EUROPEAN COMMISSION

Community Research

SEVENTH FRAMEWORK PROGRAMME

ARCHER

Collaborative Project (CP)

Co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme

Grant Agreement Number : 269892

Start date : 01/02/2011 Duration : 48 Months

www.archer-project.eu

PIE report of low dose irradiation experiment at 750°C

Authors : HEIJNA Maurits (NRG)

ARCHER - Contract Number: 269892
Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D
EC Scientific Officer: Dr. Panagiotis Manolatos

Document title	PIE report of low dose irradiation experiment at 750°C
Author(s)	HEIJNA Maurits
Number of pages	50
Document type	Deliverable
Work Package	WP 41
Document number	D41.21
Issued by	NRG
Date of completion	11/07/2014
Dissemination level	Confidential, only for members of the consortium (including the Commission Services).

Summary

In the European graphite irradiation programme, the irradiation behaviour of modern graphite grades is investigated at two irradiation temperatures, 750°C and 950°C. Following up on the irradiation experiments performed in the HTR-M and RAPHAEL projects, a low dose irradiation experiment at 750°C was performed to investigate materials properties changes induced by neutron irradiation. This report describes the PIE results of this low dose irradiation experiment, called INNOGRAPH-1C.

Approval

Date	By
28/07/2014	Arjan VREELING
27/08/2014	Derek BUCKTHORPE
09/09/2014	Steven KNOL

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	Through the EC participant portal
All beneficiaries	ARCHER	Through the private online workspace

D41.21 Low dose irradiation experiment at 750°C

PIE of INNOGRAPH-1C

Confidential

Under the contract of Euratom grant agreement 269892

rev. no.	date	description
A		Final version first revision

author(s):	Heijna, M.C.R. 11-7-14	reviewed:	T.O. van Staveren 11-7-14
name:	D41.21 INNOGRAPH-1C PIE	approved:	J.R. Westlake
reference.:	22906/14.127616	status:	final 11/07/2014
1 pages	08/07/2014		

Contents

Summary

In the European graphite irradiation programme, the irradiation behaviour of modern graphite grades is investigated at two irradiation temperatures, 750°C and 950°C. Following up on the irradiation experiments performed in the HTR-M and RAPHAEL projects, a low dose irradiation experiment at 750°C was performed to investigate materials properties changes induced by neutron irradiation. This report describes the PIE results of this low dose irradiation experiment, called INNOGRAPH-1C.

The work described was performed with financial support from the European Union and the Dutch Ministry of Economic Affairs, Agriculture, and Innovation. The views expressed in this report are those of the authors and do not necessarily represent those of the European Union, nor those of the Dutch government.

1 Introduction

Graphite is a suitable material to be used as a neutron moderator and reflector in nuclear reactors. Graphite has been used in Advanced Gas-Cooled Reactors, Magnox reactors, RBMK's (a Russian acronym meaning "reactor cooled by water and moderated by graphite"), Research Reactors, Materials Test Reactors and High Temperature Reactors (HTR's). Since the end of the 20th century there has been a renewed interest in HTR's. Two prototypes, one in Japan (HTTR) and one in China (HTR-10) are in operation. A demonstration plant is under construction in China (HTR-PM). The Next Generation Nuclear Plant NGNP in the US is in development. The European Commission is supporting research projects for the development of HTR technology to determine the technological requirements for designing and constructing an HTR in Europe.

Much research has been done on the behaviour of graphite grades in a nuclear reactor environment, because graphite is already being used in reactors for decades. However, these graphite grades are no longer commercially available since the raw materials no longer exist. In addition, most data from the past are from low temperature experiments (<550°C), whereas for HTR's the graphite temperatures will generally be higher than 550°C. In order to be able to design a European HTR, it was decided by the European commission to create a database that contains data of the materials behaviour of available graphite grades under neutron irradiation at temperatures relevant for the HTR's. This will allow the 'best' graphite(s) to be chosen, and provide the necessary data to allow the core design to be carried out.

The irradiation behaviour of HTR graphite grade candidates is investigated in the European programme on High Temperature Technology, started in 2001. Within the HTR-M1 and RAPHAEL-IP framework, graphite irradiation experiments were performed at 750°C and 950°C in the High Flux Reactor (HFR) in Petten. These were named INNOGRAPH-1B (750°C, high dose), INNOGRAPH-2A (950°C, medium dose) and INNOGRAPH-2B (950°C, high dose). In every experiment a few graphites were also irradiated at lower temperatures of 650°C (in the 1B) and 850°C (in the 2A and 2B). Figure 1-1 shows schematically the volume change of graphite with neutron fluence at the two main irradiation temperatures. The boxes on the curves indicate the five different irradiation experiments. Box 1A indicates the low dose irradiation at 750°C named INNOGRAPH-1A. This has been performed within HTR-M1 in the 5th Framework Programme and had a target dose of 8 dpa [1]. Box 1B indicates INNOGRAPH-1B, the high dose (up to ~25 dpa) experiment at the same temperature. Boxes 2A and 2B indicate the medium and high dose experiments at 950°C, INNOGRAPH-2A and INNOGRAPH-2B respectively. Results of these experiments are reported in [2]. Box 1C indicates the low dose irradiation experiment at 750°C that is performed in the framework of the ARCHER project, of which the results are presented in this report.

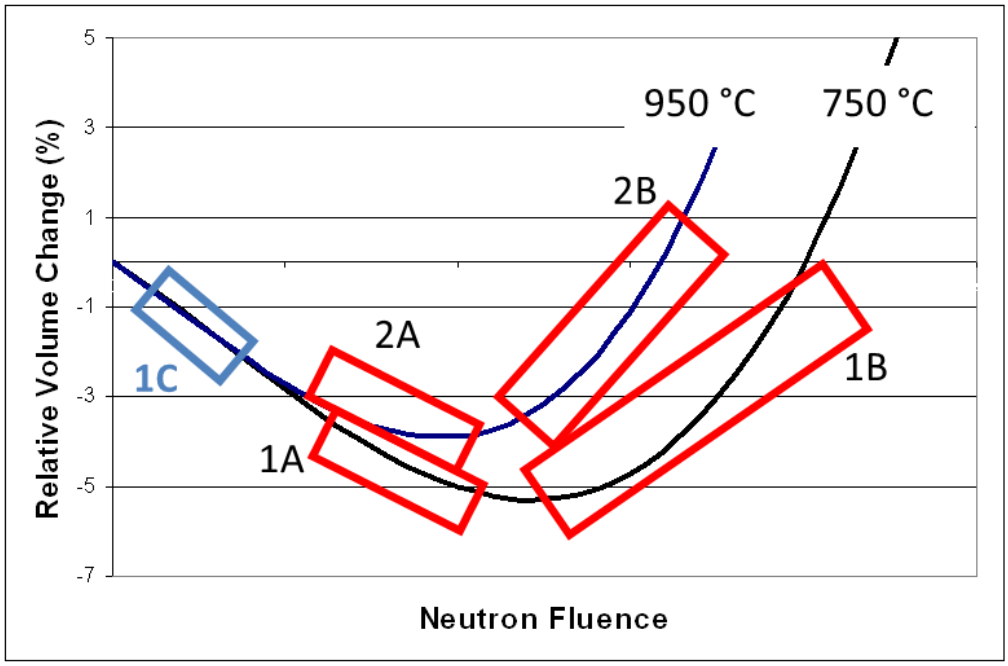

Figure 1-1 Schematic overview of the five INNOGRAPH irradiation experiments

2 Experiment and measurement techniques

2.1 Test matrix

2.1.1 Grades

The INNOGRAPH-1C is a follow-up experiment of the INNOGRAPH-1A and -1B experiments. Therefore, graphite grades are selected based on their presence in these preceding experiments [3]. The selection of the graphite grades for the INNOGRAPH irradiation experiments is based on several factors such as thermal and mechanical properties, impurity levels and availability [1]. The four major grades, produced by SGL Carbon and Graftech are chosen in such a way that the graphites cover a variety of microstructures. This is achieved by selecting grades based on different raw materials, i.e. coal tar pitch coke or petroleum coke, and different manufacturing methods, i.e. extrusion, isostatic-moulding or fibro-moulding.

The minor grades include graphites from three different manufacturers, SGL Carbon, Graftech and Toyo Tanso. The minor grades include iso-moulded graphites and graphites based on needle coke. The graphites used in the experiments are listed in Table 1.

Next to the major and minor grades that also were presented in the preceding irradiation experiments, a number of "specials" were present in the INNOGRAPH-1C. These include fuel matrix material supplied by Furnaces Nuclear Applications Grenoble (FNAG), graphite grades supplied by GrafTech and SGL, and Highly Oriented Pyrolitic Graphite (HOPG).

Table 1 Overview of the graphite grades selected for the INNOGRAPH-1C irradiation experiment

Grade	Manufacturer	Coke	Process	Major/minor
NBG-10	**SGL**	**Pitch**	**Extrusion**	**Major**
NBG-18	**SGL**	**Pitch**	**Vibro-moulding**	**Major**
PCEA	**GrafTech**	**Petroleum**	**Extrusion**	**Major**
PPEA	**GrafTech**	**Pitch**	**Extrusion**	**Major**
IG-110	Toyo Tanso	Petroleum	Iso-moulding	Minor
IG-430	Toyo Tanso	Pitch	Iso-moulding	Minor
LPEB/BAN	GrafTech	Needle	Extrusion	Minor
LPIB	GrafTech	Needle	Iso-moulding	Minor
NBG-17	SGL	Pitch	Vibro-moulding	Minor
NBG-20	SGL	Petroleum	Extrusion	Minor
NBG-25	SGL	Petroleum	Iso-moulding	Minor
PCIB	GrafTech	Petroleum	Iso-moulding	Minor

2.1.2 Specimen geometry

All specimens loaded in the INNOGRAPH experiments are cylindrical. The diameter of all specimens is 8 mm and the length is 6 mm. Specimens of these sizes are small enough to allow a sufficient number of specimens in the irradiation rig, and large enough to perform reasonably accurate measurements. The specimens are suitable for all type of measurements (dimensional changes, dynamic Young's modulus, coefficient of thermal expansion and thermal diffusivity).

The cylindrically shaped specimens are flattened by milling a plane with a width of 3 mm along the length. Figure 2-1 schematically shows the flattening. Producing a plane with a width of 3 mm mills only 1% of the volume of the cylinders. The benefits of this plane are threefold. The first benefit is the possibility to indicate the z-direction from the original graphite blocks in the specimen. The plane is milled perpendicular to the *z*-direction if the axial direction of the cylinder is parallel to the *xy*-direction, and therefore the *z*-direction in the specimen is known after fabrication. The plane is milled on an arbitrary position if the axial direction of the cylinders is parallel to the *z*-direction, because in that case the *z*-direction is already indicated by the axial direction.

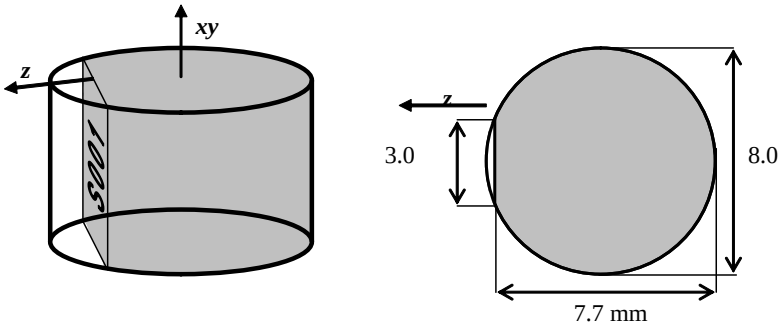

Figure 2-1 Flattening of the specimens. The figure on the left-hand side exaggeratedly shows the flatting of the cylinder. The figure on the right-hand side is a top-view of the specimen

The second benefit of the plane is that it gives an area to engrave the specimen with a unique code. This code is necessary to easily identify a specimen. The code consists of four characters. The code is formed by three numbers and one letter. The letter indicates the graphite manufacturer (S= SGL, U= UCAR (Graftech) and T= Toyo Tanso). The letter Z is used for a number of special samples by various manufacturers.

A third benefit is that the milled plane can act as a marking that defines the measuring positions during the dimensional measurements before and after irradiation.

2.1.3 Test matrix

In Table 2 the test matrix of the INNOGRAPH-1C irradiation experiment is presented. Samples are machined from the centre and edge of the original graphite blocks to allow studying effects of variation within the blocks. Samples are taken in two directions: with the axial direction of the sample parallel to the With Grain (WG) direction in the graphite or parallel to the against grain direction (AG) in the graphite to analyse the anisotropy in irradiation behaviour of graphite. The focus lies on the major grades. Therefore, the number of major grade samples in the experiments typically is larger than the number of minor grade samples.

Table 2 Test matrix of the INNOGRAPH-1C irradiation

Grade	No. of specimens	Centre		Edge	
		WG	AG	WG	AG
NBG-10	24	6	6	6	6
NBG-17	18	7	5	3	3
NBG-18	23	6	6	6	5
NBG-25	17	4	5	3	5
PCEA	25	6	7	6	6
PCIB	18	7	5	3	3
PPEA	25	7	6	6	6
IG-110	14	4	4	3	3
IG-430	13	4	5	2	2
MLRF	7	3	4	0	0
Coated NBG-17	5	n/a	n/a	n/a	n/a
LPEB	6	2	2	1	1
LPIB	2	1	1	0	0
TS5324	5	n/a	n/a	n/a	n/a
TS5328	5	n/a	n/a	n/a	n/a
Fuel matrix	8	n/a	n/a	n/a	n/a
HOPG	4	n/a	n/a	n/a	n/a
Total:	**219**				

2.2 Irradiation experiment

The INNOGRAPH-1C rig consists of a stack of eight TZM (0.5Ti, 0.08Zr, 0.42 Mo) drums that are used as specimen-holders (Figure 2-2). The rig contained seven drums with a height of 60 mm and one drum with a height of 30 mm. In each drum, three channels are present to contain the samples. In between

drums, a thin graphite foil is placed to prevent specimens moving axially into the drum below. The high density of TZM makes it possible to reach the required nominal temperature of 750°C. Because of the relatively low neutron flux in the top drum, this drum cannot reach the 750°C. However, this drum is still usable to irradiate graphite specimens at a slightly lower temperature. The top drum is separated from the drums below by a thermal barrier and is designed to have a temperature of 650°C. For the rest of the rig the design temperature is 750°C. The capsule is instrumented with 24 thermocouples that are placed on different radial and axial positions to monitor the temperature during irradiation. Temperature was controlled by changing the He/Ne gas mixture in the second containment and the vertical displacement of the experiment in the reactor core. The temperature was controlled for the 750°C drums; the temperature for the top drum at 650°C is not controlled.

In the centre of each drum a hole was drilled to place neutron fluence detector sets. Five fluence detector sets were distributed axially over the rig with TZM fillers in between. Four fluence detector sets are distributed radially in two drums to monitor the radial gradients. The detector sets are analysed after the experiment to determine the neutron fluence.

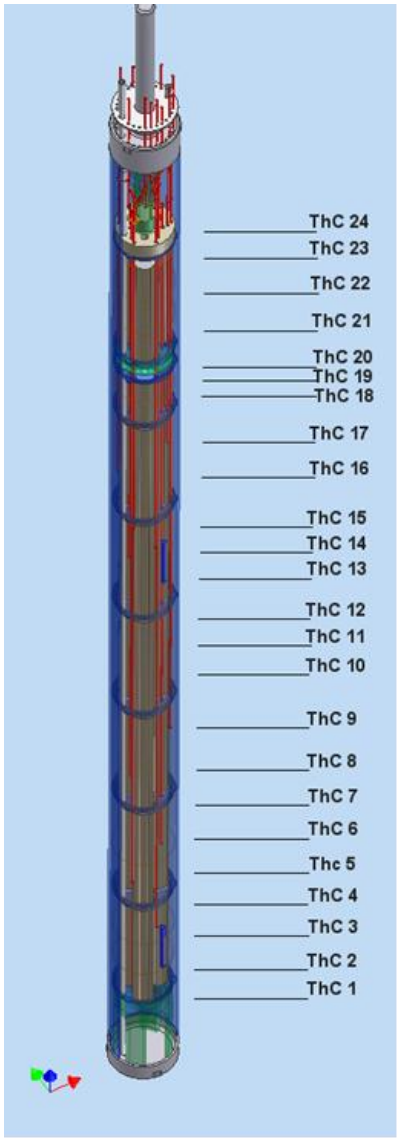

Figure 2-2 Drawing of the INNOGRAPH-1C irradiation rig

2.3 Measurement techniques

2.3.1 Dimensions

The dimensions of the samples are measured by inductive probes (Mahr, Type P 2104 MB) with a measurement range of 4 mm and accuracy of 0.1 um. The measurement is a comparison of the dimension of the sample and the dimension of a well-known caliber. The length (l) is measured at 5 positions at both sides of the sample (10 measurements in total). The diameter (d) is measured at three positions at every 90º (12 measurements in total). The size of the sample perpendicular to the flat side (x) is measured at three positions. The average values of l, d and x are reported.

2.3.2 Mass

The mass (m) is measured with a Mettler AT261 balance with an accuracy of 0.01 mg. The measurement is repeated three times and the average value is reported. Measurements are performed in a glove box.

2.3.3 Dynamic Young's Modulus

The Dynamic Young's Modulus (DYM) is determined by measuring the velocity of sound in a sample. A 1 MHz wave packet is generated by Krautkrämer USM 25 controller box. This box is connected by two Krautkrämer (MK1S) acoustical transducers, one acting as the transmitter and one as the receiver. The input and output signals are analysed and digitally stored by using an oscilloscope. The velocity of sound is determined by measuring the time difference between input and output.

The DYM can be calculated by multiplying the density and the velocity of sound squared. A true measure of the Young's Modulus is obtained by taking into account the Poisson's ratio. This results in a correction factor. For example, the Young's modulus is reduced by 10 per cent for a Poisson ration of 0.2. However, because the Poisson ratios of the irradiated samples are not known, the correction factor is not taken into account in this work.

2.3.4 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) is measured in a Netzsch dilatometer DIL402C using an alumina sample holder. The furnace is purged with He to prevent oxidation during heating. The measurement consists of three temperature cycles up to the irradiation temperature of 750°. The first cycle is for setting the system and the second and third cycle are considered as the measurements. The heating rate during the measurement cycles is 5 K/min. The average of the result of the second and third heat-up cycle is reported as the CTE value. Measurements are repeated in case of a difference between second and third heat-up cycle larger than 0.1×10^{-6} K^{-1}.

2.3.5 Thermal Diffusivity and Conductivity

The coefficient of thermal diffusivity is measured by laser flash method with a LFA 457 MicroFlash from Netzsch. The Microflash uses a laser to give the heat input. The transmitted heat is detected using an IR-pyrometer. Three samples can be placed at the same time in the furnace by using a carrousel. Measurements can be performed in vacuum or in a helium atmosphere; the PIE measurements were performed in a helium atmosphere. The temperature of the furnace can be controlled from room

temperature to a maximum of 1100ºC. The maximum measurement temperature is limited to either the irradiation temperature (to avoid annealing during the measurements) or the maximum temperature of the equipment (1100ºC). At each defined measurement temperature, the samples were measured three times. The average result of these three measurements is taken as the final result. The thermal diffusivity was measured at intervals of 100°C as a compromise between number of data points to get a curve and the time needed to complete a measurement.

The coefficient of thermal conductivity is calculated from the measured coefficient of thermal diffusivity by multiplying this value with the specific heat (tabulated in ASTM 781-96) and the density. It is assumed that the specific heat is not changed due to neutron irradiation.

3 Results & Discussions

3.1 Irradiation experiment

3.1.1 Irradiation

The INNOGRAPH-1C has been irradiated for three cycles, corresponding to 84 full power days at 45 MW. The irradiation started on the 13th of October 2012. The irradiation rig was irradiated in HFR core position C7. After the completion of the first cycle, the continuation of the experiment was delayed due to an outage of the HFR. The second cyle of the INNOGRAPH-1C was performed in June 2013, and the third in september 2013. The nominal temperature inside the irradiation rig during operation was 750°C for all three cycles.

3.1.2 Dosimetry

Due to issues with retrieving the fluence detector sets, this revision of the PIE report contains not the measured but the a priori calculated dpa values. It is expected that the fluence detector sets will be processed before the end of the ARCHER project to provide actual dpa values. Figure 3-1shows the calculated dpa profile over the length of the experiment.

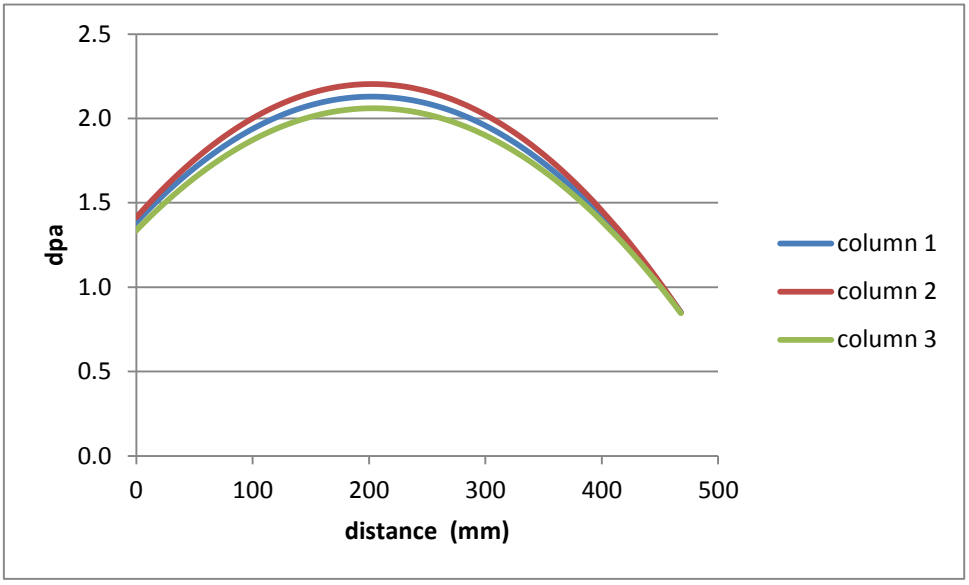

Figure 3-1 Calculated dpa profile over the length of the experiment for each of the three sample columns

3.2 Post-Irradiation Examination

In this section, the results of the post-irradiation examination of the low irradiation experiments at 750°C INNOGRAPH-1C, are presented. These results include PIE data from the INNOGRAPH-1A and -1B irradiations is included in the graphs to give a complete set of data. The PIE data of the INNOGRAPH-1C irradiation experiments are also presented in tables in Appendix A to C. These tables include the data for the "specials". Post-irradiation dimensions has been measured for all samples, except for the HOPG samples. DYM, CTE and thermal diffusivity has been measured for a selection of samples only due to financial limitations.
The results of the mass measurements and the density calculated from these and the dimensional measurements are presented in Appendix A. These are used in calculations for dynamic Young's modulus and thermal conductivity.

