

The influence of low dose neutron irradiation on the thermal conductivity of Allcomp carbon foam



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Material Science and Technology Division

**THE INFLUENCE OF LOW DOSE NEUTRON IRRADIATION ON THE THERMAL
CONDUCTIVITY OF ALLCOMP CARBON FOAM**

Timothy D. Burchell, Wallace D. Porter and Joel L. McDuffee

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ABSTRACT

Oak Ridge National Laboratory was contracted via a Work for Others Agreement with Allcomp Inc. (NFE-14-05011-MSOF: “Carbon Foam for Beam Stop Applications”) to determine the influence of low irradiation dose on the thermal conductivity of Allcomp Carbon Foam. Samples (6 mm dia. x 5 mm thick) were successfully irradiated in a rabbit capsule in a hydraulic tube in the target region of the High Flux Isotope Reactor at the Oak Ridge National Laboratory. The specimens were irradiated at $T_{irr} = 750^{\circ}\text{C}$ to a neutron damage dose of 0.2 dpa.

There is a small dimensional and volume shrinkage as would be anticipated for a low dose graphite irradiation. There was also an unexpected, small, but consistent mass loss for all specimens. The small changes in density, dimensions or volume are not of concern. At 0.2 dpa the irradiation shrinkage rate difference between the glassy carbon skeleton and the CVD coating was not sufficient to cause a large enough irradiation induced strain to create any mechanical degradation. Similarly differential thermal expansion was not a problem. It appears that only the thermal conductivity was affected by 0.2 dpa.

For the intended application conditions, i.e. @ 400°C and 0 DPA (start-up) the foam thermal conductivity is about 57 W/m.K and at 700°C and 0.2 DPA (end of life) the foam thermal conductivity is approx. 30.7 W/m.K. The room temp thermal conductivity drops from 100-120 W/m.K to approximately 30 W/m.K after 0.2 dpa of neutron irradiation.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) was contracted via a Work for Others (WFO) Agreement with Allcomp Inc. (NFE-14-05011-MSO: “Carbon Foam for Beam Stop Applications”) to determine the influence of low irradiation dose on the thermal conductivity of Allcomp Carbon Foam.

A High Flux Isotope Reactor (HFIR) rabbit capsule (No. GF 1501) was designed to irradiate eight foam samples at the desired 750°C and 0.2 displacements per atom (dpa). The irradiation temperature was determined from SiC temperature monitors included in the capsule.

The thermal conductivity was determined on 6 mm diameter x 5 mm thick foam samples over the temperature range 25-900°C. Prior to finalizing the specimen size a size effects study was conducted and it was determined that a 6 mm dia. x 5 mm thick foam sample was sufficiently representative of the bulk foam structure and thermal conductivity to allow irradiation.

2. EXPERIMENTAL

2.1 MATERIALS

The carbon foam samples were cut as shown in Figure 1, from a small block provided by Allcomp Inc.

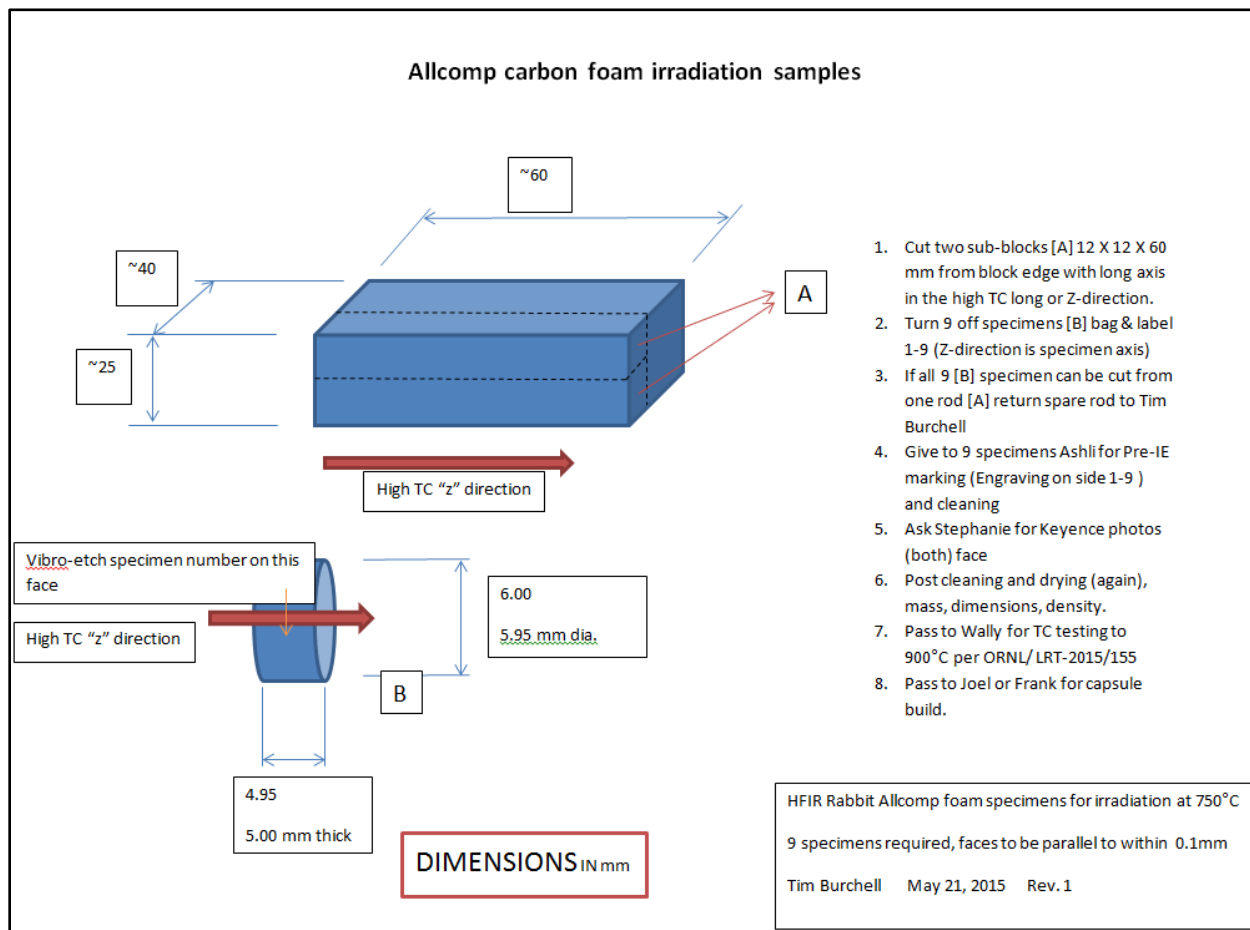


Figure 1 Cutting drawing for the Allcomp foam block and irradiation specimens

2.2 IRRADIATION CAPSULE

An engineering drawing (number S15-33-GRAPA-01) of the capsule is shown in Figure 2. The capsule was irradiated in HFIR during cycle 462.

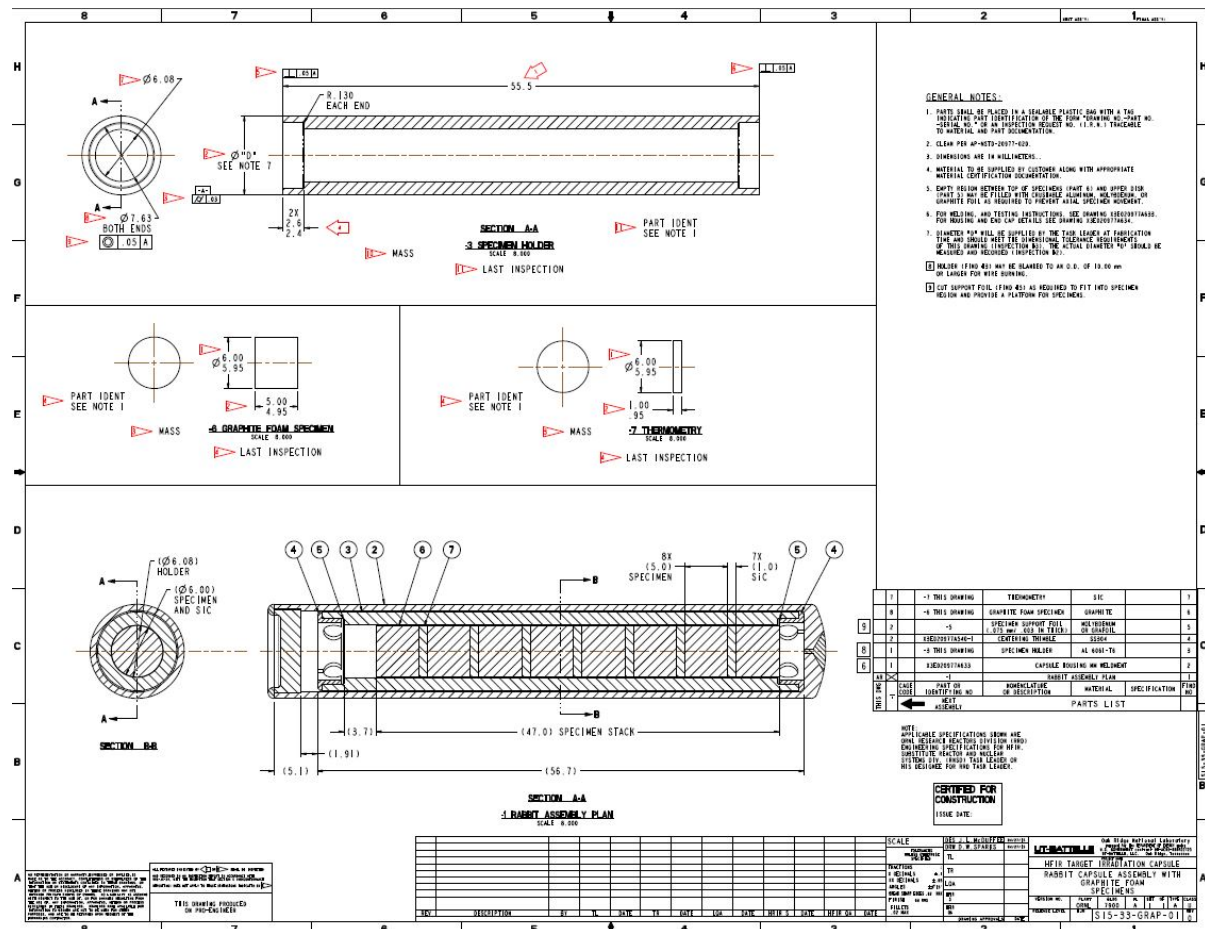


Figure 2 Rabbit capsule assembly drawing

2.2.1 Irradiation Dose

The capsules irradiation dose was fixed by the neutron flux (depends on position in reactor core) and the capsules in-core dwell time. The desired dose (0.2 dpa) was achieved through 81.967 hours of irradiation in HFIR Target channel HT/5 (B3-5) giving an actual dose of 1.917×10^{-1} dpa (Table 1) to all of the foam samples.

Table 1 HFIR capsule neutronics details

HFIR Location	HFIR Flux [E>0.1 MeV]	Required Fluence	Actual Fluence		ACTUAL TIME
	n/cm ² .s	DPA	n/cm2 [E>.1 MeV]	dpa	Hours
HT/5 (B3-5)	8.9000E+14	2.0000E-01	2.6262E+20	1.9171E-01	81.9670

2.2.2 Irradiation Temperature

The irradiation sample temperature was determined by the post-irradiation examination of SiC temperature monitors. The capsule contained seven monitors and four were examined, one via the thermal expansion, and three via the thermal diffusivity. Interrogation of the SiC irradiation temperature monitors showed the irradiation temperature to be approximately $750 \pm 25^\circ\text{C}$ (Table 2).

Table 2 Indicated irradiation temperatures for the four temperature monitors interrogated

SiC Monitor #	Test Method	Indicated Irradiation Temperature, $^\circ\text{C}$
7	Thermal Expansion	740
1	Thermal Diffusivity	770
2	Thermal Diffusivity	730
3	Thermal Diffusivity	750
Mean		747.5 (750)

2.2.2.1 SiC Thermal Expansion

The thermal expansion behavior of the diameter of one of the SiC temperature monitor (TM #7) was examined. An inflection in the dL/L_0 and α vs. measurement temperature plots indicated the point at which the irradiation temperature was exceeded and annealing begun (note, the red curves correspond to heating and the blue curves to cooling). Based on the thermal expansion behavior curve in Figure 3 the capsule irradiation temperature was $\sim 740^\circ\text{C}$.

