RADIATION EFFECTS ON A FIBER OPTIC REPEATER

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INTRODUCTION

A digital communication network using fiber optics is under consideration for the Booster. The main benefits of a fiber optic network are the electrical isolation of the network nodes and the immunity to electromagnetic interference. However, the benefits of a fiber optic system can be offset by the performance degradation caused by exposure to radiation. This study was undertaken to estimate the "order-of-magnitude" of radiation induced performance degradation on some typical fiber optic components.

Data from previous studies can be used as a guide for selecting the components for radiation tests. However, the data is directly applicable only under specific conditions. This is because the damage to a device, caused by radiation, generally depends nonlinearly on the dose rate and cumulative dose. As a result it is necessary to perform preliminary radiation testing ourselves.

For testing purposes, four fiber optic pulse repeaters using commercial grade components were constructed and tested. The fiber optic components used were the Hewlett-Packard HFBR-0400/HFBR-0410 evaluation kits. Each kit contains a matched pair of AlGaAs transmit and receive photodiodes and a short length of connectorized fiber optic cable. Some additional fiber optic from AMP was also used. In addition to the optical components, silicon bipolar ICs were used as part of the repeater circuitry. The objectives of the testing are outlined below:

- attenuation in commercial fibers (plastic and glass)
- degradation in the transmit and receive diodes
- degradation of the silicon bipolar ICs
- degradation of the repeater performance

The main result of this investigation is the confirmation of the result that commercial grade AlGaAs photodiodes performed well in radiation environments.[1] The transmit diodes tested displayed less than a 1 db reduction in optical output power after absorbing approximately 28,000 rads. The receiver diodes had less than a 2 db reduction in sensitivity after absorbing the same dose. Because of cladding mode

propagation effects which are prevalent in short (≤30 m) fiber optic cables meaningful measurement of the fiber attenuation were not possible. The only valid conclusion concerning the cables is that the 2-6 m long cables provided adequate operation in this application at the radiation levels absorbed.

The remainder of this paper discusses the following topics:

- test set-up
- test method
- basic circuit design for the repeaters
- performance degradation of the repeater components
- performance degradation of each repeater
- conclusions and recommendations

TEST SET-UP

A diagram of the test set-up is shown in Figure 1. As shown in the figure there were four repeaters tested. Each repeater was tested using a digital pulse train output from a variable pulse generator. The repeater then converts each electrical pulse into an optical pulse. The optical power in each pulse was controlled by the power supply output voltage Vp. The optical pulses traveled through a fiber optic cable and then were converted by the repeater back to electrical pulses. The electrical pulses were then output by the repeater and sent to a digital storage oscilloscope for measurement and observation. The oscilloscope was also used to measure the pulse generator form parameters. For measurement of the diode forward voltage (Vp) and forward current (I_f) outputs two digital voltmeters were used.

To monitor the ionizing radiation environment thermo-luminescent detectors (TLDs) were placed on all the components. The maximum cumulative dose that can be measured by the TLDs is approximately 10^4 rads with an accuracy of 10 - 20%. Therefore, to measure the expected cumulative dose of greater than 2 x 10^4 rads, several sets of detectors were required. Each set of detectors was limited to exposures of less than 5 x 10^3 rads. Neutron detectors were not used, because none could be located in the time frame available for setting up the test.

TEST METHOD

Listed below are the system parameters that were measured (as a function of cum dose) during the test:

- Rise/fall time of repeater output
- Propagation delay of repeater
- Pulse width distortion
- Output pulse amplitude variation
- Optical receiver detection threshold current
- Transmitter diode current vs. control voltage

FIGURE 1 TEST SET-UP

- Maximum pulse repetition frequency of the repeaters
- Total dose effects on transmitter photodiodes
- Total dose effect on cable attenuation

In the pre-irradiation bench testing all of the components and repeaters were tested to determine the initial value of the circuit parameters. One fiber optic component of each type was selected at random for use as a "calibrated" reference to maintain a consistent measurement standard for the post-irradiation testing. After the pre-irradiation testing was completed the repeaters were placed in the ring, near the F-20 magnet, and tested again. This allows the effects of the cabling to the AGS ring to be separated from the circuit performance. At the conclusion of the irradiation, the hardware was removed from the ring and bench tested again. In the post-irradiation tests the reference components were substituted into the test set-up to aid in determining the degradation of the irradiated components. A complete discussion of the results of this experiment is the section labeled Experimental Results.

