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INTERLABORATORY COMPARISON OF RADIATION-INDUCED ATTENUATION IN OPTICAL FIBERS
PART III: TRANSIENT EXPOSURES

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INTERLABORATORY COMPARISON OF RADIATION-INDUCED ATTENUATION IN OPTICAL FIBERS. PART III: TRANSIENT EXPOSURES

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ABSTRACT

A comparison of the losses induced in step index multimode, graded index multimode and single mode fibers by pulsed radiation exposure has been made among 12 laboratories over a period of 5 years. The recoveries of the incremental attenuations from 10^{-9} to 10^{1} s are reported. Although a standard set of measurement parameters was attempted, differences between the laboratories are evident; possible origins for these are discussed.

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INTRODUCTION

Radiation effects in fiber optics have been studied at a number of laboratories,[1,2] but there have often been significant differences in the results reported, even on similar fibers irradiated under nominally identical conditions. Two previous papers, Parts I and II of this series,[3,4] have discussed the results of steady state irradiations carried out on identical fibers by different laboratories of the NATO Panel IV, Research Study Group 12 Fiber Optic Nuclear Effects Task Group, and a summary of steady state and transient measurements has been presented.[5] The aim of the interlaboratory comparisons of both steady state and transient radiation-induced attenuation was to investigate the level of specification necessary for standardized testing of radiation effects in fiber optic waveguides.

The irradiations of these studies were carried out on a series of fibers; in general, each was pulled from a single preform in an attempt to insure that the samples provided to all laboratories were as identical as possible. The initial set of measurements were undertaken in 1984-1985 on two silica core, doped silica clad, step index fibers with the laboratories performing the tests using their own "standard" conditions. Considerable divergence was found in the steady state results[3] due to differences in dose, dose rate, injected optical power, operating wavelength, etc. More stringent test parameter specifications were used on the subsequent rounds of steady state tests,[4] which included additional silica core multimode fibers in 1986 and 1987, graded index and single mode waveguides in 1988, and single mode fibers in 1989. As a result, there has been increased success in reconciling the differences among the laboratories and identifying which parameters had the most influence on the measured steady state radiation response of fiber waveguides.

Although the major portion of the literature on radiation effects in fiber optics is devoted to attenuation induced by steady state ^{60}Co exposure, there is considerable interest in the transient response as well. Data link applications near radiation sources such as pulsed fusion reactors, pulsed laboratory facilities, or military radiation environments may require knowledge of the recovery of the incremental loss following transient exposures of < 100 ns. Furthermore, knowledge of the behavior of the fiber at very short times after irradiation is necessary to fully understand the fundamental radiation damage mechanisms.

This paper will describe the results of interlaboratory comparisons of the responses of fibers exposed to various pulsed radiation sources. The samples tested in general parallel those studied with steady state irradiations: the tests have progressed from step index silica core multimode fibers at 0.85 μm to 1.3 μm, followed by measurements of graded index fibers at 1.3 μm and single mode waveguides at both 0.85 and 1.3 μm.

EXPERIMENTAL

Fibers Studied. Fibers were supplied by various manufacturers over the 1985-1989 time period of the tests, and the 1-2.5 km samples which were divided among the investigators were generally pulled from a single preform. Table I summarizes the fibers studied. Step index 100/140 silica core-doped silica clad fibers were initially chosen for investigation because of their lower transient response[6,7] and the fact that effects such as light-induced annealing[8,9] might make them more sensitive to variations in test parameters. The 1985 tests were performed on fibers A and B, which were two

100/140 silica core fibers with core OH contents of 3-5 ppm and 1200 ppm, respectively. The 1986 tests used these two fibers and added fiber C which was pulled from a preform similar to that used for fiber B. The 1987 tests were performed on both fibers A and B in the first window of 0.85 μm and fiber D in the second window at 1.3 μm. The 1988 round consisted of radiation-hardened graded index fibers E and F at 1.3 μm and two silica core single mode fibers G and H at 0.85 and 1.3 μm, respectively. Finally, the 1989 tests were conducted on silica core single mode fibers I and J at 0.85 and 1.3 μm. The cores of the single mode fibers G, H, I, and J, were of the same silica as multimode fibers A and D. For brevity, only representative data reported during the 1985-89 period will be included in this paper; complete data sets and contributions by laboratories on other fibers are contained in the summaries of the meetings.[10-14]

Throughout the 1985-89 time period, various laboratories participated in the transient tests. These included the Air Force Weapons Laboratory (AFWL), Boeing Aerospace Corporation, Commissariat à l'Energie Atomique (CEA) and Direction des Recherches, Etudes et Techniques-Etablissement Technique Central de l'Armement-Centre d'Etudes de Gramat (CEG) in France, EG&G Santa Barbara Operations, Fraunhofer-Institut für Naturwissenschaftlich-Technische Trendanalysen (F-INT) in W. Germany, Harry Diamond Laboratories (HDL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Messerschmidt-Bölkow-Blohm GmbH (MBB) in W. Germany, Naval Research Laboratory (NRL), and Royal Military College of Science (RMCS) and Standard Telecommunications and Cables, LTD (STC) in the UK. Except as noted above, the laboratories were in the US.

Experimental Apparatus. Although the experimental setup used to measure transient response varied among the laboratories and in detail from year to year, Fig. 1 shows a typical apparatus. In this configuration, which is used at NRL, a pulsed laser diode is used as the optical source, and two detectors are used to span a broad time regime. The radiation source is a Febetron 706 pulsed electron generator, which irradiates the fiber with a 2 ns pulse of 0.5 MeV electrons. The aluminum filter in the beam attenuates the low energy component and scatters the electrons to give a more uniform dose to the fiber.[15] Dosimetry is accomplished on each shot with the Faraday cup referenced to radiachromic film,[16] and the dose at the fiber core is determined by performing measurements on a stack of film sandwiched between sheets of aluminum foil.[15] One important point is that the measurement of transient fiber response is not trivial and requires wide bandwidth (GHz to DC) detectors and electronics, careful grounding and Faraday cages to eliminate rf interference generated by the irradiation source itself, and precise synchronization of the laser diode optical pulse (unless a cw diode is used), irradiation trigger, and data acquisition. In some cases optical filters are necessary between the fiber and detector to remove Cerenkov radiation and/or luminescence.

To insure uniformity of test conditions among the laboratories, the optical parameters such as wavelength, injection conditions and launched power can be specified in transient measurements. However, in contrast to steady state measurements[3,4] where all laboratories used well-calibrated ^{60}Co sources to irradiate the fibers to an identical total dose, a number of different pulsed sources were used for the transient measurements, as shown in Table II. This gives rise to variations in pulse energy and width, beam size and uniformity, and even total dose among the investigators.

An additional complication in transient measurements is dosimetry. Because of the inherent instability of the machines, there may be significant pulse-to-pulse variation in dose requiring that the dose of each pulse be monitored. Typical dosimeters include a Faraday cup or microcalorimeter for electrons and a PIN diode or LiF TLD for x-rays. In some cases the dosimeters must be calibrated or corrected by either ferric chloride solution or radiachromic film, and this calibration may change when a different output aperture of the source is used to obtain different doses. In the best of circumstances, the accuracy of the pulse dose is probably no better than ± 10%. It is also significant to note that the output of some of these machines is not monoenergetic so that an Al filter is often used (as shown in Fig. 1) to remove the low energy portion of the spectrum and to narrow the radiation pulse.[15] In addition, the low energy of some machines causes non-uniform dose through the fiber diameter so that the dose at the fiber core must be correctly calibrated.

Because of the variations in sources, it is not possible to fully specify the radiation parameters for the interlaboratory comparison of fiber transient response. Rather, it may be possible to determine how the differences in these parameters affect the results of the measurements.

RESULTS AND DISCUSSION

1985 Tests.

The initial round of tests was conducted on 100/140 step index fibers A and B by LANL, LLNL, and MBB/F-INT. The specifications for this test were purposefully vague--the laboratories were to irradiate the fibers using their standard conditions and measure the recovery in the first window spectral region, i.e. near 0.85 μm. As shown in Table III, pulse doses from 44 to 120 krad(Si) were used. [All absorbed doses subsequently reported in this paper are in rad(Si).] In addition, there were differences in the length of fiber exposed, the type of optical source, and injected power; in some cases the power was not reported.

The data plotted in Fig. 2 have been scaled to 45 krad since 3 of the 6 irradiations were performed at that dose. The scaling was by $\propto D$, where D is the dose, since the transient incremental attenuation in pure silica core fibers varies as $\propto D$ in this dose range.[17] The LLNL data, which were obtained spectrally over the wavelength range 0.50 - 0.78 μm with a flash lamp and streak camera, have been extrapolated to 0.84 μm using the induced losses measured at 0.70 μm. A very short length of fiber was exposed by LLNL, so that significant errors will be introduced into the calculation of attenuation (dB/m) if the beam is not uniform over the exposed length of fiber or if the exposed length is not precisely known.

The LLNL and LANL recovery data of both fibers A and B shown in Fig. 2 seem to be in agreement in the < 100 ns range, and the LLNL/LANL data at short times appears consistent with the MBB/F-INT data at longer times. However, the extrapolations that were made in dose and wavelength of the fairly noisy LLNL data significantly weaken the agreement with LANL, and the lack of measurements in the 10^{-7} to 10^{-3} s range connecting the two sets make it difficult to firmly establish a correlation and to determine what factors affect the measurement of transient response.

For the next round of tests it was proposed that irradiations be performed at the same dose levels, that all investigators used the same wavelength sources, and that the temporal range of the data be expanded to provide overlap between the laboratories.

1986 TESTS.

Dosimetry. One of the most significant accomplishments of the 1986 round of tests was an intercomparison of dosimetry undertaken by F-INT and LANL.[11,18] The dosimeter used by F-INT is a microcalorimeter consisting of a 100-200 μm thick by 3 cm diameter Al disk attached to a Cu-constantan thermocouple; the output is read by a precision digital nanovoltmeter interfaced to a computer. LANL (as well as NRL) use a Faraday cup dosimeter calibrated with radiachromic film, which is a solid solution of hexahydroxyethyl aminotriphenylnitrile in thin nylon sheets.[16]

Both types of dosimetry were used on each electron pulse. A number of pulses was accumulated on the film sufficient to increase the optical density to 0.4 above the background absorption, corresponding to a total dose of 530 krad; the calorimeter output was recorded for each pulse.

Six measurement series were completed. Since the film is calibrated in rad(H_2O) and the calorimeter in rad(Al), it was necessary to correct for the difference in electron stopping power for the two materials (1.25 for H_2O relative to Al at the Febetron 705 electron energy of 1.5 MeV). This led to an average film/calorimeter dose ratio of 0.92 with a standard deviation of only 0.02, thus providing a high level of confidence in the dosimetry comparison between the two laboratories.

High Dose Irradiations. Figure 3 shows the agreement obtained among the laboratories for the 10 and 100 krad irradiations of 100/140 silica core fibers A and C. There is excellent continuity from the LANL data at short times to the F-INT/MBB data at longer times for both fiber C (Fig. 3b) and fiber B (data not shown), while there is a slight discrepancy between the laboratories in the data of fiber A, as shown in Fig. 3a. Unfortunately, there is a limited temporal range where data are available from both LANL and F-INT/MBB, but good agreement is suggested. As shown in Table IV, there are a number of differences in the parameters used by the two, including source wavelength and optical power, irradiation pulse width, and energy. Since the dosimetry was intercorrelated, the data of Fig. 3 suggest that none of these are significant within the ranges used.

The incremental loss measured by LLNL on these fibers is slightly higher than that reported by LANL. Since F-INT and LLNL used sources of approximately the same wavelength and since the actual exposure doses of LANL and LLNL were identical, it seems likely that the observed differences between LANL and LLNL are due to the uncertainty in calculating induced loss in short length of fiber exposed in a somewhat nonuniform beam.

The incremental losses reported by CEA in fibers C and B (Fig. 3b) were significantly greater than those measured by LANL, while there is good agreement between the two laboratories on fiber A (Fig. 3a). The origin of these discrepancies is not understood at this time but may be due to the extrapolation of the CEA data from high dose, as mentioned in Table IV.

Also shown in Fig. 3b are data obtained by F-INT/MBB on fiber C at two optical power levels to investigate light-induced annealing of the transient attenuation. Photobleaching appears to become effective only at times longer than 10^{-4} to 10^{-5} s for the modest optical powers used here.[18] Thus, it does not seem necessary to strictly specify the optical power to obtain consistent transient loss measurements in these fibers at shorter times.

Low Dose Irradiations. Since low dose pulsed exposures are of interest for some applications, it was suggested that a comparison of measured incremental losses be made at 500 rad. As shown in Table IV, none of the laboratories irradiated the fibers with exactly this dose, but the doses used by CEG, HDL, and STC were sufficiently close to 500 rad that extrapolations to 500 rad were performed; at these low doses, linear scaling is valid.[17] The 500 rad data for MBB/F-INT and LANL were interpolated from induced loss vs. dose plots, which were highly nonlinear, and there is significant uncertainty in the LANL data.

As shown in Fig. 4, there is good agreement among all the laboratories except for the data of fibers A and B reported by MBB/F-INT. Since the F-INT data were obtained at 2 μW, it might be expected that they would be intermediate between the STC data taken at low and high power levels. It seems reasonable to attribute the discrepancy to the extrapolation used to obtain the MBB/F-INT data. Interestingly, there was excellent agreement at 500 rad between CEG and MBB/F-INT in fiber C (data not shown).

