EUROPEAN COMMISSION

5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M1

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°

FIKI-CT-2001-00135

HTR-M1 Report on preliminary irradiation testing of selected graphites for HTR – report on irradiation and post irradiation tests

F. Schmalz
J.A. Vreeling
D.S. d'Hulst
W. Molijn
P. ten Pierick

NRG
Netherlands

Dissemination level: CO
Document Number: HTR-M1-05/12-D-2.3.39
Deliverable: D9

Preliminary irradiation testing of selected graphite grades for HTR

Final report on HTR-M1 WP3

F. Schmalz
J.A. Vreeling
D.S. d'Hulst
W. Molijn
P. ten Pierick

Petten, 19 December 2005

DRAFT

20787/05.71179/P

Under the contract of

rev. no	date	description
A	2005/12/30	2nd draft
A	2005/12/19	1st draft

author :	F. Schmalz	reviewed :	J.G. van der Laan
40 page(s)	MMI/FS/NO	approved :	B. van der Schaaf
final report htr-m1 draft(j).doc			

Contents

List of tables

List of figures

Summary

As part of the European development programme for high temperature reactor technologies, NRG has contributed to the materials project HTR-M1. This project is oriented on the substantiation of graphite selection for a European HTR, with a view to get allow core design evaluations by about 2011. NRG has re-established graphite irradiation and qualification methods, and initiated an irradiation programme on selected graphites. The properties of primary interests are Dimensional change, Dynamic Young's Modulus, Coefficient of Thermal Expansion and Thermal conductivity/diffusivity

The initiating irradiation campaign has been performed in 2004 and 2005, at a nominal temperature of 750°C and a target dose of 8 dpa_g. The graphite grades have been selected in close interaction with manufacturers SGL and UCAR (Graftech), and collaboration has been initiated with JAERI (HTTR) to connect with the database on IG-110, the material applied in HTTR and HTR-10.

This report covers the results up to the dimensional change and youngs modulus measurements after the first irradiation campaign, with a peak dose of 9.8 dpa_g (or 7.8 x 10^{25} m^{-2} EDN fluence). It is found that the grades selected represent various type of behaviour, with maximum volumetric shrinkage around 6%, and significant differences in anisotropy effects. Extended data and the final neutron dosimetry analyses will be obtained in 2006, mostly as part of the RAPHAEL Integrated Project.

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 Testing Reactors and High Temperature Reactors (HTR's). Recently, there has been a renewal of interest in HTR's. Two prototypes, one in Japan (HTTR) and one in China (HTR-10) are operated. The development of the Pebble Bed Modular Reactor (PBMR) in South Africa and the Gas Turbine Modular Helium Reactor (GT-MHR) are at an advance stage. The European Commission is also supporting research projects for the development of HTR technology with the aim to create 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 because the raw materials do not exist anymore. 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. A review of the available data on the irradiation behaviour of graphites at high temperatures is given in [1].
It is decided to create a database that contains the data of the materials behaviour of available graphite grades under neutron irradiation at HTR relevant temperatures, in order to be able to design a European HTR. This will allow the 'best' graphite(s) to be chosen, and provide all the data necessary to allow a full core design to be carried out.

The first step in achieving this is an irradiation experiment carried out under HTR-M1 as part of the 5th Framework Programme. The irradiation experiment (called INNOGRAPH-01A) is performed in the High Flux Reactor (HFR) in Petten. Five graphites have been selected from those available, two made by Graftech (previously named UCAR), two made by SGL-Carbon and one made by Toyo Tanso. These will be the main focus of the experiment. In addition, three 'minor' graphites have been selected, one from each manufacturer. These are included as 'piggy back' samples in the first experiment, and will give an early indication of their suitability for inclusion in further experiments. The experiment will give data on dimensional changes, Dynamic Young's Modulus, Coefficient of Thermal Expansion and Thermal Diffusivity (from which the thermal conductivity coefficient can be obtained). The material selection and testing requirements are described in [2].

This report gives the results of a selection of high dose specimens that concludes the work specified under HTR-M1.

2 Experiments

2.1 Graphite grades

The selection of the graphite grades for the HTR-M1 programme is based on factors like properties, impurity levels and availability. The 5 major grades 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 manufacturing methods, i.e. extrusion or iso-moulding.

There are three graphite manufacturers selected: Graftech (UCAR), SGL-Carbon and Toyo Tanso. The first two companies contribute two grades and Toyo Tanso contributes one grade. The Toyo Tanso grade (IG-110) is selected because some irradiation data are available on this material, and therefore acts as a kind of reference. The five major grades are given in table 1. More details on the selection criteria are given in [2].

All three companies contributed one extra grade in the case there is some space left in the irradiation rig. Some of these grades are developmental and some preliminary irradiation data may give an indication of the suitability of the materials for future experiments. It should be noted that only a small batch of these specimens is tested. These grades are referred to as minor grades. The minor grades are given in table 2.

table 1 Selected graphite grades: major grades

Grade	Manufacturer	Coke	Process
PCEA	Graftech	Petroleum	Extrusion
PCIB-SFG	Graftech	Petroleum	Iso-moulding
NGB-10	SGL	Pitch	Extrusion
NBG-25	SGL	Petroleum	Iso-moulding
IG-110	Toyo Tanso	Petroleum	Iso-moulding

table 2 Selected graphite grades: minor grades

Grade	Manufacturer	Coke	Process
PPEA	Graftech	Pitch	Extrusion
NGB-20	SGL	Petroleum	Extrusion
IG-430	Toyo Tanso	Pitch	Iso-Moulding

2.2 Specimen type

The specimen shape is cylindrical. The cylindrical specimens are flattened by milling a plane with a width of 3 mm along the length. This plane is used to engrave the specimen number and fix the orientation of the specimen. Figure shows a drawing of the specimen. The specimen diameter is 8 mm and the length is either 6 mm or 12 mm. This size allows insertion of a sufficient number of specimens in the irradiation rig, and big enough to perform reasonably accurate measurements. The specimens with a length of 6 mm are suitable for type of measurements (dimensional changes, Dynamic Young's Modulus, Coefficient of Thermal Expansion and Thermal Diffusivity Coefficient). The Thermal Diffusivity Coefficient measurements cannot be performed on the 12 mm specimens because a length of 12 mm is too long. These samples are included to have some data points with higher measurement accuracy in mainly the dimensional change measurements.

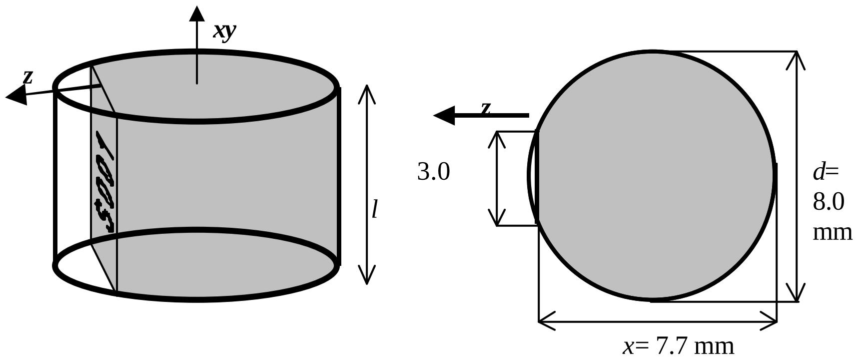

figure 1 The shape of the specimen. The figure on the left-hand side exaggeratedly shows the flatting of the cylinder. The milled plane is perpendicular to the z-direction when the axial direction of the cylinders in the xy-direction. The specimen number is engraved on the plane. The figure on the right-hand side is a top-view of the specimen. The important dimensions are indicated.

2.3 Irradiation

For this project the irradiation campaign consists of one irradiation rig, originally called INNOGRAPH-01. It is planned that part of the specimens of this rig will be re-irradiated after the Post Irradiation Examination in a similar rig as part of the 6th Framework Programme. That rig will be called INNOGRAPH-01B. Therefore the first rig will be renamed INNOGRAPH-01A.

figure 2 TZM drum and its loading that consists of 4 columns of graphite specimens.

The INNOGRAPH irradiation rig consists of 8 drums made of TZM steel. Each drum has 4 columns with a stacking height of 60 mm. In these columns the graphite specimens are stacked. The graphite specimens are separated from the TZM by graphite foil. The irradiation rig is described in [3]. An example of a drum and a typical loading is shown in figure 2.
The target temperature of the irradiation is 750°C and the target dose is 8 dpa_g (dpa in graphite).

2.4 Testmatrix

The specimens of each graphite grade, orientation and location are distributed over the drums to achieve a spread in neutron dose. Originally it was planned to investigate 30 specimens for each major grade, see [4]. This means 15 specimens per main direction (WG and AG) per grade. The specimens are acquired from the centre as well as near the edge of the blocks to get representative results of the entire graphite blocks. For the minor grades a maximum of 10 specimens per grade was envisaged. These amounts were based on a design for ±150 specimens.

table 3 Number of specimens per grade that were included in INNOGRAPH-1A

Supplier	Grade	Total per grade	Orientation	Total per orientation	Centre		Edge	
					6 mm	12 mm	6 mm	12 mm
SGL-Carbon	NBG-10	32	AG	17	7	3	5	2
			WG	15	5	3	5	2
	NBG-25	30	AG	15	5	3	5	2
			WG	15	5	3	5	2
	NBG-20	14	AG	7	5	2	-	-
			WG	7	5	2	-	-
Toyo Tanso	IG-110	30	AG	15	5	3	5	2
			WG	15	5	3	5	2
	IG-430	18	AG	9	5	2	2	-
			WG	9	5	2	2	-
Graftech	PCEA	30	AG	15	5	3	5	2
			WG	15	5	3	5	2
	PCIB	30	AG	15	5	3	5	2
			WG	15	5	3	5	2
	PPEA	14	AG	7	5	2	-	-
			WG	7	5	2	-	-

Due to design improvements a larger amount of specimens were included in INNOGRAPH-1A, as given in table 3. In addition, some special piggy-backs were included in INNOGRAPH-1A to gain extra knowledge in the irradiation behaviour of graphite. The complete loading scheme is given in [5].

2.5 Measurements

In this report only the results of a selection of the specimens will be reported. Further data along with the measurements of the Coefficient of Thermal Expansion and the Coefficient of Thermal Diffusivity will be obtained in the follow-up, like the RAPHAEL Integrated Project.

2.5.1 Dimensional changes

The dimensions of all specimens are measured before and after the irradiation. The measurements are performed with Mahr inductive probes (Mahr, type P 2104 MB) with a measurement range of 4 mm and an accuracy of 0.1 µm. The measurement is a comparison of the dimensions of a known calliper and the unknown specimen. The dimension of the calliper is measured before and after the sample to check the origin. The length of the specimens is measured on six positions, the diameter on four and the diameter across the flattening on three. The set-up used is shown in figure 3. The time span between the measurements before and after irradiation is about two years. To prevent differences in the measurement procedure before and after irradiation the complete procedure is formalised via a working instruction, see [6].

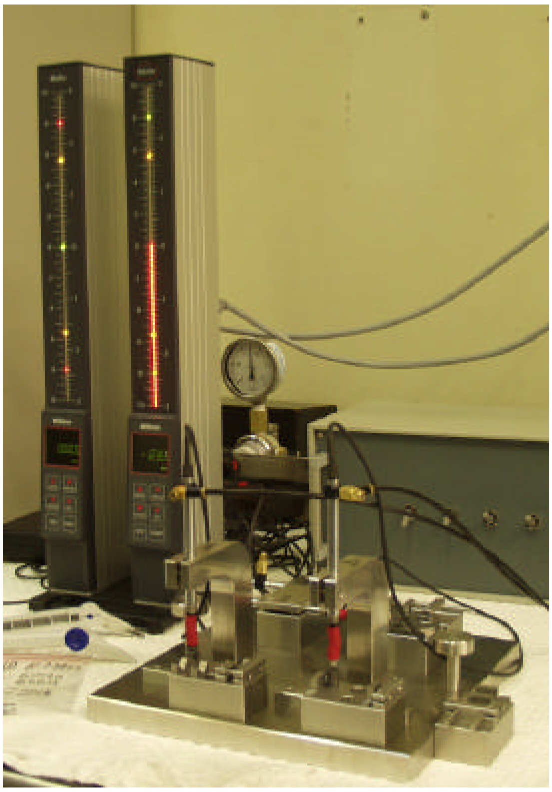

figure 3 Set-up used for dimensional measurements

2.5.2 Density

The volume of each specimen is calculated based on the measured dimensions. The mass of each specimen is determined with a Mettler AT261 scale with an accuracy of 0.01 mg. The mass is determined three times. The reported density is the measured mass divided by the determined volume.

2.5.3 Dynamic Young's Modulus

The Dynamic Young's Modulus (DYM) is determined by measuring the velocity of sound in the sample. According to ASTM standard C769, see [7], the DYM is obtained as follows:

$$E = rv^2 \qquad (1),$$

E = Dynamic Young's Modulus (Pa),
? = Density (kg/m^3), and
v = Velocity of sound (m/s).

The velocity of sound is determined with an Agfa-Krautkramer USM 25, see figure 4, using a nominal frequency of 5 MHz. The set-up is calibrated using a steel sample with a known velocity of sound. The calibration is done before each measurement series and repeated after 20 measurements. The USM 25 measures the traverse time and transforms it into a travel distance based on the selected velocity of sound and a calibration correction for the travel time through the transducers. The velocity of sound is measured by changing the selected velocity of sound to match the travel distance to the specimen thickness. The velocity of sound of each sample is determined three times. To get an indication of the accuracy the velocity of sound is determined for a specimen thickness, which deviates from the actual thickness by 0.02 mm. These accuracy values are only used for internal crosschecks and are not reported.

figure 4 Set-up used for ultrasonic time-of-flight measurements

3 Results

3.1 Irradiation

The aim of the irradiation was to get a large spread in dose with a target of 8 dpa_g. Figure 5 shows the actual variation of the interpolated dose with the position of the specimen in the irradiation rig. The median dose achieved is 7.92 dpa_g or 6.32 x 10^{25} m^{-2} EDN, with a maximum of 9.88 dpa_g (or 7.88 x 10^{25} m^{-2} EDN) and a minimum of 2.92 dpa_g (or 2.33 x 10^{25} m^{-2} EDN). This implies that within the irradiation position used, the radial flux gradient has added a surplus of about 0.8 dpa_g on the expected peak value.