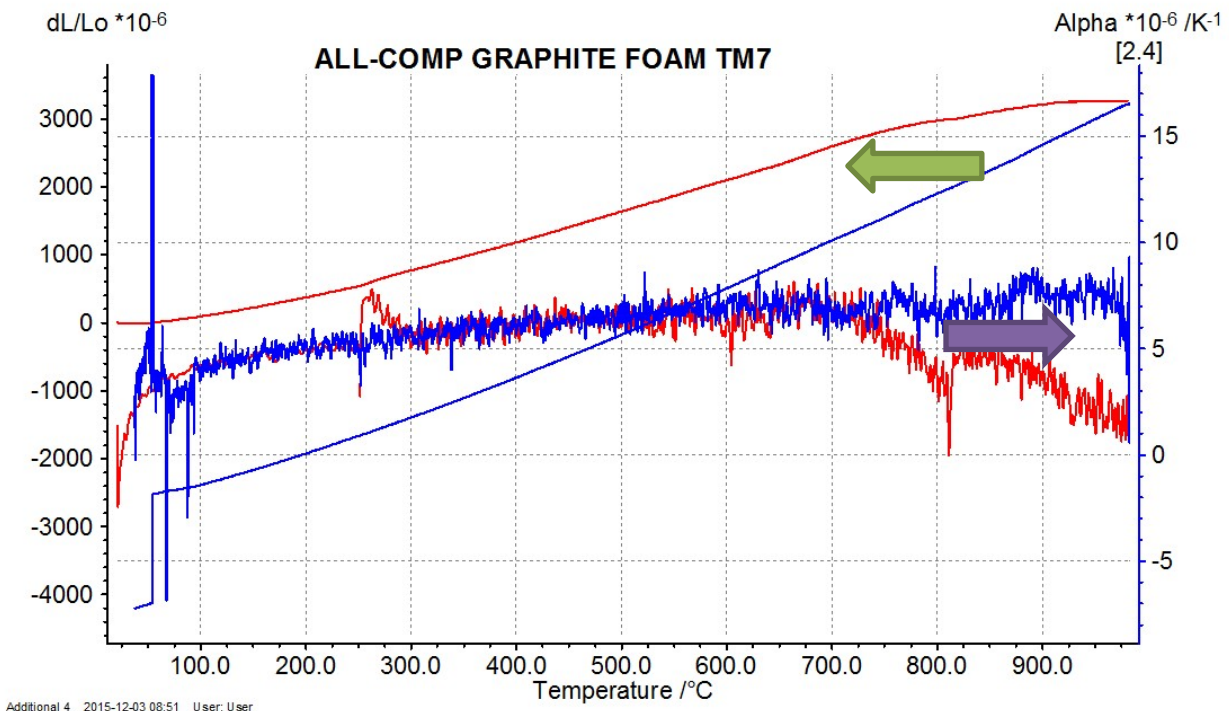


Figure 3 Thermal expansion behavior of SiC temperature monitor No. 7

2.2.2.2 SiC Thermal Diffusivity

The thermal diffusivity behavior at the annealing/measurement temperature of three of the SiC temperature monitors (TM #1, #2, & #3) was examined. The specimens were annealed *in-situ* using the laser flash equipment. A prominent inflection in the relative diffusivity vs. measurement temperature plots indicated the point at which the irradiation temperature was exceeded and the annealing of diffusivity begun. Based on the thermal diffusivity behavior plots in Figure 4 to Figure 6 the indicated capsule irradiation temperatures were ~770°C for TM#1, ~730°C for TM#2 and ~750°C for TM#3.

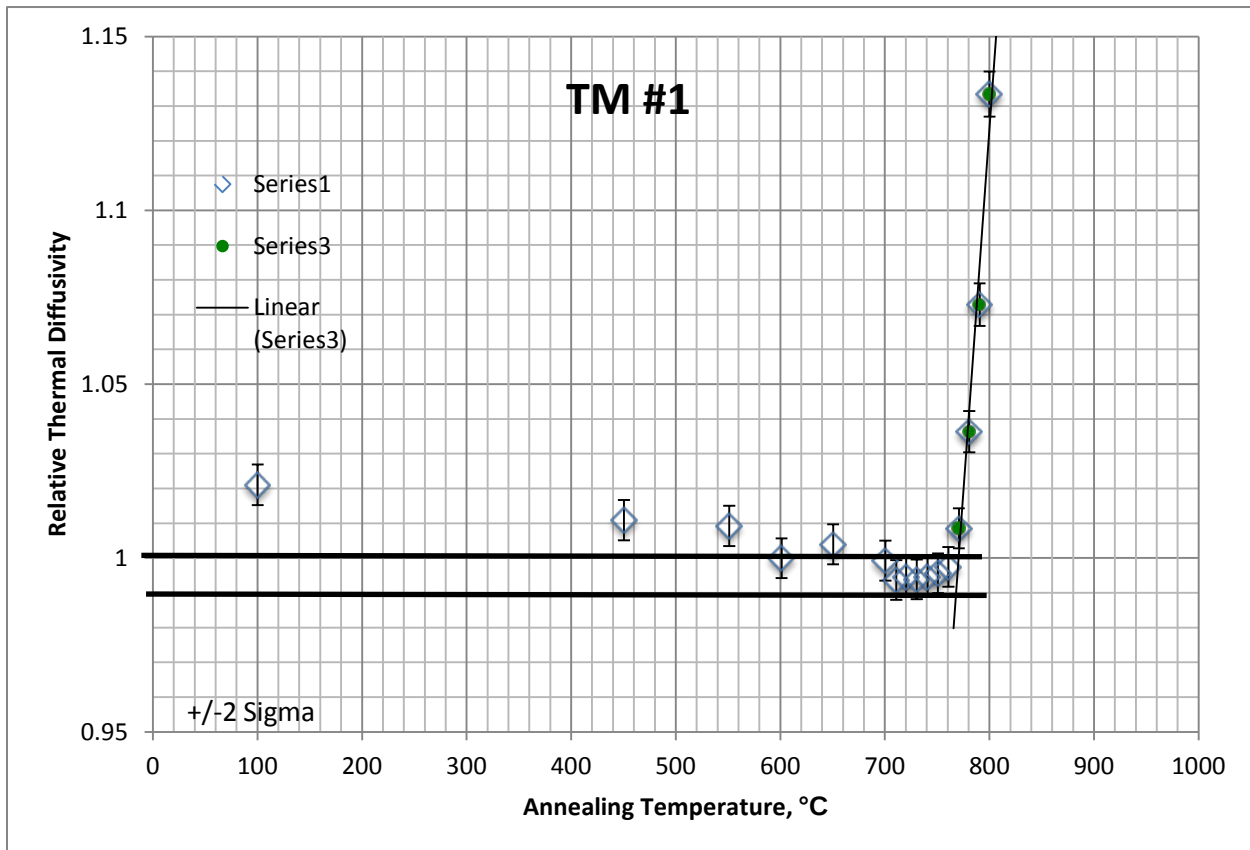


Figure 4 Relative thermal diffusivity behavior of SiC temperature monitor No. 1 with increasing annealing temperature, measured at 100°C

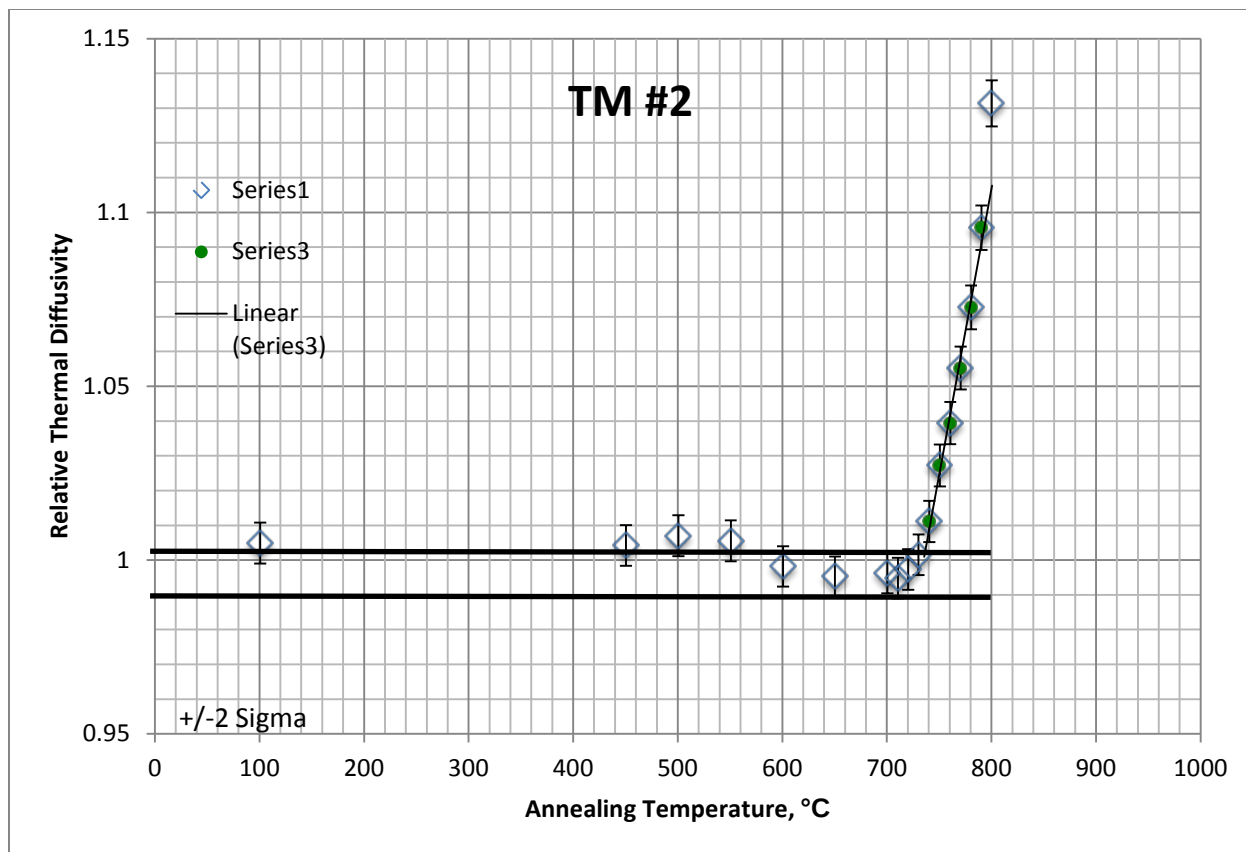


Figure 5 Relative thermal diffusivity behavior of SiC temperature monitor No. 2 with increasing annealing temperature, measured at 100°C

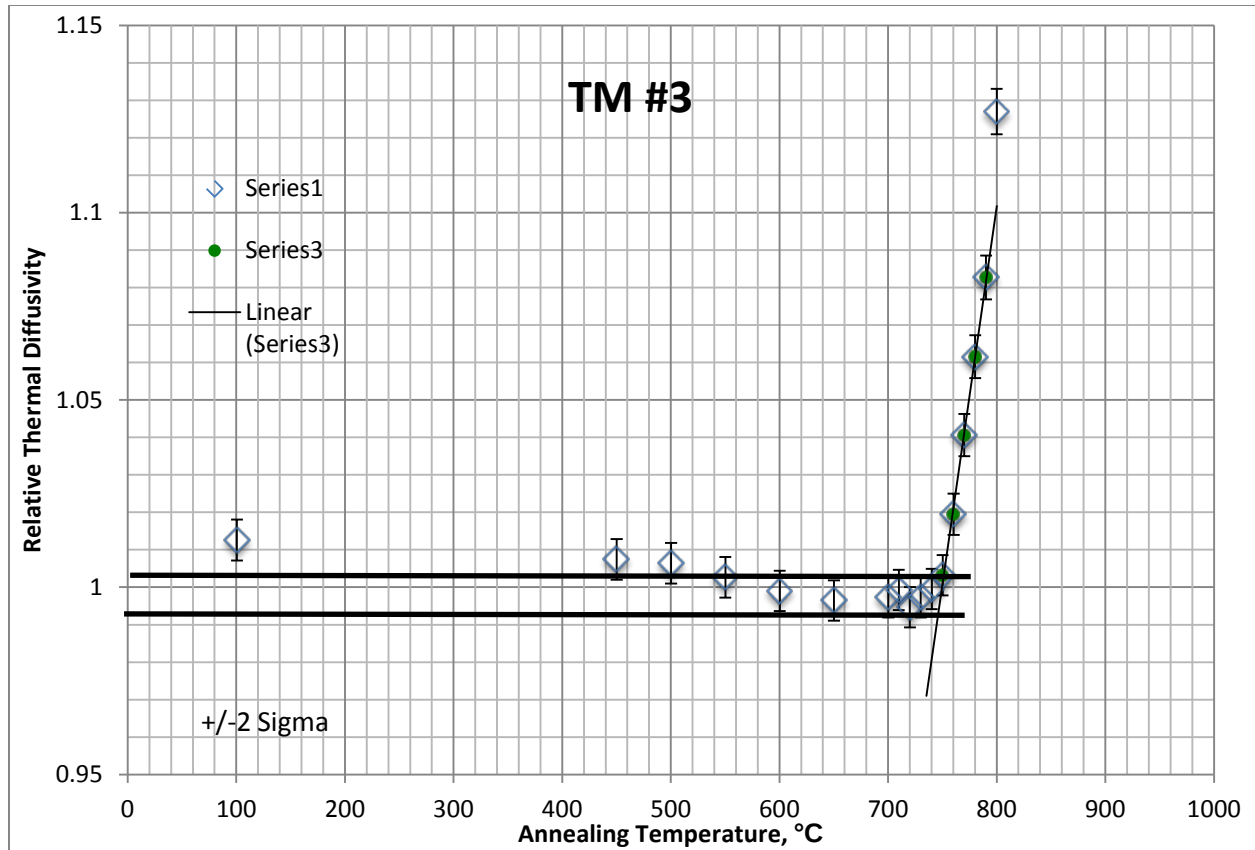


Figure 6 Relative thermal diffusivity behavior of SiC temperature monitor No. 3 with increasing annealing temperature, measured at 100°C

2.3 CARBON FOAM THERMAL CONDUCTIVITY DETERMINATION

The thermal conductivity of the foam was determined by the LASER flash diffusivity method [1] using the Netzsch LFA 457 (Figure 7) system. Measurements of the thermal diffusivity were made at the following temperatures: heating; RT, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900. Cooling: 600, 300, 100 °C. At each temperature the LASER flash pulse was recorded and the diffusivity calculated using the Cowan [2] method.