The onset of photobleaching is clearly seen in both fibers A and B by comparing the low and high power STC data and the CEG data taken at 800 μW. Note that there is some indication in Fig. 4 that the initiation time for photobleaching decreases with increasing optical power. In addition, comparison of Figs. 3 and 4 shows that the initiation time occurs at later times after 500 rad pulses vs. 10 and 100 krad irradiations.

The 1986 tests established that the transient recoveries measured by different laboratories in silica core fibers in the first transmission window near 0.85 μm were in good agreement. The critical parameters for interlaboratory agreement included the dosimetry and the optical power for times greater than 10^{-5} to 10^{-4} s for 10 and 100 krad irradiations and greater than 10^{-3} to 10^{-2} s for 500 rad irradiations, but the data seemed relatively insensitive to irradiation pulse length and energy (within the range of machines shown in Table II) and whether the irradiation was pulsed electron or flash x-ray. Some discrepancies among the laboratories were observed, and since the range of optical source wavelengths was fairly broad, it was decided that for the next round of tests all should attempt to use sources with wavelengths as near to 0.85 μm as possible.

1987 TESTS

As shown in Table V, 4 laboratories participated in the 1987 transient tests, and for the first time the measurements were made with a relatively consistent set of test parameters. The wavelengths of the optical sources varied by no more than 0.02 μm for the first window and 0.05 μm for the second window, and the data were obtained at or near the prescribed doses of 10 and 100 krad.

Figure 5 contains a summary of the transient data obtained on the fiber D at 0.85 and 1.3 μm. The NRL data were scaled to 10 krad from the higher doses (Table IV) by $\propto D$. As shown in Fig. 5a, excellent agreement was obtained between the LANL and NRL 10 krad data for the fiber D measured in the first window, and the LANL and F-INT/MBB 100 krad data also appear to be consistent.

The larger incremental loss reported for fiber D by F-INT/MBB than NRL at 0.85 μm and 10 krad (Fig. 5a) is similar to the offset between the F-INT/MBB and LANL fiber A data of the 1986 tests shown in Fig. 3a. The offset for this fiber is greater in the 1987 data than in 1986, i.e. 2x vs 1.5 x, perhaps due to the longer sample length used by F-INT/MBB in 1987, which would reduce the energy available for photobleaching.[8,9] (Note that the offset occurs for $t \geq 10^{-4}$ sec, which is the temporal region where photobleaching becomes effective, as demonstrated in Fig. 3b. It is unfortunate that there was not additional overlap of data at shorter times to verify this assumption.) In addition, although all fibers were supplied from a common preform, there could be some differences in radiation sensitivity among the lengths provided to the laboratories. It should be mentioned that excellent agreement was obtained between MBB/F-INT and NRL for fiber B exposed to 10 krad over the 10^{-8} to 10^{2} s range (data not shown).

As shown in Fig. 5a, there is also a significant difference in the 500 rad radiation-induced loss measured by CEG data at high optical power and F-INT/MBB at 1 μW, although the effect of photobleaching is evident in the divergence of the curves near 10^{-3} s. The comparison of the data of the two laboratories is complicated by the fact that the F-INT/MBB data were obtained by interpolation of the loss vs. dose data between 24 and 2840 rad.

An additional set of measurements were made in the second wavelength window of 1.3 μm by 3 laboratories, and these are shown in Fig. 5b. With the unfortunate lack of data in the 10^{-7} to 10^{-4} s time range for the 100 and 100 krad irradiations, it is difficult to ascertain the degree of correlation between laboratories at this wavelength. However, the data do not indicate any severe discrepancies at these doses. In contrast, there is once again a significant difference between the CEG and F-INT/MBB data at 500 rad, which could arise from a number of factors, as described above.

Thus, good interlaboratory agreement was generally obtained in the 1987 tests, and the factors such as optical power, which seems to have a significant influence on the measured transient recovery of some types of step index silica core fibers, were identified.

1988 TESTS

With the commercial emphasis on telecommunications and sensor fibers, the 1988 round of tests was directed towards graded index and single mode waveguides. The test plan was similar to that used previously, i.e. the wavelengths of the optical sources should be 0.85 and 1.3 μm, and the fibers should be irradiated at 500, 10^4 and 10^5 rad. Mode stripping was used prior to the detector by some laboratories, and the optical power in the fiber was left to the individual experimenter.

Graded Index Fibers. The graded index fibers chosen for the test were developed for tactical radiation hardness over an extended temperature range. It was anticipated that the transient radiation response of these fibers would be significantly larger than that measured for the silica core fibers based on previous measurements of the transient response of similar Ge-doped silica core fibers.[6,7] In addition, significant photobleaching has not been observed in Ge-doped silica core fibers under steady state radiation exposure and seemed unlikely in these experiments.[9]

The transient response data for fiber E are shown in Fig. 6. It is apparent that in some instances there is excellent agreement between different laboratories, e.g. in the 10 krad data between Boeing, F-INT, and NRL and in the fiber F between CEG and F-INT at 500 rad and F-INT and AFWL at 10 krad (data not shown). However, in general the interlaboratory agreement is not as good as had been obtained in the step index silica core fibers. At 500 rad the CEG data is 2 times greater that of F-INT, while at 100 krad the CEA data for both fibers E and F is almost 3 times that of F-INT. However, the data generally agree within a factor of 2 in all other cases.

F-INT also provided data taken at 1 and 10 μW to investigate possible dependence of measured induced loss in doped silica core fibers on optical power, and the Boeing data were taken with two different power levels, i.e. 0.1 μW for times < 10^{-4} s and 16 μW at longer times. It is apparent from Fig. 6 that there is little, if any, photobleaching, and thus optical power need not be tightly specified to obtain consistent transient results in these fibers.

The origin of the discrepancies shown in Fig. 6 is not clear. The F-INT data of both the graded index fibers establish that the induced loss scales linearly with dose between 500 and 10^5 rad, the discrepancy between the CEG and F-INT data at 500 rad imply dosimetry errors of a factor of 2. However, a more reasonable explanation is the fact that CEG used a flash X-ray source, while F-INT irradiated the fiber with electrons. The differences between the CEA and F-INT data at 100 krad may be due to dosimetry, or to the extrapolation of the CEA data from 350 krad.

Single Mode Fibers. The single mode fibers chosen for this study had pure silica cores since multimode fibers with undoped cores have been shown to have much less transient radiation response than typical doped silica core waveguides.[6,7] The two fibers were designed to have cutoffs appropriate for single mode operation at 0.85 and 1.3 μm.

The data reported by the 5 laboratories who measured the transient induced attenuation in these fibers are shown in Fig. 7. With the exception of the NRL data, good agreement was obtained for the 0.85 μm fiber G, as shown in Fig. 7a and b. The different curvatures in the 500 rad data can be reasonably attributed to photobleaching since EG&G, CEG, and F-INT used optical power levels of 7 mW, 25 μW and 1 μW, respectively, and the offset between the F-INT data and the CEA and EG&G measurements may be due to the factors discussed above. Likewise, the slightly lower attenuation measured by LANL than F-INT at both 10 and 100 krad (Figs. 7a and b) could be attributed to the 300 μW power used by the former.

The 10 krad transient response reported by NRL for this fiber is greater than that measured by F-INT and LANL, but variance in dose does not appear to be a reasonable explanation. Since the loss vs. dose behavior is highly saturated, as shown in Figs. 7a and b, doses in excess of 200 krad would have been required to obtain incremental attenuations equivalent to that reported by NRL for a 10 krad exposure, and errors of this magnitude are not likely. One possible origin of the discrepancy in the 10 krad data is in the different sample geometry used by NRL vis a vis the other laboratories (Table VI), and this effect is currently under investigation. A second possibility is length-to-length variations in the fiber radiation sensitivity. Otherwise, the differences in measured induced loss are not understood at this time.

The data of the 1.3 μm single mode fiber H are shown in Figs. 7b-d. In general, there is good agreement among the laboratories at all doses with the exception of the 10 krad NRL data, which are a factor of 2.1 times greater than F-INT; the origin of this discrepancy remains unresolved. The 500 rad CEG and F-INT data in Fig. 7c clearly show the dependence on the significant variations in optical power among the data sets, but the fact that the F-INT data at 10 and 100 krad in Figs. 7d and b are 1.6 and 1.3 times greater than that of LANL at 10^{-6} s cannot be attributed to photobleaching although LANL used 220 μW for their measurements vis a vis the 1 and 10 μW used by F-INT. However, the data taken by the laboratories on the 1.3 μm single mode fiber establish that photobleaching is a concern at $t > 10^{-4}$ s at 1.3 μm as well as at 0.85 μm, so that the optical power level must be carefully specified to obtain consistent measurements of the transient radiation response of silica core single mode fibers. Note that there does not appear to be any dependence of the measured transient induced loss on the nature, energy, or pulse length (for times > pulse length) of the radiation source.

1989 Tests

The 1989 round of tests was again directed to 0.85 and 1.3 μm single mode fibers because of their technological importance for telecommunications and sensor applications and because of the significant discrepancies in measured radiation-induced attenuation reported in 1988 for single mode fibers (see Fig. 7). Fibers I and J, which were obtained from a different vendor from fibers G and H, had better intrinsic optical properties than G and H, and it was hoped that their radiation response might be more consistent.

The results of the 1989 tests shown in Fig. 8 indicate a remarkable improvement in interlaboratory agreement. In all cases there was significant temporal overlap, and for the first time 6 laboratories reported measurements on a fiber (i.e. Fiber I measured at 10 krad). The experimental parameters are listed in Table VII.

The data of the 0.85 μm fiber I at 10 krad shown in Fig. 8a are typical of the good accord among all the contributors. The slight discrepancy between AFWL, Boeing and F-INT at > 10^{-2} s cannot be attributed to photobleaching since all three laboratories used an optical power of 1 μW. There is agreement within a factor of 2 among all 6 laboratories for times < 10^{-2} sec.

Likewise, good agreement was obtained among the laboratories that measured Fiber J at 1.3 μm following a 10 krad exposure, as shown in Fig. 8b. The divergence between the LANL/NRL and Boeing/F-INT data sets at long times is reasonably attributed to photobleaching since the former used >200 μW vs. 1 μW optical power; the origin of the offset at shorter times is not understood. There is a significant discrepancy between the CEG data and that of the other laboratories, perhaps due to the fact that the CEG data were linearly scaled from 8.5 krad. (Note that scaling by $\sqrt{D}$ would only slightly improve the agreement.) Nevertheless, agreement within a factor of 2 has been obtained among all the laboratories in the region where photobleaching is not a factor. Excellent overlap was also obtained between F-INT and LANL on both fibers I and J following a 100 krad pulse, as shown in Fig. 8c.

The data reported following a 500 rad exposure are shown in Figs. 8d and 8e, and once again, the sets from the different laboratories are in concordance. The larger loss reported by RMCS vs. F-INT at long times can be attributed to a lack of photobleaching since very low power and long fiber length was used by the former (Table VII). The discrepancy in the NRL data may be due to photobleaching or extrapolation of the dosimetry from higher dose.

The excellent agreement obtained among the laboratories in the 1989 round of tests was achieved primarily through stricter adherence to suggested test parameters and improved dosimetry. For example, for the 10 krad irradiations NRL recalibrated their Faraday cup voltage to radiachromic film and determined the dose absorbed at the fiber core by irradiating a stack of alternate layers of film and Al foil.[15] The film calibration was performed in their ^{60}Co source by placing the film in a plexiglas cylinder to remove low energy electrons generated by ionization of the air by the γ-rays.

SUMMARY

Interlaboratory comparisons of the transient radiation response of optical fiber waveguides have shown that the principle determinants of consistent results are the total dose to which the fiber is exposed and the wavelength of the optical source. The dosimetry of the radiation pulse is non-trivial, and the best agreements have been obtained between two laboratories that cross-correlated their techniques and in 1989 when great care was taken by all contributing laboratories. For consistency, it is suggested that all laboratories reference their dosimetry to the same technique, e.g. microcalorimetry or radiachromic film. The optical power in the fiber has been found to be critical at times > 10^{-5} s in undoped silica core step index and single mode fibers at both 0.85 and 1.3 μm, but not in Ge-doped silica core graded index fibers at 1.3 μm. Some discrepancies between laboratories have been observed, but it appears possible to obtain consistent results by careful specification of the experimental parameters discussed above.

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FIGURE CAPTIONS

1. An example of a typical experimental apparatus for measuring the transient attenuation induced in optical fibers by pulsed radiation exposure.

2. Transient radiation-induced absorption near 0.85 μm reported by 3 laboratories in 1985 on 100/140 silica core fibers A and B. The parameters used by the laboratories are shown in Table III.

3. Transient radiation-induced absorption near 0.85 μm reported by 3-4 laboratories in 1986 on fibers (a) A and (b) C following exposures of 10 and 100 krad. The parameters used by the laboratories are shown in Table IV.

4. Transient radiation-induced absorption near 0.85 μm reported by 5 laboratories in 1986 on fibers (a) B and (b) A following an exposure of 500 rad. The parameters used by the laboratories are shown in Table IV.

5. Transient radiation-induced absorption reported by 3-4 laboratories in 1987 on fiber D following exposures of 0.5, 10 and 100 krad. Measurements reported in (a) were made at 0.85 μm; those in (b) were made at 1.3 μm. The parameters used by the laboratories are shown in Table IV.

