ORNL/TM-2015/285

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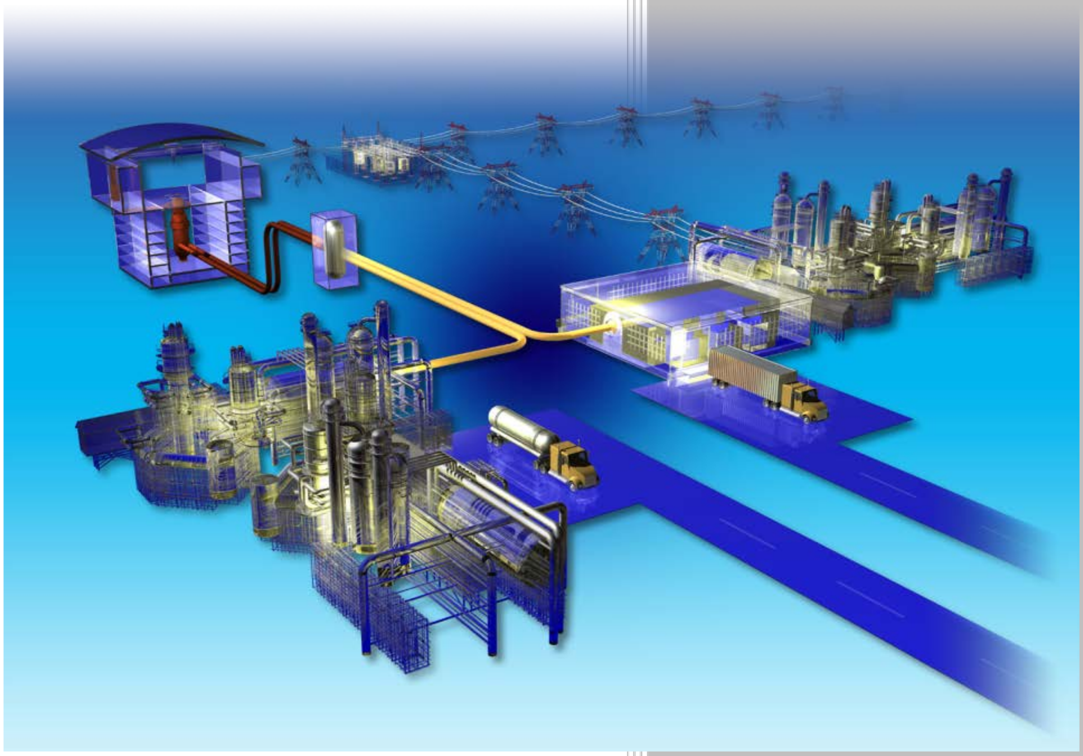

Tim Burchell

February 2016

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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HTR Graphite R&D

THE ANALYSIS OF RESULTS FROM 3-POINT FLEXURE TESTING OF IRRADIATED AGC-1 GRAPHITE CREEP SPECIMENS

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Summary

Here we report the analysis of test data from AGC-1 specimen 3-pt flexure testing. At this time all mechanical (flexural) testing of AGC-1 specimens has been completed. Individual force-extension curves are available as .txt files recorded electronically from the author (burchelltd@ornl.gov). This Technical Memorandum meets Idaho National Laboratories statement of Work No. 10752 Rev. 3 deliverable 4.4C "Issue a draft ORNL TM report summarizing the results and data analysis of all mechanical testing to INL no later than May 15, 2015." The data and analysis was provided in a timely fashion as an excel s/s with data analysis plots. This TM follows on and formalizes transmission of the data. The major conclusion from this analysis is that there is no additional effect of creep strain on the flexure strength of graphite.

1. Introduction

Initially, glued ends tensile testing of the AGC-1 specimens was planned. However, the results of sister specimen testing [1] showed this technique to be unreliable, with multiple fractures occurring at or around the glued specimen end. Because the glued end technique was shown to be unreliable, Idaho National Laboratory researched an acceptable flexural test method that could be applied to the AGC-1 specimens. Ultimately, this led to an approved test procedure [2] which was used to flexure test the AGC-1 specimens. Prior results [3] of this testing were reported as a letter report that satisfied SOW No. 10752 Rev. 3 deliverable 4.4B due March 27th 2015. Here we report a detailed analysis, including the fractional changes in strength and the variation of flexure strength with irradiation dose to fulfill SOW No.10752 Milestone 4.4C. "Issue a draft TM report summarizing the results and data analysis of all mechanical testing" no later than May 15, 2015.

2. Experimental

2.1. Flexure Testing

Testing was carried out in accordance with the approved internal procedure (MSTD/FMNS-001 [2])

