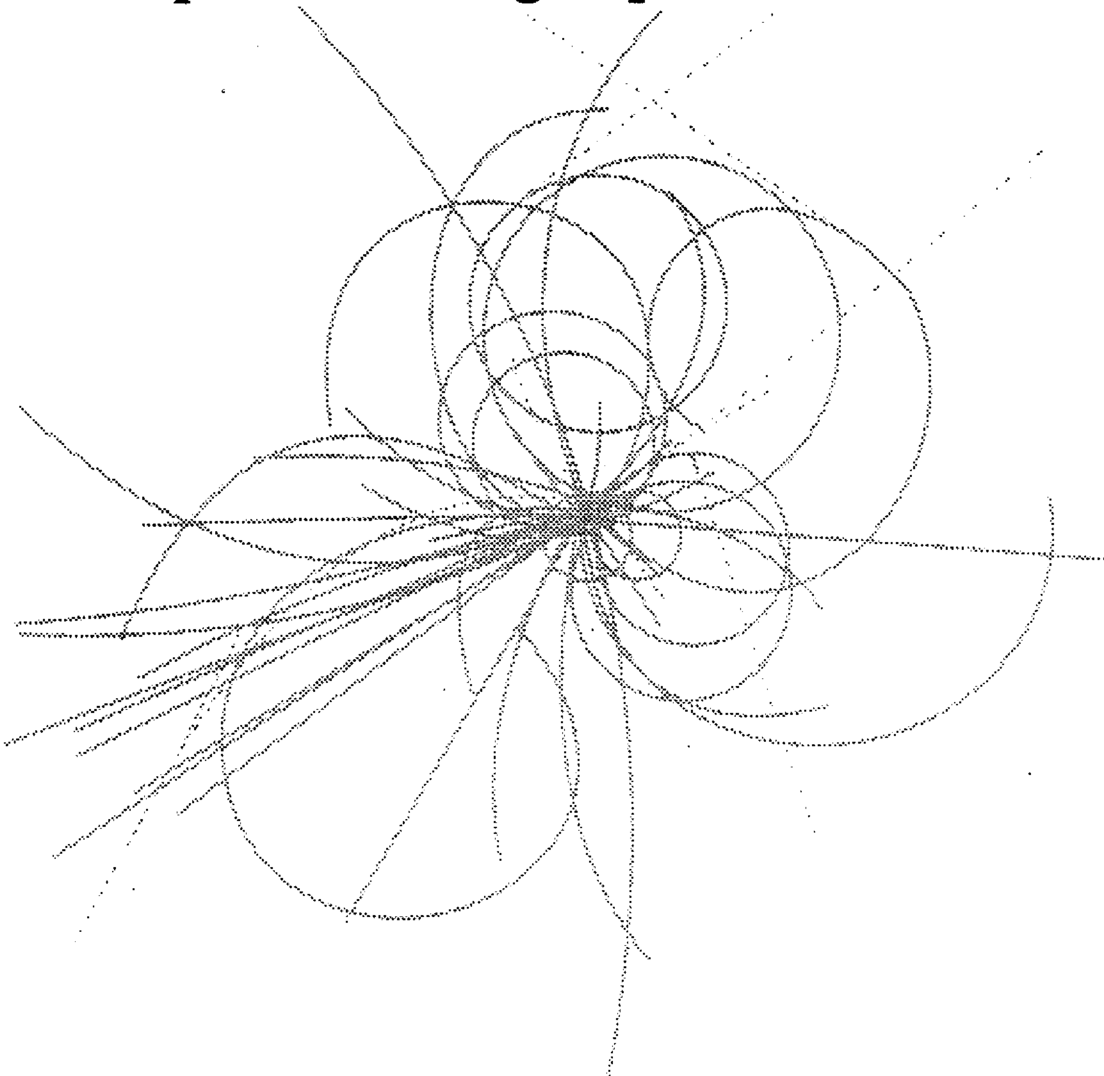
SSCL-261

Superconducting Super Collider Laboratory



Irradiation of Fiber Optics in the SSC Tunnel

C.E. Dickey

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* Operated by Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

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1. INTRODUCTION

The salient question is not whether optical fiber will survive in the Super Conducting Supercollider (SSC) tunnel, but rather how long will it survive. Current estimates indicate that single mode fiber under ideal conditions will have an expected lifetime of at least 25 years. Future development of optical fiber will lead to longer service lifetimes and increased radiation hardness. But conservatively speaking, current production optical fibers can probably not be depended upon for more than 25 years of service even under ideal conditions.