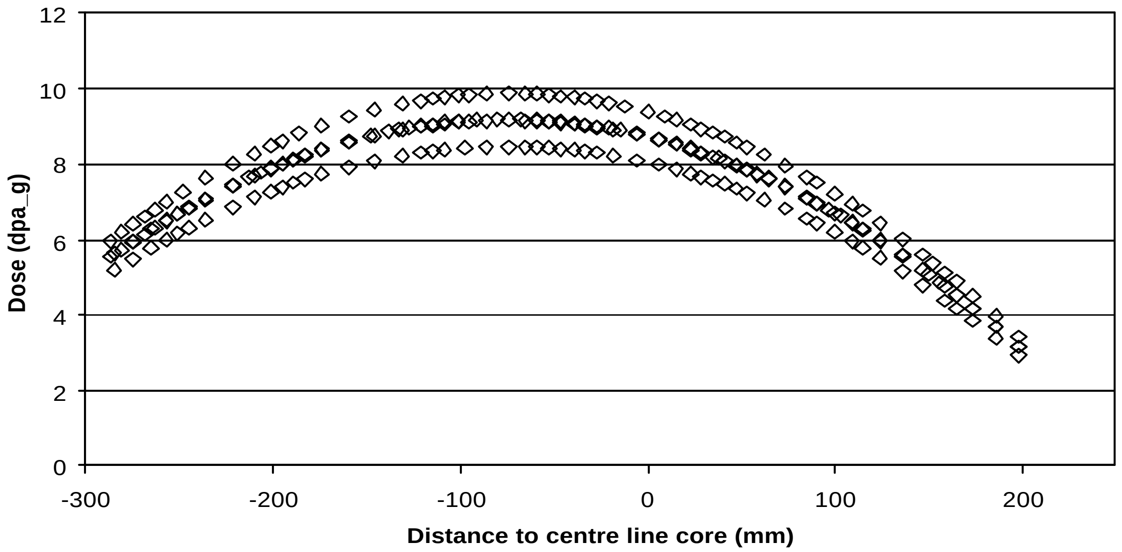

figure 5 Dose variation of specimens due to the position in INNOGRAPH-01A

The temperature readings during the full irradiation period have not been evaluated in full detail yet. The low dose specimens (< 4 dpa_g) have been irradiated at a lower temperature, in a range between about 650 and 690 °C.

3.2 Grouped results

As the total measurement time for the full test matrix is quite long, a priority has been given to about 100 high dose specimens. A selection of these specimens will be re-irradiated in an INNOGRAPH-01B rig. The effective test matrix is shown in table 4.

table 4 Number of high dose specimens per grade, including dose range

Supplier	Grade	Total per grade	Dose (dpa_g)	Orient.	Total per orientation	Centre		Edge	
						6 mm	12 mm	6 mm	12 mm
SGL-Carbon	NBG-10	14	5.93 - 9.15	AG	7	4	1	2	-
				WG	7	3	1	3	-
	NBG-25	14	6.31 - 9.84	AG	7	4	1	2	-
				WG	7	3	1	3	-
	NBG-20	8	6.60 - 9.14	AG	4	4	-	-	-
				WG	4	4	-	-	-
Toyo Tanso	IG-110	14	6.68 - 9.84	AG	7	4	1	2	-
				WG	7	3	1	3	-
	IG-430	8	6.00 - 9.63	AG	4	3	-	1	-
				WG	4	3	-	1	-
Graftech	PCEA	14	6.66 - 9.78	AG	7	3	1	3	-
				WG	7	3	1	3	-
	PCIB	14	6.16 - 9.87	AG	7	3	1	3	-
				WG	7	3	1	3	-
	PPEA	11	5.73 - 9.17	AG	6	5	1	-	-
				WG	5	4	1	-	-

3.2.1 Reference measurements

In table 5 the average results are shown of the high dose specimens before the irradiation. If available, the material data as provided by the manufacturer are also presented. The ? -columns are the standard deviations of the measurements in a single group.

table 5 Average results of all reference measurements on high dose specimens (see table 4)

			NRG		Manufacturer	NRG		Manufacturer
			? (g/cm³)	? ? (g/cm³)	? (g/cm³)	E (GPa)	? E (GPa)	E (GPa)
NBG-10	Centre	AG	1.812	0.007	1.79	12.4	0.3	9.7
		WG	1.813	0.003		13.0	0.5	9.7
	Edge	AG	1.814	0.017	1.81	12.5	0.0	9.9
		WG	1.819	0.006		13.4	0.2	10.3
NBG-25	Centre	AG	1.813	0.003	1.815	10.6	0.1	9.9
		WG	1.816	0.004		11.4	0.1	10.9
	Edge	AG	1.820	0.005		10.8	0.1	9.9
		WG	1.819	0.002		11.7	0.2	10.9
NBG-20	Centre	AG	1.800	0.007	1.78	11.4	0.1	9.4
		WG	1.751	0.015		10.6	0.3	10.2
IG-110	Centre	AG	1.751	0.006	1.77	8.9	0.2	10.8
		WG	1.771	0.003		11.0	0.4	-
	Edge	AG	1.769	0.001		9.4	0.1	10.8
		WG	1.771	0.003		10.7	0.1	-
IG-430	Centre	AG	1.789	0.002	1.82	9.7	0.1	9.7
		WG	1.794	0.010		10.9	0.1	-
	Edge	AG	1.828	-		10.4	-	9.7
		WG	1.828	-		11.7	-	-
PCEA	Centre	AG	1.810	0.007	1.821	10.9	0.1	9.9
		WG	1.813	0.002		11.0	0.1	11.3
	Edge	AG	1.838	0.006	1.839	11.4	0.2	9.9
		WG	1.838	0.002		12.2	0.2	11.3
PCIB	Centre	AG	1.857	0.004	1.858	12.1	0.1	10.7
		WG	1.857	0.007		12.4	0.1	11.1
	Edge	AG	1.856	0.004	1.857	12.1	0.1	10.7
		WG	1.860	0.003		12.8	0.0	11.1
PPEA	Centre	AG	1.826	0.003	1.854	12.9	0.2	11.1
		WG	1.817	0.003		13.4	0.3	12.5

3.2.2 INNOGRAPH-01A measurements

The results after irradiation are given as the percentage of change compared to the pre-irradiation characteristics. The results are presented in table 6. It is important to note that the average dose of each group is different and therefore it is difficult to compare the average results with each other. In table 7 the results are summarised per grade.

table 6 Average results of high dose specimens per group after irradiation. ?x is the flattening of the specimen, ?d the diameter, ?l the length and ?vol. the volume, see figure 1.

			Nr. of specimens	Dose (dpa_g)	? x (%)	? d (%)	? l (%)	? vol. (%)	? ? (%)	? E (%)
NBG-10	CENTRE	AG	5	7.99	-1.5	-1.2	-1.4	-4.0	4.0	99
		WG	4	8.24	-1.3	-1.2	-1.8	-4.2	4.2	109
	EDGE	AG	2	8.46	-1.5	-1.4	-1.2	-3.9	4.0	105
		WG	3	7.58	-1.0	-1.1	-1.7	-3.8	3.8	100
NBG-25	CENTRE	AG	5	8.41	-1.7	-1.7	-0.6	-3.9	4.1	168
		WG	4	7.91	-0.4	-1.1	-1.8	-3.7	3.8	159
	EDGE	AG	2	8.67	-1.6	-1.4	-0.7	-3.6	3.8	149
		WG	3	8.72	-0.5	-1.1	-1.9	-3.8	4.0	143
NBG-20	CENTRE	AG	4	8.31	-0.4	-0.2	-1.7	-2.2	1.9	103
		WG	4	8.17	-0.2	0.1	-2.3	-2.3	2.1	104
IG-110	CENTRE	AG	5	8.36	-1.7	-1.8	-1.0	-4.4	4.9	137
		WG	4	8.53	-1.3	-1.4	-2.0	-4.6	4.8	133
	EDGE	AG	2	8.54	-1.5	-1.8	-1.2	-4.7	4.8	145
		WG	3	8.08	-1.1	-1.2	-2.0	-4.4	4.5	125
IG-430	CENTRE	AG	3	7.96	-1.0	-0.9	0.2	-1.6	1.6	159
		WG	3	8.20	0.1	-0.5	-1.2	-2.0	1.9	145
	EDGE	AG	1	7.75	0.2	-0.1	-0.3	-0.3	0.3	139
		WG	1	8.42	-0.1	-0.1	-1.4	-1.5	1.5	140
PCEA	CENTRE	AG	4	8.51	-2.1	-1.9	-2.0	-5.7	6.0	112
		WG	4	8.51	-1.7	-1.8	-2.4	-5.8	6.1	118
	EDGE	AG	3	7.99	-2.2	-2.0	-1.8	-5.7	6.0	113
		WG	3	7.86	-1.7	-1.7	-2.3	-5.6	5.9	111
PCIB	CENTRE	AG	4	8.47	-0.8	-0.6	-0.3	-1.6	1.7	144
		WG	4	8.55	-0.3	-0.5	-0.7	-1.6	1.6	145
	EDGE	AG	3	8.90	-0.7	-0.7	-0.2	-1.6	1.6	145
		WG	3	8.79	-0.2	-0.4	-1.0	-1.7	1.7	141
PPEA	CENTRE	AG	6	7.85	-1.6	-1.3	-1.2	-4.0	4.1	105
		WG	5	8.05	-1.3	-1.2	-1.8	-4.2	4.3	107

table 7 Average results of high dose specimens per grade after irradiation. ?x is the flattening of the specimen, ?d the diameter, ?l the length and ?vol. the volume, see figure 1.

	Nr. of specimens	Dose (dpa_g)	? x (%)	? d (%)	? l (%)	?vol. (%)	? ? (%)	? E (%)
NBG-10	14	8.0	-1.3	-1.2	-1.6	-4.0	4.0	102.8
NBG-25	14	8.4	-1.1	-1.4	-1.2	-3.8	3.9	157.4
NBG-20	8	8.2	-0.3	-0.1	-2.0	-2.3	2.0	103.7
IG-110	14	8.4	-1.4	-1.6	-1.5	-4.5	4.8	134.7
IG-430	8	8.1	-0.3	-0.5	-0.6	-1.6	1.5	148.9
PCEA	14	8.3	-1.9	-1.8	-2.1	-5.7	6.0	114.0
PCIB	14	8.7	-0.5	-0.5	-0.6	-1.6	1.6	144.1
PPEA	11	7.9	-1.5	-1.3	-1.5	-4.1	4.2	105.6

3.3 Single specimen results

3.3.1 Z-direction dimensional change

For specimens of an extruded grade the length of WG specimens should give similar results as the flattening on the AG specimens. While for Iso-moulded grades the length of the AG specimens should coincide with the flattening of the WG specimens. In the following figures the results of each grade are presented separately.

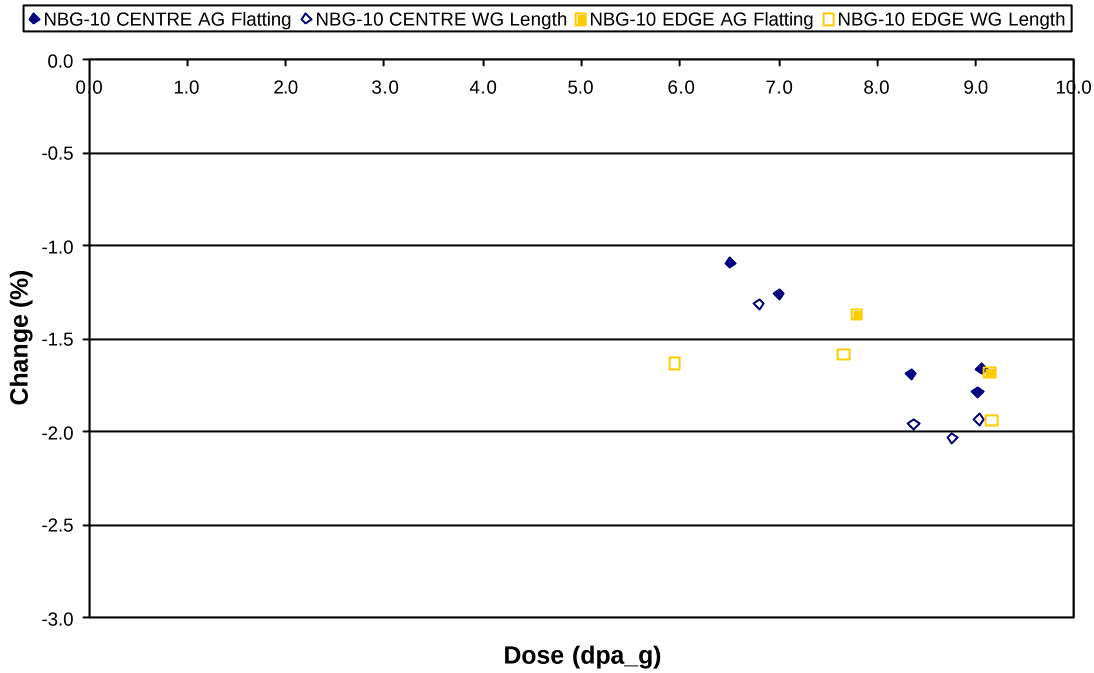

figure 6 Comparison of the dimensional change in the z-direction for NBG-10 specimens