3.2.1 Dimensions

The volumetric changes (ΔV/V0) for the low dose experiment at an irradiation temperature of 750°C are presented in Figure 3-2 to Figure 3-6, grouped by graphite manufacturer. In these graphs, the INNOGRAPH-1A and -1B data is presented by solid symbols. The INNOGRAPH-1C data is presented by open symbols.

The length changes (ΔL/L0) are presented in Figure 3-7 to Figure 3-11, also grouped by manufacturer and irradiation temperature and using the same system of open and closed symbols. For the length changes, the data in the graphs is specified by grain orientation ("against grain" and "with grain"). The INNOGRAPH-1A and -1B data show that the length change for a graphite grade can differ significantly with grain direction. Examples for which this is significant are NBG-25 and PCEA. Others show little difference, for instance PCIB and NBG-18. The INNOGRAPH-1C data appears to show the same trend.

The volume change and length change curves suggest that the neutron irradiation induced dimensional changes do not start until approximately 0.5 dpa.

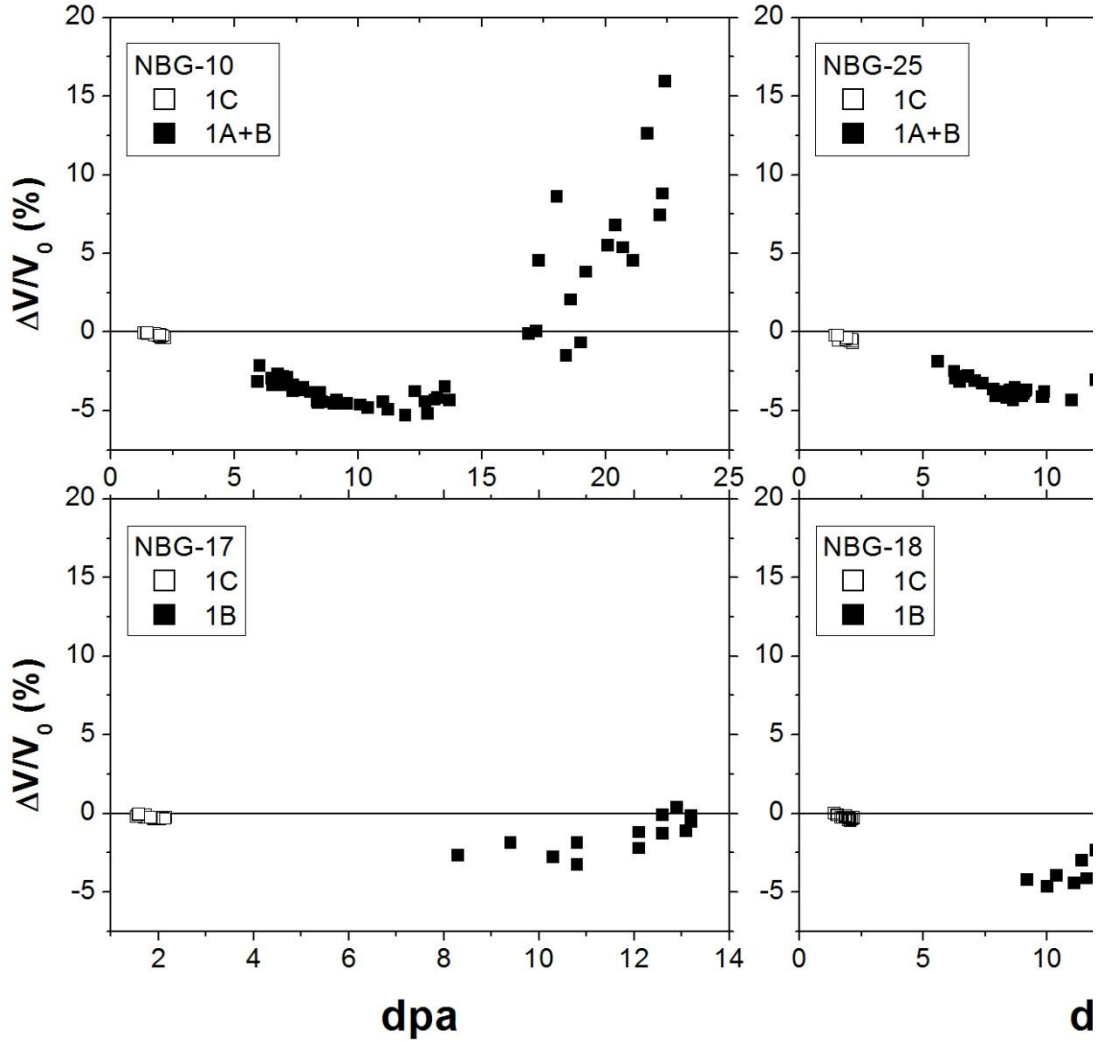

Figure 3-2 Volume change for SGL graphite grades irradiated at 750°C

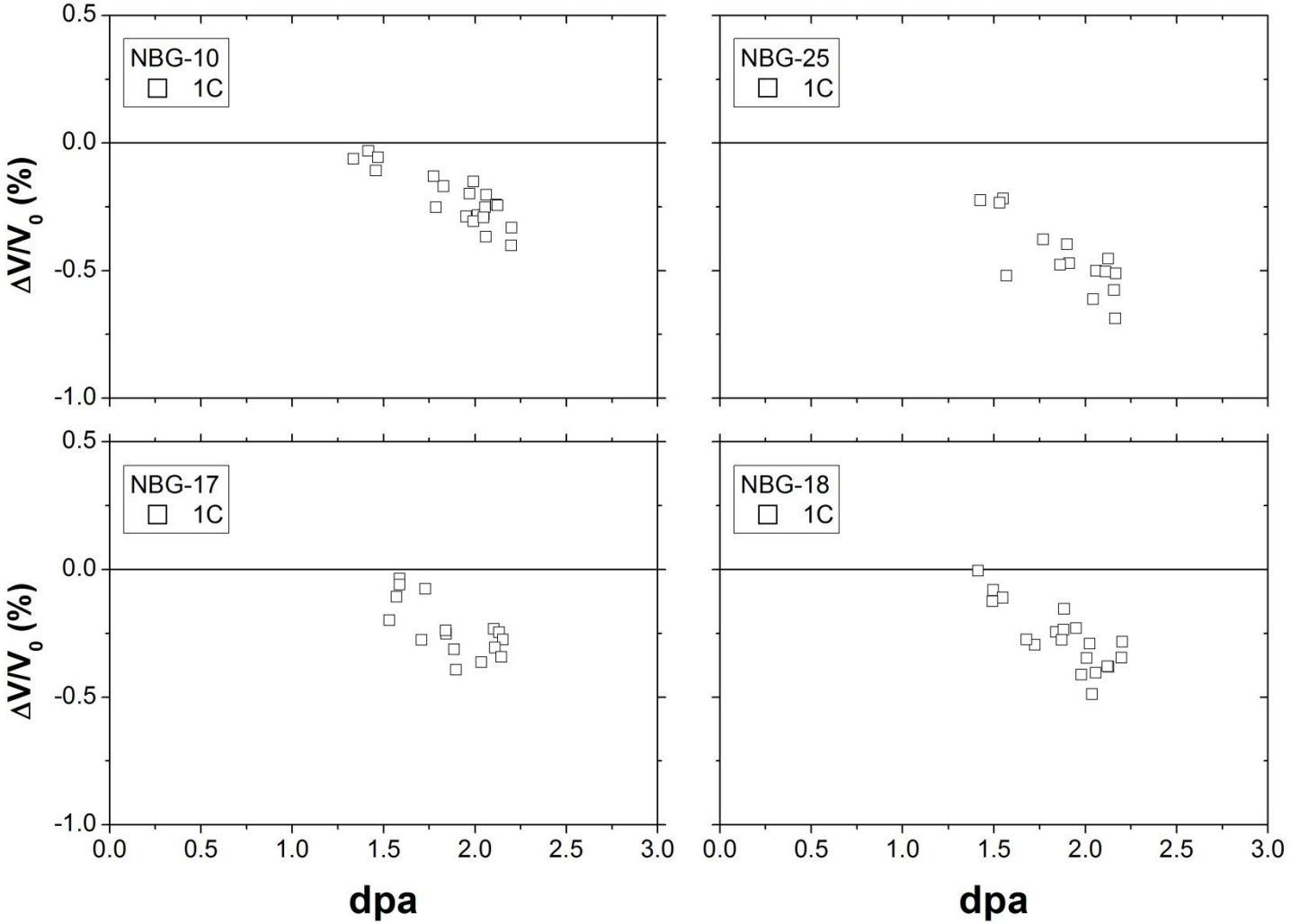

Figure 3-3 Volume change for SGL graphite grades irradiated at 750°C, zoomed in on the low dose irradiation data

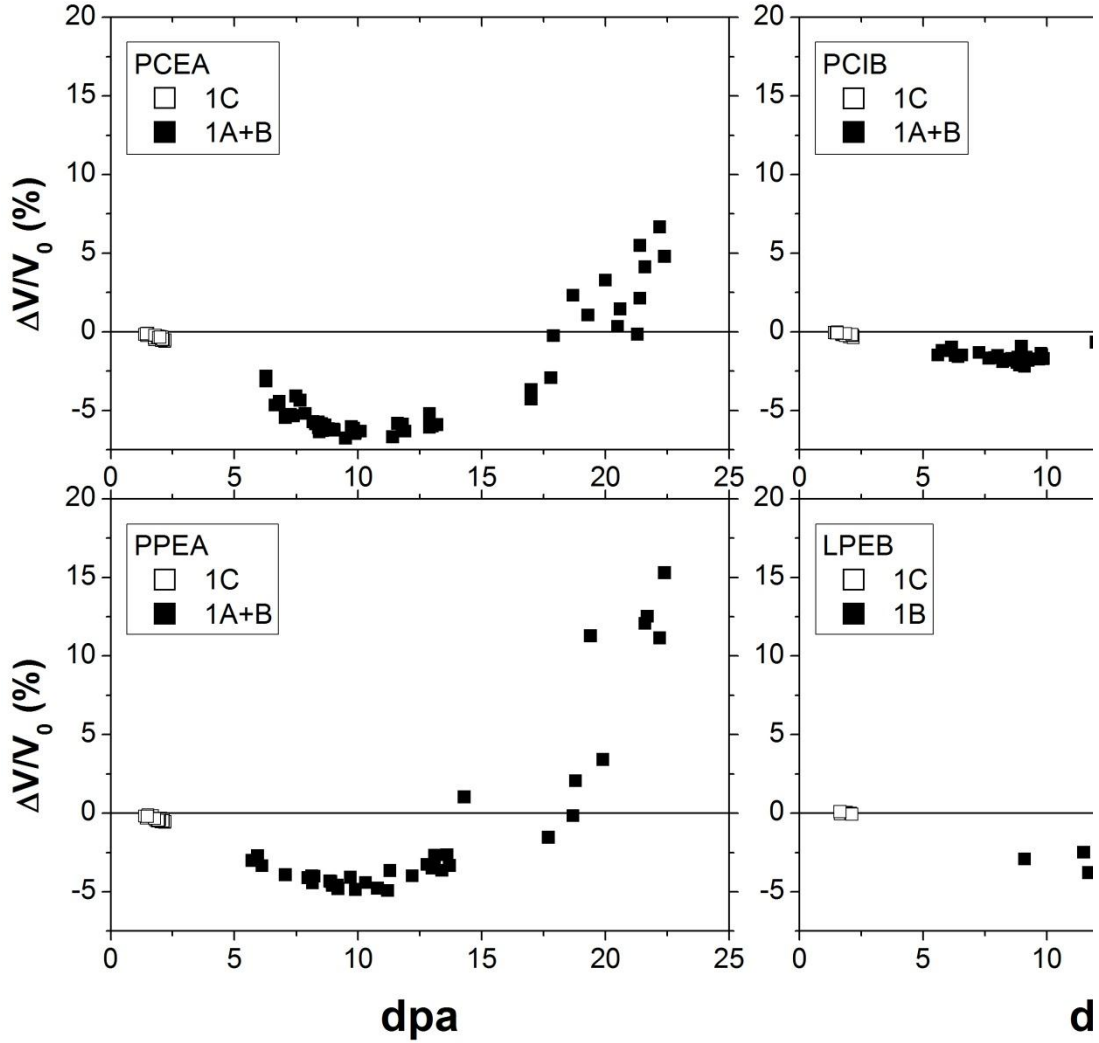

Figure 3-4 Volume change for GrafTech graphite grades irradiated at 750°C

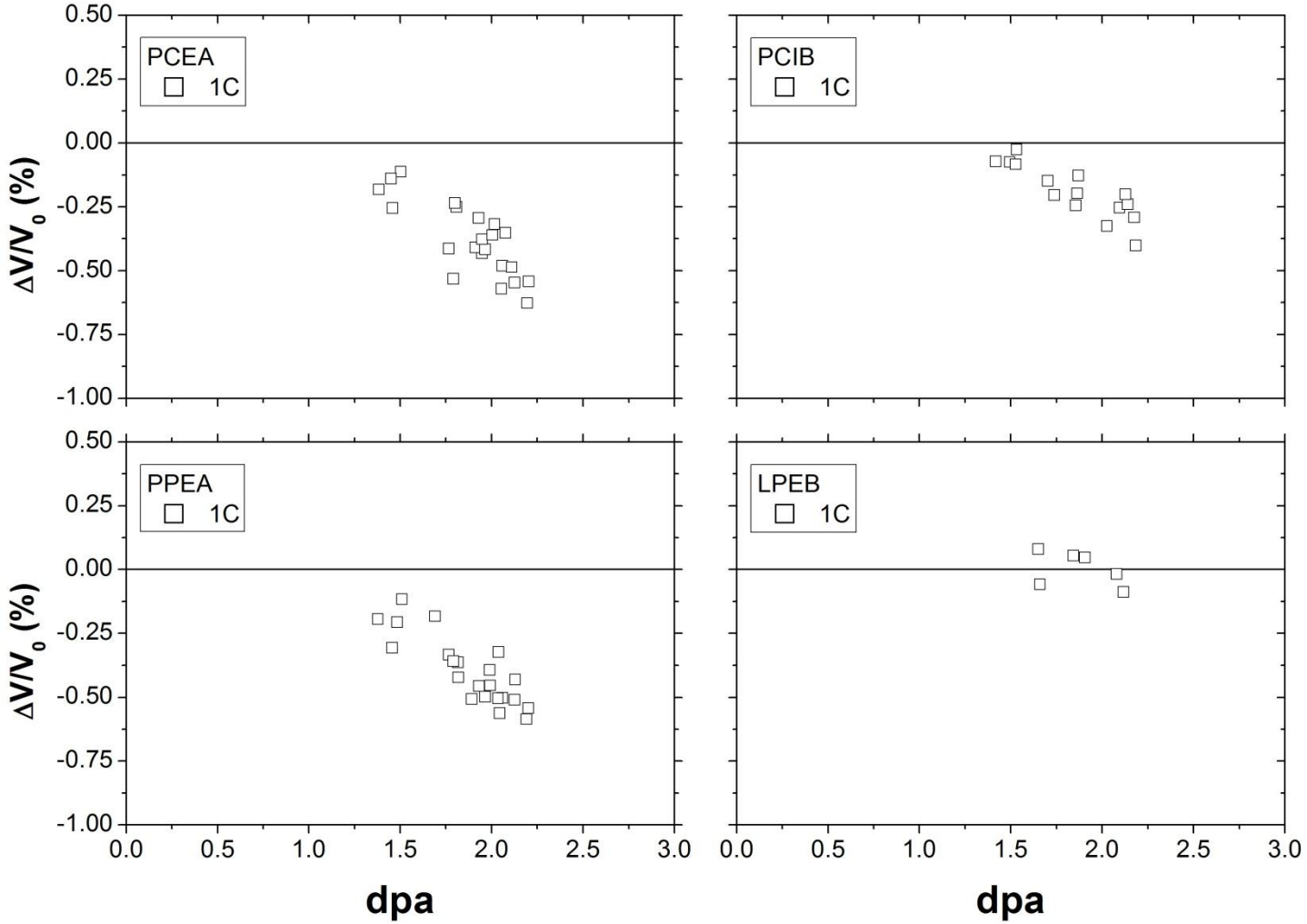

Figure 3-5 Volume change for GraphTech graphite grades irradiated at 750°C, zoomed in on the low dose irradiation data

