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Electron-Beam Induced Absorption and Hardening in Fiber-Optic Waveguides to 1060 nm Laser Pulses

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Sandia Laboratories

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Electron-Beam Induced Absorption and Hardening in Fiber-Optic
Waveguides to 1060 nm Laser Pulses*

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MASTER

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Abstract

For Corning Glass Work (CGW) and Valtac Corporation (VC) fiber-optic waveguides (FOWs), we have determined the coupling efficiencies (output/input energy) before (R_1) and after (R_2) electron-beam irradiation, the output energy density, the induced attenuation or loss (L_1) and its decrease as a function of time, and hardening as a function of number of Febetron shots (N_s). The FOWs were electron-beam irradiated with 8.3 to 12.3 J/cm² for 2.14 to 2.84×10^6 r (60Co equivalent) dose. The output laser energy density varied from 0.19 to 2.12 kJ/cm² which was about 50 percent of the input surface threshold damage level previously measured in similar FOWs. The R_1 values of 40.1 to 67.0 percent were less than those previously measured. The induced attenuation (L_1) as a function of recovery time (t) after electron-beam irradiation was linear on log-log plot for a short time ($< 2.2 \times 10^{-4}$ s), changing from 1.8 to 0.2 in slightly larger than one order of magnitude change in t . The rate of recovery decreased with increasing time so that the total change in L_1 was about 3 orders of magnitude in 6 orders of magnitude change in time. A slight hardening (decrease in $R_2 = R_1/R_2$) occurred in CGW fibers with increasing number of Febetron shots.

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TABLE OF CONTENTS

	Page
I. Introduction	1
II. Scope	1
III. Experimental Setup	2
A. Mechanical and Optical	2
B. Pebetron	3
C. Electrical	4
IV. Experimental Results	5
V. Conclusion	14
VI. Appendix	15

Figures

1. Mechanical and optical setup used in studying the radiation-induced loss to high laser transmitted energy in FOWs.	3
2. Block diagram of electrical connections of the equipment used to study the radiation-induced loss to high laser transmitted energy in FOWs.	6
3. Changes in induced losses (L_I) in two sets of CGW FOWs as a function of recovery time, t (s).	10
4. Photographs of the Pebetron trigger (upper traces) and laser light response before (4A lower traces) and after the Pebetron pulses (2B and 4C lower traces).	11
5. Change in induced losses (L_I) in CGW FOW FN19 as a function of recovery time, t (s).	12
6. Change in induced losses (L_I) of all CGW and VC FOWs tested as a function of recovery time, t (s).	12
7. Hardening effect observed in CGW FOWs FN23, 27, and 28 as illustrated in changes of $R_3 = (R_1/R_2)$ as a function of number of Pebetron shots (N_P).	14
A1 Transmission response of overlay filter and CK-25 polychlorstyrene film before and after electron-beam irradiation.	16
A2 Density of CK-25 polychlorstyrene film placed over small and large calorimeter.	17
A3 Correlation between the energy absorbed by the small and large calorimeter through the density of the CK-25 polychlorstyrene.	17

Tables

I. Physical and Optical Characteristics of Fiber-Optic Waveguides	7
II. Specifics, Results, and Calculations for Fiber-Optic Waveguides	8
AI. Characteristics of Exposed TLD-800 Crystals	18

I. INTRODUCTION

Fiber-optic waveguide (FOW) systems are being considered and used in many military and commercial applications because of inherent advantages over hardwire transmission links. These advantages include reduced susceptibility to EMP, better electrical isolation between circuits, lighter weight, larger bandwidth for multiplexing, and expected lower cost. One application under consideration includes transmitting through such fibers multistroke free-running laser pulses¹⁻³ (400 ns-duration) containing high energy and power. It is a concern whether sufficient energy density ($>100 \text{ J/cm}^2$) can be transmitted through FOWs to perform a required function after the fibers are subjected to high electron irradiation rates (10^6 rad/s) at dose rates of greater than 10^{14} rad/s . Recent measurements have been made on FOWs of radiation-induced transient and permanent attenuation⁴⁻²⁰ caused by different levels of gamma,^{2-14,17-20} x-ray,^{8,15,16} electron,^{8-13,15-20} and neutron^{12,13} ionization radiations. With low-to-moderate optical energy, these attenuations were measured in fibers with fused silica,^{5,8,10,13,15-20} doped fused silica,^{6-10,12,14-20} glass,^{4,9,11,13,14,17,19} and plastic^{8,10,12,13,18,19} cores. One study³ used high laser energy densities after fibers were gamma-ray irradiated, but no similar measurements have been made after fibers were electron irradiated. Of concern is possible bleaching,¹⁵ radiation hardening,^{17,18} or increased residual damage in certain fibers when high laser energy interacts with the irradiated fibers.