1.1 Radiation Damage In Optical Fiber

Optical fiber waveguides sustain damage when irradiated due to the development of color centers within the fiber core. The color centers are formed by radiolysis and the trapping of radiolytic electrons or holes in defect sites that either are inherent to the fiber or generated during irradiation. With the development of color centers, attenuation increases in the optical waveguide. The detailed characterization of these radiation induced effects depends on many factors related to fiber structure, radiation parameters, and operational considerations.

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These include the properties and composition of the fiber core and cladding material, dose rate, total dose, radiation type and energy, fiber operating wavelength, intensity, and temperature.

Radiolytic activity is expected with ionizing radiations. It is well known that the presence of oxygen in the fiber core can cause a high sensitivity to ionizing radiation since oxygen can become involved in free radical chemistry initiated by irradiation. Neutrons also cause extensive damage to optical fiber primarily as a result of intermediate reactions which produce high energy alpha, beta and gamma secondaries. Currently many optical fibers contain boron in the cladding material and probably in the fiber core as well. Boron has a well known affinity for neutrons. Boron's capture cross section is 759 barn. In comparison the capture cross section of fluorine, which is often used with or in place of boron as a cladding doping material, is 0.16 barn.

Radiation induced attenuation manifests itself in permanent and metastable components. Permanent attenuation is of primary interest when considering the use of optical fiber in the SSC tunnel. The metastable components are chiefly associated with pulsed radiation and have been studied extensively in the past to characterize fiber behavior in a transient thermonuclear environment. Consequently most metastable behavior studies have been conducted with pulses far beyond the levels anticipated for the SSC tunnel. Considering the relatively low level and steady state nature of radiation in the SSC tunnel, metastable behavior can be virtually ignored.

Radiation induced attenuation increases linearly with constant irradiation until. at higher levels. saturation occurs. Saturation is caused by a recovery process which occurs simultaneously with the attenuation increase. This saturation and recovery process is wavelength dependent and at higher wavelengths, saturation and recovery are important and tend to limit attenuation. At extremely high irradiations the optic fiber fails from embrittlement. Saturation and embrittlement failure will not be important factors for fiber optic cable located in the SSC tunnel due to the relatively low levels of radiation which are expected. Recovery will be difficult to characterize for low levels of irradiation. Recovery should probably be viewed as simply a factor in our favor, the effects of which tend to reduce attenuation.

Radiation induced attenuation is also dose rate dependent. Attenuation increases with increasing dose rate. This effect may be related to recovery. Since the irradiation rates expected for the SSC tunnel are very low, dose rate dependency is another factor in our favor.

Another important effect associated with irradiation of fiber optic cable is radiation hardening. After pre-irradiation and recovery, optical fiber displays a resistance to further increase in attenuation when again irradiated.

There are several important conclusions that can be drawn from understanding the basic physics of optical fiber irradiation effects:

1. Since oxygen content in the fiber causes high sensitivity to ionizing radiation, optical fibers with pure silicon cores are indicated as the preferred type.
2. Since boron content in the fiber cladding increases the fiber's sensitivity to neutron radiation, optical fibers that do not include boron in the cladding are indicated.
3. It is obvious from elementary radiation physics that the fiber core diameter should be as small as feasible in order to present the least possible cross section to the radiation flux. For this reason, single mode optical fibers, which have the smallest fiber core diameters, are the indicated type. (As an aside, gallium arsenide electronics and lasers tend to be more radiation hardened than silicon-based devices. This is due to the narrow channel construction employed in gallium arsenide semiconductors. In this matter we are fortunate since the high performance laser fiber optic drivers and detectors are gallium arsenide based. Currently, the low level Time Division Multiplexing (TDM) chip sets that are being contemplated for

use in the SSC tunnel are silicon based. Higher performance TDM electronics contain gallium-arsenide-based chip sets. Depending on the cost, it may be worth considering obtaining gallium arsenide chip sets for their inherent radiation hardness.)

1.2 Radiation Levels in the SSC tunnel

It has already been alluded that two principle types of radiation must be considered in the SSC tunnel. These two types of radiation are ionizing radiation (predominantly gamma) and neutrons. It will be shown later that the total ionizing radiation levels which have been estimated to be present in the SSC tunnel will have insignificant effects upon the optical fibers. The effect of neutrons on optical fiber has not been investigated until recently. However, the experimental literature indicates that the neutron flux estimated to exist in the SSC tunnel will also have an insignificant effect on optical fiber. A third type of radiation, high energy protons, should also be mentioned. Protons are, of course, ionizing radiation and would likely be very destructive to fiber optic cable and electronics. Leskovar [20] has found that 16 MeV protons are 26 times more destructive to electronics than 16 MeV neutrons.