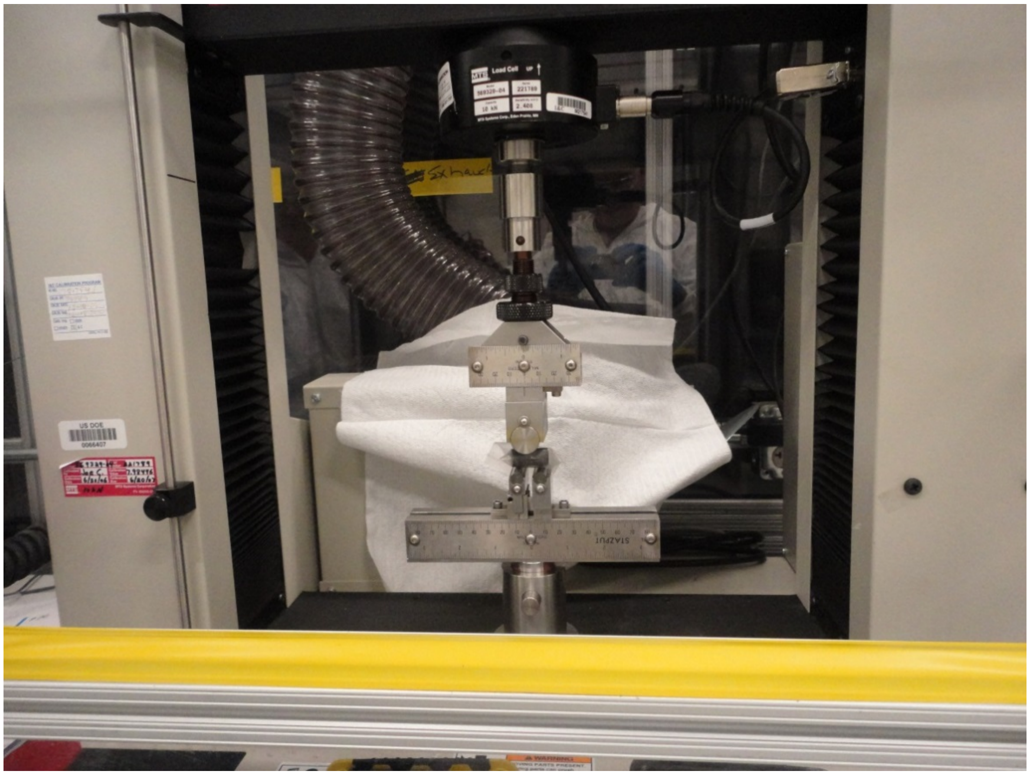

Figure 1 Test frame and load cell for AGC-1 specimen flex testing

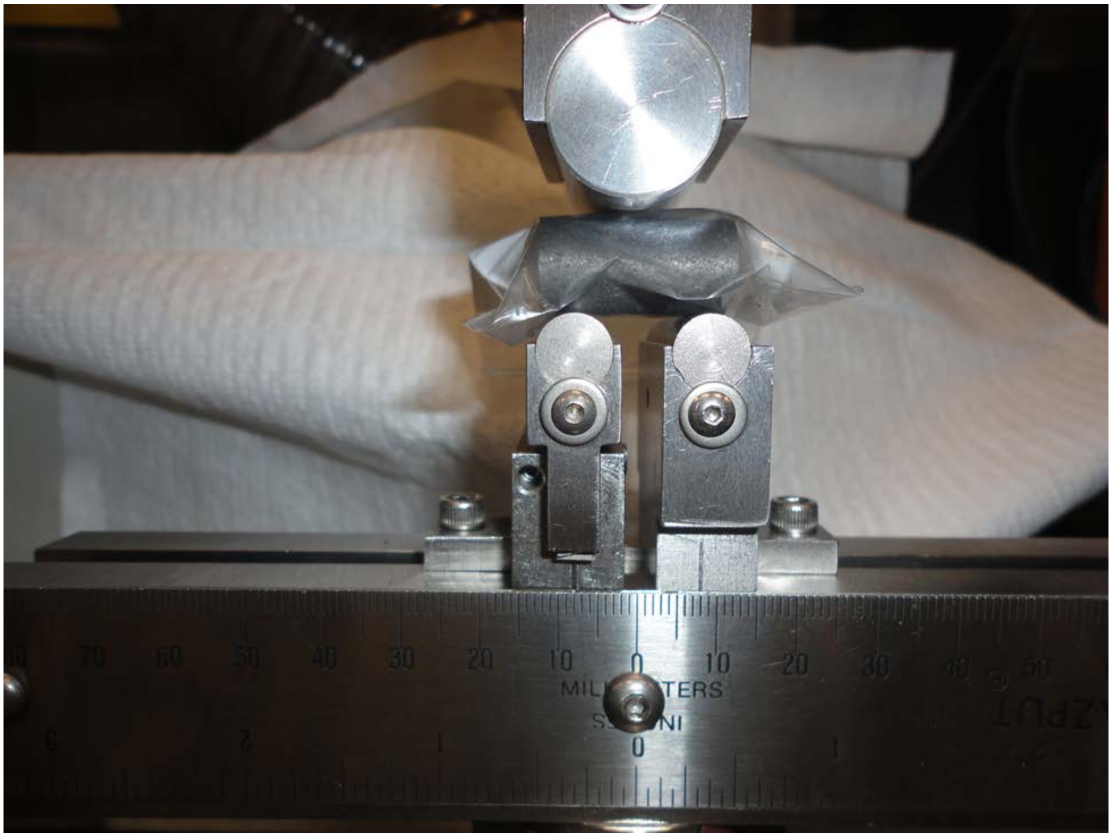

Figure 2 3-pt test fixture for flexure testing AGC Specimens

The specimen set up as in Figure 2, for a circular cross section, the flexural strength is given by:

$$\sigma = (8\ P\ L)/(\pi\ D^3)$$

Where: D = specimen diameter.

P = break force

L = support span

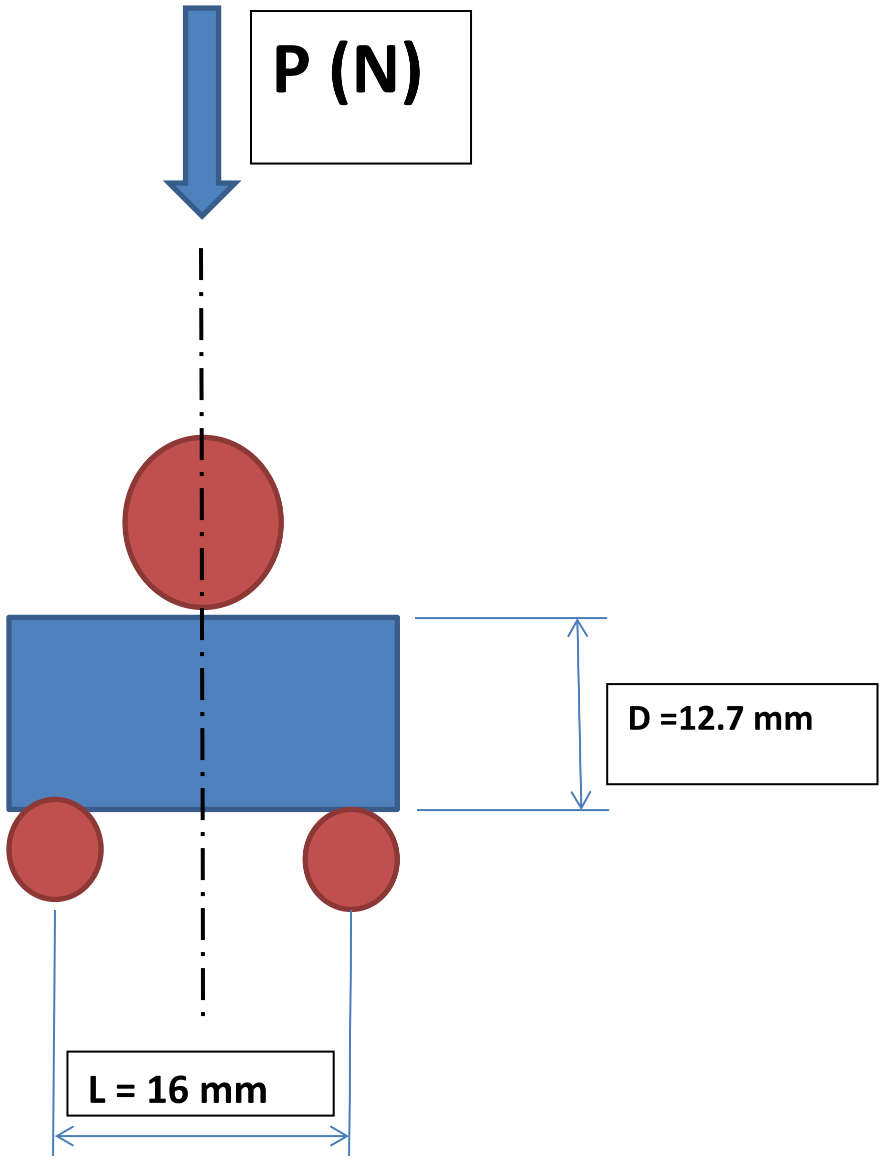

Figure 3 test set-up diagram for 3 pt. flexure defining the parameters P, D and L.

