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BISCO PRODUCTS, INC.

TECHNICAL REPORT

NO. NS-1-050 (INTERIM)

IRRADIATION STUDY OF BORAFLEX NEUTRON ABSORBER
INTERIM TEST DATA

DATE 11/25/87

REVISION 1

42683 284

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NST-87-107

IRRADIATION TESTS OF BORAFLEX

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*   P R E L I M I N A R Y   *
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Prepared for

BISCO PRODUCTS, INC.

by

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NUSURTEC INCORPORATED

Palm Harbor, Florida

1. INTRODUCTION AND HISTORICAL BACKGROUND

In late 1986, in-situ tests revealed "...gaps identified in the Boraflex neutron absorber component of the high-density spent fuel storage racks at Quad Cities Unit 1"[1] as manufactured by the Joseph Oat Corporation of Camden N.J. These gaps consisted of horizontal cracks through the Boraflex distributed randomly in both size and location in the upper ~8 feet of the poison material. In blackness tests, the largest gap observed was 3 $^{1}/_{2}$ to 4 inches wide and the average was ~1.5 inches. (Gaps less than about $^{1}/_{2}$ inches were not observable.) Underwater neutron radiography confirmed the existence of the gaps and determined that the largest gap was approximately 3$^{1}/_{2}$ inches wide.

Commonwealth Edison Co. (CECo), the licensee, retained Northeast Technology Corporation (NETCo) to evaluate the test data. In their preliminary report[2], NETCo concluded[1] that the mechanism for the gap formation "may be related to large local stresses in the Boraflex from fabrication-induced restraint within the rack and to tearing and shrinkage of the material". At about the same time, a full length sheet of Boraflex (after ~1 x 10^{10} rad total exposure) cut out of the fuel rack of the Pt. Beach plant (where the Boraflex was able to shrink un-restrained) was found to be intact. Subsequently, the author of the present report was retained by CECo to evaluate the potential impact on criticality safety of the observed Boraflex gaps. This study[3] confirmed that the reactivity consequence of the gaps was well within the capability of the Quad Cities racks.

Although earlier tests[4] had confirmed that boron was not lost from irradiated Boraflex even at very high doses (as much as 5 x 10^{11} rad[5]), the sample sizes used in this irradiation test were too small for valid dimensional checks.

Consequently, shrinkage data inferred from this earlier test cannot be relied upon as an accurate radiation-induced effect.

Based upon the qualification on shrinkage data noted above, a second Boraflex irradiation test program was initiated in the Spring of 1987 for the purpose of seeking to quantitatively determine radiation-induced shrinkage of Boraflex. These tests used larger size samples in order to improve the precision of dimensional measurements from which shrinkage data would be inferred. At the same time, an effort was made to reduce the concurrent neutron dose to which the samples were exposed so that the results would be more representative of the gamma radiation doses to which Boraflex would be exposed in a spent fuel rack environment. In general, the Boraflex absorber material would normally be exposed to a ~3 x 10^{9} to 1 x 10^{10} rad gamma dos from a single fuel cycle (depending upon specific reactor operating conditions) and approximately twice this accumulated dose if the fuel were to be left in-place throughout a postulated 40-year rack lifetime. If the same storage cell were to be used for annual refueling, the accumulated dose could reach 1 x10^{11} to 4 x 10^{11} rads gamma.

Three series of test irradiations were made exposing samples as follows:

(a) 12-inch long samples to 1 x 10^{9} rads in a Co-60 gamma cave at the University of Michigan ,

(b) 1.5 inch square coupons to 1 x 10^{11} rads in the Ford Research reactor of the University of Michigan , and

(c) 12-inch long samples to [later] in the research reactor at the University of Missouri.

Results of these test irradiations are reported herein and the detailed data are presented in Appendix A.

2.0 SUMMARY

2.1 VISUAL OBSERVATIONS

In the course of irradiation, Boraflex gradually becomes harder and less ductile. Above a radiation dose of about 1×10^9 rad, irradiated Boraflex has the appearance and "feel" of a ceramic material - strong in compression but fracturing easily in tension (brittle failure). In many respects, radiation-hardened Boraflex resembles a sheet of sintered Al_2O_3 that may fracture in large pieces but does not powder or crumble. Even at the highest doses (~1.1×10^{11} rad gamma), there was no sign of swelling.

Above a radiation dose of 1×10^{10} rad, fine grey powdering appeared on the surface of many of the samples, most marked along the edges and in for a distance of about $^1/_4$ inch. This powder could be easily wiped off - exposing the normal looking black Boraflex underneath - with no significant effect on neutron absorption as confirmed by transmission tests.

As the irradiation dose increased, the most noticeable visual change in the smaller samples irradiated in the University of Michigan reactor was a slight deterioration along the edges, a change less marked but generally confirmed by dimensional measurements. Above a dose of ~1×10^{10} rad, the edges of many samples began to lose their original sharp definition and to acquire a slightly irregular shape with the corners rounded. The edges had a smooth appearance resembling the "polishing" effect of erosion. In some cases, small amounts of edge material had been lost and the edges were friable to a depth of perhaps $^1/_{16}$ inch or less. Because of the irradiation geometry, the edges were exposed to a concurrent neutron dose which substantially increased the effective local radiation dose and could likely account for all or some of the observed edge effect. Highly reactive transient free radicals, [H],[O], and [HO_2] or H_2O_2 -

all present as a result of water radiolysis - may possibly be a contributing factor.

Small surveillance coupons from the Pt. Beach spent fuel pool apparently showed a similar edge deterioration which suggests that careful consideration should be given the rack surveillance program, particularly to the size and geometry of the coupons.

2.2 BORON CONTENT

Neutron transmission measurements made before and after irradiation confirmed that boron is not lost in the irradiation of Boraflex. The absorption remained at ~98% regardless of the radiation dose. Thickness shrinkage would not alter the boron areal density or the absorption. However, the transmission measurements are not sufficiently accurate to detect the small increase in boron concentration that theoretically would be a consequence of length or width shrinkage.

2.3 HARDNESS MEASUREMENTS

Shore A or possibly Shore D hardness measurements were at one time considered to be a means of qualitatively following accumulating radiation effects on Boraflex in spent fuel racks by means of measurements made on surveillance coupons. Results of the present test program indicate that both Shore A and Shore D hardness have saturated (ie, fully hard as might be expected of a ceramic material) at radiation doses too low for the measurements to be of real value. Shore A saturates at about 1×10^{9} rad and Shore D at less than 1×10^{10} rad as illustrated in Figure 1. These radiation doses are comparable to those from a single fuel cycle.

2.4 SPECIFIC GRAVITY MEASUREMENTS

***** LATER *****

2.5 MODULUS OF RUPTURE TESTS (TENSILE)

***** LATER *****

2.6 DIMENSIONAL MEASUREMENTS

2.6.1 GAMMA CAVE IRRADIATIONS

A total of 10 samples were irradiated in the University of Michigan Co-60 cave to an integrated gamma dose of 1×10^9 rad. Dimensional measurements on these samples are summarized in Figure 2. These data suggest a gradual nearly-linear shrinking of the Boraflex, reaching 1.5 ± 0.1 % in length at 1×10^9 rad.