This report describes measurements of coupling efficiencies (output/input energy), output energy density, induced and intrinsic attenuation (loss), rate of decrease of attenuation of time, and hardening in Valtor Corp (VC) fiber-optic waveguides made of "pure" fused silica and Corning Glass Works (CGW) fiber-optic waveguides made of doped-fused silica. The properties of these fibers were measured using 400 ns-duration Nd:YAG laser pulses before and after the fibers were irradiated with a 3 ns-duration electron beam ($2 \times 10^{16} \text{ p/}^{60}\text{Co equivalent}$).

II. SCOPE

In addition to the Introduction and Scope Sections, this report includes (1) descriptions of the experimental setup used in testing the FOWs (Section III) and of the experimental results (Section IV), (2) conclusion (Section V), and (3) appendix (Section VI).

III. EXPERIMENTAL SETUP

This section describes the mechanical and optical experimental setup used to generate and amplify the nominal 400 μ s-duration free-running laser pulses, hold the FOWs, detect the temporal profile and energy contained in each laser pulse, align the entire laser and optical fiber systems, generate the 3 ns-duration electron beam (pulse) and measure its length, and photograph the ends of the fibers. This section also describes the electrical timing of the entire system.

A. Mechanical and Optical

The mechanical and optical setup used in studying the radiation induced loss at a fixed laser transmitted energy in FOWs is shown in Figure 1. The laser oscillator²¹ (OSC) and amplifier (AMP), the He-Ne laser, and associated mirrors used in aligning and directing the laser beams, and the beam sampling stations (STA) #1 and STA #2 were as illustrated and described in a previous report.³ A station, immediately following the AMP and ahead of the limiting aperture A_2 , illustrated in previous setups^{1,2,22,23} was eliminated.

The OSC consisted of two 90-degree, chip-free, knife-edge, right-angle prisms (PR_1 and PR_2), with their knife edges oriented 90 degrees, used as end reflectors; a 50 percent reflective beamsplitter (BS₀) output coupler; Nd³⁺ glass laser rod (LR) pumped by a doubled elliptical cavity, containing two EG&G FX47C Xenon flashlamps (FL); and a 3.87-mm-diameter aperture (A_1). The laser rod, an ED-2 glass, was 0.96 cm in diameter by 17.0 cm long. The laser rod, flashlamp, and cavity walls were water cooled for more stable operation.

STA #1 and STA #2 sampled the OSC and AMP beams, respectively. The responses of the KDI photodiodes, D_1 and D_2 (manufactured by Hadron), were calibrated by energy meters EM₁ and EM₂ (manufactured by Quantronic), respectively. EM₃ measured the energy transmitted through the fiber. KDI photodiode D_3 responded to the temporal profile of the laser pulses after they passed through the fiber. The Reticon Arrays (RA) were used to determine the intensity profile of the laser beam in the directions orthogonal to its propagation direction. All mirrors, which reflected both the He-Ne and the Nd³⁺ laser beams, were coated for high reflectivity at both 632.8 and 1060 nm.

Figure 1. The mechanical and optical setup, used in studying the radiation-induced loss to high laser energy transmitted in fiber-optic waveguides, included these components: Nd^{3+} laser oscillator (OSC) and amplifier (AMP), energy meters (EM_1 , EM_2 , and EM_3), lens system (L), auto-collimator (AC), fiber-optic waveguide (fiber), directing mirrors (M_1 , M_2 , M_3 , M_4 , M_5 , M_6 , M_7 , M_8 , M_9 , and M_{10}), beamsplitters (BS_1 , BS_2 , and BS_5), optical filters (F_1 and F_2), helium neon laser (He-Ne), restricting apertures (A_2 and A_3), Febetron, Febetron electronic controls, freon (F), and air (A). Each beam sampling section had two beamsplitters (BS_3 and BS_4), a diffuser (DF), a photodiode (D_1 , or D_2), and two linear diode arrays (RA).