2.2. Irradiation Conditions

The AGC-1 creep capsule was irradiated in the Advanced Test Reactor at INL over the dose range ~3-7 dpa. The temperatures varied along the capsule length and the capsule ran hotter with each subsequent cycle.   The specimen temperatures thus varied from 470 to 716 °C [4]. However, an attempt to exclude the worst data was made when the creep strain data was analysed [5].

2.3. Statistical Significance Testing

Later in the report, we make extensive use of Significance Testing to establish whether there is a difference between the flexure strength of the irradiated (control) specimen and the irradiated and stressed (creep) specimens. The statistical significance was tested by calculating the "P" statistic (P is a function of the mean, standard deviation and population size (n)) and compared it to the probabilities defined in Students [6] "t" distribution. The "P" statistic was calculated and significance testing carried out using GraphPad [7] software.

The levels of significance used, their exact terminology, and the associated "P" values are given in Table 1.

Table 1 Significance Level and their associated "P" values

"P" Value	Terminology
Less than 0.0001	**Extremely Significant**
0.0001 to 0.001	**Extremely Significant**
0.001 to 0.01	**Very Significant**
0.01 to 0.05	**Significant**
Greater than or equal to 0.05	**Not significant**

Determinations are made as to whether CREEP properties are different from CONTROL properties based entirely on the calculated "P" values, and hence the statistical significance of any observed difference.

3. Results

The flexural strength data are sorted by control specimen, with increasing neutron dose and by creep specimen with increasing creep strain. They are further separated into groups according to the graphite grade, A, B, C, D, E or F. Tabular data are presented in the appendix and the data are plotted in this section (Table 2 identifies the graphite grades and letter designations used here).

For all of the graphite grades reported (A-F) the strength was observed to increase with neutron dose (or creep strain) (Figure 5 to Figure 16). In the case of IG-430 (grade F) (Figure 15) the strength was seen to increase initially then begin to fall with increasing neutron dose. However, it should be noted that IG-430 had the largest temperature spread and are probably the most unreliable data set.   The IG-430 specimens were also known to be running at a cooler temperature than the other graphite specimens in AGC-1. Unpredictable irradiation behavior might therefore be expected for the IG-430 specimens.
This temperature variation is shown graphically in Figure 4 where the irradiation temperatures of the IG-

430 creep and control specimens are plotted. The mean experimental specimen irradiation temperatures are from [8]. The control specimens were running tens of degrees cooler than the creep specimens and thus, in this temperature range, might be expected to exhibit turn-around behavior at lower fluences the IG-430 creep specimens, behavior that is seen in Figure 15 and Figure 24.

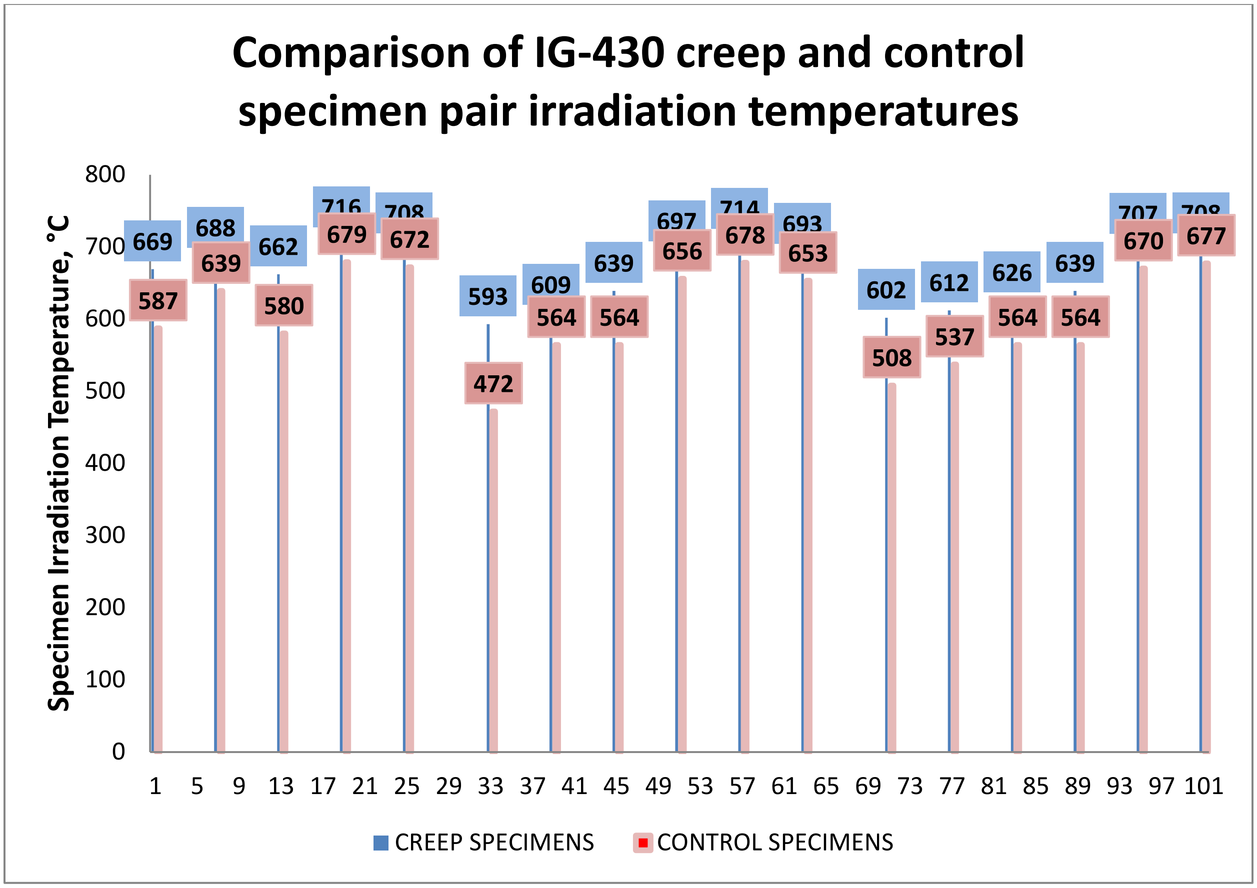

Figure 4 Comparison of IG-430 creep and control specimen pair irradiation temperatures

Moreover, the control samples ran considerably cooler than the capsule average temperature (Section 2.2).

