers are proof tested to withstand stresses of 0.35 GPa (50 ksi), although certain high-strength fibers for use in special applications are rated as high as 5.6 GPa (800 ksi), near the theoretical strength of silica. The coating as a rule does not contribute significantly to the tensile strength of the fiber. The object of the series of experiments described in this section was to determine the effect of stress on the attenuation properties of short lengths of bare fibers [18].

A controlled section of the test fiber about 33 m long was used to measure the excess loss due to tensile loading. This section of fiber was loaded with weights ranging from 0.1 to 0.5 kg. The strained fiber was passed through a series of pullies to reduce, as much as possible, the sliding resistance. Five 75 mm diameter pullies were used, each of which had a groove cut for the fiber. One end of the fiber was taped to a fixed surface with minimum deformation of the fiber. The other free end of the fiber was sandwiched between two pieces of tape and the tape was loaded with the test weight. In order to minimize microbending effects no clamping was used. The total length of the fiber did not appear to have any effect on measured tension loss. Since the attenuation due to tension was distributed throughout the test length, the total loss was somewhat more difficult to measure than the curvature loss, which is highly localized.

5.1 Results and Discussion

Due to the limited sensitivity of the OTDR used, only fibers 1 and 4 gave measurable results over the short lengths used here. For graded-index fibers, the smaller the N.A. (or Δ) the higher the attenuation of the fiber for the same structure and tension. For the two low N.A. fibers measured, the excess attenuation due to externally applied tension was proportional to the tension (fig. 9). From the slope of the attenuation versus load curves it is possible to derive loss rates (dB/N•km). Excess attenuation due to tension effects which are less than 0.1 dB over 33 m of fiber could not be measured with the present apparatus. Also, since the fibers could not be loaded by more than 0.5 kg due to the probability of failure, the measurements had a lower sensitivity limit of about 0.6 dB/N•km.

The experimental results are presented in table 2 column 3. Fibers 2 and 3 did not yield measurable tension losses.

Table 2. Comparison of deformation losses in optical fibers.

Fiber	Bend radius for 1 dB loss (cm)	Tension loss (dB/N•km)	Twisting loss (dB/twist)	Overlap radius for 1 dB loss at tension 0.014 N (cm)
1	1.84	2.0 ± 0.6	0.001	0.63 ± 0.2
2	0.056	<0.6	0.001	
3	0.20	<0.6	0.001	
4	0.95	4.0 ± 0.6	0.001	0.89 ± 0.2

6. Twisting-Loss Measurements

To measure the excess loss due to fiber twisting, a section of test fiber about 6 m long was taped at both ends and twisted in the middle around its own axis (twisting each half-section in opposite directions). During the experiment the tension on the fibers was kept to the minimum required to keep the fiber from curling.

No attenuation change was detected (less than 0.1 dB) for up to 100 twist cycles for all of the fibers tested. The upper limit for the excess loss per twist cycle is therefore 0.001 dB/twist.

7. Overlap Loss Measurements

Overlapping of fibers is common whenever spools of fibers are wrapped with more than one layer. Overlap losses are localized and therefore can be observed easily on the OTDR. However, some problems were encountered when we tried to perform these loss measurements since it is not easy to separate the various components of the deformation attenuation which contribute to the total observed loss. Wrapping requires a certain force and therefore the fiber is subjected to some tension, especially when wrapped on a small diameter spool. Also, there was some slide resistance encountered when the wrapping was done and it was possible to get different tensions in different sections of the fiber resulting in different attenuations.

In the experimental setup, two wraps of the test fiber were wound side by side on an oiled aluminum rod of known diameter. The fiber was put under a constant tension by loading one of its ends with a known load. The attenuation due to the two wraps was measured on the OTDR. The attenuation measurement was repeated after rewinding the second wrap so that it overlapped the first wrap and touched it at one point (fig. 10). By subtracting the second value from the first value of attenuation (in decibels) the attenuation due to the overlap alone is derived.

Overlap losses for different wrap diameters but constant tension (1.39 N) are presented in figure 11. Varied tensions leaving the diameter fixed are given in figures 12 and 13. The attenuation due to two wraps without overlap is also included to indicate the values subtracted.

From purely mechanical considerations the compression of the fiber due to overlap should be inversely proportional to the radius of the resulting bend. From the graph in figure 11 it may be observed that the attenuation due to the overlap is also approximately proportional to the wrap radius R for the mode distributions in this experiment. The attenuation can be represented as

$$\gamma \approx \frac{K}{R} \tag{7-1}$$

with a characteristic constant K identified with each fiber.

The observed dependence of the overlap attenuation on the fiber attenuation for a fixed diameter indicates that there is some residual overlap attenuation for zero external tension. This zero-level loss increases with the reduction of the bend radius (figs. 12 and 13).

Fiber 3 was very insensitive to overlap attenuation due to its relatively hard outer coating. Fiber 2, which was of the step-index type, had a large N.A. and perhaps for this reason was insensitive to overlap attenuation. It broke before exhibiting any measurable attenuation. Fiber 4 is more sensitive to overlap than fiber 1. The diameter that gives 1 dB attenuation is given in table 2.

A more thorough comparison of the different deformation attenuations requires a model for each deformation which was not presented in this work (special cases of the deformations are treated theoretically in references 20 and 21).

8. Summary

Excess optical fiber loss due to various types of external deformations have been measured and discussed. The use of an OTDR to measure the attenuations allows, in most cases, for each loss contribution to be analyzed separately.

An empirical model for estimating curvature loss in a given fiber was proposed. It was found experimentally that smaller N.A. fibers are more sensitive to deformation, and step-index fibers are less sensitive to deformation attenuation than are graded-index fibers with the same N.A. During this work no attention was given to the contribution of the fibers coating to the deformation attenuation, although it was found that a more rigid coating generally reduces the attenuation.

For comparison purposes the different contributions to the attenuation are summarized in table 2.

Of the external perturbations studied, the fibers seem to be the most sensitive to bending loss, and slightly less sensitive to overlap attenuation under a maximum of 0.35 GPa tension. Pure tensile forces gave observable losses only for small N.A. fibers. Attenuation due to a few twists was undetectable.