For several weeks during the high intensity high energy proton run, every four to six calendar days a complete set of tests were performed. The test set consisted of:

- DC forward current vs V_D for each transmit diode
- Pulse propagation delay for each repeater as a function of I_f
- Pulse width distortion for each repeater as a function of I_f
- Repeater output pulse rise/fall times as a function of I_f
- Operating frequency for each repeater at 25 ma and 50 ma

During the test the AGS circulating and extracted beams were monitored (Figure 2) and from this data the beam losses were determined (Figure 3). the beam was sampled approximately once every sixty minutes by the current AGS beam monitor and the data was recorded on the DEC-10 computer. The computer also records the repetition rate of the AGS at the time the sample is taken. Where there were "gaps" in the data (i.e. due to DEC-10 being off-line) the main control Log Book was used to fill in the missing samples. The samples of beam intensity were then used to generate the total number of protons accelerated and lost by assuming the recorded repetition rates are constant for each hour. The hourly data was then compressed into eight hour shifts and graphed as shown.

REPEATER DESIGN AND OPERATION

Four pulse repeaters (2 low speed and 2 high speed) were built using three different combinations of optical components. Two of the repeaters used 2 m long ST-connector 50/125um glass core cable and low speed photodiodes. The low speed photodiodes have a 2.5 MHz bandwidth. The other two links both used higher speed photodiodes 25 MHz bandwidth and SMA terminated cable. One of the high speed links used a 3 m long 1000 um plastic core cable. The other used a 6 m long 50/125 um

AGS CIRCULATING BEAM DURING IRRADIATION
OF FIBER-OPTIC LINKS AT F-20

ICBM-SUM	+ CBM-SUM	◇ 3CBM-SUM	△ XCBM-SUM
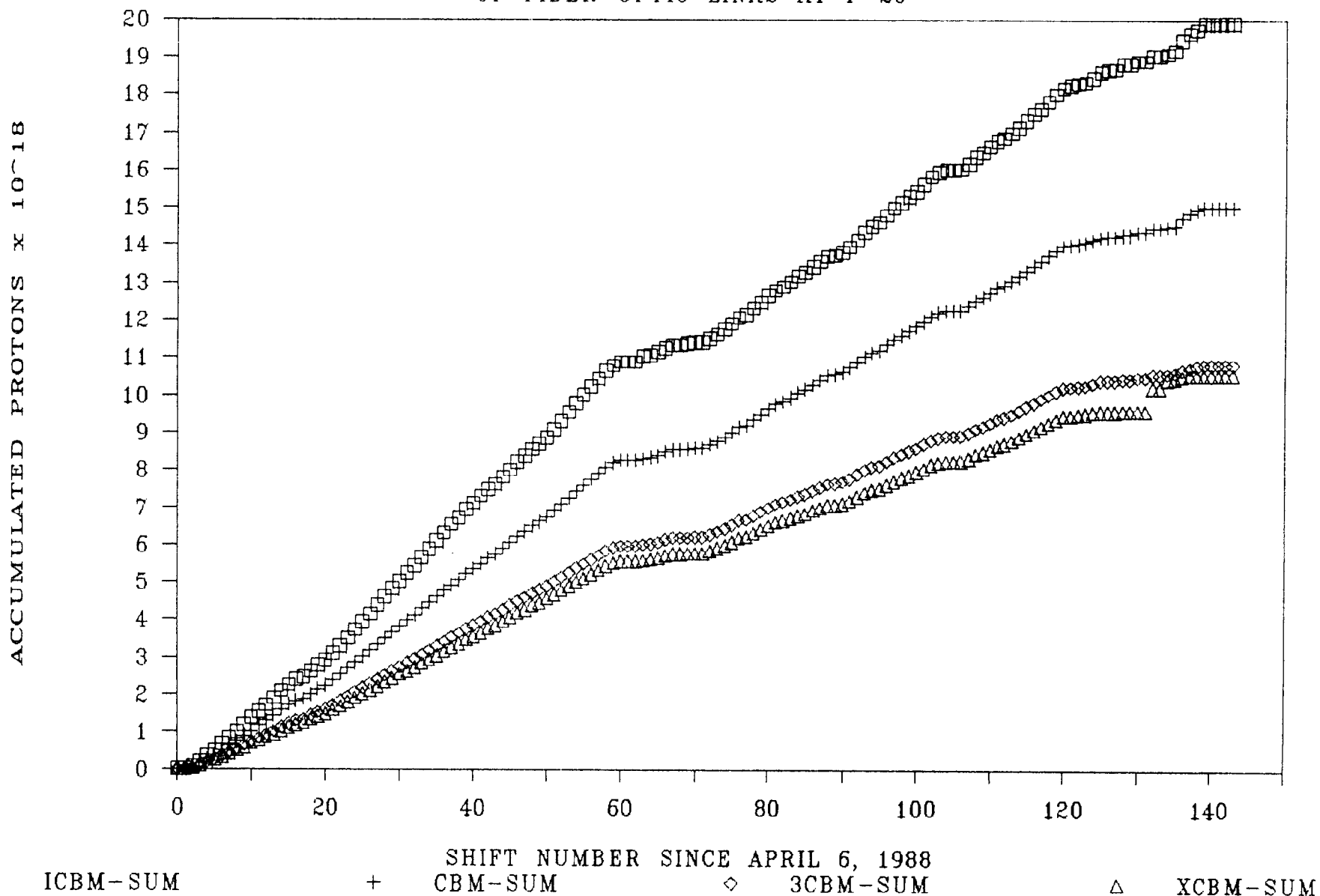
FIGURE 2

