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March 2016

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OAK RIDGE NATIONAL LABORATORY
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**ORNL/TM-2016/103**

Material Science and Technology Division

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

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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°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-MSOF: "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. EXPERIMETAL

## 2.1 MATERIALS

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

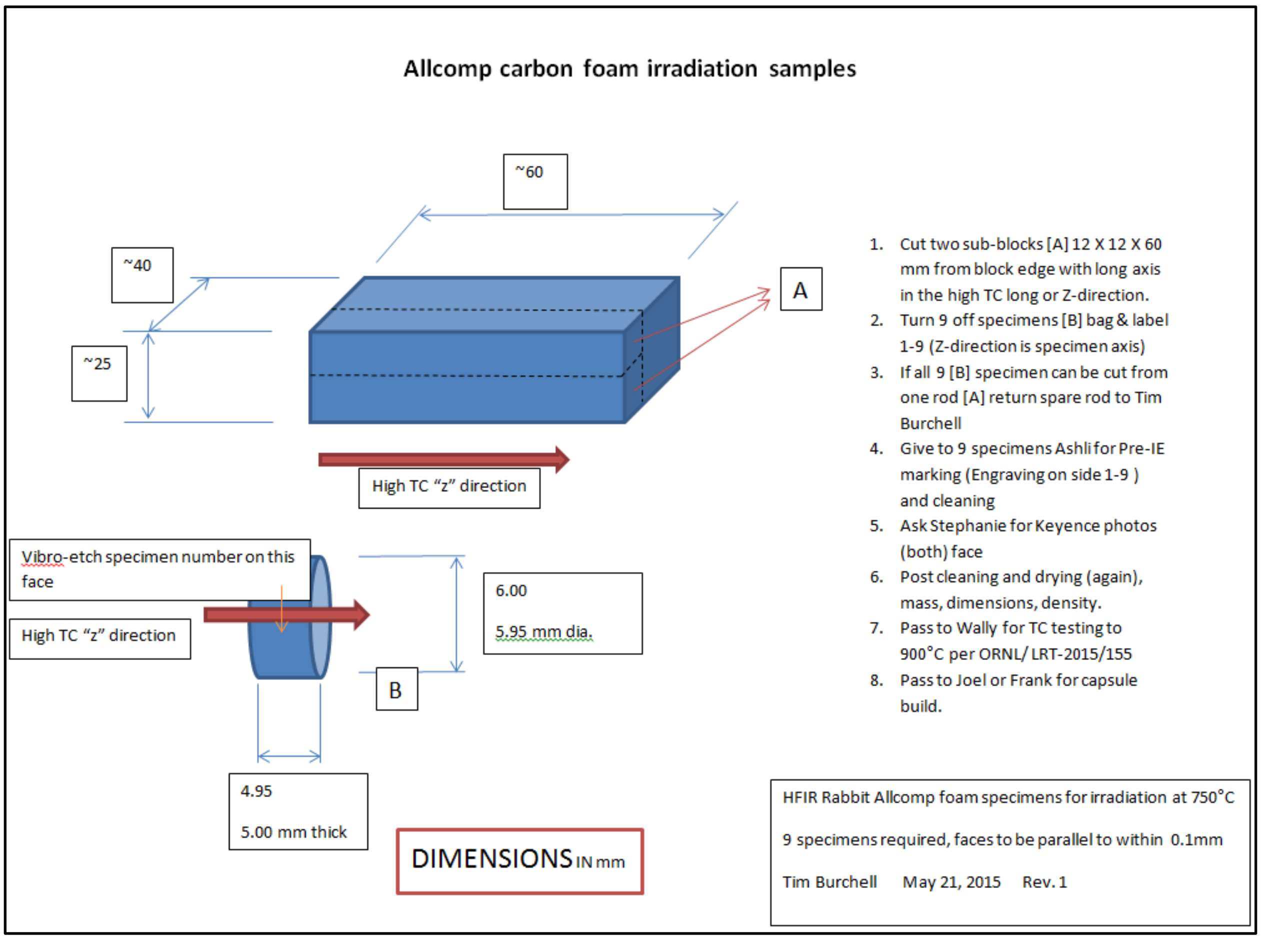


**Figure 1 Cutting drawing for the Allcomp foam block and irradiation specimens**

## 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.

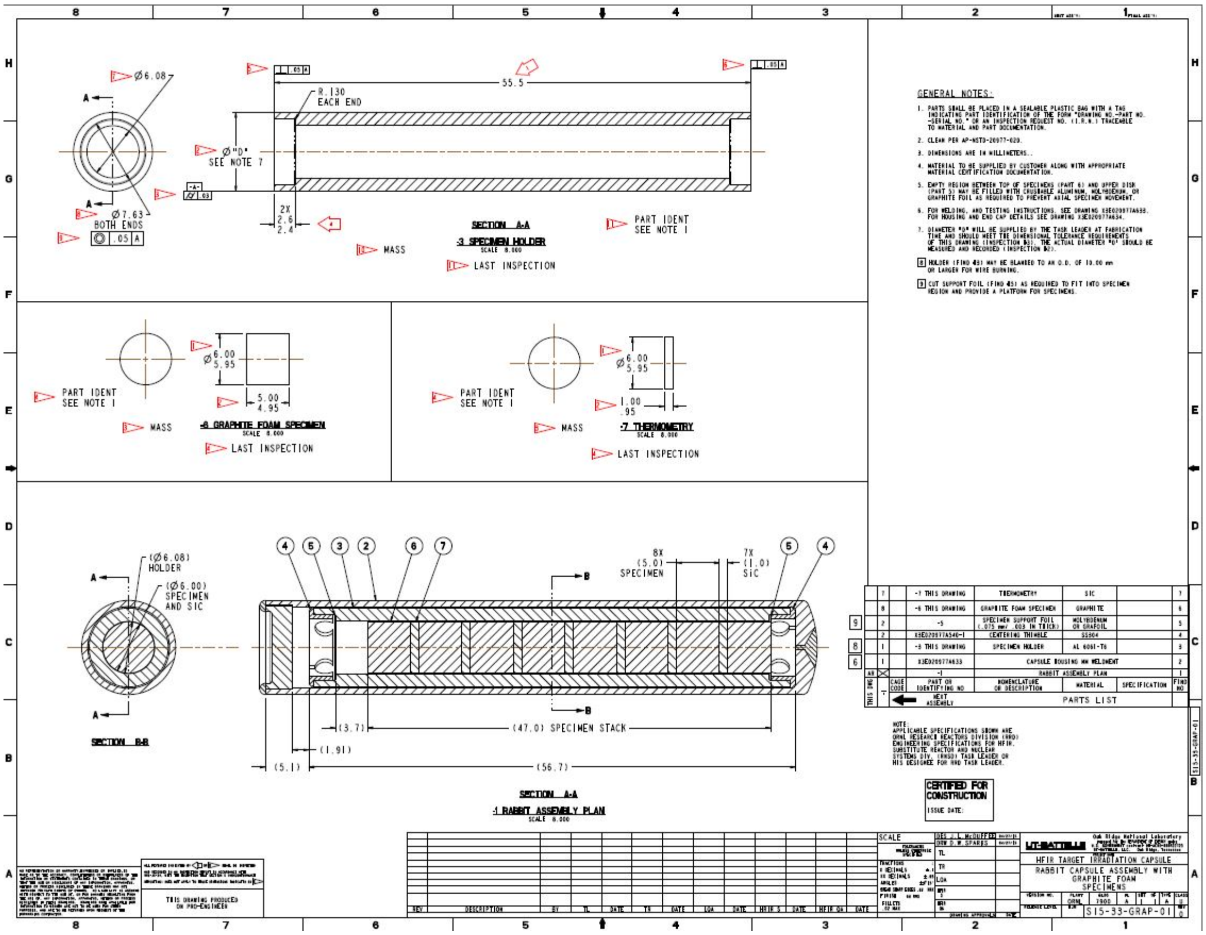


Figure 2 Rabbit capsule assembly drawing

### 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 1.917x10$^{-1}$ 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±25°C (Table 2).

Table 2 Indicated irradiation temperatures for the four temperature monitors interrogated

| SiC Monitor # | Test Method | Indicated Irradiation Temperature, °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 ~740°C.