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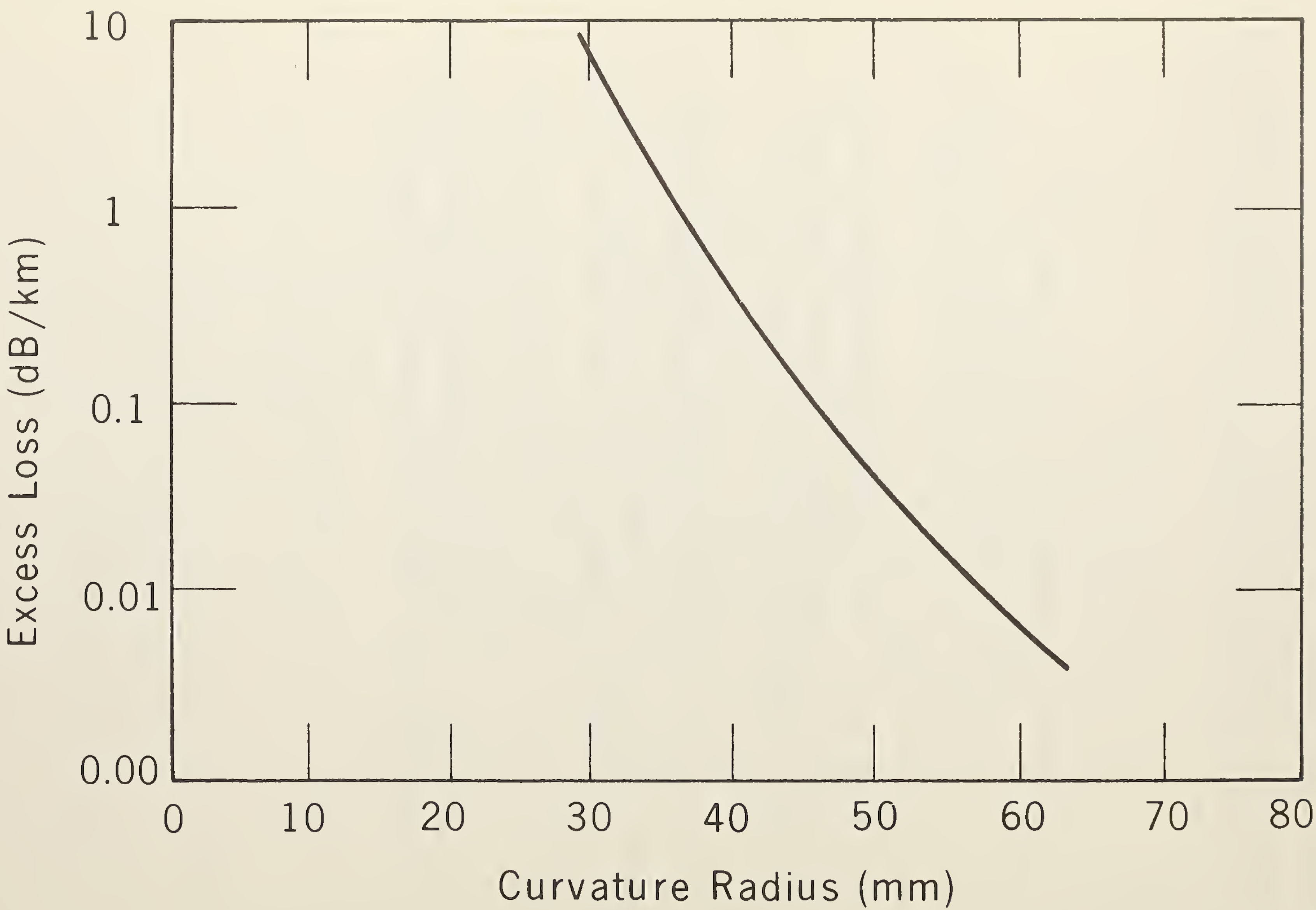

Figure 1. Approximate magnitude of the excess curvature loss (dB/km) as a function of the bend radius (adapted from Le Noane [9]).

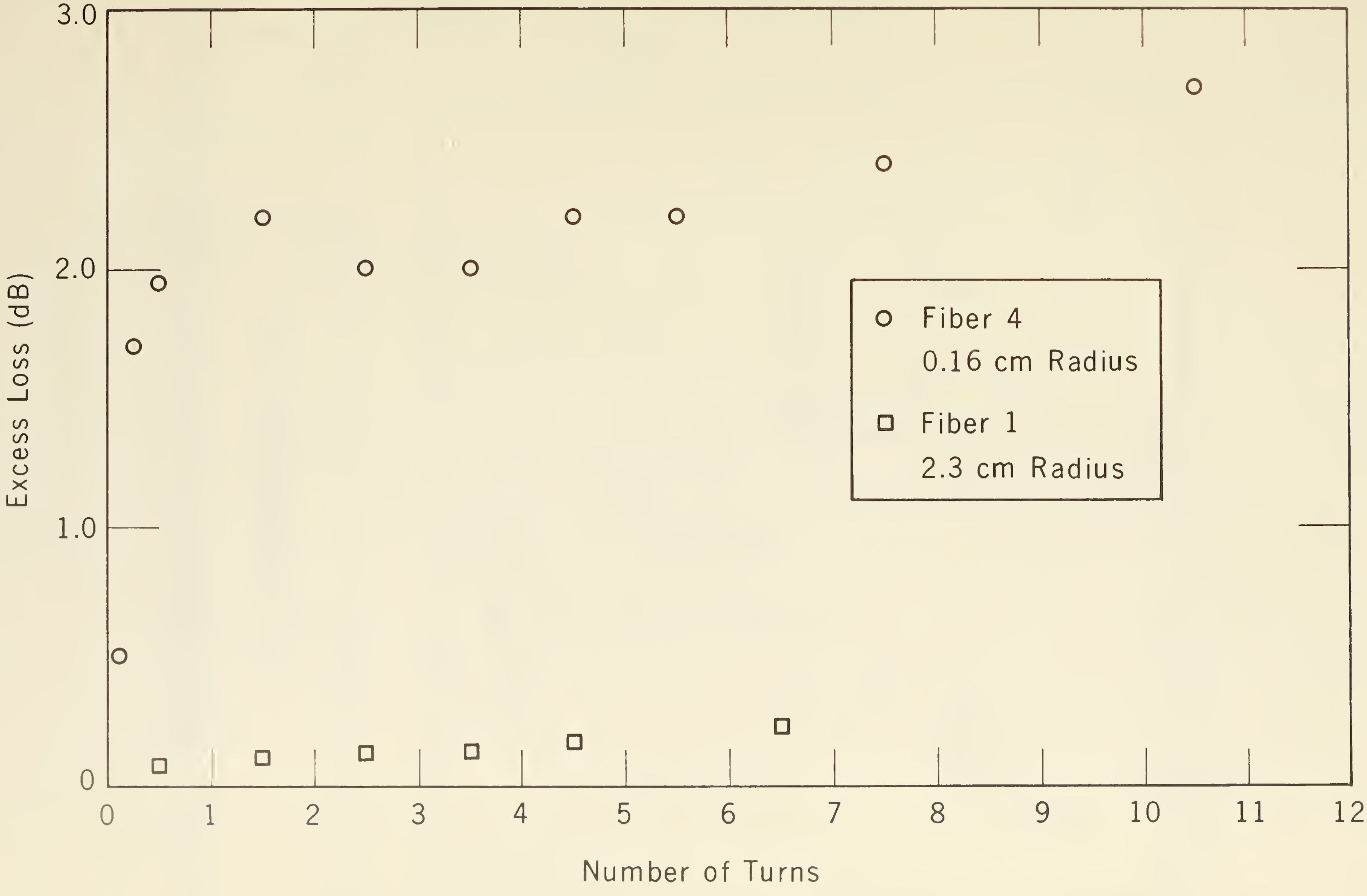

Figure 2. Excess curvature loss for two experimental fibers as a function of the number of complete bend cycles. Fiber 1 was wound on a mandrel of 2.3 cm radius, and fiber 4 was wound with a 0.16 cm radius.