Figure 7 The Netzsch LFA 457 LASER flash apparatus

The thermal conductivity was calculated from the relationship:

$$K = \alpha \times C_p \times \rho \left(\frac{W}{mK} \right)$$

Where α is the thermal diffusivity (m^2/s)

C_p is the Specific Heat at the measurement temperature ($J/kg.K$), and

ρ is the specimen's measured bulk density, kg/m^3 .

Before and after irradiation, the specimens were subjected to a similar experimental interrogation, to determine the thermal conductivity over the same temperature range (RT-900°C)

2.4 EXPERIMENTAL TESTING

Experimental testing was conducted in accordance with the experimental plan [3].

2.4.1 Specimen Size Effects study

A specimen size effect study was conducted to examine the foams sensitivity to specimen size by testing samples at 6, 8, 10 and 12.7 mm diameter and 3, 4, and 5 mm thickness. It was concluded that 6 mm dia. x 5 mm thick samples were acceptable for thermal conductivity determination.

3. RESULTS

3.1 MASS, DENSITY AND DIMENSIONAL CHANGES

The carbon foam samples were dimensionally inspected and weighed prior to irradiation as part of the Pre-Irradiation Examination (Pre-IE). This examination was repeated after irradiation in Post Irradiation Examination (PIE) and the irradiation induced changes in mass, dimensions and density evaluated. The Pre-IE, PIE and evaluated change data are in Table 3. The small mass loss was unexpected, and was probably the result of surface oxidation. The expected volume shrinkage usually causes an increase in sample density. However, here the density gain is masked by the mass loss.

Table 3 Mass, density and dimensional (volume) changes for the Allcomp Inc. carbon foam

Specimen ID	Engraving	PIE							Pre-IE							Dim or Vol change (shrinkage)			Mass Change (loss)	Density change (loss)
		Diamter mm		Average Diameter	Average Thickness	Mass g	Volume mm ³	Density	Diamter mm		Ave Diameter	Ave Thickness	Mass g	Volume mm ³	Density	DIA	THICK	VOL		
		D1	D2					g/cc	D1	D2					g/cc	%	%	%	g	%
1-1	1	5.976	5.968	5.972	4.988	0.0746	139.719	0.534	5.985	5.986	5.986	4.993	0.07546	140.492	0.537	0.2339	0.1001	0.5503	0.0009	0.572
1-2	2	5.960	5.958	5.959	4.987	0.0761	139.084	0.547	5.97	5.971	5.971	4.996	0.07739	139.880	0.553	0.2010	0.1801	0.5693	0.0013	1.057
1-3	3	5.987	5.981	5.984	4.992	0.0767	140.387	0.546	5.983	5.984	5.984	4.997	0.07759	140.497	0.552	0.0000	0.1051	0.0784	0.0009	1.024
1-4	4	5.976	5.976	5.976	4.988	0.0766	139.892	0.548	5.981	5.983	5.982	4.992	0.07767	140.307	0.554	0.1003	0.0901	0.2955	0.0011	1.162
1-5	5 (looks like a 6)	5.977	5.982	5.980	4.988	0.0766	140.063	0.547	5.991	5.988	5.990	4.994	0.07753	140.708	0.551	0.1753	0.1252	0.4584	0.0009	0.745
1-6	X	5.978	5.988	5.983	4.993	0.0754	140.361	0.537	5.984	5.981	5.983	5	0.07645	140.548	0.544	0.0000	0.1500	0.1334	0.0011	1.252
1-7	7	Not Irradiated							5.975	5.98	5.978	4.995	0.07705	140.173	0.550	Not irradiated				
1-8	8	5.990	5.985	5.988	4.996	0.0768	140.664	0.546	5.998	5.997	5.998	5.001	0.07787	141.275	0.551	0.1751	0.1050	0.4329	0.0011	0.910
1-9	9	6.016	6.004	6.010	4.927	0.0768	139.772	0.549	6.013	6.015	6.014	4.925	0.07789	139.909	0.557	0.0665	-0.0406	0.0976	0.0011	1.353
															Mean	0.1190	0.1019	0.3270	0.0010	1.0094
															St. Dev.	0.0831	0.0668	0.2029	0.0001	0.2602

3.2 STRUCTURAL CHANGE

Examples of the structure of the carbon foam before and after irradiation are shown in Figure 8 to Figure 11. All the specimen microstructural images for the foam specimens before and after irradiation have been provided to Allcomp Inc. and only limited images are included here for illustrative purposes (specimen 1 and 2).

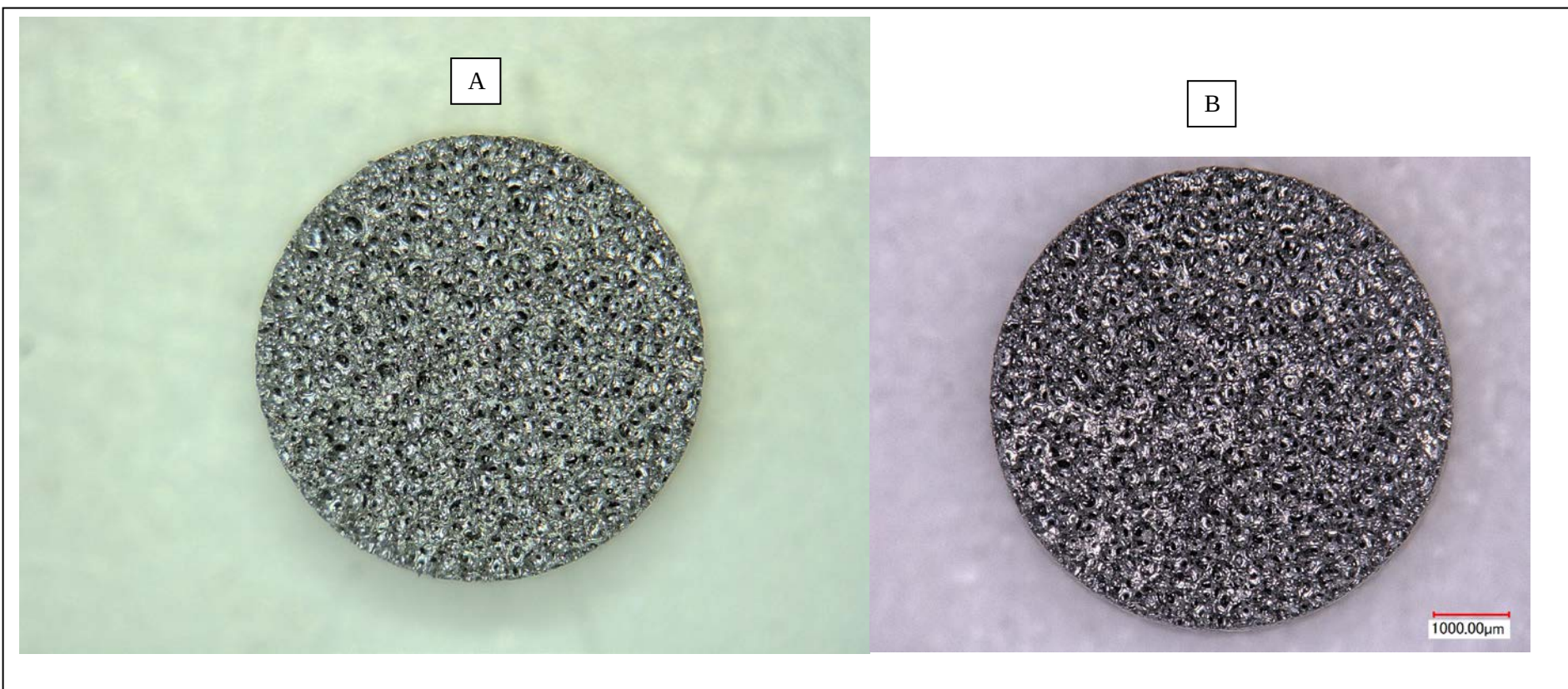


Figure 8 Top view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation

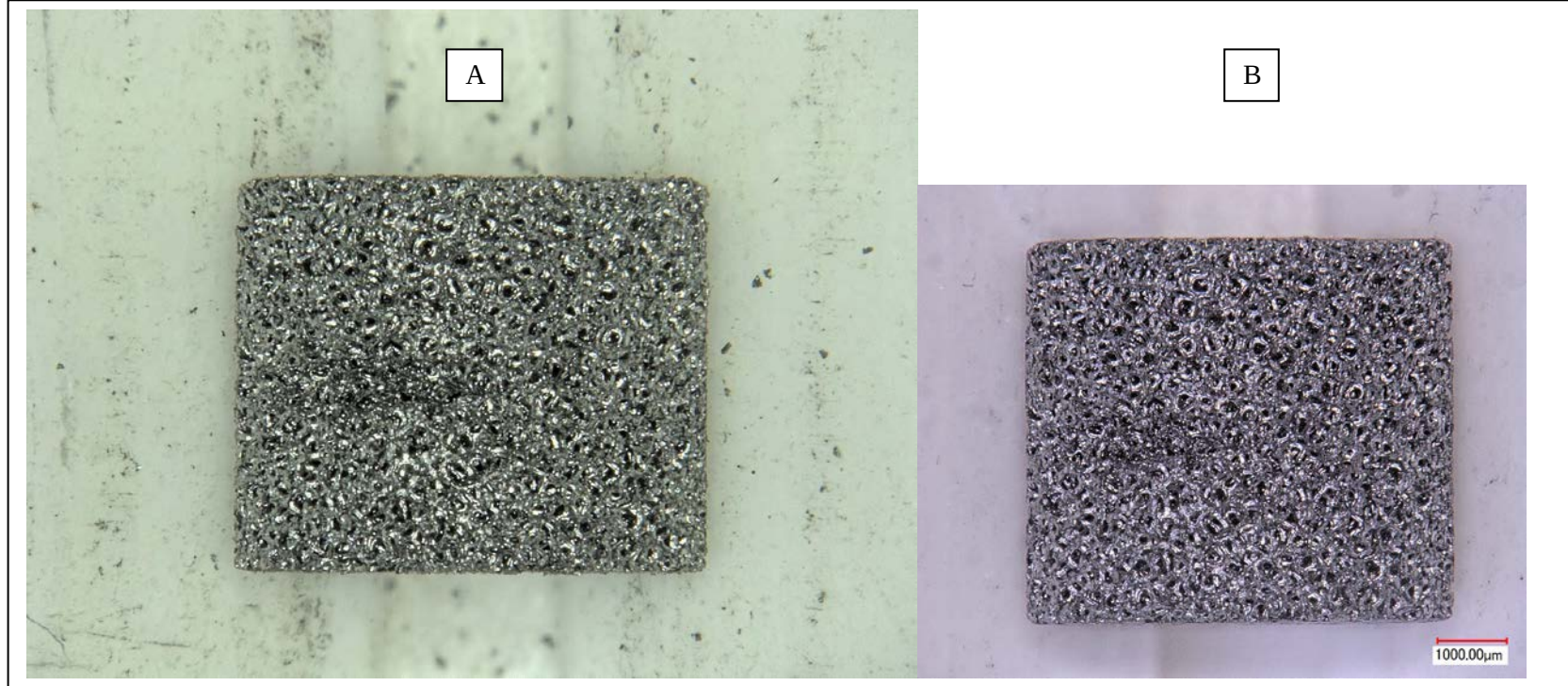


Figure 9 Side view of Allcomp carbon foam sample 1-1 [A] pre irradiation [B] post irradiation