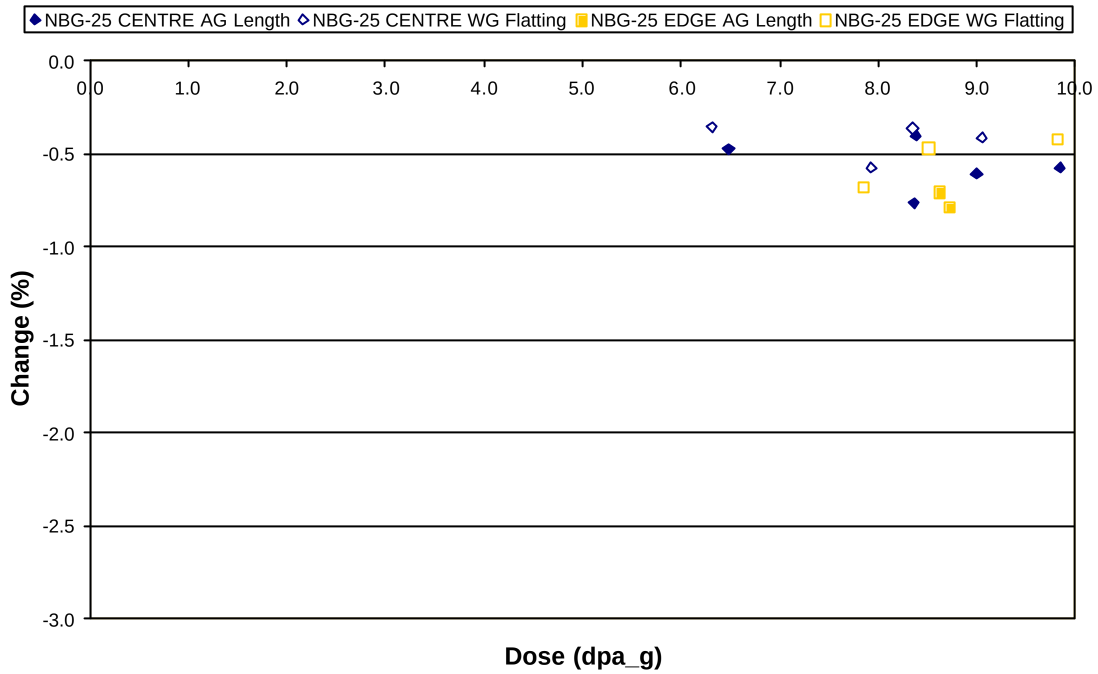

figure 7 Comparison of the dimensional change in the z-direction for NBG-25 specimens

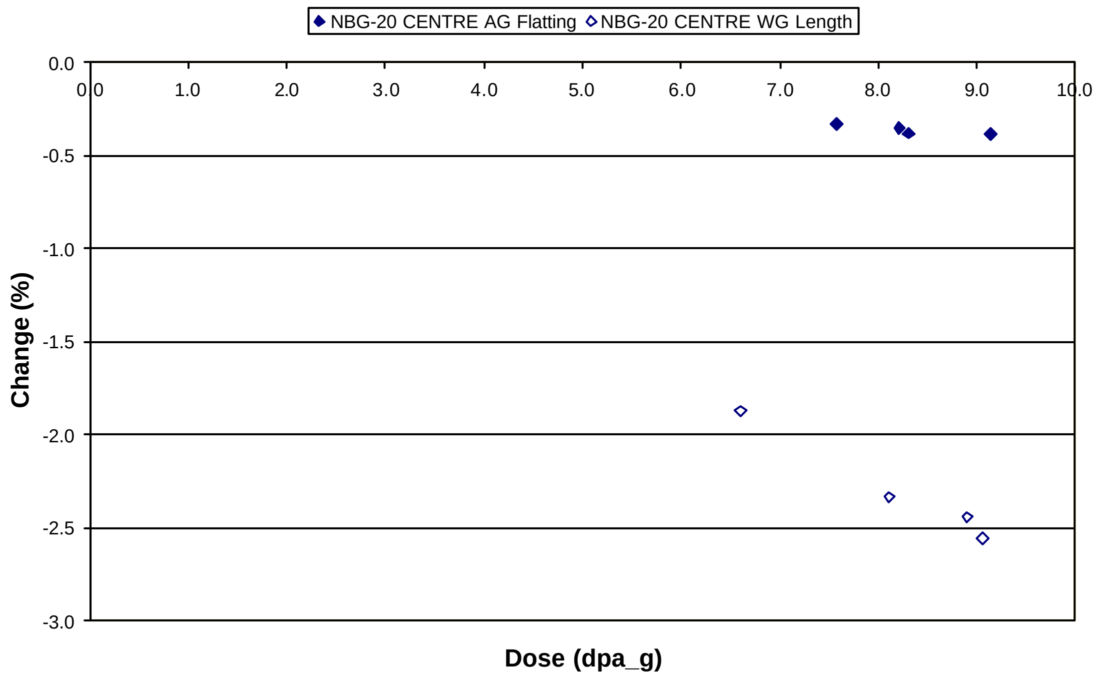

figure 8 Comparison of the dimensional change in the z-direction for NBG-20 specimens

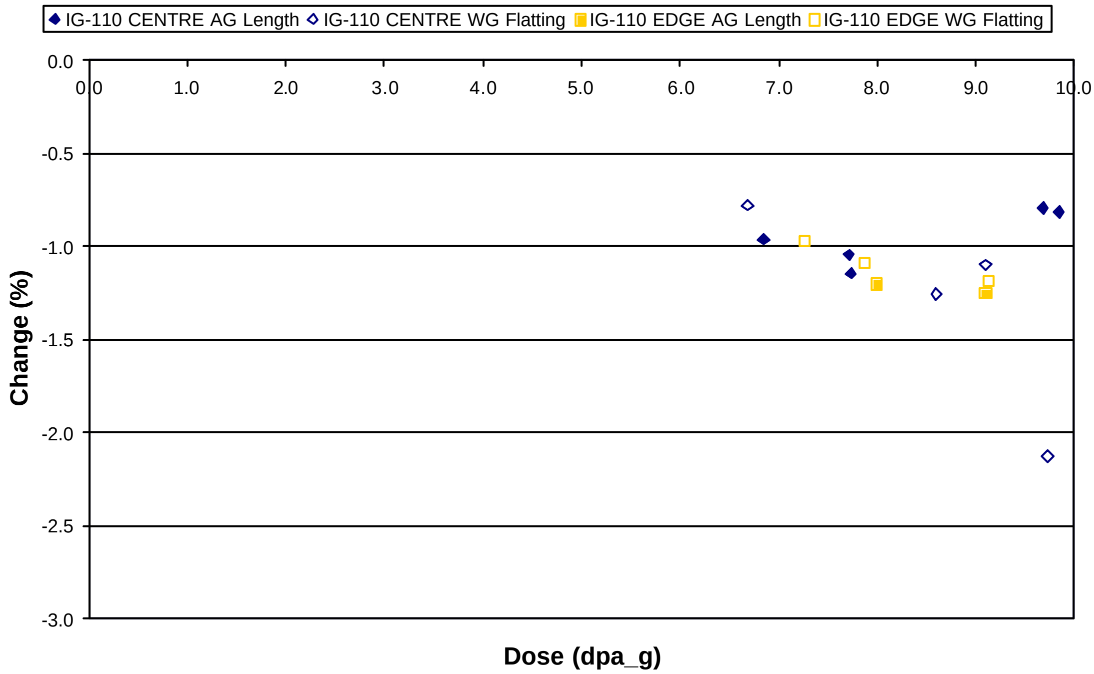

figure 9 Comparison of the dimensional change in the z-direction for IG-110 specimens

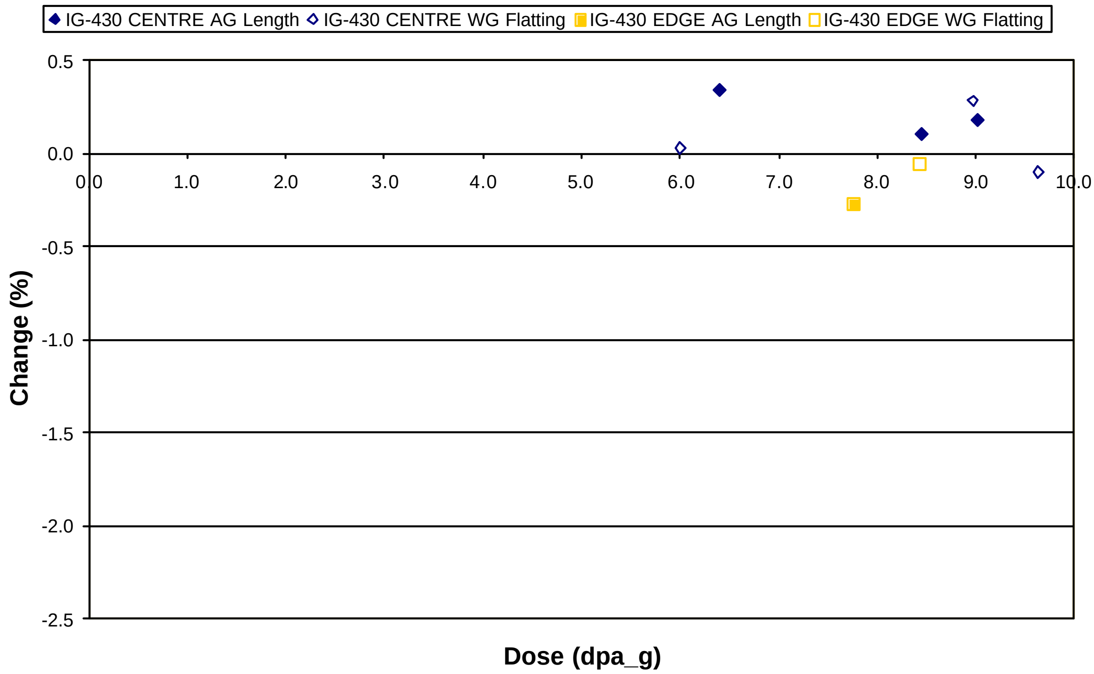

figure 10 Comparison of the dimensional change in the z-direction for IG-430 specimens

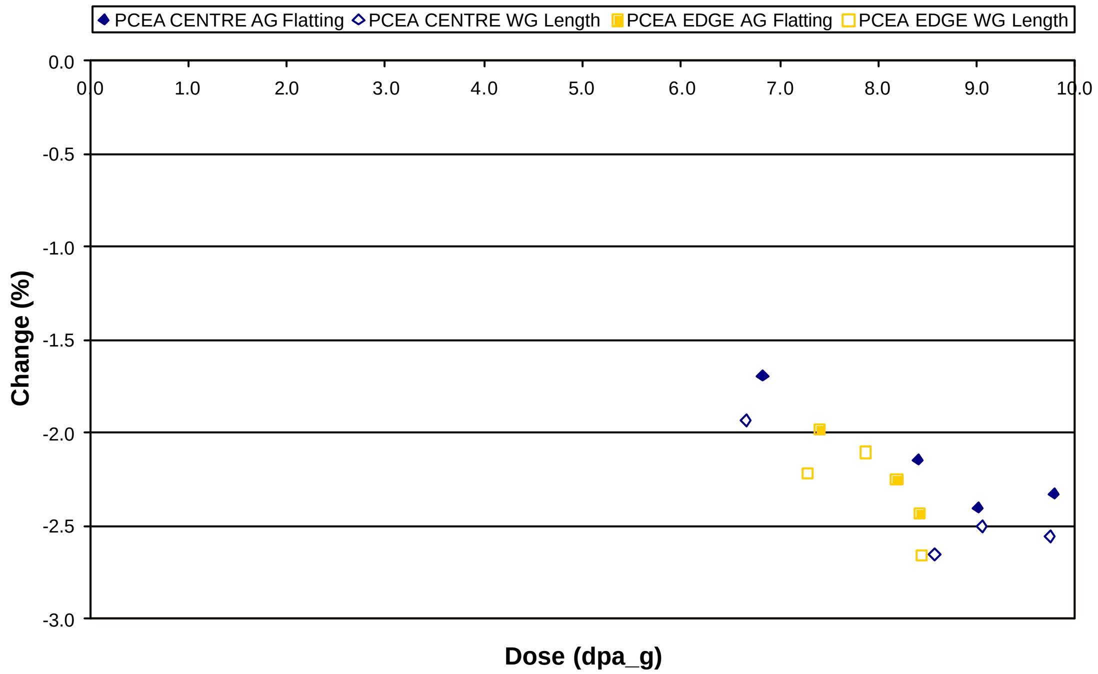

figure 11   Comparison of the dimensional change in the z-direction for PCEA specimens