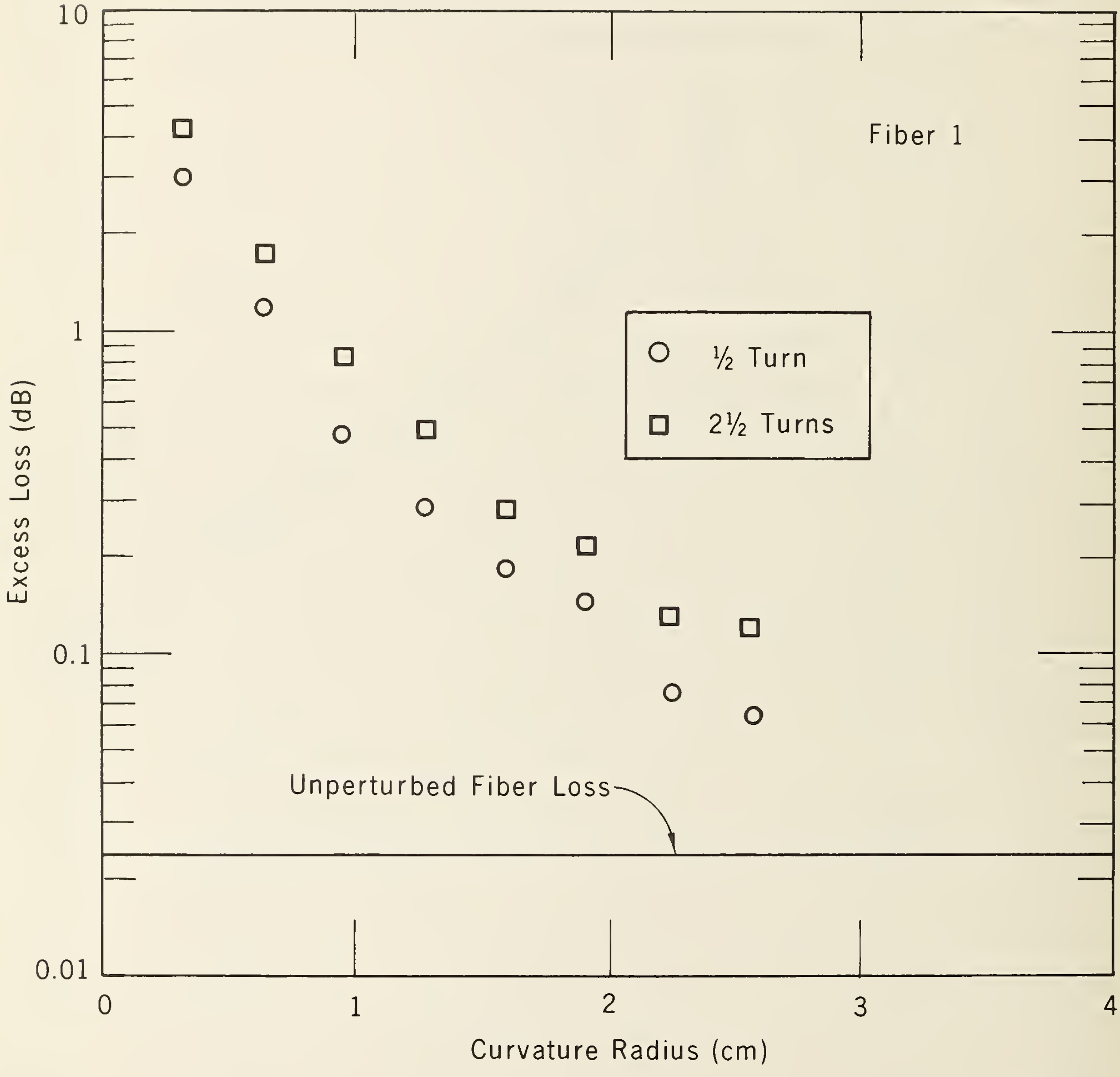

Figure 3. Excess curvature loss as a function of bend radius for fiber 1 with 1/2 and 2 1/2 turns.

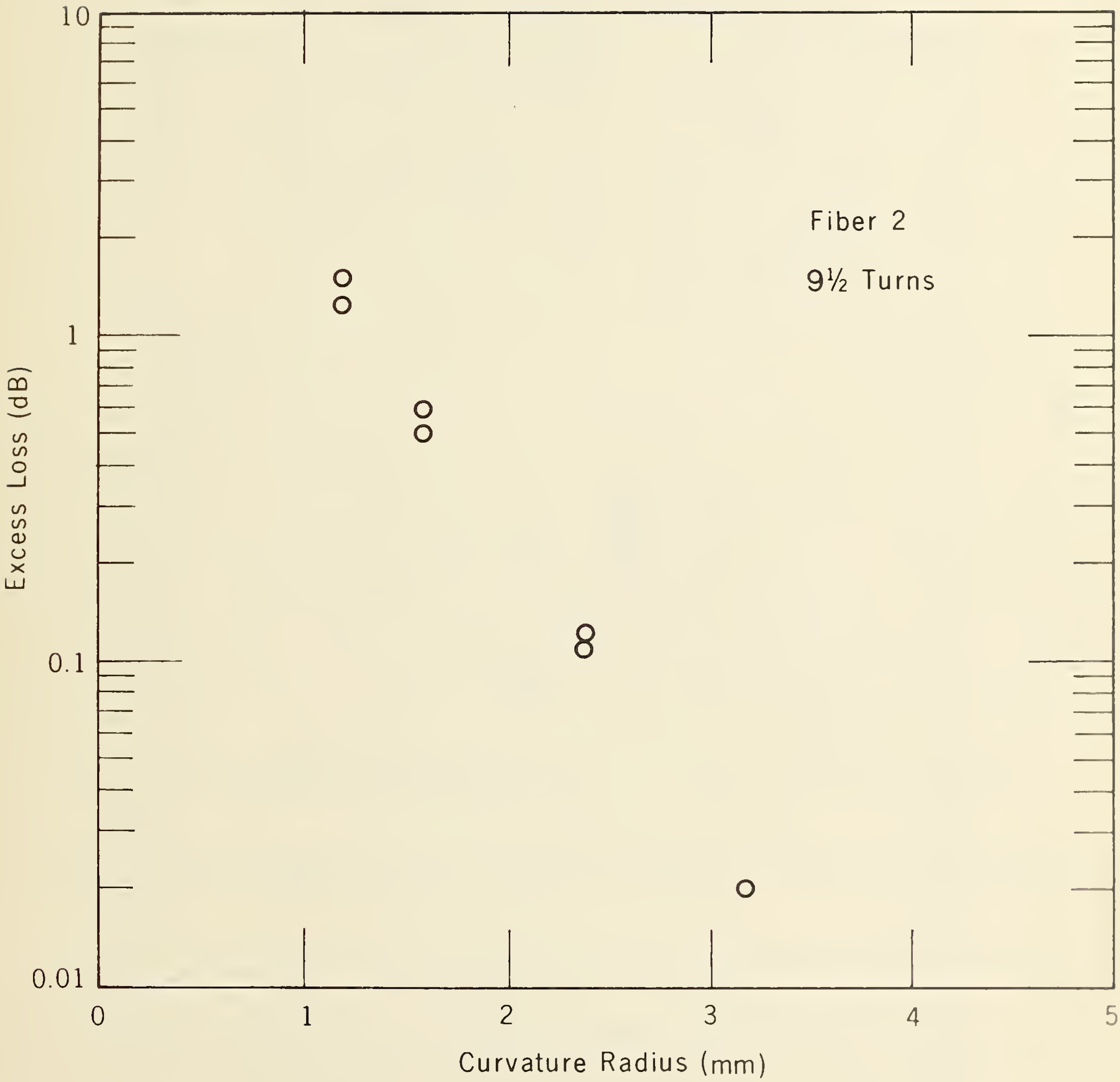

Figure 4. Excess curvature loss as a function of bend radius for fiber 2 with 9 1/2 turns.