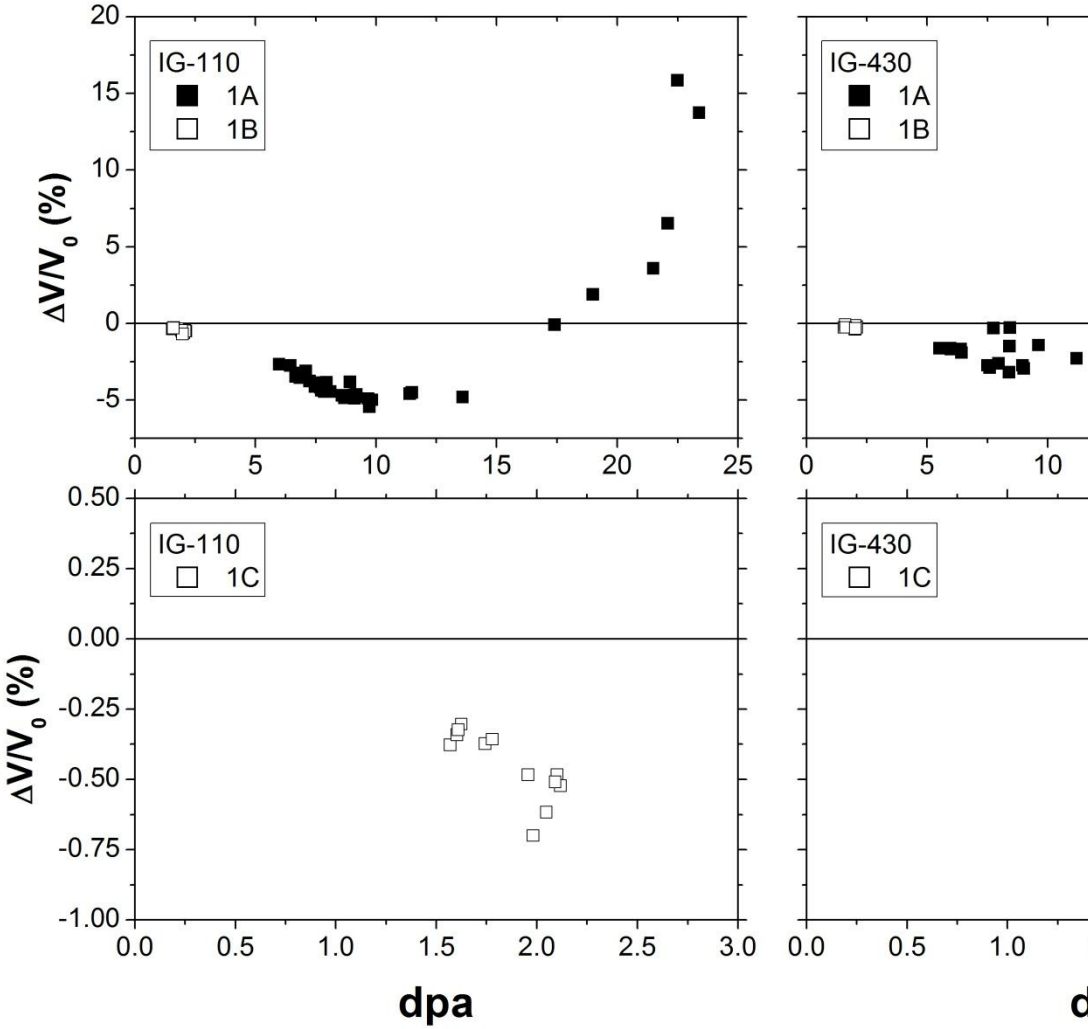

Figure 3-6 Volume change for Toyo Tanso graphite grades irradiated at 750°C

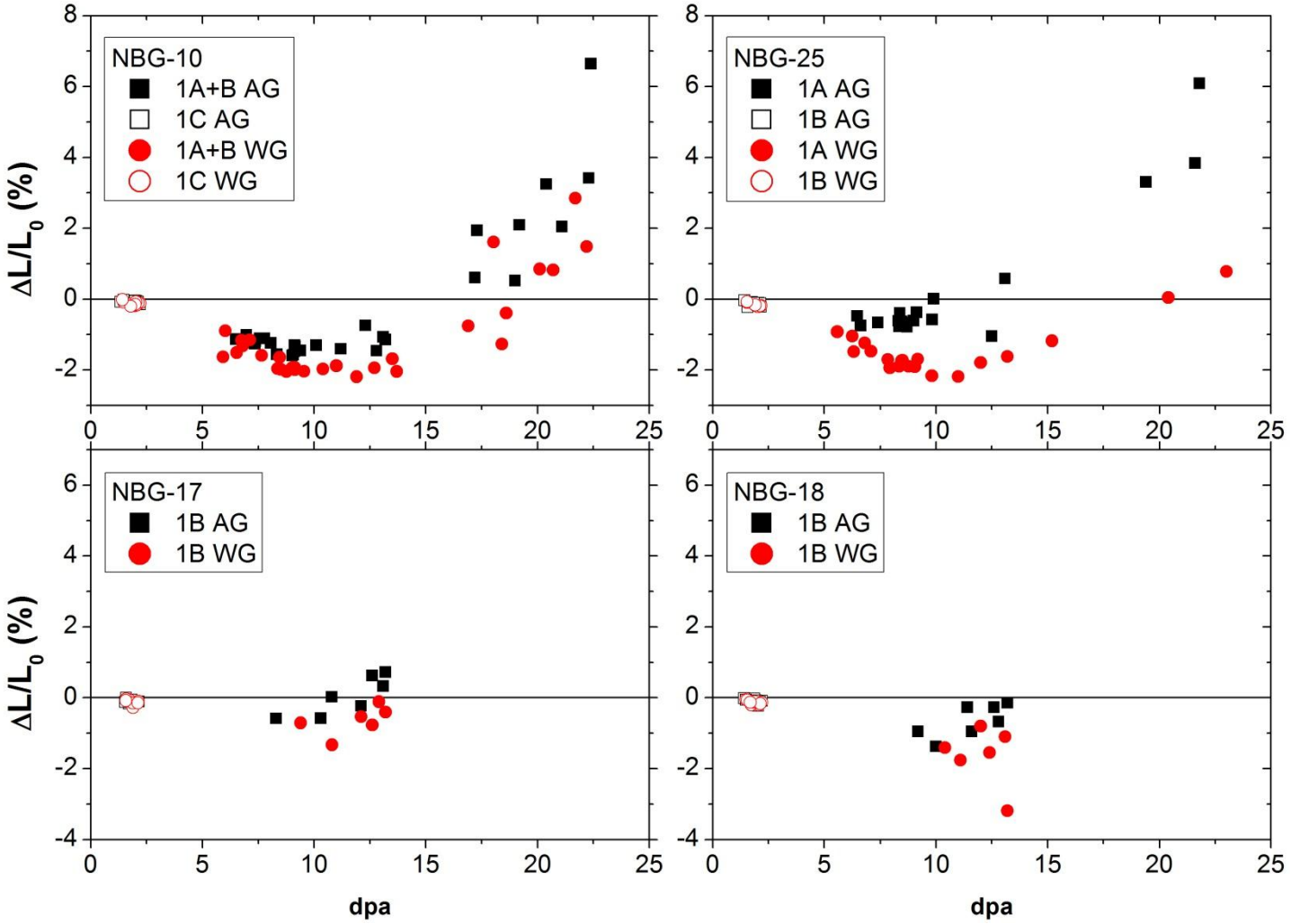

Figure 3-7 Length change for SGL graphite grades irradiated at 750°C

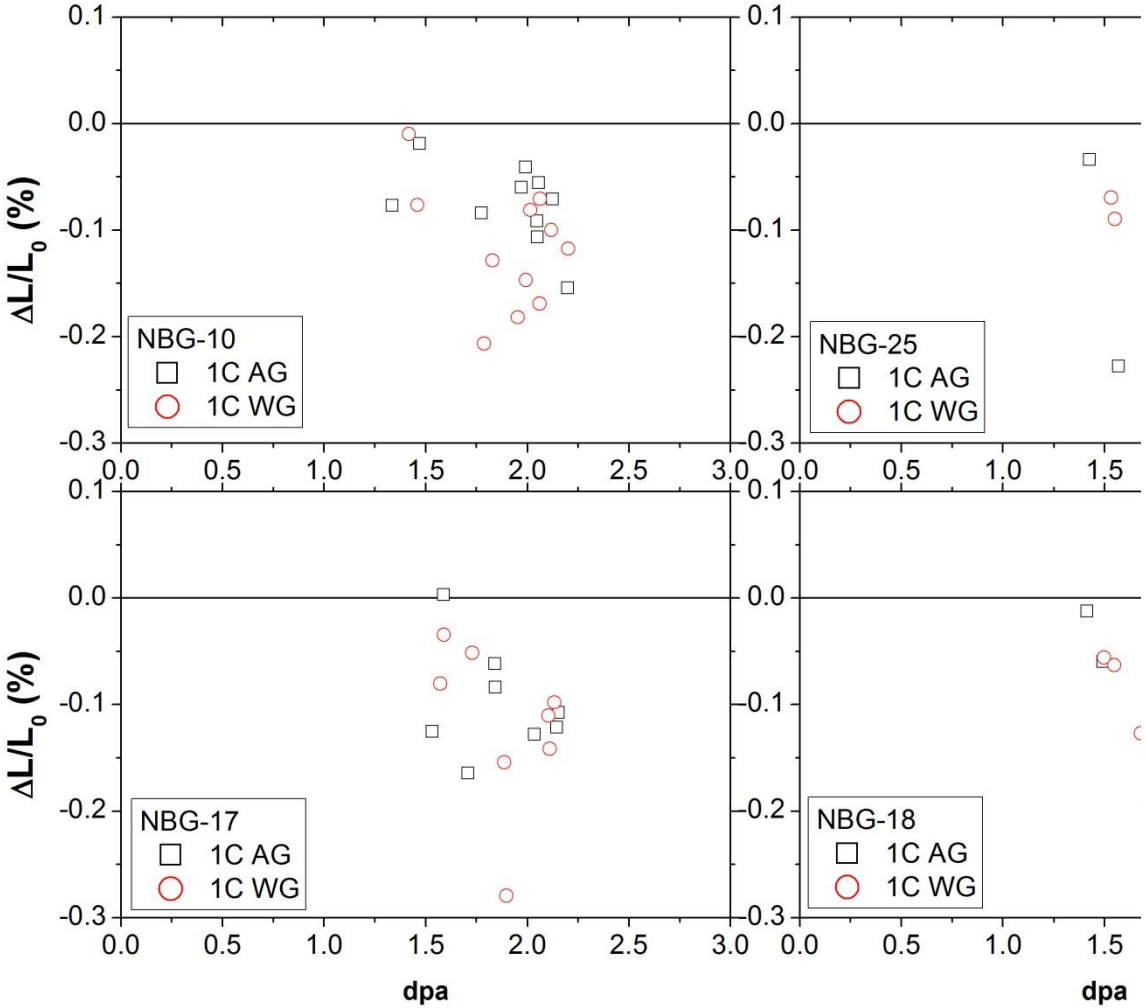

Figure 3-8 Length change for SGL graphite grades irradiated at 750°C, zoomed in on the low dose irradiation data

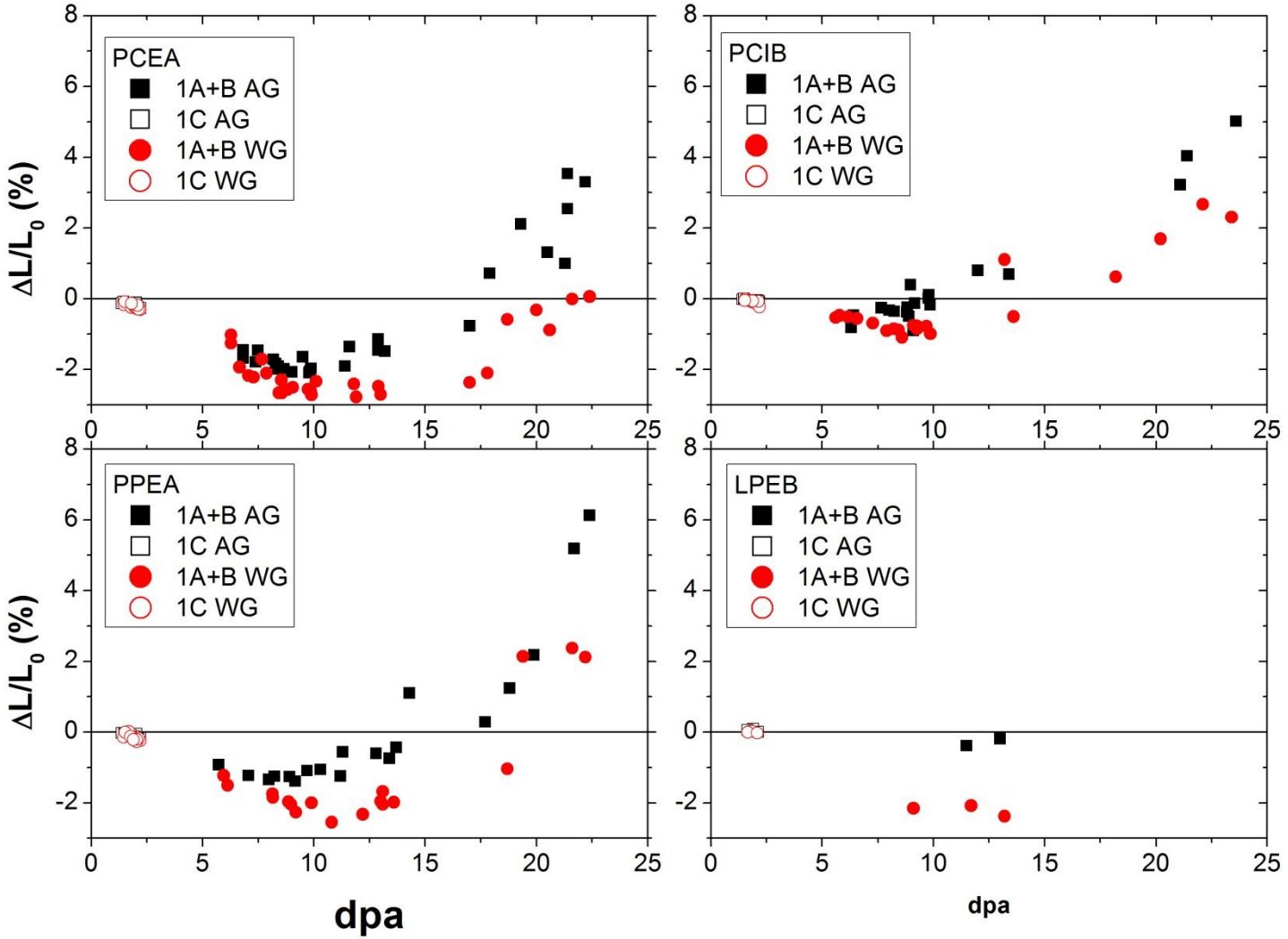

Figure 3-9 Length change for GraphTech graphite grades irradiated at 750°C

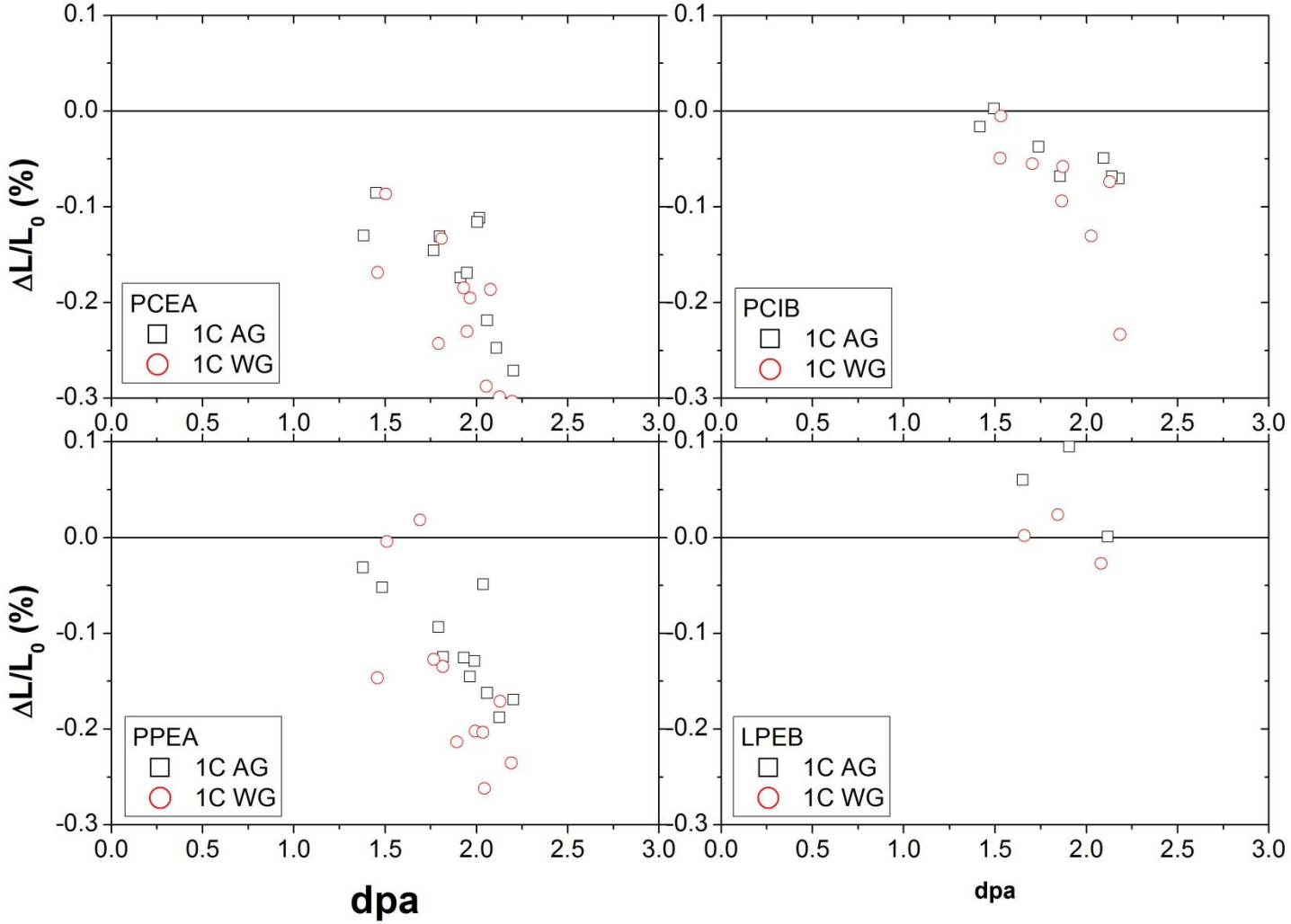

Figure 3-10 Length change for GraphTech graphite grades irradiated at 750°C, zoomed in on the low dose irradiation data

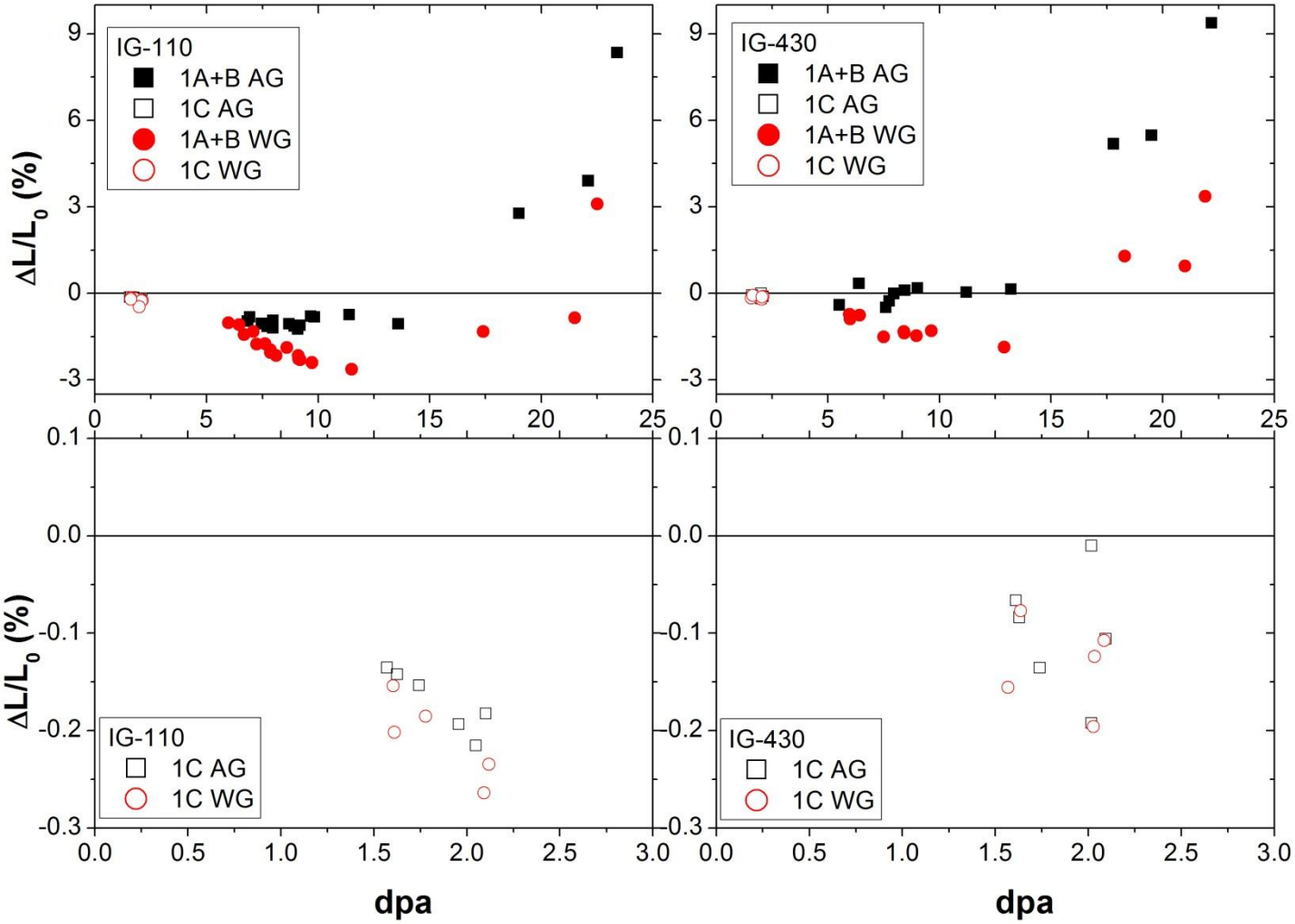

Figure 3-11 Length change for Toyo Tanso graphite grades irradiated at 750°C

3.2.2 Dynamic Young's Modulus

The Dynamic Young's Modulus (DYM) was measured for 53 out of 219 samples for the INNOGRAPH-1C irradiation. The ratio of the DYM after irradiation to the DYM before irradiation (E/E_0) is plotted in Figure 3-12 to Figure 3-14. The graphs are ordered by irradiation temperature, manufacturer, and graphite grades. The data in the graphs is specified by "A" and "B" irradiation and by "against grain" and "with grain" orientation. In general, the changes in DYM are not grain direction dependent. The typical trend shown by the INNOGRAPH-1A and –B data is an increase in DYM ratio at medium dose, a plateau at medium to high dose, and a decrease at high dose. The INNOGRAPH-1C data shows that the DYM already at low neutron dose is increased by the neutron damage. The data of the INNOGRAPH-1C irradiation suggest that in general for the graphite grades tested, a plateau exists between approximately 1 dpa and 5 dpa at E/E_0~1.5. For higher dpa's the DYM further increases up to a maximum in the expanding regime of the graphite after which DYM decreases again. Thus, the initial increase up to the 1.5x plateau occurs below 1 dpa.