AGS BEAM LOSSES DURING IRRADIATION
OF FIBER-OPTIC LINKS AT F-20

LOST PROTONS x 10^18

SHIFTS SINCE APRIL 6, 1988

OSSES   +   TRANS/ACCEL LOSSES   ◇   EXTRACTION LOSS
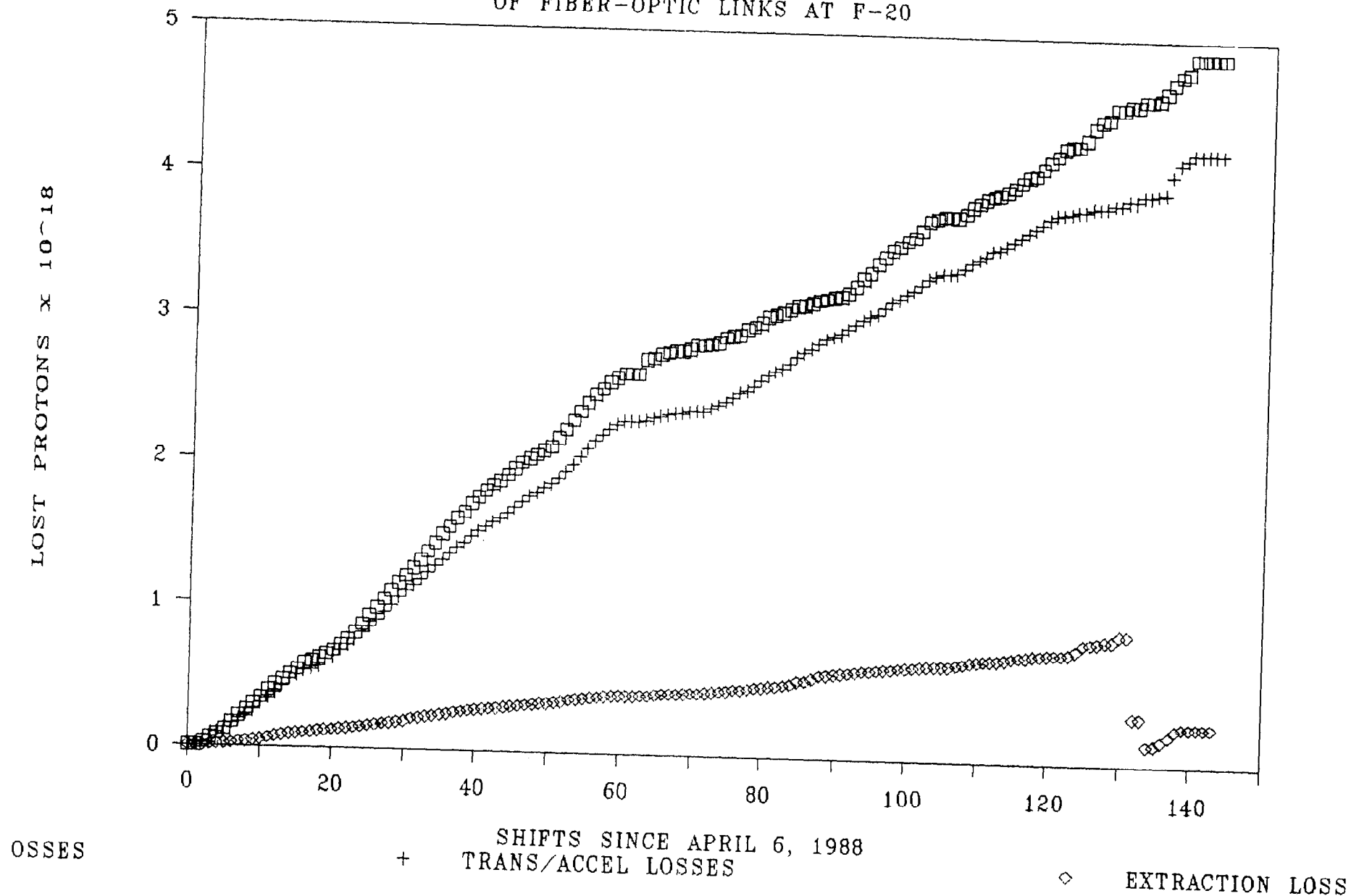
FIGURE 3

glass core cable.