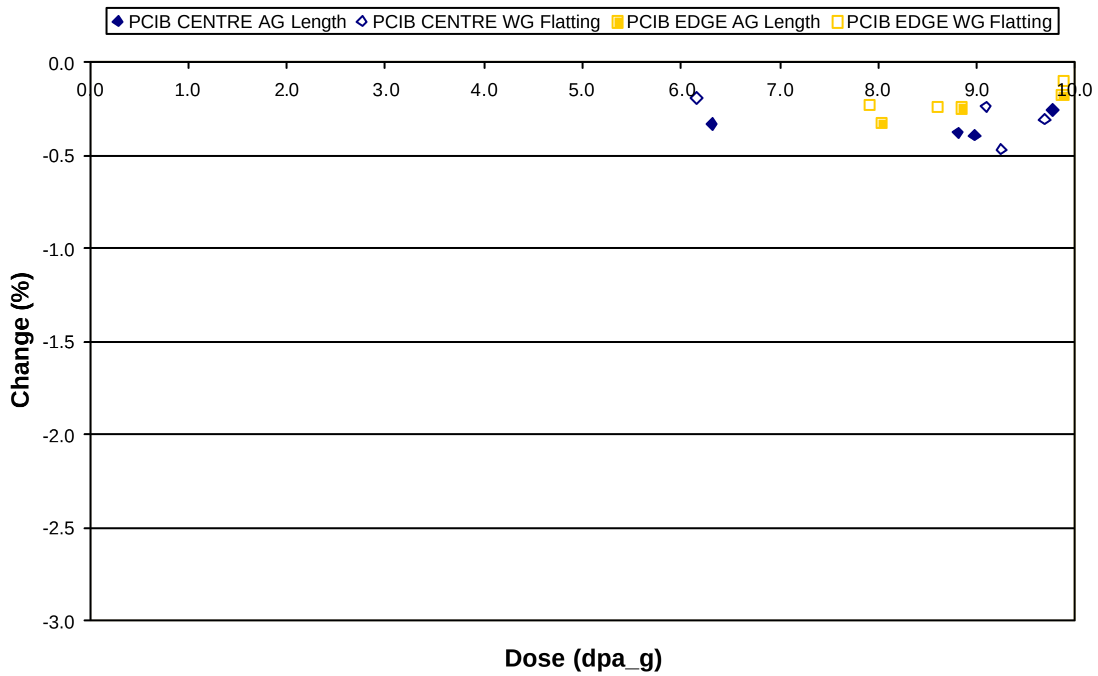

figure 12   Comparison of the dimensional change in the z-direction for PCIB specimens

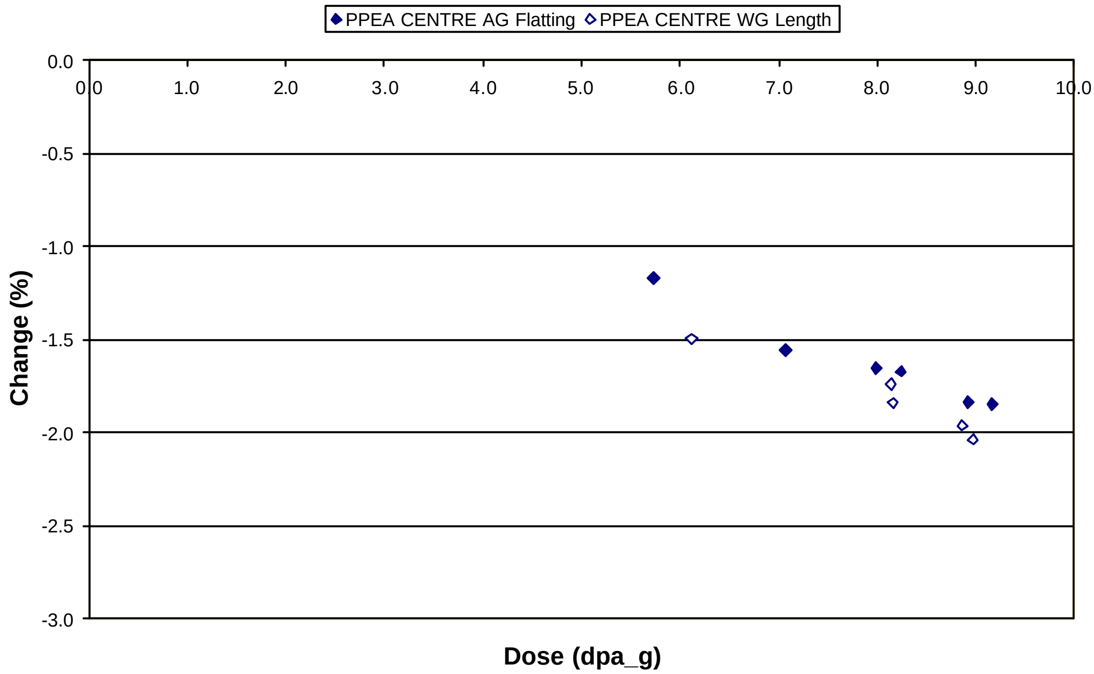

figure 13 Comparison of the dimensional change in the z-direction for PPEA specimens

3.3.2 XY-plane dimensional change

As for the z-direction, the dimensional changes in the xy-plane are presented for each grade separately in the following graphs.

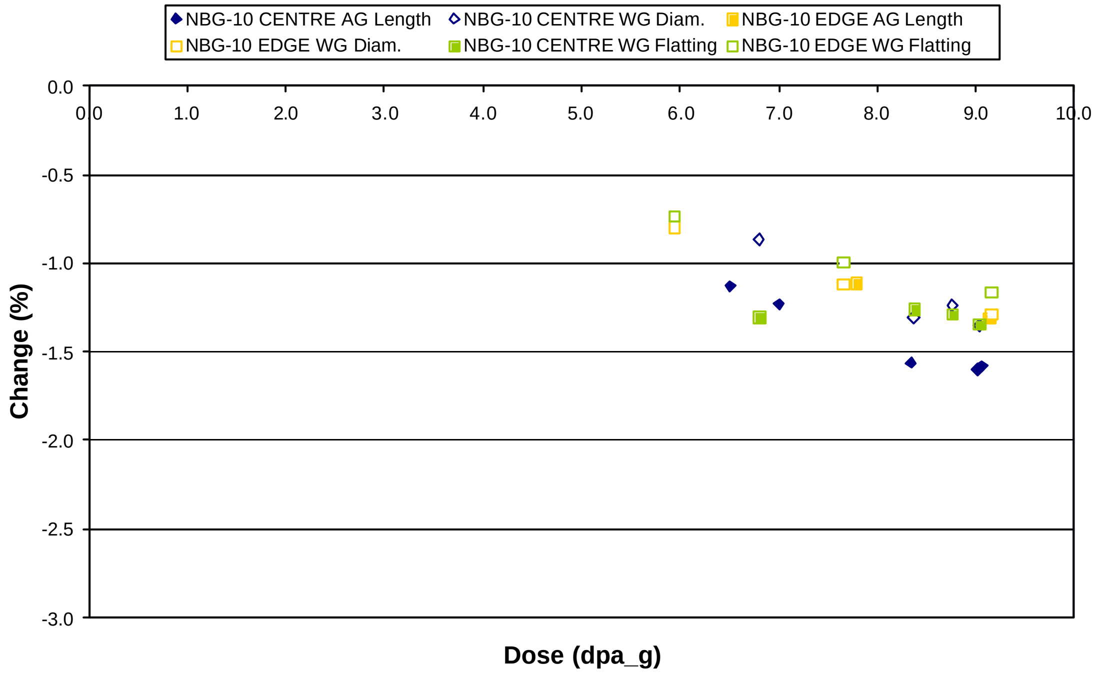

figure 14 Comparison of the dimensional change in the xy-plane for NBG-10 specimens

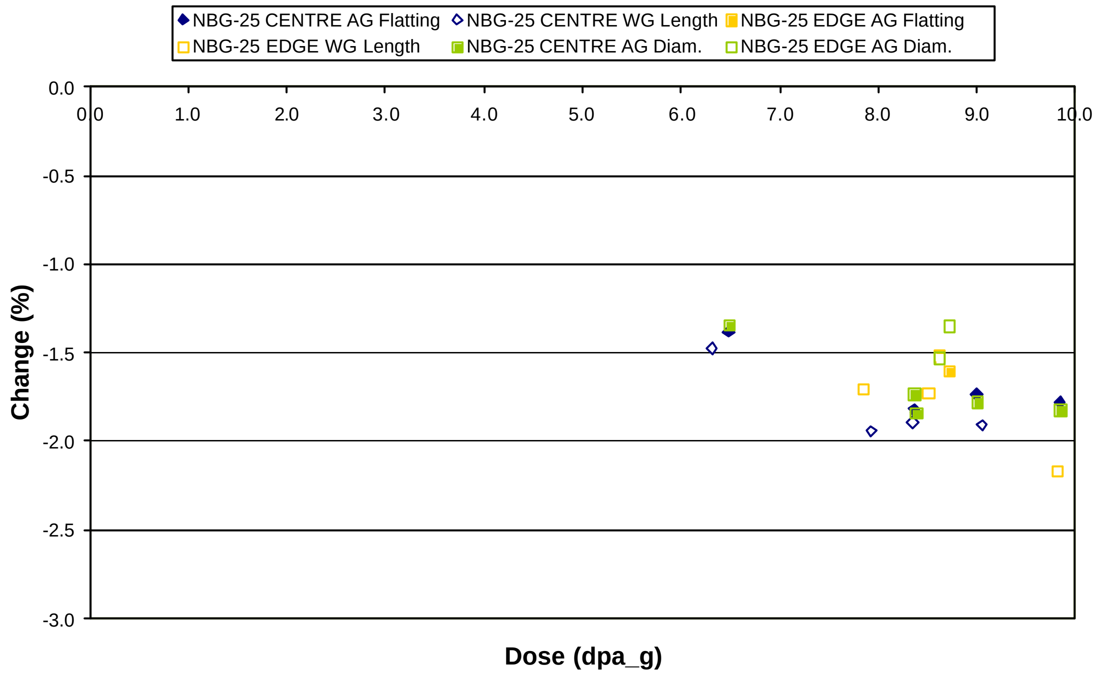

figure 15 Comparison of the dimensional change in the xy-plane for NBG-25 specimens

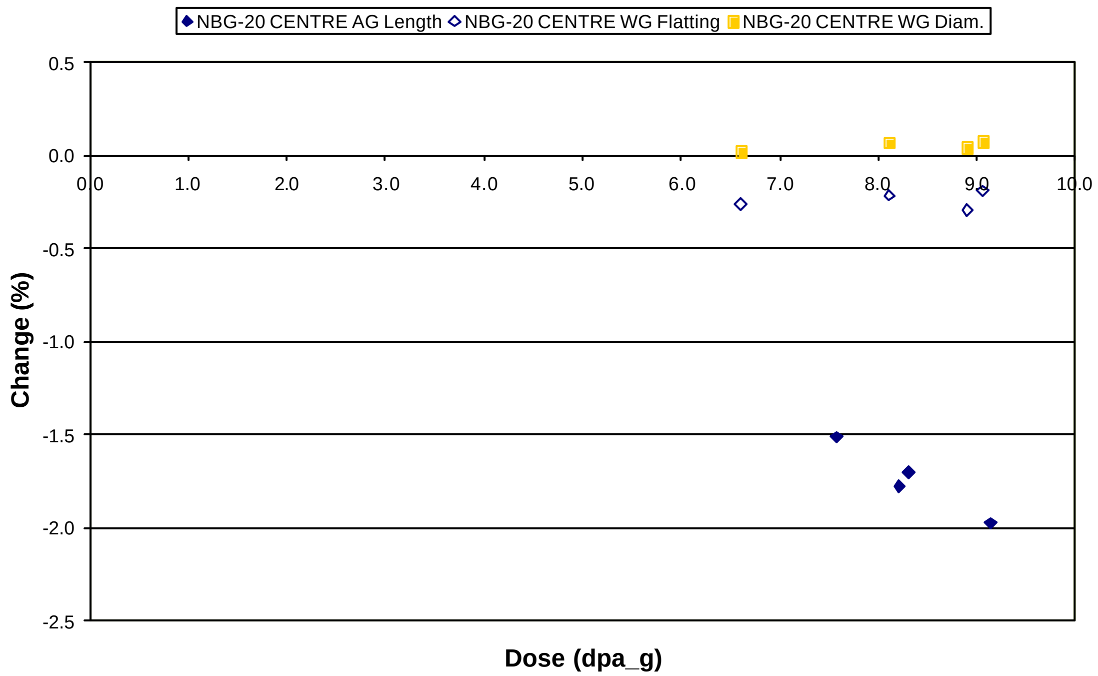

figure 16 Comparison of the dimensional change in the xy-plane for NBG-20 specimens

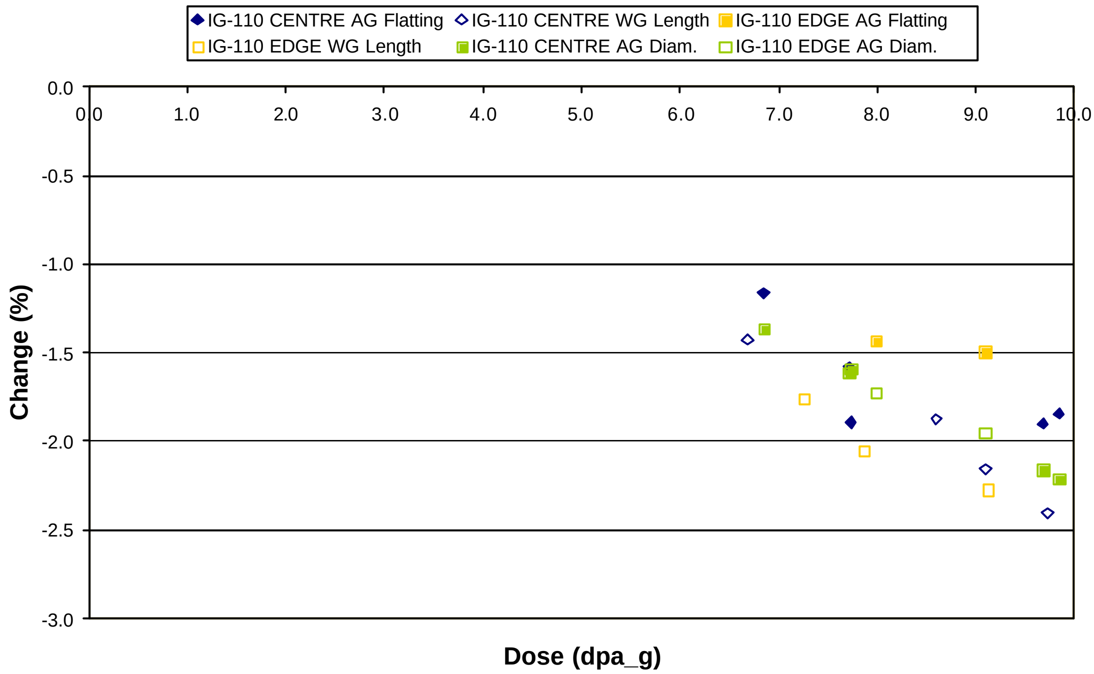

figure 17 Comparison of the dimensional change in the xy-plane for IG-110 specimens