6. Transient radiation-induced absorption reported by 5 laboratories in 1988 on radiation-hardened graded index fiber E following exposures of 0.5, 10 and 100 krad. Measurements were made at 1.3 μm. The parameters used by the laboratories are shown in Table V.

7. Transient radiation-induced absorption reported by 2-5 laboratories in 1988 on silica core single mode fibers G and H at (a,b) 0.85 μm and (c,d) 1.3 μm following exposures of 0.5, 10 and 100 krad. The parameters used by the laboratories are shown in Table VI.

8. Transient radiation-induced absorption reported by 2-6 laboratories in 1989 on silica core single mode fibers I and J at (a,c,d) 0.85 μm and

(b,c,e) 1.3 μm following exposures of 0.5, 10 and 100 krad. The parameters used by the laboratories are shown in Table VII. Note that the CEG data at 10 krad are a composite of two sets taken at different power levels (see Table VII).

TABLE I

Fibers Studied During 1985-1989

Fiber	Type	Core
A	100/140 SI	Low-OH silica
B,C	100/140 SI	High-OH silica pulled from same preform type
D	100/140 SI	Low-OH silica, similar to fiber A with improved 1.3 μm transmission
E,F	50/125 GI	Ge-doped silica
G,I	0.85 μm SM	Low-OH silica, same core material as multimode fibers A and D
H,J	1.3 μm SM	Low-OH silica, same core material as multimode fibers A and D

TABLE II

Pulse Irradiation Sources Used by the Laboratories.

Machine	Irrad.	E (MeV)	t_p (ns)	Dosimetry	Laboratory
AFWL FXR	X-ray	0.2-1.3	50	1	AFWL (1988)
Boeing FX 75	X-ray	2-3	35	1	Boeing
CEG FXR	X-ray	0.045	< 50	1*	CEG (pre 1989)
CEG FXR	X-ray	6	40	7	CEG (1989)
EG&G Linac	e^-	16	10	5	EG&G
EROS	X-ray	0.1-4	70	1	STC/RMCS
Febetron 705	e^-	1.5	30	3	F-INT (0.5-100 krad)
	Brem.		30	1	F-INT (5-100 rad)
Febetron 706	e^-	0.5	1.5-2	4,5*	LANL, NRL
				5	LLNL
Febetron 707**	e^-	1.8	10		CEA (100 krad)
HDL FXR	X-ray	4.2	24	2	HDL
Thalie	X-ray	8	50	1,6	CEA (10 krad)
WSMR Linac	e^-	25	9000	2,3	AFWL (1989)

---

*Dose calculated in fiber core

**Modified to provide monoenergetic beam

Dosimetry: 1-LiF TLD; 2-CaF_2:Mn TLD; 3-Microcalorimeter; 4-Faraday cup; 5-Radiachromic film; 6-Alumina; 7-Radiophotoluminescence

TABLE III

Optical Source Wavelength and Injected Power, Sample Coil Diameter and Irradiated Length, and Pulse Dose used in the 1985 Transient Tests

					Dose (krad)	
Laboratory	λ (μm)	P (μW)	d (cm)	L (m)	Fiber A	Fiber B
MBB/F-INT	0.84	0.2	5	1-10	45	45
LANL	0.84	300	3(1)	0.5-1(1)	65	44
LLNL	(2)	10-100	2.5	0.1	75	120

---

(1) Fiber coiled in a spiral 3.0 cm inner and 3.5 cm outer diameter; 0.5 m length used for < 150 ns, 1.0 m for data to 5 μs.

(2) Data obtained spectrally from a streak camera over 0.5 - 0.75 μm range

TABLE IV

Optical Source Wavelength and Injected Power, Sample Coil Diameter and Irradiated Length, and Pulse Dose used in the 1986 Transient Tests

Laboratory	λ (μm)	P (μW)	d (cm)	L (m)	Dose (krad)
CEA	0.82	1000			10/100
CEG	0.85	800	12-30	20	0.63
MBB/F-INT	0.805	0.2(1)	5	1	10/100
	0.805/0.84	0.2(1)	5-8	10	3
HDL	0.85	1000	10	3	0.36-0.38
LANL	0.84	300	3.0-3.5	0.5-1	10/100
					0.8 (Fiber B)
					2.3 (Fiber A)
LLNL	0.812(2)	1000	2.5	0.25	120-130
STC	0.85	(3)	10	30	0.36-0.51

---

(1) Data also obtained at 2.0 μW on fiber C

(2) Data obtained spectrally from a streak camera with a LD source at 0.812 μm

(3) Data taken at 0.046 and 360 μw on fiber A and 0.043 and 0.144 μW on fiber B

TABLE V

Optical Source Wavelength and Injected Power, Sample Coil Diameter and Irradiated Length, and Pulse Dose used in the 1987 Transient Tests

Laboratory	λ (μm)	P (μW)	d (cm)	L (m)	Dose (krad)
CEG	0.85	800	12-30	20	0.63
F-INT/MBB	0.86	1.0	5	10	10/100(1)
	1.31	1.0	5	10	10/100(1)
LANL	0.84	600	1.5-3.5	0.5-1.2	20/100
	1.28	370	1.5-3.5	0.5-1.2	20/100
NRL	0.85	100	(2)	1	12

---

(1) Data also taken at 24 and 2840 rad

(2) Fiber deployed in a butterfly pattern with straight section through beam

TABLE VI

Optical Source Wavelength and Injected Power, Sample Coil Diameter and Irradiated Length, and Pulse Dose used in 1988 for Measuring the Transient Response of Graded Index (g) or Single Mode (s) Fibers

Laboratory	λ (μm)	P (μW)	d (cm)	L (m)	Dose (krad)	Fiber
AFWL	1.3	1.5	0.8-2	5	3.8	g
Boeing	1.3	(1)	5	2	7.6	g
CEA	1.3	1,000			350	g
CEG	0.85	800	12-30	10	0.63	s
	1.3	175-230	12-30	10	0.63	g
		220/730	12-30	10	0.63	s
EG&G	0.85	7,000	1.5	2	1	s
F-INT	0.84	1/10	5	10	0.5/10/100	g,s
	1.31	1/10	5	10	0.5/10/100	g,s
LANL	0.84	300	1.5-3.5	0.5-1.2	10/60	s
	1.28	220	1.5-3.5	0.5-1.2	10/60	s
NRL	0.85	100	(2)	1	10.7	s
	1.3	13-20	(2)	1	10.7	g
		20	(2)	1	14	s

---

(1) 0.1 μW for < 4 s; 16 μW for > 4 s

(2) Fiber deployed in a butterfly pattern with straight section through beam

TABLE VII

Optical Source Wavelength and Injected Power, Sample Coil Diameter and Irradiated Length, and Pulse Dose used in 1989 for Measuring the Transient Response of Single Mode Fibers I and J

Laboratory	λ (μm)	P (μW)	d (cm)	L (m)	Dose (krad)
AFWL	0.85	4.5	4.7	10	9.7
Boeing	0.85/1.3	1(1)	5	2	0.5/6.8
CEG	0.85	1/10(2)	12-30	10/1	0.5/8.5
	1.3	1/15(3)	12-30	10/1	0.5/8.5
F-INT	0.84	1(1)	5-10	15/1.3/0.4	0.5/10/100
	1.31	1(1)	5-10	15/2/1.7	0.5/10/100
LANL	0.83	300	2.5-3.2	0.4-0.9	10/100
	1.29	230	2.5-3.2	0.8-1.4	10/100
NRL	0.85/1.3	200	(4)	1	0.5/10
RMCS	0.82/1.3	0.004/0.1	22	160	0.5

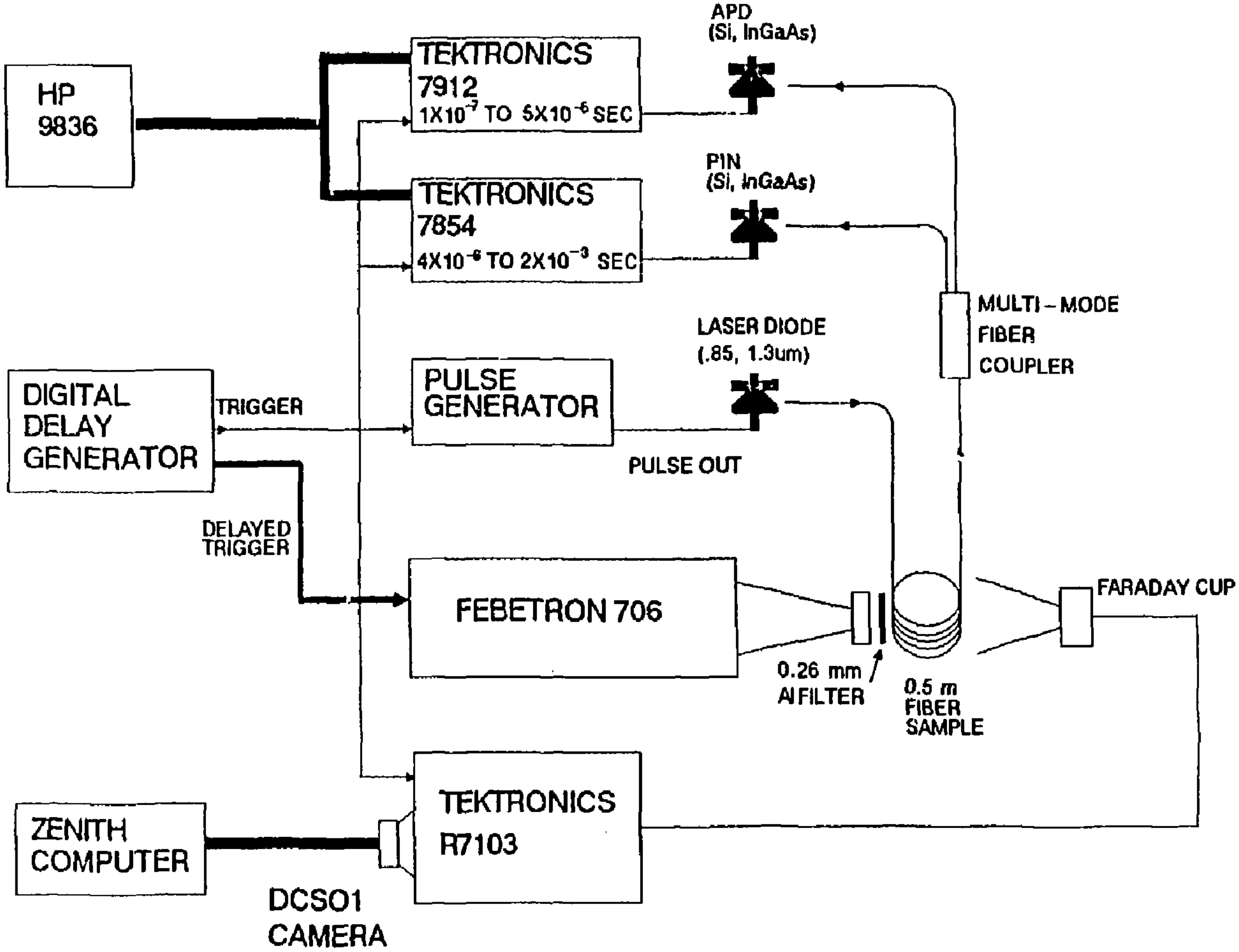
---

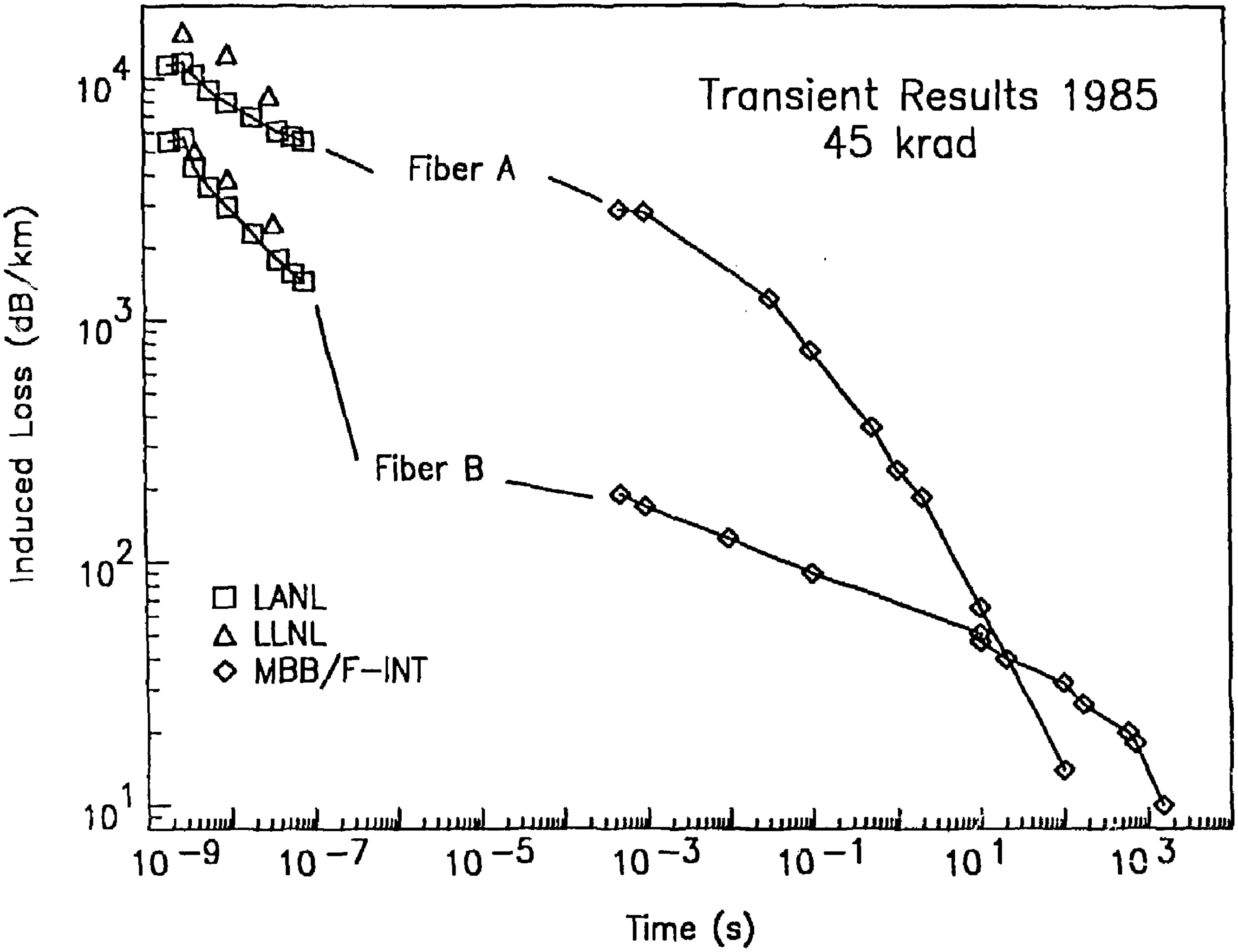
(1) Data also provided at 10 and 30 μW (0.84 μm) and 10 and 200 μW (1.31 μm)