Neutrons are generated when beam protons collide with gas molecules present in the bore tube vacuum. These neutrons are present in a fairly broad spectrum which is likely to be centered at about 1 MeV. (See Figure 1.) Simulation studies have indicated that about 80% of the neutron flux will be isotropic and about 20% direct. The isotropic nature is cause by neutrons being reflected from the tunnel boundaries and various objects.

As Toohig, [6] Groom [5, 7] and Wilcox [8] have estimated the levels of radiations likely to be present in the SSC tunnel, these estimates were focused on the niches and in the tunnel itself. While levels of radiations present in the niches are of interest, of equal or greater interest, are the levels that will be present inside the fiber conduits located under the concrete tunnel floor. Apparently no estimates have been made for the fiber conduit radiation levels.

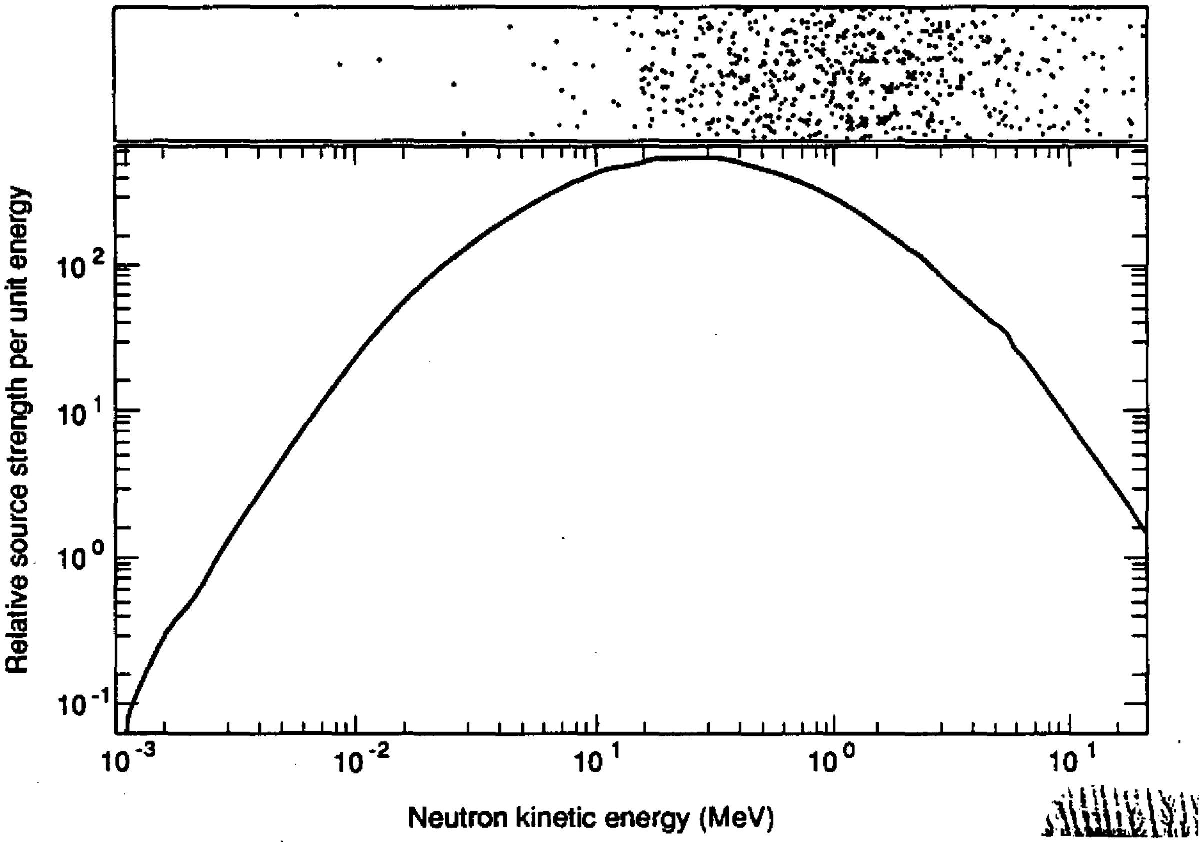

Figure 1. Predicted neutron energy spectra.

