Measurements of the Tolerance of a Class of Flexible Polymer Optical Waveguides to Ionizing Radiation

Davis Hartman, Scott Sifferman, Mike Newman, Paul Armijo
General Dynamics, Advanced Information Systems
(480) 441-0219

Bruce Booth, Robert Furmanak
Optical InterLinks LLC

1.0 Background

Recognizing the need for space qualified leading-edge photonic components to support GWOT mission objectives, General Dynamics Integrated Space Systems (ISS) has been devoting IRAD resources to evaluating these kinds of components. Our Photonics in Space initiative, started in 2005, has focused strategically on intra-satellite interconnections, with the goal of reducing SWaP while enabling very high data rate scalable switching systems. Towards these objectives, GD-AIS supports and sometimes teams with small businesses developing leading-edge photonic components.

1.1 Optical InterLinks Polymer Waveguide Technology

At GD, we became interested in the physical properties of polymer based optical elements such as holographic optical elements (HOEs) and flexible polymer waveguides. Polymer waveguide materials such as the Optical Interlinks' GuideLink™ (see Figure 1) offer the ability to flexibly interconnect multiple signals over relatively short distances and to provide a mechanically compliant med a for mating to the active devices. These devices were used in the DARPA sponsored POLO (parallel optical link organization) project in the late 1990s.

Materials: Optical InterLinks' polymer waveguide technology is a combination of unique formulation and exposure processing that no other group in the world practices. It was initially developed nearly 25 years ago by the OIL team, when they were at DuPont, under the trade name PolyGuide™. The formulations consist of a special blend of multiple monomers and polymers. When exposed under UV light, the blend creates a completely polymerized cross linked film. Higher refractive index waveguides with a broad range of dimensions are formed due to diffusion of low molecular weight monomer into the photo-mask defined waveguide regions during initial exposure. Outer clad layers of a similar but slightly different monomer mix are laminated and bonded to the outside of the waveguide forming layer to create embedded waveguides. Monomers inter-diffuse between all layers further enhancing high relative index waveguide profiles.

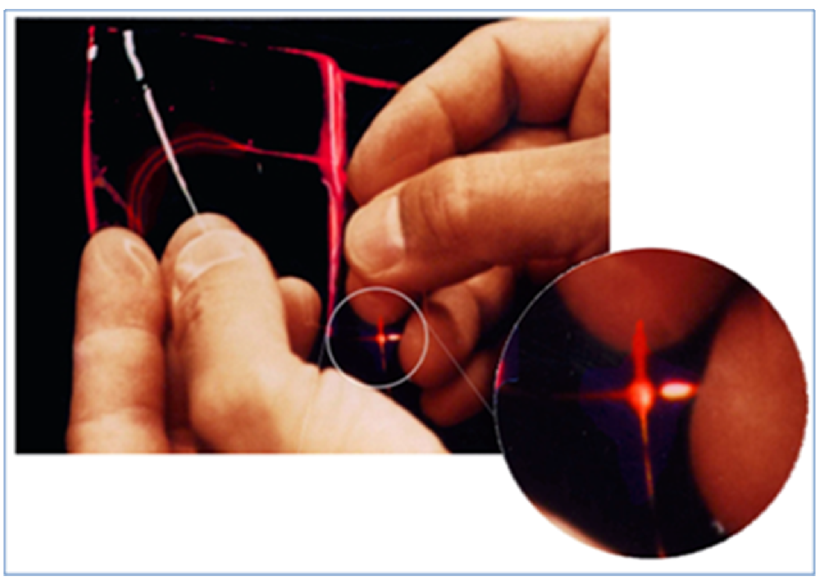

Figure 1: Flexible polymer waveguides

Processing: Photo-flooding polymerizes all remaining monomers leaving higher refractive index waveguides resulting from diffusion based monomer mass transfer into the guide forming region. A final heat-cure at over 125C for several hours assures complete polymerization and cross linking of all monomer. Protective polymer layers are usually laminated and bonded to the outside to insure an overall low CTE and high T_g system. Stable robust large film sheet structures are thus created ready for precision cutting into optical interconnecting waveguide links with multiple guide arrays with extreme high density spacing if needed, and functional devices such as splitters, combiners, star couplers, and sensors read heads. Novel low index regions can be imaged inside the multimode waveguides to create mode scramblers for stable and balanced device operation independent of modal input, efficient waveguide crossing for rerouting links, and efficient sensor read heads.