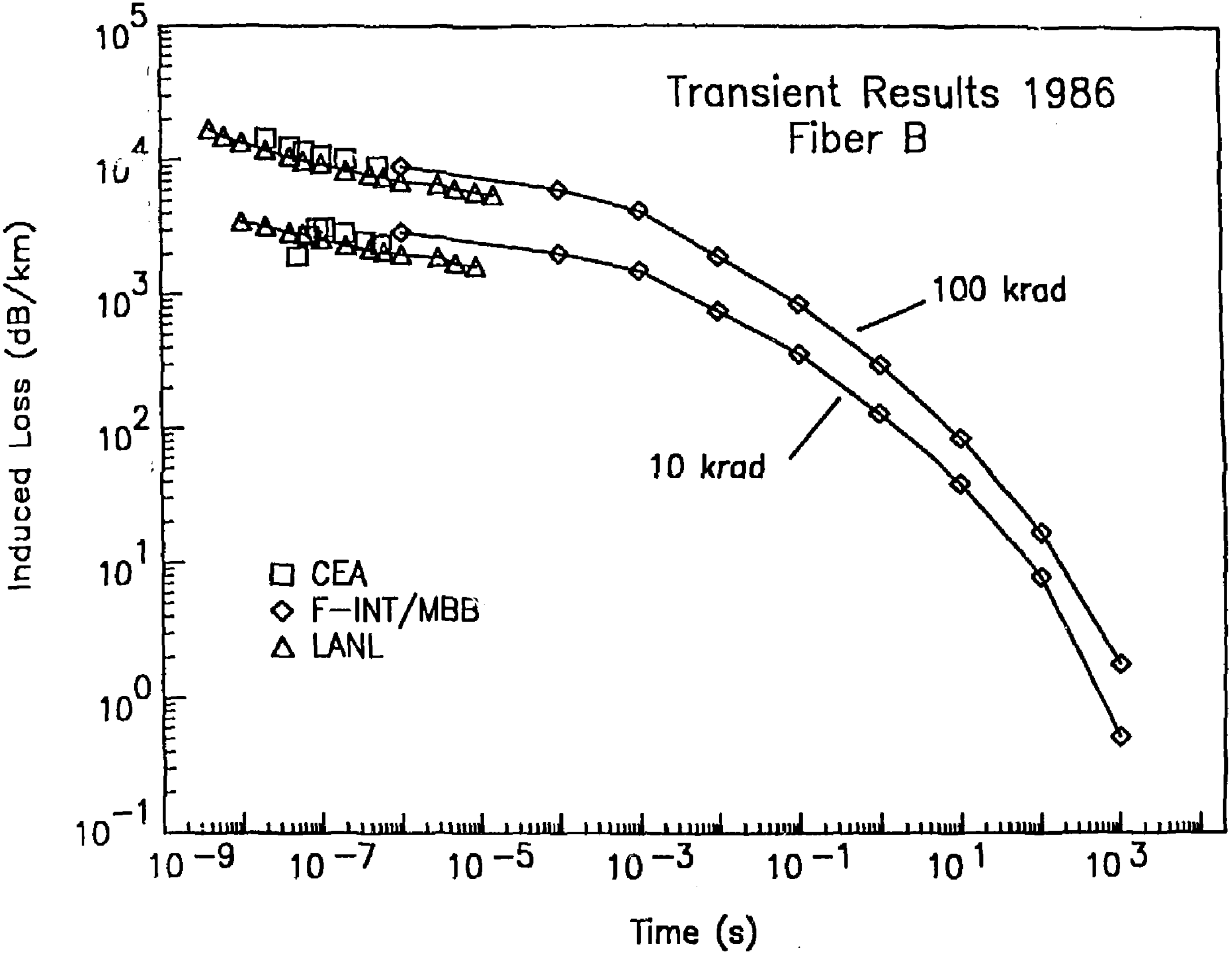
(2) 500 rad data at 10 μW; 10 krad data at 10 μW for < 0.001 s, 1 μW for ≥ 0.001 s

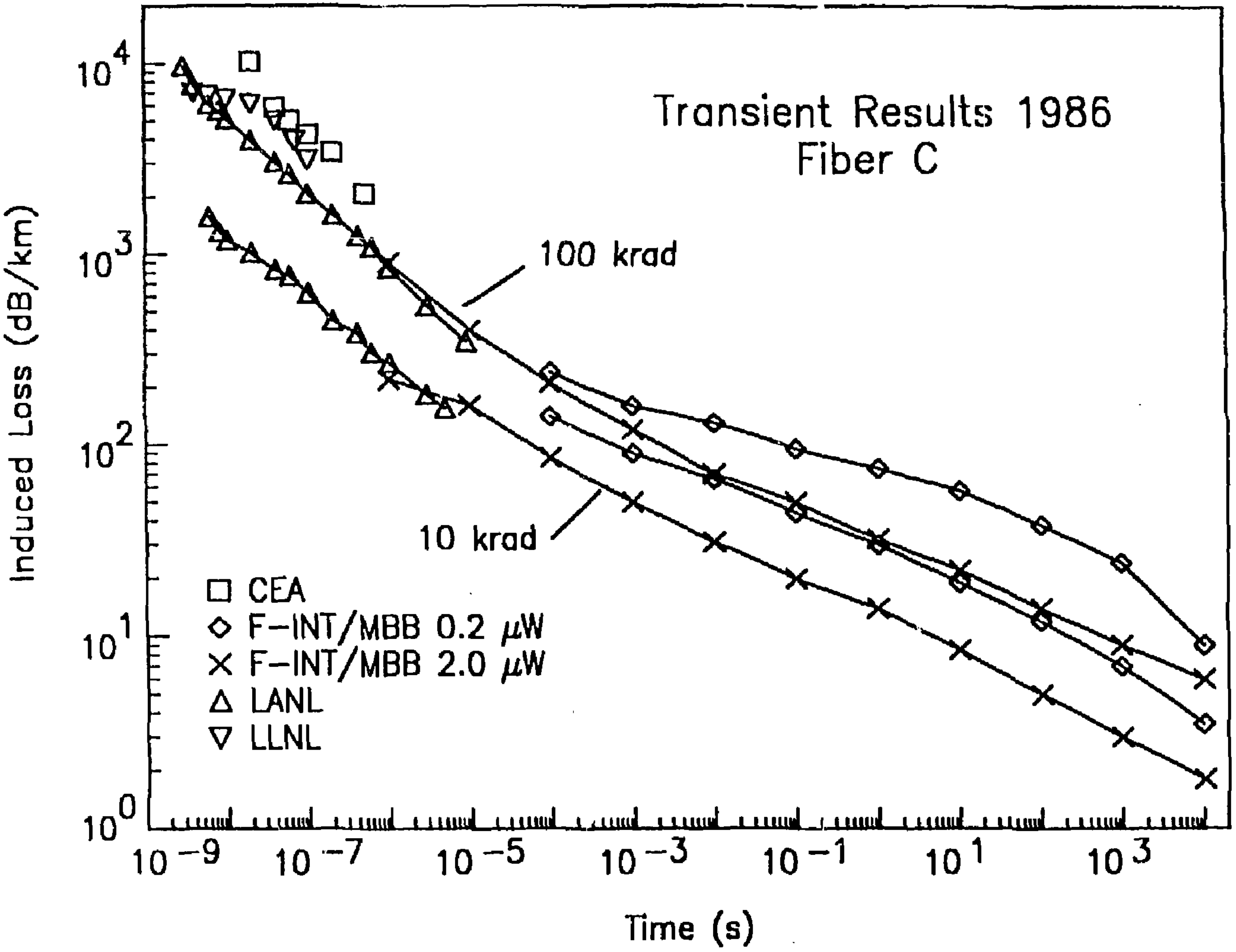
(3) 500 rad data at 15 μW for < 0.01 s, 1 μW for ≥ 0.01 s; 10 krad data at 10 μW

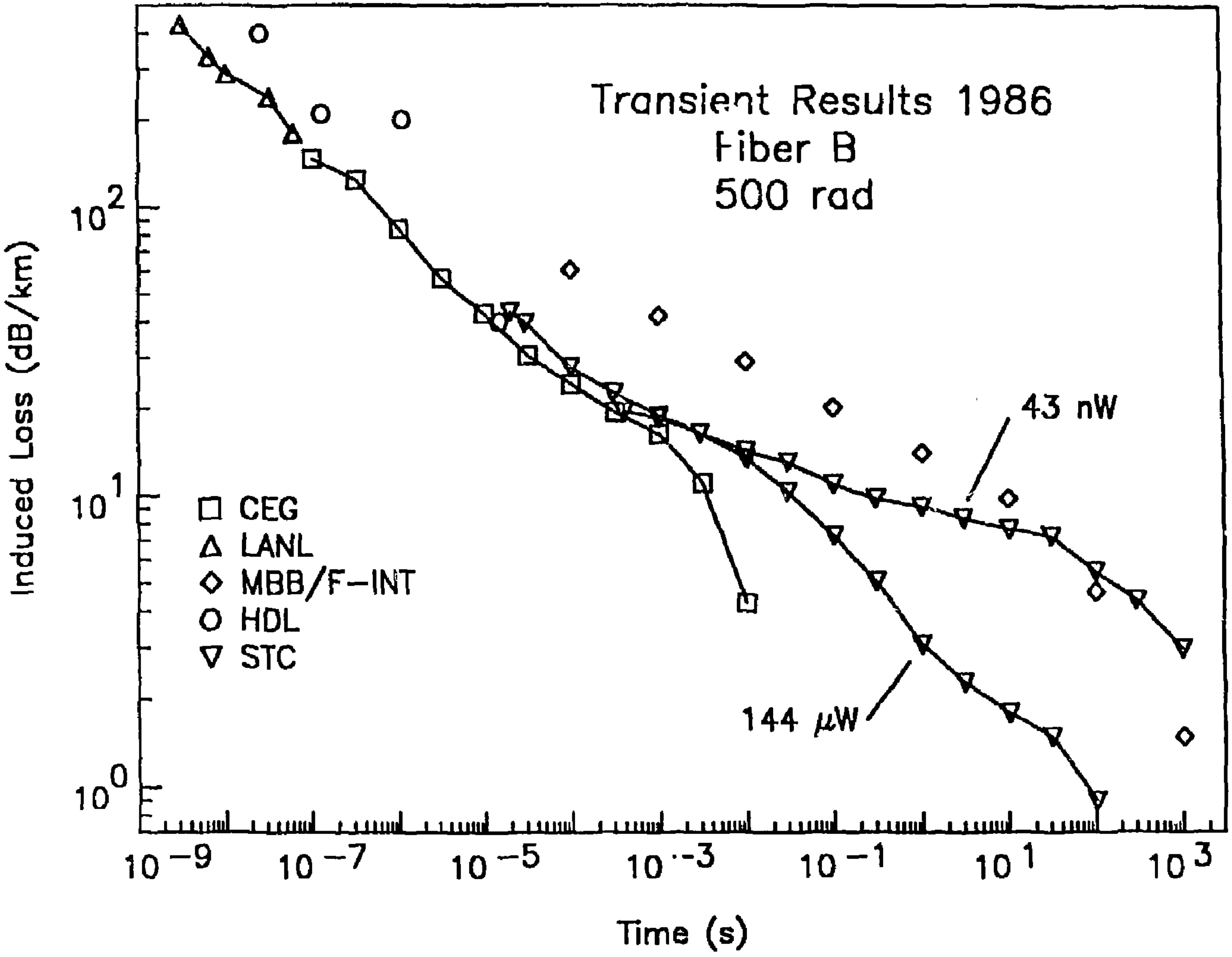
(4) Fiber deployed in a butterfly pattern with straight section through beam