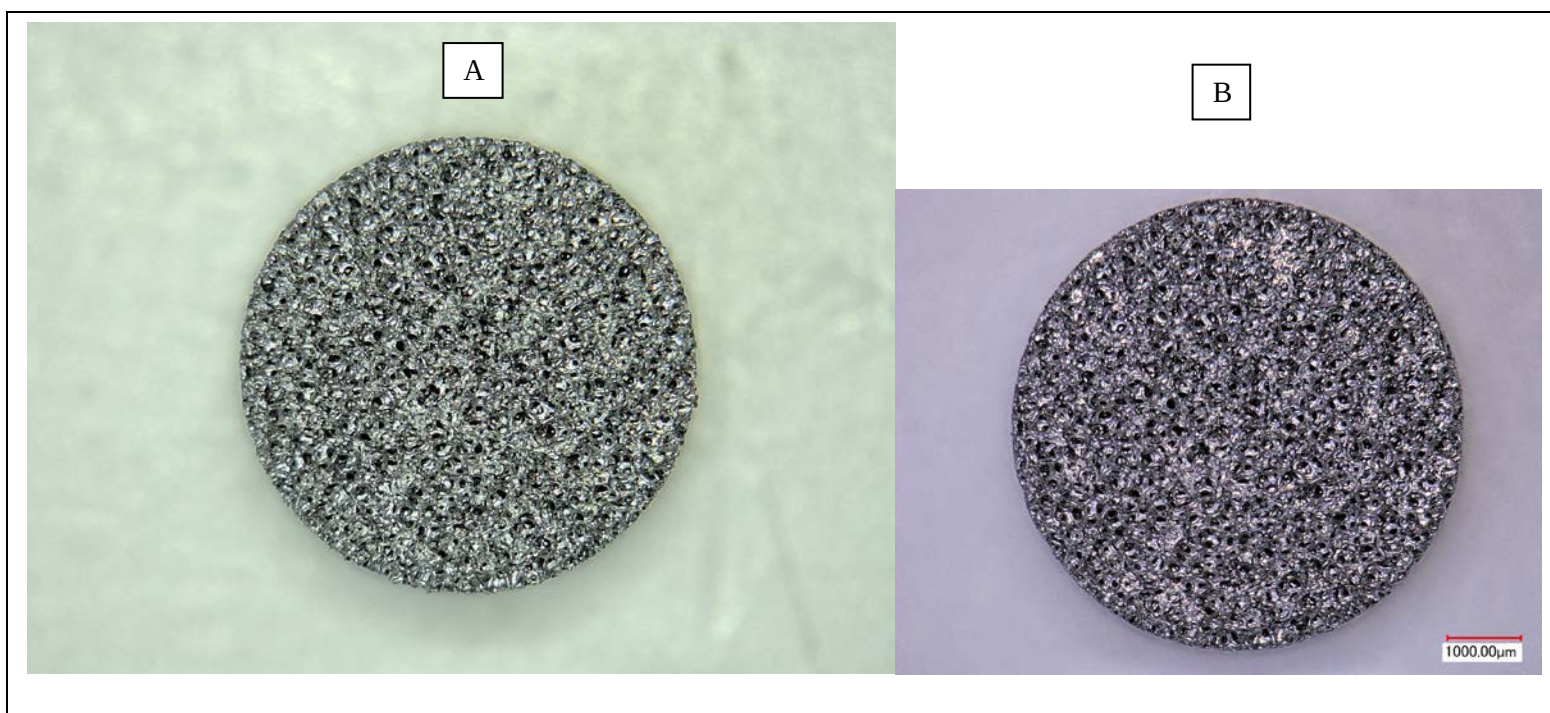


Figure 10 Top view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation

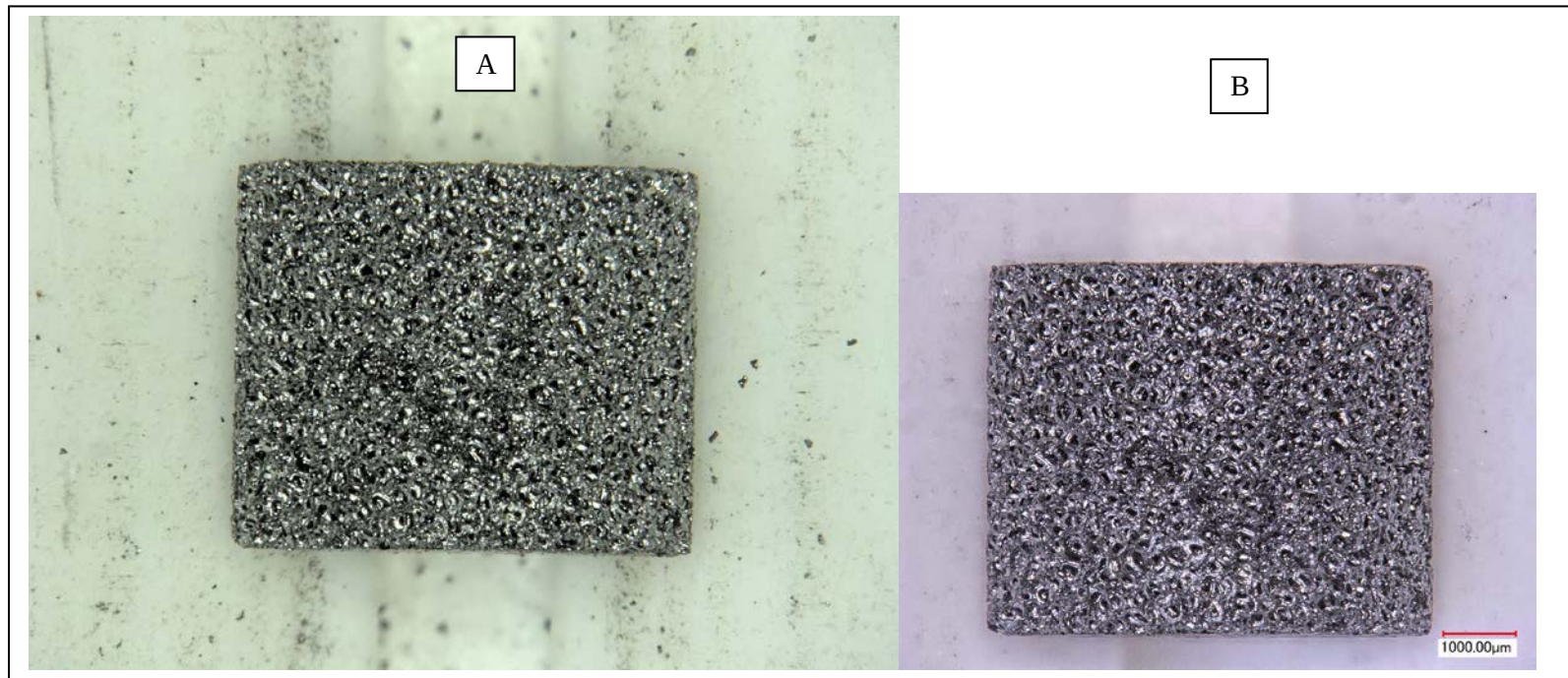


Figure 11 Side view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation

3.3 THERMAL CONDUCTIVITY

The thermal conductivity of the Allcomp specimen's, before and after irradiation are shown in to Figure 14 and the tabular data are given in Table 5 to Table 21 (Appendix A).

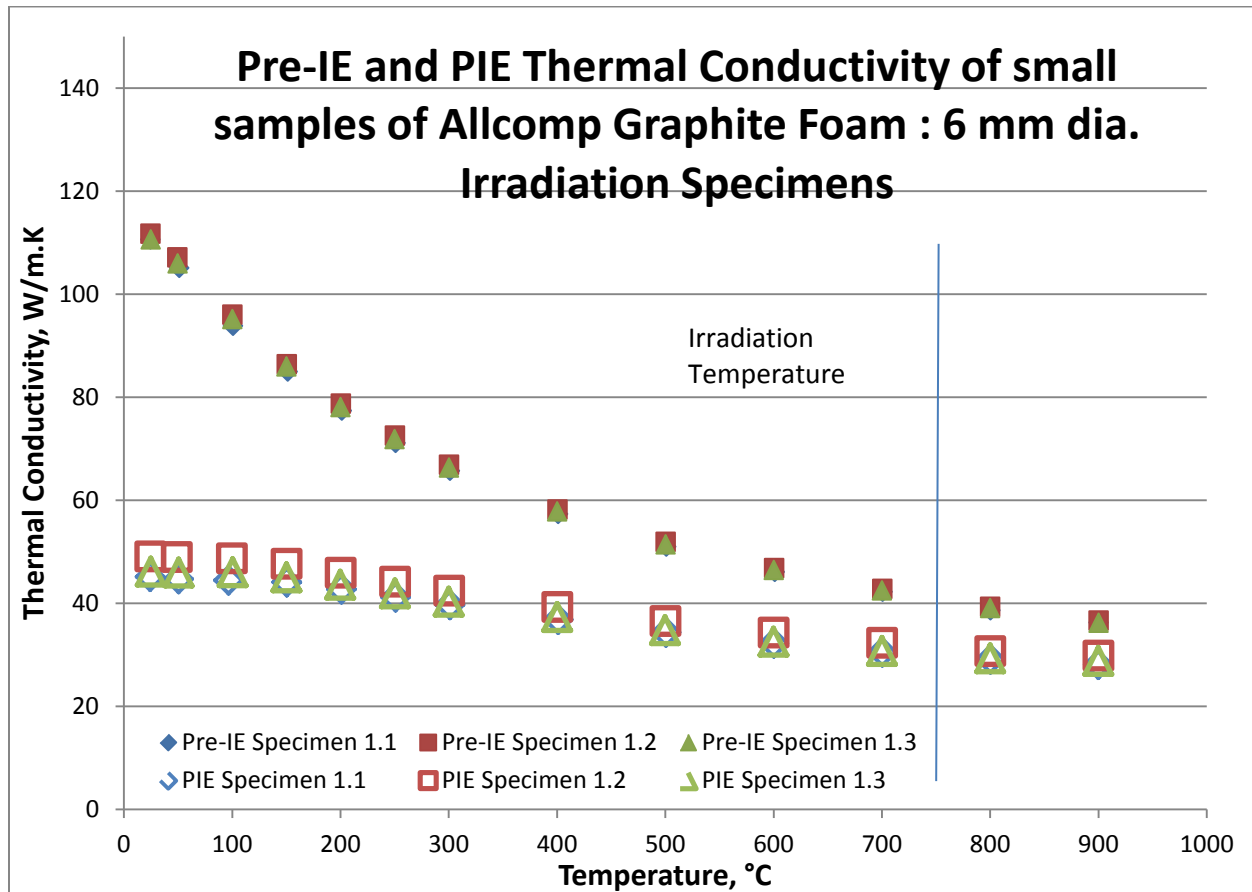


Figure 12 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 1, 2 and 3)