2.0 Measurements

The work reported here is the continuation of an earlier set of experiments, in 2006. GD obtained a set of polymer optical waveguides from Optical InterLinks LLC, and polymer holographic elements from Digital Optics, Inc. We exposed these components to moderated doses of gamma radiation (c. 125 Krads TID), and sought to measure changes in the optical properties. We found no evidence of damage. Due to funding limitations, the project went into abeyance until 2009.

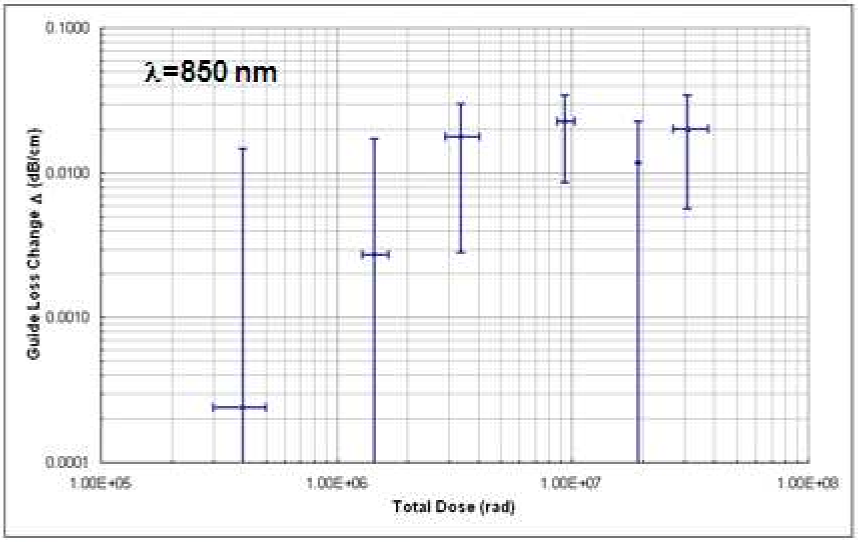

Figure 2: Gamma exposure data

With some internal funding GD performed another set of experiments on the polymer waveguides made by Optical Interlinks. In this set of experiments, we sought to irradiate with a suite of sources and doses sufficient to damage the devices in a measurable way. We describe in this report the results of this experiment. Our most important result is that the effects of the radiation on the optical waveguide loss is so small that trends and effects are only within one measurement standard deviation at best.

2.1 Gamma Irradiation Measurements

Twenty waveguide strips (typified in Figure 1), having three waveguides on each strip, were irradiated at the Arizona State University Radiation Damage Facility. The source was Co^{60} (1.2 MeV). The average dose rate was 14,532 R/min (free air), and the average distance of the DUTs from the source was 25 mm. A variety of total dose exposures were done with the available samples. These measurement sets were binned (as shown in Figure 2) to provide optimum data statistics.

The waveguides were fabricated and measured for waveguide loss at Optical InterLinks LLC (Kennett Square, PA). The measurements were made both before and after exposure. Some waveguides were re-exposed to higher levels, the result being a set of data with varying degrees of irradiation and varying sample size. Appendix 1 gives a representative example of the raw data as received from Optical Interlinks after guide loss measurements were made.

The plot in Figure 2 shows the aggregated data from these exposure exercises. The horizontal error bars represent aggregated runs having total exposure dose within the error bars. This binning was done to provide sufficient statistics to minimize vertical (guide loss change) errors. Because the incurred guide losses were small (in the 20% range), instrument errors were significant.