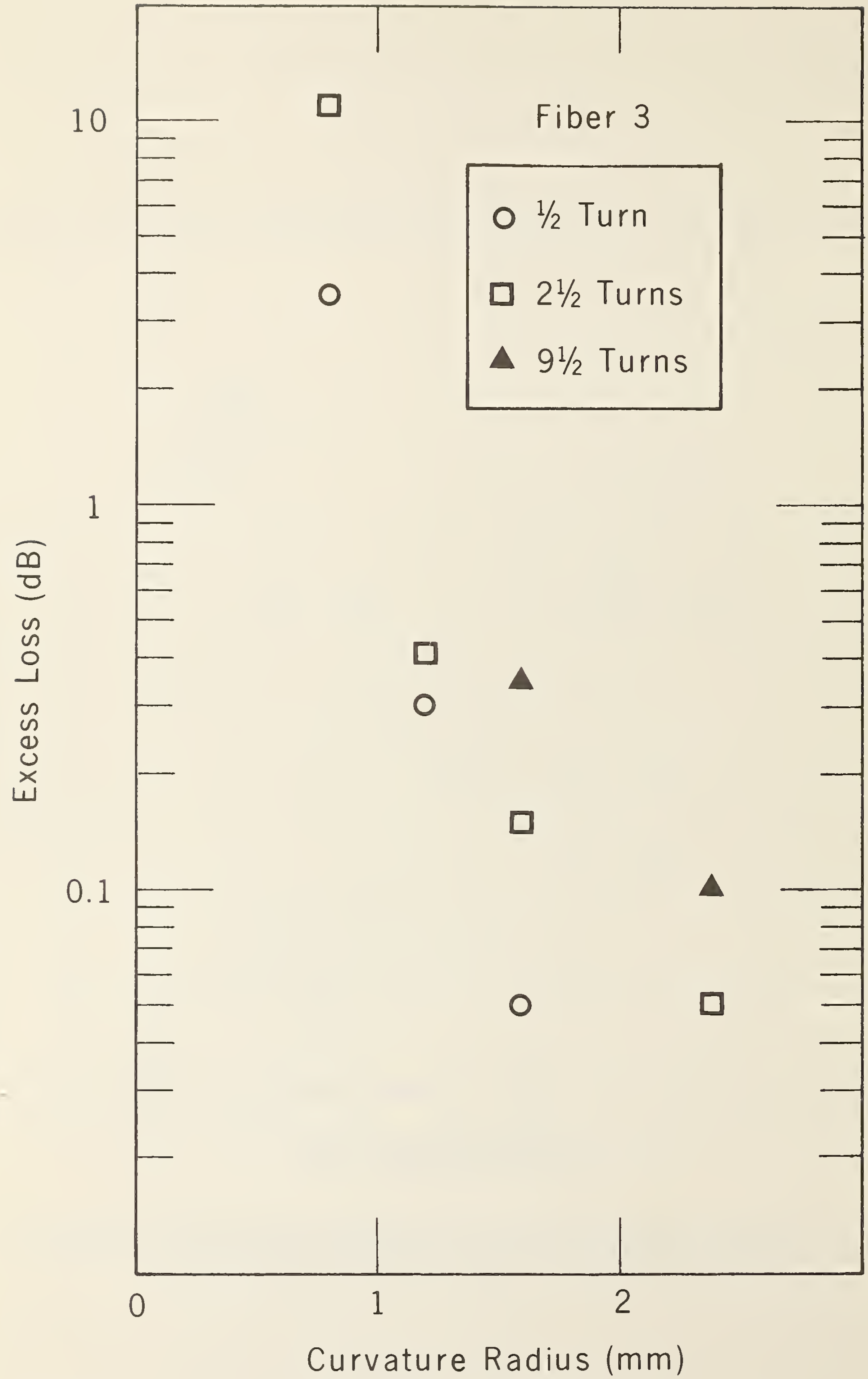

Figure 5. Excess curvature loss as a function of bend radius for fiber 3 with different turns.

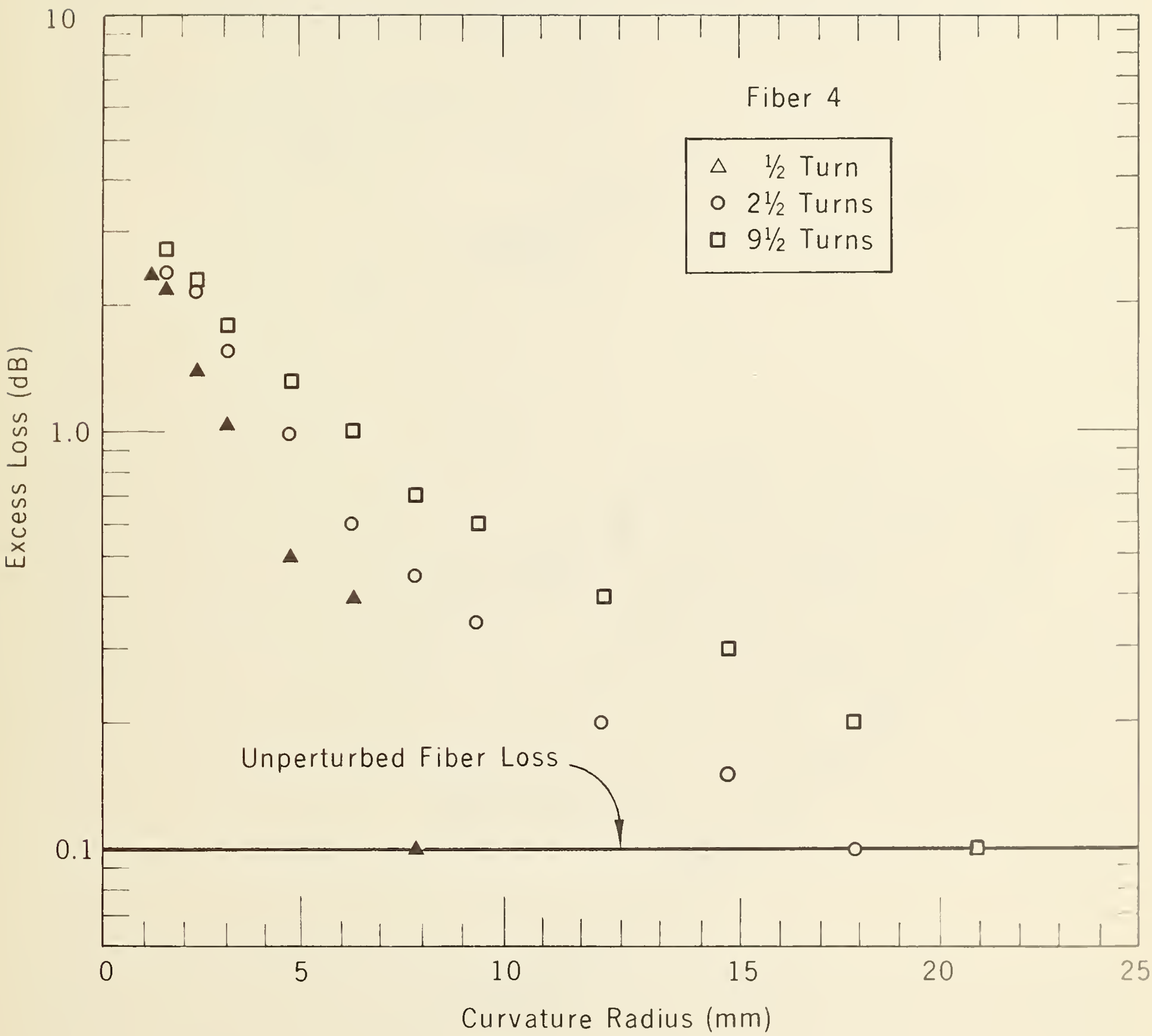

Figure 6. Excess curvature loss as a function of bend radius for fiber 4 with several different turns.