For a 2-ft shielded niche, the neutron flux estimate is:

$$\phi = 4.04 \times 10^7 \ \mathrm{n/cm^2/yr}$$

and for an unshielded niche, the gamma flux estimate is:

$$\phi = 3.45 \times 10^{-3} \ \mathrm{Gy/yr} \ (\text{where } 1 \ \mathrm{Gy} = 1 \ \mathrm{J/kg}) \,.$$

To proceed it can be argued that radiation levels in the fiber conduits will be near the levels in the niches. First, considering that the neutron flux is highly isotropic, distance to source effects tend to be minimized. Second, the fiber conduits will be covered with a thickness of concrete which can be assumed to be near the 2-ft thick shield thickness used in the niche level estimates. However it is clear that the thickness of the floor concrete must be specified and calculations may need to be performed to estimate the neutron fluence in the fiber conduits.

1.3 Compilation of Relevant Experimental Results

Previously it was argued that single mode fiber was preferred due to its smaller fiber core diameter. Figures 2 and 3 permit comparison of current state of the art radiation hardened fibers from Sumitomo and AT&T. Note that at the 1300-nm wavelength, the single mode Sumitomo fiber, which has the smaller core diameter, is considerably less sensitive to ionizing radiation. (The necessary conversion is: 1 rad = 0.01 J/kg = 0.01 Gy.) The Sumitomo fiber's attenuation is about 1 dB after a total dose of 760 Gy (76 krad), while the multimode fiber has developed about 17 dB of attenuation for the same total dose. (The Sumitomo fiber has a core diameter of 8.3 μmeters and the AT&T fiber has a core diameter of 50 μmeters.) We also may now compare the expected ionizing radiation levels given previously to the fibers' sensitivity.

Over a 25-year period, a fiber located in the tunnel should see approximately 0.0863 Gy, or equivalently 8.63 rad. Referring again to Figure 2, note that a total ionizing dose of 1000 Gy has produced a little more than 1 dB of attenuation. Therefore, the 0.0863 Gy lifetime dose that is expected to occur in the SSC tunnel will produce an insignificant attenuation increase in the fiber optic cable. Even if actual ionizing radiation in the SSC tunnel turns out to be one thousand times greater than the estimate, the increase in attenuation in the optical fiber over a 25-year period will still be insignificant. Keep in mind that with neutrons, it is the ionizing secondaries that are the primary cause of attenuation increase and therefore ionizing radiation hardness remains an important figure of merit for an optical fiber.

It was previously stated that oxygen content in the fiber core results in increased radiation sensitivity. Figure 4 indicates the performance of a popular

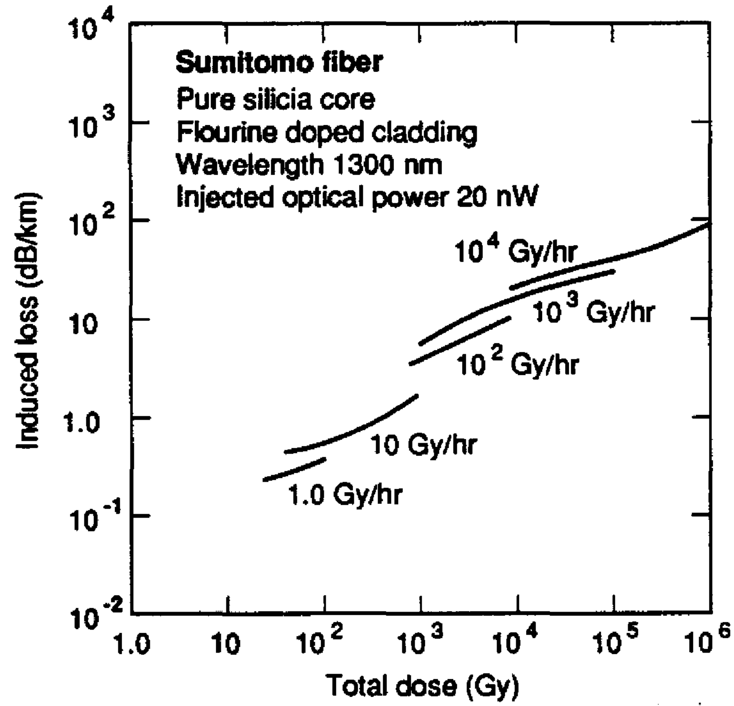

Figure 2. Current single mode rad hard fiber performance.