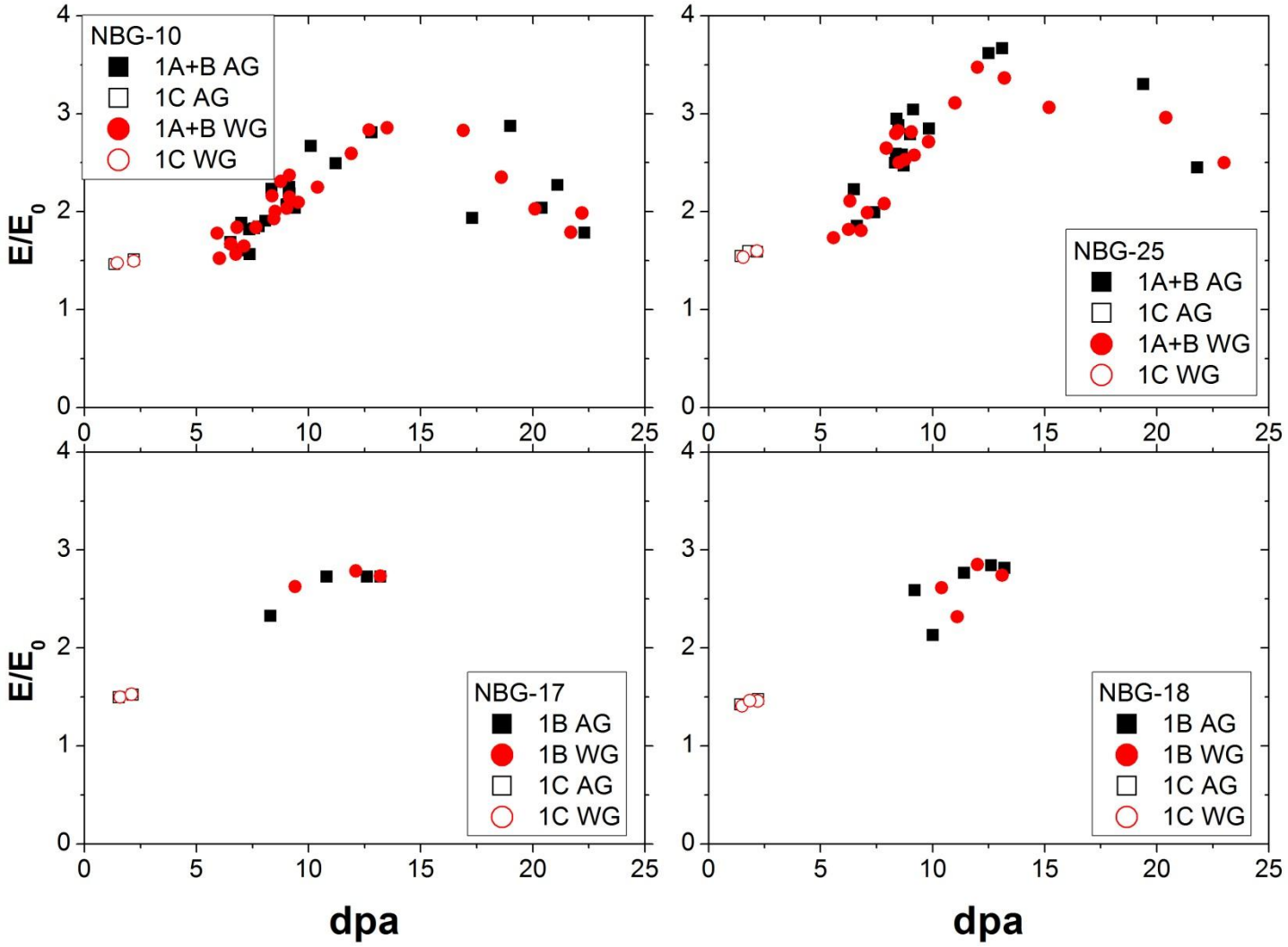

Figure 3-12 DYM change for SGL graphite grades irradiated at 750°C

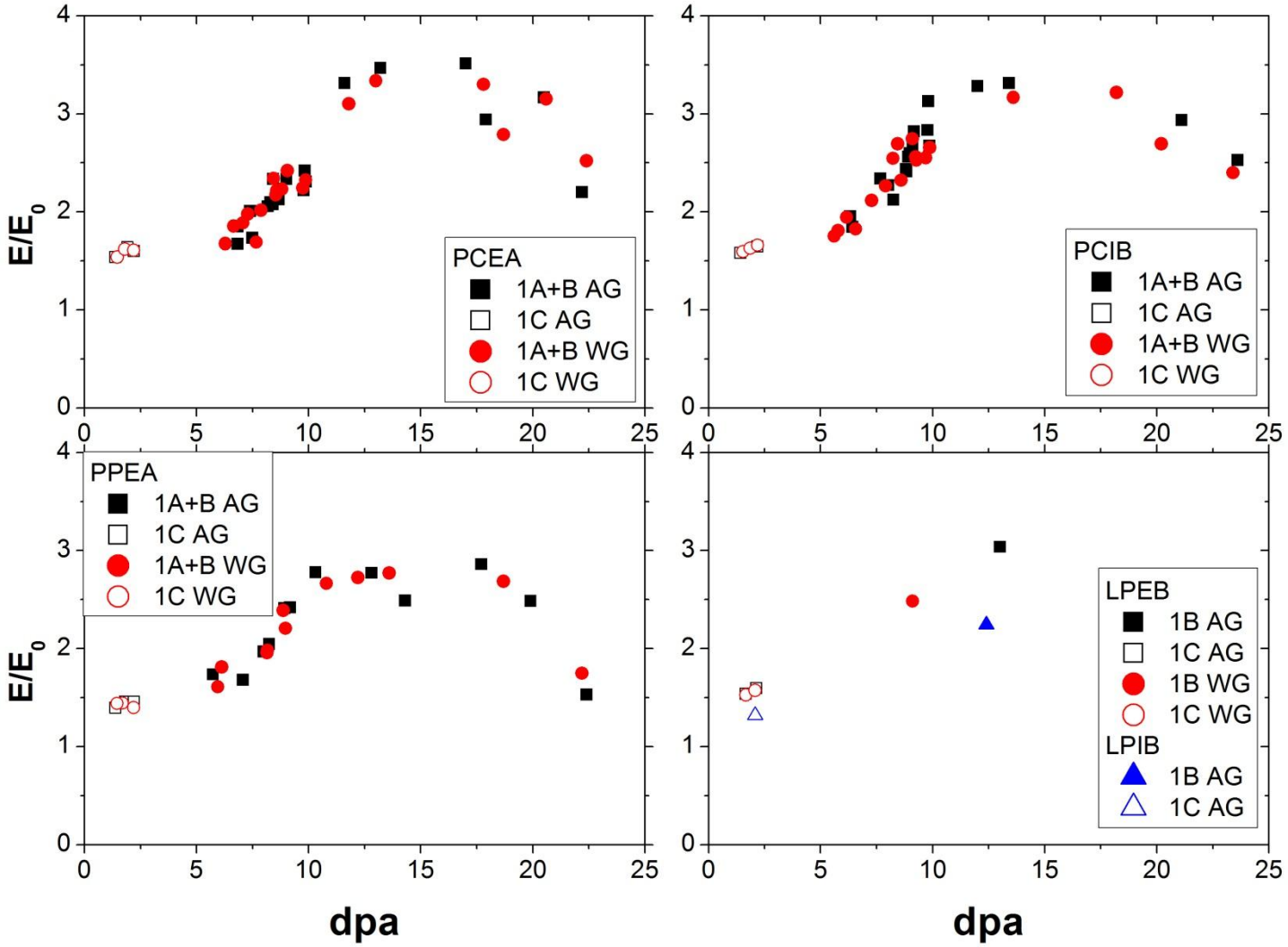

Figure 3-13 DYM change for GrafTech graphite grades irradiated at 750°C

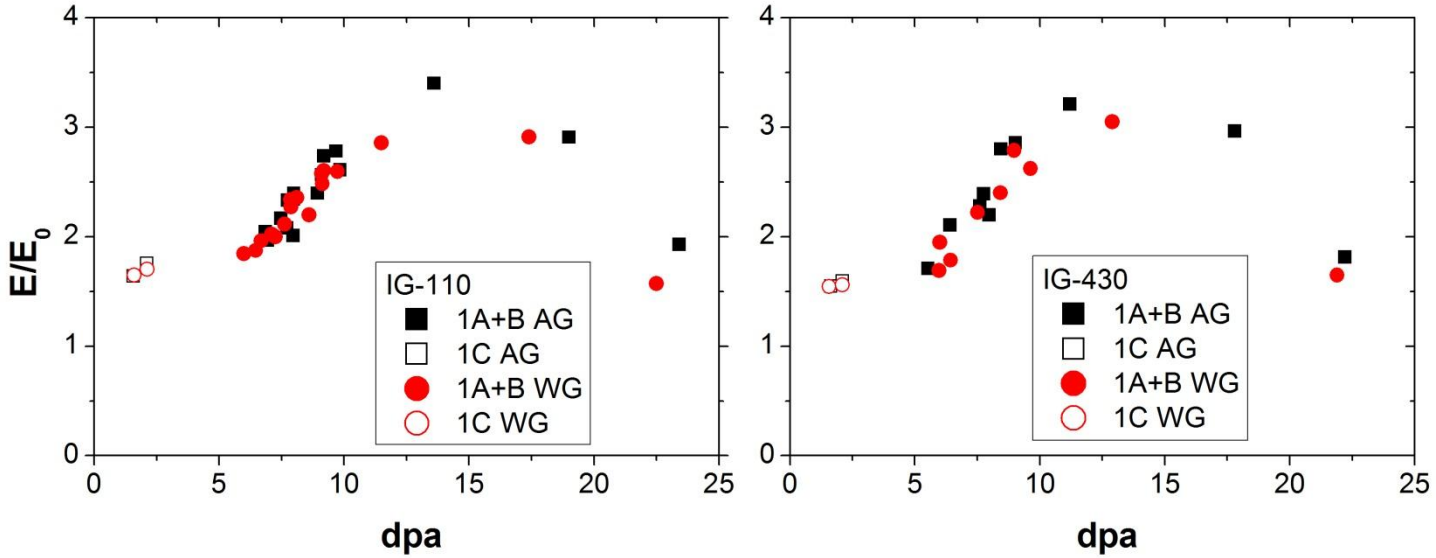

Figure 3-14 DYM change for Toyo Tanso graphite grades irradiated at 750°C

3.2.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion (CTE) as function of neutron irradiation damage is presented in Figure 3-15 to Figure 3-17, arranged by manufacturer, grade, and irradiation experiment. For reference, the CTEs of unirradiated graphite grades are included. Presented is the technical coefficient of thermal expansion over the range of 30°C to 750°C. The CTE data for other intervals are presented in Appendix B. These intervals are 30°C-120°C, and 30°C-200°C.

The general trend observed in the preceding irradiation experiments is a drop in CTE at medium dose followed by a stable plateau at medium to high dose. The plateaux start approximately at volume change turn-around. The data points added in the INNOGRAPH-1C experiment show an initial increase in CTE. The maximum in CTE lies without the range of the INNOGRAPH experiments in 2 and 5 dpa. The gradient in increase and decrease (and thus the width of the peak in the CTE curve) is graphite grade dependent.

At medium to high dose rate no difference is noticed in the irradiation behaviour of the coefficient of thermal expansion with respect to grain direction. At low dose, however, the data suggests a difference in with grain and against grain thermal expansion for most of the graphite grades. Data for NBG-17 and -18 is inconclusive. Thus, it appears that an initial anisotropy in thermal expansion in the end is cancelled by the increase in neutron damage.

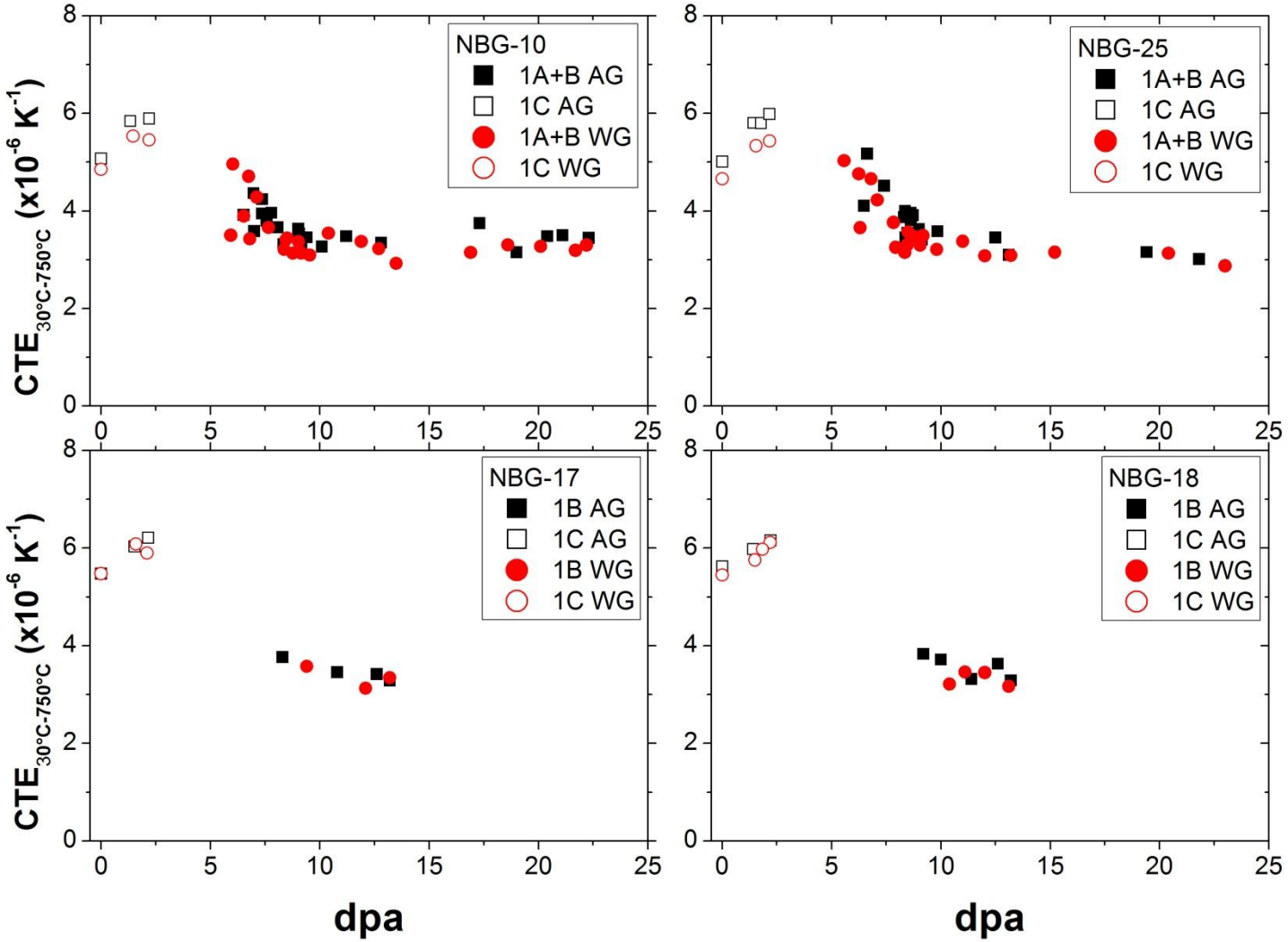

Figure 3-15 Coefficient of Thermal Expansion for SGL graphite grades irradiated at 750°C

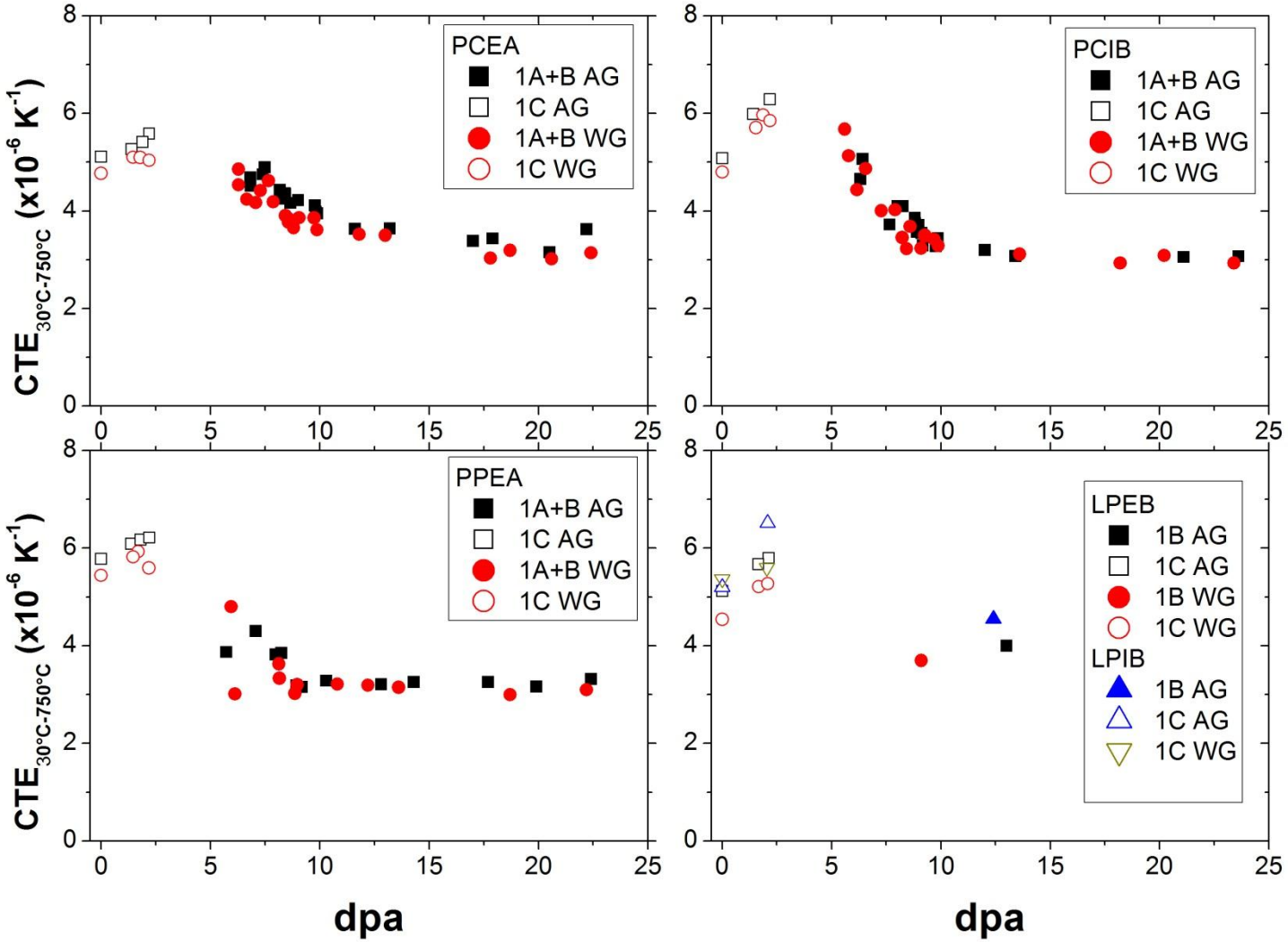

Figure 3-16 Coefficient of Thermal Expansion for GrafTech graphite grades irradiated at 750°C

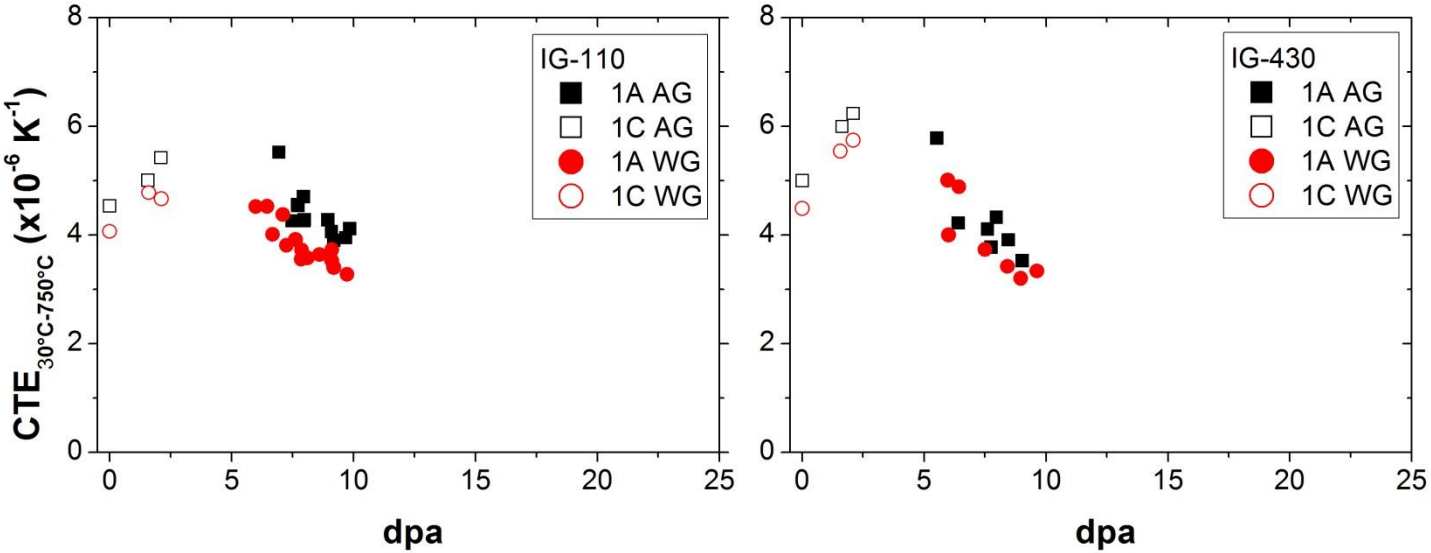

Figure 3-17 Coefficient of Thermal Expansion for Toyo Tanso graphite grades irradiated at 750°C

3.2.4 Thermal Diffusivity and Conductivity

Thermal diffusivity was measured at temperatures from room temperature up to irradiation temperature in steps of 100°C. Thermal conductivity was calculated from the measured thermal diffusivity, measured density, and tabulated specific heat (ASTM 781-96). It is assumed that the specific heat is not changed due to neutron irradiation.

Figure 3-18 to Figure 3-20 show the thermal diffusivity of the INNOGRAPH-1C specimens as well as those of the INNOGRAPH-1A and -1B specimens at 700°C. Figure 3-21 to Figure 3-23 show the thermal conductivity (k) of these specimens at 700°C. Included for both are the reference values for the graphite grade at 0 dpa. The thermal diffusivity and conductivity at temperatures other than 700°C are reported in Appendix C. For the graphs, presentation of data at 700°C is chosen because reference data for the INNOGRAPH-1A and -1B is available only up to 700°C.

The INNOGRAPH-1C data shows that for all graphite grades, the thermal diffusivity and conductivity drops rapidly within 1-2 dpa. After the initial drop, the diffusivity and conductivity remain almost constant over a wide dpa range, decreasing slowly towards high dpa values.