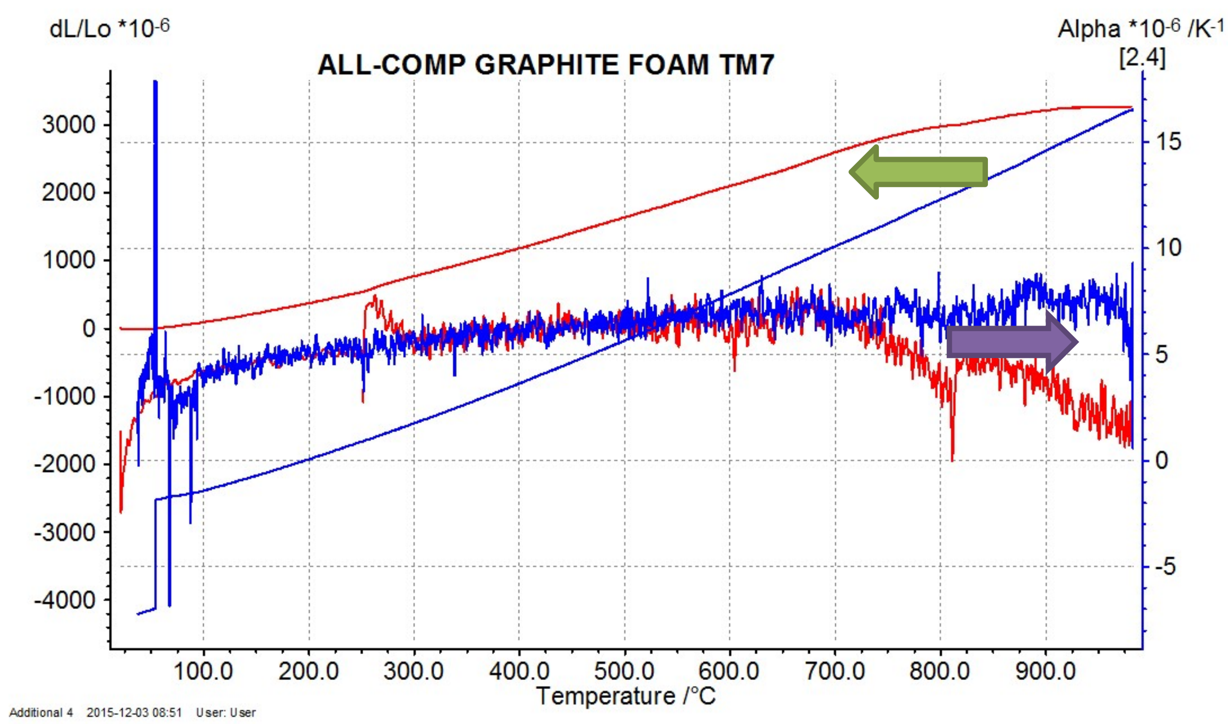


Figure 3 Thermal expansion behavior of SiC temperature monitor No. 7

#### 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.

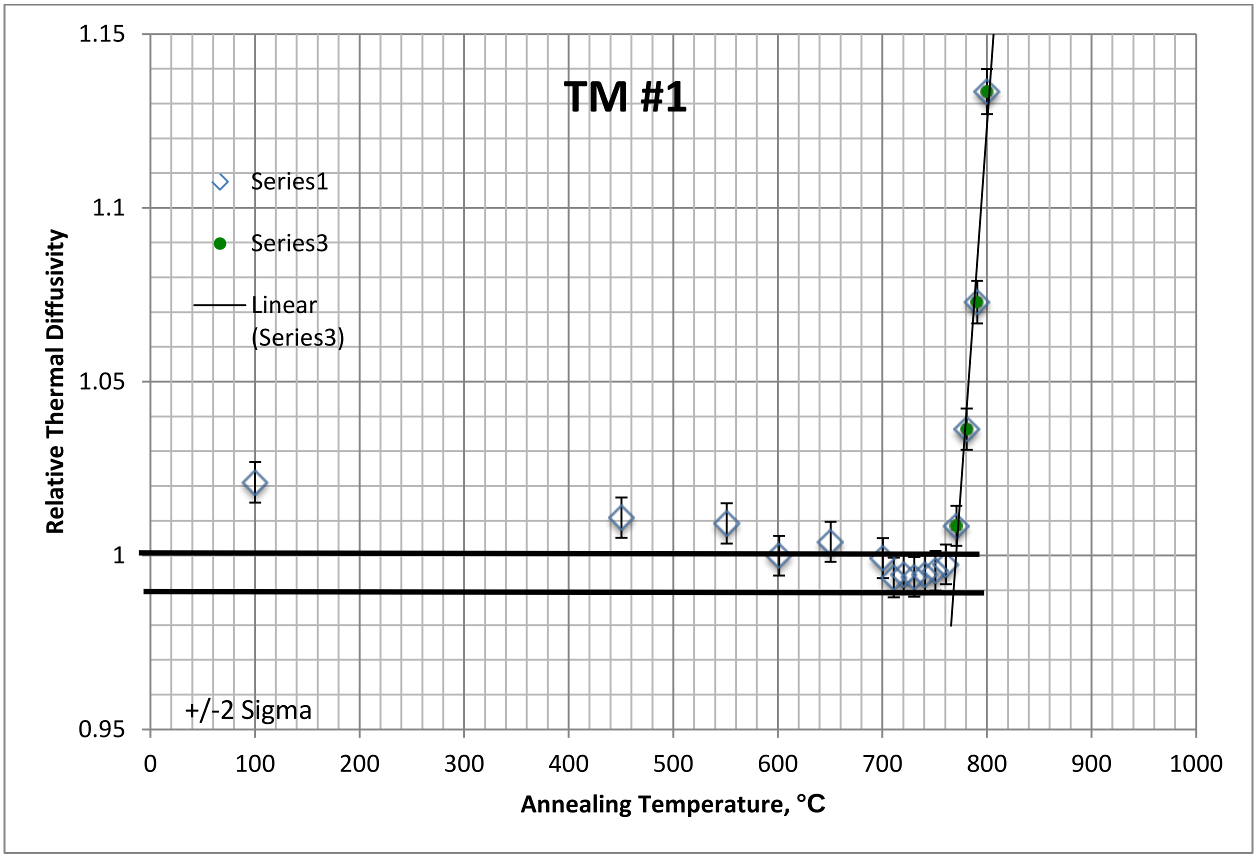


**Figure 4 Relative thermal diffusivity behavior of SiC temperature monitor No. 1 with increasing annealing temperature, measured at 100°C**

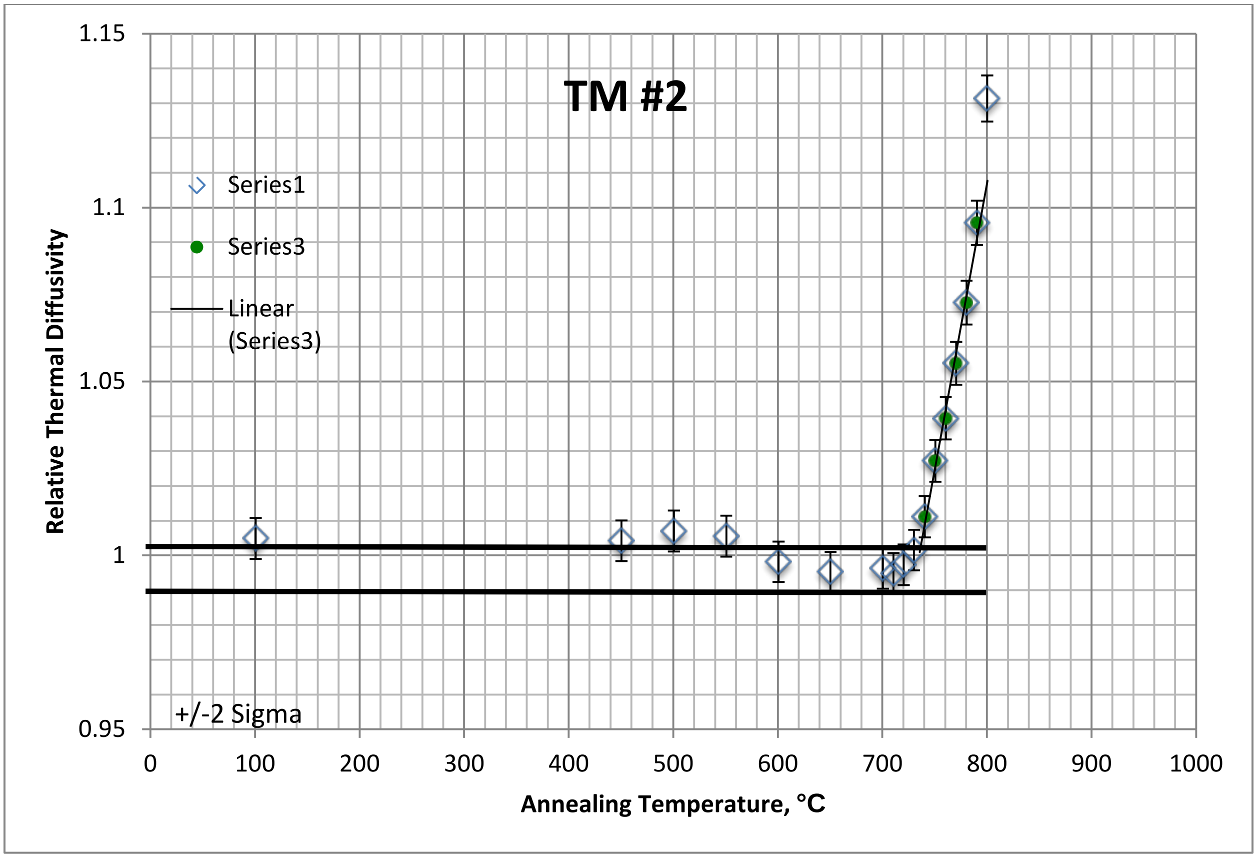


**Figure 5 Relative thermal diffusivity behavior of SiC temperature monitor No. 2 with increasing annealing temperature, measured at 100°C**