3.1. Grade A, NBG-17

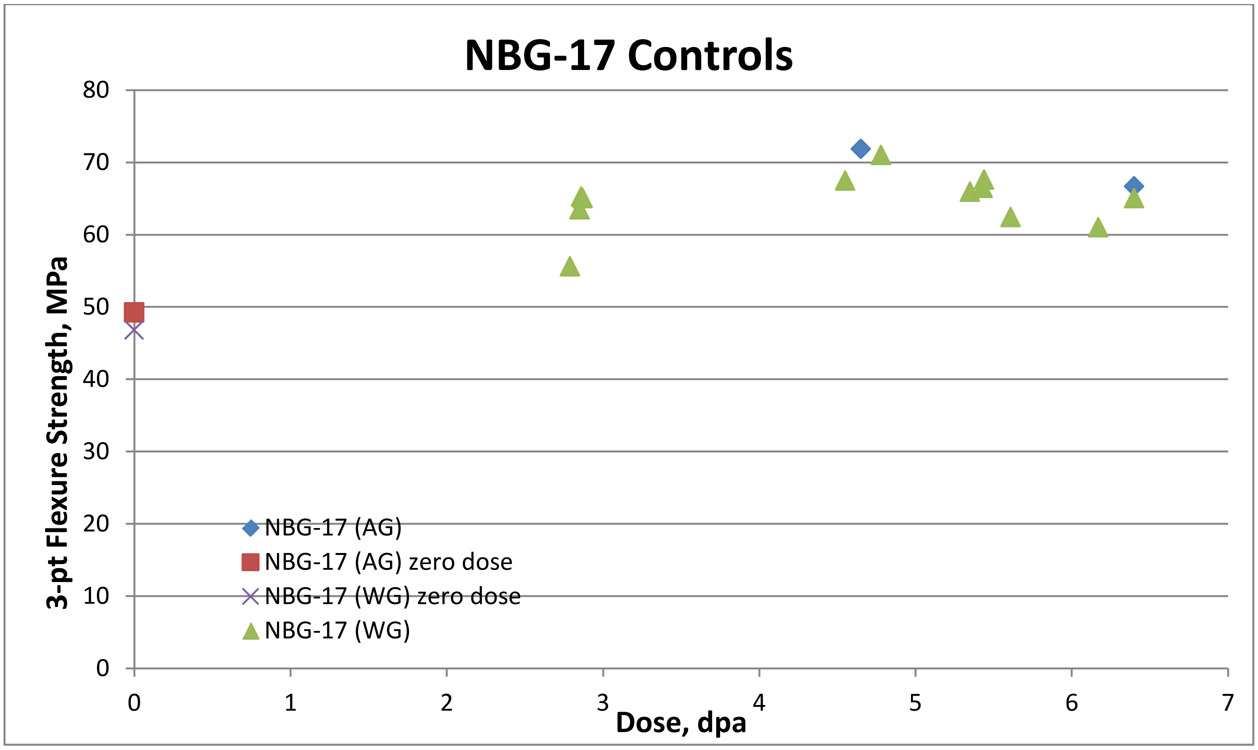

Figure 5 Variation of 3-pt flexure strength with neutron dose for control specimens of NBG-17 Graphite