The lens (L), inside the screen room, was a Hadron trinocular viewing and focusing (HTVF) system. With its flip-flop mirror up, a burn was made on Hadron "fingerprint" paper placed at the input end of the fiber, near the focal point of the 9.33 cm focal length lens of the HTVF system. With the flip-flop mirror down, the crosshair of the viewing eyepiece was centered over the image of the burn. After the burn was removed, the image of the input end of the fiber was centered on the crosshair by moving the input end of the fiber.

A Zeiss Model FS-45 Trinocular Polarizing Tube and a Nikon Photomicrographic Attachment (Model EFM) containing a relay lens, an eyepiece, and a polaroid adapter were used to photograph the input end of each fiber before and after it received both the electron and optical energy from the Febetron and laser, respectively.

Both the OSC and AMP were operated at only one high output level. Filter F_1 was used to attenuate the laser beam to the proper amplitude before it entered the fiber. Filter F_2 was added to the laser beam only during the alignment of the HTVF system. F_2 was positioned on a kinematic mount for ease of removal during the testing of the fiber. Since access into the screen room was through a door located on the right side of the screen room, M_1 was also positioned on a kinematic mount for ease of removal during the exchange of the fiber and preparation of the Febetron for firing.

B. Febetron

The Febetron, Model No. 706, its controlling electronics, gas bottles of purified air (A) and freon (F), the HTVF system, electron beam calorimeter, paper recorder, and the POW being tested were all located inside a double-screened Faraday Screen Room. The specially modified Febetron was hung so that the output of Model No. 5515 Electron Tube pointed vertically downward. The HTVF system was secured onto the Electron Tube housing flange. The fibers were secured onto a kinematic-type mount, (for ease of removal and precise repositioning without realignment) which was also attached to the Electron Tube housing flange. This mount also held the electron beam calorimeter. (Calibration procedures are described in the Appendix.) Small holes in the walls of the screen room allowed the pulse laser beam in (hole diameter about 1-cm) and the POWs out (hole diameter about 0.5-cm).

The Febetron delivered a 3 ns-duration electron pulse of 0.6 MeV peak energy. Thermoluminescent LiF (TLD-100) and $\text{Li}_2\text{B}_4\text{O}_7$ (TLD-800) crystals were used to measure dosage received by the fiber. (For details see Appendix.) A Faraday cup was used to confirm the

temporal shape of the radiation pulse. The integrated electron-beam energy (t_0) was measured with an aluminum calorimeter as defined in the Febetron operating manual dated 1969 (for details see Appendix). Our Febetron system delivered an average of 2.7×10^6 R (^{60}Co equivalent) at 30 kV, an exposure rate of 9.0×10^{14} rad/s, at a distance of 2.54 cm from the window of the Electron Tube. TLD-8U0, $\text{Li}_4\text{B}_4\text{O}_7$ crystals were used to verify the dose.

C. Electrical

Figure 2 shows the block diagram of the electrical connections of the laser OSC and AMP, oscilloscopes (SCOPE), photodiodes (KDI), Reticon arrays (RA) for the horizontal (H) and vertical (V) laser beam readout, and associated equipment (generators and power supplies). The timing sequence is shown in the lower portion of the figure. A hand-operated switch initiated the triggers of the Rutherford Generator at $T_0 = 0$. All the timing on the Rutherford Generator could be left fixed, yet by changing only the timing on channel 2 of the Rutherford Generator, the laser emission time could be made to occur before, during, or after the Febetron electron emission time. HP214 Generator #2 provided the large voltage signal required to drive the light emitting diode contained in the optical switch (OS) used in controlling the Febetron emission from outside the Faraday Screen Room without using wires through the screen. Since the output voltage of the OS was too small to trigger the Febetron, HP214 Generator #3 amplified this voltage and it provided more delay between the Febetron and laser pulses.

The trigger T_6 to Section A of SCOPES 1 and 2 was adjusted to the free-lasing pulse emission time. The oscilloscope sweep speeds were adjusted so that each array was read out in ten divisions, making each scale division 0.127 cm for each RA. Trigger T_5 to Section A of SCOPES 3 and 4 occurred in time to allow recording both the free-running laser pulse (RT) and the Febetron electron pulse (M). SCOPE 5 displayed the output of the two KDIs of STA #1 and STA #2 (D_1 and D_2).

IV. Experimental Results

Free-running laser pulses were transmitted through FOWs manufactured by Corning Glass Works (CGW) and Valtec Corporation (VC).²⁴ Most of the results were obtained from CGW fibers whose silica cores were doped with Ge and whose silica claddings were doped with boron. The VC fibers had pure silica cores and plastic claddings. Measurements were made before, during, or after the fibers were irradiated with electrons.