2.6.2 REACTOR IRRADIATION OF COUPON SAMPLES

A total of 108 samples (~1.6 inches square) were irradiated to doses between 1×10^8 and 1×10^{11} rad. Pre- and post-irradiation dimensional measurements were obtained and these data are summarized in Figure 3 showing separate plots of weight, thickness, length and width. At the lower doses, the changes in weight, length and width are not greatly different from those observed in the gamma cave irradiation, despite the higher dose rates and the concurrent neutron flux.

The onset of slight edge deterioration is most clearly seen in the plot of weight change in Figure 3. Up to a radiation level of ~2.5×10^{10} rad, the weight consistently increases, probably due to water absorption. However, above that radiation level, the weight change decreases signalling the onset of the slight edge deterioration. Length and width dimensional changes do not show as drastic a change, presumably because the micrometer jaws would span the small gaps along the edge where some degree of spalling appears to have occurred. In the small samples used for these tests, the edge effect, although less than $^{1}/_{16}$ inch, is a relatively large percentage of the small 1.6 inch coupon dimension. In a spent fuel rack, an edge deterioration of $1/16$ inch on both sides of each Boraflex sheet would have a nearly inconsequential reactivity effect.

The coupons used in these tests were mounted as a "sandwich" with the outer samples providing a shield against thermal neutrons. These outer coupons showed evidence of accumulating higher radiation doses (indicated by the rate of increase in sample hardness) then the inner samples of each 9-sample batch. Consequently, the averaged data presented herein excludes the outer two samples in each batch and considered only the inner seven samples. Simple and approximate calculations suggest that the thermal neutron dose in the inner samples (from fast neutrons thermalized in the Boraflex) was perhaps 10 to 20% of the indicated gamma dose. However, the edges of all samples were exposed to a significant thermal neutron dose which likely contributes to the edge deterioration observed.

Although there is considerable uncertainty in the length and width changes especially at the higher doses, the shrinkage appears to have saturated at about 2 - $2^{1}/_{2}$ % in length and about 4% in width, including the edge deterioration which would tend to increase the apparent shrinkage. Due to the small coupon size of the University of Michigan test specimens, the $^{1}/_{16}$ inch edge deterioration introduces a significant potential error in the shrinkage data inferred from dimensional measurements. Test specimens in the University of Missouri reactor are twelve inches long and are better shielded from thermal neutron radiation damage. Consequently, the shrinkage data from these irradiation tests will be subject to a much lower error factor from potential edge deterioration.

2.6.3 REACTOR IRRADIATION OF LARGE SAMPLES

**** LATER ****

3.0 CONCLUSIONS AND RECOMMENDATIONS

On the basis of the test irradiations, the following conclusions and recommendations may be made.

- For irradiation levels comparable to or in excess of those expected during a 40 year service life of Boraflex in spent fuel storage racks, there does not appear to be degradation of a magnitude to prevent Boraflex from performing its intended function.

- On irradiation, Boraflex becomes a hard ceramic, strong in compression and relatively weak in tension. When cracking occurs, it is a brittle fracture characteristic of a ceramic.

- Radiation-hardened Boraflex is a stable ceramic with no further apparent radiation-induced changes (with the possible exception of a small edge effect) up to the maximum dose expected in a typical 40-year in-service lifetime.

- Irradiation of Boraflex does not result in a measurable loss of boron.

- There appears to be erosion or chemical etching and spallation along the cut edges of Boraflex sheets to a maximum depth of ~$^{1}/_{16}$ inch but none on the flat finished surfaces.

- Because of the slight possible edge effect, it is conservatively recommended that rack designs include an allowance of $^{1}/_{16}$ to $^{1}/_{8}$ inch in width for potentially enhanced edge deterioration.

- Care should be exercised in planning a surveillance program to insure that axial shrinkage in particular can be measured with sufficient accuracy and that the small edge effects do not produce ambiguous results. This will require coupons larger than those currently in general use, with 10 inches being the recommended minimum length.

- Boraflex reaches full hardness (Shore A or Shore D) at a radiation dose of ~1×10^{10} rads or approximately that of a single fuel cycle. Therefore hardness measurements do not generally provide an effective means of tracking radiation-induced changes in Boraflex over its expected 40-year in-service lifetime.

- In the radiation-induced conversion to a ceramic, Boraflex undergoes shrinkage of approximately 2 to $2^1/_2$ percent in the axial direction which should be allowed for in the rack design. Shrinkage in thickness does not alter the boron-10 areal density (grams/cm^2) and width shrinkage is included in the recommended allowance for edge effects.

- Because of the 2 to $2^1/_2$ percent radiation induced shrinkage, it is recommended that rack designs permit the free contraction of the Boraflex sheets and avoid strong restraints that could lead to large local stresses. This will eliminate the gap-formation mechanism attributed to fabricator-induced restraint as experienced in the fuel racks of the Quad Cities Station.

- Modulus of Rupture *** later ***

REFERENCES

(1) USNRC Information Notice No. 87-43, September 8, 1987

(2) Northeast Technology Corp. "Preliminary Assessment of Boraflex Performance in the Quad Cities Spent Fuel Storage Racks", February 1987

(3) S. E. Turner, "Criticality Safety Evaluation of Boraflex Degradation in the Quad Cities Spent Fuel Storage Racks", June 1987

(4) J.S. Anderson, Irradiation Study of Boraflex Neutron Shielding Materials, NS-1-001, Bisco Products, Inc., August 1981

(5) Private communication, R.R.Burn, University of Michigan to S. E. Turner, November 1983