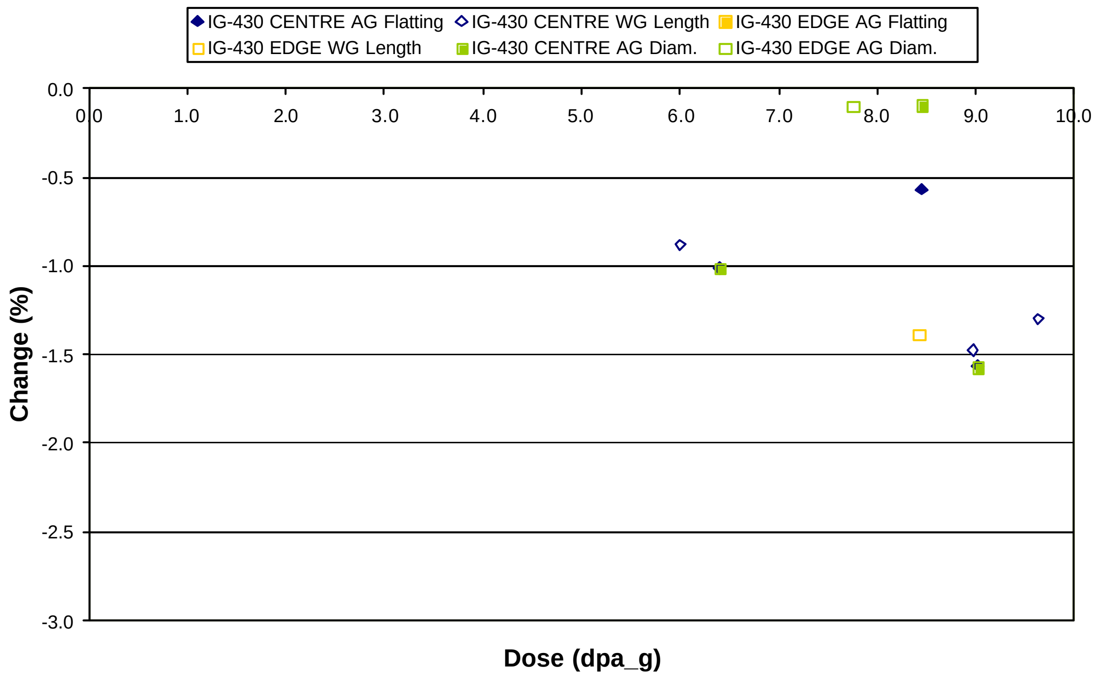

figure 18 Comparison of the dimensional change in the xy-plane for IG-430 specimens

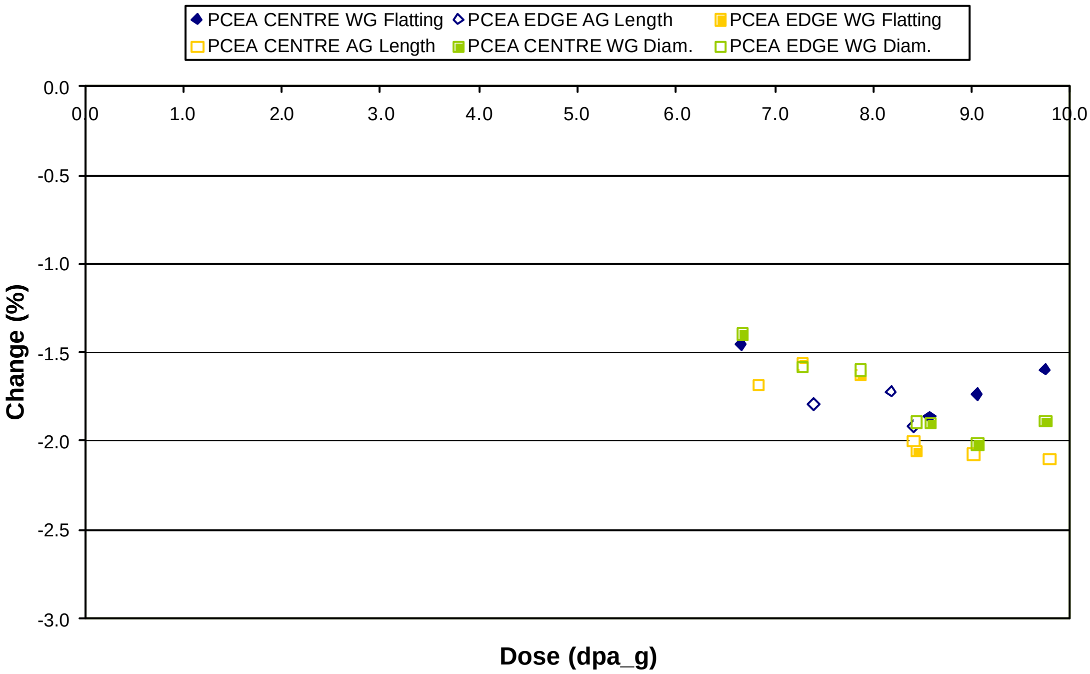

figure 19 Comparison of the dimensional change in the xy-plane for PCEA specimens

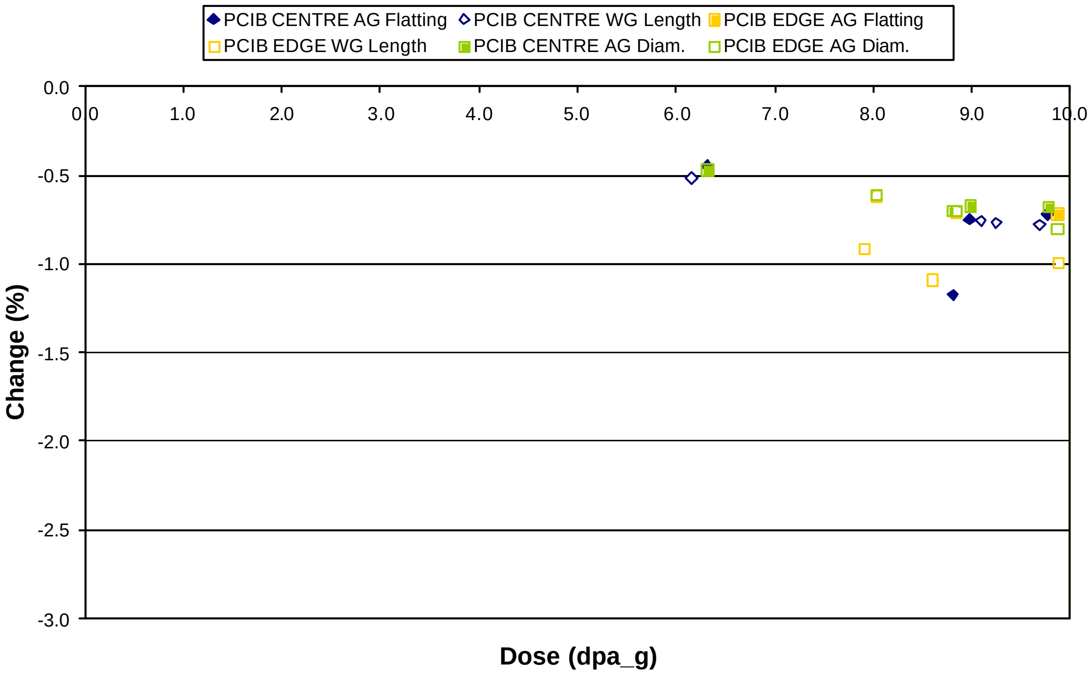

figure 20 Comparison of the dimensional change in the xy-plane for PCIB specimens

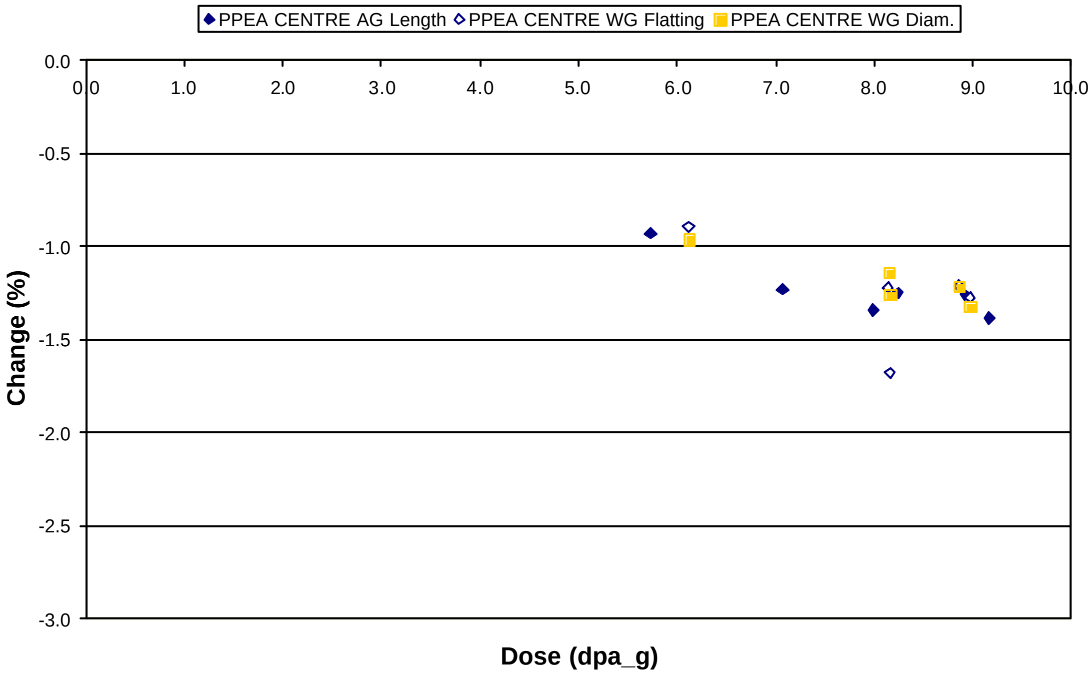

figure 21 Comparison of the dimensional change in the xy-plane for PPEA specimens

3.3.3 Volumetric change

The volumetric change of each specimen grouped per grade is presented in the following graphs.