The circuit design for all four repeaters is very similar (see Figures 4 nan 5 . Both circuits use a 100 Ohm termination at the input to reduce the voltage reflections caused by the fast pulse edges (5-50 ns). The LM319 is set-up as a pulse squarer. This circuit eliminates the effects of capacitive loading of the long coaxial input cables. The transistor is driven by the comparator and acts as a voltage controlled current switch. When the switch is closed (saturation) the fiber optic diode emits a light pulse. The optical power transmitted depends on the value of V_p. The light pulses travel through the fiber optic cable into the receive diode. The the low speed link the receiver module consists of a open-collector Schotky transistor. Therefore, the receiver module directly converts the optical pulses into digital electrical pulses. In the high speed link, the receiver module consists of only the photodiode. Therefore, the output is analog with an output voltage range ≤ 1 V. To regenerate the digital nature of the input pulses, another comparator was used. In both the low and high speed circuits an LH0002 is used as a current buffer to drive the coaxial output cable.

EXPERIMENTAL RESULTS

This section will discuss the results of the experiments performed during the radiation testing. Summarized below are the effects of radiation on the:

- Narrow band transmit and receive LEDs (HP-2412/HP-1412)
- Wide band transmit and receive LEDs (HP-2404/HP-1404)
- 3 m ST-connectored 50 um glass core cables
- 6 m SMA-connectored 50 um glass core cables
- 2 m SMA-connectored 1000 um core cables
- Low speed repeater links
- High speed repeater links
- Semiconductor electronics

LEDs

A graph of diode forward current vs. power output for the low speed and high speed transmitters are shown in Figures 6 and 7. In both figures the reference (non-irradiated) and irradiated diodes are denoted with the markings C, 1 and 2 respectively. All of the diodes irradiated received approximately 28,000 rads. This is equivalent to the estimated dose for a 5 year exposure at a typical point and a 1 year exposure at a worst case point on the floor in the Booster [1,2]. The low speed diodes have output maximum power deviation from the reference diode of 1 db (Figure 6), while the high speed diodes (Figure 7) deviate by less that .25 db. Also, the transmit-transmitter forward current vs. applied voltage (V_p vs. I_f) characteristic was moni-tored and it was unaffected by the radiation.

Both the low speed and high speed receivers showed less than a 2 db increase in the receiver's optical power threshold. This estimate of receiver degradation was
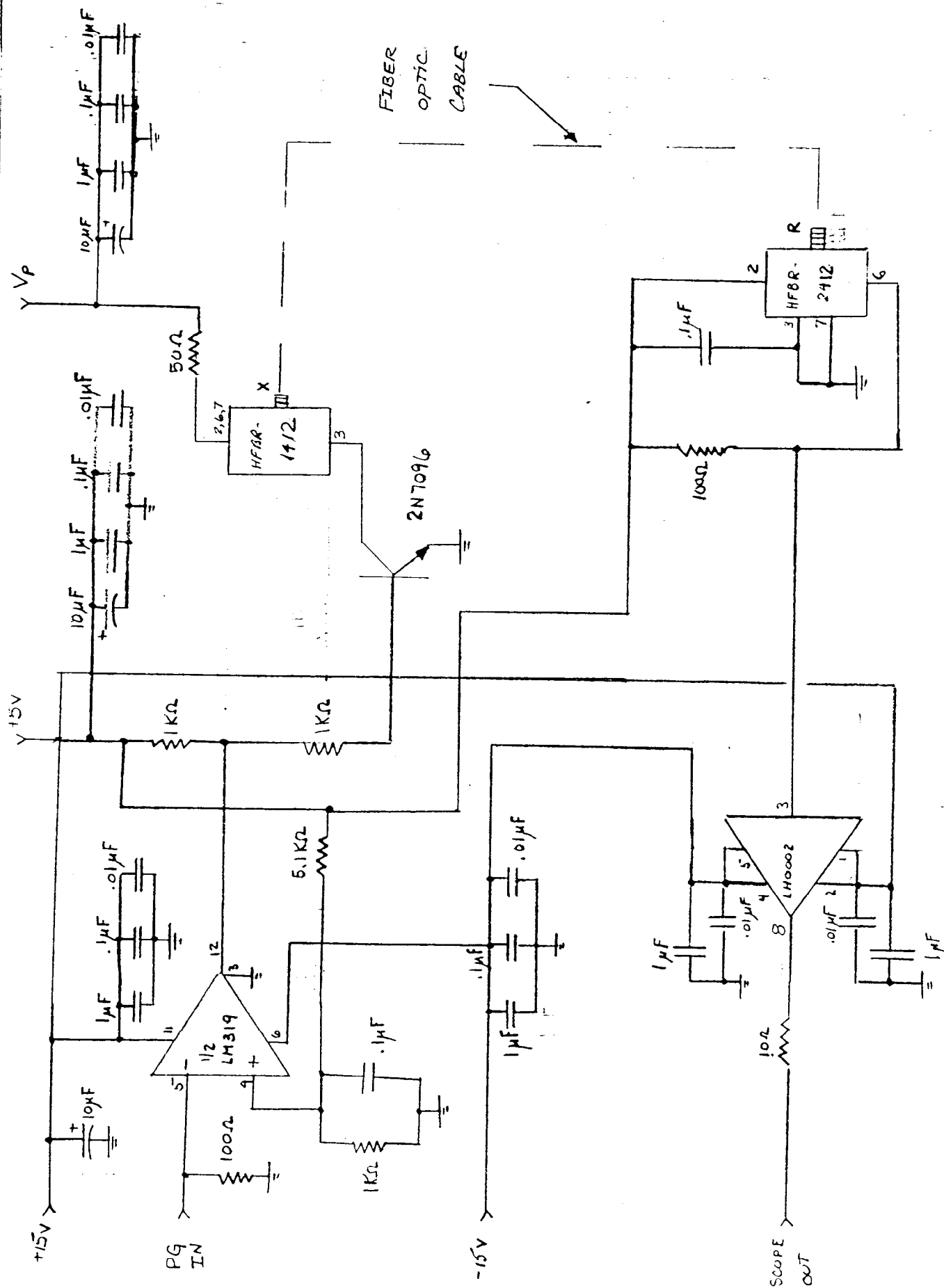
HFBR-1412/2412 F.O. LINK