Figure 2. This block diagram illustrates the electrical connections of the laser OSC and AMP, Febetron Model 706, oscilloscopes (SCOPE), photodiodes (KD1), Reticon Arrays (RA in the H and V directions), and associated equipment (HP214 GEN. #1, #2, and #3, Rutherford generator, Cordia generator, DC power supply, Reticon power supply, and RA controls RC 100). The relative timing sequence is shown in the lower portion.

Table I lists the physical and optical characteristics of the CGW and VC fibers. "Ref. loss %" in Table I refers to Fresnel reflection losses per surface at the input and output ends of the fibers as calculated from

$$R_0 = \left[(\eta_0 - \eta_2) / (\eta_0 + \eta_2) \right]^2, \quad (1)$$

where η_0 and η_2 are the refractive indices of the air and fiber core material at $\lambda = 1060$ nm, respectively. The transmission (T) through the fiber is given by

$$T = \left[1 - (\eta_0 - \eta_2)^2 / (\eta_0 + \eta_2)^2 \right]^2. \quad (2)$$

The numerical aperture given by

$$NA = \left[\eta_2^2 - \eta_1^2 \right]^{1/2}, \quad (3)$$

where η_1 is the refractive index of the fiber cladding, was calculated at $\lambda = 1060$ nm.

TABLE I

PHYSICAL AND OPTICAL CHARACTERISTICS OF FIBER-OPTIC WAVEGUIDES

Fiber No.	Mfg.	Core Mat.	Core diam (μ)	Core η_2	Ref Loss %	T	NA
FN11-FN39	CGW	Silica	87-96	1.467	3.58	.929	.18
FN40-FN41	VC	Silica	100-140	1.449	3.36	.934	.30

Initially, only about 1 cm of the 30-cm-long FOW bundle, left in their jackets, was electron irradiated. The energy transmitted through the fibers was coupled to EM_3 or D_3 by a previously tested^{1,2,22,23} American Optical Co. (AOC) fiber bundle. Failure to detect induced attenuation led to irradiating longer, unshielded fiber. These fibers were held in a single flat-layer coil. Only approximately 1 cm of fiber length per turn was irradiated. The coil contained up to 50 turns for VC fibers and up to 70 turns for CGW fibers. Repeated laser shots caused deterioration at the input end of the AOC coupling fiber. This led to its replacement and finally its removal from the system. After removal of the AOC coupling fiber, the single unshielded output end of the FOWs was pulled through the screen room and their outputs were directed into EM_3 or D_3 (Figure 1).

Table II lists the specifics, results, and calculations pertaining to the FOWs tested. These include the number of turns of FOW exposed to electron irradiation (N_T), the number of Febetron shots into the FOWs (N_F), the electron-beam energy density (E_e) to FWHM of the beam as explained in the Appendix, the laser energy density through the FOWs (E_1) obtained by dividing the energy transmitted through the FOW core by its area, the ratio of laser energy transmitted through the FOWs before (R_2) and during or after (R_1) the electron-beam irradiation compared to that of the laser energy incident onto the input face of the FOW before (E_1) and during or after (E_1') the electron-beam irradiation ($R_1 = E_2/E_1$ and $R_2 = E_2'/E_1'$), the ratio of R_2 to R_1 ($R_3 = R_2/R_1$), the induced loss caused by electron-beam irradiation (L_I), and the time between the center of the 100 μ s-duration laser pulse and the electron emission pulse (t). For a specific fiber, when N_F was greater than 1, the listing in Table II pertains to the first Febetron shot into the fiber.