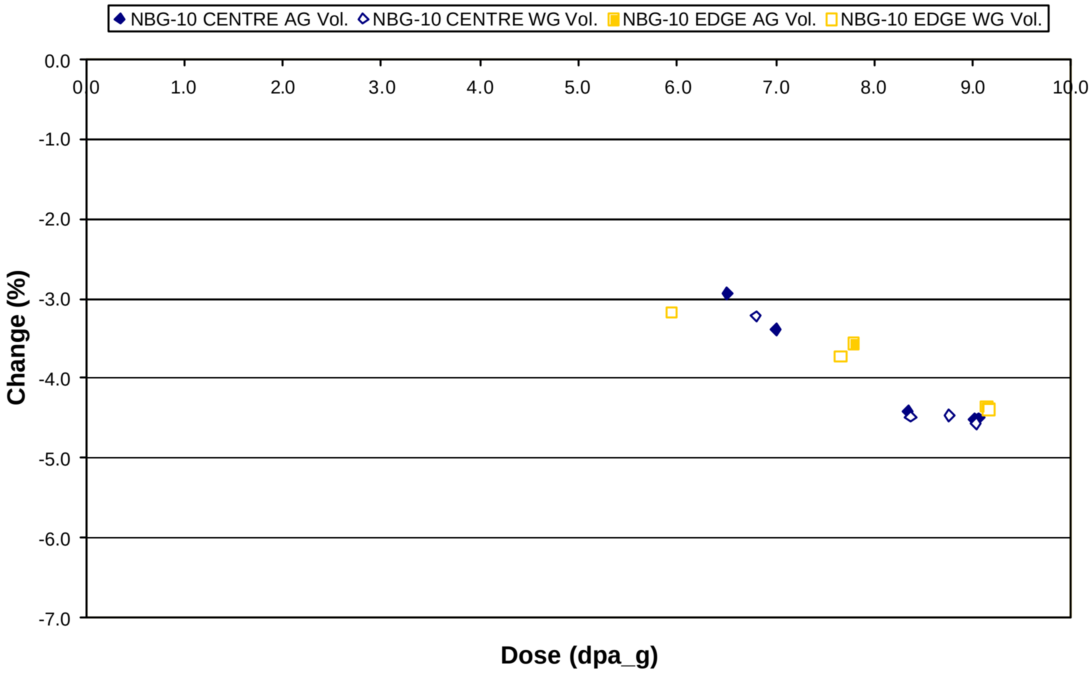

figure 22 Comparison of the volumetric change for NBG-10 specimens

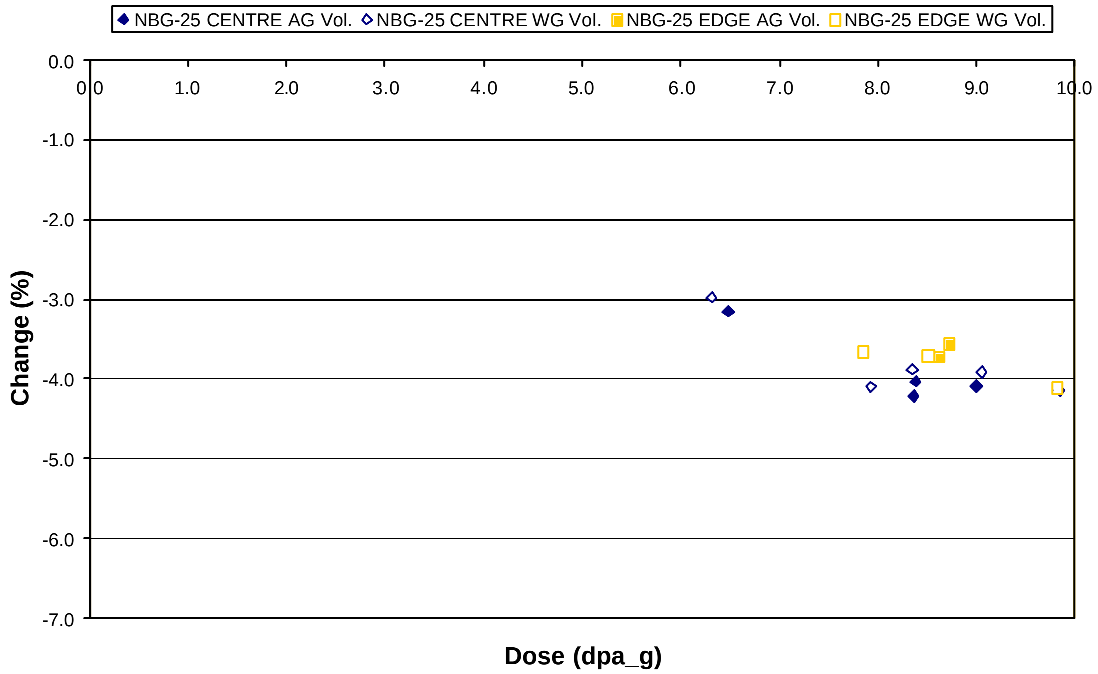

figure 23 Comparison of the volumetric change for NBG-25 specimens

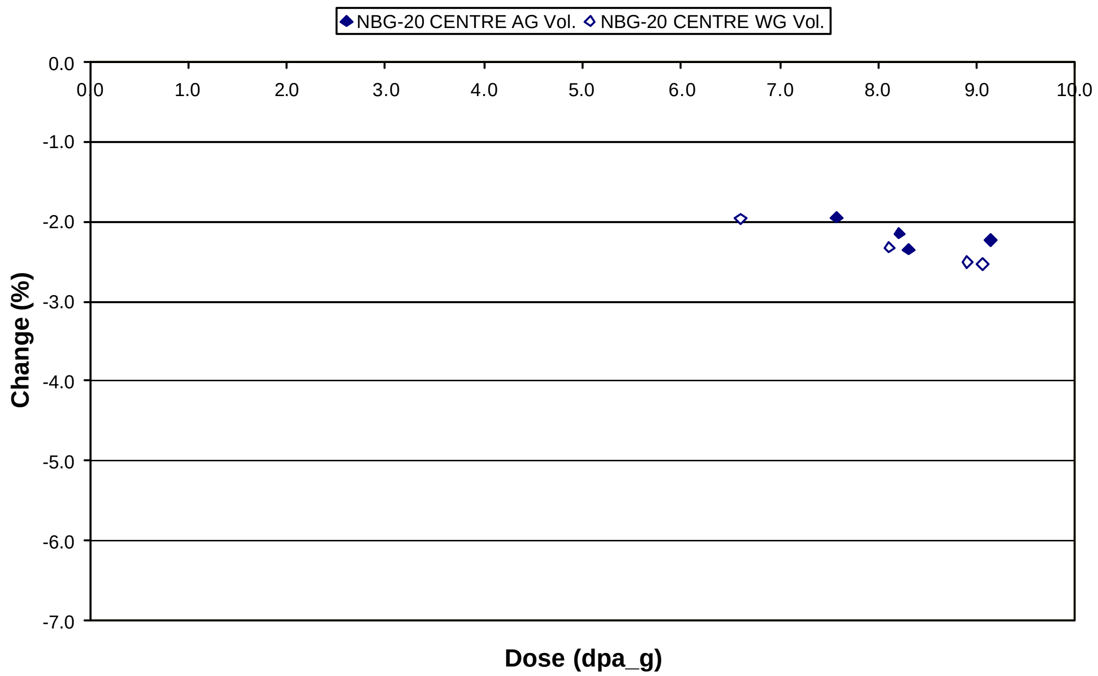

figure 24 Comparison of the volumetric change for NBG-20 specimens

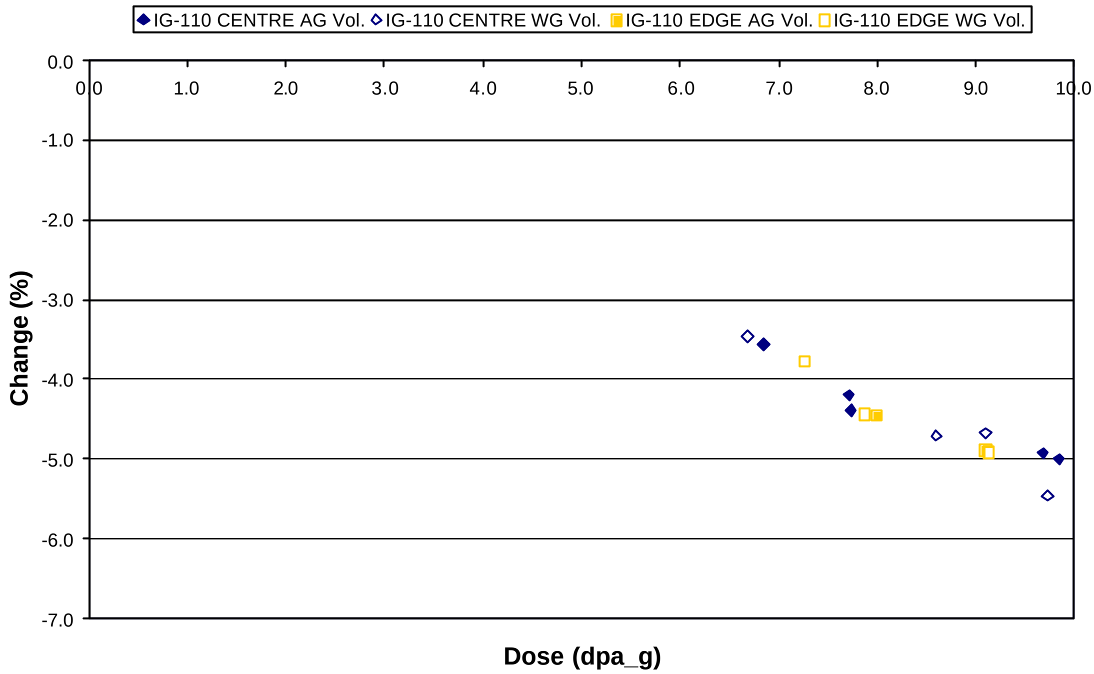

figure 25 Comparison of the volumetric change for IG-110 specimens

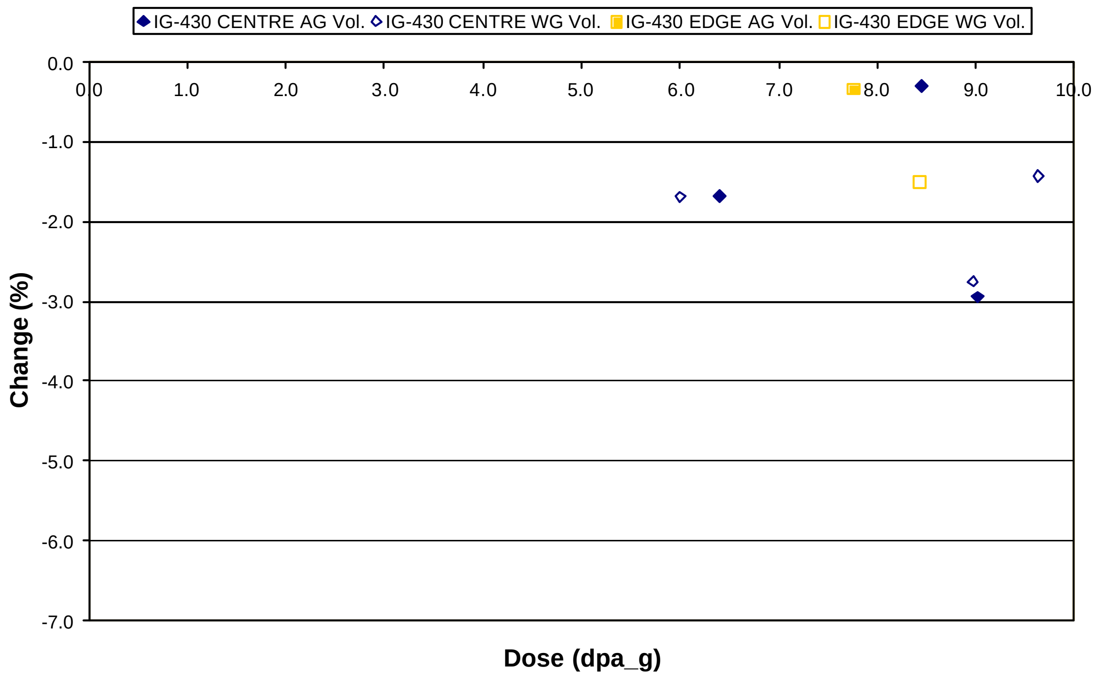

figure 26 Comparison of the volumetric change for IG-430 specimens

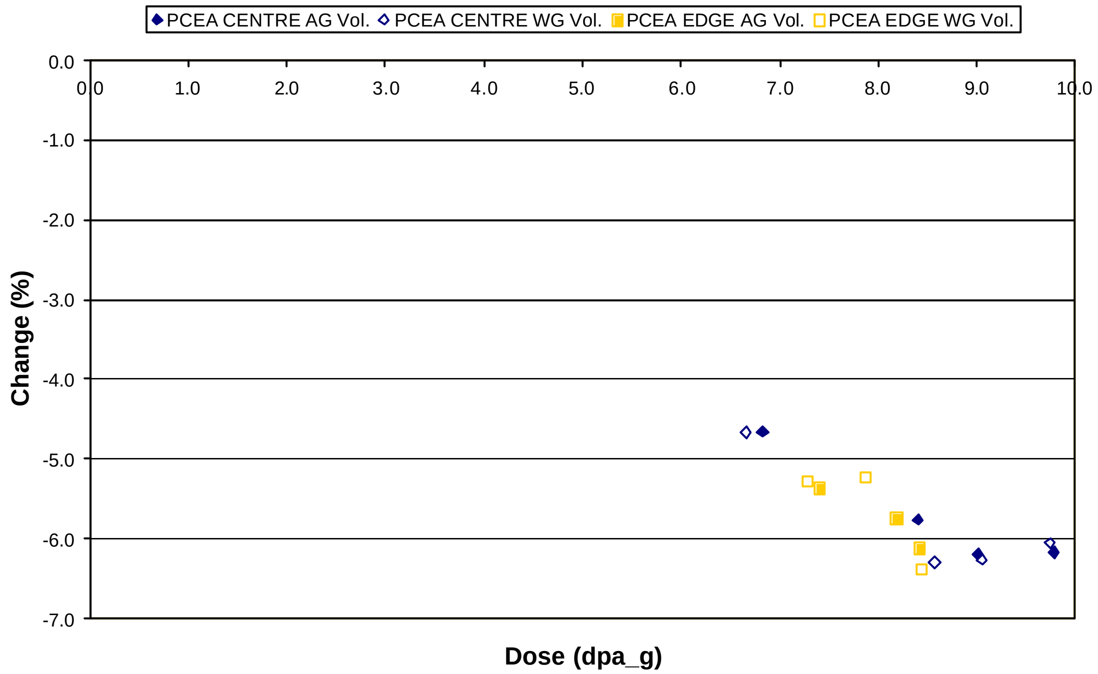

figure 27 Comparison of the volumetric change for PCEA specimens

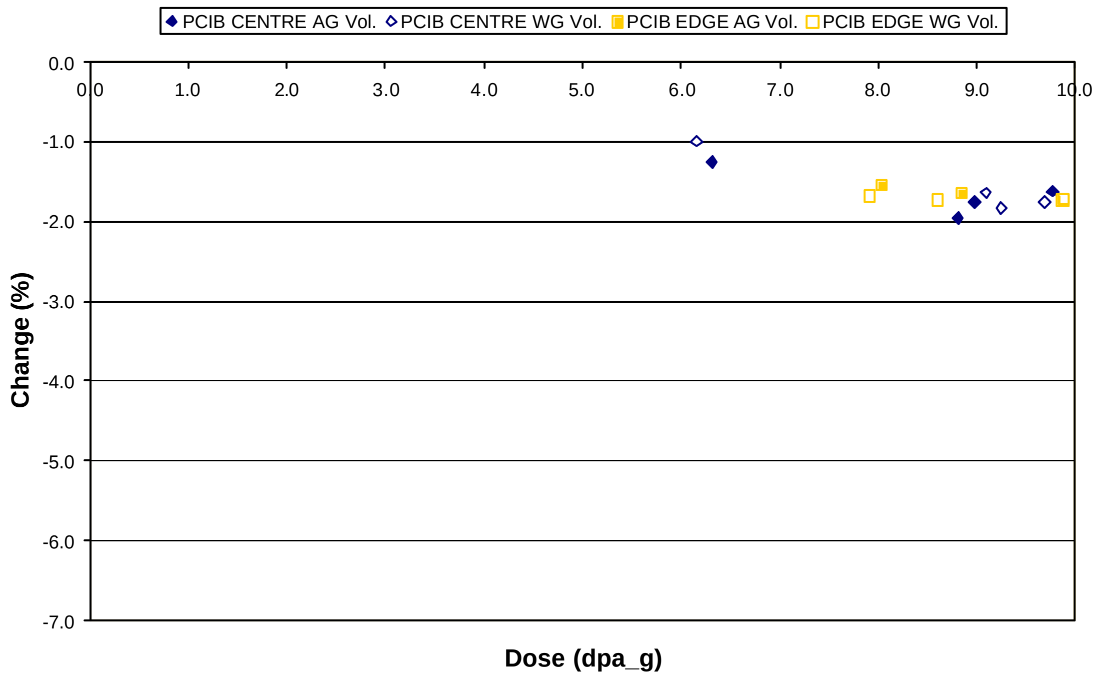

figure 28 Comparison of the volumetric change for PCIB specimens

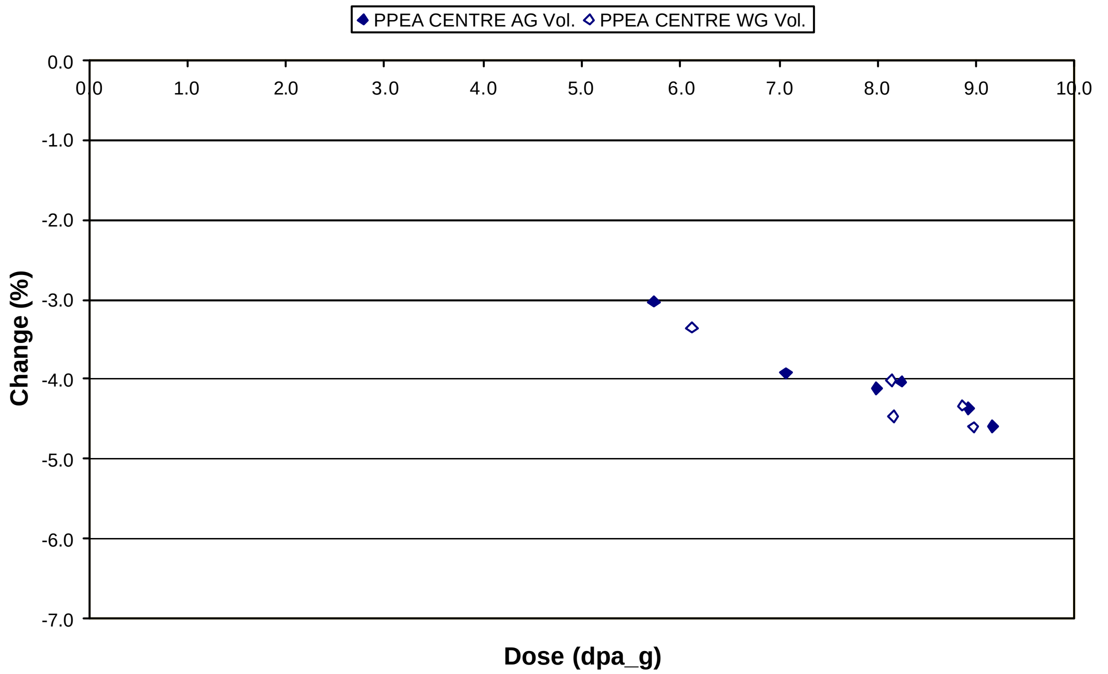

figure 29 Comparison of the volumetric change for PPEA specimens

3.3.4 Dynamic Youngs Modulus change

The DYM change results are presented in the following graphs

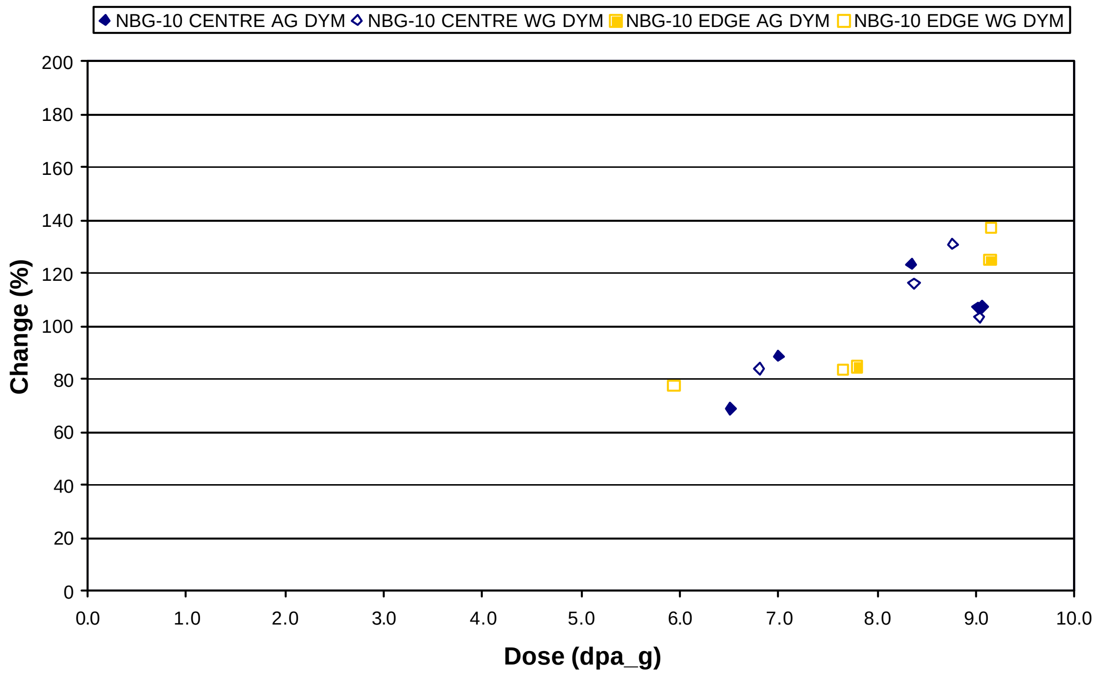

figure 30 Comparison of the DYM change for NBG-10 specimens

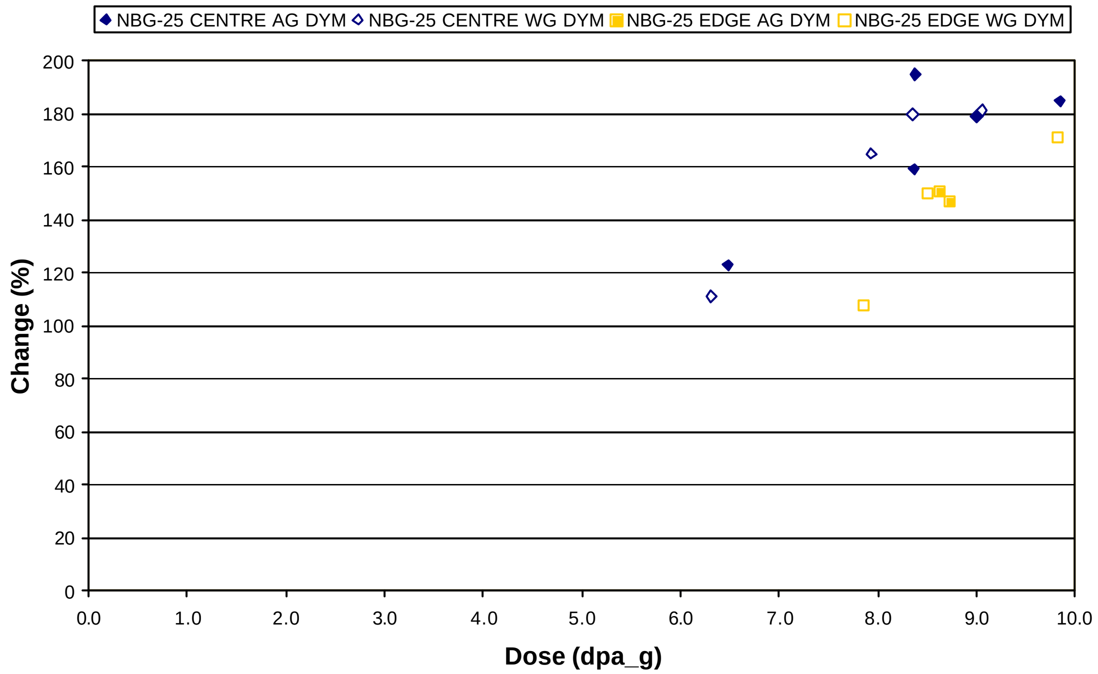

figure 31 Comparison of the DYM change for NBG-25 specimens

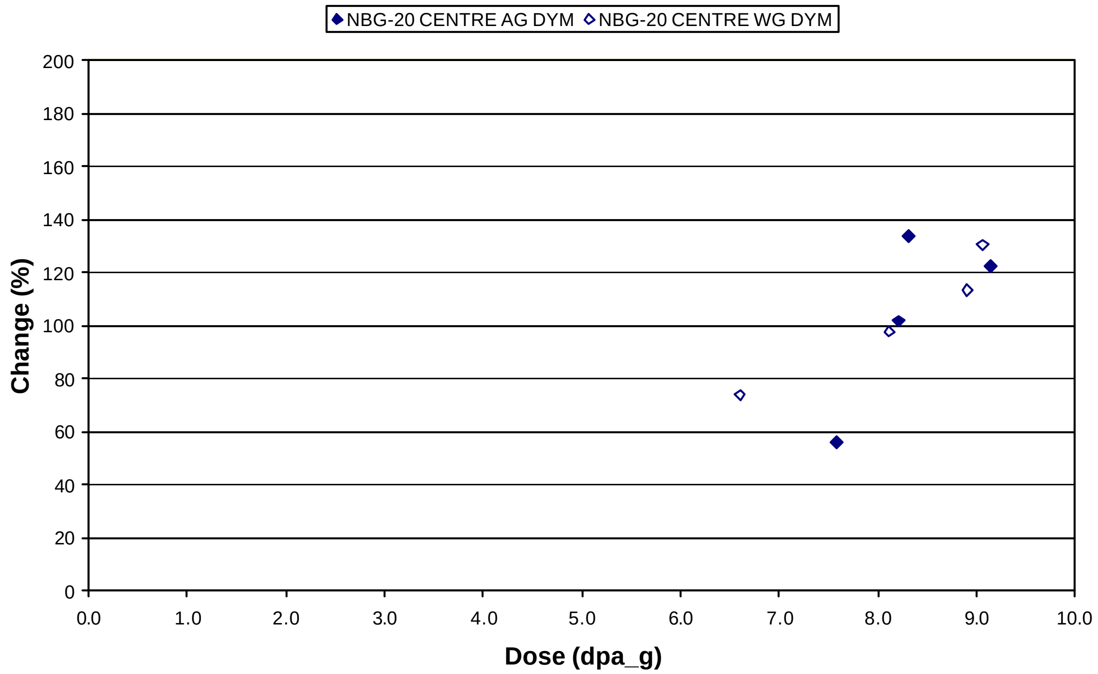

figure 32 Comparison of the DYM change for NBG-20 specimens

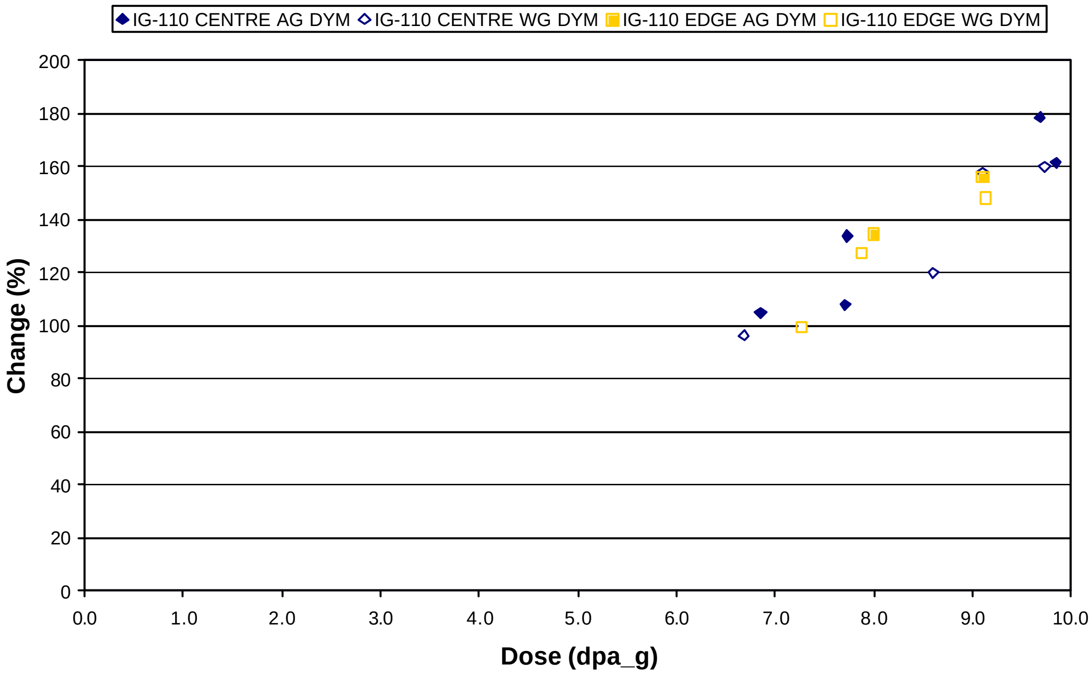

figure 33 Comparison of the DYM change for IG-110 specimens

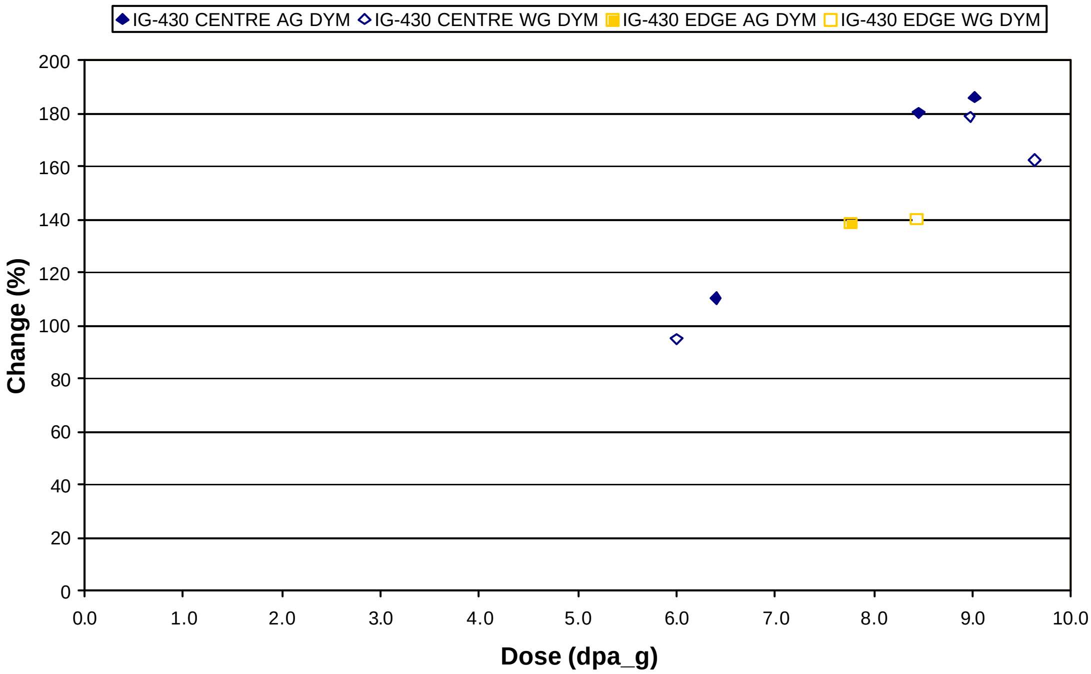

figure 34 Comparison of the DYM change for IG-430 specimens

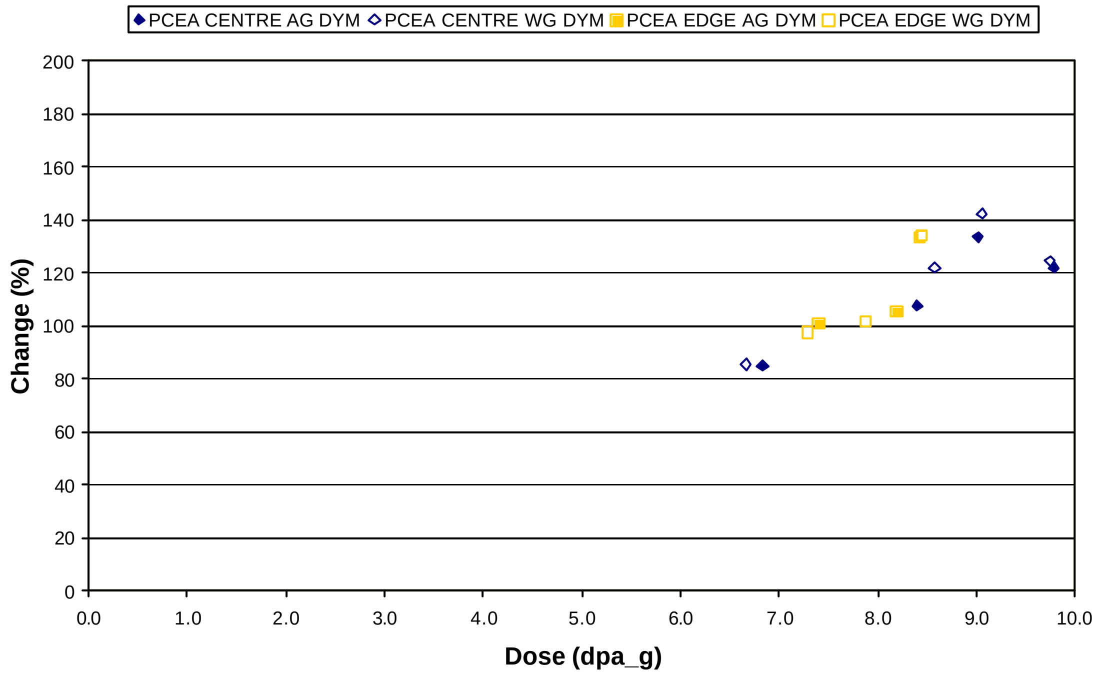

figure 35 Comparison of the DYM change for PCEA specimens

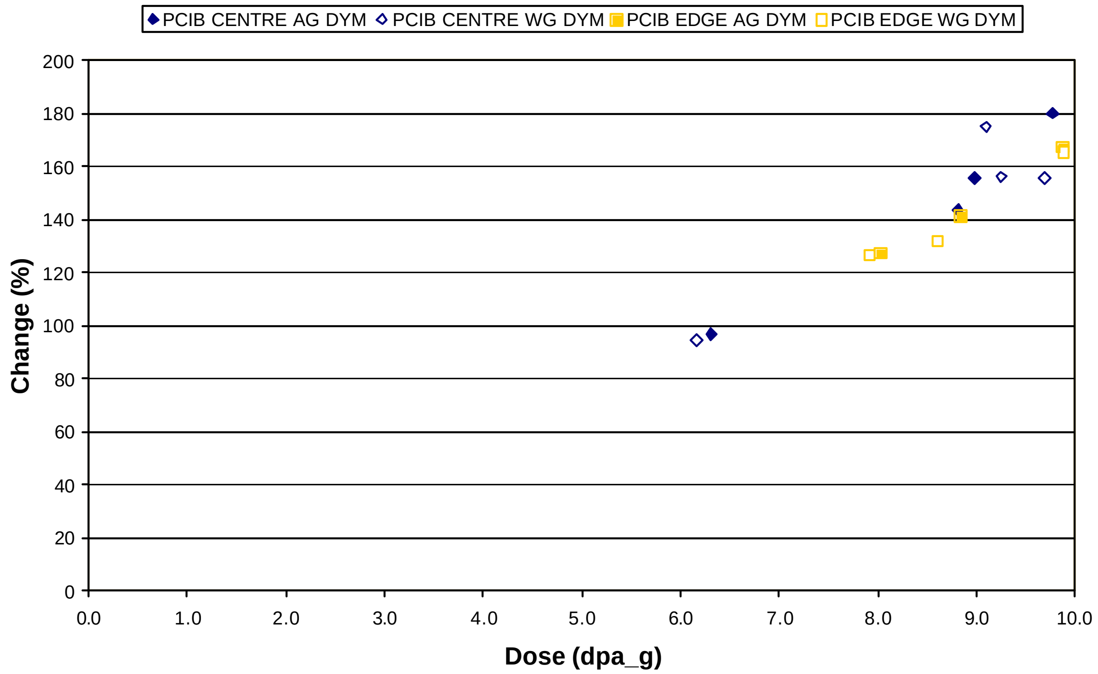

figure 36 Comparison of the DYM change for PCIB specimens

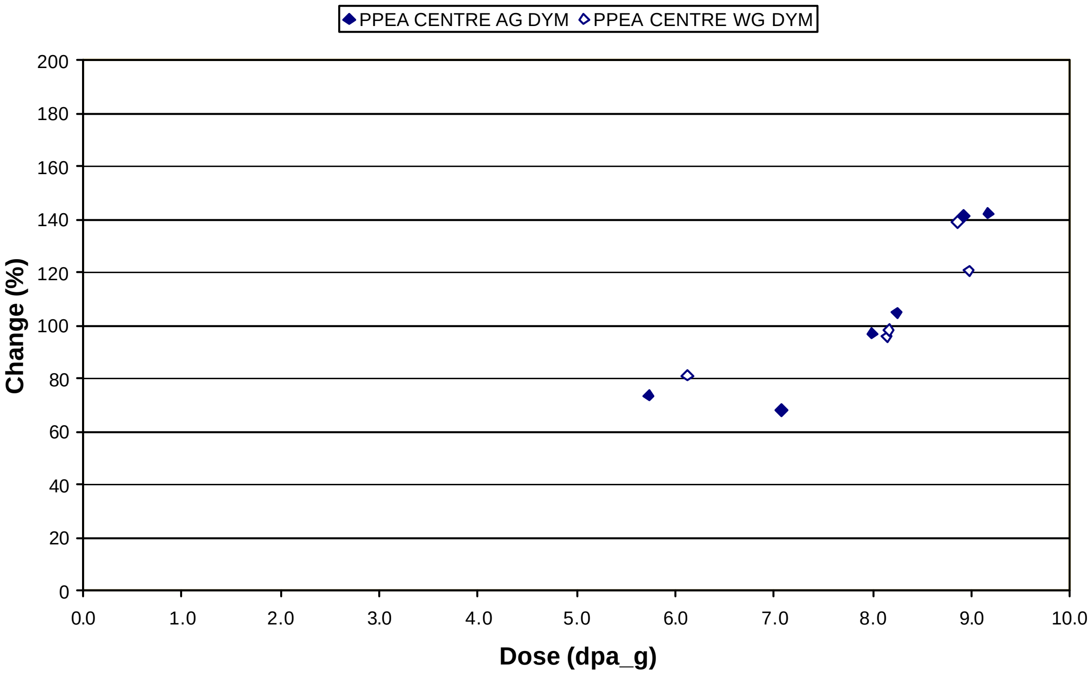

figure 37 Comparison of the DYM change for PPEA specimens

4 Discussion

All results show a reasonable amount of scatter, which underlines the need for further measurements on remaining specimens for adequate statistics.
The results obtained on minor grades IG-430 (for large scatter) and NBG-20 (for strong anisotropy in dimensional change) need further elaboration.