ERB

4-7-88

(Low Speed Link)

FIGURE 4

FIGURE 5

HFBR- 1404/2404 F.O. LINK

4-7-88   ERB
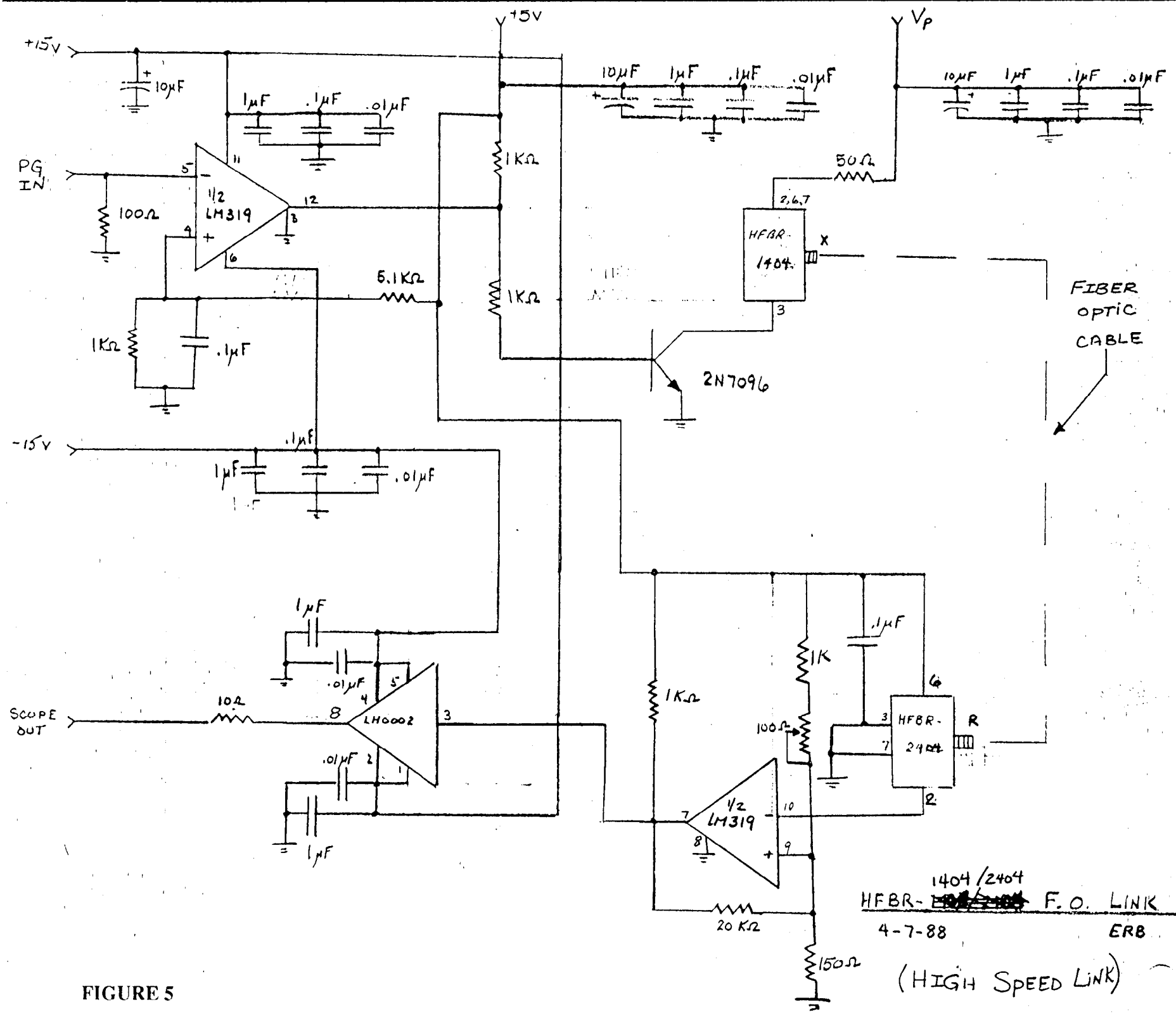
(HIGH SPEED LINK)