2.2 Neutron Irradiation Experiments (first set)

Because the measured results from gamma irradiation were smaller than anticipated, we proceeded to prepare another set of samples for irradiation using the University of Massachusetts Lowell Radiation Laboratory (UMLRL) Fast Neutron Irradiation (FNI) Facility. Fast neutrons for atomic displacement research are produced by both the One MW reactor and the 5.5 MV Pulsed van-de-Graaff accelerator. The fast neutron flux was approximately 10^{11} n/cm^2/sec at 1 MeV with exposure times up to several hours. Total irradiation exposures ranged from 2 x 10^{11} n/cm^2 to 2 x 10^{15} n/cm^2.

For reference purposes, 4 x 10^4 p/cm^2/sec is the typical proton flux in the Van Allen belt. One year's exposure amounts to 6.3 x 10^{11} protons per cm^2. Therefore, exposure ranges used in these experiments are roughly equivalent to exposure times in the Van Allen belt from a minimum of 0.3 years (2 x 10^{11} n/cm^2) to more than 3,000 years (2 x 10^{15} n/cm^2).

In this first set of experiments, we irradiated the devices to this (10^{11} n/cm^2/sec) neutron flux, for total exposure doses of 2 x 10^{13} n/cm^2 and 2 x 10^{14} /cm^2. The guide losses, in dB/cm, were measured individually before and after irradiation. We carried 'control samples' of guides through the set of experiments. The control samples were never exposed to radiation, but they traveled with these samples, and their guide losses were measured after each experiment. Inspection of the raw data indicates the measurement uncertainty (due to instrument error, calibration drifts, etc.) that the experiments were subject to. Measurements were not traceable to an accuracy standard. The measured loss data are normalized to these control samples as a part of the data reduction process.

Figure 3 shows these measurement results. The two data points show a small change in guide loss (<2%). However, the large sample size produced a data set that shows a change in guide loss that is statistically significant.

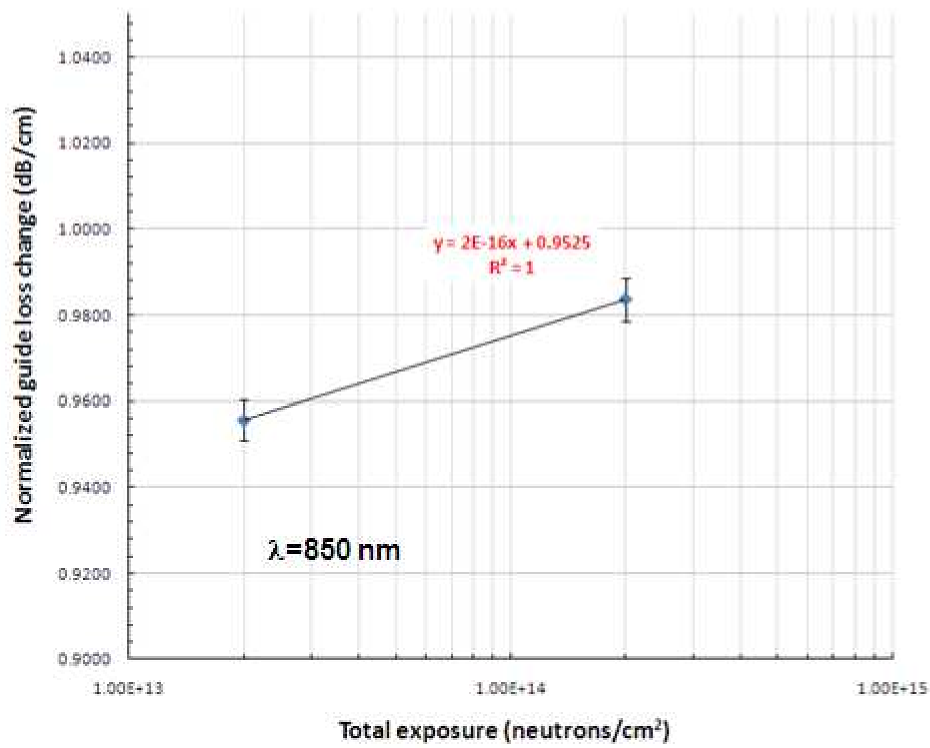

Figure 3: Neutron irradiation data

2.3 Neutron Irradiation Experiments (second set)

The initial set of experiments revealed very small effects of a very large exposure to neutrons. These results motivated us to theorize on possible causes of the devices' radiation tolerance. We postulated that the guide cladding (nominally 65 microns thick) could be protecting the core guide region. To test this hypothesis, we fabricated a family of guide samples with varying cladding thicknesses, all the way to zero thickness (no cladding at all). Optical InterLinks LLC fabricated guides with cladding thicknesses of 0, 10, 20, 40 and 80 microns.