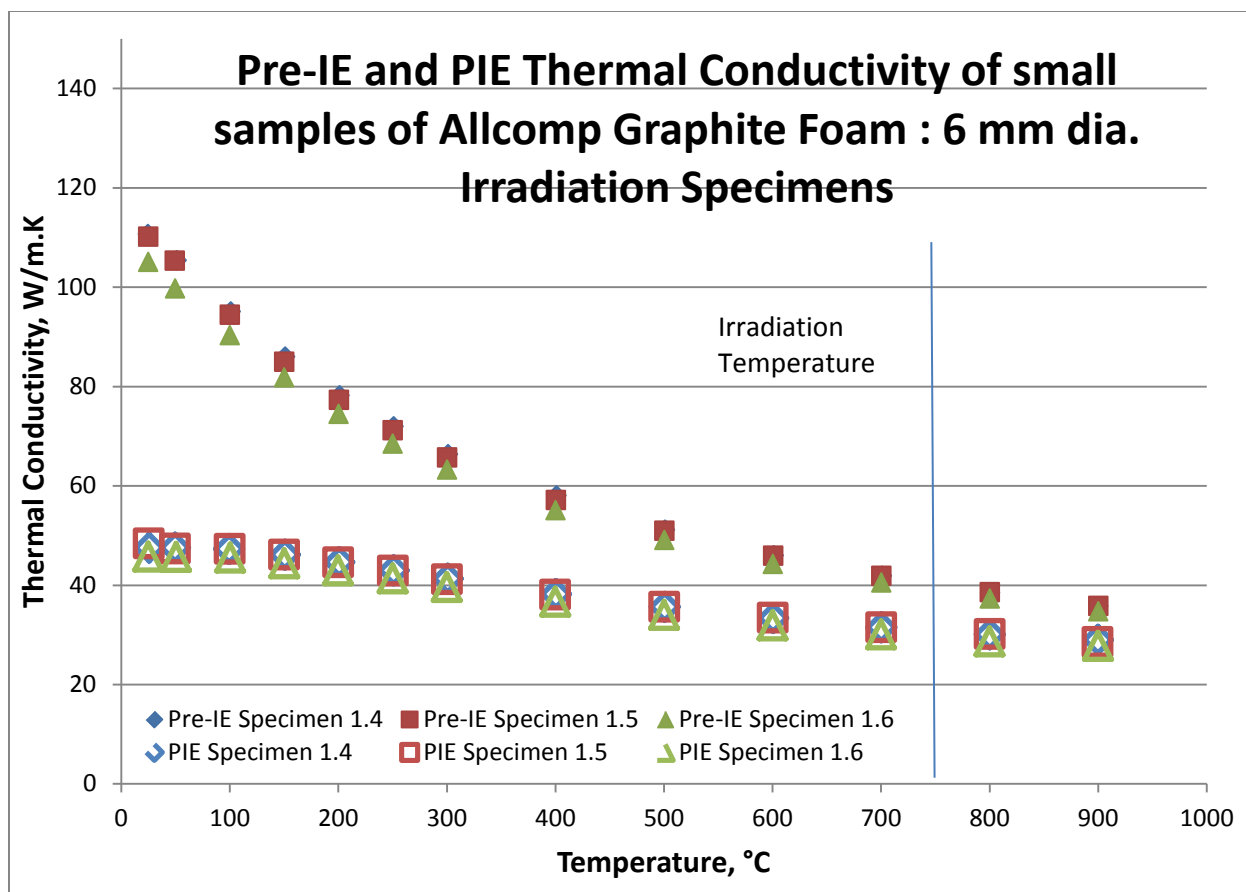


Figure 13 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 4, 5 and 6)

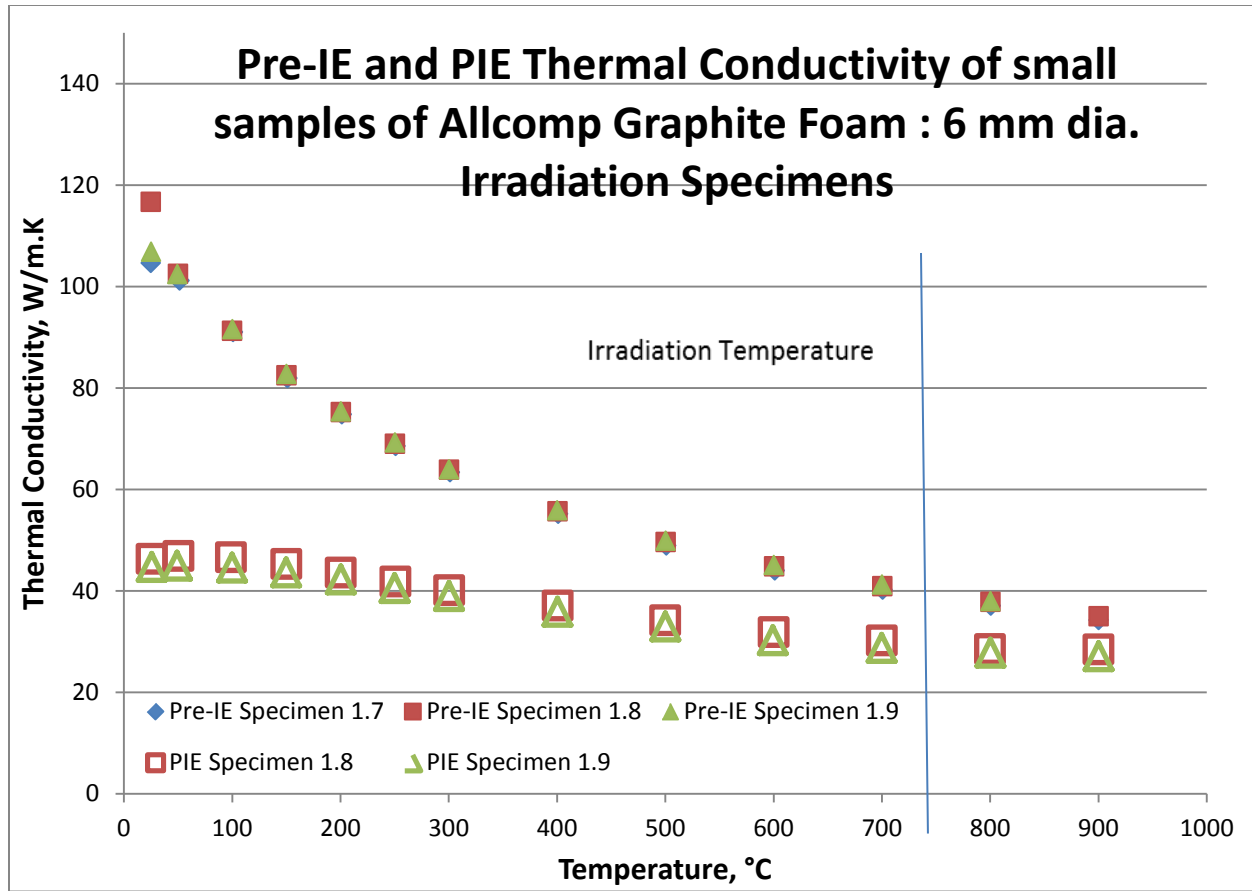


Figure 14 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 8 and 9)

4. DISCUSSION

Irradiation to 0.2 dpa induced a small dimensional and volume shrinkage in the carbon foam, although the magnitude of the changes was very small (a few tenths of a percent). The observed reduction of the dimensions and volume of the foam specimens upon neutron irradiation is entirely consistent with the behavior of polycrystalline graphite.

The unexpected decrease of the mass and density on irradiation of ~1.3% (Table 3) can probably be attributed to some oxidative mass loss due to surface oxygen, occurring when the foam specimen temperature rises to the irradiation temperature. If the mass loss of the specimens were absent, we would expect the density to increase (constant mass and reducing foam specimen volume).

At 0.2 dpa the irradiation induced shrinkage rate differences between the glassy carbon skeleton and the foam's CVD coating were not sufficient to cause enough strain to create any mechanical degradation (Figure 8 to Figure 11). Similarly differential thermal expansion was not a problem.

Graphite and Carbons foams are phonon conductors of heat [4]. The thermal resistance at any temperature after irradiation is the result of contributions from phonon-phonon scattering and defect (both intrinsic and extrinsic, i.e., irradiation induced) scattering. The thermal conductivity of the Allcomp carbon foam determined from the irradiation samples before and after irradiation is shown in to Figure 14 .

The thermal conductivity of a graphitic single crystal is highly anisotropic, reflecting the different bond types within and between the carbon basal planes. In the crystallographic $\langle a \rangle$ directions (within the basal plane) the atom bonding is of the primary, covalent type; whereas between the basal planes (crystallographic $\langle c \rangle$ direction) the bonding is of the much weaker secondary, or van der Waals, type. Phonons (elastic waves) may thus travel considerably more easily in the $\langle a \rangle$ direction than in the $\langle c \rangle$ direction within a graphite single crystal. The conductive deposited layer (pyrolytic carbon) of the Allcomp foam will be predominantly oriented with the crystallographic $\langle a \rangle$ planes parallel to the Allcomp foams ligaments and cell walls.

Kelly [5] has reviewed the data for the thermal conductivity of natural and pyrolytic graphite (single crystal similes). The room temperature thermal conductivity parallel to the basal planes is typically $> 1000 \text{ W/m.K}$, whereas perpendicular to the basal planes the room temperature thermal conductivity is typically $< 10 \text{ W/m.K}$. The thermal conductivity of graphite shows a maximum with temperature at approximately 100 K. Below this maximum the conductivity is dominated by the specific heat and varies as $\sim T^3$. At higher temperatures, above the maxima, the thermal conductivity decreases with increasing temperature due to phonon scattering. Measurements on single crystals by Smith and Rasor [6] showed that the maxima in thermal conductivity parallel to the basal plane was located at $\sim 80 \text{ K}$ at a value of 2800 W/m.K . Nihira and Iwata [7] reported the maximum thermal conductivity (perpendicular to the basal planes) for a pyrolytic graphite to be located at 75 K with a value of $\sim 20 \text{ W/m.K}$. At extremely low temperatures, i.e., $T < 10 \text{ K}$ the thermal conductivity is dominated by an electronic contribution, which is proportional to temperature.

The temperature dependence of the in-plane thermal conductivity is shown in Figure 15 for various forms of pyrolytic graphites. Substantial improvements in thermal conductivity caused by thermal annealing and/or compression annealing are attributed to increased crystal perfection and increases in the size of the regions of coherent ordering (crystallites), which minimizes the extent of phonon-defect scattering and results in a larger phonon mean-free path. With increasing temperature, the dominant phonon interaction becomes phonon-phonon scattering (Umklapp processes). Therefore, the observed reduction in thermal conductivity with increasing temperature and the convergence of the curves in Figure 15 are attributed to the dominant effect of Umklapp scattering in reducing phonon mean-free path.

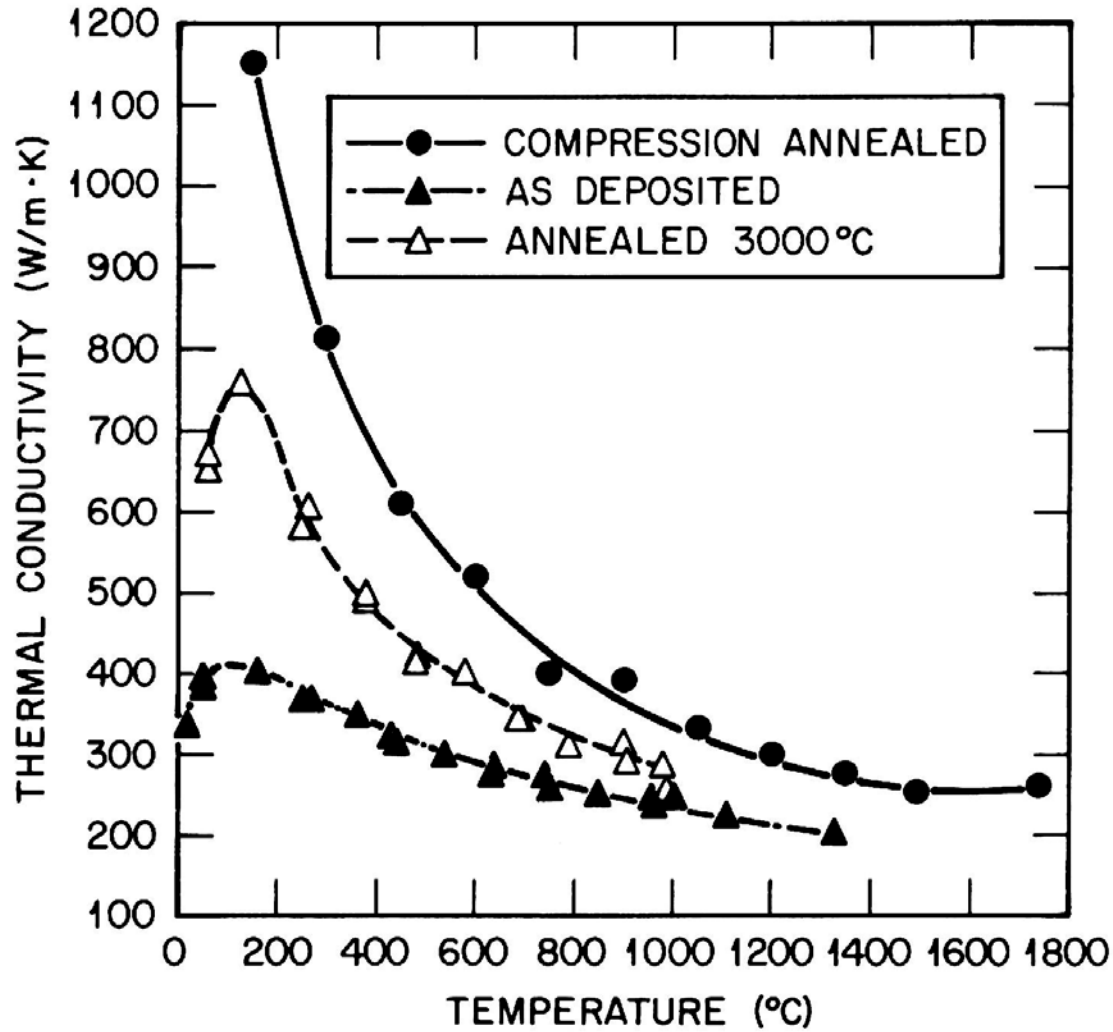


Figure 15 Temperature dependence of thermal conductivity for pyrolytic graphite in the as-deposited, annealed, and compression annealed condition. Adapted from Roth et al [8]

As discussed previously, graphite and carbon are phonon conductors of heat. Thus any reduction in the intrinsic defect population causes a reduction in the degree of phonon-defect scattering, an increase in the phonon mean free path, and results in an increase in the thermal conductivity. In graphite such thermally induced improvements are attributable to increases in crystal perfection and a concomitant increase in the size of the regions of coherent ordering upon graphitization. With increasing temperature the dominant phonon interaction becomes phonon-phonon scattering (Umklapp processes). Therefore, there is a reduction of thermal conductivity with increasing temperature [9]. This decrease in the thermal conductivity with increasing temperature can clearly be seen in Figure 16.