FIGURE 6

HIGH SPEED DIODES

C = CONTROL DIODE
1 = 14-1 DIODE
2 = 14-2 DIODE
(NOTE: #1 & #2 RCVD ~3×10⁴ RADS)
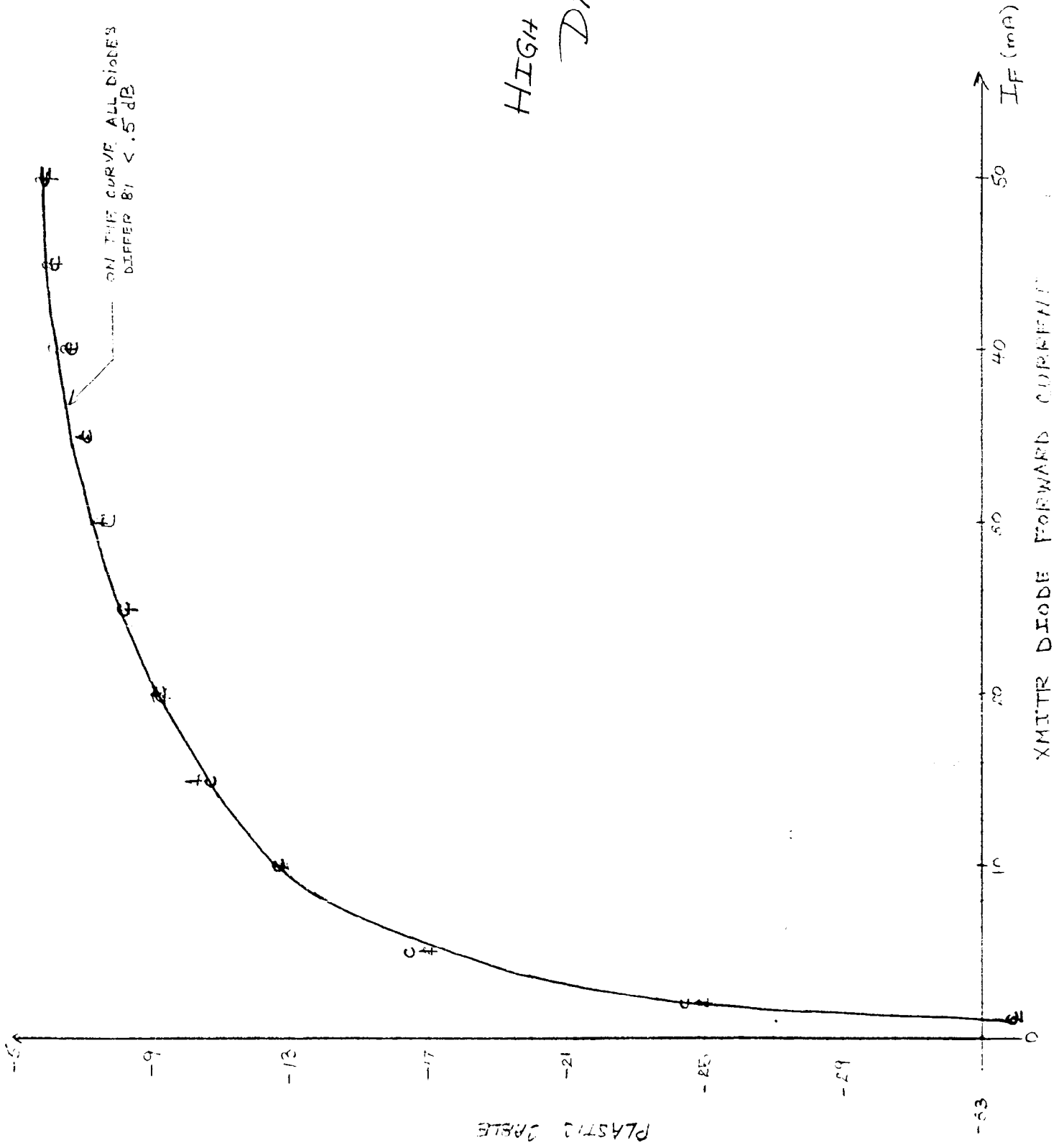
ON THIS CURVE ALL DIODES DIFFER BY < .5 dB