The average results per grade show that up to ±8 dpa IG-110 shows the largest shrinkage (4.5%), while IG-430 and PCIB both show only 1.6% shrinkage. Although this would suggest that these latter two are more stable, it depends on the behaviour after the turnaround which grade shows the better final dimensional stability.

The final results after INNOGRAPH-01B should provide this information.

5 Conclusions

The substantiation of graphite selection for a European HTR has been set in 2000 as the initial HTR-M/M1 target, by NNC, FZJ and NRG. This report covers the achievement of the important milestones for HTR-M1. The project objectives have been:

- Re-establishment of graphite irradiation and qualification methods within Europe while the available experience and facilities exist;
- Initiate irradiation programme on chosen graphites to determine the variations in their physical and mechanical properties up to low/medium irradiation dose: focus on engineering design data:
  - Dimensional change
  - Dynamic Young's Modulus
  - Coefficient of Thermal Expansion
  - Thermal conductivity/diffusivity

The project has been laid out to obtain sufficient data by the year 2010 to allow for the design of a European HTR. The review of current designs have shown the Pebble-Bed HTR as most demanding for the graphite structures:

- Fluence $2E^{26}$ m^{-2} EDN or 25 dpa_g
- Temperature 600 to 900ºC

A target temperature of 750°C and a target dose of 7 to 8 dpag_g has been selected for the initiating irradiation campaign.

The graphite selection process has been performed in an open discussion with the manufacturers SGL and UCAR (Graftech) associated to the EU HTR-M/M1 projects. Further collaboration has been initiated with JAERI (HTTR) to connect with the data base on IG-110, the material applied in HTTR and HTR-10.

The final choice of 'major' and 'minor grades' has been made in anticipation of new or improved grades to be included in the project follow-up in FP6.