HP 9836
TEKTRONICS 7912
1X10⁻⁷ TO 5X10⁻⁶ SEC
TEKTRONICS 7854
4X10⁻⁶ TO 2X10⁻³ SEC
APD (Si, InGaAs)
PIN (Si, InGaAs)
MULTI-MODE FIBER COUPLER
LASER DIODE (.85, 1.3um)
DIGITAL DELAY GENERATOR
TRIGGER
PULSE GENERATOR
PULSE OUT
DELAYED TRIGGER
FEBETRON 706
0.26 mm Al FILTER
0.5 m FIBER SAMPLE
FARADAY CUP
ZENITH COMPUTER
DCSO1 CAMERA
TEKTRONICS R7103

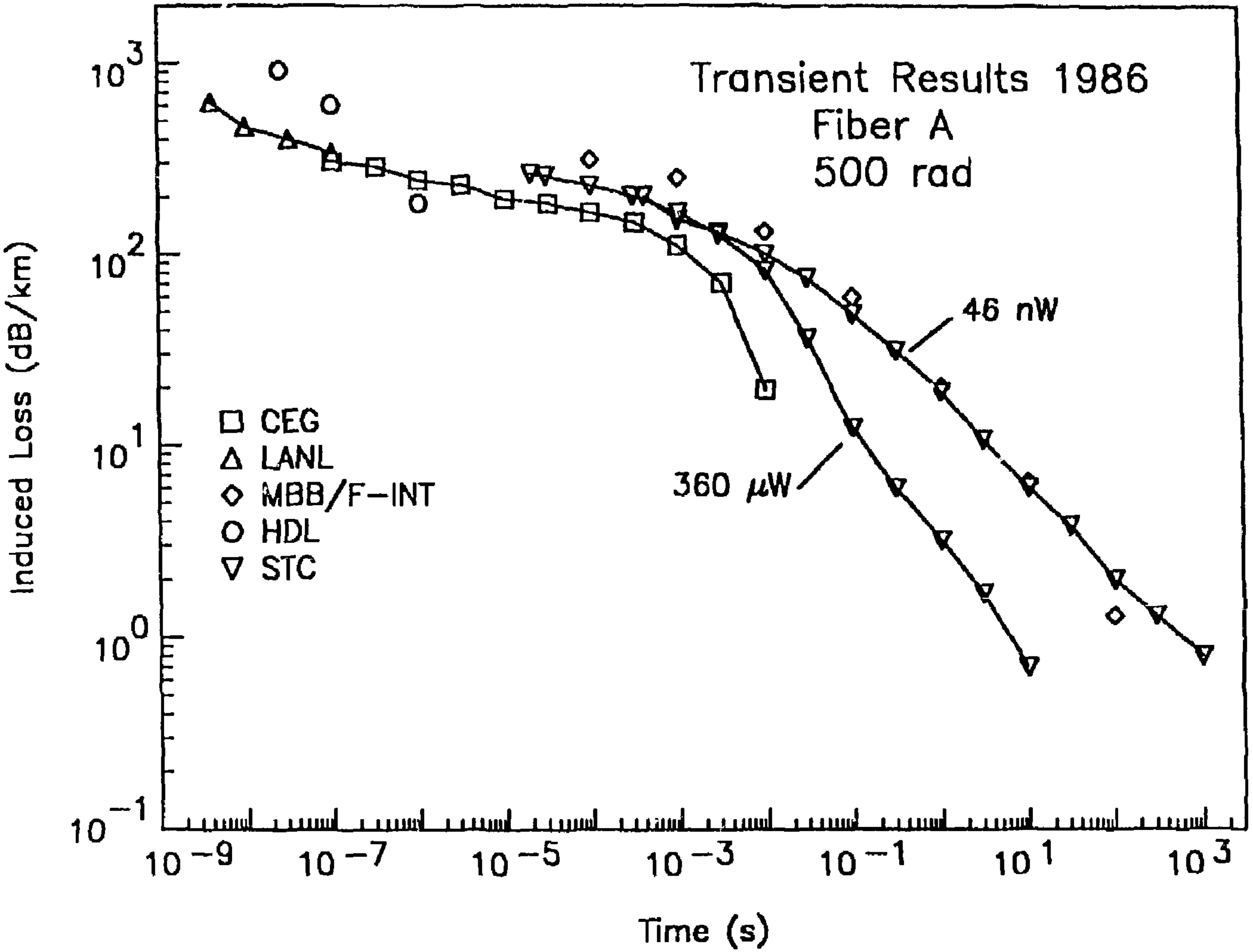

Transient Results 1985
45 krad
Fiber A
Fiber B
Induced Loss (dB/km)
10^4
10^3
10^2
10^1
LANL
LLNL
MBB/F-INT
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^1
10^3
Time (s)


Transient Results 1986
Fiber B
100 krad
10 krad
□ CEA
◇ F-INT/MBB
△ LANL
Induced Loss (dB/km)
Time (s)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^1
10^3

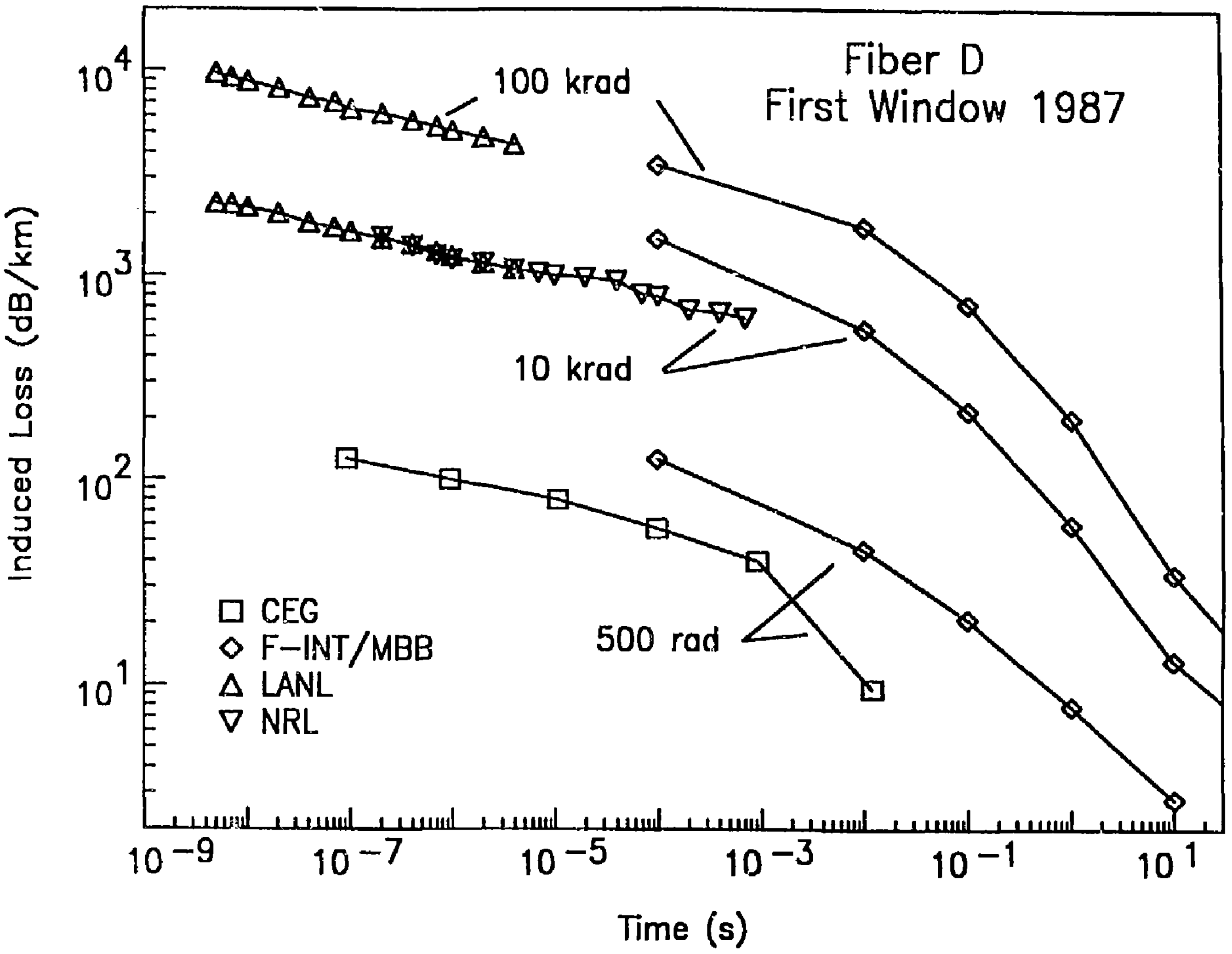

Transient Results 1986
Fiber C
100 krad
10 krad
Induced Loss (dB/km)
Time (s)
10^0
10^1
10^2
10^3
10^4
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^1
10^3
□ CEA
◇ F-INT/MBB 0.2 μW
× F-INT/MBB 2.0 μW
△ LANL
▽ LLNL

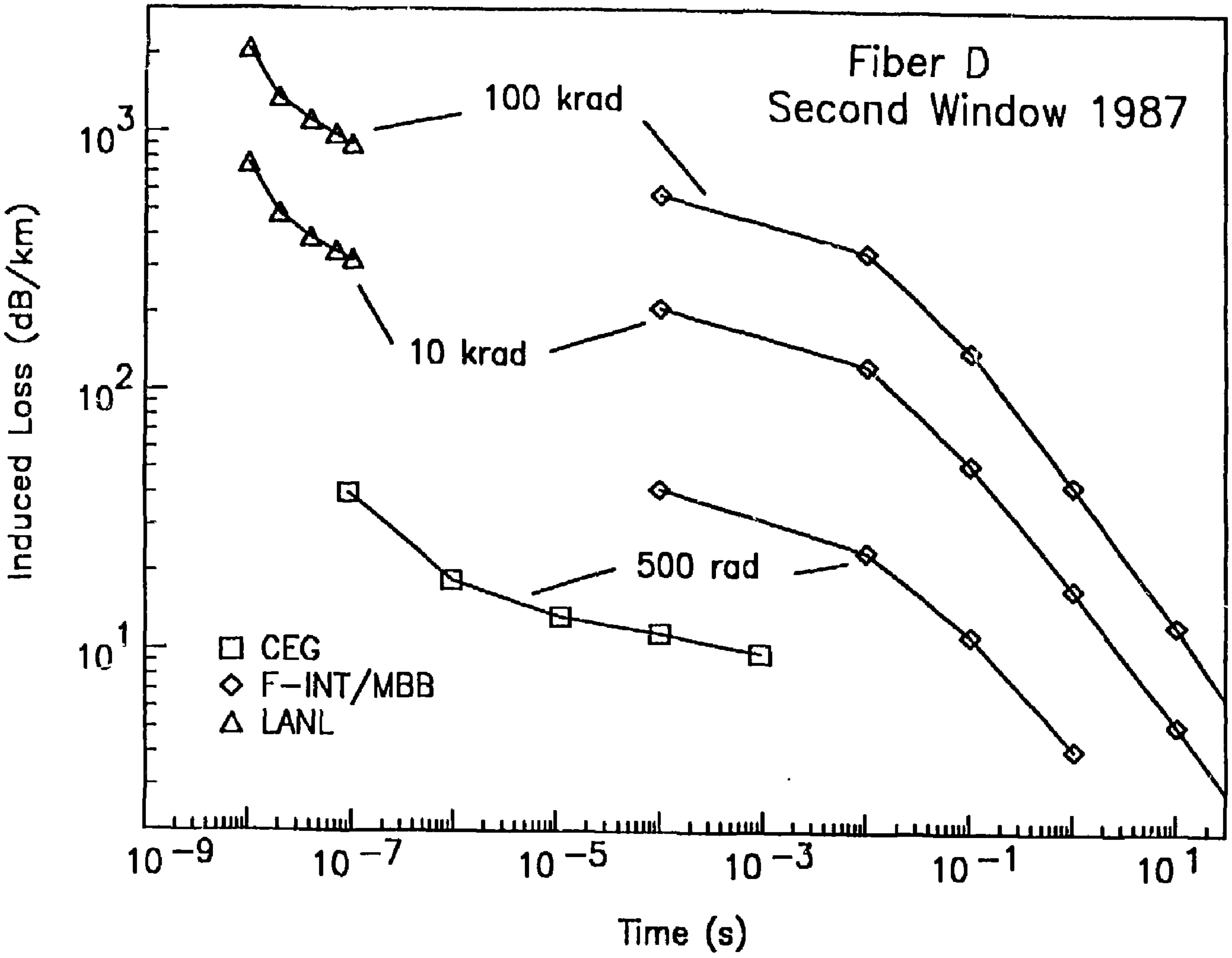

Transient Results 1986
Fiber B
500 rad
43 nW
144 μW
□ CEG
△ LANL
◇ MBB/F-INT
○ HDL
▽ STC
Induced Loss (dB/km)
10^0
10^1
10^2
Time (s)
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}