The results of these experiments are shown in Figure 4. The figure shows the reduced data from exposure to neutrons. Two sets of data, representing total exposure of 2 x 10^{12} n/cm^2 and 2 x 10^{15} n/cm^2 are shown in the figure. Plotted on the ordinate is the increase in guide loss (again normalized against the control samples; 1.0 means no change), while the abscissa plots the cladding thickness. The two sample sets were equally sized. In each case the measured variance in guide loss is small, in spite of the substantial exposures.

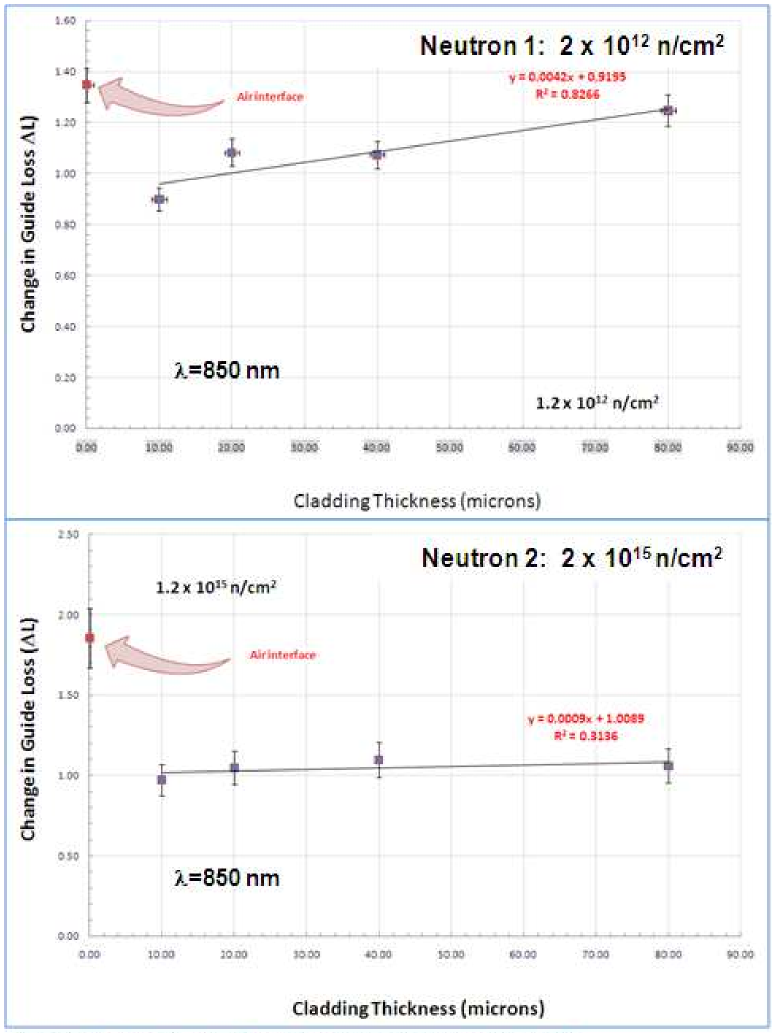

Figure 4: Neutron irradiation; guide cladding sensitivity

The figures suggest that the data obtained from the air interface guides appears an outlying data point. If we arbitrarily eliminate the zero cladding data point and fit the remaining (2 x 10^{12} n/cm^2 exposure) curve to a straight line we find a good R^2 fit with approximately 0.5% increase in guide loss for every micron of cladding thickness. Similarly fitting a straight line to the 2 x 10^{15} n/cm^2 exposure data excluding this one point reveals a slope near zero and an R^2 that is not as good.