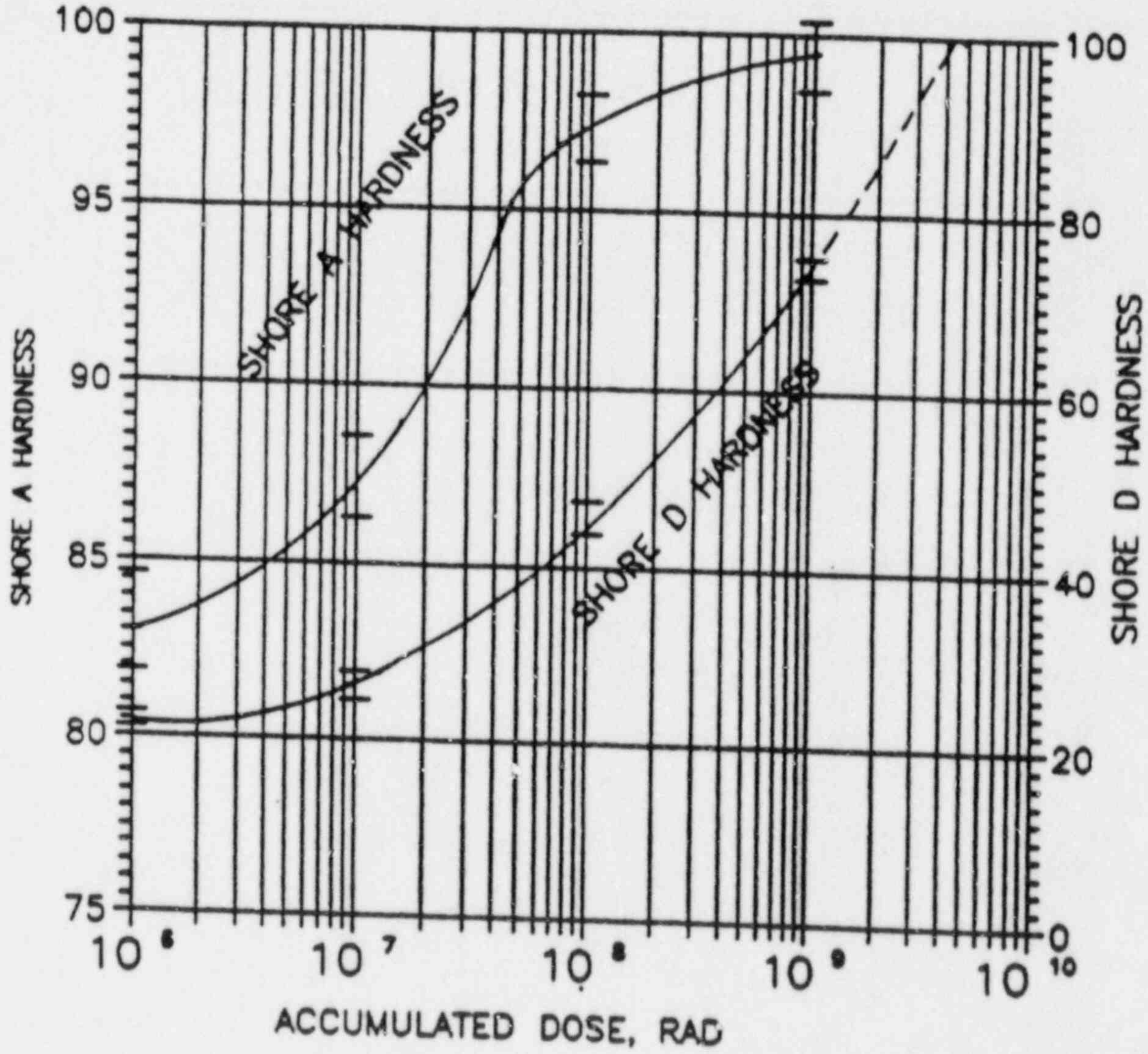

Figure 1 RADIATION INDUCED HARDNESS OF BORAFLEX

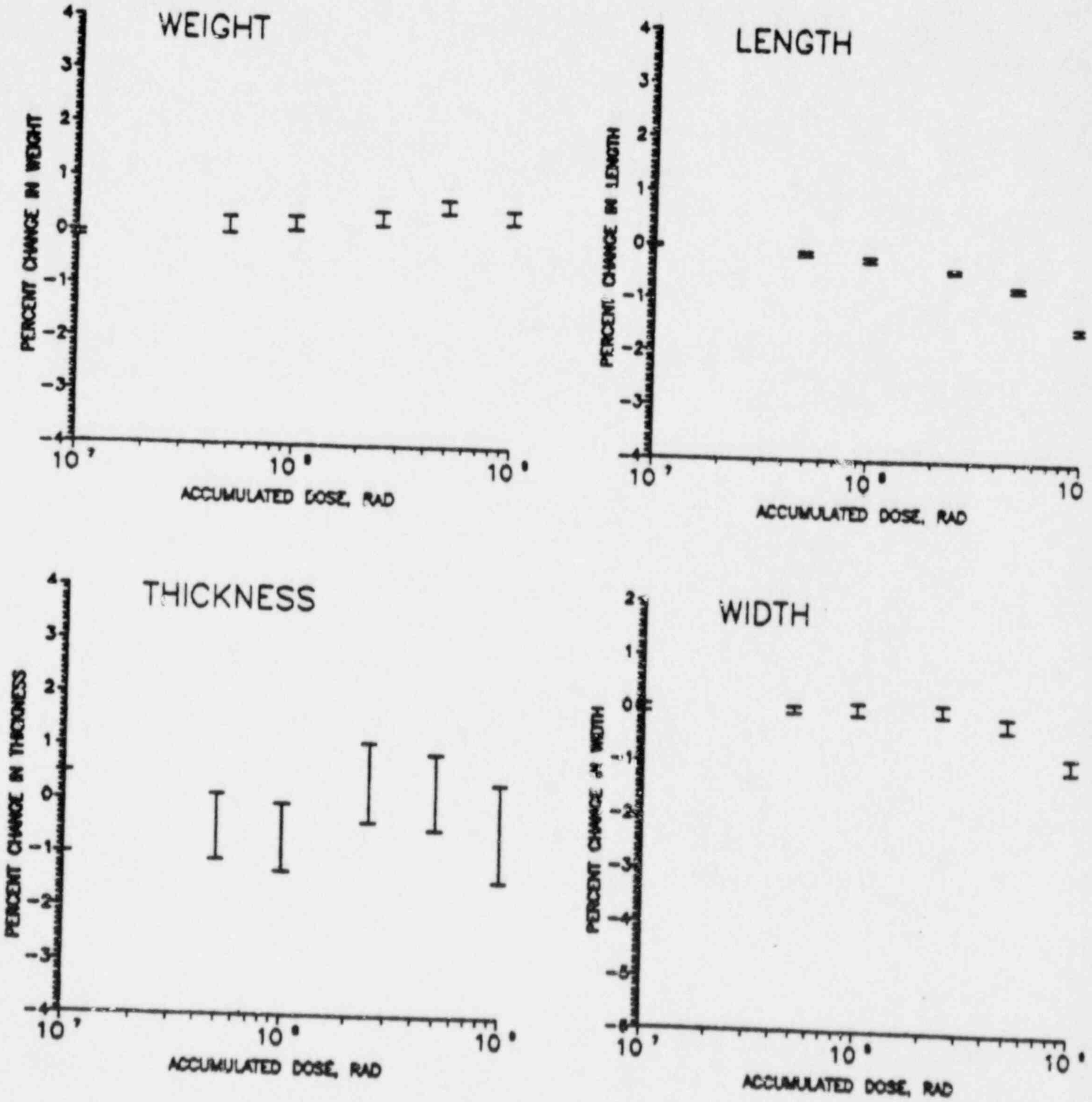

Figure 2 DIMENSIONAL CHANGES IN BORAFLEX FROM CO-60 GAMMA RADIATION

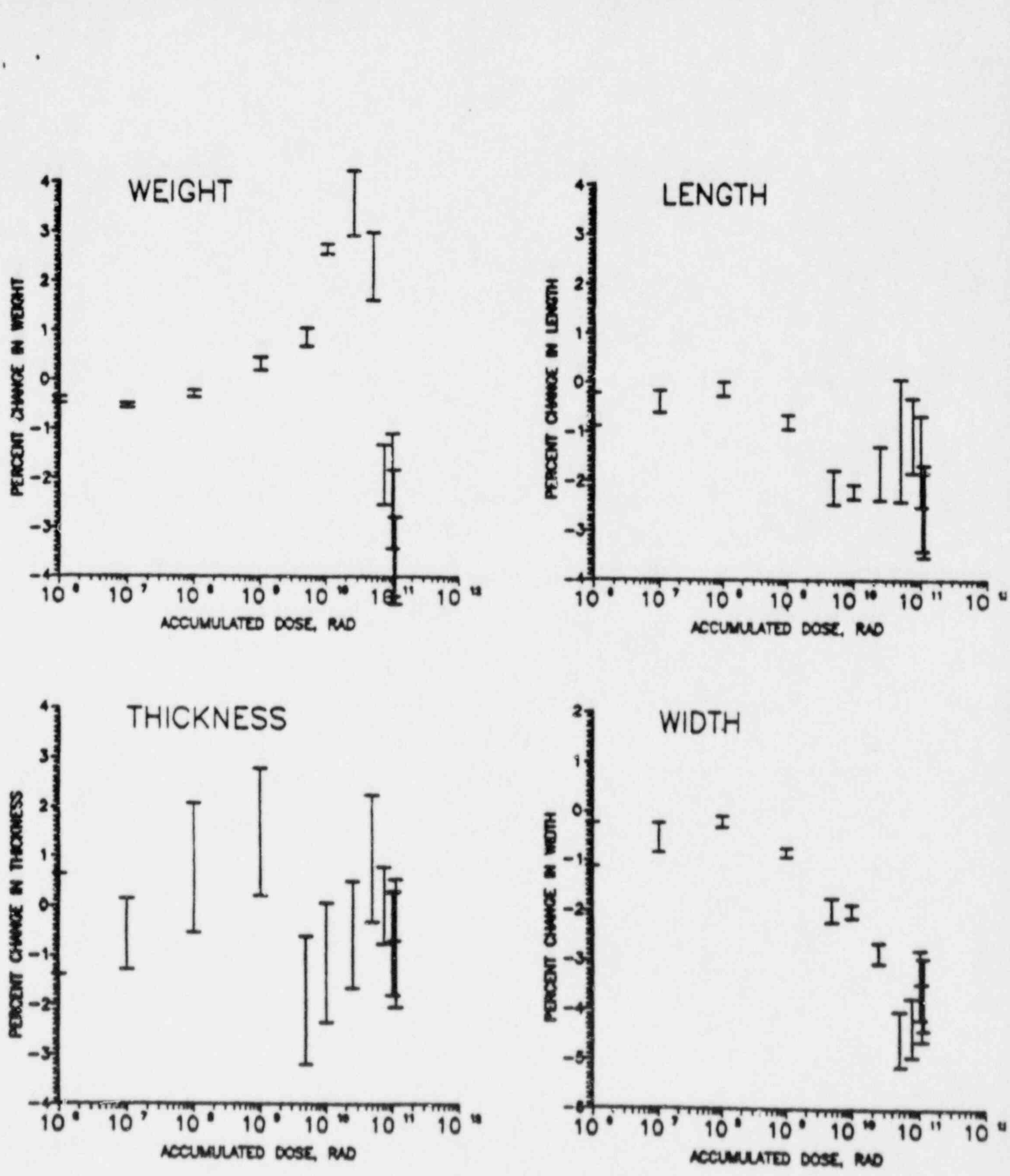

Figure 3 DIMENSIONAL CHANGES IN BORAFLEX FROM REACTOR IRRADIATION

Table 1 Co-60 Irradiation - WEIGHT CHANGES

RADS	SAMPLE WEIGHTS, gm									
0.0E+00	67.90	66.25	66.05	67.10	67.00	66.65	66.05	66.85	66.95	67.20
1.0E+07	67.85	66.25	66.00	67.00	66.95	66.60	66.00	66.80	66.90	67.20
5.0E+07	67.90	66.30	66.00	67.10	67.10	66.70	66.20	67.00	67.10	67.50
1.0E+08	67.90	66.30	66.10	67.20	67.20	66.70	66.20	67.00	67.10	67.50
2.5E+08	68.10	66.40	66.10	67.30	67.20	66.80	66.20	67.10	67.20	67.60
5.0E+08	68.20	66.50	66.30	67.40	67.30	67.00	66.40	67.30	67.40	67.70
1.0E+09	68.10	66.40	66.10	67.30	67.30	66.90	66.30	67.20	67.20	67.50

RADS	PERCENT CHANGE FROM INITIAL WEIGHT										AVE.	1-SIGMA
1.0E+07	-0.07	0.00	-0.08	-0.15	-0.07	-0.08	-0.08	-0.07	-0.07	0.00	-0.07	0.04