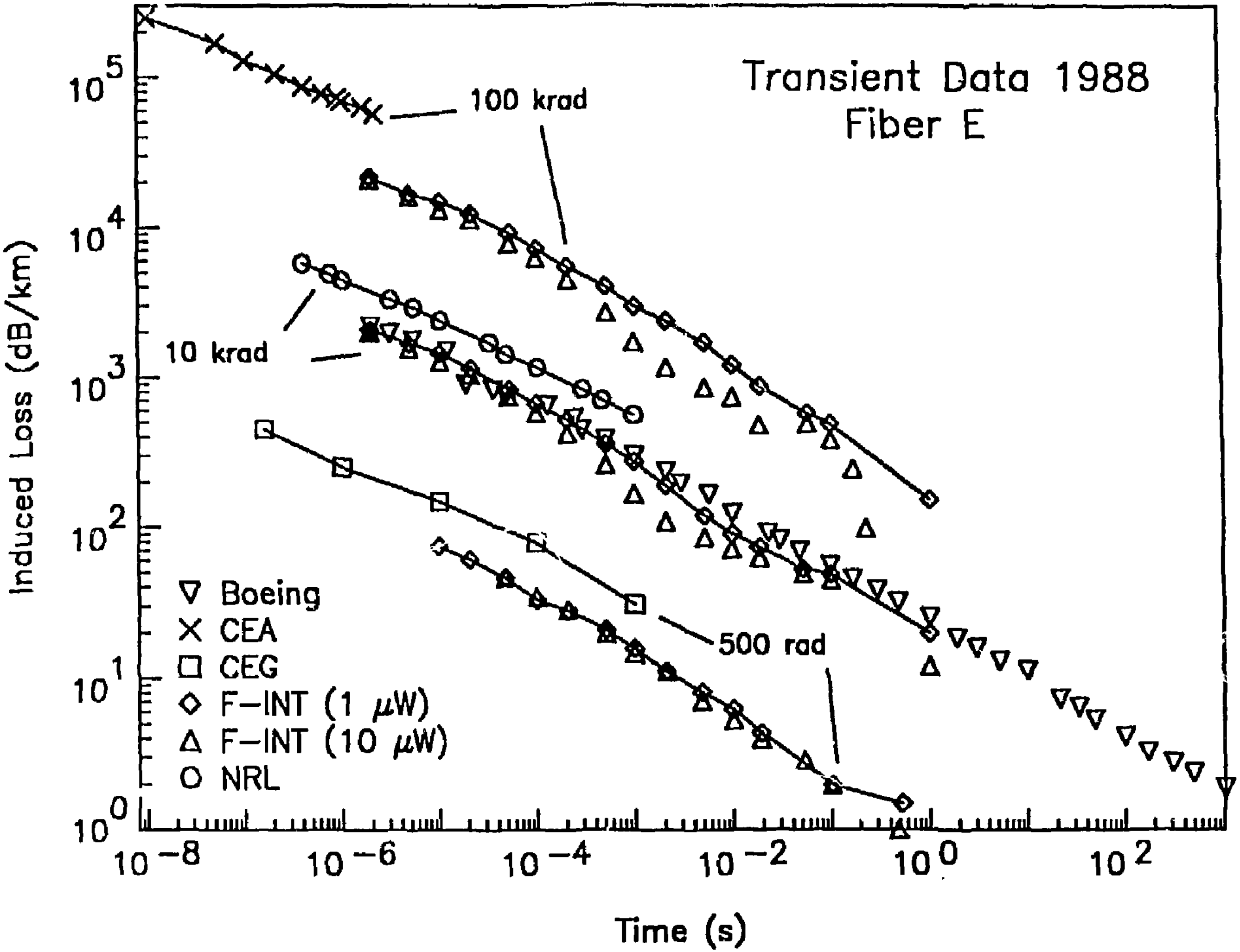
9a

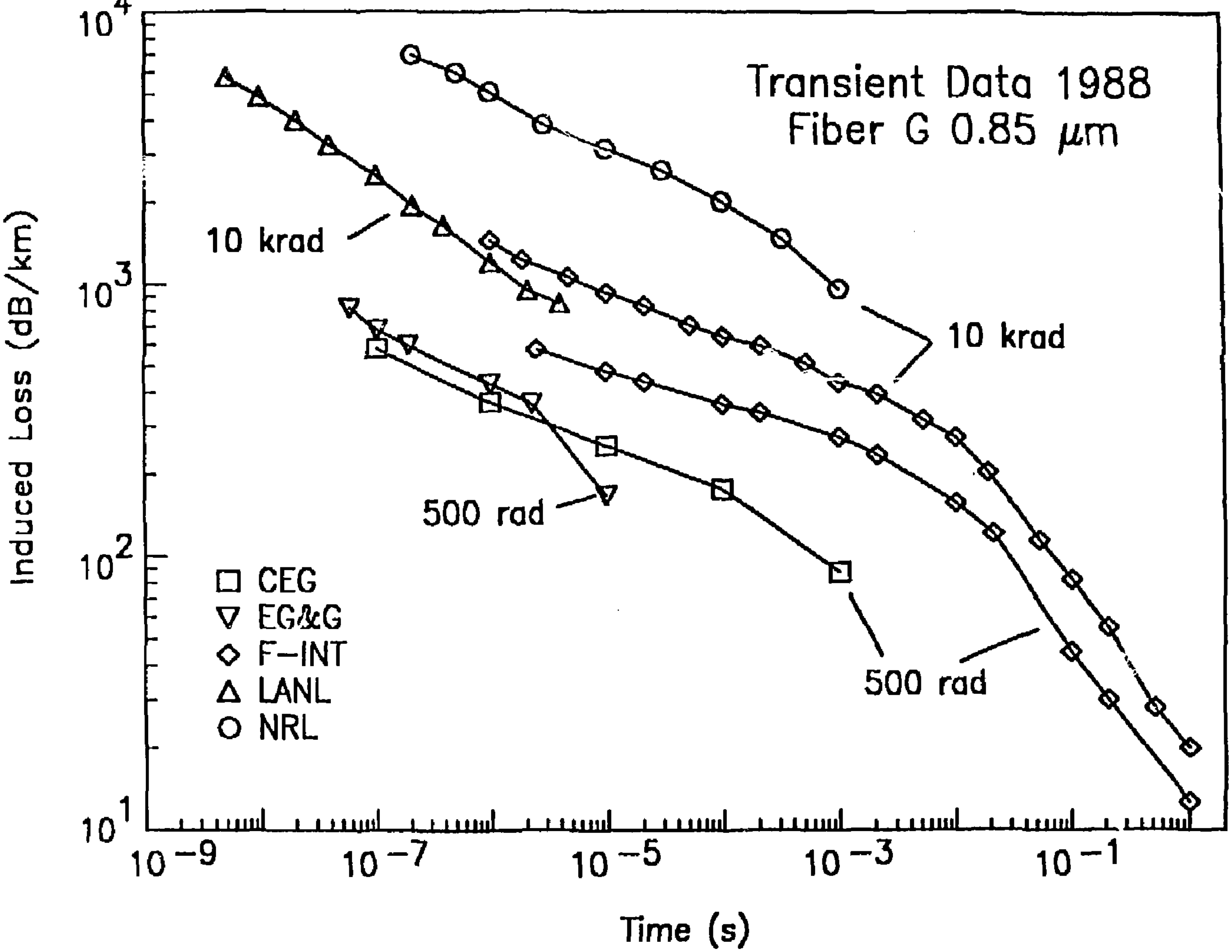
Transient Results 1986
Fiber A
500 rad
Induced Loss (dB/km)
Time (s)
10^3
10^2
10^1
10^0
10^{-1}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^1
10^3
□ CEG
△ LANL
◇ MBB/F-INT
○ HDL
▽ STC
46 nW
360 µW

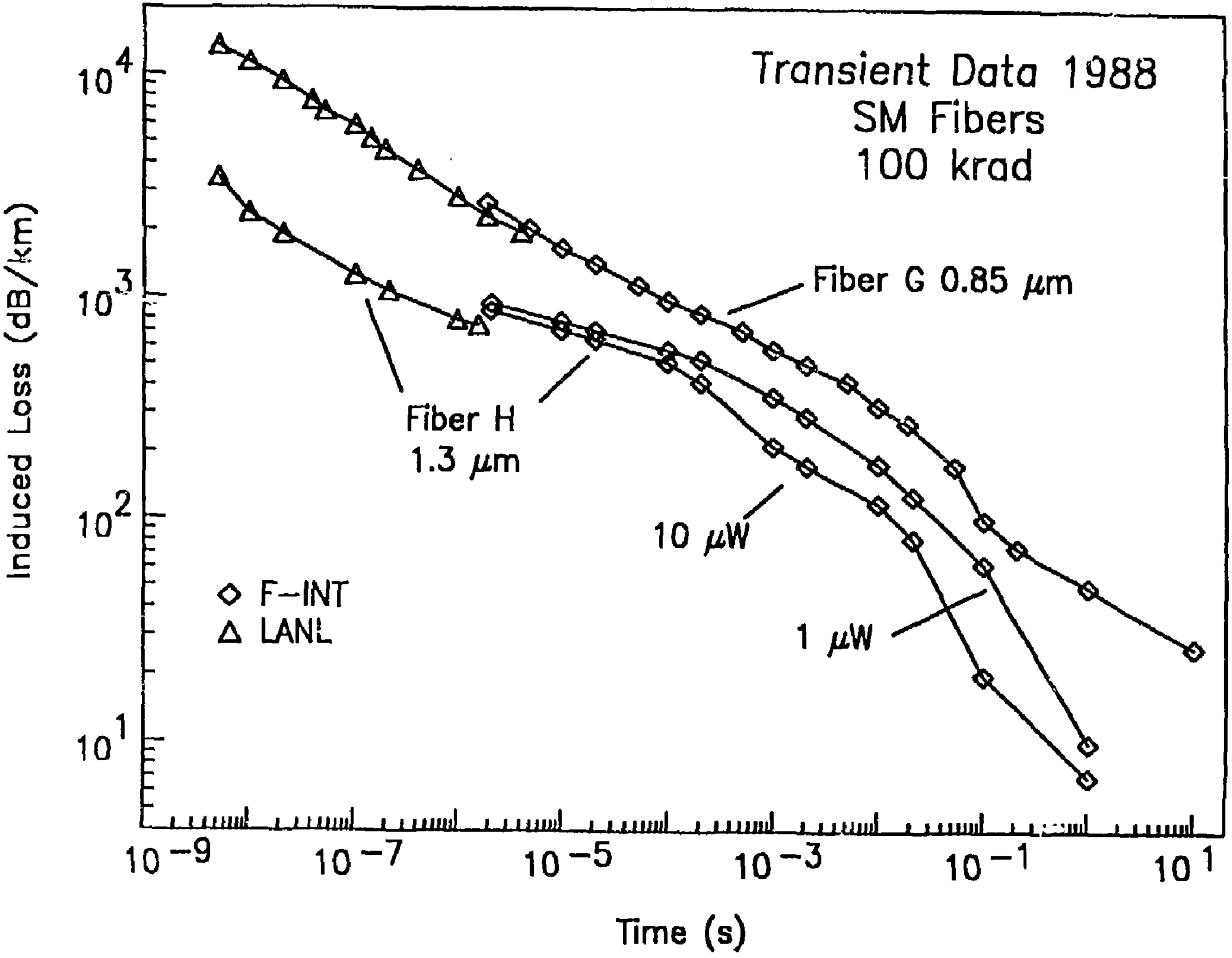
4b


Fiber D
First Window 1987
100 krad
10 krad
500 rad
□ CEG
◇ F-INT/MBB
△ LANL
▽ NRL
Induced Loss (dB/km)
10^4
10^3
10^2
10^1
Time (s)
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^1

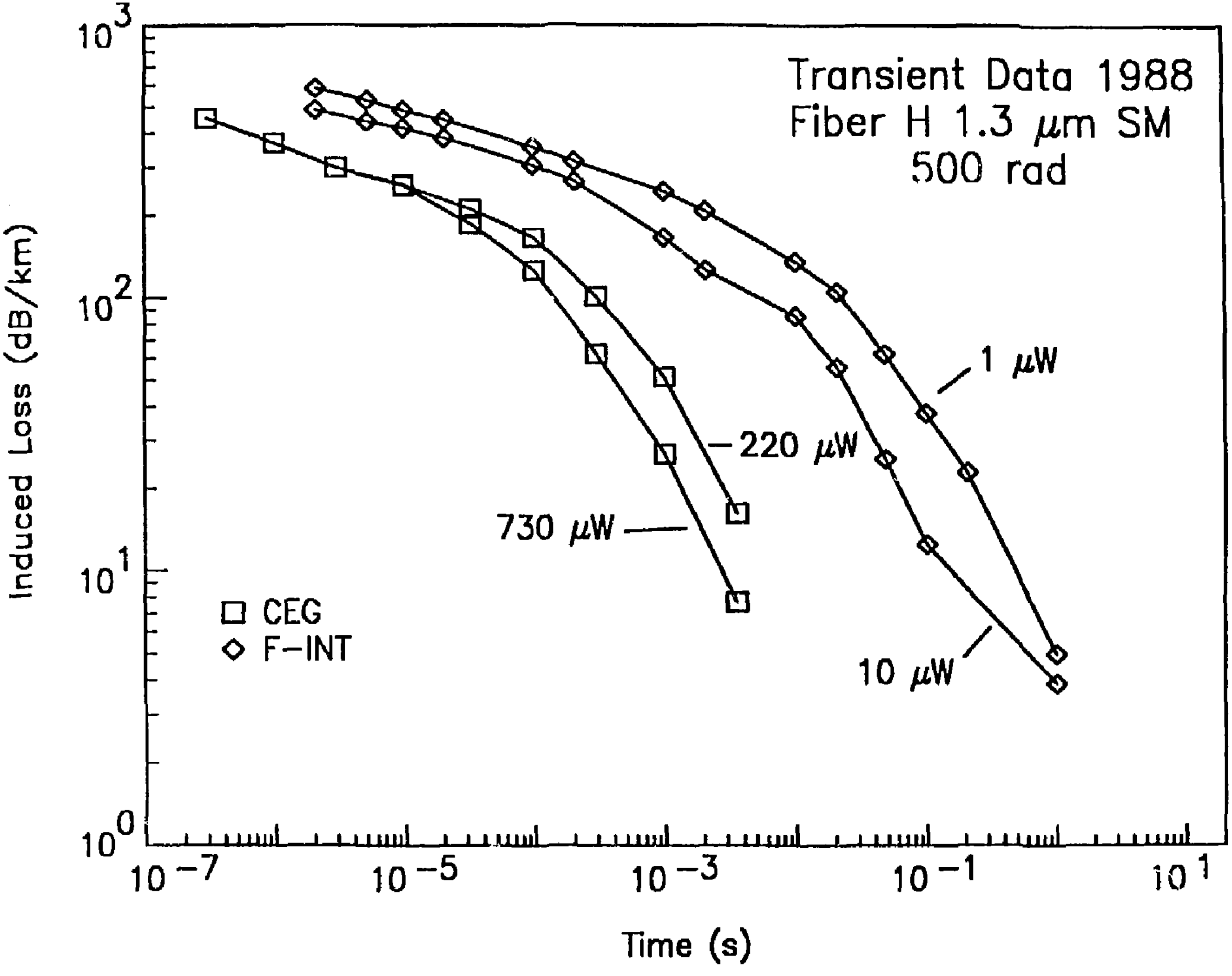

Fiber D
Second Window 1987
100 krad
10 krad
500 rad
□ CEG
◇ F-INT/MBB
△ LANL
Induced Loss (dB/km)
10^3
10^2
10^1
Time (s)
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}