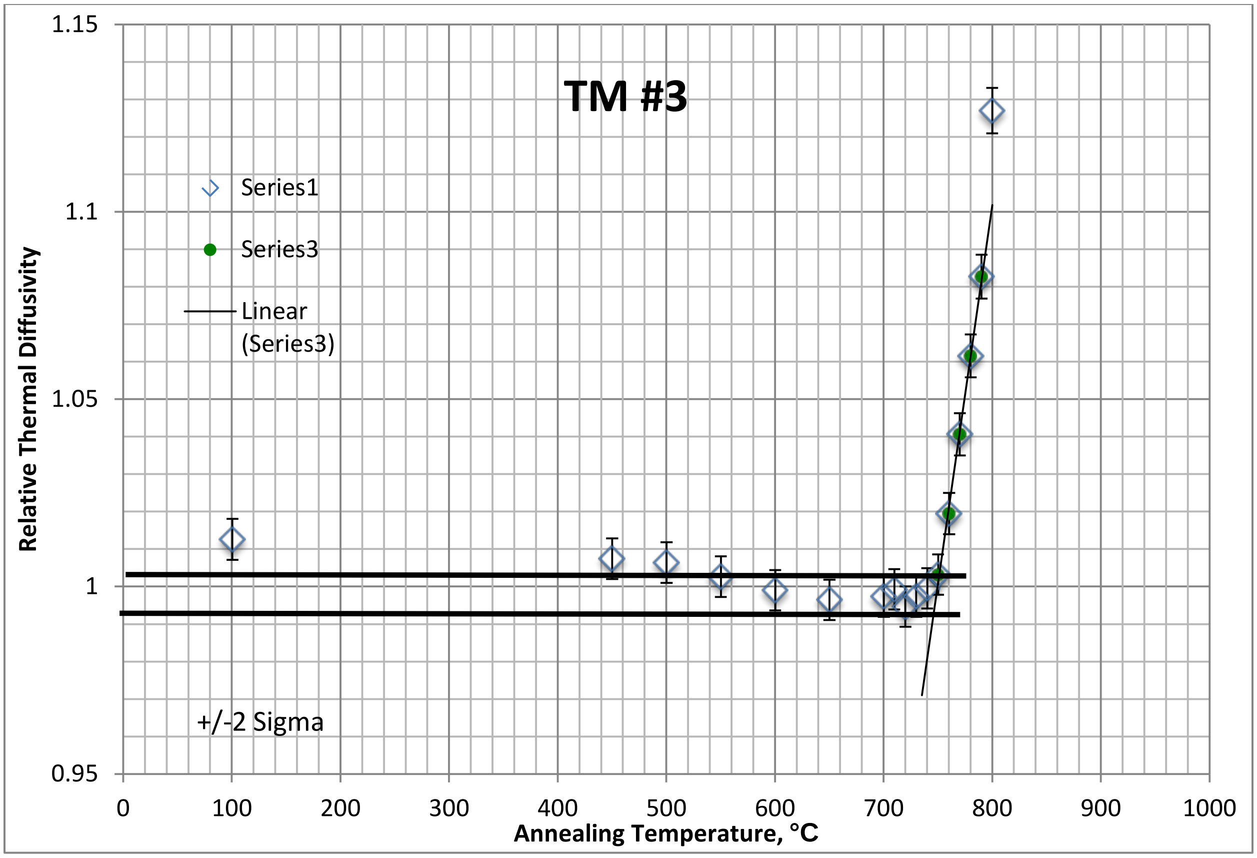


Figure 6 Relative thermal diffusivity behavior of SiC temperature monitor No. 3 with increasing annealing temperature, measured at 100°C

## 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.

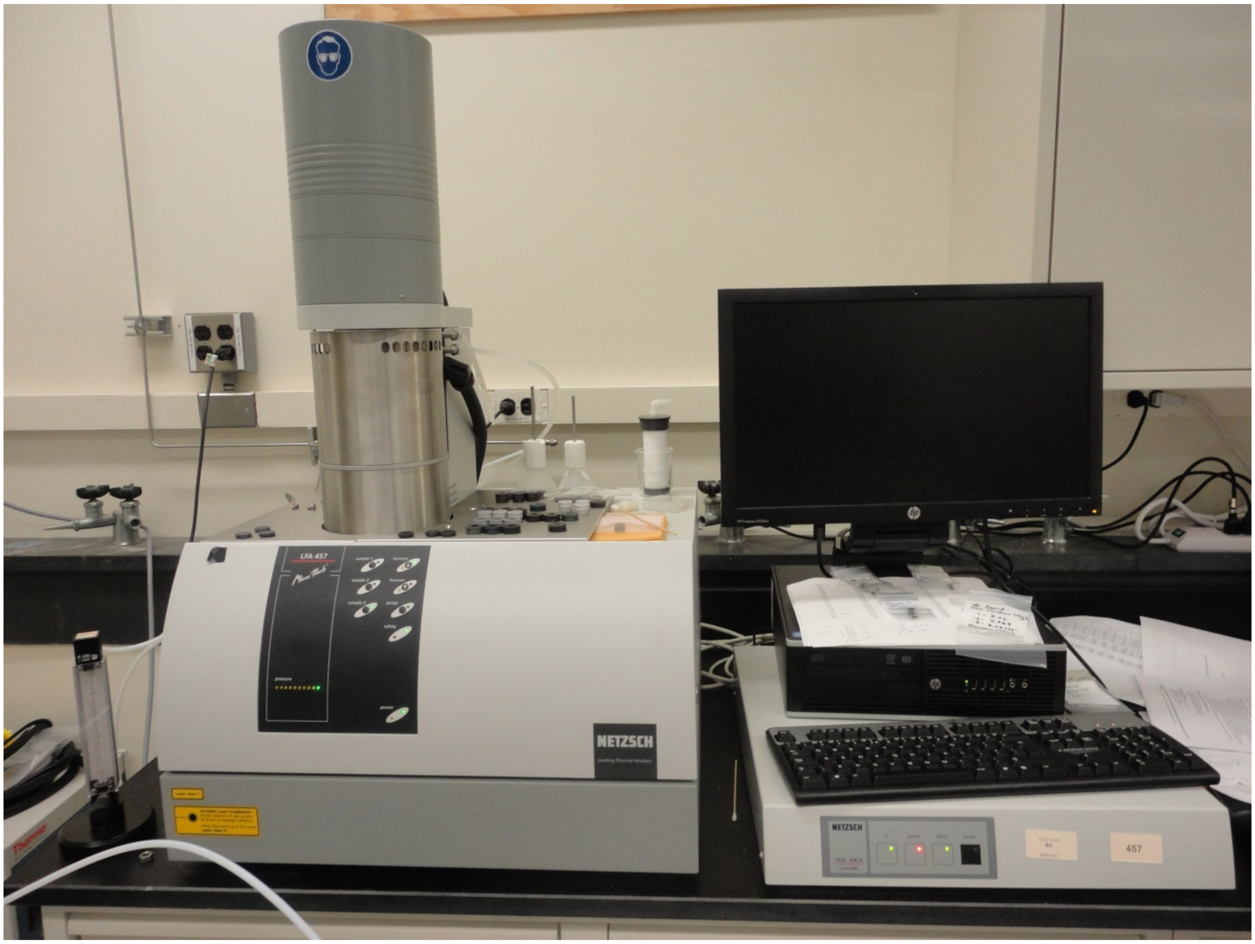

Figure 7 The Netzsch LFA 457 LASER flash apparatus

The thermal conductivity was calculated from the relationship:

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

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 EXPERMENTAL 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).