5.0E+07	0.00	0.08	-0.08	0.00	0.15	0.08	0.23	0.22	0.22	0.45	0.13	0.15
1.0E+08	0.00	0.08	0.08	0.15	0.30	0.08	0.23	0.22	0.22	0.45	0.10	0.13
2.5E+08	0.29	0.23	0.08	0.30	0.30	0.23	0.23	0.37	0.37	0.60	0.30	0.14
5.0E+08	0.44	0.38	0.38	0.45	0.45	0.53	0.53	0.67	0.67	0.74	0.52	0.13
1.0E+09	0.29	0.23	0.08	0.30	0.45	0.38	0.38	0.52	0.37	0.45	0.34	0.13

Table 1 Continued Co-60 Irradiation - LENGTH CHANGES

RADS	SAMPLE LENGTHS, inches								
0.0E+00	12.012	12.004	12.041	12.046	12.015	12.017	12.017	12.018	12.029	12.025
1.0E+07	12.012	12.003	12.042	12.041	12.007	12.019	12.013	12.012	12.029	12.026
5.0E+07	12.001	11.986	12.024	12.023	11.991	11.999	11.991	11.996	12.014	12.014
1.0E+08	11.987	11.973	12.013	12.013	11.981	11.989	11.984	11.986	12.008	12.005
2.5E+08	11.965	11.954	11.990	11.990	11.956	11.965	11.962	11.964	11.982	11.982
5.0E+08	11.925	11.915	11.955	11.952	11.917	11.927	11.924	11.922	11.946	11.941
1.0E+09	11.835	11.827	11.866	11.867	11.828	11.838	11.832	11.827	11.849	11.845