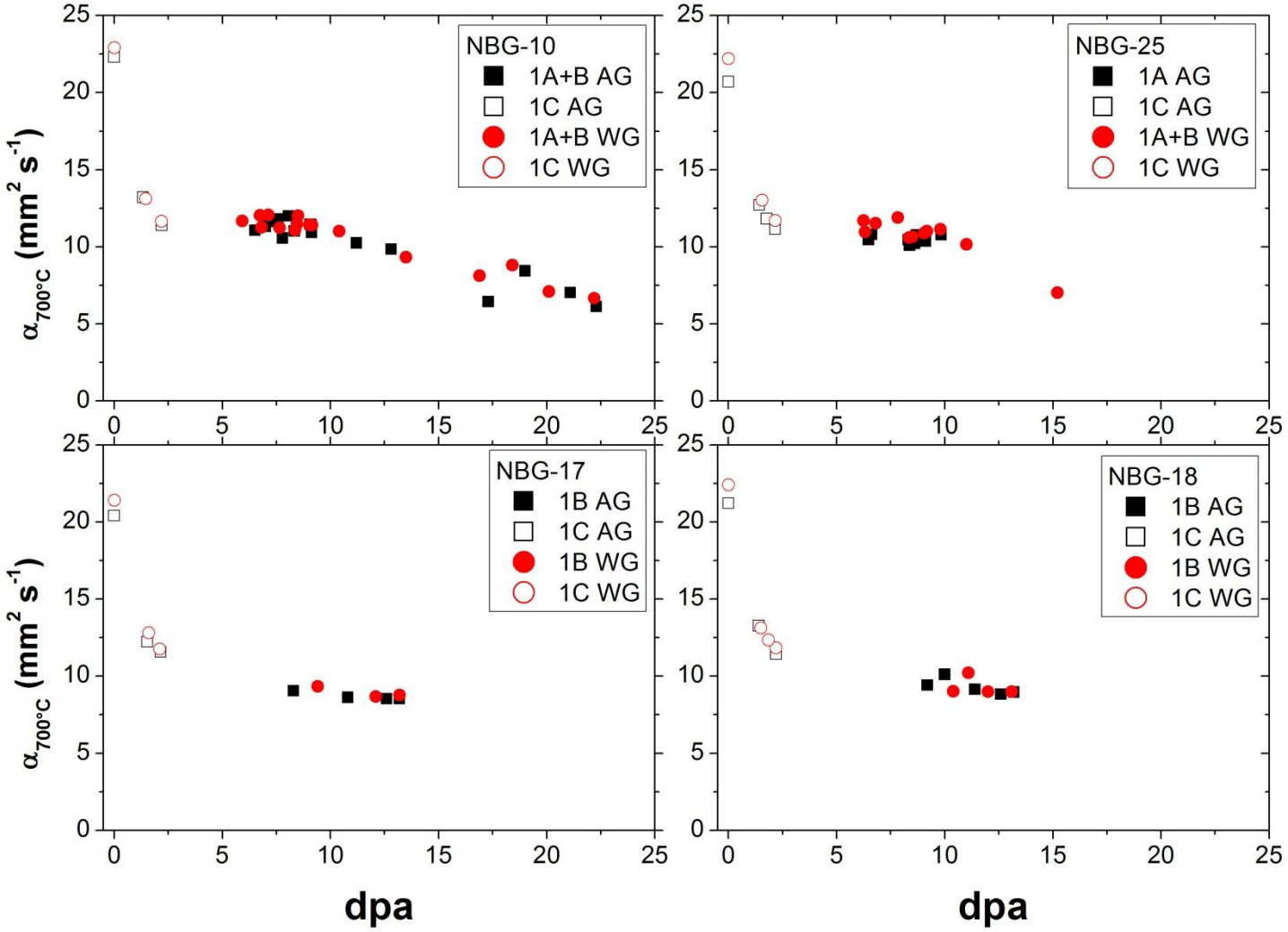

Figure 3-18 Thermal diffusivity at 700°C for SGL graphite grades irradiated at 750°C

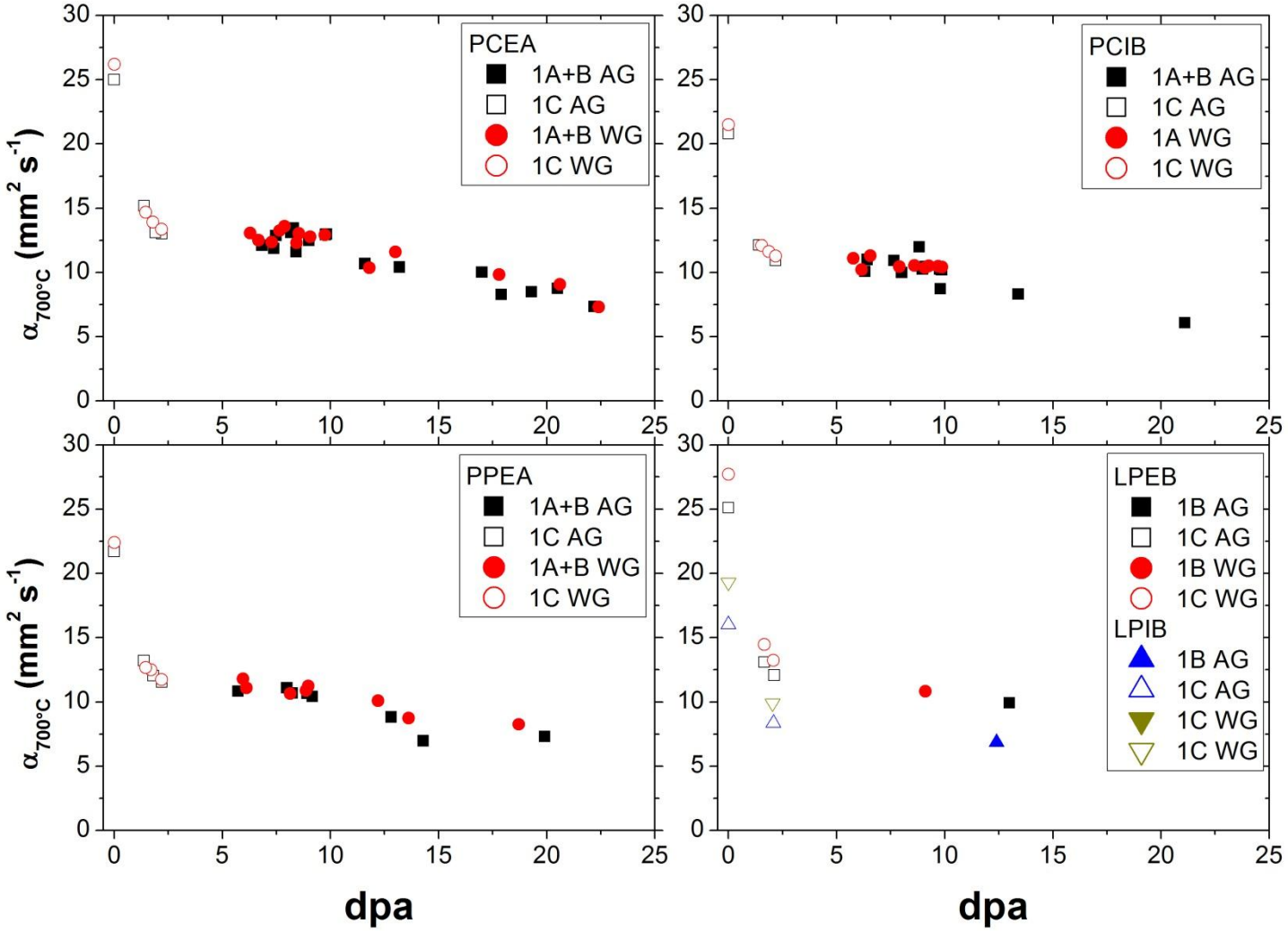

Figure 3-19 Thermal diffusivity at 700°C for Graftech graphite grades irradiated at 750°C

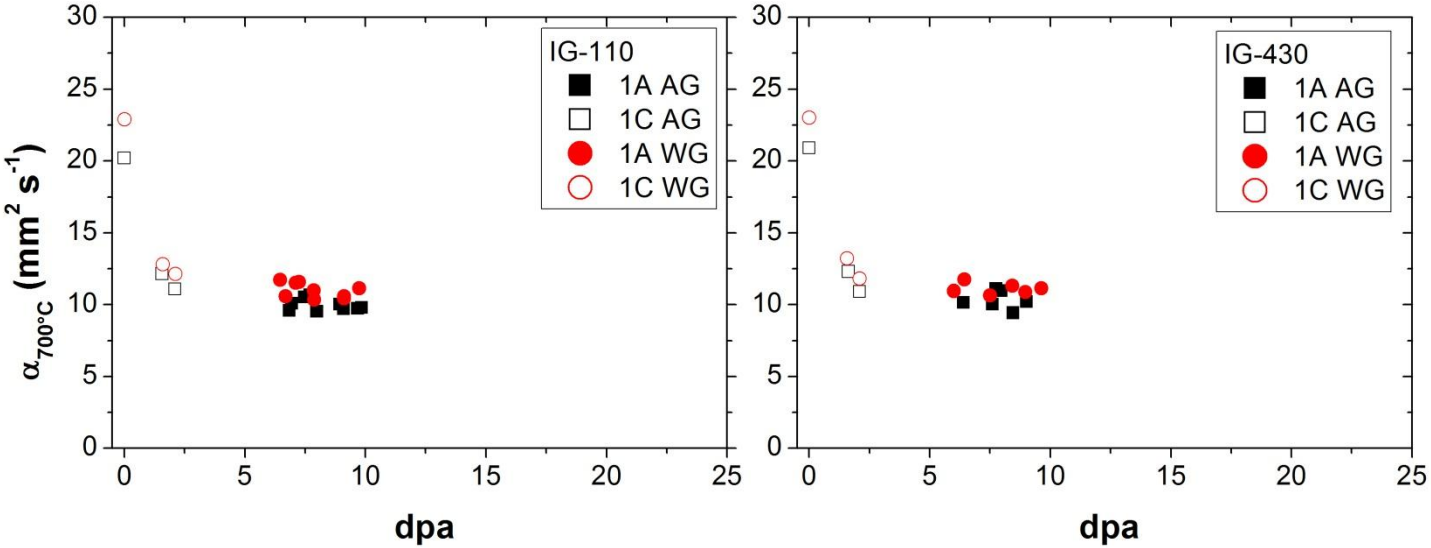

Figure 3-20 Thermal diffusivity at 700°C for Toyo Tanso graphite grades irradiated at 750°C

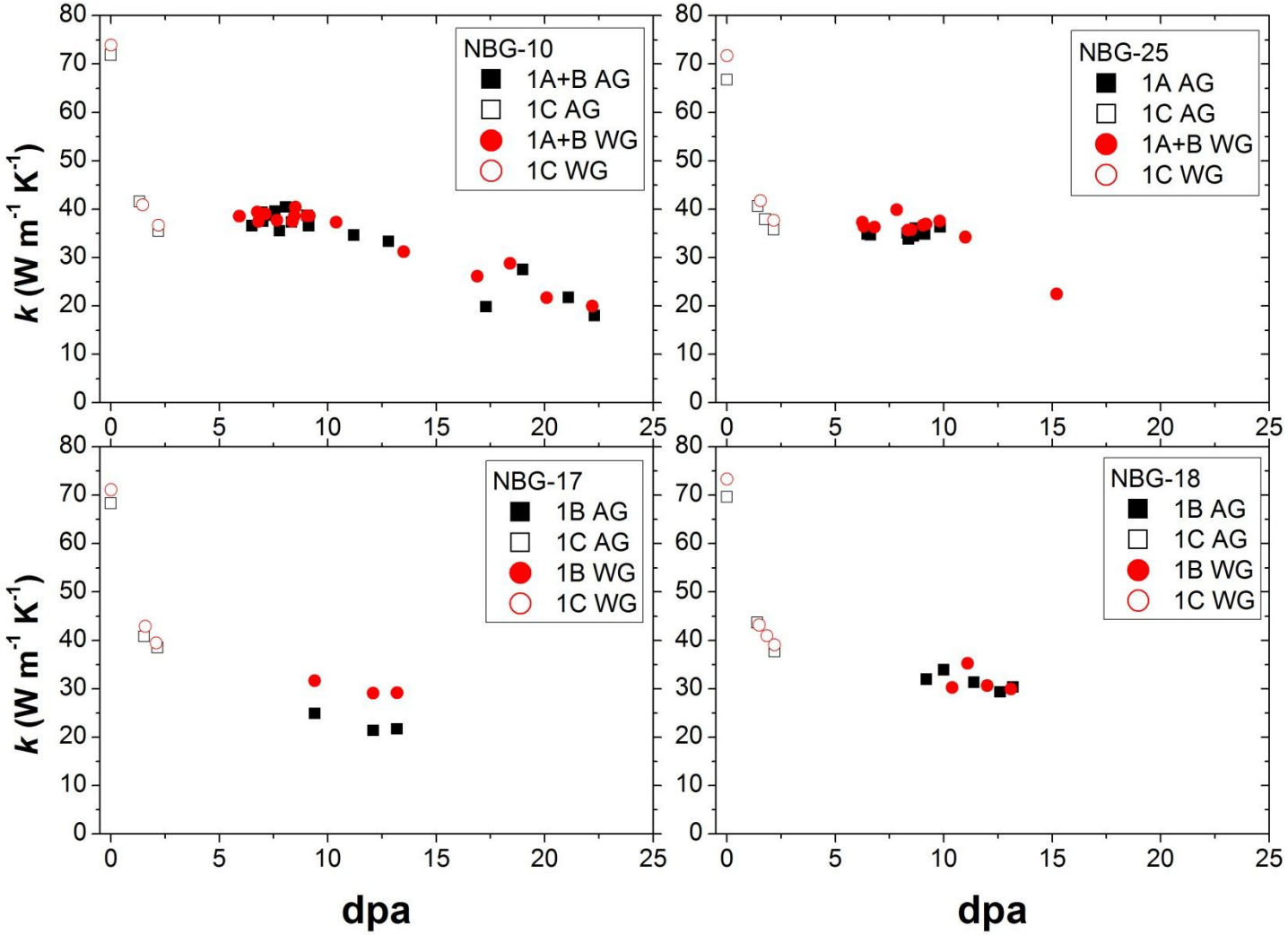

Figure 3-21 Thermal conductivity measured at 700°C for SGL graphite grades irradiated at 750°C

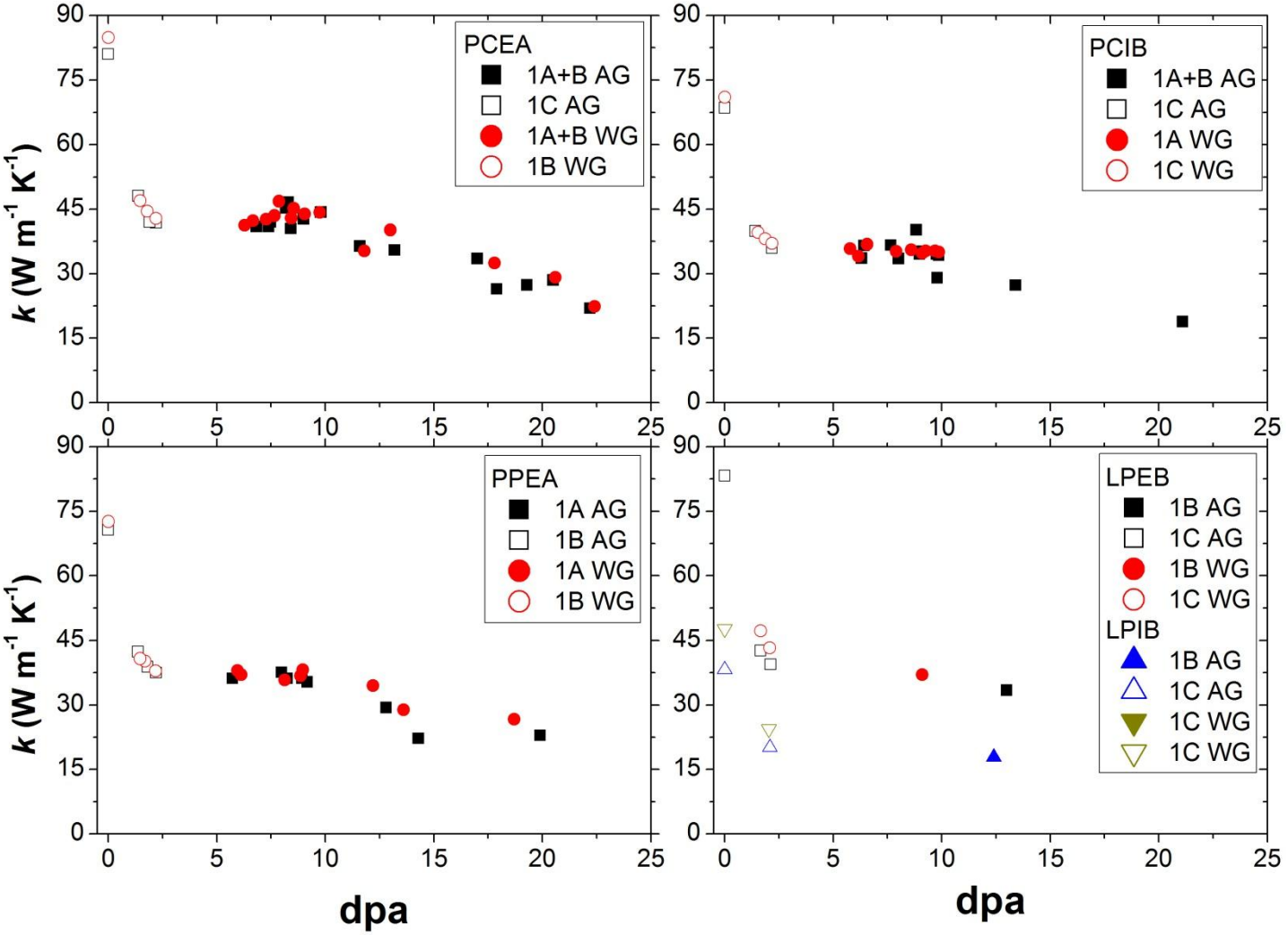

Figure 3-22 Thermal conductivity measured at 700°C for GrafTech graphite grades irradiated at 750°C

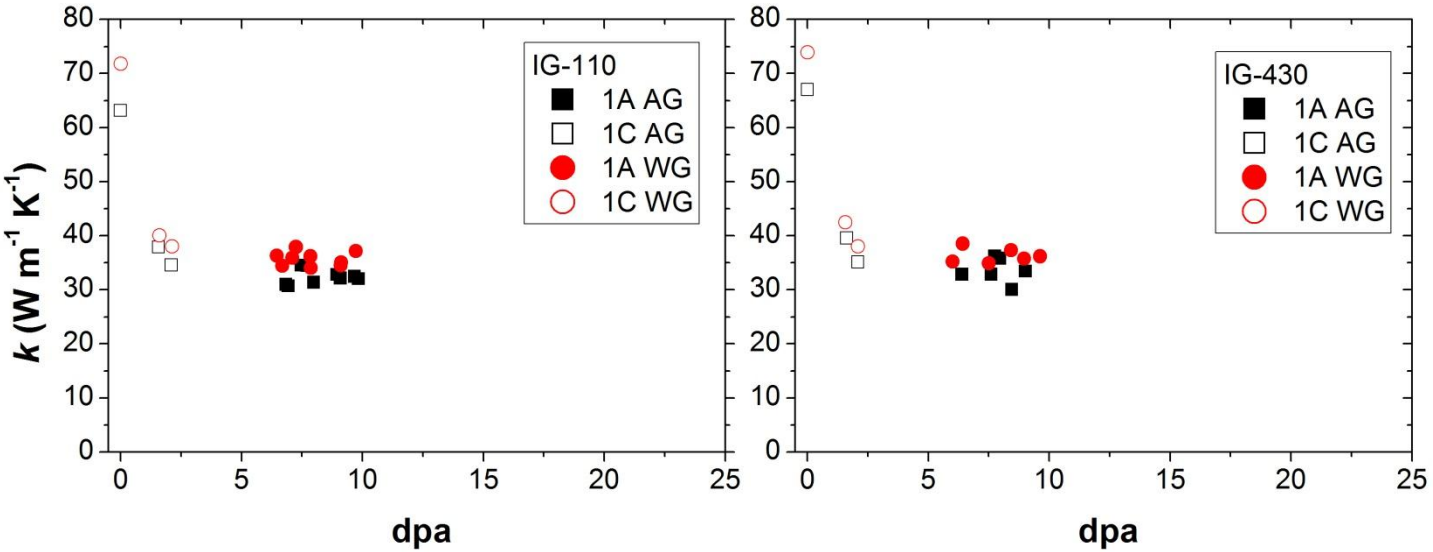

Figure 3-23 Thermal conductivity measured at 700°C for Toyo Tanso graphite grades irradiated at 750°C

4 Conclusions

Following the INNOGRAPH-1A and -1B experiments conducted in the HTR-M1 and RAPHAEL project and the “1B” PIE in the ARCHER project, the INNOGRAPH-1C experiment was conducted within the ARCHER project to add data to the gap between 0 and 5 dpa in the materials properties curves of modern HTR graphite grades.

The INNOGRAPH-1C irradiation with a nominal temperature of 750°was successfully completed. The INNOGRAPH-1C irradiation experiment was a low dose irradiation experiment with dpa ranging from 1 to 2.2 dpa.

Dimensional data show shrinkage to start at around 1 dpa for the graphite grades tested in this experiment. Dynamic Young’s modules increases between 0 and 1 dpa to a plateau at approximately 1.5 times the virgin value before it continues to increase at around 5 dpa. Thermal expansion data show the Coefficient of Thermal Expansion to increase before droping down to a stable level at 10 dpa that is lower than the virgin CTE value. Thermal diffusivity and conductivity drop down to a stable level two to three time slower than the virgin values within 1-2 dpa for the graphite grades tested in the INNOGRAPH programme.