I_F (mA)

XMITTR DIODE FORWARD CURRENT

OPTICAL POWER RCVD IN A 3M (1000μm) PLASTIC CABLE

-5   -9   -13   -17   -21   -25   -29   -33

50   40   30   20   10

FIGURE 7

DATE 3.21/82   BY ERB
CHKD. BY   DATE
DEPT OR PROJECT
SUBJECT   JOB No.
SHEET No.   OF

CABLE TYPE	CORE MATERIAL	CABLE DIAMETER	ABSORBED DOSE	TOTAL ATTENUATION INCREASE	LENGTH	
ST-CONNECTORED	glass	50/125μm	25,000 R	.1 dB	3m	
ST-CONNECTORED	glass	50/125μm	25,000 R	.3 dB	3m	
SMA-CONNECTORED	plastic	1000μm	21,500 R	.4 dB	2m	
SMA-CONNECTORED	plastic	1000μm	21,500 R	.9 dB	2m	
SMA-CONNECTORED	glass (Si)	50/125μm	≈11,000	3.9 dB	6m	*
SMA-CONNECTORED	glass (Si)	50/125μm	≈11,000 R	3.7 dB	6m	+

FIGURE 8   TABLE OF CABLE PERFORMANCE

* ONLY CABLE IRRADIATED IN "INACTIVE" STATE

+ CABLES SWAPPED BECAUSE OF LINK FAILURE

made by testing for a difference in forward current threshold between optical links using the reference and irradiated receivers.

The main result of the diode testing is the confirmation of the previously published data that commercial grade AlGaAs LEDs perform well in radiation environments. This is significant for two reasons. The first is that radiation induced degradation of the transmitters and receivers does not have a significant impact on the link optical power budget. Secondly, the cost savings of using commercial components rather than rad-hardened ones is substantial. Also, we have found that radiation induced damaged to the photodiodes appears to be independent of the diode's bandwidth. This result is significant because there is a large selection of higher speed (≥ 50 MHz) AlGaAs and GaAs LEDs available off-the-shelf.

CABLES

The performance of the irradiated cables is summarized in Figure 8. While the cables were being irradiated they were in the "active" state (guiding light) greater than 95% of the time. The optical power sent through the cables was in the mid-range of the transmitter's capability. Also, the cables did not show any externally visible signs of damage nor did they become brittle.

Because the cable samples tested are very short, the measurements made during this test are not to be a valid indicator of the performance of longer cables (i.e. ≥ 30 m). This is because in short cables the cladding can carry a significant portion of the optical power to the receiver. Therefore, even if the core fiber is damaged so that it attenuates all the light entering the core, the cladding will still pass some optical power. This effect is known as cladding mode propagation and this can greatly distort the measurement of the attenuation of a core material when using an optical power meter. Also, data gathered from this test should not be extrapolated for prediction of long length cables because of the cladding mode propagation becomes negligible after approximately 30 m. Therefore, in the future to test for radiation damage to a core material, cables greater than 30 m should be used.

LINK PERFORMANCE TESTING

The low and high speed fiber optic repeater link testing and performance results are summarized in this section. The link parameters measured during the testing are summarized below:

- Output pulse rise/fall time
- Propagation delay
- Output pulse width
- Forward current threshold
- Output pulse amplitude (high/low)
- Data rate