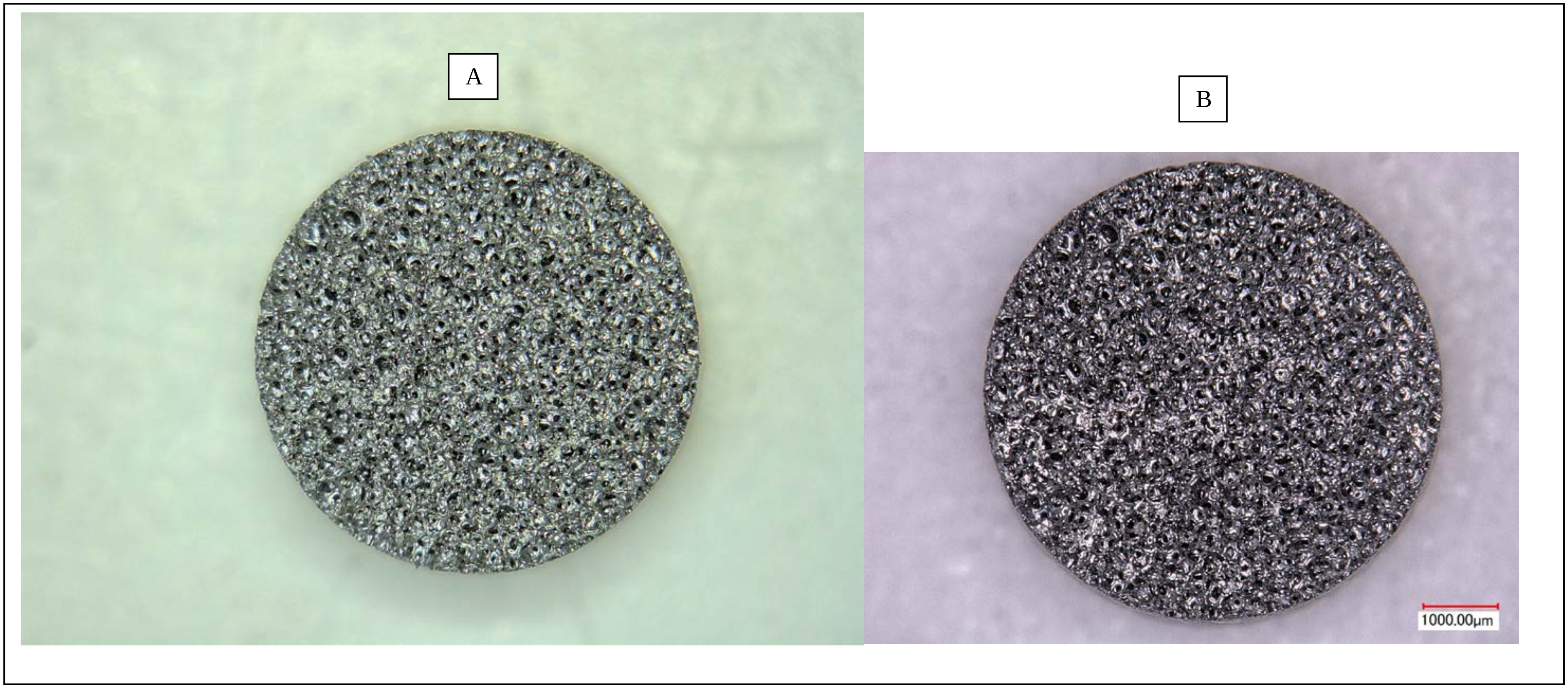


**Figure 8 Top view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation**

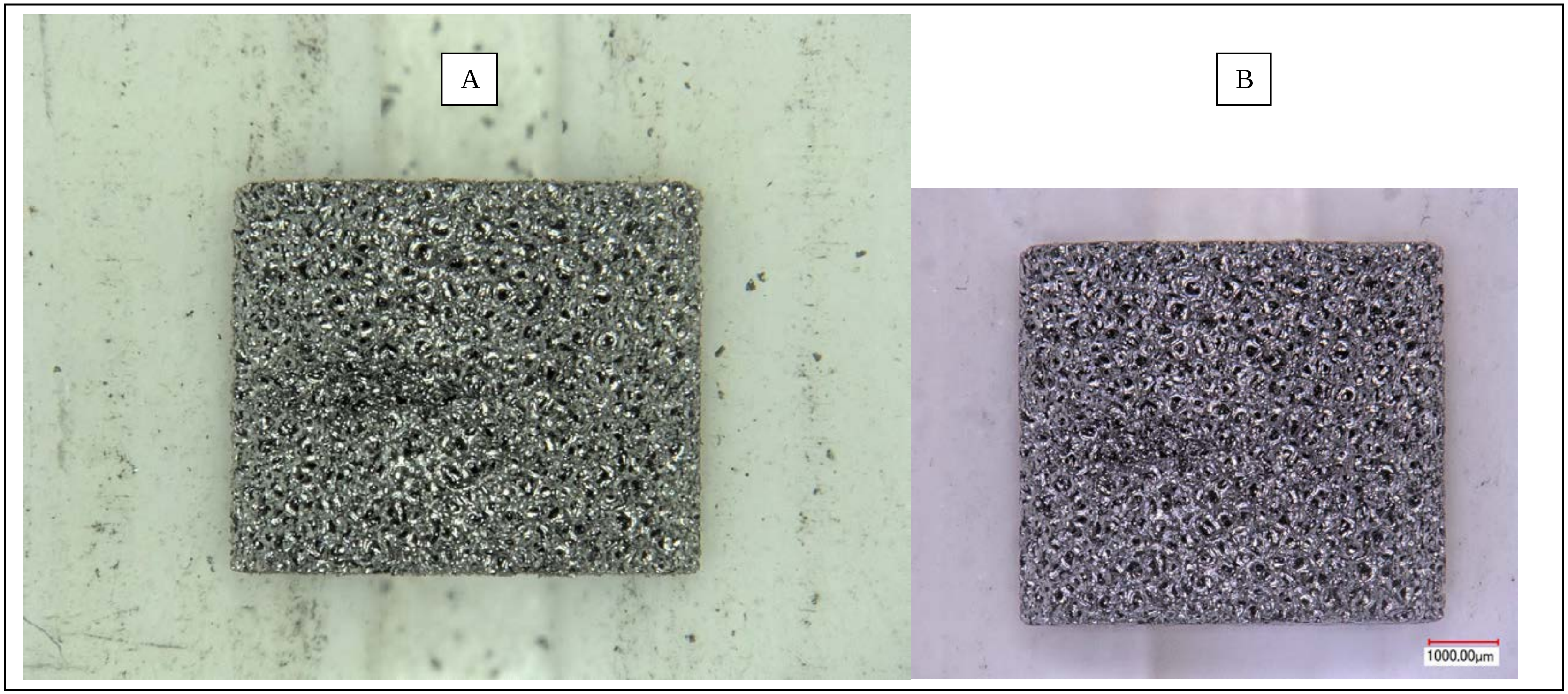


**Figure 9 Side view of Allcomp carbon foam sample 1-1 [A] pre irradiation [B] post irradiation**

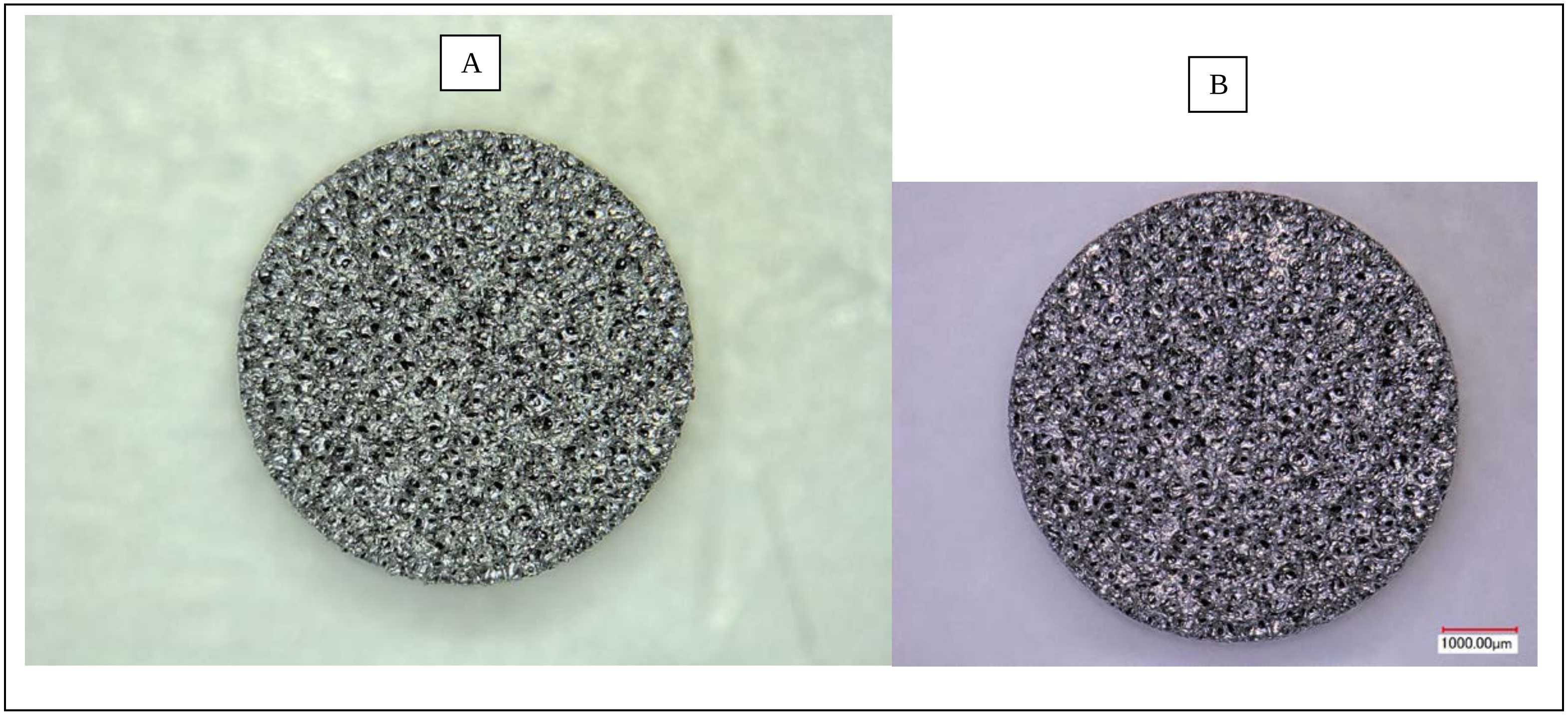