RADS	PERCENT CHANGE FROM INITIAL LENGTH										AVE.	1-SIGMA
1.0E+07	0.000	-0.008	0.008	-0.042	-0.067	0.017	-0.033	-0.050	0.000	0.008	-0.017	0.029
5.0E+07	-0.092	-0.150	-0.141	-0.191	-0.200	-0.150	-0.216	-0.183	-0.125	-0.091	-0.154	0.044
1.0E+08	-0.208	-0.258	-0.233	-0.274	-0.283	-0.233	-0.275	-0.266	-0.175	-0.166	-0.237	0.042
2.5E+08	-0.391	-0.417	-0.424	-0.465	-0.491	-0.433	-0.458	-0.449	-0.391	-0.358	-0.420	0.040
5.0E+08	-0.724	-0.741	-0.714	-0.780	-0.816	-0.749	-0.774	-0.799	-0.690	-0.699	-0.749	0.043
1.0E+09	-1.474	-1.475	-1.453	-1.486	-1.556	-1.490	-1.539	-1.589	-1.496	-1.497	-1.506	0.043

Table 1 Continued Co-60 Irradia[illegible] - WIDTH CHANGES

RADS	SAMPLE WIDTHS, inches									
0.0E+00	2.513	2.503	2.487	2.505	2.516	2.515	2.517	2.511	2.506	2.534
0.0E+00	2.534	2.507	2.492	2.507	2.498	2.509	2.498	2.514	2.497	2.512
0.0E+00	2.557	2.510	2.491	2.492	2.474	2.506	2.492	2.501	2.498	2.507
1.0E+07	2.512	2.502	2.488	2.50[illegible]	2.513	2.515	2.514	2.509	2.505	2.529
1.0E+07	2.534	2.506	2.493	2.56[illegible]	2.498	2.512	2.496	2.514	2.499	2.511
1.0E+07	2.562	2.510	2.490	2.491	2.472	2.509	2.492	2.490	2.497	2.507
5.0E+07	2.511	2.502	2.488	2.504	2.513	2.515	2.514	2.508	2.506	2.529
5.0E+07	2.533	2.505	2.493	2.500	2.498	2.513	2.497	2.511	2.500	2.513
5.0E+07	2.562	2.569	2.498	2.491	2.472	2.509	2.493	2.491	2.497	2.507
1.0E+08	2.511	2.503	2.489	2.502	2.513	2.513	2.514	2.506	2.503	2.529
1.0E+08	2.535	2.505	2.498	2.510	2.501	2.517	2.498	2.515	2.506	2.515
1.0E+08	2.563	2.500	2.502	2.485	2.460	2.507	2.494	2.491	2.498	2.504
2.5E+08	2.500	2.501	2.489	2.503	2.513	2.513	2.514	2.505	2.504	2.530
2.5E+08	2.534	2.505	2.496	2.513	2.502	2.510	2.497	2.513	2.504	2.512
2.5E+08	2.563	2.509	2.504	2.480	2.469	2.510	2.493	2.491	2.495	2.503
5.0E+08	2.502	2.496	2.483	2.496	2.500	2.500	2.500	2.499	2.498	2.525
5.0E+08	2.526	2.498	2.490	2.506	2.495	2.511	2.492	2.505	2.497	2.504
5.0E+08	2.562	2.504	2.499	2.483	2.470	2.505	2.488	2.485	2.490	2.496
1.0E+09	2.484	2.481	2.467	2.480	2.493	2.493	2.491	2.483	2.481	2.509
1.0E+09	2.506	2.477	2.460	2.482	2.475	2.491	2.470	2.484	2.475	2.480
1.0E+09	2.543	2.486	2.480	2.464	2.45[illegible]	2.488	2.471	2.460	2.472	2.477

RADS	PERCENT CHANGE IN AVERAGE WIDTHS										AVE.	1-SIGMA
1.0E+07	0.052	-0.027	0.120	-0.013	-0.067	0.0[illegible]0	-0.066	-0.040	0.000	-0.079	-0.004	0.094
5.0E+07	0.025	-0.053	0.120	-0.013	-0.067	0.093	-0.040	-0.080	0.027	-0.053	-0.004	0.103
1.0E+08	0.065	-0.053	0.254	-0.094	-0.081	0.093	-0.013	-0.053	0.080	-0.066	0.013	0.177
2.5E+08	0.012	-0.067	0.254	-0.000	-0.054	0.146	-0.040	-0.093	0.027	-0.106	0.900	0.103
5.0E+08	-0.106	-0.293	0.027	-0.253	-0.200	-0.000	-0.253	-0.359	-0.213	-0.371	-0.218	0.190
1.0E+09	-0.935	-1.011	-0.736	-1.040	-0.881	-0.770	-0.999	-1.077	-0.973	-1.152	-0.957	0.191

Table 1 Continued   Co-60 Irradiation - THICKNESS CHANGES

RADS	SAMPLE THICKNESS, inches									
0.0E+00	0.077	0.075	0.075	0.076	0.076	0.076	0.075	0.077	0.075	0.076
0.0E+00	0.076	0.075	0.075	0.076	0.077	0.075	0.076	[illegible]	0.076	0.076
0.0E+00	0.077	0.000	0.076	0.076	0.077	0.075	0.076	[illegible]	0.076	0.077
1.0E+07	0.077	0.075	0.075	0.076	0.076	0.075	0.075	[illegible]	0.075	0.075
1.0E+07	0.076	0.075	0.075	0.076	0.077	0.075	0.075	0.076	0.076	0.076
1.0E+07	0.077	0.075	0.076	0.075	0.077	0.075	0.076	0.076	0.076	0.076
5.0E+07	0.077	0.075	0.075	0.076	0.076	0.075	0.075	0.077	0.075	0.075
5.0E+07	0.076	0.075	0.075	0.076	0.077	0.075	0.075	0.076	0.076	0.076
5.0E+07	0.076	0.075	0.076	0.075	0.076	0.075	0.076	0.076	0.076	0.076
1.0E+08	0.077	0.075	0.075	0.076	0.075	0.075	0.074	0.076	0.075	0.075
1.0E+08	0.076	0.075	0.076	0.076	0.076	0.075	0.075	0.077	0.076	0.076
1.0E+08	0.076	0.075	0.076	0.075	0.076	0.075	0.076	0.076	0.076	0.076
2.5E+08	0.077	0.076	0.076	0.077	0.076	0.076	0.074	0.077	0.076	0.076
2.5E+08	0.077	0.075	0.076	0.077	0.077	0.075	0.076	0.077	0.077	0.077
2.5E+08	0.077	0.076	0.077	0.076	0.077	0.075	0.077	0.076	0.077	0.077
5.0E+08	0.077	0.076	0.075	0.077	0.076	0.076	0.075	0.077	0.076	0.076
5.0E+08	0.076	0.075	0.076	0.076	0.077	0.075	0.076	0.077	0.076	0.077
5.0E+08	0.077	0.075	0.077	0.076	0.077	0.075	0.077	0.076	0.077	0.077
1.0E+09	0.076	0.075	0.076	0.076	0.076	0.075	0.075	0.077	0.076	0.075
1.0E+09	0.075	0.074	0.075	0.076	0.076	0.075	0.075	0.076	0.076	0.076
1.0E+09	0.076	0.075	0.076	0.076	0.076	0.074	0.076	0.076	0.076	0.077