TABLE II
SPECIFICS, RESULTS, AND CALCULATIONS FOR FIBER-OPTIC WAVEGUIDES

Fiber No.	N_T	N_F	E_e (J/cm ²)	E_1 (kJ/cm ²)	R_1 (%)	R_2 (%)	R_3 (%)	L_I (dB/cm)	t (s)
FN11	51	1	10.0	.52	16.2	1.7	10.9	.21	2.2×10^{-4}
FN12	12	2	10.6	.28	17.1	8.7	51.0	.26	2.2×10^{-4}
FN13	12	1	8.9	.19	15.1	5.6	36.7	.39	2.2×10^{-4}
FN18	13	1	9.9	1.22	51.2	26.6	46.1	.28	2.2×10^{-4}
FN19	13	2	10.5	1.27	48.2	40.9	84.9	.059	2.2×10^{-4}
FN20	13	1	11.2	1.31	48.0	39.0	81.2	.076	2.2×10^{-2}
FN22	13	1	9.7	1.24	54.9	43.4	79.1	.085	2.2×10^{-4}
FN23	13	8	10.3	.77	59.5	49.1	82.5	.070	$.4 \times 10^{-3}$
FN24	20	1	10.0	1.02	53.4	31.4	58.8	.130	2.2×10^{-4}
FN25	20	1	11.2	1.56	57.8	40.7	83.3	.043	1.2×10^{-3}
FN26	20	1	10.0	1.59	52.4	51.6	98.4	.0038	1
FN27	20	2	10.2	2.12	59.4	52.6	88.5	.029	7×10^{-4}
FN28	20	1	9.9	1.95	48.0	46.8	97.5	.006	10^{-2}
FN29	20	1	10.5	2.09	67.0	50.6	75.5	.066	2.2×10^{-4}
FN30	20	1	9.9	2.09	59.0	50.0	84.7	.039	1.2×10^{-3}
FN31	20	1	11.2	1.88	57.2	46.6	81.4	.049	1.2×10^{-3}
FN32	20	1	10.5	1.67	55.4	45.7	82.4	.046	7×10^{-4}
FN33	20	1	9.9	1.77	59.6	56.6	94.9	.012	10^{-2}
FN37	70	5	9.2	1.04	40.1	37.6	93.8	.0043	300
FN38	20	5	10.9	.68	45.8	26.5	56.0	.14	2.2×10^{-4}
FN39	20	3	10.6	1.21	--	--	--	--	--
FN40	20	1	12.2	.27	21.8	21.6	99.1	.0021	2.2×10^{-4}
FN41	20	1	8.3	.69	55.4	53.7	96.7	.0074	2.2×10^{-4}

In determining L_1 in the FOW, it was important that the laser pulse not change its beam characteristics, i.e., divergence, beam direction, and energy. The L_1 values were determined from

$$L_1 \text{ (dB/cm)} = (10 \log R_1^{1/2}/n) \quad (4)$$

where n is the number of turns of fiber being electron irradiated over an effective length of $l = 0.92$ cm which is the FWHM of the electron-beam energy. Equation (4) becomes

$$L_1 \text{ (dB/cm)} = (10 \log E_2^{1/2}/E_2) n \quad (5)$$

since $R_1 = E_1^{1/2}$, $P_2^{1/2} = E_2^{1/2}/\tau$, $P_1 = E_1/\tau$, and τ is the laser pulse duration of 400 n.s.

The spread in the electron-beam energy density E_e of 8.3 to 12.3 J/cm² resulted in a spread in the electron-beam power density ($E_e/3 \times 10^{-9}$ s) of 2.7 to 4.1 GW/cm². The spread in laser energy density E_1 of 0.19 to 2.12 kJ/cm² resulted in a spread in the laser power density ($E_1/4 \times 10^{-4}$ s) of 0.48 to 5.3 MW/cm². The largest laser energy density levels were about 50 percent less than the values which caused damage to similar CGW FOWs.¹⁻³ The R_1 values were smallest when the AOC transfer fiber was used for FN11 through FN13 and FN40. For other FOWs, R_1 varied from 40.1 to 67.0 percent. These values are smaller* than those previously coupled into similar CGW FOWs.¹⁻³ The R_2 values were similar to the R_1 values, in that, the smallest R_2 values occurred when the AOC transfer fiber was used. The R_2 , R_3 , and L_1 values also depended upon N_T and t . For comparable t values, the R_2 and R_3 values decreased with increase in N_T values. For the same N_T values, the R_2 and R_3 values increased with an increase in t .

Since L_1 is a log function of a number less than 1, the opposite occurred for L_1 rather than for R_2 and R_3 , i.e., L_1 decreased with an increase in t . The specific changes in induced losses (L_1) as a function of recovery time (t) for two sets of CGW FOWs are illustrated in Figure 3. Each data point represents the first laser shot and Febetron shot in one FOW sample. One set covers only about 2 orders of magnitude of t , while the other covers 4 orders. The maximum change in L_1 was less than 100.

*The smaller values of R_1 for these CGW FOWs, than for similar FOWs tested previously, could have been caused by the different technique used to hold the input end of the FOWs and the position of the attenuation filters, P_2 .