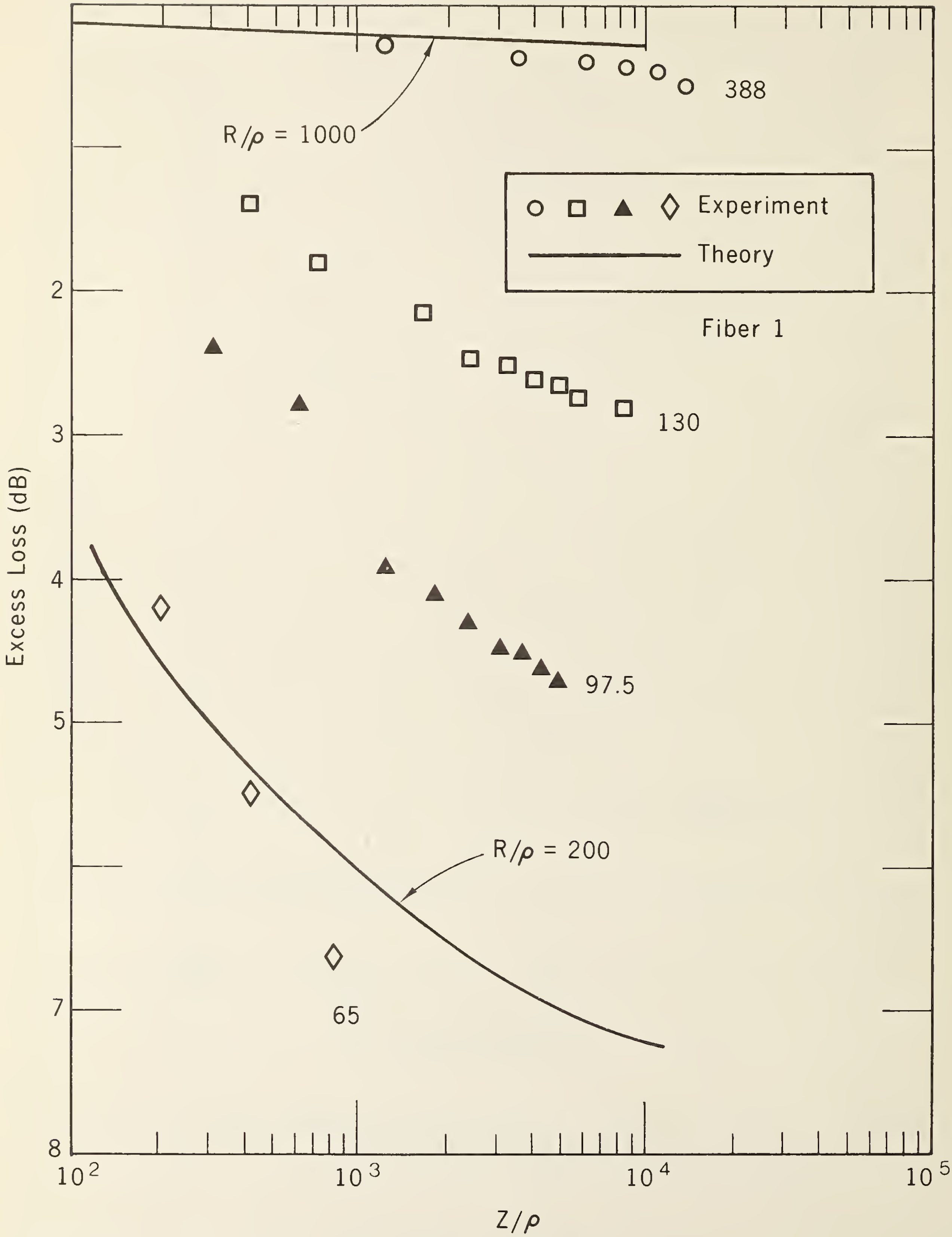

Figure 7. Comparison of the present experimental work with the theory of Snyder and Love [4]. The individual points are for fiber 1 which has a near-parabolic index profile.