Transient Data 1988
Fiber E
100 krad
10 krad
500 rad
Induced Loss (dB/km)
Time (s)
10^0
10^1
10^2
10^3
10^4
10^5
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
▽ Boeing
✕ CEA
□ CEG
◇ F-INT (1 μW)
△ F-INT (10 μW)
○ NRL

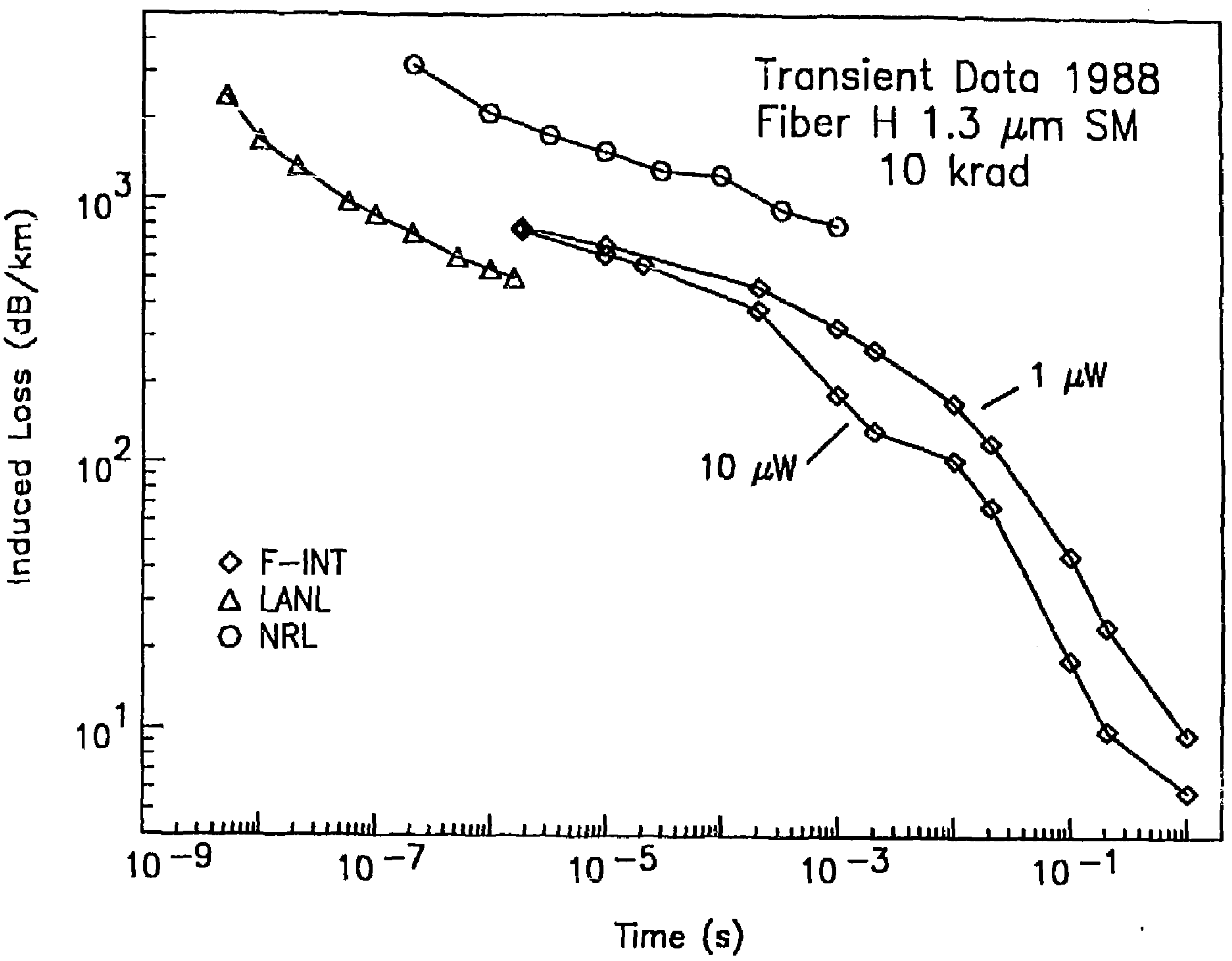

Transient Data 1988
Fiber G 0.85 μm
Induced Loss (dB/km)
Time (s)
10^4
10^3
10^2
10^1
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10 krad
10 krad
500 rad
500 rad
□ CEG
▽ EG&G
◇ F-INT
△ LANL
○ NRL

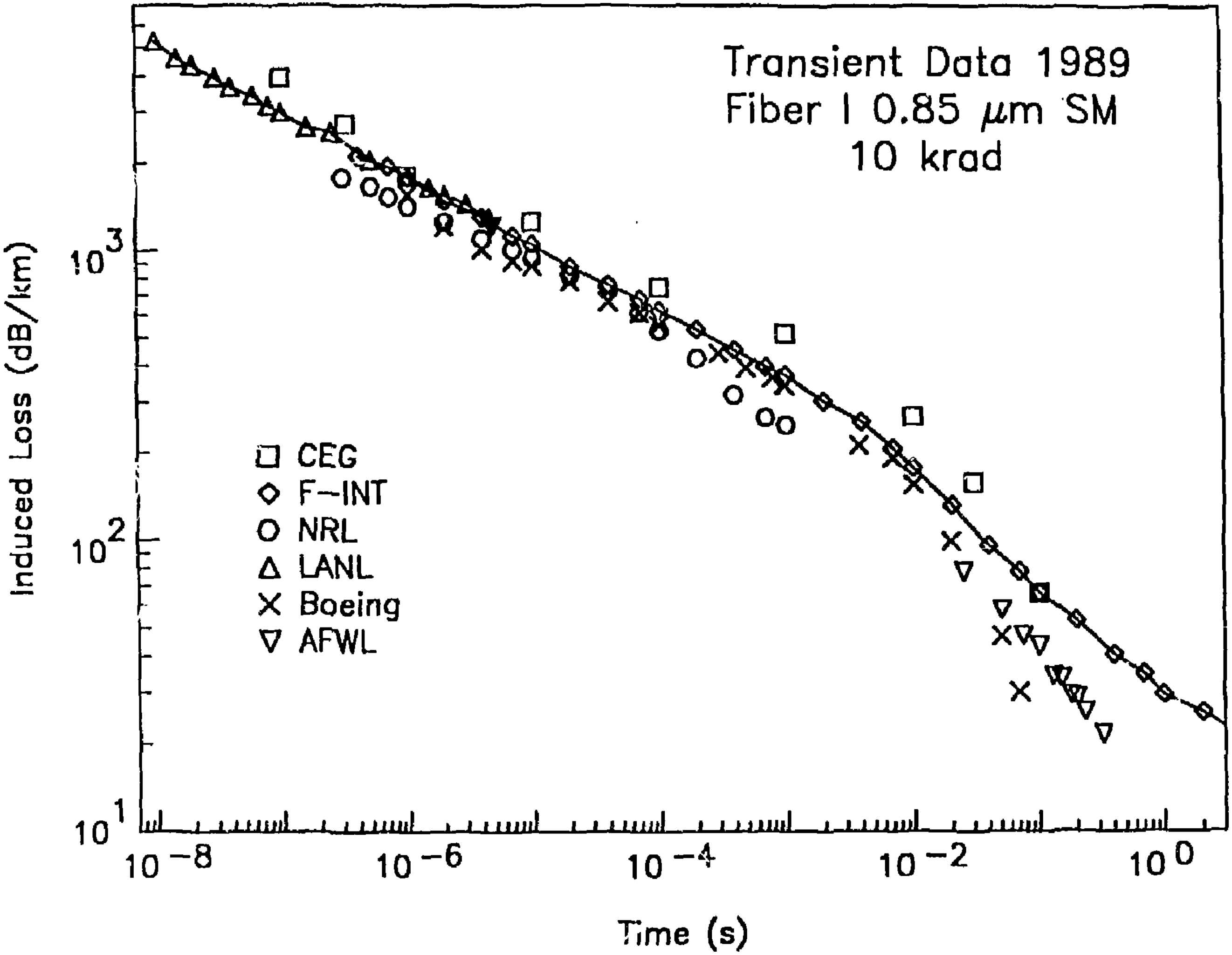

Transient Data 1988
SM Fibers
100 krad
Fiber G 0.85 μm
Fiber H
1.3 μm
10 μW
1 μW
◇ F–INT
△ LANL
Induced Loss (dB/km)
10^4
10^3
10^2
10^1
Time (s)
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