**Figure 10 Top view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation**

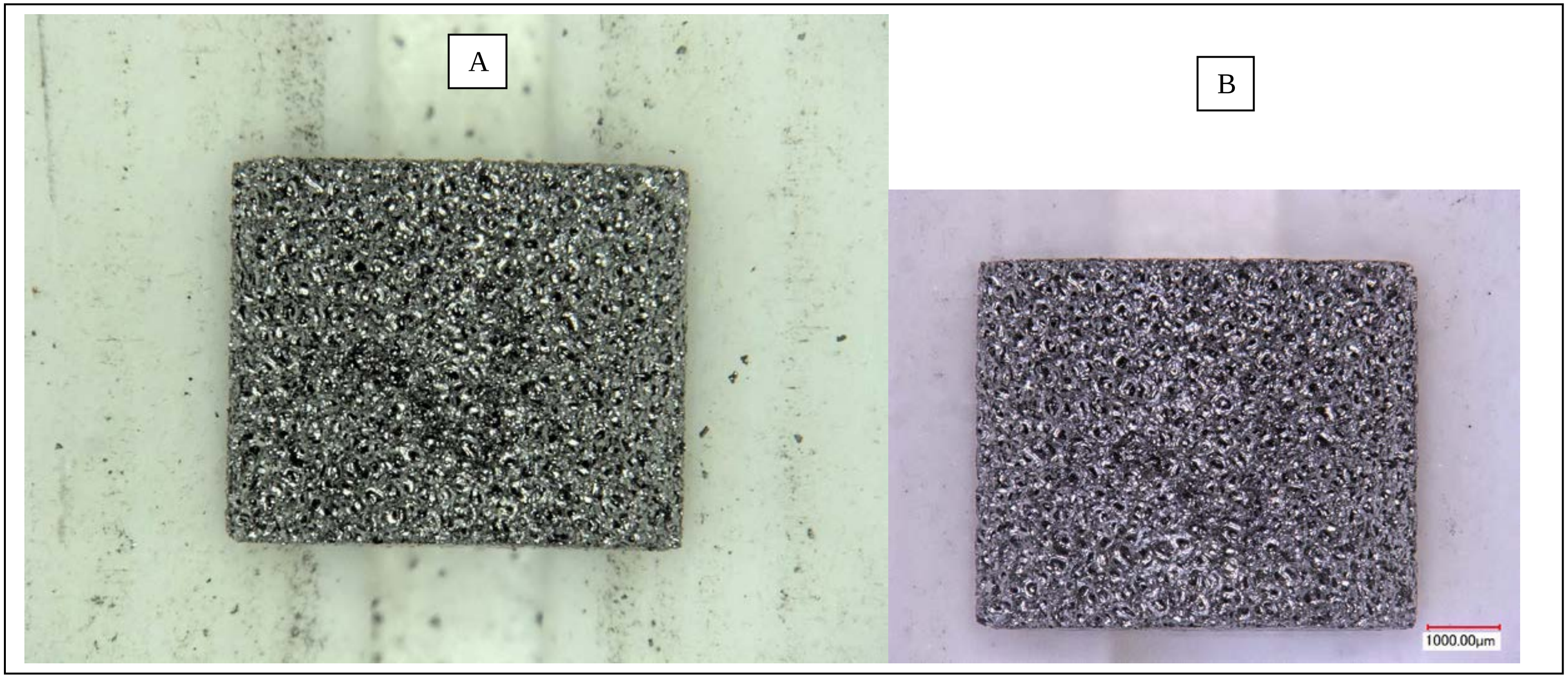


**Figure 11 Side view of Allcomp carbon foam sample 1-2 [A] pre irradiation [B] post irradiation**

## 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).

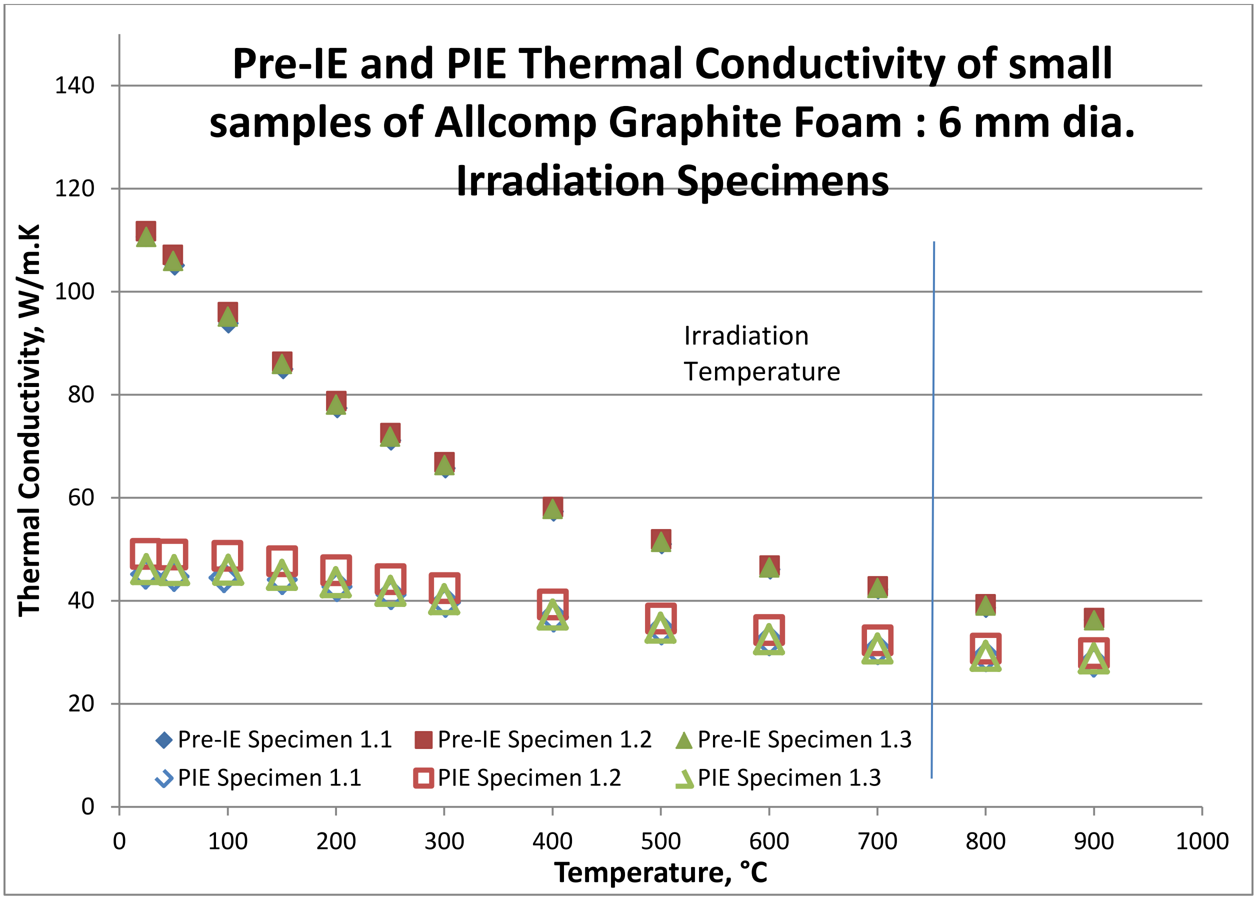

Figure 12 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 1, 2 and 3)