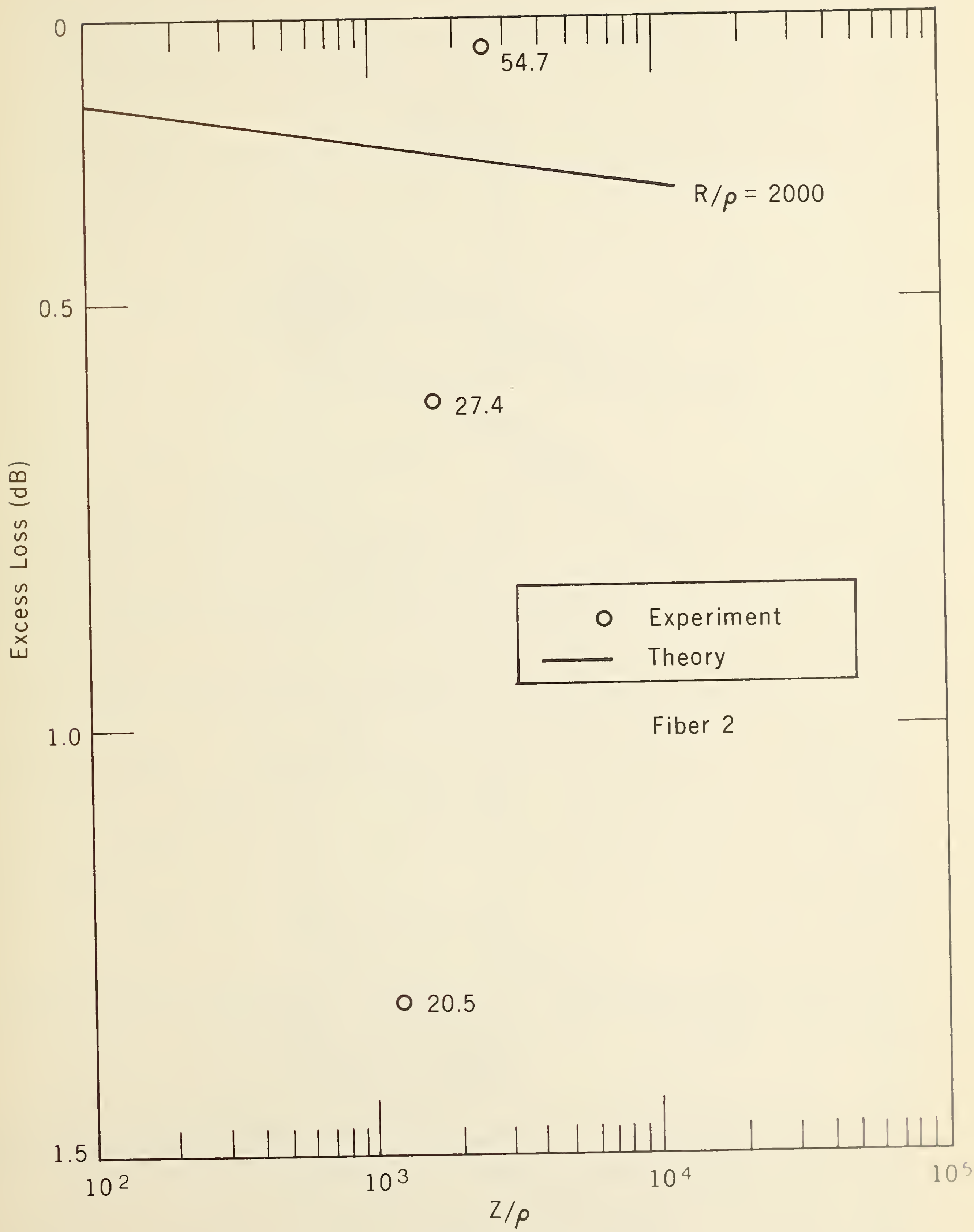

Figure 8. A comparison of the curvature loss theory of Snyder and Love [4] for fiber 2 which has a step-index profile.

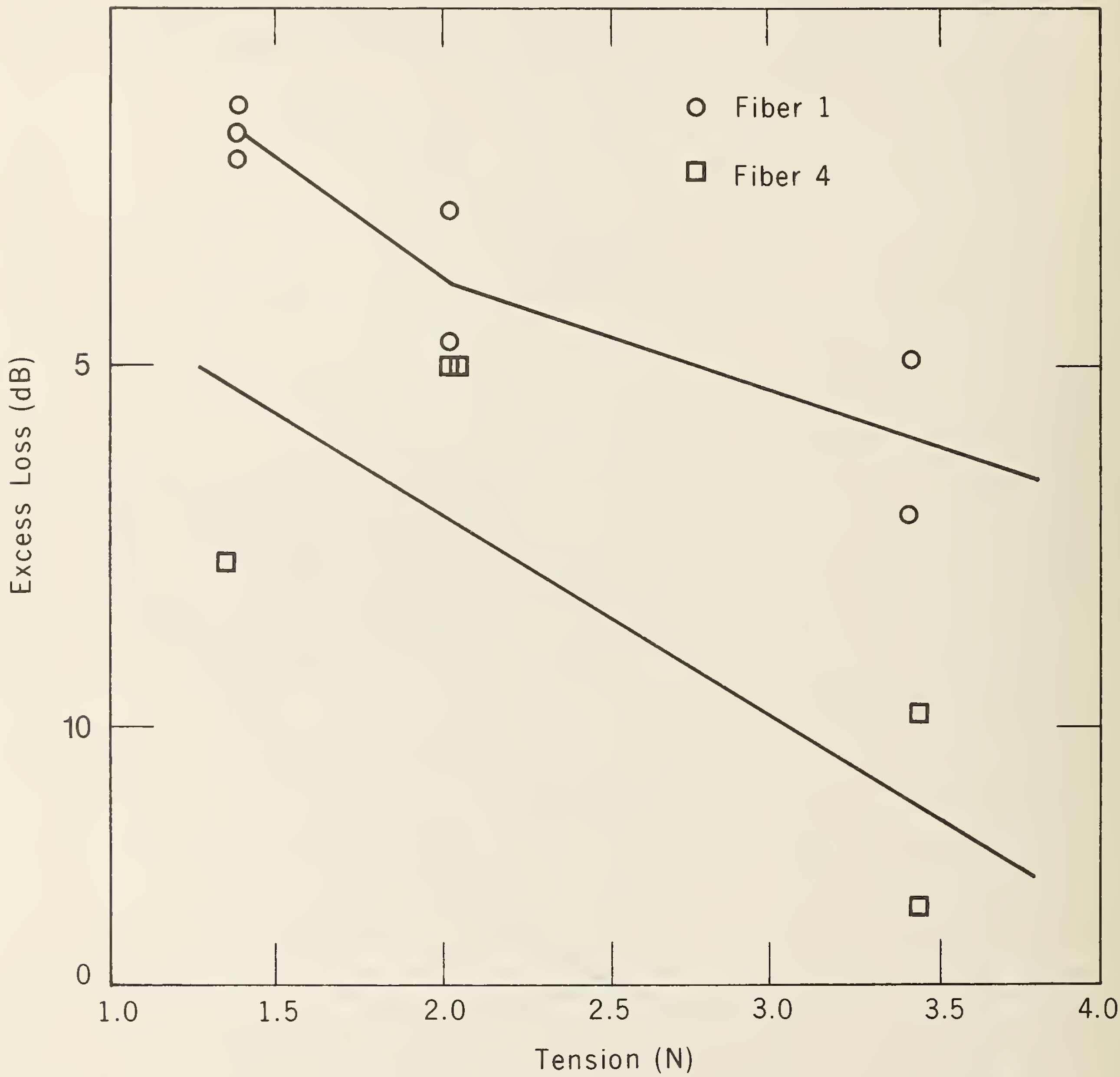

Figure 9. Excess loss due to tension for fibers 1 and 4. Note: Error here is estimated to be ±0.2 dB, but due to other unknown factors can be much higher.