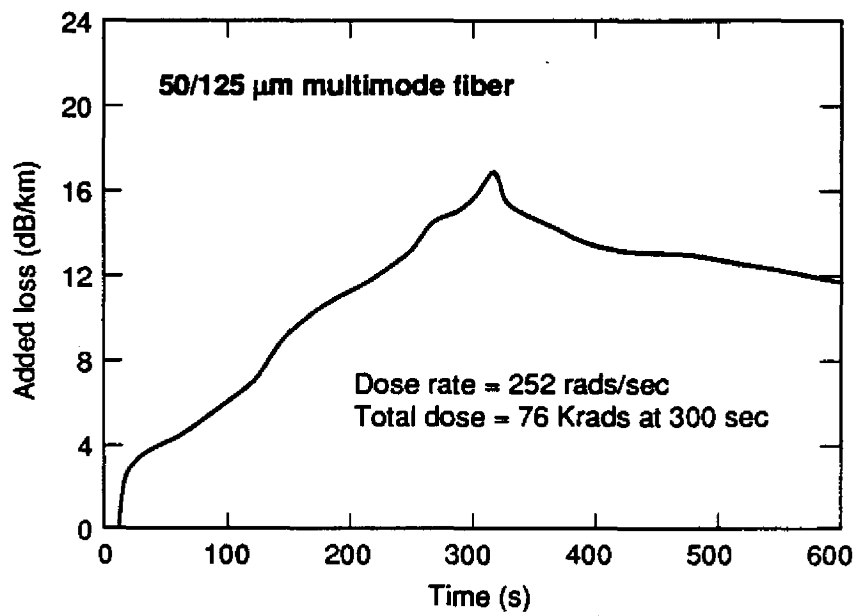

Figure 3. Current multimode rad hard fiber performance.

circa 1970 fiber FLUOSIL SS 1.4. This multimode fiber has a 100 μmeter diameter core of silicon oxide. Taking 20 dB as a reference attenuation level, note that the FLUOSIL fiber reaches 20 dB attenuation at 0.6 Gy (60 rad) total dose. Comparing this with the Figure 5 multimode AT&T fiber which has a pure silicon core, note that the reference level of 20 dB is reached after a total exposure of about 7600 rad. While this comparison is not totally fair since the FLUOSIL fiber has a larger core diameter than the AT&T fiber, it is nevertheless clear that the pure silicon core fiber is at least 50 times more radiation hard than the silicon oxide core fiber. If FLUOSIL SS 1.4 is compared with the Sumitomo single mode fiber in Figure 2 operating at 1300 nm, it is obvious that the development of radiation hardened fibers has been highly successful.

The presence of boron in the fiber cladding has been suspected of causing an increased sensitivity to neutron fluence. Figures 6 and 7 allow comparison of experimental results obtained from irradiating a fiber with 5% boron content in its cladding and a fiber without boron in its cladding. Figure 6 shows a plot of the results of irradiating the fiber sample without boron in its cladding. The five curves correspond to data taken at 1-hour intervals. Taking a reference wavelength of 750 nm the induced loss is near 13 dB. Figure 7 shows a plot of the results of irradiating the fiber sample with 5% boron in its cladding. Again taking a 750-nm reference point, note that the induced loss is near 40 dB. The total neutron dose in each of the cases was approximately 6.9 $\times$ 10E12 neutrons. This total dose corresponds to operating the machine for about 170,000 years at the neutron fluence estimated for the SSC tunnel.

Figure 6 also illustrates the saturation/recovery effect. Note that for lower wavelengths, the attenuation continues to grow with increasing irradiation. However, at higher wavelengths, saturation clearly limits the attenuation increase. Again, keep in mind that these levels of irradiation are far higher than those expected to exist in the SSC tunnel.