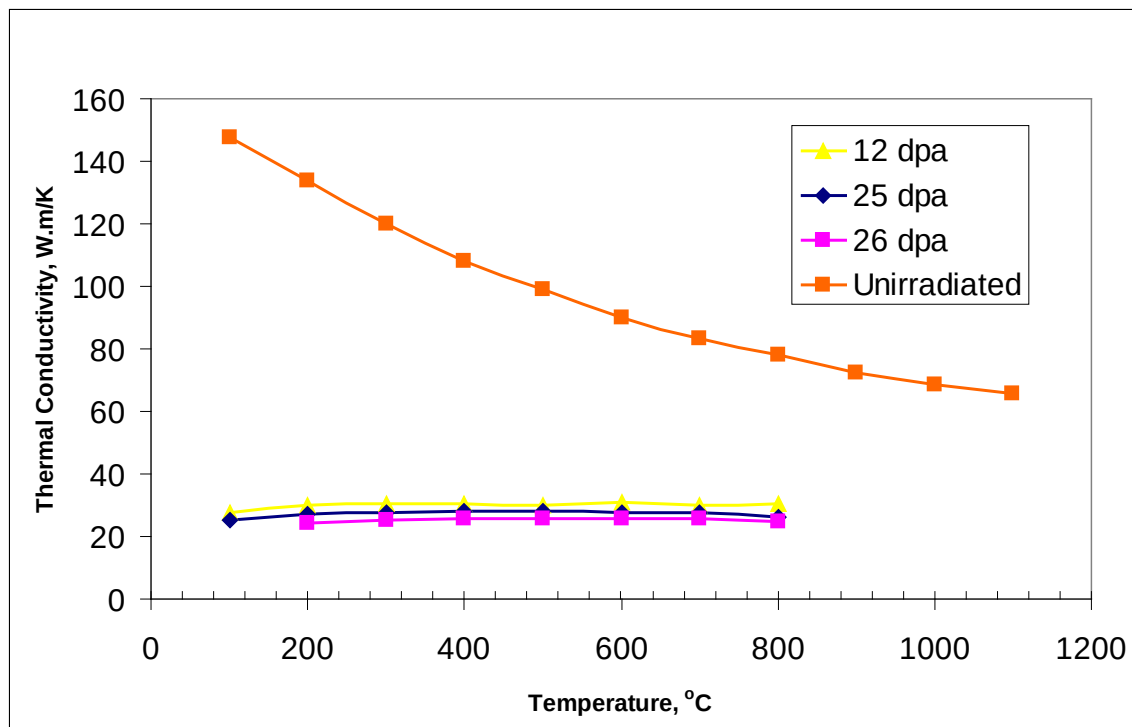


Figure 16 Temperature dependence of thermal conductivity in the irradiated and unirradiated condition for typical nuclear grade graphite. Irradiation temperature = 600°C.

The mechanism of thermal conductivity and the degradation of thermal conductivity have been extensively reviewed [5,9,10,11,12] and recently described in brief for irradiated nuclear graphite by Burchell [13]. Increases of thermal resistance due to irradiation damage have been ascribed by Taylor *et al* [14] to the formation of: (i) submicroscopic interstitial clusters, containing 4 ± 2 carbon atoms; (ii) vacant lattice sites, existing as singles, pairs, or small groups; and (iii) vacancy loops, which exist in the graphite crystal basal plane and are too small to have collapsed parallel to the hexagonal axis. The contribution of collapsed lines of vacant lattice sites and interstitial loops, to the increased thermal resistance, is negligible.

The reduction in thermal conductivity due to irradiation damage is temperature and dose sensitive. At any irradiation temperature, the decreasing thermal conductivity will reach a "saturation limit." This limit is not exceeded until the graphite undergoes gross structural changes at very high doses. The "saturated" value of conductivity will be attained more rapidly, and will be lower, at lower irradiation temperatures [15]. In graphite, the neutron irradiation-induced degradation of thermal conductivity can be very large, as illustrated in Figure 16. This reduction is particularly large at low temperatures. Bell *et al* [16] have reported that the room temperature thermal conductivity of PGA graphite is reduced by more than a factor of 70 when irradiated at 155°C to a dose of ~ 0.6 DPA. At an irradiation temperature of 355°C the room temperature thermal conductivity of PGA was reduced by less than a factor of 10 at doses twice that obtained at 155°C. Above 600°C the reduction of thermal conductivity is less significant. For example, Kelly [17] reported the degradation of PGA at higher temperatures: At an irradiation temperature of 600°C and a dose of ~ 13 DPA, the thermal conductivity was only degraded by a factor of ~ 6 ; at irradiation temperatures of 920°C and 1150°C the degradation was minimal (less than a factor of 4 at ~ 7 DPA). For the fine-grained, isomolded graphite shown in Figure 16 the degradation of thermal conductivity at the irradiation temperature (600°C plus) was only a factor of ~ 3 , but was a factor ~ 6 at a measurement temperature of 100°C.

Thus the observed behavior of the Allcomp foam is entirely in line with our expectations and our current theoretical understanding of graphite thermal transport behavior. Moreover, the behavior is in agreement with prior experimental work by Gallego *et al* [18] on mesophase pitch derived foam samples. Gallego *et al* reported the room temperature thermal conductivity dropped from ~ 70 W/m.K to ~ 30 W/m.K after irradiation at 740°C and 0.3 dpa. The Allcomp foam when irradiated a 750°C to 0.2 dpa experience a drop in the room temperature thermal conductivity from ~ 110 W/m.K to ~ 45 W/m.K. Figure 17 to Figure 19 show the thermal conductivity of the Allcomp foam specimens 1.3, 1.6 and 1.9 during heating and cooling from 900°C after irradiation. During cooling the thermal conductivity was measured at temperatures of 100, 300, and 600°C . The thermal conductivity shows a small recovery as a result of thermal annealing at $\sim 150^\circ\text{C}$ above the irradiation temperature. Clearly, there is some potential for thermal annealing of the extrinsic (particle displacement) damage.

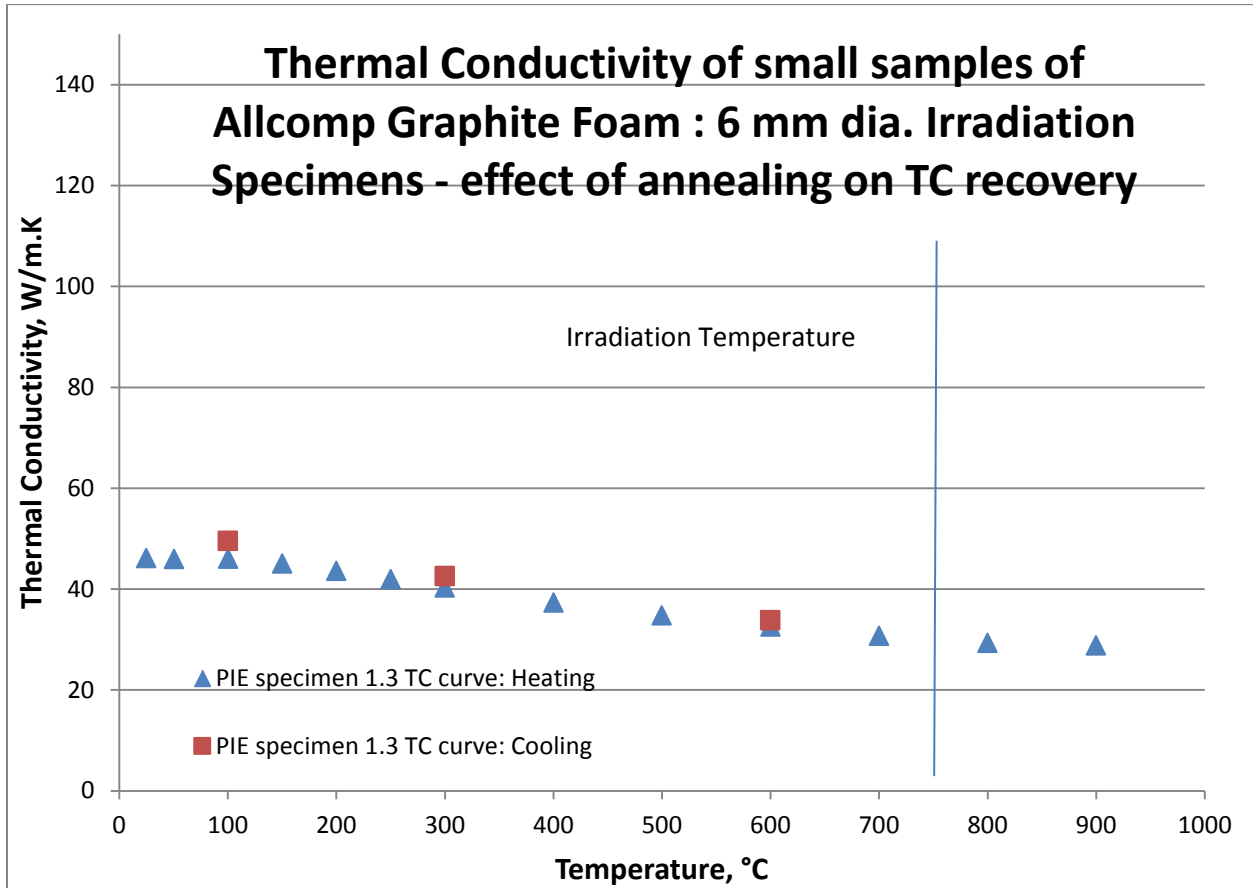


Figure 17 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 3 (Tirr= 750°C , 0.2 dpa)

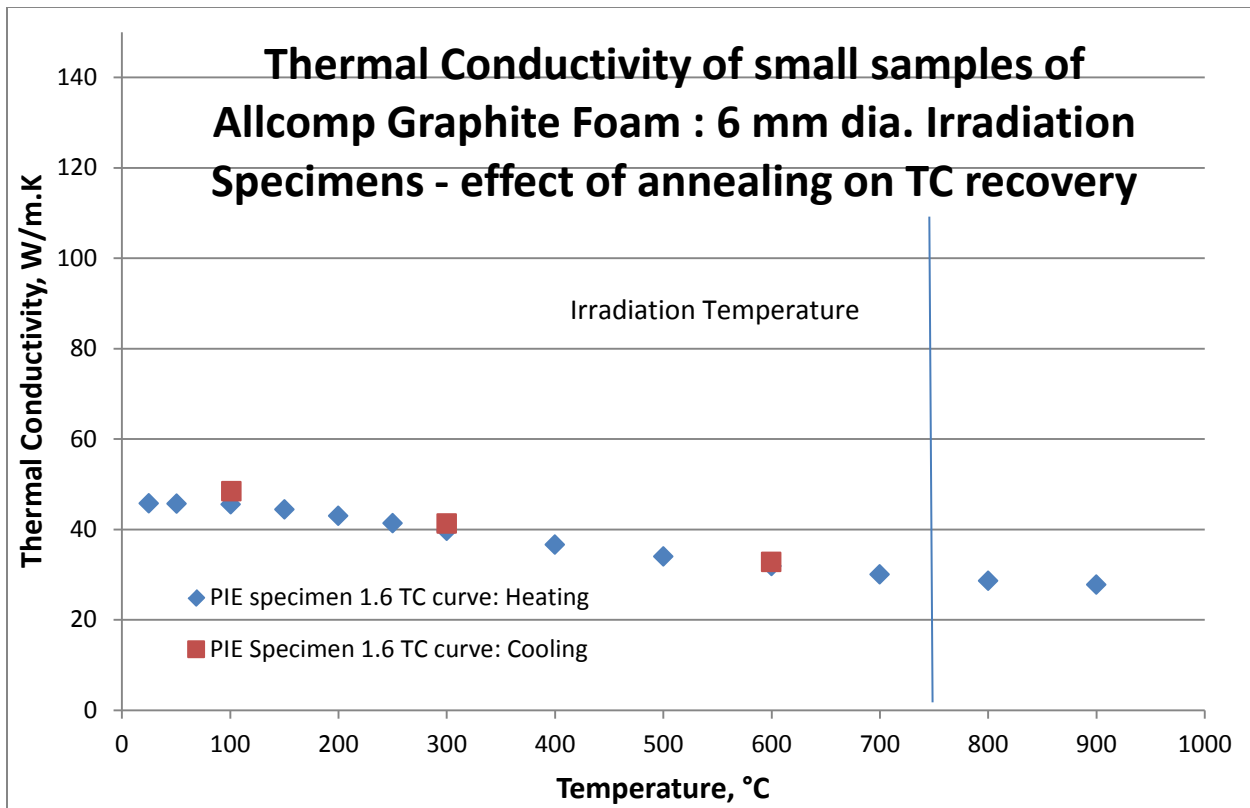


Figure 18 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 6 (Tirr=750°C, 0.2 dpa)