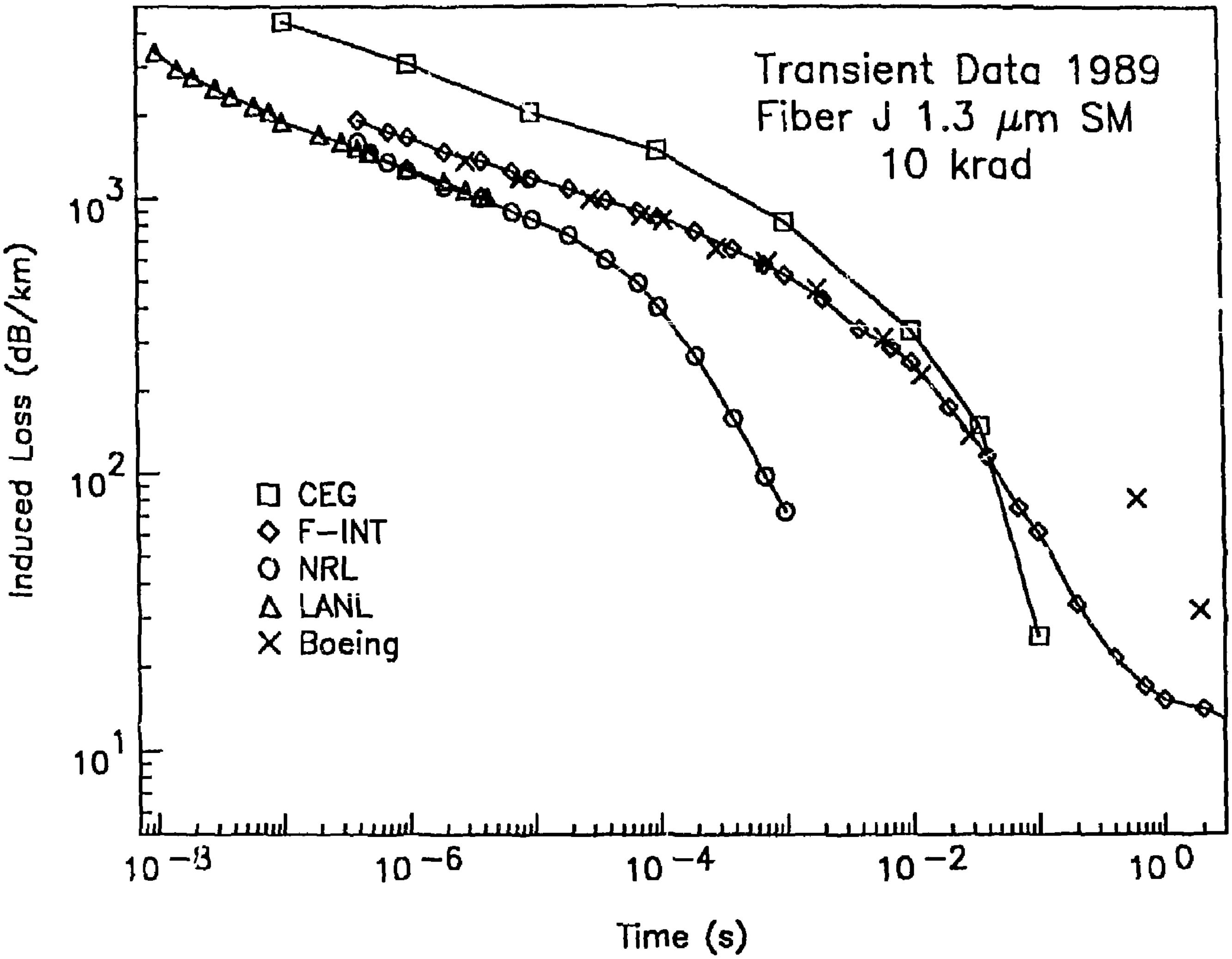
7b

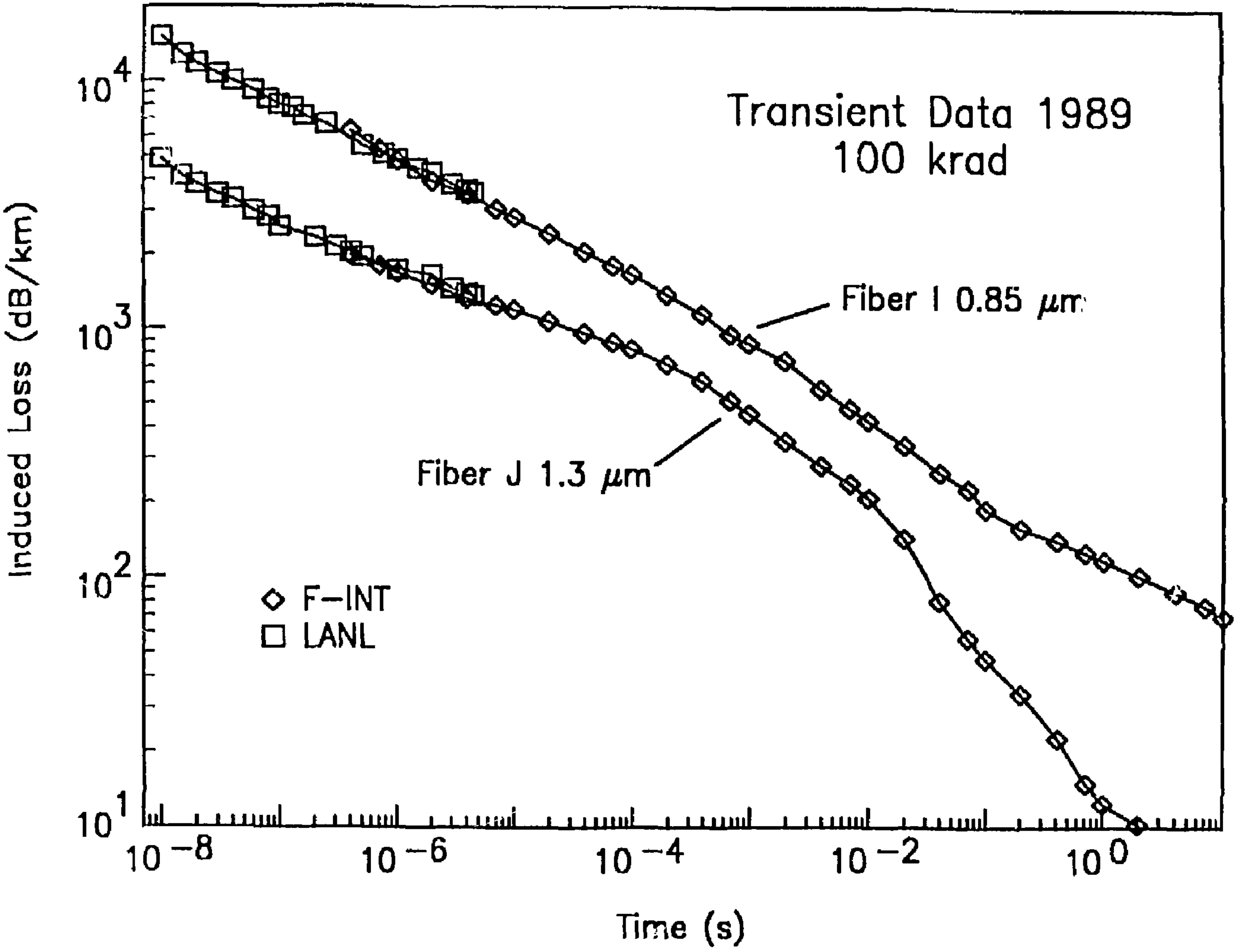

Transient Data 1988
Fiber H 1.3 μm SM
500 rad
Induced Loss (dB/km)
10^3
10^2
10^1
10^0
Time (s)
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
1 μW
10 μW
220 μW
730 μW
□ CEG
◇ F-INT

7c.


Transient Data 1988
Fiber H 1.3 μm SM
10 krad
Induced Loss (dB/km)
10^3
10^2
10^1
Time (s)
10^−9
10^−7
10^−5
10^−3
10^−1
◇ F–INT
△ LANL
○ NRL
1 μW
10 μW


Transient Data 1989
Fiber I 0.85 μm SM
10 krad
□ CEG
◇ F–INT
○ NRL
△ LANL
× Boeing
▽ AFWL
Induced Loss (dB/km)
10^3
10^2
10^1
10^-8
10^-6
10^-4
10^-2
10^0
Time (s)


Transient Data 1989
Fiber J 1.3 μm SM
10 krad
Induced Loss (dB/km)
10^3
10^2
10^1
Time (s)
10^-8
10^-6
10^-4
10^-2
10^0
□ CEG
◇ F-INT
○ NRL
△ LANL
× Boeing


Transient Data 1989
100 krad
Fiber I 0.85 μm
Fiber J 1.3 μm
◇ F—INT
□ LANL
Induced Loss (dB/km)
10^4
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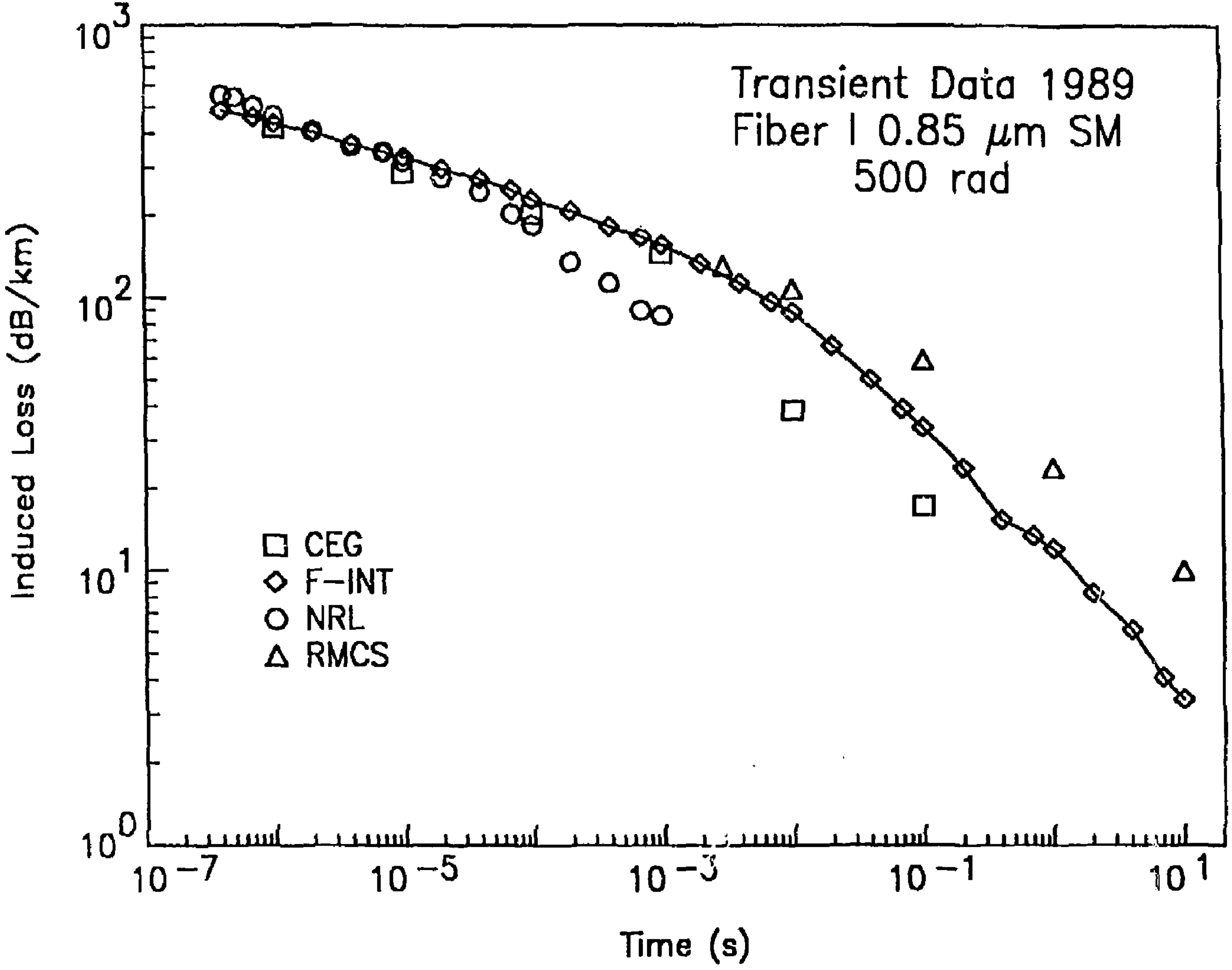
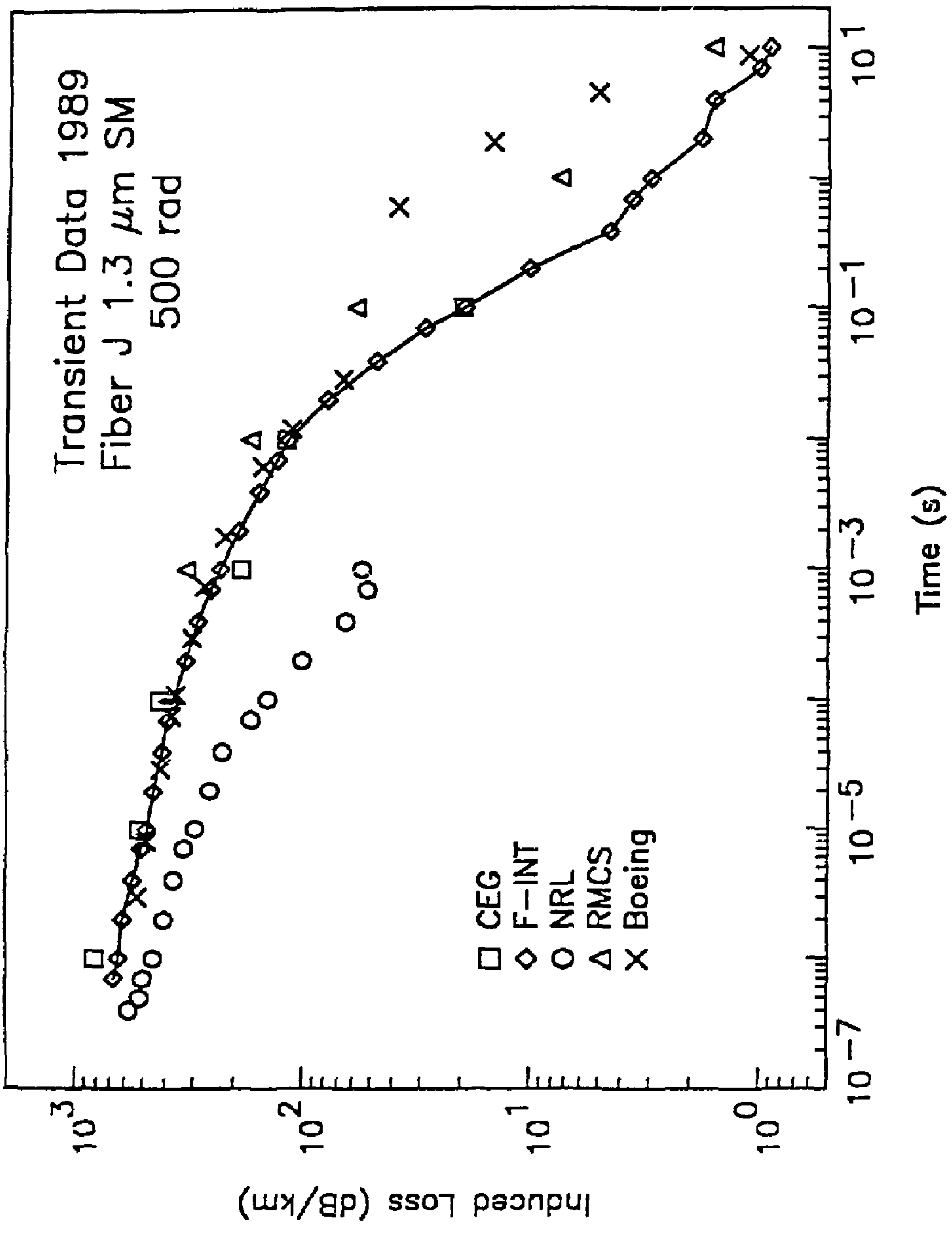
10^-4
10^-2
10^0
Time (s)


Transient Data 1989
Fiber I 0.85 μm SM
500 rad
Induced Loss (dB/km)
Time (s)
10^3
10^2
10^1
10^0
10^-7
10^-5
10^-3
10^-1
10^1
□ CEG
◇ F-INT
○ NRL
△ RMCS


Transient Data 1989
Fiber J 1.3 μm SM
500 rad
□ CEG
◇ F-INT
○ NRL
△ RMCS
× Boeing
Induced Loss (dB/km)
Time (s)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}