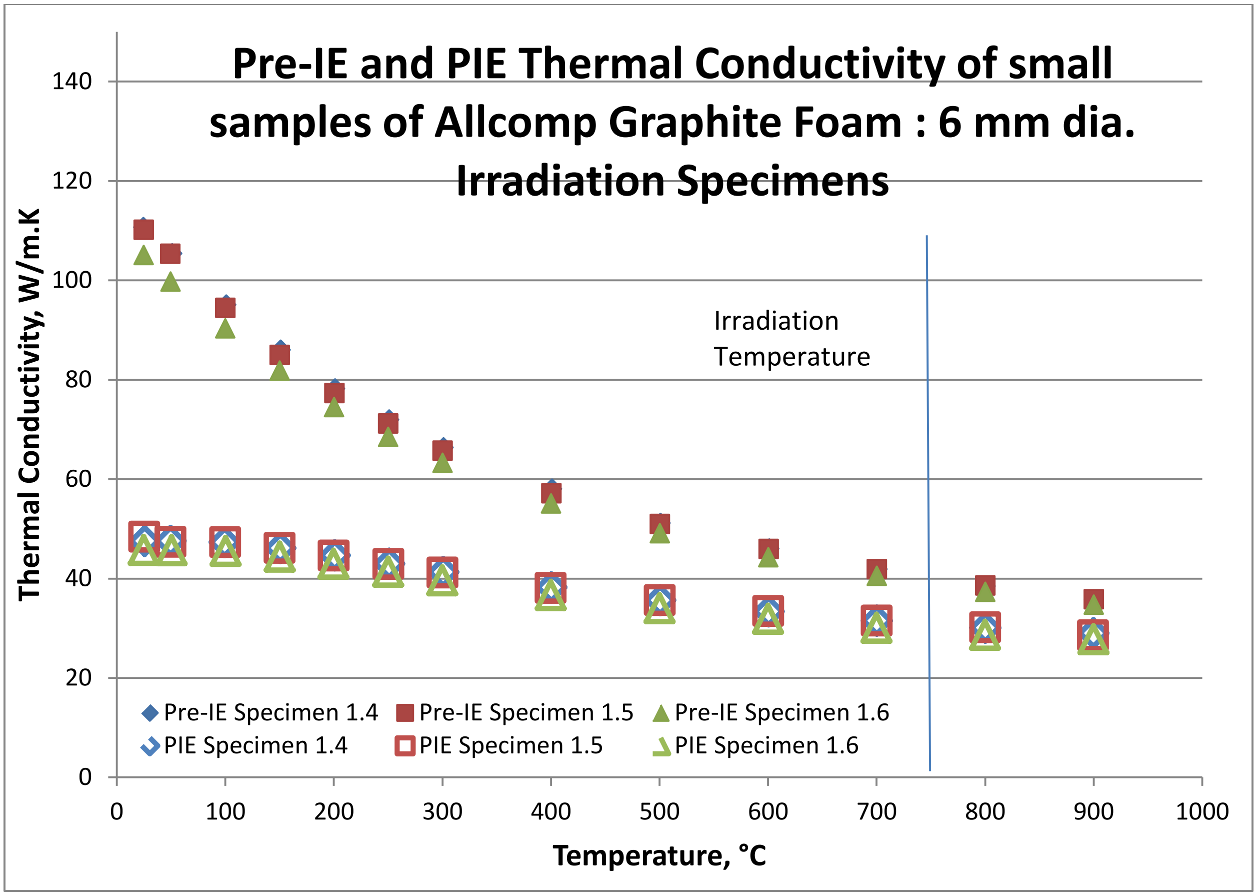


Figure 13 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 4, 5 and 6)

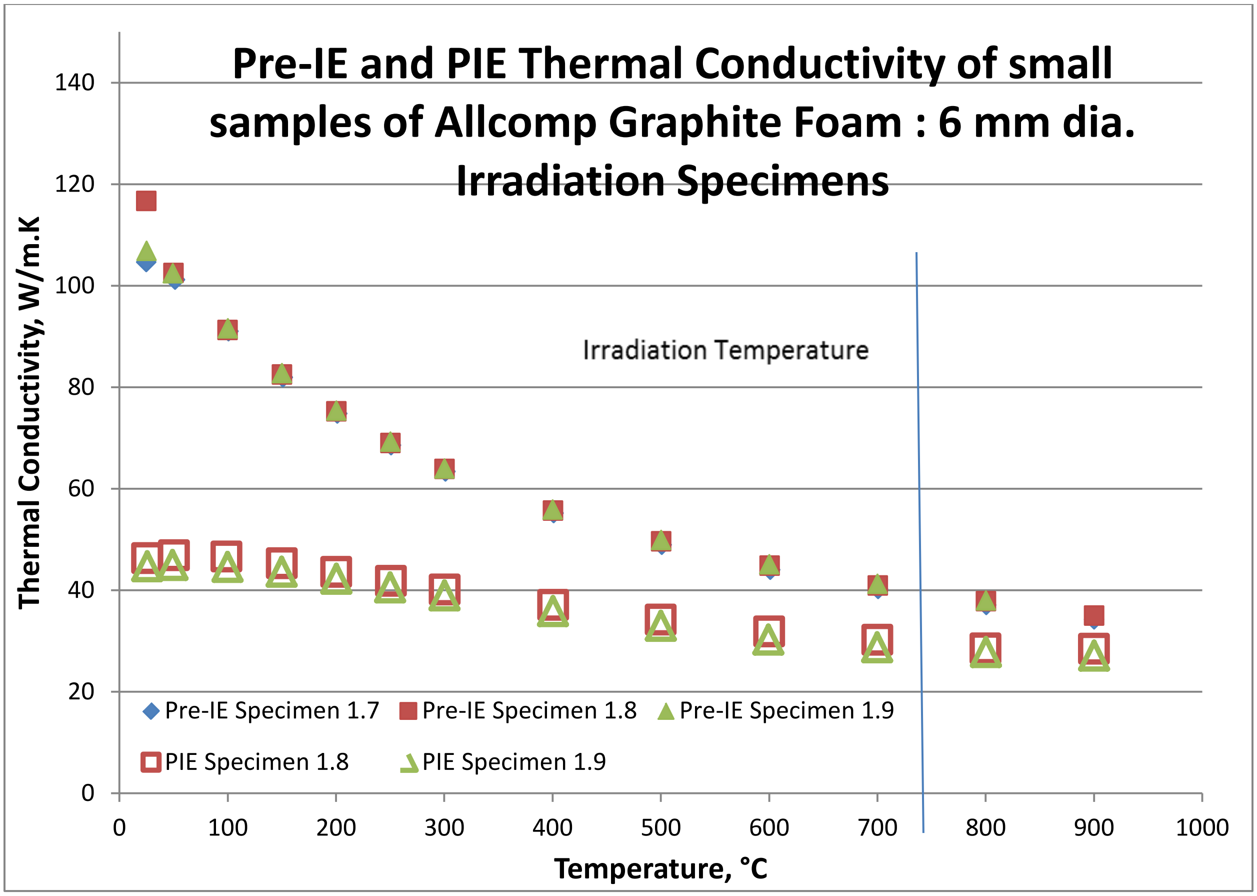


Figure 14 Temperature dependence of Allcomp carbon foam before and after irradiation to 0.2 dpa (specimens 8 and 9)

## 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 <a> directions (within the basal plane) the atom bonding is of the primary, covalent type; whereas between the basal planes (crystallographic <c> 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 <a> direction than in the <c> direction within a graphite single crystal. The conductive deposited layer (pyrolytic carbon) of the Allcomp foam will be predominantly oriented with the crystallographic <a> 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 W/m.K, whereas perpendicular to the basal planes the room temperature thermal conductivity is typically < 10 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 ~ $T^3$. 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 ~ 80 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 ~ 20 W/m.K. At extremely low temperatures, i.e., T < 10 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.