References

[1] F. Schmalz et al., *Preliminary irradiation testing of selected graphite grades for HTR, Final report on HTR-M1 WP3*, NRG-20787/05.71179/P, 19 December 2005

[2] M.C.R. Heijna, *D41.12: High dose experiments at 750°C and 950°C - Full PIE of INNOGRAPH-IB and INNOGRAPH-2B*, NRG-22906/12.111097, 3 April 2012

[3] M.C.R. Heijna, *D41.13 Final Design Proposal Low Dose Irradiation*, NRG-22906/12.114053, 24 April 2012

List of tables

List of figures

Appendix A Dimensions, density and DYM data

Table 3 Measurement results of dimensions, mass, volume, density, and DYM for the INNOGRAPH-1C irradiation experiment

Sample						Post irradiation							Pre irradiation						
Specimen code	Grade	Location	Orientation	T_{irr} [°C]	calc. dpa	x	d	l	m	V	ρ	E	x	d	l	m	V	ρ	E
						[mm]	[mm]	[mm]	[g]	[mm³]	[g/cm³]	[GPa]	[mm]	[mm]	[mm]	[g]	[mm³]	[g/cm³]	[GPa]
0S00	NBG-10	heart	WG	750	1.5	7.698	7.992	5.955	0.5181	295.2	1.755	17.3	7.700	7.993	5.960	0.5186	295.5	1.755	11.7
0S01	NBG-10	heart	WG	750	1.8	7.699	7.980	5.951		294.3			7.698	7.983	5.959	0.5130	294.8	1.740	11.5
0S02	NBG-10	heart	WG	750	2.0	7.690	7.967	5.958		293.8			7.695	7.971	5.968	0.5171	294.6	1.755	11.7
0S03	NBG-10	heart	WG	750	2.2	7.687	7.958	5.955	0.5198	293.1	1.773	18.0	7.698	7.966	5.962	0.5205	294.1	1.770	12.0
0S04	NBG-10	heart	WG	750	2.1	7.686	7.952	5.950		292.5			7.691	7.961	5.960	0.5159	293.6	1.757	11.7
0S05	NBG-10	heart	WG	650	1.1								7.693	7.969	5.972	0.5181	294.6	1.759	11.9
0S25	NBG-10	heart	AG	750	1.3	7.696	8.004	5.961	0.5237	296.2	1.768	17.0	7.695	8.004	5.966	0.5241	296.4	1.769	11.6
0S26	NBG-10	heart	AG	750	2.0	7.687	7.991	5.961	0.0000	295.3			7.693	7.995	5.964	0.5232	295.7	1.769	12.0
0S27	NBG-10	heart	AG	750	2.2	7.686	7.983	5.959	0.5153	294.7	1.749	17.2	7.694	7.993	5.968	0.5159	295.8	1.744	11.4
0S28	NBG-10	heart	AG	750	2.1	7.685	7.985	5.951		294.4			7.693	7.992	5.957	0.5157	295.2	1.747	11.7
0S29	NBG-10	heart	AG	750	1.8	7.690	7.992	5.958		295.2			7.693	7.993	5.963	0.5181	295.6	1.753	11.5
0S30	NBG-10	heart	AG	650	0.9								7.693	7.974	5.958	0.5228	294.3	1.777	11.8
0S50	NBG-10	edge	WG	750	2.1	7.680	7.973	5.967		294.4			7.683	7.979	5.972	0.5268	295.0	1.786	12.5
0S51	NBG-10	edge	WG	750	2.1	7.686	7.992	5.961		295.3			7.691	7.998	5.967	0.5241	296.0	1.771	12.2
0S52	NBG-10	edge	WG	750	2.0	7.686	7.987	5.954		294.7			7.699	7.993	5.959	0.5267	295.5	1.782	12.3
0S53	NBG-10	edge	WG	750	2.0	7.686	7.981	5.958		294.5			7.692	7.987	5.967	0.5253	295.4	1.778	12.3
0S54	NBG-10	edge	WG	750	1.8	7.688	7.991	5.958		295.1			7.695	7.991	5.971	0.5250	295.9	1.774	12.4
0S55	NBG-10	edge	WG	750	1.4	7.692	7.984	5.947		294.2			7.693	7.984	5.948	0.5263	294.3	1.788	12.3
0S80	NBG-10	edge	AG	750	2.1	7.682	7.990	5.959		295.0			7.687	7.999	5.962	0.5269	295.7	1.782	12.2
0S82	NBG-10	edge	AG	650	1.3								7.685	7.990	5.944	0.5262	294.3	1.788	12.4
0S85	NBG-10	edge	AG	750	1.5	7.700	8.007	5.947		295.6			7.702	8.008	5.948	0.5266	295.8	1.780	12.1
0S87	NBG-10	edge	AG	750	2.0	7.690	7.985	5.943		294.1			7.701	7.993	5.949	0.5246	295.0	1.778	12.1
0S88	NBG-10	edge	AG	750	2.1	7.690	7.984	5.947		294.2			7.698	7.990	5.951	0.5263	294.9	1.785	12.1
0S89	NBG-10	edge	AG	750	2.0	7.687	7.980	5.959		294.5			7.694	7.985	5.962	0.5252	295.1	1.780	11.9
0T00	IG-110	heart	AG	750	1.7	7.702	7.976	5.919		292.6			7.710	7.985	5.928	0.5126	293.7	1.745	9.4
0T01	IG-110	heart	AG	750	2.1	7.714	7.967	5.922	0.5131	292.4	1.755	16.3	7.712	7.983	5.933	0.5133	293.8	1.747	9.3
0T02	IG-110	heart	AG	750	2.0	7.695	7.957	5.927		291.7			7.708	7.974	5.939	0.5174	293.6	1.763	9.3
0T03	IG-110	heart	AG	750	1.6	7.707	7.966	5.932	0.5132	292.7	1.753	16.0	7.714	7.977	5.940	0.5138	293.9	1.749	9.7
0T12	IG-110	heart	WG	750	1.8	7.683	7.941	5.942		291.4			7.688	7.948	5.954	0.5106	292.4	1.746	10.2
0T13	IG-110	heart	WG	750	1.6	7.691	7.953	5.938	0.5134	292.0	1.758	17.4	7.696	7.961	5.948	0.5138	293.0	1.753	10.5
0T14	IG-110	heart	WG	750	2.1	7.703	7.982	5.906	0.5153	292.3	1.763	17.7	7.710	7.994	5.920	0.5164	293.8	1.758	10.4
0T15	IG-110	heart	WG	750	2.1	7.703	7.980	5.919		292.8			7.712	7.990	5.934	0.5165	294.3	1.755	10.5
0T24	IG-110	edge	AG	750	1.6	7.706	7.970	5.939		293.3			7.712	7.977	5.947	0.5159	294.2	1.754	9.0
0T25	IG-110	edge	AG	750	2.0	7.702	7.964	5.917		291.8			7.715	7.975	5.929	0.5150	293.2	1.756	9.0
0T26	IG-110	edge	AG	650	1.0								7.706	7.951	5.948	0.5134	292.7	1.754	9.1
0T36	IG-110	edge	WG	750	2.0	7.696	7.987	5.911		292.7			7.704	7.996	5.939	0.5172	294.8	1.755	10.4
0T37	IG-110	edge	WG	750	1.6	7.703	7.986	5.914		292.9			7.706	7.991	5.926	0.5164	293.9	1.757	10.3
0T38	IG-110	edge	WG	650	1.2								7.705	7.981	5.931	0.5154	293.5	1.756	10.2
0T57	IG-430	heart	AG	750	1.6	7.691	7.986	5.948	0.5322	294.4	1.808	15.9	7.691	7.990	5.953	0.5330	294.8	1.808	10.3
0T58	IG-430	heart	AG	750	2.1	7.691	7.977	5.954	0.5312	294.2	1.806	16.7	7.691	7.983	5.960	0.5316	294.8	1.803	10.4
0T59	IG-430	heart	AG	750	2.0	7.675	7.973	5.942		293.0			7.682	7.981	5.953	0.5318	294.2	1.807	10.7
0T60	IG-430	heart	AG	750	1.7	7.682	7.976	5.957		294.1			7.687	7.982	5.965	0.5337	294.9	1.809	11.0
0T61	IG-430	heart	AG	650	1.0								7.690	7.983	5.957	0.5327	294.6	1.808	10.9
0T62	IG-430	heart	WG	750	2.1	7.686	7.956	5.963	0.5312	293.4	1.811	17.1	7.690	7.963	5.970	0.5319	294.1	1.808	10.9
0T63	IG-430	heart	WG	750	2.0	7.698	7.976	5.951		294.1			7.697	7.981	5.963	0.5306	294.9	1.799	11.4
0T64	IG-430	heart	WG	750	1.6	7.698	7.978	5.959	0.5322	294.6	1.806	17.8	7.699	7.984	5.968	0.5329	295.4	1.804	11.5
0T65	IG-430	heart	WG	650	1.2								7.697	7.984	5.956	0.5322	294.8	1.806	11.0
0T74	IG-430	edge	AG	750	2.0	7.697	7.965	5.961		293.9			7.701	7.970	5.961	0.5328	294.3	1.810	10.1
0T75	IG-430	edge	AG	750	1.6	7.699	7.969	5.964		294.3			7.700	7.970	5.968	0.5336	294.6	1.811	10.2
0T86	IG-430	edge	WG	750	1.6	7.671	7.968	5.975		294.3			7.671	7.979	5.979	0.5360	295.2	1.816	11.4
0T87	IG-430	edge	WG	750	2.0	7.679	7.971	5.963		294.1			7.678	7.983	5.970	0.5378	295.1	1.823	11.2
0U05	PCEA	heart	WG	750	1.5	7.687	7.978	5.925	0.5256	292.7	1.796	17.2	7.686	7.983	5.935	0.5260	293.5	1.792	11.2
0U06	PCEA	heart	WG	750	1.9	7.694	7.977	5.935		293.3			7.689	7.984	5.946	0.5261	294.1	1.789	11.3
0U07	PCEA	heart	WG	750	1.8	7.687	7.978	5.940	0.5275	293.4	1.798	18.3	7.696	7.990	5.954	0.5278	295.0	1.789	11.3
0U08	PCEA	heart	WG	750	2.2	7.690	7.978	5.930	0.5278	293.0	1.802	18.3	7.699	7.992	5.948	0.5283	294.8	1.792	11.4
0U12	PCEA	heart	WG	750	2.1	7.688	7.970	5.910		291.6			7.697	7.982	5.927	0.5251	293.3	1.791	11.1
0U13	PCEA	heart	WG	750	1.9	7.686	7.966	5.901		290.9			7.695	7.974	5.915	0.5235	292.1	1.792	11.3
0U26	PCEA	heart	AG	750	1.8	7.683	7.972	5.930		292.6			7.693	7.983	5.938	0.5265	293.8	1.792	10.9
0U27	PCEA	heart	AG	650	1.3								7.691	7.984	5.946	0.5282	294.2	1.795	11.0
0U30	PCEA	heart	AG	750	1.4	7.702	7.984	5.937	0.5234	293.9	1.781	16.4	7.704	7.986	5.945	0.5242	294.4	1.780	10.7
0U31	PCEA	heart	AG	750	2.0	7.692	7.975	5.960		294.4			7.700	7.983	5.967	0.5270	295.3	1.784	10.8
0U32	PCEA	heart	AG	750	2.2	7.686	7.971	5.910	0.5263	291.5	1.805	17.4	7.699	7.981	5.926	0.5267	293.1	1.797	10.9
0U33	PCEA	heart	AG	750	2.1	7.688	7.968	5.931		292.5			7.699	7.978	5.944	0.5262	293.9	1.791	10.9
0U34	PCEA	heart	AG	750	1.9	7.685	7.970	5.918	0.5248	291.9	1.798	17.7	7.697	7.978	5.928	0.5252	293.1	1.792	10.8
0U55	PCEA	edge	WG	750	1.5	7.690	7.986	5.912		292.6			7.695	7.986	5.917	0.5343	292.9	1.824	12.2
0U56	PCEA	edge	WG	750	2.0	7.689	7.977	5.918		292.4			7.696	7.987	5.930	0.5358	293.6	1.825	12.4
0U57	PCEA	edge	WG	750	2.1	7.685	7.975	5.895		291.0			7.697	7.985	5.912	0.5339	292.6	1.825	12.6
0U58	PCEA	edge	WG	750	2.1	7.689	7.979	5.905		291.8			7.696	7.985	5.916	0.5357	292.8	1.829	12.5
0U62	PCEA	edge	WG	750	1.8	7.691	7.979	5.916		292.4			7.696	7.984	5.924	0.5338	293.2	1.821	12.3
0U63	PCEA	edge	WG	650	1.2								7.698	7.982	5.923	0.5338	293.0	1.822	11.9
0U77	PCEA	edge	AG	750	1.5	7.694	7.985	5.924		293.2			7.699	7.986	5.929	0.5367	293.6	1.828	11.5
0U78	PCEA	edge	AG	650	0.9								7.697	7.986	5.917	0.5367	293.0	1.832	11.6
0U80	PCEA	edge	AG	750	1.8	7.699	7.985	5.942		294.2			7.702	7.990	5.950	0.5390	294.9	1.828	11.6
0U81	PCEA	edge	AG	750	1.9	7.691	7.985	5.926		293.2			7.699	7.993	5.936	0.5393	294.3	1.832	11.5
0U82	PCEA	edge	AG	750	2.1	7.691	7.985	5.915		292.7			7.698	7.995	5.930	0.5386	294.1	1.831	11.5
0U83	PCEA	edge	AG	750	2.0	7.687	7.983	5.922		292.8			7.698	7.992	5.929	0.5376	293.9	1.829	11.6
1S00	NBG-17	heart	WG	750	1.7	7.734	7.948	5.959		293.4			7.730	7.950	5.962	0.5525	293.7	1.881	14.2
1S01	NBG-17	heart	WG	750	1.6	7.718	7.961	5.954	0.5525	293.7	1.881	21.4	7.719	7.961	5.956	0.5528	293.8	1.881	14.3
1S02	NBG-17	heart	WG	750	2.1	7.704	7.965	5.961	0.5535	294.0	1.883	21.7	7.707	7.970	5.968	0.5542	294.7	1.880	14.2
1S03	NBG-17	heart	WG	750	2.1	7.693	7.974	5.943		293.5			7.698	7.981	5.949	0.5521	294.2	1.876	14.3
1S04	NBG-17	heart	WG	750	1.9	7.685	7.983	5.960		294.7			7.688	7.987	5.977	0.5537	295.8	1.872	14.1
1S05	NBG-17	heart	WG	650	1.3								7.680	7.991	5.955	0.5523	294.8	1.873	14.1
1S06	NBG-17	heart	WG	650	1.0								7.673	7.995	5.960	0.5514	295.1	1.868	13.9
1S25	NBG-17	heart	AG	750	1.8	7.710	7.976	5.967		295.1			7.717	7.982	5.972	0.5539	295.8	1.872	13.5
1S26	NBG-17	heart	AG	750	2.0	7.706	7.971	5.946		293.7			7.714	7.980	5.953	0.5530	294.7	1.876	13.5
1S27	NBG-17	heart	AG	750	2.2	7.725	7.989	5.960	0.5538	295.7	1.873	20.6	7.730	7.996	5.966	0.5543	296.5	1.869	13.5
1S28	NBG-17	heart	AG	750	1.7	7.718	7.969	5.949		293.9			7.723	7.973	5.959	0.5537	294.7	1.879	13.7
1S29	NBG-17	heart	AG	750	1.5	7.715	7.973	5.958	0.5526	294.5	1.876	20.2	7.717	7.976	5.965	0.5529	295.1	1.873	13.5
1S55	NBG-17	edge	WG	750	1.9	7.712	7.981	5.951		294.6			7.718	7.987	5.960	0.5390	295.5	1.824	12.9
1S56	NBG-17	edge	WG	750	2.1	7.707	7.980	5.958		294.9			7.716	7.986	5.967	0.5422	295.8	1.833	12.9
1S57	NBG-17	edge	WG	750	1.6	7.714	7.985	5.963		295.4			7.715	7.986	5.968	0.5378	295.8	1.818	12.5
1S79	NBG-17	edge	AG	750	1.6	7.719	7.982	5.967		295.6			7.722	7.984	5.967	0.5219	295.7	1.765	10.4
1S80	NBG-17	edge	AG	750	2.1	7.714	7.976	5.933		293.4			7.724	7.984	5.940	0.5323	294.4	1.808	11.7
1S81	NBG-17	edge	AG	750	1.8	7.715	7.965	5.951		293.7			7.721	7.972	5.954	0.5143	294.4	1.747	10.5