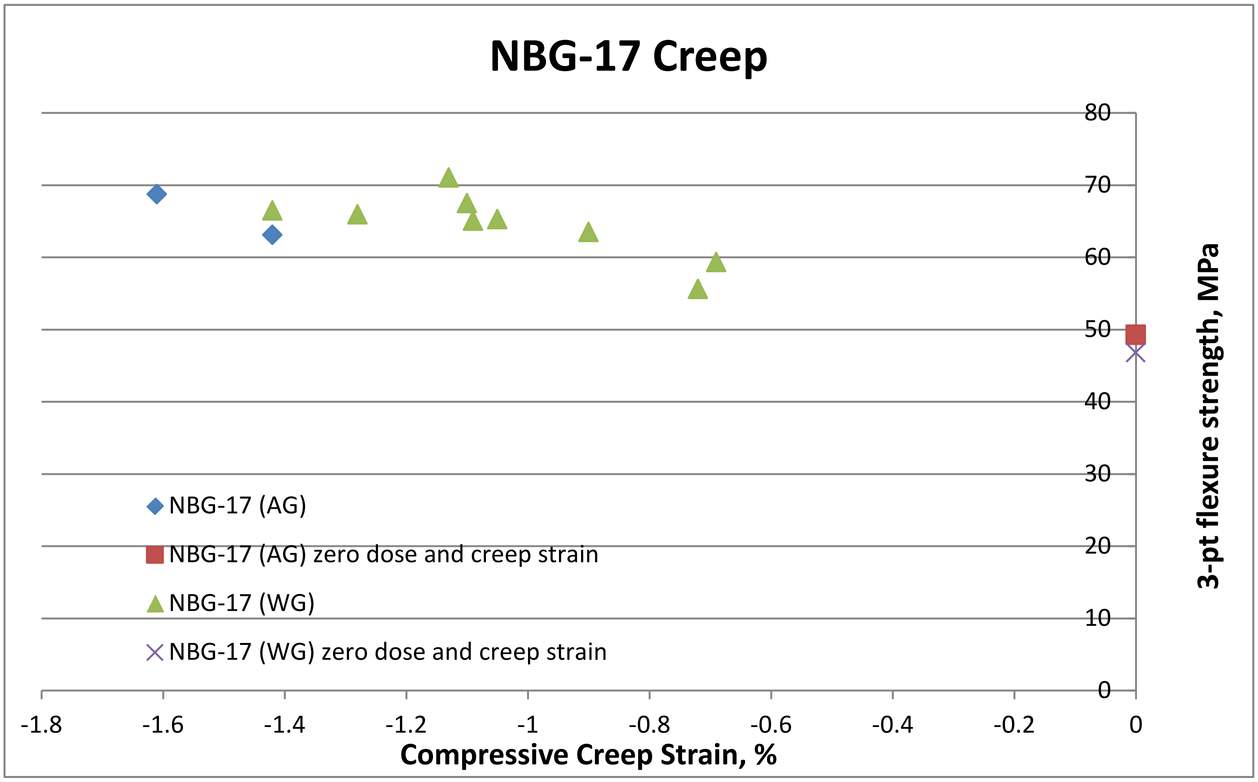

Figure 6 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of NBG-17 Graphite

3.2. Grade B, NBG-18

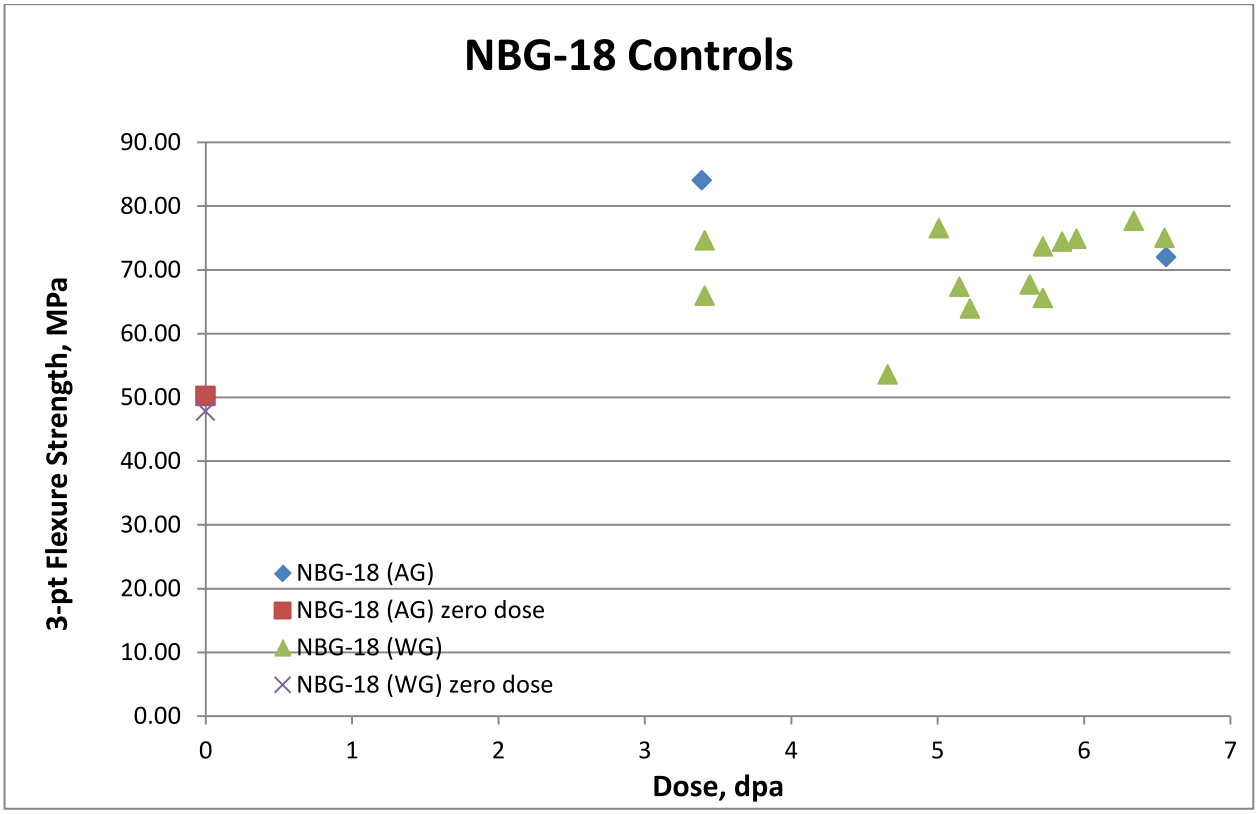

Figure 7 Variation of 3-pt flexure strength with neutron dose for control specimens of NBG-18 Graphite