The high and low speed link rise and fall times both during and after irradiation were found to be within 10% of their initial (non-irradiated) values. Also, the link propagation delay of the low speed link (trr, trf) and the high speed link (trf,tfr) remained within 10% of their initial values. The repeater's electrical output pulsewidth for both links varied less than 6%, and in most cases was within 3% of their initial values. It should be noted that some of the parameter variatons are due to the limitedresolution of the test set-up. As expected, there was some pulsewidth distortion present at current levels near the current thresholds and this was due to the amount overdrive used drive the transmit LEDs. During each test run the forward current threshold for each link was recorded. The low speed repeaters demonstrated an increase from 4.5 mA and 5 mA to 6.3 mA and 8.2 ma, respectively. The change in forward current corresponds to an increase in optical power of 1.6 db and 2.1 db. The high speed link showed an increase from 8.6 mA to 18 mA (1000 um core), and the other link increased from 7.4 mA to 41 mA (50 um core). These increases occurred gradually during the irradiation portion of the test. In this case the change in forward current corresponds to an increase in optical power of 2.8 and 4.2 db. In the low speed link it has been determined that the increase in the forward current threshold is due to the receiver degradation. In optical links significantly longer than 3 m this may not be the case because of increased signal loss in the optical cables. In the high speed links the receiver degradation and the higher cable attenuation both contribute to the increase in the forward current threshold. Finally, the maximum pulse repetition frequency (PRF) of each of the repeaters was tested. This test was performed by visually observing the repeater's electrical pulse output (repeated waveform) on the oscilloscope. Each time this test was performed the same PRF was used and the output waveshapes were compared with the previous test. Over the course of the testing, the maximum PRF did not decrease. However, it is important to note that the PRF of the repeaters was limited by the LM319s and not the LEDs.

The 50 um core high speed link failed twice during irradiation. This is because of the minimal optical power budget available when using mis-matched LEDs and cables. The cables have a 50 um fiber and the HP 1404 diodes are designed for matching to 1000 um cores. The mismatch in diameter causes a large loss of optical power at the transmitter. This loss degrades the optical power margin by the ratio of the diameter mis-match, approximately 13 db in this case. After taking the optical loss into account the power budget (power margin) was approximately 6 db. The result is that even a small amount of radiation induced damage can render the link inoperable. In this case the cables have an induced attenuation of 3.7 - 3.9 db and the diodes degraded an additional 2 - 3 db. Thus, the total loss in the system is 5.7 to 6.9 db. This exceeds the power budget and causes the links to fail without any components being dramatically effected. Therefore, it is very important to match all the system components for optimum performance.

ELECTRONICS

No bipolar IC failures attributable to radiation damage occurred. The only component failure was an LH0002 that pulled the ± 15 V supply rails down. This

failure was quickly corrected without impact on the test. No failures of the epoxy block power supplies were observed.

CONCLUSIONS

The test results indicate that unshielded optical links can withstand a cumulative dose of ionizing radiation equivalent to a 5 year exposure at a typical point on the floor of the Booster.[2] Published data indicates that unshielded optical links of 10 - 20 m, with proper component selection, can withstand a dose equivalent to more than a 50 year exposure at a typical point on the floor.[1,2] To further quantify the achievable level of performance of an optical system in the Booster a second phase of testing is required.

For the second phase of testing several fibers should be procured and tested in a radiation environment similar to that of the Booster. In this phase of testing both neutron fluence and ionizing radiation levels should be monitored. This is because both types of radiation can have significant effects on semiconductor and fiber optic components. Also, long lengths of cable (20-100 m) should be tested in order to remove the effects of cladding mode propagation. In selecting the fibers attention should be paid when specifying cable parameters such as:

- Core diameter
- Mode (single/multi)
- Index (graded/step)
- Core material
- LED wavelength

This is because the proper selection of these parameters can present certain advantages. For example, the larger diameter fibers (≥ 200 um) can be field terminated with less than a 1 db loss. This compares favorably with cable diameters below 50 um that can have field termination losses exceeding 10 db. Most published papers suggest that pure silica core stepped index fibers are the best choice for radiation environments. However, core materials other than silica should be fully investigated. One core material that should be fully explored is plastic because of the cost savings of plastic over silica core fibers.

There are also several diode manufacturers that should be surveyed because there are other higher speed GaAs LEDs, than the ones tested here, available as off the shelf items. Currently there are high-speed ($\geq$ 50 MHz) commercial grade GaAs-basedphotodiodes and rad-hardened fibers available that make it possible to construct rad-hard links capable of transmitting up to 100 Mbps (NRZ) data. These links can be designed and constructed inexpensively and in fact rad-hard cables, modems, and GaAs photodiodes are standard products of several companies.
The leading manufacturers seem to be Honeywell, Hewlett-Packard and Motorola.

Many of the components for testing, even the expensive ones, can be obtained

free of charge by sharing the radiation test data with the manufacturer. Already Hewlett-Packard and Hughes Aircraft have expressed this interest.

REFERENCE:

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2. A. Stevens, "Estimate of Radiation Environment in the Booster Ring", BNL Memorandum, September 30, 1987.