3.0 Interpretation of the data

The radiation damage indicated by the data obtained from these experiments is much smaller than was anticipated at the experiment's outset. Initial scanning of the data suggested that the devices are unaffected by the radiation; this interpretation seems implausible, in light of the energy of the ionizing particles and the physical size of the polymer molecules. Toward making the best use of the data thus far gleaned, we have statistically analyzed the data to the fullest extent, in search of trend evidence.

3.1 Gamma Data

The data presented in Figure 2 weakly suggest a monotonic increase in guide loss with increasing gamma dose, up to about 10 Mrad. The total change in guide loss is approximately 25%. Within one standard deviation, the guide loss degradation levels off (or saturates) from 10 Mrad to the maximum exposure dose of 30 Mrad. Clearly, measurement error imposed by the small changes in guide loss limit our ability to interpret these data. Whether the small monotonic increase in loss is statistically significant is arguable. What is clear (and difficult to explain) is that the incurred losses are surprisingly small, given the large exposure doses.

3.2 Neutron Data (First Set)

The data are represented by two data points, which are guide loss change for neutron integrated flux of 2×10^{13} and 2×10^{14} n/cm^2. These two points however include 54 separate measurements. Measurement statistics are relatively good for these data; hence the smaller error bars. It must be noted, however, that statistical precision does not preclude possible systematic errors, such as equipment drift, calibration error, etc. As shown in Figure 3, the measured guide loss is again very small (<2%). These surprising results are difficult to interpret in physics terms. It appears that other measurements are needed.

3.3 Neutron Data (Second Set)

The data shown in Figure 4 suggest that the unclad waveguide (zero cladding thickness) is subject to a unique effect. The underlying physics cannot be known without other data. However, a plausible explanation is that surface contamination at the core/air interface decoupled light from the guides, resulting in higher guide loss. Another possibility is cladding in the less-than ten micron but greater-than-zero range is where the protection from irradiation is taking place. This again is a very small number, but the measurement statistics are reasonable. The fact of a lower slope than the first set of data presented is curious, and probably attests to the poor R^2 fit more than anything else.

3.4 General Interpretation

Radiation effects on polymers generally consist of several mechanisms, some of which are recoverable. The type of radiation and total dose determine the final outcome, with most polymers suffering only minor loss in mechanical properties at levels that equate to GEO orbit space environment. However, other properties such as optical or electrical, can suffer irrecoverable damage which may affect the performance of the optical or electrical system. Surprisingly, we are thus far unable to detect these expected effects.

Damage Mechanisms: Radiation damage occurs by several mechanisms, including changes in saturation, polymer chain scission, oxidation, cyclization, isomerization, amorphization or crystallization. There are a number of routes to the damage or decomposition products. Protons can displace atoms within the polymer structure resulting in chain scission. The resulting collision can cause other displacements until the proton looses energy or passes completely through the polymer. Another change that occurs as a result of these collisions is cross linking. That is, the number of cross links (or the existence of cross links in thermoplastics) increases.

Self-Healing: Chain scission can result in low molecular weight fractions that can consist of gaseous or liquid by-products. In some instances, the chain scission can "heal" itself in much the same way the original polymer structure was formed, i.e. energetic particle collisions. Chains are broken, leaving free radicals that may recombine with other low molecular weight fractions reforming the polymer chain and restoring most of the original properties of the polymer. To determine if self-healing mechanisms are taking place in the irradiation process will require in-situ irradiation/measurement.

4.0 Conclusions

The measurements reported here indicate that the polymer blends making up the Optical InterLinks' flexible waveguide structures are surprisingly tolerant of various forms of ionizing radiation. While the data suggest this, the results measured are so small that the failure mechanisms have not yet been identified.

Because these components possess such an unusual combination of optical and mechanical properties, further measurements may be in order, to ascertain the underlying physics driving their unusual radiation tolerance. Some of these further measurements explore self-annealing mechanisms through loss monitoring in-situ or immediately after exposure, in addition to the evaluation of the impact of thinner 3 to 10 micron clad layers and of using higher radiation flux or exposure times.

The experiments described in this report suggest that this class of flexible polymer waveguides hold potential to be implemented in practical space photonic interconnection applications.