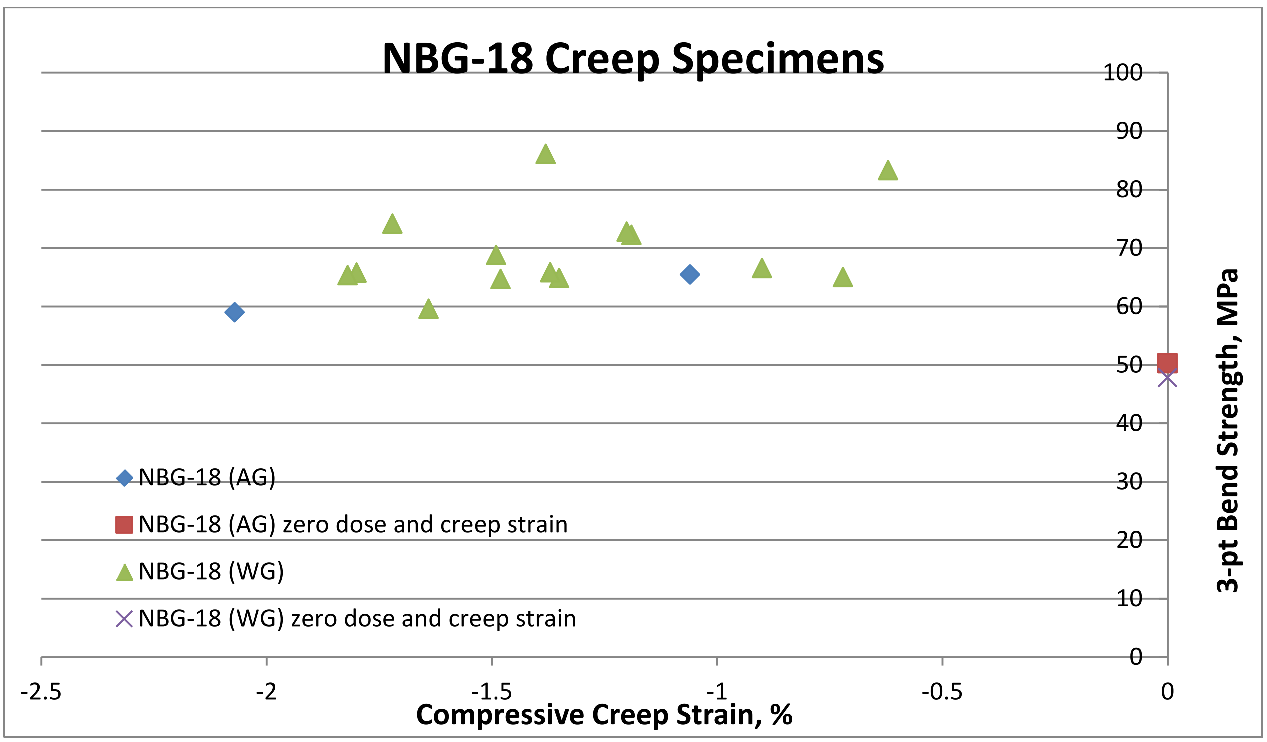

Figure 8 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of NBG-18 Graphite

3.3. Grade C, H-451

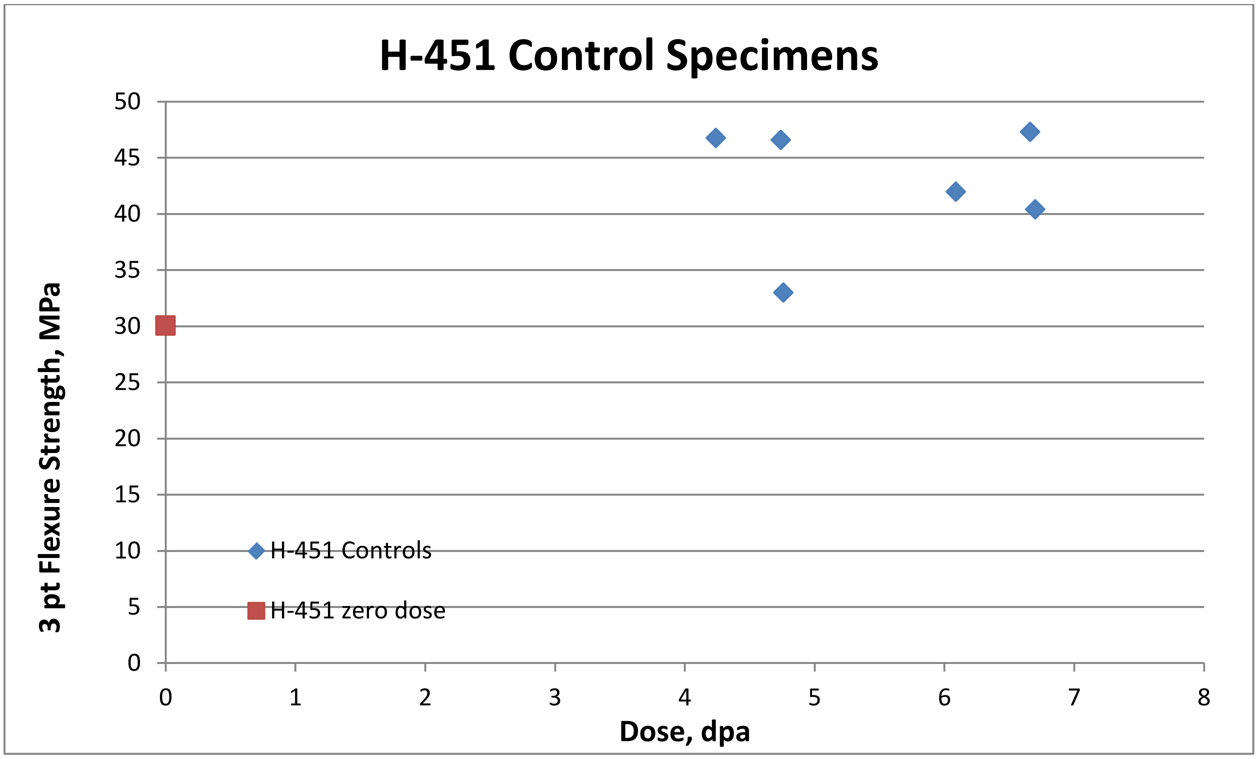

Figure 9 Variation of 3-pt flexure strength with neutron dose for control specimens of H-451 Graphite