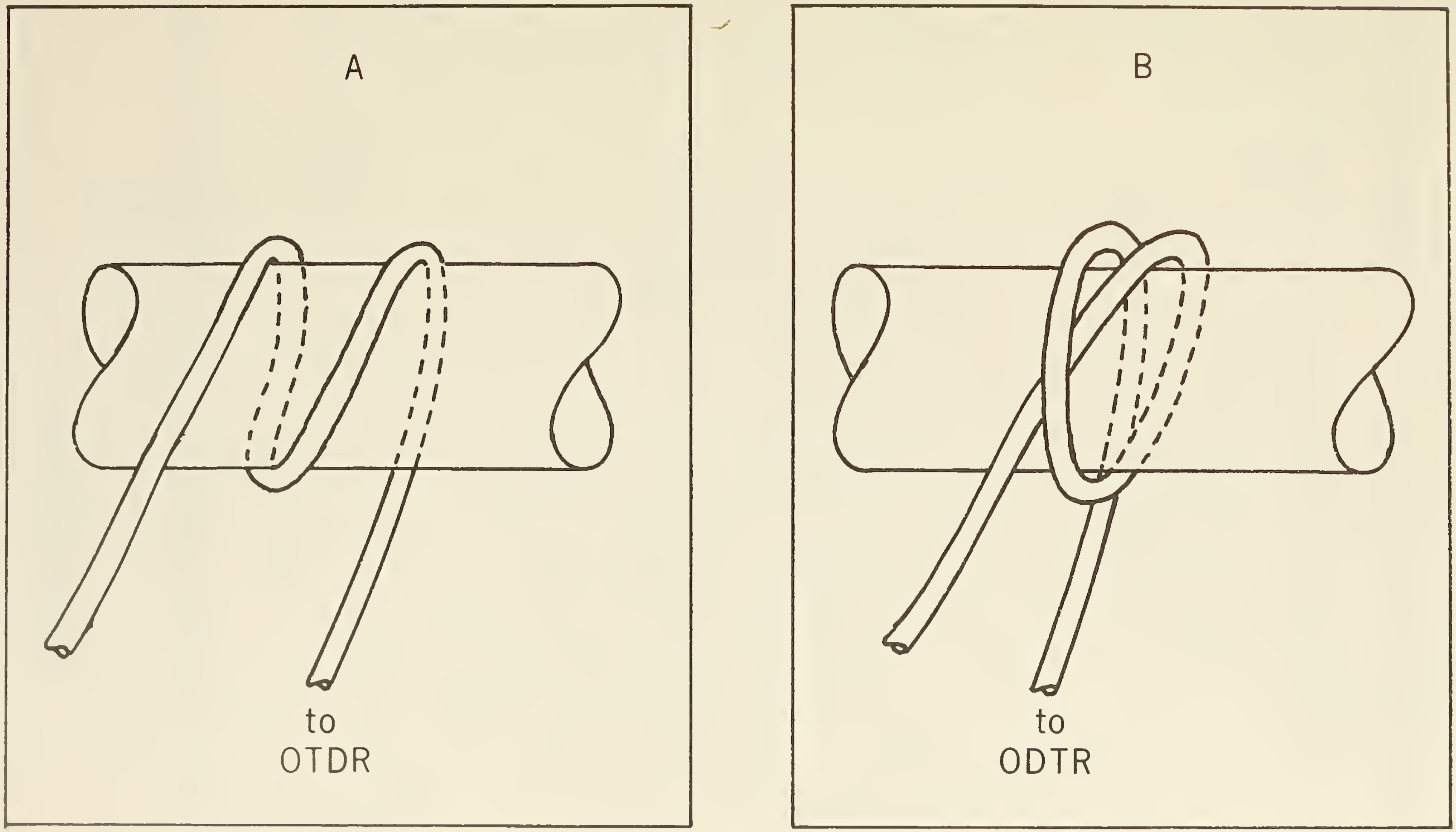

Figure 10. Experimental configuration for testing the magnitude of the excess loss due to fiber overlap (A) and pure curvature (B).

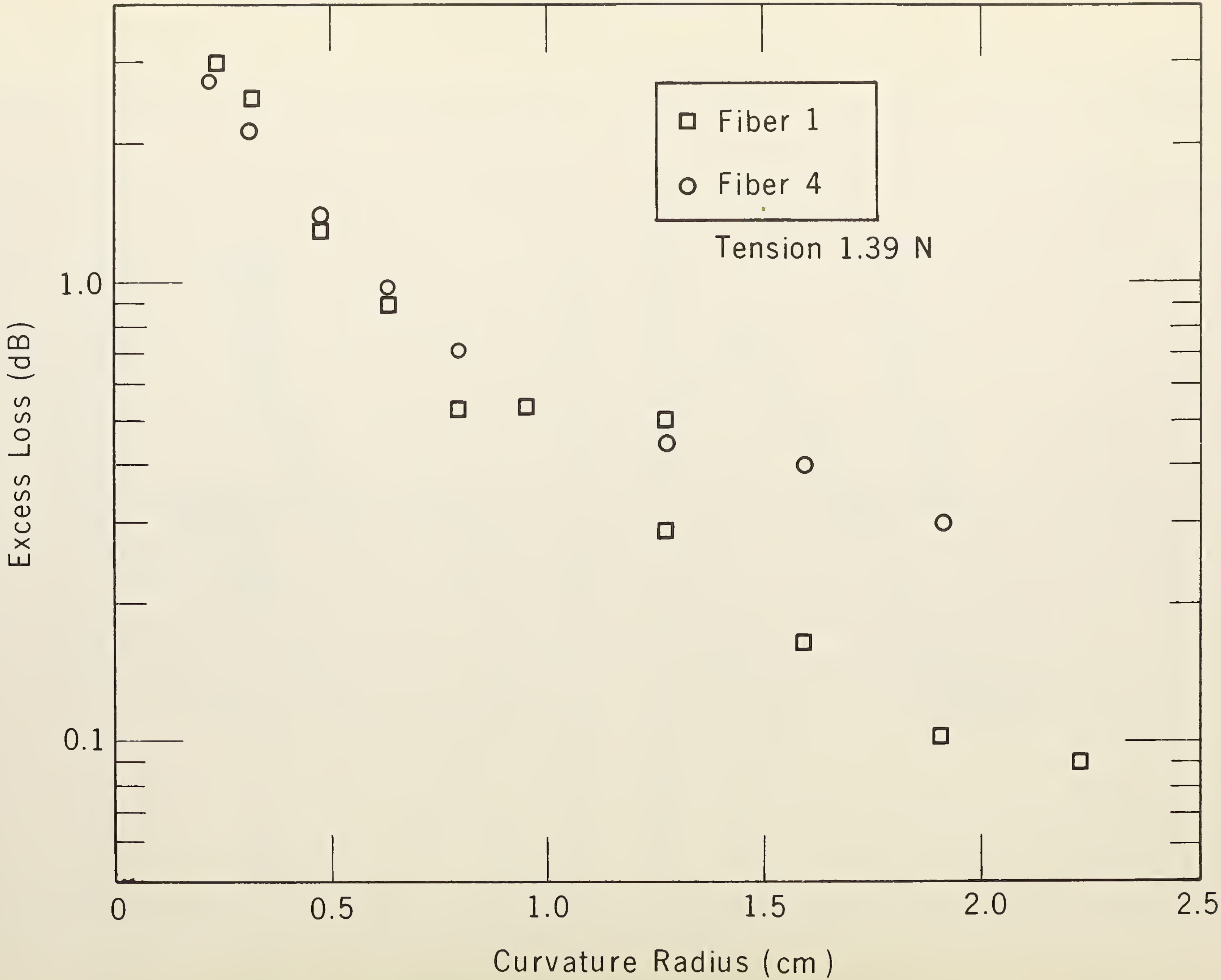

Figure 11. Excess overlap loss in fibers 1 and 4 due to tension as a function of mandrel radius.