Figure 3. The changes in induced losses (L_I) in CGW FOWs are illustrated as a function of recovery time, t (s), for two sets of FOWs.

For FN39, the induced losses (L_I) for values of recovery time (t) less than 2×10^{-4} s were estimated using detector D_3 instead of energy meter EM_3 (see Figure 1). The lower trace in the photograph of Figure 4-A shows the response of D_3 for a laser shot before the Febetron pulse and in Figures 4-B and 4-C of another laser shot after the Febetron pulse. The upper trace in each photograph is of the trigger to the Febetron. The amplitudes of the individual laser spikes in Figure 4-B and 4-C were compared to the one laser spike amplitude of Figure 4-A. Figure 5 shows that the induced loss (L_I) of CGW FN39 as a function of recovery time (t) is linear (within experimental error) on a log-log plot. The data were taken after the third electron pulse. (In this case, t is the time for emission of the specific laser spike in the laser emission pulse train being measured. The spread in the data is due to the statistical variation in the amplitude of the free-laser pulses as shown in the lower traces of Figure 4-B and 4-C.)

Figure 4. The lower traces of 4A-4C are of photodiode D_3 showing the response of a laser shot before (4A) and after (4B and 4C) the Febetron pulse. The upper traces are of the trigger to the Febetron.

Figure 5. The induced losses (L_I) for CGW POW FN39 are illustrated as a function of recovery time, t (s).

Figure 6 illustrates the induced loss (L_I) as a function of recovery time (t) for the data in Table II, Figure 3, and Figure 5. For CGW fibers about 3 orders of magnitude changes in L_I were observed for 8 orders of magnitude changes in recovery time between 10^{-5} to 10^3 s for FN18-FN38. The largest L_I value measured was 1.83 dB/cm on the high-induced absorption end, and the smallest was 0.0021 dB/cm on the low-induced absorption end. The spread in L_I at $t = 2.2 \times 10^{-4}$ s was from 0.059 to 0.28 dB/cm. This spread is attributed to material variations in FOW as previously suggested¹⁵ since for all test parameters (and the R_I values in CGW FOWs varied only from 40 to 67 percent.)

The two VC fused quartz core FOWs exhibited a change in L_I at $t = 2.2 \times 10^{-4}$ s of from 0.0021 to 0.0074 dB/cm or about 3.5 times. The average of L_I for the VC FOWs was at 0.0048 dB/cm, or an absorption coefficient about 35 times less than for the average of the CGW FOWs.

The two VC FOWs exhibited a change in L_I of less than 1 order of magnitude for 7 orders of magnitude of t , starting at $t = 2.2 \times 10^{-4}$ s. Over the same time span, the CGW FOWs exhibited greater than 2 orders of magnitude change in L_I . The reduced changes in L_I for fused-quartz FOWs were expected and agree with previous measurements.^{8,13,15-20}

Figure 6. The induced losses (L_I) of the data in Table II, Figure 3, and Figure 5 are plotted as function of recovery time, t (s), for CGW and VC FOWs.

Figure 7 illustrates an apparent hardening effect which we observed in three dopant CGW FOWs (FN23, 37, and 38), not observed in previous measurements.¹⁸ Hardening has been observed in pure-silica (Suprasil 1) FOWs.¹⁷ The specifics for FOWs FN23, 37, and 38 are given in Table II with $N_T = 13, 70, \text{ and } 20$, and $E_1 = \text{from } 0.77 \text{ to } 0.92, 0.99 \text{ to } 1.1, \text{ and } 0.58 \text{ to } 0.68 \text{ kJ/cm}^2$, respectively. The different absolute value of R_3 for each FOW is time (t) dependent, the FOW with the largest value of t (the time between the Febetron and laser pulses) producing the largest value of R_3 or the smallest induced absorption loss. Each FOW experienced an increase in R_3 or a decrease in induced absorption loss for increased number of Febetron shots (N_F). The values of R_3 for FN23 and 38 were due to transient and residual-induced absorption losses, while the values of R_3 for FN37 were due to residual-induced absorption losses.

Figure 7. The observed hardening effect of three CGW FOWs (FN23, 27, and 28) is illustrated in the change of the ratio $R_3 = R_2/R_1$ as a function of number of Febetron shots (N_F).