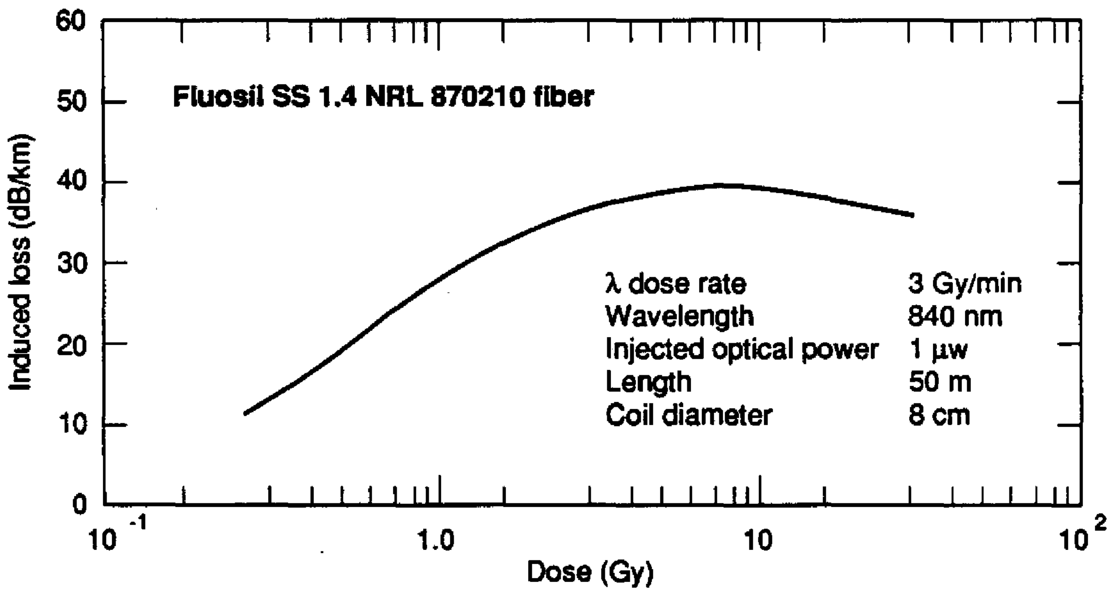

Figure 4. Attenuation increase in a fiber with silicon oxide core.

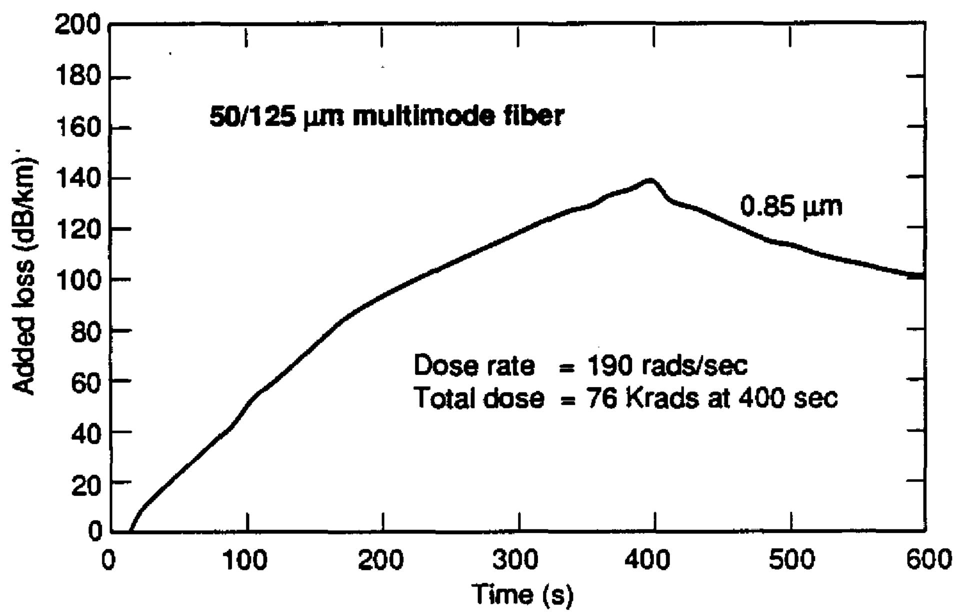

Figure 5. AT&T pure silicon core.