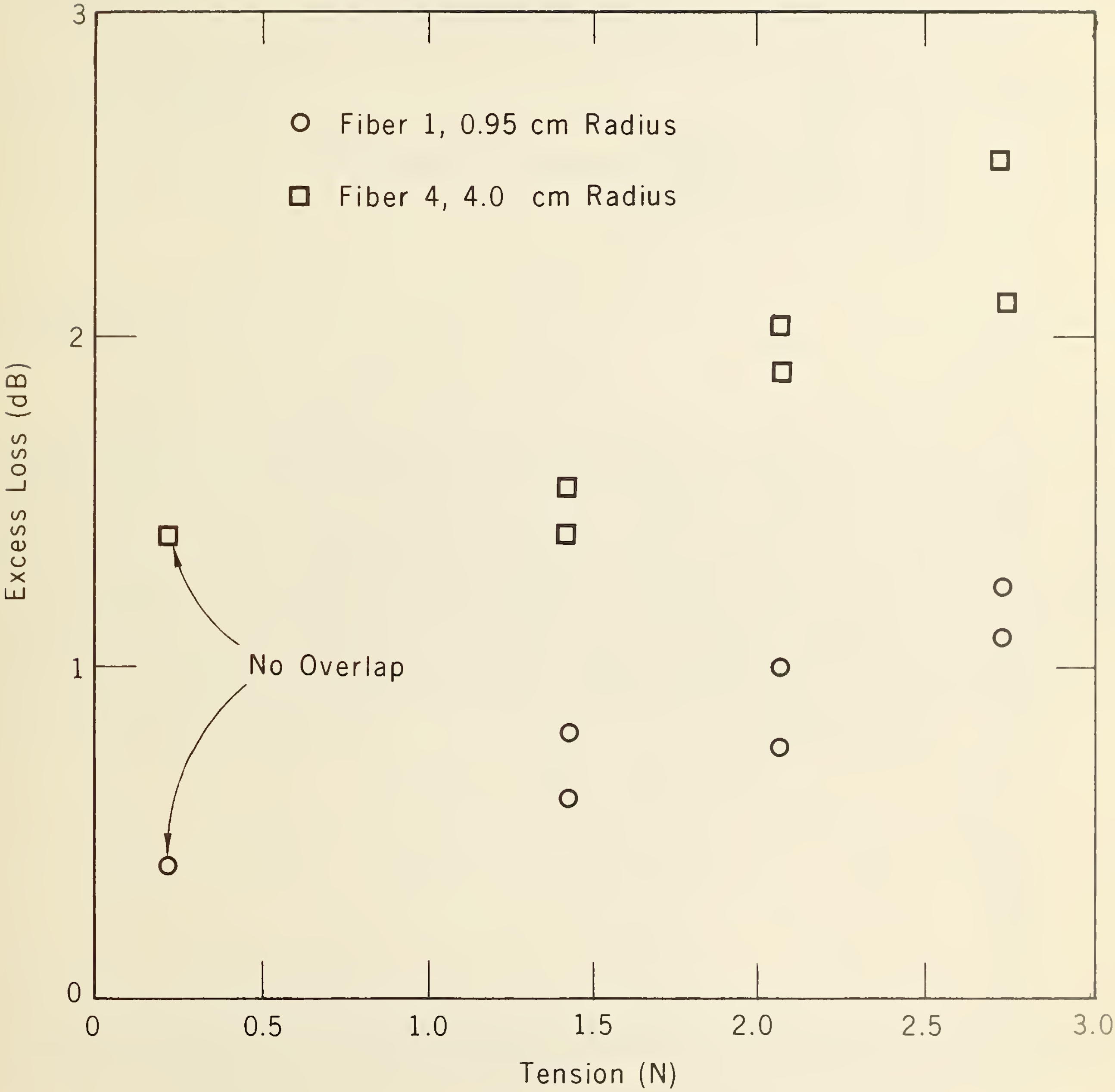

Figure 12. Excess overlap loss in fibers 1 and 4 under constant curvature as a function of applied tensile loading.

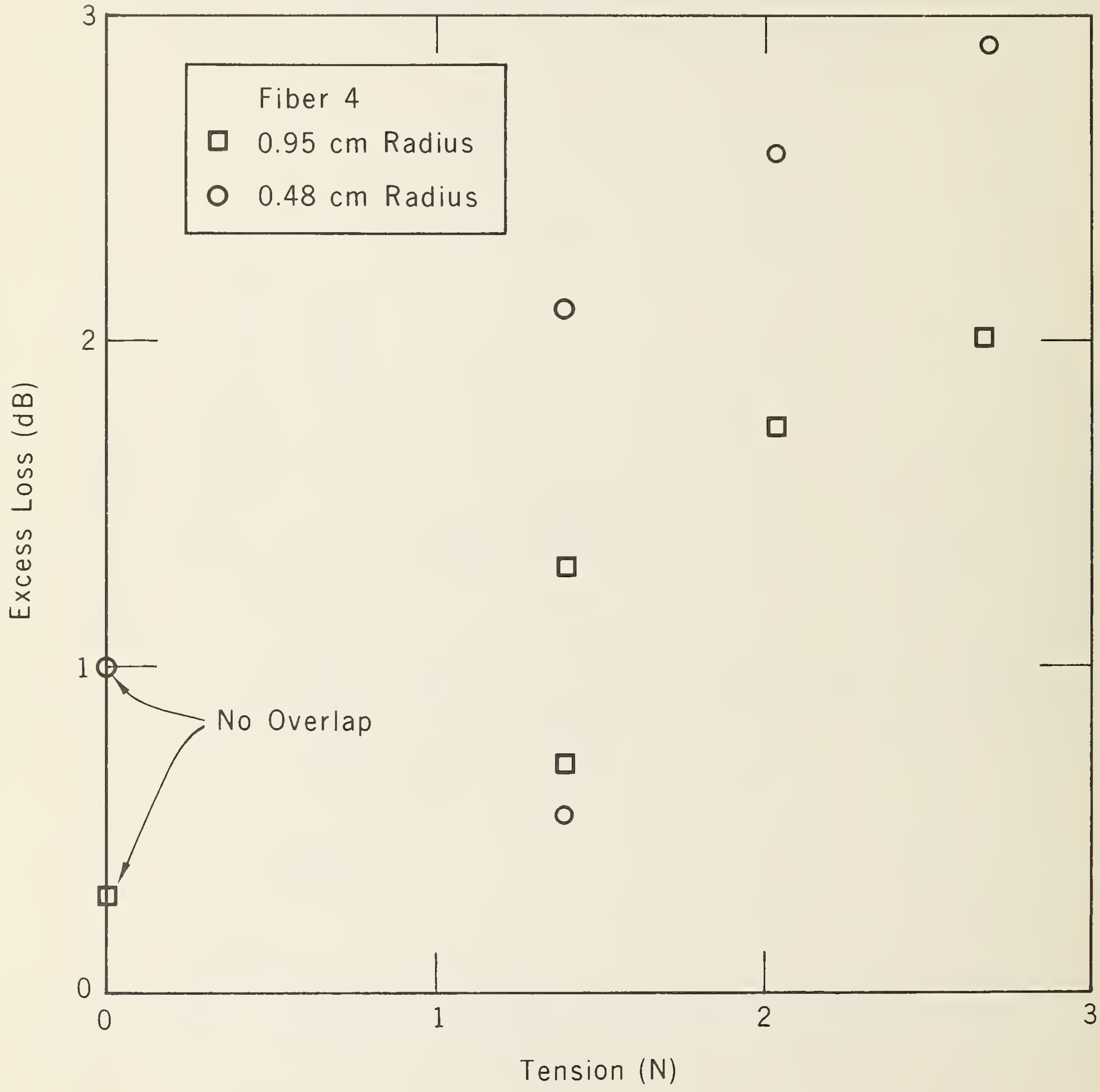

Figure 13. Excess overlap loss in fiber 4 as a function of tension for two different mandrel radii.

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[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Attenuation measurements were made on several different optical fibers subjected to bending, tension, twisting, and overlapping. The measurements were performed with an optical time-domain reflectometer which gives a partial separation between the various contributions to the measured deformation loss. The graded and step-index multimode fibers had a variety of different dimensions and coatings. The results of bending attenuation are compared with models and other reported experimental loss data. Based on the results of the present experiments, an empirical model has been derived which permits a prediction of the smallest bend radius consistent with a given allowed attenuation.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

attenuation; bending attenuation; bending loss; light guides; optical fibers; optical fiber waveguides

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