For FN37 at $t = 5$ min, the value of R_3 is greater than 1.00 after the third Febetron shot, i.e., $R_2 > R_1$ or $E_2'/E_1' > E_2/E_1$. With $E_1' \approx E_1$ this implies that $E_2' > E_2$. This can occur if (1) the input or output surface losses of the FOW decreased, (2) the laser beam moved or increased in energy in such a way to increase R_2 and not R_1 , or (3) the intrinsic or inherent absorption loss in the FOW decreased. Both (1) and (2) could occur since the output laser energies E_2' and E_2 were measured for different laser shots. From previous data^{13,22} it is unlikely that the input or output surface losses of the FOWs decreased because the input laser energy density level of about 1.0 kJ/cm^2 caused surface cleaning. The laser did not increase in output energy in such a way as to increase R_2 and not R_1 , rather the output of the laser varied statistically. The value of R_1 changing a maximum of 1. percent for FN23, 2.9 percent for FN37, and 4.6 percent for FN38 when three laser shots were used in determining the average value of R_1 which was used in determining each value of R_3 in Figure 7 and Table II. The small variation in R_1 also indicates that the laser beam did not move in such a manner as to increase R_2 and R_1 .²² A reduction in the intrinsic or inherent absorption could occur if the number of electron-ion pairs¹⁵ or free radicals producing the intrinsic absorption are disassociated by the electron-beam irradiation or its irradiation rate and caused a decrease in the number of pairs with increased number of Febetron shots. More data are required before this last conjecture can be verified.

V. Conclusion

The CGW and VC FOWs were irradiated with an electron beam containing from 8.3 to 12.2 J cm^{-2} of energy density, corresponding from 2.36 to $2.84 \times 10^6 \text{ R}$ (^{60}Co equivalent). The output laser energy density of 0.19 to 2.12 kJ/cm^2 incident onto the input end of the FOWs was about 50 percent below the damage level of similar FOWs previously tested.³ The values of R_1 measured, from 40.1 to 67.0 percent, were less than those previously coupled in similar CGW FOWs.¹⁻³ For CGW FOWs, the induced absorption L_1 values changed about 3 orders of magnitude in about 8 orders of magnitude of time (between 10^{-5} to 10^3 s after the Febetron shot). For short delay times after electron irradiation, the L_1 vs. t values resulted in a straight line on a log-log plot. Smaller changes in L_1 were observed for VC fused-quartz core FOWs than for CGW FOWs at a lower average value of L_1 . An apparent slight hardening effect was observed in CGW FOWs for both transient- and residual-induced absorption losses.

VI. Appendix

The purpose of the detector model 206 operating in the electron gun was calibration. We were able to determine its electron-beam energy density, and the other things.

1. Energy measurements--Calorimetric measurements were obtained with an aluminum (Al) disc, a chromel-alumel thermocouple, and CL-25 polychlorstyrene film manufactured by Ray West Technology. The energy measured is given by

$$W = 4.186 \text{ kcal/g} \cdot \Delta V \cdot D \cdot K$$

or

$$W = M_1 \Delta V \cdot (J) \cdot K$$

where K is the thermal constant of the thermocouple wire (25 mV/°C for chromel-alumel), m is the mass of the Al disc ($m = 2.44$ grams for the large disc, and 0.415 gram for the small disc), c_p is the specific heat of Al ($\frac{0.22 \text{ cal}}{\text{g} \cdot ^\circ\text{C}}$), ΔV is the voltage recorded on a strip chart record in millivolts ($\Delta V \times 200 \text{ mV}$), 4.186 is conversion of calories to joules (4.186 J/cal), and N_1 is 56.176 for the large calorimeter and 14.543 for the small one.

The large calorimeter was placed in the center of the electron beam, so as to collect all but the approximately 5 percent which is backscattered. The small calorimeter was placed to the side of the beam so that the FOW was in the center of the electron beam. The small calorimeter was used with the FOWs. During all the measurements, the relative position of the FOWs, the small calorimeter, and the Electron Tube were fixed. For each electron irradiation in the FOWs, the energy absorbed by the small calorimeter was recorded and correlated to the electron-beam energy.

The actual electron-beam energy received by the fiber was determined by relating the energy collected by the small calorimeter to the actual energy present in the electron beam by previous large calorimeter readings. The energy of the small and large calorimeters was related to the change in density recorded in the CL-25 polychlorstyrene film placed over either calorimeter. Each calorimeter was placed 2.54 cm from the output face of the Model 5515 Electron Tube. The absorption of the film at 630 nm was monitored with a Joyce Lobe Isodensitracer Recorder, Model Mark 3CS.