RADS	PERCENT CHANGE IN AVERAGE THICKNESS										AVE.	1-SIGMA
1.0E+07	0.000	-2.003	0.000	-0.439	0.000	-0.439	-0.439	0.000	0.000	-0.071	-0.427	1.206
5.0E+07	-0.433	-2.003	0.000	-0.439	-0.433	-0.439	-0.439	0.000	0.000	-0.071	-0.516	1.220
1.0E+08	-0.433	-2.003	0.444	-0.439	-1.304	-0.439	-0.003	0.006	0.000	-0.071	-0.600	1.321
2.5E+08	0.439	-1.222	1.327	0.077	0.000	0.000	-0.006	0.439	1.322	0.439	0.361	1.253
5.0E+08	0.000	-1.639	0.003	0.439	0.000	0.000	0.439	0.439	0.003	0.439	0.100	1.361
1.0E+09	-1.304	-2.520	0.444	0.000	-0.066	-0.003	-0.439	0.000	0.444	-0.439	-0.557	1.320

Table 2 Reactor Irradiation - WEIGHT CHANGES

SAMPLE WEIGHTS, gm

INITIAL	5.1440	5.1397	4.9961	5.0670	5.1427	5.1205	4.8302	4.8060	4.8600		
1E+6 RADS	5.1192	5.1220	4.9726	5.0457	5.1205	5.1105	4.8069	4.7835	4.8360	AVE.	1-SIGMA
CHANGE, %	-0.482	-0.320	-0.470	-0.437	-0.431	-0.350	-0.481	-0.468	-0.510	-0.440	0.062
INITIAL	4.8281	4.9972	4.9830	4.8339	4.9729	4.9247	4.9037	4.8834	4.9241		
1E+7 RADS	4.8012	4.9717	4.9641	4.8075	4.9447	4.8964	4.8760	4.8606	4.9080	AVE.	1-SIGMA
CHANGE, %	-0.557	-0.510	-0.499	-0.547	-0.566	-0.575	-0.565	-0.467	-0.326	-0.512	0.079
INITIAL	4.8803	4.9321	4.8459	5.0773	4.9620	4.9129	5.0190	5.0401	4.9142		
1E+8 RADS	4.8628	4.9142	4.8291	5.0625	4.9476	4.8967	5.0108	5.0299	4.9075	AVE.	1-SIGMA
CHANGE, %	-0.358	-0.363	-0.346	-0.291	-0.290	-0.329	-0.163	-0.202	-0.136	-0.275	0.087
INITIAL	4.9588	4.9063	4.8947	5.0583	5.0365	4.9761	5.1597	5.2299	5.1469		
1E+9 RADS	4.9880	4.9194	4.9103	5.0752	5.0523	4.9919	5.1719	5.2359	5.1718	AVE.	1-SIGMA
CHANGE, %	0.588	0.267	0.319	0.335	0.313	0.317	0.237	0.115	0.485	0.331	0.137
INITIAL	5.8887	5.7950	5.8387	5.9168	5.8589	5.8254	5.8333	5.9740	5.9067		
5E+9 RADS	6.0809	5.8630	5.8975	5.9752	5.9053	5.8715	5.8763	6.0149	5.9959	AVE.	1-SIGMA
CHANGE, %	3.263	1.107	1.006	0.987	0.792	0.792	0.737	0.685	1.510	1.218	0.810
INITIAL	5.9625	6.0310	5.9316	5.9694	5.8847	5.8238	5.6844	5.8071	5.8186		
1E+10 RADS	6.1293	6.1860	6.0873	6.1265	6.0485	5.9856	5.8397	5.9563	5.9931	AVE.	1-SIGMA
CHANGE, %	2.798	2.557	2.625	2.631	2.765	2.779	2.732	2.569	2.998	2.719	0.140
INITIAL	5.7242	5.7752	5.8043	5.8404	5.8657	5.9207	6.0104	5.9515	5.9966		
2.5E+10 R	5.9077	5.9257	6.0439	6.2012	6.0806	6.1339	6.2752	6.1406	6.2044	AVE.	1-SIGMA
CHANGE, %	3.206	2.605	4.127	6.178	3.664	3.600	4.406	3.177	3.465	3.825	1.020
INITIAL	5.9599	5.9500	5.8618	5.8132	5.7876	5.6522	5.6054	5.6226	5.5349		
5E+10 RADS	5.8337	6.0343	5.9669	6.0005	5.9220	5.7594	5.7392	5.8022	5.5333	AVE.	1-SIGMA
CHANGE, %	-2.118	1.403	1.794	3.221	2.322	1.896	2.386	3.193	-0.029	1.563	1.693
INITIAL	5.6122	5.7549	5.9060	5.7319	5.7113	5.6978	5.7303	5.8082	5.7461		
7.5E+10 R	5.2463	5.6420	5.7274	5.6422	5.5950	5.6388	5.6269	5.6915	5.2572	AVE.	1-SIGMA
CHANGE, %	-6.519	-1.940	-3.036	-1.565	-2.021	-1.036	-1.819	-2.009	-8.508	-3.162	2.570
INITIAL	5.8238	5.7574	5.8004	5.8579	5.7925	5.8192	5.7434	5.7168	5.7435		
1E+11 RADS	5.3263	5.5596	5.6857	5.6049	5.7022	5.7453	5.6410	5.6354	5.5643	AVE.	1-SIGMA
CHANGE, %	-8.543	-3.435	-1.977	-4.319	-1.558	-1.269	-1.783	-1.424	-3.121	-3.040	2.311
INITIAL	5.7465	5.6060	5.6505	5.7006	5.8599	5.7943	5.7082	5.8761	5.9462		
1.06E+11 R	5.3861	5.4506	5.5190	5.5910	5.7132	5.6080	5.6036	5.5328	5.1207	AVE.	1-SIGMA
CHANGE, %	-6.272	-2.771	-2.328	-1.923	-2.503	-3.215	-3.190	-5.843	-13.883	-4.659	3.783
INITIAL	5.9717	5.8472	5.9405	5.8718	5.8399	5.7702	5.7354	5.8026	5.6440		
1.12E+11 R	4.9841	5.5452	5.5296	5.6360	5.6343	5.5676	5.5469	5.6580	5.2199	AVE.	1-SIGMA
CHANGE, %	-16.539	-5.165	-7.042	-4.016	-3.521	-3.512	-3.286	-2.493	-7.515	-5.899	4.344