Table 3 continued

Sample						Post irradiation							Pre irradiation						
Specimen code	Grade	Location	Orientation	T_{irr} [°C]	calc. dpa	x	d	l	m	V	ρ	E	x	d	l	m	V	ρ	E
						[mm]	[mm]	[mm]	[g]	[mm^3]	[g/cm^3]	[GPa]	[mm]	[mm]	[mm]	[g]	[mm^3]	[g/cm^3]	[GPa]
1U05	PCIB	heart	AG	750	1.4	7.712	7.981	5.969	0.5458	295.5	1.847	18.5	7.715	7.983	5.970	0.5463	295.7	1.847	11.7
1U06	PCIB	heart	AG	750	2.1	7.705	7.975	5.947		293.9			7.713	7.983	5.950	0.5424	294.7	1.841	11.3
1U07	PCIB	heart	AG	750	2.2	7.705	7.975	5.954	0.5440	294.3	1.849	19.0	7.714	7.983	5.958	0.5447	295.1	1.846	11.5
1U08	PCIB	heart	AG	750	1.7	7.704	7.975	5.961		294.6			7.712	7.982	5.963	0.5451	295.2	1.846	11.4
1U09	PCIB	heart	AG	650	1.1								7.710	7.984	5.959	0.5429	295.1	1.840	11.4
1U25	PCIB	heart	WG	750	1.5	7.706	7.982	5.976	0.5439	295.9	1.838	19.1	7.707	7.983	5.977	0.5444	295.9	1.840	12.0
1U26	PCIB	heart	WG	750	1.9	7.704	7.977	5.959	0.5424	294.6	1.841	19.4	7.707	7.981	5.964	0.5429	295.2	1.839	11.9
1U27	PCIB	heart	WG	750	2.0	7.701	7.966	5.951		293.6			7.707	7.975	5.959	0.5414	294.6	1.838	11.9
1U28	PCIB	heart	WG	750	2.2	7.700	7.963	5.962	0.5431	293.9	1.848	19.8	7.706	7.970	5.976	0.5436	295.1	1.842	12.0
1U29	PCIB	heart	WG	750	1.7	7.705	7.966	5.955		293.8			7.708	7.970	5.958	0.5430	294.3	1.845	12.0
1U31	PCIB	heart	WG	650	1.2								7.709	7.988	5.959	0.5426	295.3	1.837	11.8
1U32	PCIB	heart	WG	650	1.0								7.711	7.985	5.943	0.5409	294.5	1.837	11.8
1U56	PCIB	edge	AG	750	1.9	7.707	7.977	5.943		293.9			7.717	7.983	5.947	0.5424	294.6	1.841	11.6
1U57	PCIB	edge	AG	750	2.1	7.704	7.977	5.948		294.1			7.712	7.983	5.952	0.5434	294.8	1.843	11.6
1U58	PCIB	edge	AG	750	1.5	7.707	7.980	5.945		294.2			7.710	7.983	5.945	0.5441	294.4	1.848	11.6
1U81	PCIB	edge	WG	750	2.1	7.708	7.982	5.948		294.5			7.712	7.988	5.953	0.5440	295.1	1.843	12.0
1U82	PCIB	edge	WG	750	1.9	7.711	7.984	5.954		294.9			7.711	7.988	5.958	0.5447	295.3	1.844	11.9
1U83	PCIB	edge	WG	750	1.5	7.711	7.986	5.951		294.9			7.711	7.988	5.954	0.5443	295.1	1.844	12.0
2S00	NBG-18	heart	WG	750	1.5	7.657	7.981	5.961	0.5443	294.2	1.850	21.0	7.659	7.982	5.965	0.5447	294.4	1.850	14.9
2S01	NBG-18	heart	WG	750	2.2	7.666	7.983	5.933	0.5442	293.0	1.857	21.3	7.673	7.992	5.940	0.5449	294.0	1.853	14.6
2S02	NBG-18	heart	WG	750	2.1	7.680	7.997	5.907		292.7			7.686	8.006	5.918	0.5463	293.9	1.859	14.5
2S03	NBG-18	heart	WG	750	2.0	7.694	8.001	5.911		293.4			7.702	8.008	5.920	0.5497	294.4	1.867	14.4
2S04	NBG-18	heart	WG	750	1.7	7.709	8.000	5.923		294.3			7.712	8.004	5.935	0.5399	295.1	1.829	13.8
2S05	NBG-18	heart	WG	750	1.8	7.712	7.987	5.924	0.5468	293.6	1.862	21.2	7.717	7.992	5.932	0.5473	294.4	1.859	14.5
2S25	NBG-18	heart	AG	750	1.4	7.708	7.986	5.951	0.5460	294.8	1.852	19.8	7.710	7.985	5.951	0.5465	294.8	1.854	13.9
2S26	NBG-18	heart	AG	750	1.9	7.706	7.982	5.946		294.3			7.709	7.988	5.948	0.5469	294.8	1.855	13.8
2S27	NBG-18	heart	AG	750	2.2	7.697	7.981	5.938	0.5456	293.7	1.858	20.0	7.705	7.988	5.943	0.5461	294.5	1.854	13.5
2S28	NBG-18	heart	AG	750	2.0	7.699	7.978	5.931		293.2			7.707	7.988	5.945	0.5473	294.7	1.857	13.7
2S29	NBG-18	heart	AG	750	2.0	7.700	7.982	5.943		294.1			7.706	7.988	5.948	0.5445	294.7	1.847	13.6
2S30	NBG-18	heart	AG	650	0.8								7.709	7.989	5.938	0.5431	294.3	1.845	13.4
2S50	NBG-18	edge	WG	750	1.5	7.705	7.984	5.960		295.1			7.706	7.986	5.964	0.5356	295.5	1.813	13.4
2S51	NBG-18	edge	WG	750	1.9	7.709	7.996	5.932		294.5			7.715	8.001	5.939	0.5385	295.2	1.824	13.4
2S52	NBG-18	edge	WG	750	2.1	7.712	7.993	5.946		295.0			7.720	8.001	5.955	0.5365	296.1	1.812	13.4
2S53	NBG-18	edge	WG	750	1.7	7.718	7.991	5.949		295.2			7.722	7.997	5.957	0.5382	296.0	1.818	13.5
2S54	NBG-18	edge	WG	650	1.2								7.721	7.995	5.952	0.5356	295.6	1.812	13.1
2S55	NBG-18	edge	WG	650	1.0								7.721	7.992	5.958	0.5381	295.8	1.819	13.4
2S75	NBG-18	edge	AG	750	2.1	7.698	7.978	5.942		293.8			7.708	7.989	5.949	0.5346	294.9	1.813	12.5
2S77	NBG-18	edge	AG	750	2.0	7.699	7.981	5.945		294.1			7.706	7.988	5.951	0.5400	294.9	1.831	13.2
2S79	NBG-18	edge	AG	750	2.0	7.695	7.984	5.959		294.9			7.705	7.996	5.967	0.5349	296.1	1.806	12.7
2S81	NBG-18	edge	AG	750	1.9	7.699	7.986	5.964		295.3			7.706	7.994	5.969	0.5368	296.1	1.813	12.7
2S83	NBG-18	edge	AG	750	1.5	7.704	7.972	5.963		294.5			7.707	7.974	5.966	0.5335	294.9	1.809	12.5
2U00	PPEA	heart	WG	750	2.2	7.684	7.977	5.955	0.5345	294.1	1.817	19.1	7.697	7.991	5.969	0.5352	295.8	1.809	13.7
2U01	PPEA	heart	WG	750	2.0	7.690	7.978	5.950		294.0			7.699	7.990	5.966	0.5346	295.6	1.808	13.5
2U02	PPEA	heart	WG	750	1.8	7.691	7.982	5.944		293.9			7.700	7.991	5.952	0.5355	295.0	1.815	13.4
2U03	PPEA	heart	WG	750	1.7	7.693	7.982	5.963	0.5336	294.9	1.809	19.1	7.700	7.991	5.962	0.5341	295.5	1.808	13.2
2U04	PPEA	heart	WG	750	1.5	7.699	7.982	5.948	0.5327	294.3	1.810	19.1	7.704	7.989	5.957	0.5335	295.2	1.807	13.3
2U06	PPEA	heart	WG	650	1.0								7.698	7.990	5.951	0.5331	294.9	1.808	13.2
2U07	PPEA	heart	WG	650	1.3								7.697	7.987	5.957	0.5344	295.0	1.812	13.3
2U25	PPEA	heart	AG	750	1.4	7.691	7.983	5.971	0.5328	295.4	1.804	18.7	7.698	7.989	5.973	0.5340	295.9	1.804	13.4
2U26	PPEA	heart	AG	750	2.0	7.689	7.979	5.947		293.9			7.700	7.989	5.950	0.5326	294.8	1.806	13.4
2U27	PPEA	heart	AG	750	1.8	7.689	7.977	5.948	0.5331	293.8	1.814	19.6	7.701	7.989	5.955	0.5339	295.1	1.809	13.4
2U28	PPEA	heart	AG	750	2.2	7.689	7.975	5.939	0.5354	293.3	1.826	19.9	7.702	7.990	5.949	0.5364	294.9	1.819	13.6
2U32	PPEA	heart	AG	750	2.1	7.689	7.982	5.927		293.1			7.702	7.995	5.937	0.5348	294.6	1.815	13.4
2U33	PPEA	heart	AG	650	1.1								7.707	7.995	5.945	0.5355	295.0	1.815	13.4
2U55	PPEA	edge	WG	750	1.5	7.698	7.981	5.944		294.0			7.704	7.985	5.944	0.5388	294.4	1.830	14.0
2U56	PPEA	edge	WG	750	2.0	7.693	7.974	5.941		293.4			7.702	7.985	5.953	0.5380	294.8	1.825	14.2
2U57	PPEA	edge	WG	750	1.8	7.694	7.977	5.949		294.0			7.703	7.985	5.956	0.5394	295.0	1.829	14.2
2U58	PPEA	edge	WG	750	2.1	7.692	7.976	5.942		293.5			7.701	7.986	5.952	0.5383	294.8	1.826	14.1
2U62	PPEA	edge	WG	750	2.0	7.688	7.973	5.944		293.4			7.700	7.985	5.956	0.5353	294.9	1.815	13.9
2U63	PPEA	edge	WG	750	1.9	7.687	7.973	5.940		293.2			7.697	7.985	5.953	0.5348	294.7	1.815	14.0
2U75	PPEA	edge	AG	750	2.1	7.696	7.971	5.940		293.2			7.709	7.983	5.951	0.5384	294.7	1.827	13.8
2U76	PPEA	edge	AG	750	2.0	7.694	7.972	5.942		293.4			7.705	7.982	5.950	0.5395	294.5	1.832	13.7
2U77	PPEA	edge	AG	750	2.0	7.690	7.969	5.951		293.5			7.703	7.983	5.959	0.5386	295.0	1.826	13.8
2U78	PPEA	edge	AG	750	1.9	7.687	7.971	5.940		293.1			7.699	7.984	5.948	0.5384	294.4	1.829	13.5
2U82	PPEA	edge	AG	750	1.8	7.692	7.972	5.955		293.9			7.703	7.982	5.960	0.5408	295.0	1.833	13.6
2U83	PPEA	edge	AG	750	1.5	7.696	7.976	5.963		294.6			7.703	7.982	5.966	0.5413	295.3	1.833	13.5
3S00	NBG-25	heart	AG	750	1.4	7.698	7.983	5.965	0.5311	295.2	1.799	16.5	7.706	7.991	5.967	0.5319	295.9	1.798	10.7
3S01	NBG-25	heart	AG	750	1.8	7.693	7.975	5.953	0.5307	294.0	1.805	17.3	7.703	7.987	5.958	0.5312	295.1	1.800	10.9
3S02	NBG-25	heart	AG	750	2.1	7.690	7.967	5.947		293.2			7.707	7.983	5.953	0.5307	294.7	1.801	10.7
3S03	NBG-25	heart	AG	750	2.1	7.692	7.962	5.951		293.2			7.705	7.977	5.959	0.5309	294.7	1.802	10.9
3S04	NBG-25	heart	AG	750	2.2	7.690	7.955	5.962	0.5295	293.3	1.805	17.4	7.706	7.974	5.975	0.5304	295.3	1.796	10.9
3S35	NBG-25	heart	WG	750	1.5	7.712	7.989	5.952	0.5328	295.1	1.805	17.8	7.715	7.995	5.957	0.5332	295.8	1.803	11.6
3S36	NBG-25	heart	WG	750	1.9	7.705	7.980	5.953		294.5			7.714	7.992	5.964	0.5330	295.9	1.801	11.5
3S37	NBG-25	heart	WG	750	2.2	7.704	7.976	5.948	0.5321	294.1	1.809	18.2	7.714	7.990	5.959	0.5324	295.6	1.801	11.4
3S38	NBG-25	heart	WG	750	2.0	7.699	7.966	5.941		293.0			7.711	7.983	5.953	0.5311	294.9	1.801	11.3
3S70	NBG-25	edge	AG	750	1.6	7.659	7.961	5.928		291.4			7.668	7.973	5.941	0.5275	292.9	1.801	10.8
3S71	NBG-25	edge	AG	750	2.2	7.656	7.948	5.938		291.1			7.670	7.967	5.945	0.5279	292.8	1.803	10.8
3S72	NBG-25	edge	AG	750	1.9	7.679	7.987	5.902		291.9			7.692	8.002	5.908	0.5297	293.3	1.806	10.8
3S73	NBG-25	edge	AG	650	1.3								7.697	8.000	5.910	0.5298	293.4	1.806	10.6
3S74	NBG-25	edge	AG	650	0.9								7.702	7.996	5.912	0.5293	293.4	1.804	10.6
3S86	NBG-25	edge	WG	750	2.1	7.706	7.958	5.944		292.8			7.710	7.970	5.955	0.5319	294.2	1.808	11.6
3S87	NBG-25	edge	WG	750	1.9	7.702	7.961	5.930		292.2			7.710	7.970	5.940	0.5308	293.4	1.809	11.4
3S88	NBG-25	edge	WG	750	1.5	7.708	7.970	5.939		293.3			7.711	7.978	5.943	0.5315	294.0	1.808	11.5
3U00	TS5324	heart	AG	750	1.7	7.720	8.035	6.019		301.2			7.716	8.033	6.010	0.5578	300.6	1.856	14.1
3U01	TS5324	heart	AG	750	1.9	7.713	7.977	6.006	0.5495	297.1	1.850	20.0	7.713	7.980	6.010	0.5502	297.5	1.849	14.1
3U02	TS5324	heart	AG	750	2.0	7.698	8.045	6.005		300.7			7.698	8.045	6.007	0.5554	300.8	1.847	14.1
3U03	TS5324	heart	AG	750	2.2	7.706	7.979	6.010		297.3			7.705	7.975	6.001	0.5500	296.7	1.854	14.3
3U04	TS5324	heart	AG	650	0.8								7.686	7.997	5.985	0.5453	296.7	1.838	13.9
3U30	TS5328	heart	AG	750	1.7	7.712	8.061	6.018		302.5			7.710	8.071	6.014	0.5160	302.8	1.704	8.4
3U31	TS5328	heart	AG	750	2.0	7.687	8.054	5.977		299.6			7.699	8.069	5.983	0.5124	300.9	1.703	8.4
3U32	TS5328	heart	AG	750	2.1	7.683	8.016	5.992		298.1			7.692	8.030	5.992	0.5091	299.1	1.702	8.9
3U33	TS5328	heart	AG	750	1.9	7.697	8.053	6.017	0.5145	301.7	1.705	13.2	7.706	8.067	6.016	0.5152	302.6	1.703	8.1
3U34	TS5328	heart	AG	650	0.9								7.694	8.045	5.985	0.5088	299.6	1.698	8.0
4S06	coated NBG-17	heart	AG	750	1.7								7.664	7.980	5.872	0.5255	289.8	1.813	14.1
4S07	coated NBG-17	heart	AG	750	2.1								7.665	7.986	5.432	0.4891	268.4	1.822	14.2
4S08	coated NBG-17	heart	AG	750	1.8								7.659	7.952	5.415	0.4828	265.7	1.817	13.4
4S09	coated NBG-17	heart	AG	750	1.9								7.666	8.008	5.742	0.5172	284.9	1.815	13.9
4S10	coated NBG-17	heart	AG	650	1.2								7.665	7.989	5.414	0.4866	267.7	1.818	13.2

Table 3 continued

Sample						Post irradiation							Pre irradiation						
Specimen code	Grade	Location	Orientation	T_{irr} [°C]	calc. dpa	x [mm]	d [mm]	l [mm]	m [g]	V [mm^3]	ρ [g/cm^3]	E [GPa]	x [mm]	d [mm]	l [mm]	m [g]	V [mm^3]	ρ [g/cm^3]	E [GPa]
4S40	MLRF	heart	WG	750	2.1	7.635	7.966	5.956		292.6			7.637	7.968	5.965	0.5061	293.2	1.726	9.6
4S41	MLRF	heart	WG	750	1.8	7.723	7.960	5.956	0.5087	293.9	1.731	15.1	7.726	7.964	5.963	0.5092	294.5	1.729	9.4
4S42	MLRF	heart	WG	750	1.6	7.713	7.987	5.956		295.2			7.714	7.985	5.960	0.5104	295.3	1.728	9.7
4S45	MLRF	heart	AG	750	1.9	7.720	7.965	5.955		294.0			7.727	7.966	5.959	0.5097	294.4	1.731	7.4
4S46	MLRF	heart	AG	750	1.7	7.715	7.962	5.960	0.5066	294.0	1.723	11.9	7.721	7.968	5.964	0.5073	294.6	1.722	7.3
4S48	MLRF	heart	AG	650	1.1								7.718	7.950	5.962	0.5110	293.5	1.741	7.3
4S49	MLRF	heart	AG	750	2.1	7.712	7.949	5.960		293.2			7.719	7.953	5.964	0.5055	293.8	1.721	7.1
U336	LPEB	edge	WG	750	1.8	7.767	8.001	6.035		300.8			7.767	7.999	6.033	0.5575	300.7	1.854	11.5
U351	LPEB	edge	AG	750	1.9	7.759	8.006	6.025		300.5			7.760	8.008	6.019	0.5552	300.4	1.848	9.8
U361	LPEB	heart	WG	750	1.7	7.755	7.982	6.048	0.5516	300.2	1.837	16.9	7.765	7.983	6.048	0.5520	300.4	1.838	11.1
U362	LPEB	heart	WG	750	2.1	7.757	7.976	6.045	0.5506	299.7	1.837	17.3	7.756	7.975	6.047	0.5509	299.8	1.838	11.0
U370	LPEB	heart	AG	750	2.1	7.752	7.988	6.038	0.5504	300.0	1.835	15.2	7.756	7.992	6.037	0.5508	300.3	1.834	9.5
U372	LPEB	heart	AG	750	1.7	7.746	7.996	6.026	0.5490	299.8	1.832	15.3	7.748	7.994	6.023	0.5497	299.5	1.835	9.9
U377	LPIB	heart	AG	750	2.1	7.777	7.998	6.049	0.4080	301.6	1.353	5.8	7.782	7.996	6.042	0.4088	301.2	1.357	4.4
U386	LPIB	heart	WG	750	2.0	7.770	8.017	6.047	0.4191	302.5	1.386	7.4	7.762	8.015	6.049	0.4196	302.3	1.388	5.5
Z000	FNAG	heart	AG	750	2.0	7.708	8.009	5.975	0.5573	297.3	1.874	20.7	7.735	8.043	5.989	0.5573	300.5	1.855	12.2
Z001	FNAG	heart	AG	750	2.1	7.684	8.023	5.985	0.4819	298.2	1.616	9.5	7.700	8.047	5.990	0.4818	300.1	1.606	5.2
Z002	FNAG	heart	WG	650	1.2	7.718	8.040	5.995	0.4777	300.3	1.591	12.9	7.724	8.042	5.997	0.4777	300.6	1.589	7.0
Z003	FNAG	heart	WG	750	2.1	7.708	8.027	5.983	0.4756	298.7	1.592	12.2	7.720	8.043	5.976	0.4756	299.5	1.588	7.0
Z004	FNAG	heart	AG	750	1.7	7.709	8.047	6.003	0.4808	300.8	1.598	12.6	7.717	8.061	5.996	0.4807	301.5	1.594	7.5
Z005	FNAG	heart	WG	750	1.6	7.716	8.016	6.001	0.4706	299.1	1.573	10.8	7.721	8.020	5.990	0.4706	298.9	1.574	6.2
Z006	FNAG	heart	WG	750	2.0		8.013	5.987	0.5143				0.000	8.033	5.984	0.4917	0.0	0.000	0.0
Z007	FNAG	heart	AG	650	1.1	7.715	8.016	6.007	0.4759	299.4	1.589	13.2	7.713	8.020	6.005	0.4760	299.5	1.589	7.1

Appendix B CTE data

Table 4 CTE measurement results for the INNOGRAPH-1C irradiation experiment

Sample						Post irradiation CTE [10^{-6} K^{-1}]			Pre irradiation CTE [10^{-6} K^{-1}]		
Specimen code	Grade	Location	Orientation	Tirr [°C]	calc. dpa	30-120°C	30-200°C	30-750°C	30-120°C	30-200°C	30-750°C
0S00	NBG-10	heart	WG	750	1.5	4.21	4.42	5.54	4.09	4.27	5.10
0S03	NBG-10	heart	WG	750	2.2	4.16	4.36	5.47	4.09	4.27	5.10
0S25	NBG-10	heart	AG	750	1.3	4.48	4.71	5.84	4.35	4.56	5.64
0S27	NBG-10	heart	AG	750	2.2	4.58	4.84	5.89	4.29	4.49	5.49
0T01	IG-110	heart	AG	750	2.1	4.02	4.24	5.41	3.59	3.80	4.88
0T03	IG-110	heart	AG	750	1.6	3.68	3.86	5.00	3.59	3.80	4.88
0T13	IG-110	heart	WG	750	1.6	3.23	3.50	4.75	3.11	3.31	4.26
0T14	IG-110	heart	WG	750	2.1	3.30	3.50	4.64	3.11	3.31	4.26
0T57	IG-430	heart	AG	750	1.6	4.63	4.82	5.98	4.71	4.83	5.62
0T58	IG-430	heart	AG	750	2.1	4.75	5.00	6.22	4.71	4.83	5.62
0T62	IG-430	heart	WG	750	2.1	4.34	4.56	5.72	4.20	4.38	5.29
0T64	IG-430	heart	WG	750	1.6	4.09	4.33	5.51	3.81	4.00	5.03
0U05	PCEA	heart	WG	750	1.5	3.83	4.04	5.12	3.72	3.93	4.99
0U07	PCEA	heart	WG	750	1.8	3.65	3.92	5.09	3.61	3.85	4.73
0U08	PCEA	heart	WG	750	2.2	3.70	3.92	5.05	3.61	3.85	4.73
0U30	PCEA	heart	AG	750	1.4	3.98	4.19	5.28	3.94	4.18	5.26
0U32	PCEA	heart	AG	750	2.2	4.56	4.73	5.57	3.99	4.22	5.28
0U34	PCEA	heart	AG	750	1.9	4.05	4.27	5.41	3.75	3.97	4.83
1S01	NBG-17	heart	WG	750	1.6	4.77	4.98	6.06	4.48	4.65	5.65
1S02	NBG-17	heart	WG	750	2.1	4.60	4.80	5.90	4.48	4.65	5.65
1S27	NBG-17	heart	AG	750	2.2	4.90	5.14	6.21	4.86	5.02	5.86
1S29	NBG-17	heart	AG	750	1.5	4.78	4.98	6.04	4.86	5.02	5.86
1U05	PCIB	heart	AG	750	1.4	4.62	4.84	5.98	4.34	4.56	5.57
1U07	PCIB	heart	AG	750	2.2	4.89	5.12	6.28	4.21	4.42	5.45
1U25	PCIB	heart	WG	750	1.5	4.35	4.56	5.70	4.20	4.38	5.27
1U26	PCIB	heart	WG	750	1.9	4.60	4.82	5.95	4.20	4.38	5.27
1U28	PCIB	heart	WG	750	2.2	4.46	4.68	5.84	4.20	4.38	5.27
2S00	NBG-18	heart	WG	750	1.5	4.56	4.72	5.76	4.52	4.73	5.63
2S01	NBG-18	heart	WG	750	2.2	4.75	4.96	6.10	4.52	4.73	5.63
2S05	NBG-18	heart	WG	750	1.8	4.55	4.80	5.98	4.52	4.73	5.63
2S25	NBG-18	heart	AG	750	1.4	4.73	4.94	5.99	4.67	4.87	5.77
2S27	NBG-18	heart	AG	750	2.2	4.86	5.10	6.14	4.67	4.87	5.77
2U00	PPEA	heart	WG	750	2.2	4.31	4.53	5.60	4.32	4.55	5.61
2U03	PPEA	heart	WG	750	1.7	4.74	4.94	5.92	4.32	4.55	5.61
2U04	PPEA	heart	WG	750	1.5	4.55	4.75	5.83	4.41	4.62	5.60
2U25	PPEA	heart	AG	750	1.4	4.80	5.03	6.09	4.59	4.79	5.84
2U27	PPEA	heart	AG	750	1.8	4.82	5.07	6.16	4.86	5.04	5.95
2U28	PPEA	heart	AG	750	2.2	4.84	5.08	6.19	4.86	5.04	5.95
3S00	NBG-25	heart	AG	750	1.4	4.47	4.68	5.80	4.25	4.44	5.33
3S01	NBG-25	heart	AG	750	1.8	4.43	4.63	5.81	4.25	4.44	5.33
3S04	NBG-25	heart	AG	750	2.2	4.62	4.83	5.98	4.13	4.37	5.30
3S35	NBG-25	heart	WG	750	1.5	4.02	4.24	5.34	3.70	3.93	4.99
3S37	NBG-25	heart	WG	750	2.2	4.06	4.30	5.44	3.70	3.93	4.99
3U01	TS5324	heart	AG	750	1.9	5.25	5.44	6.54	4.88	5.09	6.04
3U33	TS5328	heart	AG	750	1.9	4.58	4.75	5.83	4.25	4.43	5.36
4S41	MLRF	heart	WG	750	1.8	2.60	2.84	4.04	2.40	2.60	3.76
4S46	MLRF	heart	AG	750	1.7	3.39	3.64	4.80	3.35	3.53	4.61
U361	LPEB	heart	WG	750	1.7	3.89	4.10	5.18	3.51	3.71	4.59
U362	LPEB	heart	WG	750	2.1	3.94	4.15	5.26	3.65	3.81	4.63
U370	LPEB	heart	AG	750	2.1	4.47	4.67	5.81	4.13	4.32	5.16
U372	LPEB	heart	AG	750	1.7	4.44	4.62	5.68	4.18	4.36	5.13
U377	LPIB	heart	AG	750	2.1	5.28	5.50	6.51	4.87	5.07	5.92
U386	LPIB	heart	WG	750	2.0	4.38	4.56	5.59	4.20	4.39	5.41

Appendix C Thermal diffusivity and conductivity data

Table 5 Thermal diffusivity measurements for the INNOGRAPH-1C irradiation experiment