APPENDIX 1: Representative raw data obtained from measuring guide loss before exposure and then after radiation exposure

Each 5 cm long sample had approximately 12 waveguides. 3 wavegudes were randomly tested in each sample.
Samplles were irridated up to 4 times. No measuremnt were taken between exposures # 3 & 4, for they were not returned between the two exposures.

Before irradiation						
Loss Meas. Data# 1 6/10/2009 11:18						
	800	800	1300	1300	1550	1550
	loss in dB	loss in dB/cm	loss in dB	loss in dB/cm	loss in dB	loss in dB/cm
817-26	0.671	0.1342	1.643	0.3286	6.522	1.3044
	0.637	0.1274	1.579	0.3158	6.423	1.2846
	0.58	0.116	1.539	0.3078	6.398	1.2796
816-11	0.618	0.1236	1.636	0.3272	6.575	1.315
	0.607	0.1214	1.617	0.3234	6.581	1.3162
	0.675	0.135	1.628	0.3256	6.534	1.3068
817-17	0.579	0.1158	1.502	0.3004	6.326	1.2652
	0.573	0.1146	1.544	0.3088	6.336	1.2672
	0.647	0.1294	1.519	0.3038	6.316	1.2632
816-18	0.671	0.1342	1.66	0.332	6.557	1.3114
	0.695	0.139	1.683	0.3366	6.568	1.3136
	0.679	0.1358	1.656	0.3312	6.545	1.309
816-7	0.681	0.1362	1.646	0.3292	6.736	1.3472
	0.777	0.1554	1.764	0.3528	6.913	1.3826
	0.692	0.1384	1.669	0.3338	6.641	1.3282
817-10	0.725	0.145	1.594	0.3188	6.541	1.3082
	0.718	0.1436	1.606	0.3212	6.535	1.307
	0.7	0.14	1.591	0.3182	6.513	1.3026
817-3	0.709	0.1418	1.583	0.3166	6.574	1.3148
	0.67	0.134	1.546	0.3092	6.541	1.3082
	0.652	0.1304	1.583	0.3166	6.586	1.3172
816-1	0.683	0.1366	1.685	0.337	6.765	1.353
	0.673	0.1346	1.668	0.3336	6.697	1.3394
	0.695	0.139	1.775	0.355	6.794	1.3588
After First Rad exposure						
Loss Meas. Data# 7 8/19/2009 15:17						
817-26	0.679	0.1358	1.694	0.3388	6.656	1.3312
300k 5.5 hours	0.658	0.1316	1.688	0.3376	6.656	1.3312
	0.649	0.1298	1.672	0.3344	6.686	1.3372
816-11	0.737	0.1474	1.75	0.35	6.657	1.3314
300k 5.5 hours	0.709	0.1418	1.737	0.3474	6.658	1.3316
	0.754	0.1508	1.766	0.3532	6.666	1.3332
817-17	0.694	0.1388	1.672	0.3344	6.589	1.3178
500k 9.1 hours	0.642	0.1284	1.66	0.332	6.545	1.309
	0.631	0.1262	1.644	0.3288	6.52	1.304
816-18	0.663	0.1326	1.684	0.3368	6.664	1.3328
500k 9.1 hours	0.671	0.1342	1.696	0.3392	6.683	1.3366
	0.692	0.1384	1.697	0.3394	6.734	1.3468
816-7	0.646	0.1292	1.775	0.355	6.812	1.3624
1.3m 23.6 hours	0.658	0.1316	1.769	0.3538	6.805	1.361
	0.655	0.131	1.766	0.3532	6.924	1.3848
817-10	0.702	0.1404	1.749	0.3498	6.836	1.3672
1.3m 23.6 hours	0.719	0.1438	1.749	0.3498	6.808	1.3616
	0.691	0.1382	1.721	0.3442	6.793	1.3586
817-3	0.693	0.1386	1.711	0.3422	6.862	1.3724
1.6m 29 hours	0.795	0.159	1.765	0.353	6.958	1.3916
	0.696	0.1392	1.744	0.3488	6.939	1.3878
816-1	0.694	0.1388	1.784	0.3568	6.831	1.3662
1.6m 29 hours	0.682	0.1364	1.734	0.3468	6.807	1.3614
	0.698	0.1396	1.793	0.3586	6.878	1.3756