Table 2 Continued   Reactor Irradiation - THICKNESS CHANGES

SAMPLE THICKNESS, cm

INITIAL	0.076	0.076	0.076	0.075	0.074	0.075	0.074	0.075	0.075		
1E+6 RADS	0.075	0.075	0.075	0.075	0.075	0.075	0.074	0.074	0.075	AVE.	1-SIGMA
CHANGE, %	-1.32	-1.32	-1.32	0.00	1.35	0.00	0.00	-1.33	0.00	-0.437	0.941
INITIAL	0.075	0.075	0.075	0.075	0.074	0.075	0.075	0.075	0.076		
1E+7 RADS	0.075	0.074	0.075	0.074	0.074	0.074	0.075	0.075	0.075	AVE.	1-SIGMA
CHANGE, %	0.00	-1.33	0.00	-1.33	0.00	-1.33	0.00	0.00	-1.32	-0.591	0.700
INITIAL	0.075	0.075	0.075	0.075	0.074	0.074	0.076	0.076	0.076		
1E+8 RADS	0.076	0.075	0.076	0.076	0.076	0.075	0.076	0.075	0.076	AVE.	1-SIGMA
CHANGE, %	1.33	0.00	1.33	1.33	2.70	1.35	0.00	-1.32	0.00	0.749	1.101
INITIAL	0.075	0.071	0.076	0.075	0.075	0.075	0.076	0.076	0.076		
1E+9 RADS	0.076	0.074	0.076	0.076	0.077	0.076	0.076	0.077	0.077	AVE.	1-SIGMA
CHANGE, %	1.33	4.23	0.00	1.33	2.67	1.33	0.00	1.32	1.32	1.503	1.296
INITIAL	0.075	0.075	0.076	0.073	0.073	0.074	0.075	0.075	0.075		
5E+9 RADS	0.075	0.073	0.074	0.072	0.073	0.073	0.072	0.074	0.075	AVE.	1-SIGMA
CHANGE, %	0.00	-2.67	-2.63	-1.37	0.00	-1.35	-4.00	-1.33	0.00	-1.484	1.401
INITIAL	0.075	0.075	0.075	0.075	0.075	0.074	0.074	0.074	0.074		
1E+10 RADS	0.074	0.075	0.074	0.073	0.073	0.074	0.073	0.074	0.073	AVE.	1-SIGMA
CHANGE, %	-1.33	0.00	-1.33	-2.67	-2.67	0.00	-1.35	0.00	-1.35	-1.109	1.043
INITIAL	0.073	0.073	0.073	0.073	0.074	0.074	0.075	0.074	0.075		
2.5E+10 R	0.078	0.074	0.072	0.072	0.073	0.074	0.074	0.074	0.074	AVE.	1-SIGMA
CHANGE, %	6.85	1.37	-1.37	-1.37	-1.35	0.00	-1.33	0.00	-1.33	0.162	2.605
INITIAL	0.074	0.075	0.073	0.075	0.075	0.074	0.073	0.073	0.072		
5E+10 RADS	0.075	0.075	0.073	0.075	0.077	0.074	0.075	0.074	0.073	AVE.	1-SIGMA
CHANGE, %	1.35	0.00	0.00	0.00	2.67	0.00	2.74	1.37	1.39	1.057	1.120
INITIAL	0.072	0.073	0.075	0.074	0.074	0.073	0.074	0.075	0.075		
7.5E+10 R	0.074	0.073	0.075	0.074	0.074	0.074	0.074	0.074	0.076	AVE.	1-SIGMA
CHANGE, %	2.70	0.00	0.00	0.00	0.00	1.37	0.00	-1.33	1.33	0.461	1.105
INITIAL	0.076	0.076	0.075	0.077	0.077	0.075	0.075	0.075	0.074		
1E+11 RADS	0.076	0.074	0.075	0.076	0.076	0.075	0.075	0.075	0.074	AVE.	1-SIGMA
CHANGE, %	0.00	-2.63	0.00	-1.30	-1.30	0.00	0.00	0.00	0.00	-0.501	0.953
INITIAL	0.074	0.073	0.07[illegible]	0.074	0.075	0.074	0.075	0.076	0.076		
1.06E+11 R	0.075	0.073	[illegible]	0.074	0.074	0.074	0.075	0.076	0.073	AVE.	1-SIGMA
CHANGE, %	1.35	0.00	0.00	0.00	-1.33	0.00	0.00	0.00	-3.95	-0.437	1.470
INITIAL	0.077	0.077	0.076	0.077	0.075	0.075	0.075	0.074	0.075		
1.12E+11 R	0.078	0.076	0.075	0.075	0.075	0.076	0.074	0.074	0.075	AVE.	1-SIGMA
CHANGE, %	1.30	-1.30	-1.32	-2.60	0.00	1.33	-1.33	0.00	0.00	-0.435	1.309