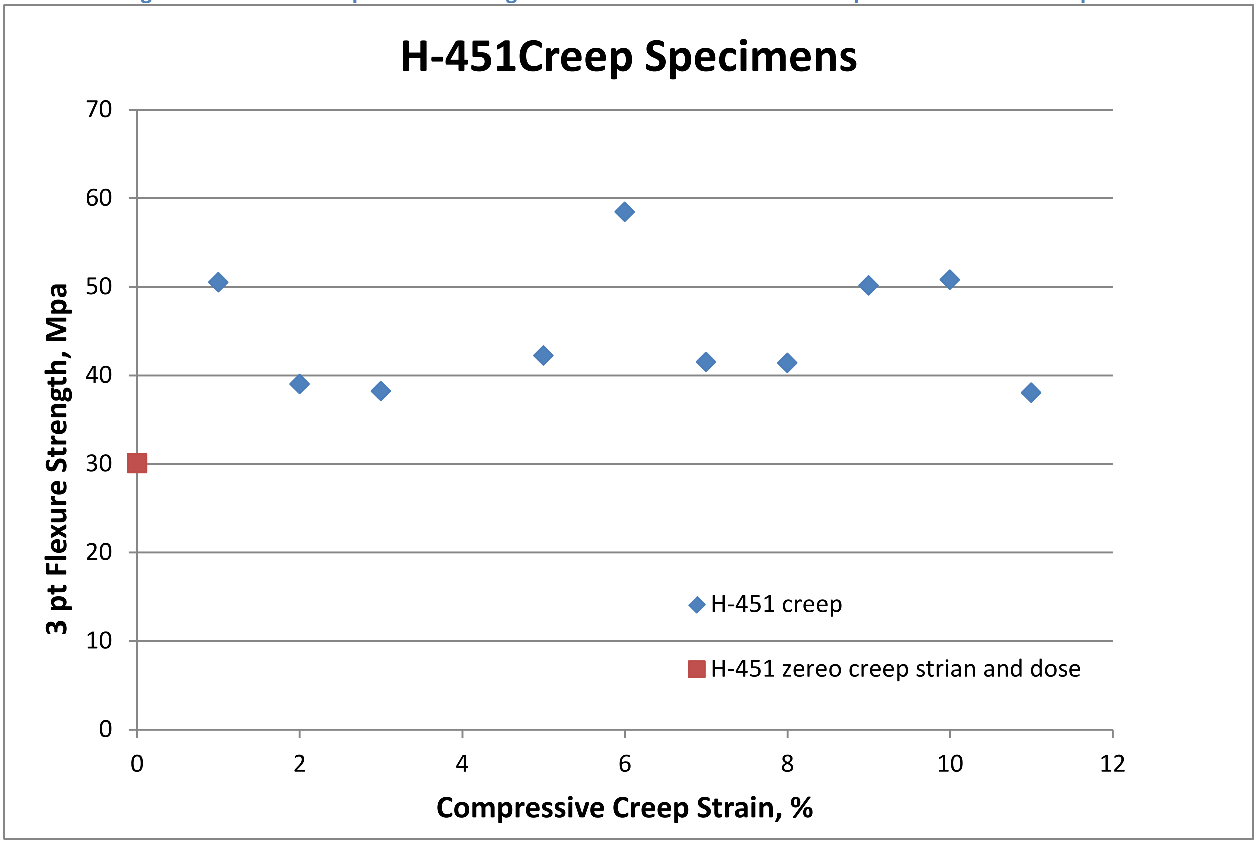

Figure 10 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of H-451 Graphite

3.4. Grade D, PCEA

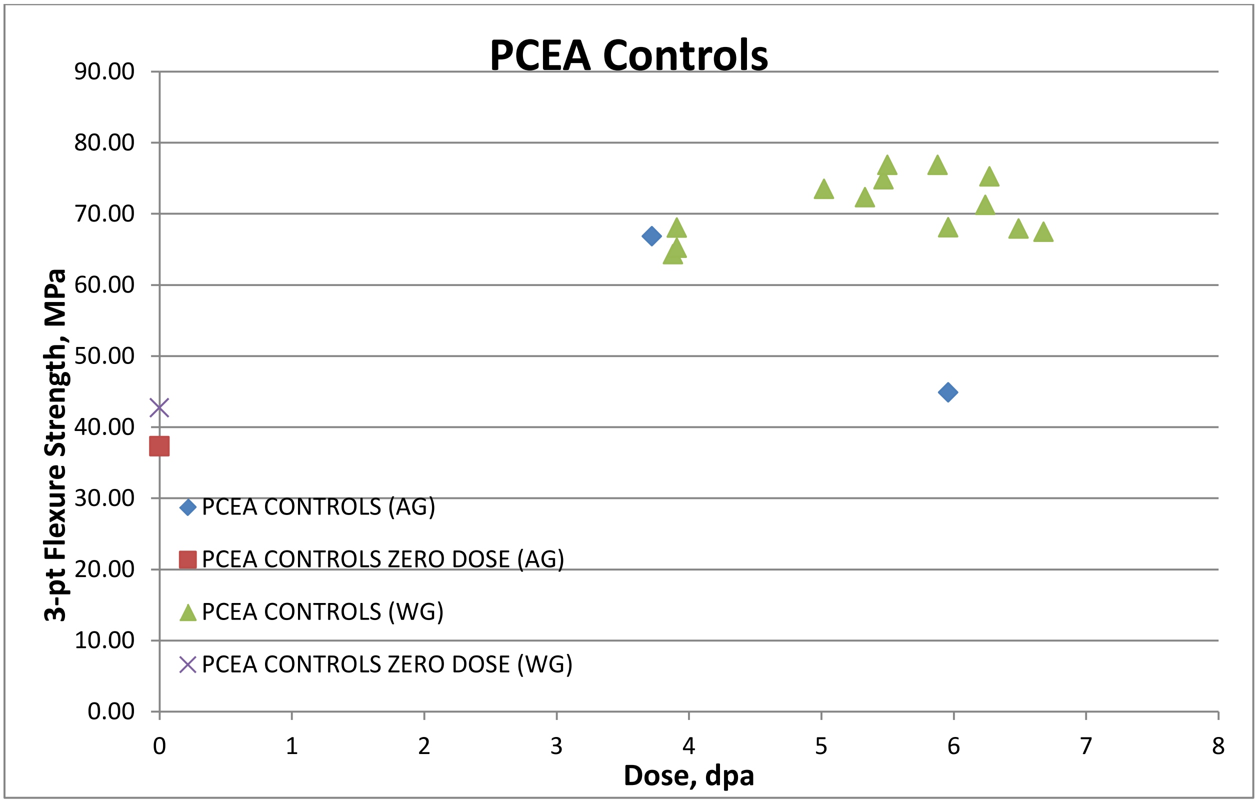

Figure 11 Variation of 3-pt flexure strength with neutron dose for control specimens of PCEA Graphite