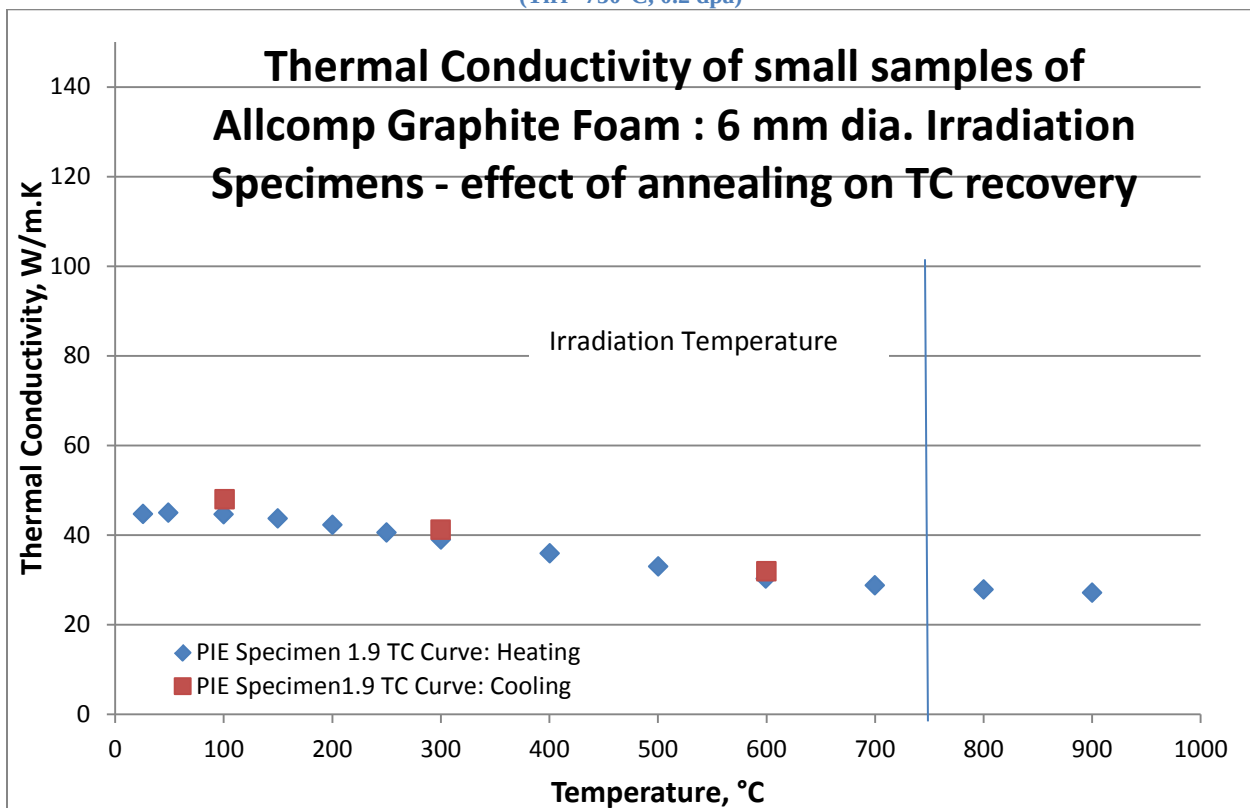


Figure 19 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 9 (Tirr=750°C, 0.2 dpa)

Discussions with Allcomp suggests the operating temperature of the carbon foam beam dump is approximately 400°C at the beginning of life (zero dpa) and at end of life (i.e., at 0.2 dpa) the operating temperature is approximately 700°C. Referring to Table 5 to Table 21 (summarized in Table 4) the thermal conductivity at 400°C is 56.7 W/m.K and the thermal conductivity at 700°C (after 0.2 dpa) is 30.7 W/m.K.

Table 4 Thermal conductivities at the beam stop foam operating temperatures and particle displacements

TC @ 400°C and 0 dpa		TC @ 700°C and 0.2 dpa	
Specimen No.	Thermal Conductivity W/m.K	Specimen No.	Thermal Conductivity W/m.K
1.1	57.33	1.1	30.49
1.2	58.16	1.2	32.29
1.3	57.79	1.3	30.74
1.4	58.02	1.4	31.52
1.5	57.17	1.5	31.52
1.6	55.07	1.6	30.06
1.7	55.18	1.7	-
1.8	55.66	1.8	30.2
1.9	55.86	1.9	28.77
MEAN @ 400°C	56.69	MEAN @ 700°C	30.70

5. CONCLUSIONS

Allcomp foam samples (6 mm dia. x 5 mm thick) were successfully irradiated in a rabbit capsule in a hydraulic tube in the target region of the high flux isotope reactor at the Oak Ridge National Laboratory. The specimens were irradiated at $T_{irr} = 747.5^\circ\text{C}$ to 0.2 dpa.

There is a small dimensional and volume shrinkage and the mass and density appear reduced (we would expect density to increase as volume reduces at constant mass). It is postulated that the small mass loss was due to thermal oxidation in the capsule, i.e., at the irradiation temperature, from chemisorbed O_2 on the foam surface. The small changes in density, dimensions or volume are not of concern. At 0.2 dpa the irradiation shrinkage rate difference between the glassy carbon skeleton and the CVD coating was not sufficient to cause a large enough irradiation induced strain to create any mechanical degradation. Similarly, differential thermal expansion was not seen to be a problem. It appears that only the thermal conductivity was affected by a displacement dose of 0.2 dpa.

For the intended application conditions, i.e. @ 400°C and 0 DPA (start-up) the foam thermal conductivity was about 57 W/m.K and at 700°C and 0.2 DPA (end of life) the foam thermal conductivity was approx. 30.7 W/m.K. The room temperature thermal conductivity drops from 100-120 W/m.K to approximately 30 W/m.K after 0.2 dpa of neutron irradiation.

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7. DISTRIBUTION

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APPENDIX A. THERMAL CONDUCTIVITY DATA

APPENDIX A. THERMAL CODUCTIVITY DATA

Table 5 calculated thermal conductivity variation with temperature for sample 1 (unirradiated)

1.1: Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm2/sec	J/kg.K	g/cm3	W/m.K
24.6	297.75	281.41	731.78	0.5371	110.61
51.2	324.35	243.20	804.62	0.5371	105.11
100.9	374.05	187.30	932.90	0.5371	93.85
151.4	424.55	150.31	1052.03	0.5371	84.93
201.2	474.35	124.41	1158.33	0.5371	77.40
251	524.15	105.55	1253.99	0.5371	71.09
301.1	574.25	91.28	1340.26	0.5371	65.71
401.1	674.25	71.82	1486.18	0.5371	57.33
501.1	774.25	59.24	1603.01	0.5371	51.01
601.2	874.35	50.55	1697.09	0.5371	46.08
700.9	974.05	44.35	1773.06	0.5371	42.24
800.3	1073.45	39.16	1835.02	0.5371	38.60
900.2	1173.35	35.79	1886.40	0.5371	36.26
599.7	872.85	50.56	1695.82	0.5371	46.05
299.4	572.55	91.71	1337.49	0.5371	65.88

Table 6 calculated thermal conductivity variation with temperature for sample 2 (unirradiated)

1.2: Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm2/sec	J/kg.K	g/cm3	W/m.K
24.7	297.85	275.825	732.06	0.5533	111.71
49.5	322.65	241.973	800.05	0.5533	107.11
100.2	373.35	186.384	931.17	0.5533	96.02
150.4	423.55	148.689	1049.78	0.5533	86.36
200.5	473.65	123.068	1156.91	0.5533	78.77
250.3	523.45	104.642	1252.71	0.5533	72.52
300.3	573.45	90.275	1338.96	0.5533	66.87
400.4	673.55	70.782	1485.26	0.5533	58.16
500.5	773.65	58.562	1602.38	0.5533	51.92
600.6	873.75	49.871	1696.58	0.5533	46.81
700.5	973.65	43.61	1772.78	0.5533	42.77
800.1	1073.25	38.725	1834.91	0.5533	39.31
900.1	1173.25	35.099	1886.35	0.5533	36.63
599.8	872.95	49.799	1695.91	0.5533	46.73

Table 7 calculated thermal conductivity variation with temperature for sample 3 (unirradiated)

1.3: Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.8	297.95	273.478	732.33	0.5523	110.60
49.6	322.75	239.771	800.32	0.5523	105.97
100.2	373.35	185.052	931.17	0.5523	95.16
150.3	423.45	148.26	1049.56	0.5523	85.93
200.2	473.35	122.25	1156.30	0.5523	78.07
250.2	523.35	103.833	1252.53	0.5523	71.82
300.3	573.45	89.721	1338.96	0.5523	66.34
400.3	673.45	70.464	1485.13	0.5523	57.79
500.4	773.55	58.124	1602.27	0.5523	51.43
600.4	873.55	49.574	1696.41	0.5523	46.44
700.3	973.45	43.354	1772.64	0.5523	42.44
800.1	1073.25	38.523	1834.91	0.5523	39.04
900.1	1173.25	34.745	1886.35	0.5523	36.20
600	873.15	49.542	1696.07	0.5523	46.40

Table 8 calculated thermal conductivity variation with temperature for sample 4 (unirradiated)

1.4 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.6	297.75	273.154	731.78	0.5536	110.65
51.2	324.35	236.624	804.62	0.5536	105.40
100.9	374.05	184.079	932.90	0.5536	95.06
151.1	424.25	147.723	1051.36	0.5536	85.98
201.3	474.45	121.995	1158.53	0.5536	78.24
251	524.15	103.707	1253.99	0.5536	71.99
301.1	574.25	89.408	1340.26	0.5536	66.33
401.1	674.25	70.523	1486.18	0.5536	58.02
501.1	774.25	57.625	1603.01	0.5536	51.14
601.2	874.35	48.984	1697.09	0.5536	46.02
700.8	973.95	42.667	1772.99	0.5536	41.88
800.5	1073.65	37.851	1835.13	0.5536	38.45
900.2	1173.35	34.215	1886.40	0.5536	35.73
599.4	872.55	48.979	1695.57	0.5536	45.97
299.4	572.55	89.97	1337.49	0.5536	66.61

Table 9 calculated thermal conductivity variation with temperature for sample 5 (unirradiated)

1.5 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.8	297.95	273.077	732.33	0.5510	110.1906
49.4	322.55	239.008	799.78	0.5510	105.3251
100.2	373.35	184.056	931.17	0.5510	94.43429
150.2	423.35	147.002	1049.33	0.5510	84.99367
200.5	473.65	121.314	1156.91	0.5510	77.33213
250.3	523.45	103.096	1252.71	0.5510	71.16129
300.3	573.45	89.036	1338.96	0.5510	65.68739
400.4	673.55	69.857	1485.26	0.5510	57.16938
500.5	773.65	57.688	1602.38	0.5510	50.9332
600.6	873.75	49.143	1696.58	0.5510	45.93955
700.4	973.55	42.898	1772.71	0.5510	41.9011
800.2	1073.35	38.186	1834.96	0.5510	38.60838
900.1	1173.25	34.429	1886.35	0.5510	35.78469
599.8	872.95	49.135	1695.91	0.5510	45.91376
299.8	572.95	88.844	1338.14	0.5510	65.50579

Table 10 calculated thermal conductivity variation with temperature for sample 6 (unirradiated)

1.6 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.9	298.05	263.627	732.61	0.5439	105.055
49.7	322.85	229.082	800.59	0.5439	99.75874
100.2	373.35	178.307	931.17	0.5439	90.31296
150.3	423.45	143.365	1049.56	0.5439	81.84678
200.3	473.45	118.373	1156.50	0.5439	74.46484
250.3	523.45	100.483	1252.71	0.5439	68.4694
300.4	573.55	86.816	1339.12	0.5439	63.23696
400.3	673.45	68.183	1485.13	0.5439	55.07994
500.3	773.45	56.315	1602.17	0.5439	49.07776
600.4	873.55	47.985	1696.41	0.5439	44.27813
700.3	973.45	42.016	1772.64	0.5439	40.51242
800.2	1073.35	37.389	1834.96	0.5439	37.31842
900.1	1173.25	33.856	1886.35	0.5439	34.73845
600	873.15	48.025	1696.07	0.5439	44.30621
300	573.15	86.671	1338.47	0.5439	63.10058