A typical type #630 Joyce Lohel filter passing λ_1 (trace A) and film transmission response before (trace B) and after (trace C for a reference shot) electron-beam irradiation are shown in Figure A1. Typical density responses recorded when the film was placed over the large and small calorimeters with the Febetron operating at 30 kV are shown in Figure A2. The listings at FWHM are the values used as the diameter of a circle whose area A_c was divided into the peak energy value of the electron beam in determining the electron-beam energy density (E_0) listed in Table II. The listings at the peak are the values used as the density at λ_1 in arbitrary units to correlate the energy absorbed by the two calorimeters.

Figure A1. A typical type #630 Joyce Lohel filter transmission response (trace A at λ_1), CK-25 polychlorstyrene film transmission response before (trace B) and after (trace C) electron-beam irradiation.

The correlation between the energy absorbed by both calorimeters and the density at λ_1 of their respective film overlays is plotted in Figure A3. For each small calorimeter energy reading (E_s), a specific electron-beam energy (E_e) can be assigned by using the density value from its corresponding E_s value, and from that density, obtain E_e , which is equal to the expected t_e value. For example, an E_s of 1.1 J yields an $E_e = t_e$ of 4.5 J (Figure A3). In this manner, each E_s value recorded for each Febetron shot was converted to an E_e value and it is this t_e/A_e , S_e value, which appears in Table II.

Figure A2. Density of a typical CL-25 polychlorostyrene film corresponding to the large and the small calorimeter with listing at their FWHMs and at their peaks.

Figure A3. The correlation of the energy recorded for the small (E_s) and the large (E_e) calorimeter through the density of the CL-25 polychlorostyrene film monitored at λ_1 .

2. Exposure measurements--Exposure measurements were obtained through the use of LiF (TLD-100) and $\text{Li}_2\text{B}_4\text{O}_7\text{:Mn}$, $1/8 \times 1/8 \times .035$ inch (TLD-800) crystals. We first used the LiF (TLD-100) crystals, but at the electron-beam energy and power density these crystals were subjected to, they discolored and cracked because their thermal limits were exceeded. The TLD-800 crystals survived and proved acceptable. These crystals have a useful range from one hundred rad to several million rad, a small energy dependence to photons, and a negligible fading of the stored signal at room temperature.

The TLD was read on an Eberline TLR-5 reader. A standard procedure was used. The light emitted by the heated TLD was read by a photomultiplier. The light output (LU) is proportional to the energy absorbed by TLD.

The TLD reading system was calibrated by making reference to TLD crystals exposed to numerous levels of ^{60}Co . The exposure-response curve generated, resulted in a conversion factor of .143 R/LU. The exposure levels for the electron measurements in this experiment are not true exposure, but rather relative response values equivalent to a ^{60}Co exposure.

Table A1 illustrates the shot number, the operating voltage (kV) on the charging capacitor of the Pebetron system, the light level (LU) emitted by the crystals, and the relative exposure (^{60}Co equivalent) in Rankins (R). The mean-free path of electrons in quartz is of such a nature that all the exposure measured by the TLD-800 should be absorbed by the FOW.¹⁶ At the 30-kV operating level of the Pebetron, the average exposure of the FOWs is then taken as the average of the 30-kV listing of 2.7×10^6 R (^{60}Co equivalent).

TABLE A1

CHARACTERISTICS OF EXPOSED TLD-800 CRYSTALS

Shot No.	Voltage (kV)	Reading (LU) $\times 10^7$	Relative Exposure (R) $\times 10^6$
1	30	1.90	2.71
2	30	1.89	2.69
3	30	1.75	2.50
4	30	1.99	2.84
5	30	1.93	2.76
6	28	1.84	2.63
7	28	1.69	2.42
8	28	1.77	2.54
9	28	1.87	2.68
10	28	1.74	2.49
11	26	1.82	2.60
12	26	1.67	2.39
13	25	1.80	2.57
14	26	1.74	2.48
15	26	1.65	2.36

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24. a. CGW fibers were Code No. 1452-1300 and Code No. 49-1003 OVPO with intrinsic attenuation of 3.7 dB/km at $\lambda = 820$ nm.
b. VC fibers were PC05 with intrinsic attenuation of < 40 dB/km at $\lambda = 820$ nm.

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