As shown in this report, NRG has performed successfully an irradiation campaign of 200 graphite specimens in the High Flux Reactor at Petten, The Netherlands, with target dose of 8 dpa_g (or 6.3 x 10^{25} m^{-2} EDN) at 750°C. This has been accompanied by the installation of state-of-the-art pre- and post-irradiation test facilities for measurement of key physical properties. A full traceability of materials and data has been implemented. By participation in international meetings the groundwork has been laid for a strong European position in graphite qualification programmes for HTR core structures.

The HTR-M1 objectives for NRG have been fully achieved, with the screening test results being available 2005, as given in this report. Full data sets and validations will be obtained in 2006 and beyond as part of the RAPHAEL integrated project. The University of Manchester has performed pre-irradiation x-ray tomography on about 60 samples on a voluntary basis. Integration of future results is part of the RAPHAEL IP.

References

[1] M.W. Davies, G.Haag, State of the art review of graphite materials and behaviour, HTR-M-02/6-D-3.1.37. NNC report C6463/TR/011

[2] M.W. Davies, Report on selection of graphites and testing requirements, HTR-M1-02/11-D-2.1.9. NNC report C6657/TR/001.

[3] M.A.C. Kranenburg, J.A. Vreeling, INNOGRAPH Irradiation (352-01), Design and Safety Report, 25138/03.55595/I, Petten, January 2004.

[4] J.A. Vreeling, Report on specimen fabrication and procurement for the graphite irradiation tests, HTR-M1-03/4-D-2.2.13, NRG report 20787/03.56078/P, March 2003

[5] J.A. Vreeling, D.S. d'Hulst, M.A.C. van Kranenburg, INNOGRAPH (352-01) - specimens and loading, NRG report 20787/03.56080/I, December 2003

[6] J.A. Vreeling, F.A. van den Berg, D.S. D'Hulst, Werkvoorschrift voor dimensiemetingen aan grafiet, NRG report 20787/03.52001/I, January 2003

[7] ASTM standard C769-98, Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Young's Modulus, Annual book of ASTM Standards 2003, vol. 05.05, ISBN 0-8031-3540-8