Table 11 calculated thermal conductivity variation with temperature for sample 7 (unirradiated)

1.7 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.9	298.05	259.754	732.61	0.5497	104.60
51.4	324.55	228.603	805.16	0.5497	101.17
100.9	374.05	177.49	932.90	0.5497	91.02
151.1	424.25	141.78	1051.36	0.5497	81.94
201.3	474.45	117.506	1158.53	0.5497	74.83
251	524.15	99.427	1253.99	0.5497	68.53
301.1	574.25	86.052	1340.26	0.5497	63.40
401.1	674.25	67.541	1486.18	0.5497	55.18
501.1	774.25	55.542	1603.01	0.5497	48.94
601.1	874.25	47.207	1697.00	0.5497	44.03
700.8	973.95	41.293	1772.99	0.5497	40.24
800.5	1073.65	36.754	1835.13	0.5497	37.07
900.2	1173.35	32.992	1886.40	0.5497	34.21
299.4	572.55	86.279	1337.49	0.5497	63.43
100.2	373.35	178.265	931.17	0.5497	91.24

Table 12 calculated thermal conductivity variation with temperature for sample 8 (unirradiated)

1.8 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
25	323.25	264.126	801.66	0.5512	116.7098
50	323.15	232.024	801.39	0.5512	102.4904
100.1	373.25	177.865	930.92	0.5512	91.26602
150.2	423.35	142.616	1049.33	0.5512	82.48709
200.5	473.65	118.033	1156.91	0.5512	75.26739
250.3	523.45	99.884	1252.71	0.5512	68.96874
300.4	573.55	86.569	1339.12	0.5512	63.89782
400.4	673.55	67.994	1485.26	0.5512	55.66453
500.5	773.65	56.201	1602.38	0.5512	49.63795
600.6	873.75	47.975	1696.58	0.5512	44.86363
700.4	973.55	41.88	1772.71	0.5512	40.92131
800.2	1073.35	37.414	1834.96	0.5512	37.84129
900.1	1173.25	33.674	1886.35	0.5512	35.0124
599.7	872.85	47.809	1695.82	0.5512	44.68835
299.8	572.95	86.522	1338.14	0.5512	63.81644
100.1	373.25	177.92	930.92	0.5512	91.29424

Table 13 calculated thermal conductivity variation with temperature for sample 9 (unirradiated)

1.9 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
25.1	298.25	261.811	733.17	0.557	106.8635
49.4	322.55	229.981	799.78	0.557	102.3995
100.2	373.35	176.625	931.17	0.557	91.56265
150.3	423.45	141.573	1049.56	0.557	82.72245
200.4	473.55	117.017	1156.70	0.557	75.35434
250.3	523.45	99.27	1252.71	0.557	69.23193
300.3	573.45	85.792	1338.96	0.557	63.95133
400.3	673.45	67.556	1485.13	0.557	55.85548
500.4	773.55	55.926	1602.27	0.557	49.88699
600.4	873.55	47.72	1696.41	0.557	45.06804
700.3	973.45	41.78	1772.64	0.557	41.23125
800.2	1073.35	37.163	1834.96	0.557	37.96424
900.2	1173.35	33.568	1886.40	0.557	35.25295
600	873.15	47.707	1696.07	0.557	45.04679
300.1	573.25	85.722	1338.63	0.557	63.88358
100.1	373.25	176.704	930.92	0.557	91.57925

Table 14 calculated thermal conductivity variation with temperature for sample 1 (irradiated)

1.1: PIE Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.2	297.35	115.70	730.66	0.5340	45.14
50.7	323.85	104.29	803.28	0.5340	44.73
96.6	369.75	90.27	922.23	0.5340	44.46
150.6	423.75	78.56	1050.23	0.5340	44.06
201	474.15	69.11	1157.92	0.5340	42.74
251.1	524.25	61.50	1254.17	0.5340	41.19
301.1	574.25	55.44	1340.26	0.5340	39.68
401	674.15	46.37	1486.04	0.5340	36.79
500.7	773.85	40.12	1602.59	0.5340	34.34
600.3	873.45	35.55	1696.33	0.5340	32.20
700.4	973.55	32.21	1772.71	0.5340	30.49
800.3	1073.45	29.74	1835.02	0.5340	29.14
899.8	1172.95	27.88	1886.21	0.5340	28.09
299.1	572.25	59.23	1337.00	0.5340	42.29
99.1	372.25	98.02	928.45	0.5340	48.59

Table 15 calculated thermal conductivity variation with temperature for sample 2 (irradiated)

1.2: PIE Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.7	297.85	122.572	732.06	0.5470	49.08
49.1	322.25	111.923	798.97	0.5470	48.91
100.1	373.25	95.635	930.92	0.5470	48.70
150.4	423.55	82.946	1049.78	0.5470	47.63
200.5	473.65	72.533	1156.91	0.5470	45.90
250.6	523.75	64.357	1253.26	0.5470	44.12
300.7	573.85	57.886	1339.61	0.5470	42.42
400.6	673.75	48.255	1485.52	0.5470	39.21
500.4	773.55	41.638	1602.27	0.5470	36.49
600.4	873.55	36.923	1696.41	0.5470	34.26
700.4	973.55	33.303	1772.71	0.5470	32.29
800.3	1073.45	30.572	1835.02	0.5470	30.69
900.1	1173.25	28.854	1886.35	0.5470	29.77
599.9	873.05	38.092	1695.99	0.5470	35.34
299.7	572.85	60.657	1337.98	0.5470	44.39
100.6	373.75	101.619	932.16	0.5470	51.81

Table 16 calculated thermal conductivity variation with temperature for sample 3 (irradiated)

1.3: Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
24.8	297.95	115.427	732.33	0.5460	46.15
50.7	323.85	104.814	803.28	0.5460	45.97
100.5	373.65	90.41	931.91	0.5460	46.00
150.2	423.35	78.584	1049.33	0.5460	45.02
199.9	473.05	69.068	1155.69	0.5460	43.58
250.3	523.45	61.284	1252.71	0.5460	41.92
300.1	573.25	55.143	1338.63	0.5460	40.30
400.2	673.35	46.043	1485.00	0.5460	37.33
499.9	773.05	39.745	1601.75	0.5460	34.76
600.1	873.25	35.132	1696.16	0.5460	32.54
700.1	973.25	31.762	1772.51	0.5460	30.74
800.1	1073.25	29.274	1834.91	0.5460	29.33
900	1173.15	27.958	1886.30	0.5460	28.79
599.7	872.85	36.503	1695.82	0.5460	33.80
299.9	573.05	58.31	1338.30	0.5460	42.61
100.2	373.35	97.503	931.17	0.5460	49.57

Table 17 calculated thermal conductivity variation with temperature for sample 4 (irradiated)

1.4 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
25.8	298.95	117.964	735.12	0.5480	47.52
49.8	322.95	108.283	800.85	0.5480	47.52
99.5	372.65	92.871	929.44	0.5480	47.30
150.8	423.95	80.158	1050.68	0.5480	46.15
201	474.15	70.378	1157.92	0.5480	44.66
251.1	524.25	62.502	1254.17	0.5480	42.96
300.8	573.95	56.282	1339.77	0.5480	41.32
400.6	673.75	46.93	1485.52	0.5480	38.20
500.8	773.95	40.535	1602.69	0.5480	35.60
600.6	873.75	35.894	1696.58	0.5480	33.37
700.4	973.55	32.447	1772.71	0.5480	31.52
800.3	1073.45	29.902	1835.02	0.5480	30.07
900	1173.15	28.043	1886.30	0.5480	28.99
599.2	872.35	37.433	1695.40	0.5480	34.78
299.1	572.25	59.334	1337.00	0.5480	43.47
99.5	372.65	99.594	929.44	0.5480	50.73

Table 18 calculated thermal conductivity variation with temperature for sample 5 (irradiated)

1.5 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
25.4	298.55	120.493	734.01	0.5470	48.3781
49.8	322.95	108.069	800.85	0.5470	47.34153
100	373.15	92.888	930.68	0.5470	47.28739
150.3	423.45	80.285	1049.56	0.5470	46.09226
200	473.15	70.552	1155.89	0.5470	44.60816
250.5	523.65	62.575	1253.08	0.5470	42.891
300.3	573.45	56.209	1338.96	0.5470	41.16795
399.9	673.05	46.87	1484.61	0.5470	38.06228
500.5	773.65	40.626	1602.38	0.5470	35.60874
600.4	873.55	35.996	1696.41	0.5470	33.40205
700.3	973.45	32.508	1772.64	0.5470	31.52092
800.3	1073.45	30.061	1835.02	0.5470	30.17389
899.6	1172.75	27.669	1886.12	0.5470	28.54628
600	873.15	37.213	1696.07	0.5470	34.52447
299.6	572.75	59.087	1337.81	0.5470	43.2389
101.2	374.35	98.811	933.64	0.5470	50.46313

Table 19 calculated thermal conductivity variation with temperature for sample 6 (irradiated)

1.6 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm2/sec	J/kg.K	g/cm3	W/m.K
25	298.15	116.27	732.89	0.5370	45.75954
50.6	323.75	105.854	803.01	0.5370	45.64582
100.4	373.55	91.041	931.67	0.5370	45.54824
150.3	423.45	78.796	1049.56	0.5370	44.4104
199.8	472.95	69.293	1155.49	0.5370	42.99606
250.2	523.35	61.445	1252.53	0.5370	41.32848
300	573.15	55.159	1338.47	0.5370	39.64587
399.8	672.95	45.969	1484.48	0.5370	36.64491
500	773.15	39.559	1601.86	0.5370	34.02851
600	873.15	34.99	1696.07	0.5370	31.86862
700	973.15	31.578	1772.44	0.5370	30.05589
800.1	1073.25	29.075	1834.91	0.5370	28.64889
899.8	1172.95	27.42	1886.21	0.5370	27.77359
599.8	872.95	36.012	1695.91	0.5370	32.79618
300.1	573.25	57.444	1338.63	0.5370	41.29326
101.2	374.35	96.656	933.64	0.5370	48.46014

Table 20 calculated thermal conductivity variation with temperature for sample 7 (irradiated)

1.8 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm2/sec	J/kg.K	g/cm3	W/m.K
25.7	298.85	115.4222	734.84	0.5460	46.31011
50.7	323.85	106.828	803.28	0.5460	46.85355
99	372.15	92.016	928.20	0.5460	46.6333
150.3	423.45	79.05	1049.56	0.5460	45.30027
200.4	473.55	69.045	1156.70	0.5460	43.60612
250.9	524.05	61.079	1253.81	0.5460	41.81333
300.7	573.85	54.802	1339.61	0.5460	40.08359
400.9	674.05	45.696	1485.91	0.5460	37.07359
500.2	773.35	39.06	1602.06	0.5460	34.16685
600.3	873.45	34.406	1696.33	0.5460	31.86668
700.2	973.35	31.202	1772.57	0.5460	30.19809
800	1073.15	28.48	1834.85	0.5460	28.53206
900.1	1173.25	27.608	1886.35	0.5460	28.4348
599	872.15	35.703	1695.23	0.5460	33.04651
298.7	571.85	57.637	1336.34	0.5460	42.05439
100	373.15	97.462	930.68	0.5460	49.52522

Table 21 calculated thermal conductivity variation with temperature for sample 8 (irradiated)

1.9 Thermal Conductivity Calculation					
Temperature		Diff	Cp	Density	TC
C	K	cm ² /sec	J/kg.K	g/cm ³	W/m.K
25.7	298.85	110.828	734.84	0.549	44.71113
49	322.15	102.602	798.70	0.549	44.98957
100.1	373.25	87.242	930.92	0.549	44.58738
149.8	422.95	75.855	1048.43	0.549	43.66131
200.3	473.45	66.559	1156.50	0.549	42.25962
250.1	523.25	58.977	1252.35	0.549	40.54902
300.2	573.35	52.982	1338.79	0.549	38.94161
400.4	673.55	44.027	1485.26	0.549	35.90003
500.2	773.35	37.491	1602.06	0.549	32.97459
599.5	872.65	32.482	1695.65	0.549	30.23791
700	973.15	29.564	1772.44	0.549	28.76778
800.2	1073.35	27.621	1834.96	0.549	27.82524
900.2	1173.35	26.167	1886.40	0.549	27.09939
599.9	873.05	34.302	1695.99	0.549	31.93855
299.9	573.05	56.023	1338.30	0.549	41.16168
100.8	373.95	93.717	932.66	0.549	47.98573