Table 2 Continued Reactor Irradiation - LENGTH CHANGES

SAMPLE LENGTH, cm

										AVE.	1-SIGMA
INITIAL	1.5020	1.5000	1.5070	1.5160	1.5790	1.5110	1.4920	1.4760	1.4910		
1E+6 RADS	1.4960	1.4960	1.4950	1.5050	1.5800	1.4970	1.4820	1.4680	1.4770		
CHANGE, %	-0.399	-0.267	-0.796	-0.726	0.063	-0.927	-0.670	-0.542	-0.939	-0.578	0.330
INITIAL	1.4990	1.4820	1.4880	1.5000	1.5240	1.5070	1.4960	1.5150	1.5000		
1E+7 RADS	1.4860	1.4780	1.4830	1.4920	1.5150	1.5050	1.4850	1.5120	1.4920		
CHANGE, %	-0.867	-0.270	-0.336	-0.533	-0.591	-0.133	-0.735	-0.198	-0.533	-0.466	0.249
INITIAL	1.5000	1.4980	1.5010	1.5340	1.5290	1.5310	1.5010	1.5200	1.5070		
1E+8 RADS	1.4960	1.4980	1.5010	1.5360	1.5250	1.5260	1.5000	1.5190	1.5030		
CHANGE, %	-0.267	0.000	0.000	-0.261	-0.262	-0.327	-0.067	-0.066	-0.265	-0.168	0.132
INITIAL	1.5100	1.5180	1.5220	1.5200	1.5210	1.5220	1.5410	1.5520	1.5770		
1E+9 RADS	1.4960	1.5050	1.5130	1.5100	1.5100	1.5100	1.5280	1.5400	1.5600		
CHANGE, %	-0.927	-0.856	-0.591	-0.654	-0.723	-0.788	-0.844	-0.773	-1.078	-0.804	0.146
INITIAL	1.6420	1.6420	1.6410	1.6420	1.6400	1.6450	1.6460	1.6500	1.6290		
5E+9 RADS	1.6080	1.6000	1.6040	1.6180	1.6050	1.6080	1.6100	1.6170	1.5980		
CHANGE, %	-2.071	-2.558	-2.255	-1.462	-2.134	-2.249	-2.187	-2.000	-1.903	-2.091	0.300
INITIAL	1.6400	1.6420	1.6280	1.6420	1.6430	1.6330	1.6190	1.6460	1.6540		
1E+10 RADS	1.6000	1.6060	1.5940	1.6030	1.6030	1.5960	1.5860	1.6110	1.6180		
CHANGE, %	-2.439	-2.192	-2.088	-2.375	-2.435	-2.266	-2.038	-2.126	-2.177	-2.237	0.150
INITIAL	1.6460	1.6480	1.6440	1.6490	1.6570	1.6620	1.6640	1.6200	1.6550		
2.5E+10 R	1.6000	1.6000	1.6190	1.6220	1.6270	1.6400	1.6400	1.5850	1.6380		
CHANGE, %	-2.795	-2.913	-1.521	-1.637	-1.810	-1.324	-1.442	-2.160	-1.027	-1.848	0.651
INITIAL	1.6520	1.6500	1.6310	1.6180	1.6100	1.5790	1.5750	1.5790	1.5800		
5E+10 RADS	1.6200	1.6200	1.5860	1.5970	1.5780	1.5600	1.5790	1.5900	1.5640		
CHANGE, %	-1.937	-1.818	-2.759	-1.298	-1.988	-1.203	0.254	0.697	-1.013	-1.229	1.103
INITIAL	1.5980	1.6090	1.6170	1.6180	1.6160	1.6030	1.6030	1.5990	1.6200		
7.5E+10 R	1.5420	1.5850	1.5900	1.5840	1.6000	1.6050	1.5920	1.5900	1.5760		
CHANGE, %	-3.504	-1.492	-1.670	-2.101	-0.990	0.125	-0.686	-0.563	-2.716	-1.511	1.136
INITIAL	1.6190	1.6100	1.6100	1.6060	1.6120	1.6250	1.6110	1.6130	1.6380		
1E+11 RADS	1.5850	1.5620	1.6060	1.5720	1.5950	1.5900	1.5840	1.5990	1.6080		
CHANGE, %	-2.100	-2.981	-0.248	-2.117	-1.055	-2.154	-1.676	-0.868	-1.832	-1.670	0.822
INITIAL	1.6200	1.6010	1.6150	1.6200	1.6200	1.6140	1.6090	1.6230	1.6210		
1.06E+11 R	1.5940	1.5800	1.5750	1.5870	1.5880	1.5640	1.5550	1.5660	1.5590		
CHANGE, %	-1.605	-1.312	-2.477	-2.518	-1.975	-3.098	-3.356	-3.512	-3.825	-2.631	0.881
INITIAL	1.6260	1.5950	1.6260	1.6010	1.6120	1.6040	1.6080	1.6240	1.6081		
1.12E+11 R	1.5700	1.5550	1.5610	1.5780	1.5690	1.5500	1.5840	1.5800	1.4580		
CHANGE, %	-3.444	-2.508	-3.998	-1.437	-2.667	-3.367	-1.493	-2.709	-9.334	-3.448	2.368

Table 2 Continued Reactor Irradiation - ATTENUATION

SAMPLE ABSORPTION

										AVE.	1-SIGMA
INITIAL	0.9828	0.9801	0.9820	0.9801	0.9820	0.9833	0.9820	0.9812	0.9812	0.982	0.001
1E+6 RADS	0.9817	0.9812	0.9784	0.9850	0.9782	0.9844	0.9814	0.9829	0.9791	0.981	0.002
INITIAL	0.9793	0.9840	0.9796	0.9831	0.9811	0.9843	0.9782	0.9822	0.9825	0.982	0.002
1E+7 RADS	0.9810	0.9787	0.9761	0.9814	0.9807	0.9852	0.9815	0.9862	0.9846	0.982	0.003
INITIAL	0.9825	0.9799	0.9826	0.9796	0.9797	0.9795	0.9803	0.9818	0.9800	0.981	0.001
1E+8 RADS	0.9776	0.9780	0.9811	0.9800	0.9811	0.9821	0.9829	0.9791	0.9840	0.981	0.002
INITIAL	0.9794	0.9741	0.9772	0.9799	0.9844	0.9807	0.9807	0.9820	0.9793	0.980	0.003
1E+9 RADS	0.9815	0.9815	0.9836	0.9812	0.9826	0.9840	0.9822	0.9820	0.9830	0.982	0.001
INITIAL	0.9807	0.9784	0.9785	0.9757	0.9766	0.9780	0.9775	0.9787	0.9789	0.978	0.001
5E+9 RADS	0.9816	0.9814	0.9823	0.9780	0.9818	0.9804	0.9817	0.9830	0.9821	0.981	0.002
INITIAL	0.9776	0.9799	0.9777	0.9790	0.9766	0.9780	0.9782	0.9755	0.9775	0.978	0.001
1E+10 RADS	0.9813	0.9842	0.9839	0.9824	0.9815	0.9828	0.9813	0.9804	0.9806	0.982	0.001
INITIAL	0.9758	0.9765	0.9760	0.9770	0.9776	0.9764	0.9788	0.9785	0.9775	0.977	0.001
2.5E+10 R	0.9811	0.9812	0.9775	0.9807	0.9815	0.9858	0.9829	0.9804	0.9821	0.981	0.002
INITIAL	0.9785	0.9769	0.9752	0.9797	0.9788	0.9767	0.9768	0.9765	0.9760	0.977	0.001
5E+10 RADS	0.9780	0.9812	0.9809	0.9801	0.9789	0.9815	0.9770	0.9806	0.9767	0.980	0.002
INITIAL	0.9742	0.9775	0.9795	0.9777	0.9770	0.9776	0.9795	0.9795	0.9794	0.978	0.002
7.5E+10 R	0.9762	0.9810	0.9813	0.9781	0.9781	0.9792	0.9803	0.9782	0.9776	0.979	0.002
INITIAL	0.9809	0.9817	0.9842	0.9807	0.9812	0.9805	0.9812	0.9805	0.9811	0.981	0.001
1E+11 RADS	0.9817	0.9812	0.9861	0.9839	0.9842	0.9834	0.9854	0.9808	0.9844	0.983	0.002
INITIAL	0.9801	0.9789	0.9787	0.9771	0.9789	0.9783	0.9797	0.9798	0.9804	0.979	0.001
1.06E+11 R	0.9823	0.9815	0.9812	0.9830	0.9784	0.9834	0.9823	0.9795	0.9864	0.982	0.002
INITIAL	0.9791	0.9807	0.9810	0.9813	0.9780	0.9788	0.9794	0.9791	0.9797	0.980	0.001
1.12E+11 R	0.9828	0.9834	0.9810	0.9832	0.9829	0.9844	0.9825	0.9807	0.9814	0.983	0.001

GRAND AVERAGE PRE-IRRADIATION ABSORPTION = 0.979 0.002

GRAND AVERAGE POST-IRRADIATION ABSORPTION = 0.981 0.002