Before radiation						
Loss Meas. Data# 1 6/10/2009 11:18						
	800	800	1300	1300	1550	1550
	loss in dB	loss in dB/cm	loss in dB	loss in dB/cm	loss in dB	loss in dB/cm
816-05	0.666	0.1332	1.647	0.3294	6.719	1.3438
	0.677	0.1354	1.661	0.3322	6.739	1.3478
	0.657	0.1314	1.624	0.3248	6.695	1.339
817-05	0.679	0.1358	1.575	0.315	6.529	1.3058
	0.697	0.1394	1.529	0.3058	6.495	1.299
	0.754	0.1508	1.604	0.3208	6.56	1.312
817-07	0.698	0.1396	1.567	0.3134	6.518	1.3036
	0.726	0.1452	1.588	0.3176	6.538	1.3076
	0.697	0.1394	1.589	0.3178	6.513	1.3026
816-09	0.656	0.1312	1.648	0.3296	6.617	1.3234
	0.684	0.1368	1.641	0.3282	6.703	1.3406
	0.695	0.139	1.682	0.3364	6.645	1.329
817-11	0.697	0.1394	1.573	0.3146	6.582	1.3164
	0.726	0.1452	1.617	0.3234	6.573	1.3146
	0.667	0.1334	1.587	0.3174	6.574	1.3148
816-19	0.662	0.1324	1.626	0.3252	6.531	1.3062
	0.727	0.1454	1.662	0.3324	6.578	1.3156
	0.648	0.1296	1.649	0.3298	6.533	1.3066
816-24	0.862	0.1724	1.616	0.3232	6.463	1.2926
	0.843	0.1686	1.652	0.3304	6.538	1.3076
	0.667	0.1334	1.622	0.3244	6.459	1.2918
817-24	0.608	0.1216	1.562	0.3124	6.428	1.2856
	0.637	0.1274	1.591	0.3182	6.484	1.2968
	0.621	0.1242	1.562	0.3124	6.452	1.2904
After First Rad exposure						
Loss Meas. Data# 3 8/19/2009 11:49						
816-05	0.711	0.1422	1.687	0.3374	6.726	1.3452
3.5m (BL)	0.841	0.1682	1.722	0.3444	6.859	1.3718
	0.753	0.1506	1.74	0.348	6.878	1.3756
817-05	0.81	0.162	1.66	0.332	7.03	1.406
8.4m (BL)	0.769	0.1538	1.643	0.3286	7.043	1.4086
	0.769	0.1538	1.644	0.3288	7.019	1.4038
817-07	0.791	0.1582	1.674	0.3348	6.85	1.37
3.7m (BL)	0.787	0.1574	1.659	0.3318	6.872	1.3744
	0.753	0.1506	1.657	0.3314	6.866	1.3732
816-09	0.744	0.1488	1.736	0.3472	6.707	1.3414
3.7m (BL)	0.719	0.1438	1.713	0.3426	6.707	1.3414
	0.734	0.1468	1.722	0.3444	6.693	1.3386
817-11	0.791	0.1582	1.722	0.3444	6.826	1.3652
3.5m (BL)	0.786	0.1572	1.735	0.347	6.842	1.3684
	0.811	0.1622	1.709	0.3418	6.871	1.3742
816-19	0.734	0.1468	1.67	0.334	6.649	1.3298
2.7m (BL)	0.793	0.1586	1.65	0.33	6.667	1.3334
	0.747	0.1494	1.64	0.328	6.657	1.3314
816-24	0.778	0.1556	1.61	0.322	6.79	1.358
8.4m (BL)	0.761	0.1522	1.631	0.3262	6.801	1.3602
	0.757	0.1514	1.596	0.3192	6.765	1.353
817-24	0.726	0.1452	1.655	0.331	6.729	1.3458
2.7m (BL)	0.679	0.1358	1.615	0.323	6.748	1.3496
	0.702	0.1404	1.655	0.331	6.723	1.3446