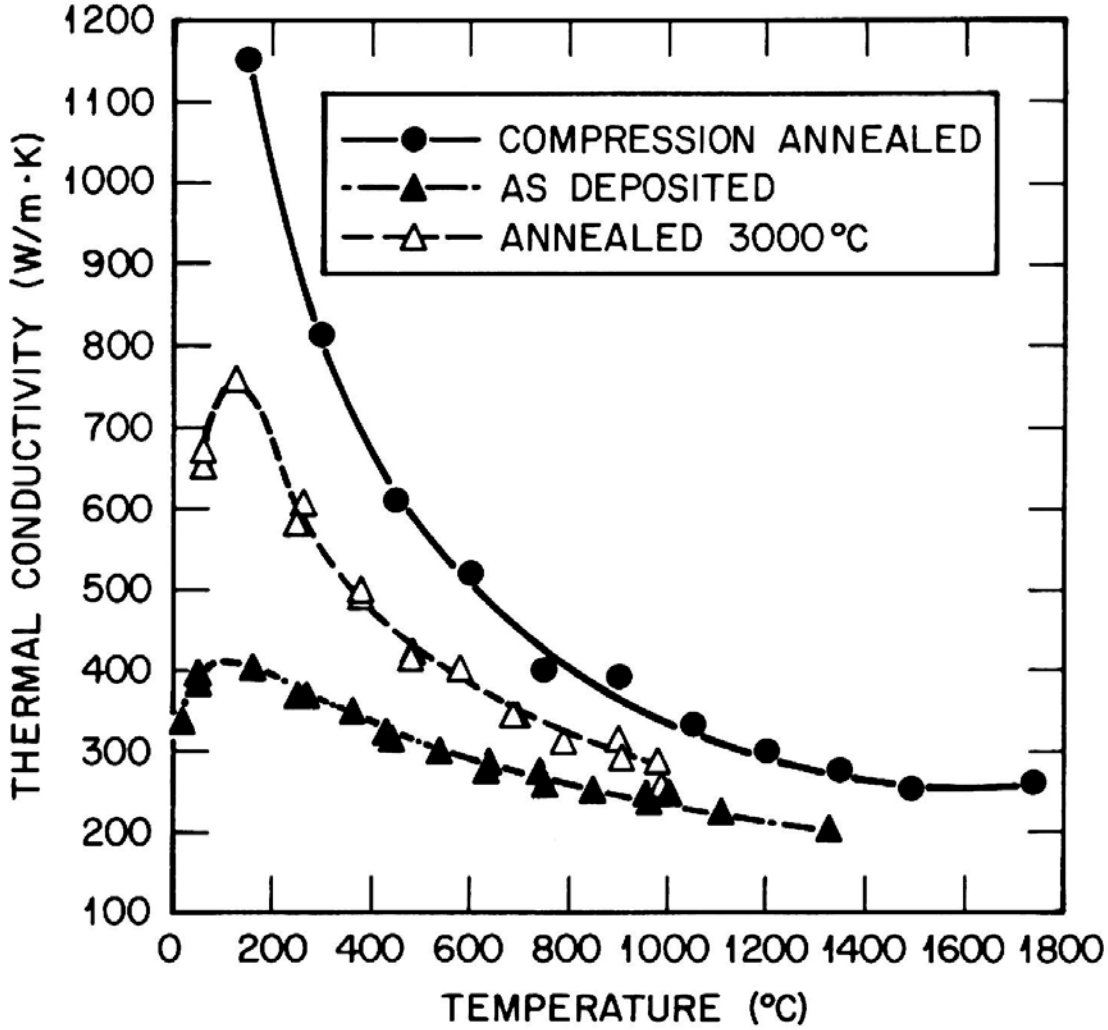


**Figure 15 Temperature dependence of thermal conductivity for pyrolytic graphite in the as-deposited, annealed, and compression annealed condition. Adapted from Roth et al [8]**

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.

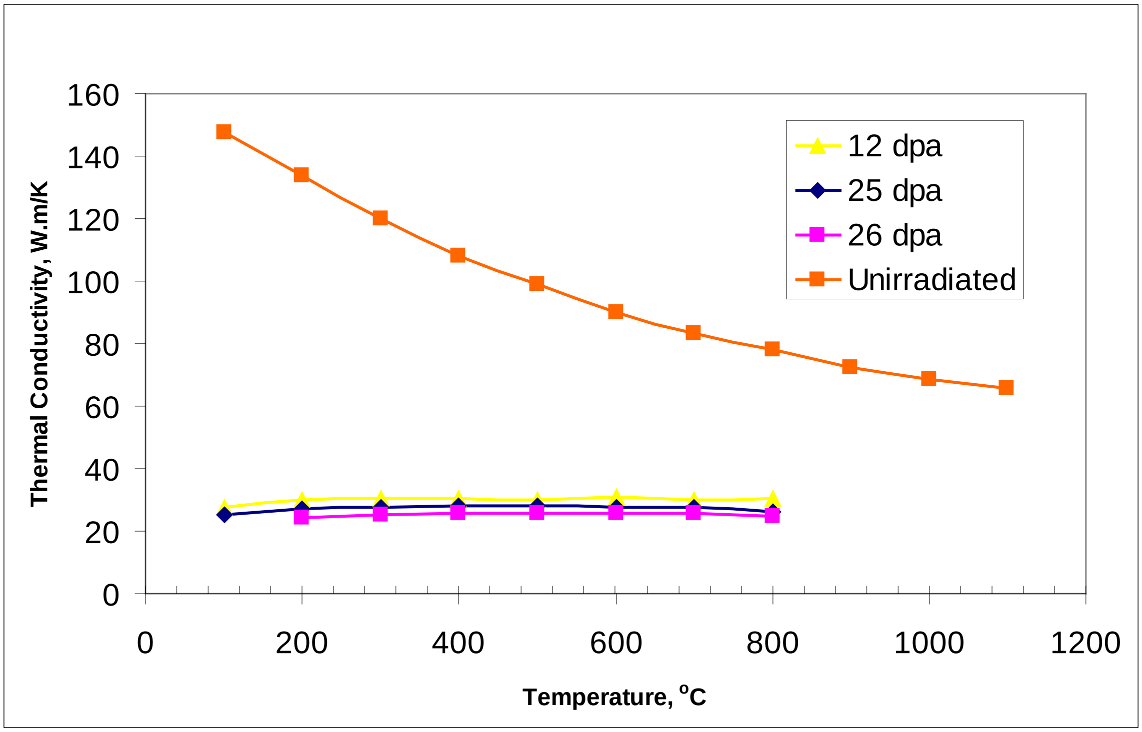


**Figure 16 Temperature dependence of thermal conductivity in the irradiated and unirradiated condition for typical nuclear grade graphite. Irradiation temperature = 600°C.**

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 ~ 150°C above the irradiation temperature. Clearly, there is some potential for thermal annealing of the extrinsic (particle displacement) damage.