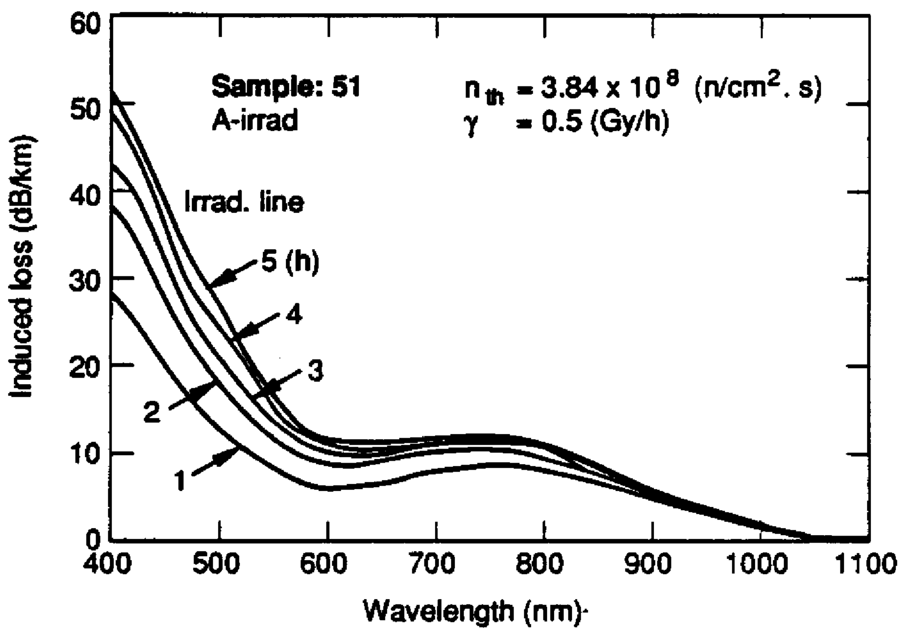

Figure 6. Attenuation increase in a fiber without boron doped clad.

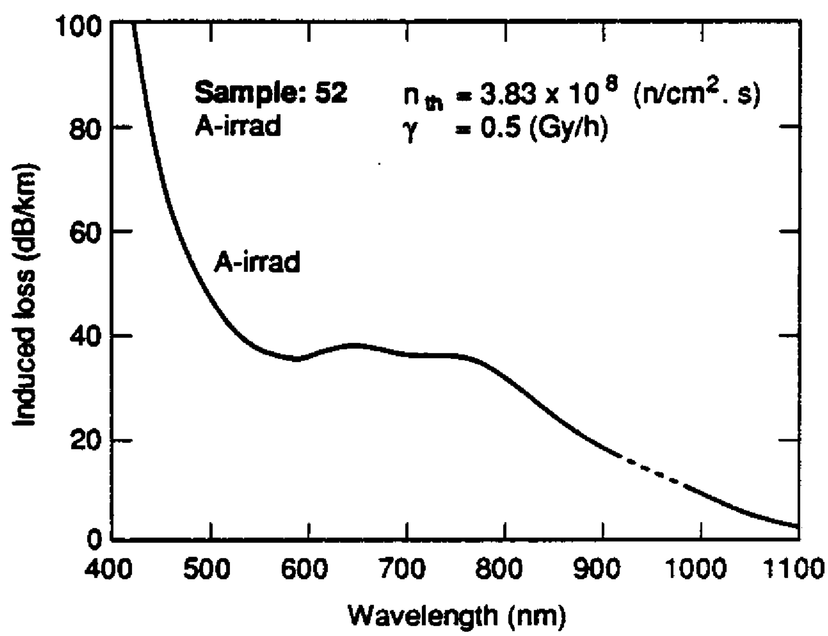

Figure 7. Attenuation increase in a fiber with boron doped clad.

Figure 8 shows results of a dose rate dependency study on a Sumitomo fiber. Note the increase in attenuation with dose rate.

Figure 9 shows the effect of radiation hardening on a FLUOSIL SS 1.4 fiber. This effect is very pronounced in this fiber.

1.4 CONCLUSION

A single mode radiation hardened fiber, operating at 1300 nm, using gallium arsenide laser sources and gallium arsenide detectors should be well within operational boundaries over a 25-year period. This conclusion is based on existing experimental literature, manufacturers data, and an understanding of the basic physics of attenuation increase due to irradiation in optical fiber. In addition this conclusion assumes that the estimated radiation levels in the SSC tunnel are realistic. It can be assumed that radiation levels near detector regions, drift spaces, transfer regions, dumps, etc., will be significantly higher than the estimates indicate. Whether these higher levels will present a significant problem is questionable and an estimate of the levels in these "hot spots" should be made. However, it does not seem unreasonable to replace optical fiber occasionally in areas of high radiation or to provide additional shielding in these areas with thicker concrete or boral conduit. (Boral conduit is constructed by encasing boron in aluminum. Boral shielding can be used to effectively attenuate neutron fluence.)