Sample						Post irradiation Thermal diffusivity [mm^2 s^{-1}]									Pre irradiation Thermal diffusivity [mm^2 s^{-1}]								
Specimen code	Grade	Location	Orientation	T_{irr} [°C]	calc. dpa	25°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	750°C	27°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	750°C
0S00	NBG-10	heart	WG	750	1.5	31.0	26.9	22.0	18.3	16.1	15.4	14.1	13.1	12.6	113.0	81.1	57.8	44.1	35.6	30.1	26.1	23.1	21.9
0S03	NBG-10	heart	WG	750	2.2	25.3	22.6	18.5	15.7	14.0	13.6	12.5	11.6	11.3	113.0	81.1	57.8	44.1	35.6	30.1	26.1	23.1	21.9
0S25	NBG-10	heart	AG	750	1.3	32.1	28.0	22.6	19.0	16.6	15.6	14.2	13.2	12.7	109.5	79.9	56.7	43.5	35.1	29.6	25.7	22.8	21.5
0S27	NBG-10	heart	AG	750	2.2	24.3	21.3	17.8	15.2	13.7	13.1	12.1	11.4	10.9	107.6	78.0	55.4	42.3	34.2	29.2	25.1	22.3	21.1
0T01	IG-110	heart	AG	750	2.1	24.8	21.2	17.7	14.8	13.3	12.8	11.8	11.1	10.7	99.6	73.8	52.6	40.3	32.7	27.7	24.1	21.3	20.2
0T03	IG-110	heart	AG	750	1.6	27.5	24.3	20.0	17.1	15.0	14.3	13.1	12.1	11.8	99.6	73.8	52.6	40.3	32.7	27.7	24.1	21.3	20.2
0T13	IG-110	heart	WG	750	1.6	31.3	25.1	21.3	17.9	15.9	14.9	13.7	12.8	12.4	113.2	82.3	58.7	44.8	36.3	31.0	26.9	23.9	22.6
0T14	IG-110	heart	WG	750	2.1	27.8	23.5	19.7	16.9	15.0	14.2	13.1	12.1	11.8	113.2	82.3	58.7	44.8	36.3	31.0	26.9	23.9	22.6
0T57	IG-430	heart	AG	750	1.6	27.7	23.9	20.1	17.0	15.0	14.3	13.2	12.3	11.9	98.5	73.2	52.5	40.3	32.9	27.9	24.2	21.4	20.3
0T58	IG-430	heart	AG	750	2.1	25.0	19.9	16.9	14.5	12.9	12.6	11.6	10.9	10.6	98.5	73.2	52.5	40.3	32.9	27.9	24.2	21.4	20.3
0T62	IG-430	heart	WG	750	2.1	25.0	22.2	18.8	15.9	14.2	13.6	12.6	11.8	11.3	106.3	78.3	56.3	43.2	35.0	29.7	25.8	22.9	21.7
0T64	IG-430	heart	WG	750	1.6	29.5	26.3	22.0	18.8	16.4	15.4	14.2	13.2	12.7	111.4	82.0	59.2	45.4	36.9	31.2	27.3	24.0	22.8
0U05	PCEA	heart	WG	750	1.5	35.5	30.7	25.3	21.4	18.7	17.4	15.9	14.7	14.2	136.4	98.3	69.1	52.1	42.0	35.4	30.8	26.9	25.4
0U07	PCEA	heart	WG	750	1.8	32.2	27.1	22.8	19.2	17.0	16.4	15.0	13.9	13.5	135.4	97.7	68.7	51.8	41.8	35.5	30.6	26.9	25.5
0U08	PCEA	heart	WG	750	2.2	28.9	24.6	21.1	17.9	16.0	15.4	14.4	13.4	13.0	135.4	97.7	68.7	51.8	41.8	35.5	30.6	26.9	25.5
0U30	PCEA	heart	AG	750	1.4	38.8	32.8	26.9	22.5	19.5	18.1	16.4	15.2	14.7	129.4	93.6	65.8	49.9	40.1	33.7	29.2	25.7	24.2
0U32	PCEA	heart	AG	750	2.2	28.2	25.2	21.1	17.9	15.9	15.3	14.0	13.0	12.6	130.9	94.7	66.6	50.4	40.7	34.1	29.5	26.1	24.6
0U34	PCEA	heart	AG	750	1.9	30.8	25.8	21.3	18.2	16.0	15.4	14.1	13.1	12.8	131.0	94.3	66.3	50.2	40.4	34.0	29.3	25.9	24.5
1S01	NBG-17	heart	WG	750	1.6	29.9	25.8	21.1	17.7	15.6	15.0	13.9	12.8	12.4	110.2	80.2	57.1	43.6	35.4	30.3	26.2	23.2	21.9
1S02	NBG-17	heart	WG	750	2.1	26.0	21.2	18.3	15.6	13.7	13.5	12.6	11.8	11.5	110.2	80.2	57.1	43.6	35.4	30.3	26.2	23.2	21.9
1S27	NBG-17	heart	AG	750	2.2	26.0	21.6	18.3	15.4	13.7	13.4	12.3	11.6	11.2	103.7	75.6	54.3	41.7	33.9	28.7	24.9	22.2	21.0
1S29	NBG-17	heart	AG	750	1.5	28.1	24.5	20.0	16.9	14.8	14.4	13.1	12.2	11.8	103.7	75.6	54.3	41.7	33.9	28.7	24.9	22.2	21.0
1U05	PCIB	heart	AG	750	1.4	29.2	24.6	20.0	17.2	15.1	14.3	13.1	12.1	11.8	93.3	69.8	51.0	39.8	32.5	27.7	24.2	21.5	20.4
1U07	PCIB	heart	AG	750	2.2	23.9	20.7	17.1	14.7	13.2	12.7	11.7	10.9	10.6	89.8	68.6	50.2	39.0	32.0	27.3	24.1	21.2	20.1
1U25	PCIB	heart	WG	750	1.5	28.2	23.9	19.7	16.8	14.9	14.2	13.1	12.1	11.7	96.2	72.1	52.4	40.7	33.3	28.3	24.8	22.1	20.8
1U26	PCIB	heart	WG	750	1.9	26.0	22.0	18.6	15.9	14.0	13.5	12.5	11.6	11.3	96.2	72.1	52.4	40.7	33.3	28.3	24.8	22.1	20.8
1U28	PCIB	heart	WG	750	2.2	23.3	21.6	17.8	15.2	13.5	13.1	12.2	11.3	11.0	96.2	72.1	52.4	40.7	33.3	28.3	24.8	22.1	20.8
2S00	NBG-18	heart	WG	750	1.5	30.5	25.6	21.3	18.2	15.9	15.4	14.1	13.1	12.7	109.7	81.0	57.8	44.2	36.0	30.6	26.7	23.6	22.4
2S01	NBG-18	heart	WG	750	2.2	25.3	22.2	18.6	15.7	14.2	13.8	12.7	11.8	11.5	109.7	81.0	57.8	44.2	36.0	30.6	26.7	23.6	22.4
2S05	NBG-18	heart	WG	750	1.8	26.7	23.9	19.7	16.8	14.9	14.4	13.2	12.4	12.0	109.7	81.0	57.8	44.2	36.0	30.6	26.7	23.6	22.4
2S25	NBG-18	heart	AG	750	1.4	32.3	26.0	21.9	18.7	16.3	15.6	14.3	13.3	12.8	107.4	77.9	56.1	43.0	34.9	29.7	25.8	22.9	21.7
2S27	NBG-18	heart	AG	750	2.2	25.1	21.5	18.1	15.4	13.7	13.3	12.2	11.4	11.1	107.4	77.9	56.1	43.0	34.9	29.7	25.8	22.9	21.7
2U00	PPEA	heart	WG	750	2.2	24.1	21.5	17.8	15.5	13.7	13.5	12.5	11.7	11.3	102.1	76.5	55.1	42.4	34.6	29.5	25.6	22.8	21.5
2U03	PPEA	heart	WG	750	1.7	30.8	24.0	20.2	17.5	15.3	14.6	13.5	12.5	12.1	102.1	76.5	55.1	42.4	34.6	29.5	25.6	22.8	21.5
2U04	PPEA	heart	WG	750	1.5	29.9	25.4	20.9	17.7	15.7	14.9	13.7	12.7	12.3	103.6	75.8	54.6	42.2	34.4	29.3	25.5	22.7	21.5
2U25	PPEA	heart	AG	750	1.4	31.1	26.4	21.9	18.4	16.2	15.5	14.2	13.2	12.8	101.3	75.4	54.7	42.2	34.5	29.3	25.6	22.7	21.5
2U27	PPEA	heart	AG	750	1.8	26.2	22.7	18.7	16.0	14.2	13.9	12.8	12.0	11.5	100.3	74.2	54.1	41.7	34.1	29.1	25.4	22.6	21.3
2U28	PPEA	heart	AG	750	2.2	24.9	21.9	18.3	15.6	13.9	13.5	12.5	11.5	11.2	100.3	74.2	54.1	41.7	34.1	29.1	25.4	22.6	21.3
3S00	NBG-25	heart	AG	750	1.4	28.5	24.4	20.9	17.6	15.5	14.9	13.7	12.7	12.3	100.2	73.5	53.4	41.2	33.5	28.5	24.9	22.2	21.0
3S01	NBG-25	heart	AG	750	1.8	26.9	22.7	18.9	16.1	14.3	13.7	12.6	11.8	11.4	100.2	73.5	53.4	41.2	33.5	28.5	24.9	22.2	21.0
3S04	NBG-25	heart	AG	750	2.2	24.5	20.3	17.2	14.9	13.3	13.0	11.9	11.1	10.9	100.5	75.4	54.6	42.3	34.5	29.2	25.5	22.6	21.4
3S35	NBG-25	heart	WG	750	1.5	30.0	25.8	21.3	18.2	16.2	15.2	14.0	13.0	12.6	104.8	77.8	56.1	43.3	35.2	29.9	26.1	23.2	22.0
3S37	NBG-25	heart	WG	750	2.2	24.4	21.4	18.4	15.7	14.0	13.5	12.5	11.7	11.3	104.8	77.8	56.1	43.3	35.2	29.9	26.1	23.2	22.0
3U01	TS5324	heart	AG	750	1.9	21.5	18.7	15.8	13.7	12.2	11.9	11.0	10.3	10.0	67.3	53.5	40.3	32.3	27.0	23.4	20.7	18.6	17.8
3U33	TS5328	heart	AG	750	1.9	21.6	19.3	16.4	13.9	12.3	11.6	10.7	10.0	9.8	91.7	66.1	47.3	36.3	29.3	24.8	21.5	19.1	18.1
4S41	MLRF	heart	WG	750	1.8	30.2	25.8	21.4	18.4	16.1	15.4	14.2	13.1	12.7	132.7	94.2	65.6	49.7	39.9	33.4	28.9	25.4	24.1
4S46	MLRF	heart	AG	750	1.7	25.4	22.0	18.2	15.4	13.5	12.9	11.9	11.1	10.8	104.3	74.5	52.2	39.2	31.7	26.5	23.0	20.2	19.1
U361	LPEB	heart	WG	750	1.7	35.1	30.5	24.9	20.7	18.2	17.1	15.6	14.5	14.1	142.9	102.4	70.5	52.7	42.2	35.4	30.4	26.6	25.2
U362	LPEB	heart	WG	750	2.1	32.1	26.8	21.8	18.4	16.1	15.6	14.4	13.2	12.9	143.4	101.5	69.8	52.2	41.6	35.1	30.3	26.5	24.9
U370	LPEB	heart	AG	750	2.1	24.9	23.3	19.7	16.8	14.8	14.2	13.0	12.1	11.8	129.7	91.0	62.9	47.2	37.5	31.6	27.2	23.8	22.5
U372	LPEB	heart	AG	750	1.7	32.4	27.3	21.9	18.3	16.1	15.5	14.2	13.1	12.6	131.2	92.6	63.8	48.0	38.2	31.9	27.5	24.2	22.8
U377	LPIB	heart	AG	750	2.1	19.8	16.8	14.1	12.1	10.7	9.8	9.0	8.3	8.0	82.6	59.2	41.6	31.6	25.5	21.5	18.6	16.4	15.6
U386	LPIB	heart	WG	750	2.0	22.8	19.7	16.4	14.3	12.6	11.5	10.6	9.9	9.7	97.7	70.3	49.3	37.3	29.9	25.2	21.8	19.3	18.2

Table 6 Thermal conductivity measurements for the INNOGRAPH-1C irradiation experiment

Sample						Post irradiation Thermal conductivity [W m^{-1} K^{-1}]									Pre irradiation Thermal conductivity [W m^{-1} K^{-1}]								
Specimen code	Grade	Location	Orientation	T_{irr} [°C]	calc. dpa	25°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	750°C	27°C	100°C	200°C	300°C	400°C	500°C	600°C	700°C	750°C
0S00	NBG-10	heart	WG	750	1.5	38.6	42.2	43.7	42.7	41.9	43.3	42.0	40.9	39.9	140.5	127.3	114.6	102.6	92.5	84.8	77.8	72.1	69.6
0S03	NBG-10	heart	WG	750	2.2	31.7	35.8	37.0	37.0	36.7	38.5	37.7	36.7	36.3	140.5	127.3	114.6	102.6	92.5	84.8	77.8	72.1	69.6
0S25	NBG-10	heart	AG	750	1.3	40.3	44.2	45.2	44.5	43.4	44.3	42.7	41.5	40.5	137.3	126.4	113.3	101.9	91.8	83.8	77.3	71.6	68.8
0S27	NBG-10	heart	AG	750	2.2	30.2	33.3	35.2	35.2	35.5	36.8	36.1	35.4	34.6	133.0	121.7	109.1	97.6	88.3	81.6	74.5	69.0	66.5
0T01	IG-110	heart	AG	750	2.1	30.8	33.2	35.1	34.5	34.5	35.9	35.1	34.6	34.1	124.4	116.3	104.7	94.0	85.3	78.3	72.2	66.9	64.5
0T03	IG-110	heart	AG	750	1.6	34.1	38.1	39.6	39.6	39.0	40.3	39.0	37.9	37.4	124.4	116.3	104.7	94.0	85.3	78.3	72.2	66.9	64.5
0T13	IG-110	heart	WG	750	1.6	39.0	39.5	42.3	41.8	41.5	41.9	40.8	40.0	39.5	141.0	129.3	116.5	104.3	94.5	87.2	80.4	74.6	71.9
0T14	IG-110	heart	WG	750	2.1	34.7	37.0	39.3	39.4	39.1	40.2	39.2	38.0	37.7	141.0	129.3	116.5	104.3	94.5	87.2	80.4	74.6	71.9
0T57	IG-430	heart	AG	750	1.6	35.6	38.6	41.1	40.8	40.1	41.6	40.5	39.5	39.1	126.3	118.3	107.3	96.5	88.0	80.7	74.2	68.9	66.4
0T58	IG-430	heart	AG	750	2.1	32.0	32.1	34.5	34.8	34.4	36.4	35.7	35.0	34.5	126.3	118.3	107.3	96.5	88.0	80.7	74.2	68.9	66.4
0T62	IG-430	heart	WG	750	2.1	32.1	35.9	38.4	38.2	38.0	39.4	38.8	38.0	37.2	136.3	126.6	115.0	103.5	93.8	86.1	79.4	73.8	71.1
0T64	IG-430	heart	WG	750	1.6	37.7	42.5	44.9	44.9	43.9	44.5	43.5	42.5	41.6	142.4	132.2	120.7	108.4	98.5	90.1	83.6	77.0	74.3
0U05	PCEA	heart	WG	750	1.5	45.2	49.3	51.4	50.9	49.7	50.2	48.6	46.9	46.1	173.4	157.5	140.0	123.8	111.3	101.8	93.9	85.6	82.3
0U07	PCEA	heart	WG	750	1.8	41.1	43.6	46.2	45.8	45.3	47.2	45.9	44.5	44.0	171.7	156.2	138.9	122.7	110.5	101.8	93.0	85.6	82.5
0U08	PCEA	heart	WG	750	2.2	36.9	39.6	42.9	42.8	42.6	44.6	44.0	42.8	42.2	171.7	156.2	138.9	122.7	110.5	101.8	93.0	85.6	82.5
0U30	PCEA	heart	AG	750	1.4	49.0	52.3	54.1	53.1	51.3	51.6	49.7	48.1	47.4	163.3	148.9	132.4	117.8	105.6	96.2	88.3	81.3	78.1
0U32	PCEA	heart	AG	750	2.2	36.1	40.6	42.9	42.7	42.5	44.2	42.8	41.8	41.1	166.8	152.2	135.1	119.9	108.2	98.3	90.2	83.4	80.0
0U34	PCEA	heart	AG	750	1.9	39.3	41.5	43.3	43.4	42.7	44.3	43.2	41.9	41.5	166.5	151.0	134.4	119.3	107.2	97.8	89.3	82.5	79.3
1S01	NBG-17	heart	WG	750	1.6	39.9	43.4	44.8	44.0	43.3	45.2	44.3	42.9	42.2	147.0	134.9	121.5	108.6	98.6	91.3	83.8	77.7	74.7
1S02	NBG-17	heart	WG	750	2.1	34.7	35.7	38.9	39.0	38.3	40.8	40.3	39.4	39.1	147.0	134.9	121.5	108.6	98.6	91.3	83.8	77.7	74.7
1S27	NBG-17	heart	AG	750	2.2	34.5	36.2	38.6	38.3	38.0	40.2	39.3	38.5	38.0	137.7	126.7	114.9	103.6	94.0	86.2	79.3	73.8	71.0
1S29	NBG-17	heart	AG	750	1.5	37.3	41.1	42.3	42.1	41.0	43.3	41.9	40.8	40.2	137.7	126.7	114.9	103.6	94.0	86.2	79.3	73.8	71.0
1U05	PCIB	heart	AG	750	1.4	38.2	40.6	41.8	42.0	41.1	42.2	41.1	39.9	39.5	122.2	115.3	106.5	97.4	88.9	82.0	76.1	70.5	68.3
1U07	PCIB	heart	AG	750	2.2	31.3	34.2	35.7	35.9	36.0	37.6	36.8	35.9	35.4	117.5	113.2	104.7	95.4	87.4	80.7	75.5	69.7	67.1
1U25	PCIB	heart	WG	750	1.5	36.8	39.3	41.0	41.0	40.5	41.9	40.8	39.6	39.0	125.5	118.5	109.0	99.3	90.7	83.5	77.7	72.1	69.4
1U26	PCIB	heart	WG	750	1.9	34.0	36.2	38.6	38.8	38.3	39.9	39.1	38.1	37.7	125.5	118.5	109.0	99.3	90.7	83.5	77.7	72.1	69.4
1U28	PCIB	heart	WG	750	2.2	30.5	35.6	37.1	37.2	37.0	38.9	38.2	37.0	36.7	125.5	118.5	109.0	99.3	90.7	83.5	77.7	72.1	69.4
2S00	NBG-18	heart	WG	750	1.5	40.0	42.4	44.6	44.6	43.6	45.6	44.4	43.2	42.6	143.9	134.0	120.9	108.3	98.6	90.7	83.8	77.7	75.0
2S01	NBG-18	heart	WG	750	2.2	33.3	36.8	38.9	38.6	38.9	41.2	40.2	39.0	38.5	143.9	134.0	120.9	108.3	98.6	90.7	83.8	77.7	75.0
2S05	NBG-18	heart	WG	750	1.8	35.3	39.7	41.4	41.4	41.0	43.1	41.7	40.9	40.5	143.9	134.0	120.9	108.3	98.6	90.7	83.8	77.7	75.0
2S25	NBG-18	heart	AG	750	1.4	42.4	43.1	45.9	45.9	44.8	46.3	45.0	43.7	42.8	141.2	129.1	117.5	105.5	95.8	88.2	81.4	75.6	72.9
2S27	NBG-18	heart	AG	750	2.2	33.1	35.6	38.0	38.0	37.7	39.5	38.6	37.7	37.2	141.2	129.1	117.5	105.5	95.8	88.2	81.4	75.6	72.9
2U00	PPEA	heart	WG	750	2.2	31.1	34.9	36.5	37.3	36.8	39.2	38.5	37.9	37.3	131.0	123.8	112.7	101.6	92.8	85.4	78.8	73.3	70.6
2U03	PPEA	heart	WG	750	1.7	39.5	38.8	41.3	41.8	40.9	42.3	41.4	40.2	39.7	131.0	123.8	112.7	101.6	92.8	85.4	78.8	73.3	70.6
2U04	PPEA	heart	WG	750	1.5	38.4	41.1	42.8	42.4	42.0	43.3	42.2	40.8	40.4	132.7	122.5	111.4	101.1	92.1	84.8	78.3	72.8	70.2
2U25	PPEA	heart	AG	750	1.4	39.8	42.5	44.7	43.9	43.3	44.7	43.5	42.3	41.7	129.6	121.6	111.5	101.0	92.1	84.7	78.5	73.0	70.2
2U27	PPEA	heart	AG	750	1.8	33.7	36.9	38.4	38.5	38.1	40.4	39.5	38.8	37.9	128.7	120.1	110.5	99.9	91.4	84.3	78.2	72.5	69.9
2U28	PPEA	heart	AG	750	2.2	32.2	35.8	37.8	37.7	37.5	39.5	38.7	37.5	37.1	128.7	120.1	110.5	99.9	91.4	84.3	78.2	72.5	69.9
3S00	NBG-25	heart	AG	750	1.4	36.4	39.3	42.4	42.0	41.2	43.1	41.8	40.6	40.2	127.7	118.1	108.4	98.0	89.2	82.2	76.1	70.8	68.3
3S01	NBG-25	heart	AG	750	1.8	34.4	36.6	38.5	38.6	38.2	39.7	38.7	37.9	37.3	127.7	118.1	108.4	98.0	89.2	82.2	76.1	70.8	68.3
3S04	NBG-25	heart	AG	750	2.2	31.3	32.8	35.0	35.5	35.4	37.6	36.6	35.7	35.5	128.0	121.1	110.9	100.8	91.6	84.2	77.8	72.3	69.7
3S35	NBG-25	heart	WG	750	1.5	38.4	41.6	43.5	43.6	43.2	44.0	43.0	41.8	41.2	133.8	125.3	114.2	103.4	93.9	86.4	79.9	74.2	71.6
3S37	NBG-25	heart	WG	750	2.2	31.3	34.7	37.6	37.7	37.5	39.2	38.5	37.7	37.1	133.8	125.3	114.2	103.4	93.9	86.4	79.9	74.2	71.6
3U01	TS5324	heart	AG	750	1.9	28.1	30.9	33.0	33.5	33.5	35.3	34.7	34.0	33.6	88.3	88.5	84.2	79.2	73.9	69.4	65.0	61.3	59.4
3U33	TS5328	heart	AG	750	1.9	26.1	29.5	31.5	31.4	31.0	31.7	31.0	30.3	30.3	110.7	100.6	91.0	81.8	73.9	67.8	62.3	57.9	55.7
4S41	MLRF	heart	WG	750	1.8	37.1	39.9	41.8	42.2	41.2	42.7	41.7	40.3	39.7	162.3	145.3	128.0	113.6	101.8	92.5	84.7	77.9	75.2
4S46	MLRF	heart	AG	750	1.7	31.0	33.9	35.4	35.0	34.5	35.5	34.7	33.9	33.8	128.1	115.3	102.0	89.9	81.1	73.6	67.7	62.3	59.9
U361	LPEB	heart	WG	750	1.7	45.7	50.1	51.6	50.4	49.4	50.3	48.8	47.2	46.7	186.3	168.3	146.4	128.3	114.7	104.4	94.8	87.0	83.8
U362	LPEB	heart	WG	750	2.1	41.8	44.0	45.3	44.8	43.7	45.9	45.0	43.2	42.8	186.9	166.8	145.1	127.2	113.2	103.4	94.5	86.5	82.9
U370	LPEB	heart	AG	750	2.1	32.4	38.3	40.8	40.8	40.1	41.9	40.6	39.4	39.0	168.7	149.2	130.5	114.6	101.8	92.9	84.7	77.7	74.6
U372	LPEB	heart	AG	750	1.7	42.0	44.7	45.4	44.4	43.7	45.4	44.1	42.6	41.6	170.7	151.9	132.4	116.8	103.8	93.9	85.7	78.8	75.6
U377	LPIB	heart	AG	750	2.1	19.0	20.3	21.5	21.8	21.5	21.2	20.6	20.1	19.7	79.5	71.8	63.8	56.9	51.1	46.7	42.9	39.6	38.3
U386	LPIB	heart	WG	750	2.0	22.4	24.4	25.7	26.3	25.9	25.5	24.9	24.4	24.3	96.1	87.3	77.3	68.6	61.5	56.1	51.4	47.6	45.7