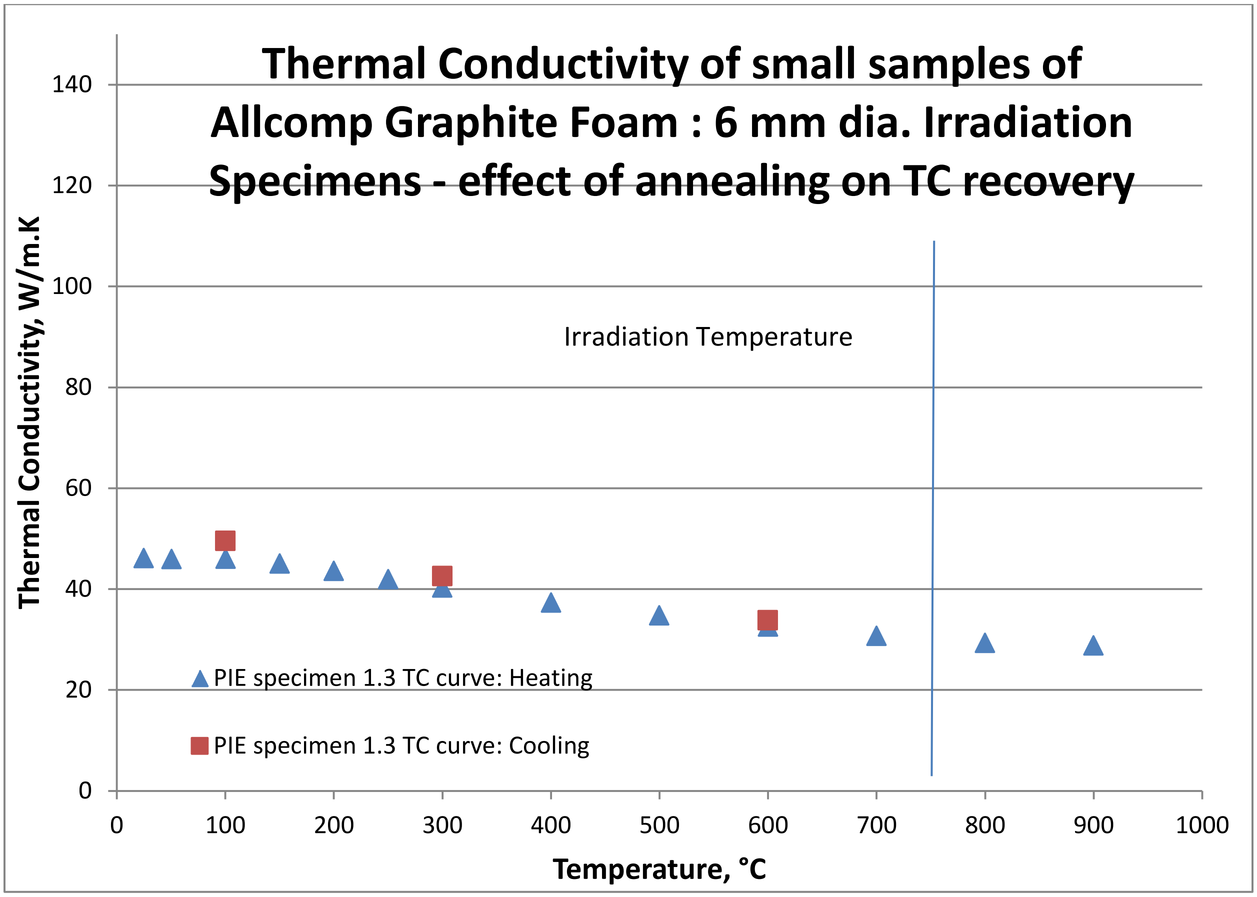


**Figure 17 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 3 (Tirr=750°C, 0.2 dpa)**

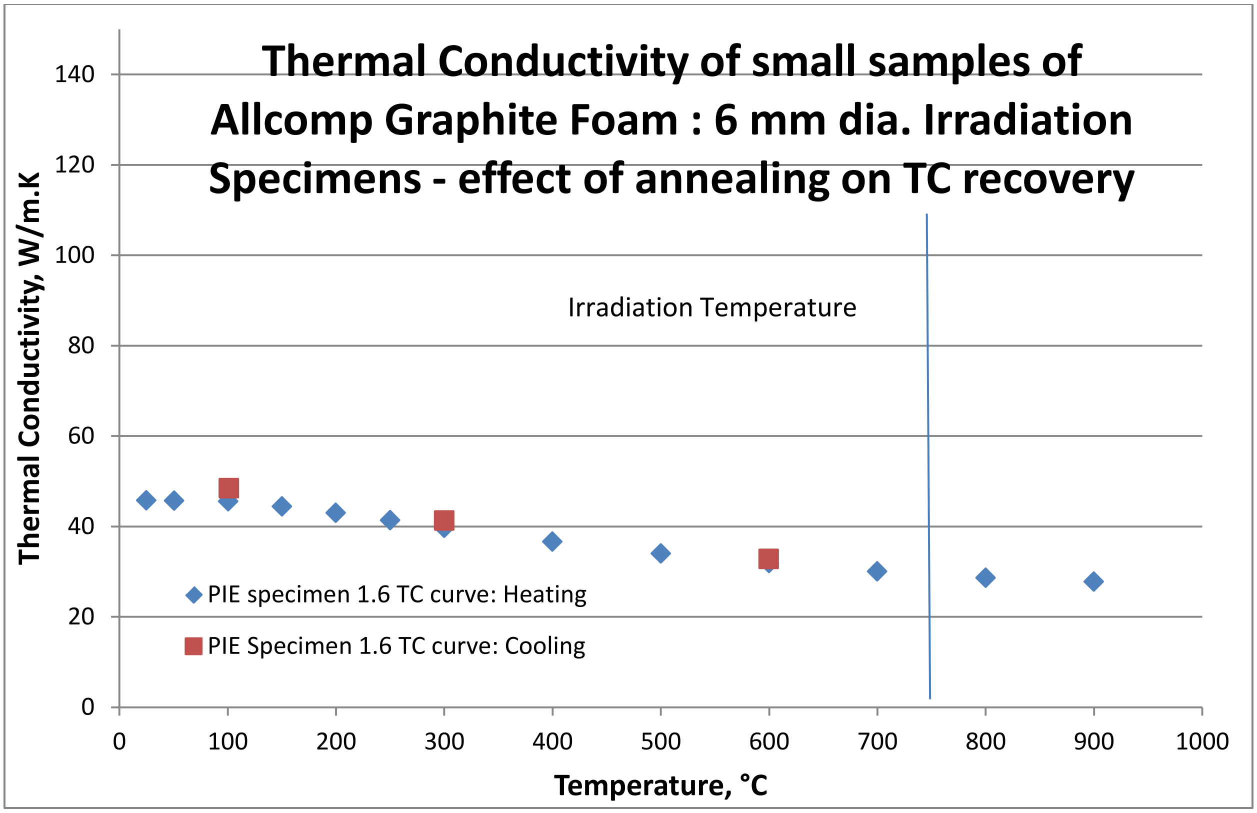


Figure 18 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 6 (Tirr=750°C, 0.2 dpa)

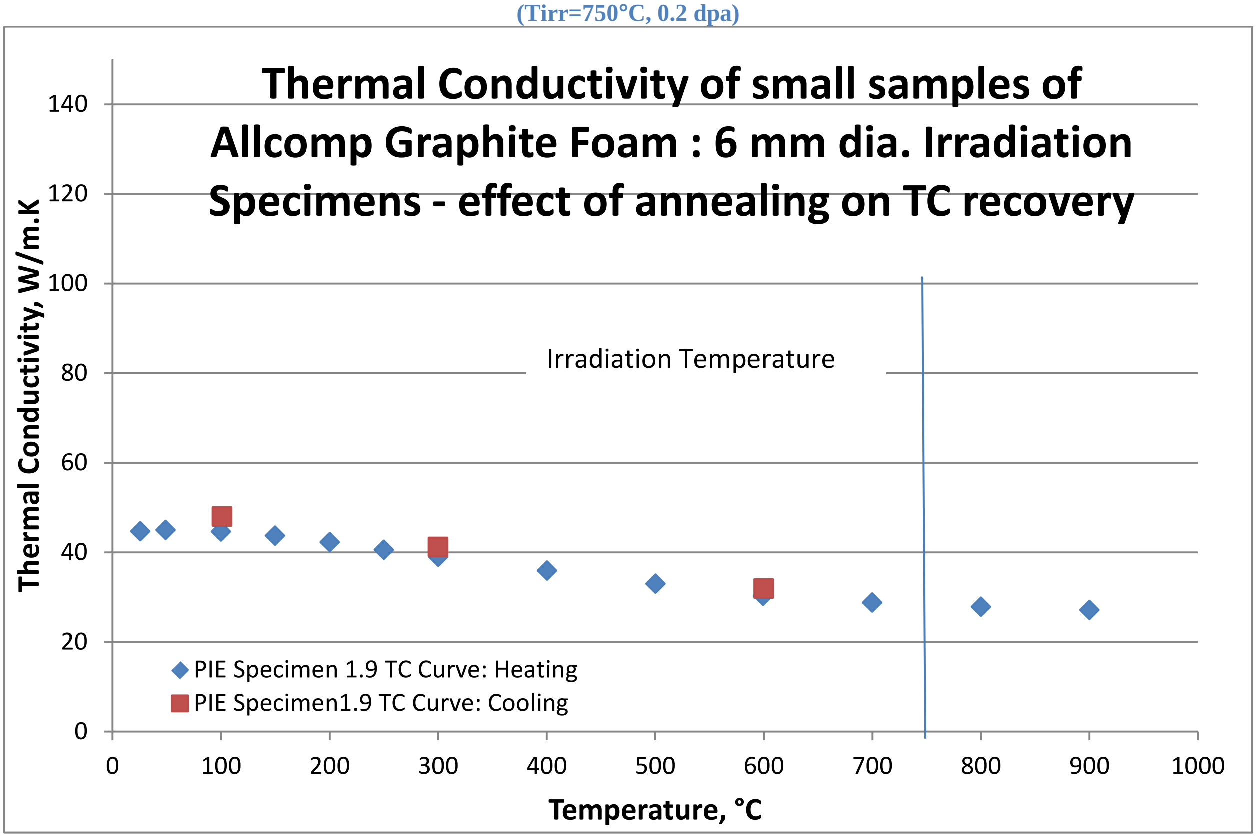


Figure 19 Heating and cooling thermal conductivity as a function of measurement temperature for irradiated specimen 9 (Tirr=750°C, 0.2 dpa)

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°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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 | cm2/sec | J/kg.K | g/cm3 | 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 |