No data has been found which characterizes fiber optic operation at the levels expected to exist in the SSC tunnel. However there appears to be no reason to believe that unexpected behavior will be displayed at low levels of irradiation. An experiment could be performed at a nuclear reactor to study the effects of low level neutron irradiation on optical fiber. However the resources of a specialized nuclear reactor will be needed and it is important to keep in mind that counting neutrons is no simple matter. To perform such an experiment will require considerable resources. [Argonne National Laboratory is conducting low level neutron irradiation experiments on electronics. Argonne and SSC Laboratory personnel

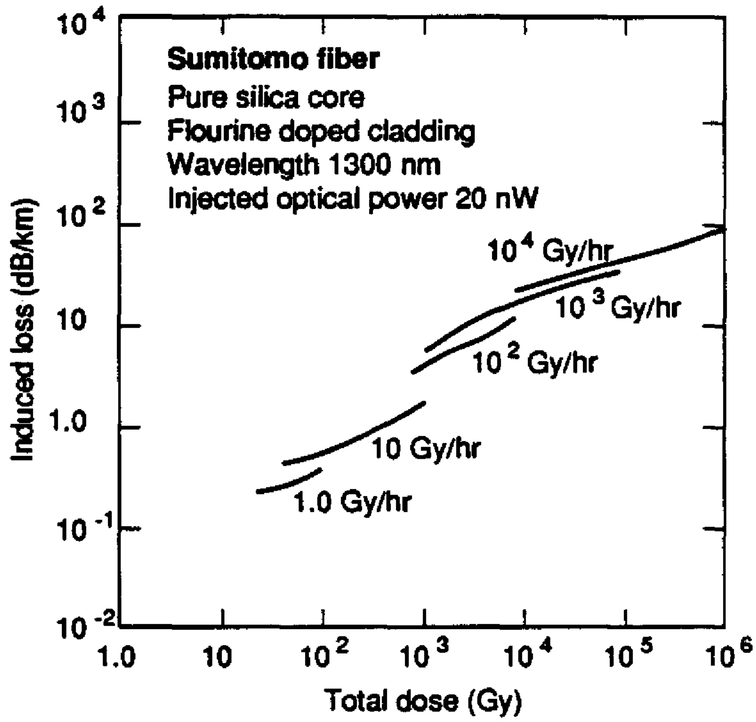

Figure 8. Rate dependency in an optical fiber.

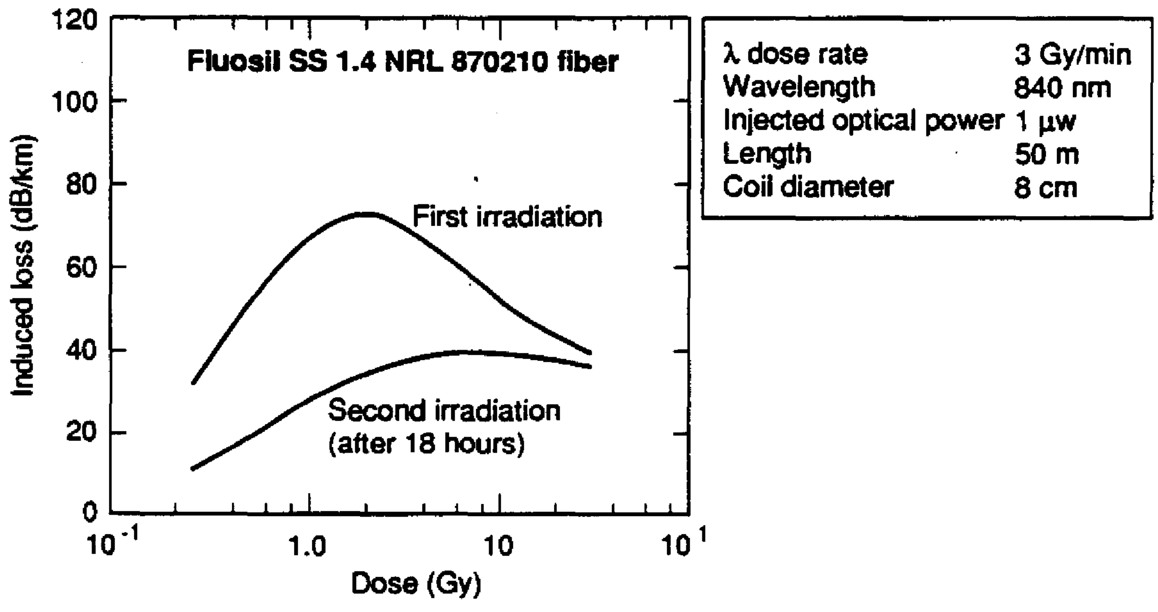

Figure 9. Radiation hardening in optical fiber.

may meet in the near future to discuss irradiation of optical fiber at low neutron fluences.] However any experiment that is conducted over a period of hours or days will still serve only as an approximation to the long-term behavior. It would take 25 years to fully qualify a fiber optic cable for use in the SSC tunnel. If fiber optic cable is used in the SSC tunnel, the application itself will be an experiment in the effects of low level radiation on optical fiber.

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