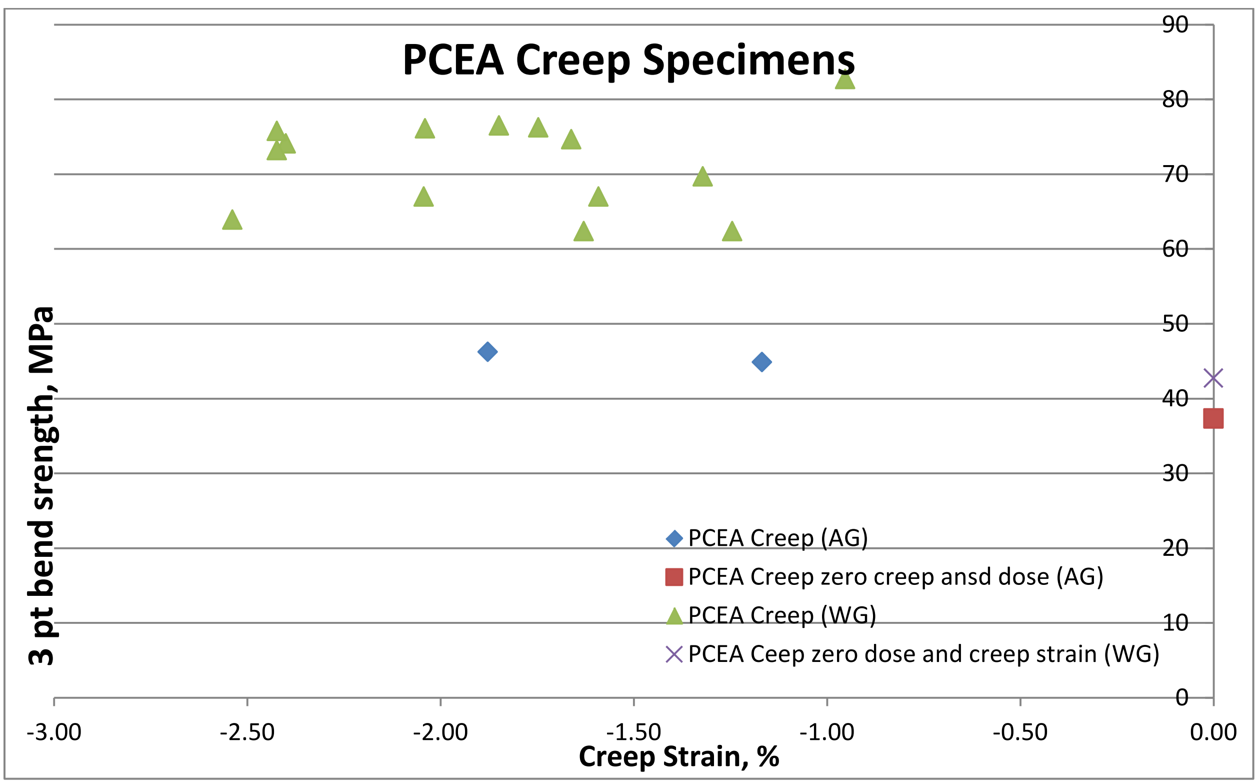

Figure 12 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of PCEA Graphite

3.5. Grade E, IG-110

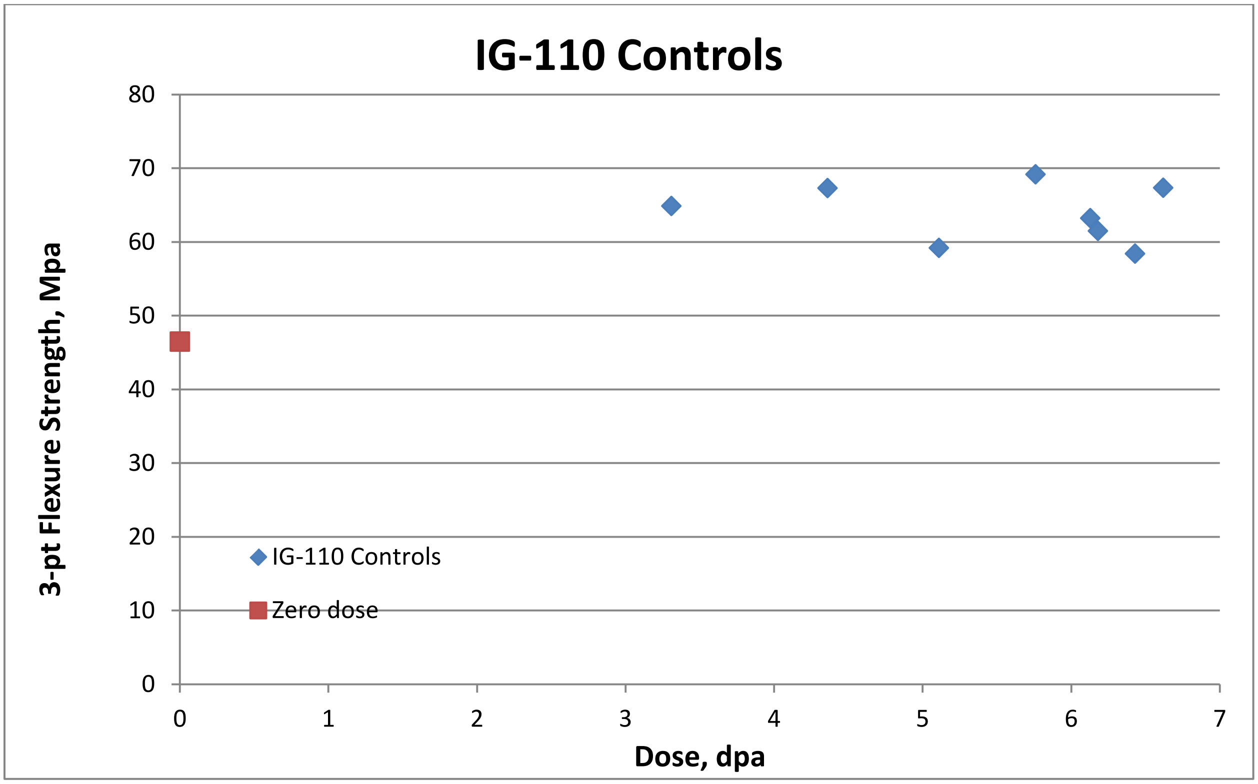

Figure 13 Variation of 3-pt flexure strength with neutron dose for control specimens of IG-110 Graphite

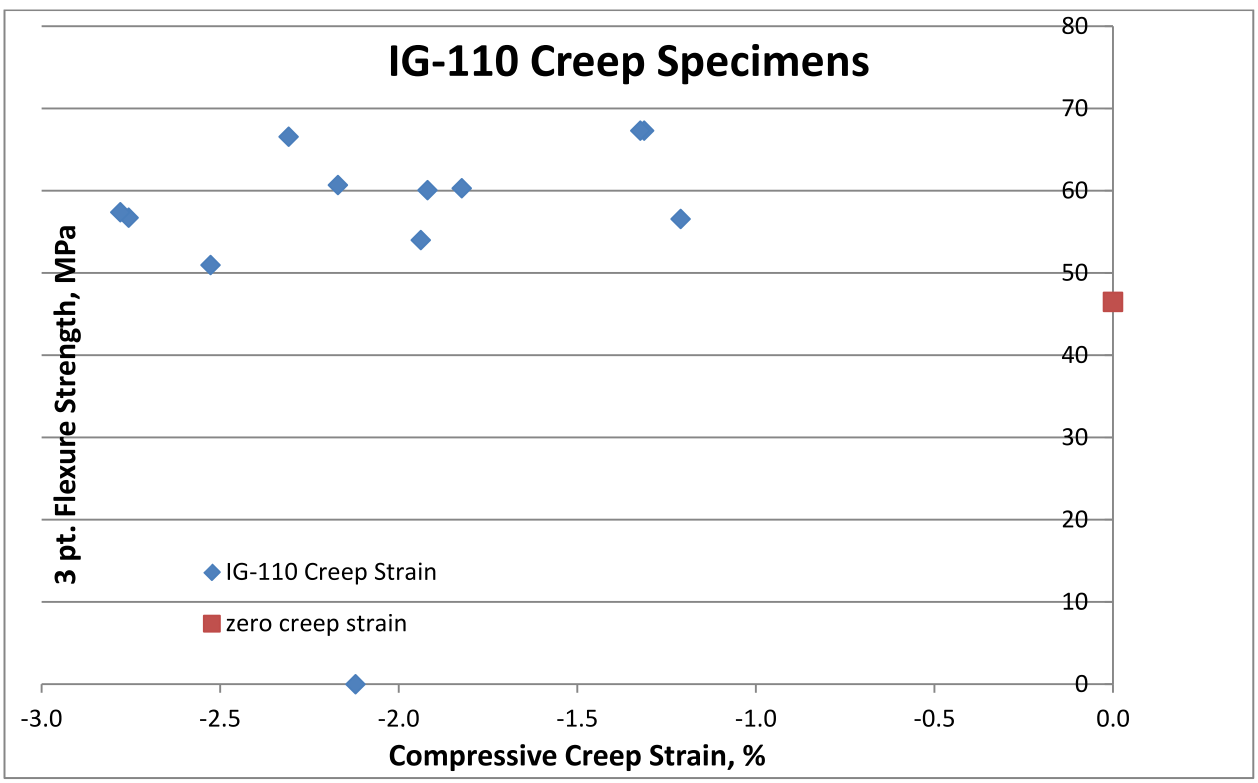

Figure 14 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of IG-110 Graphite

3.6. Grade F, IG-430

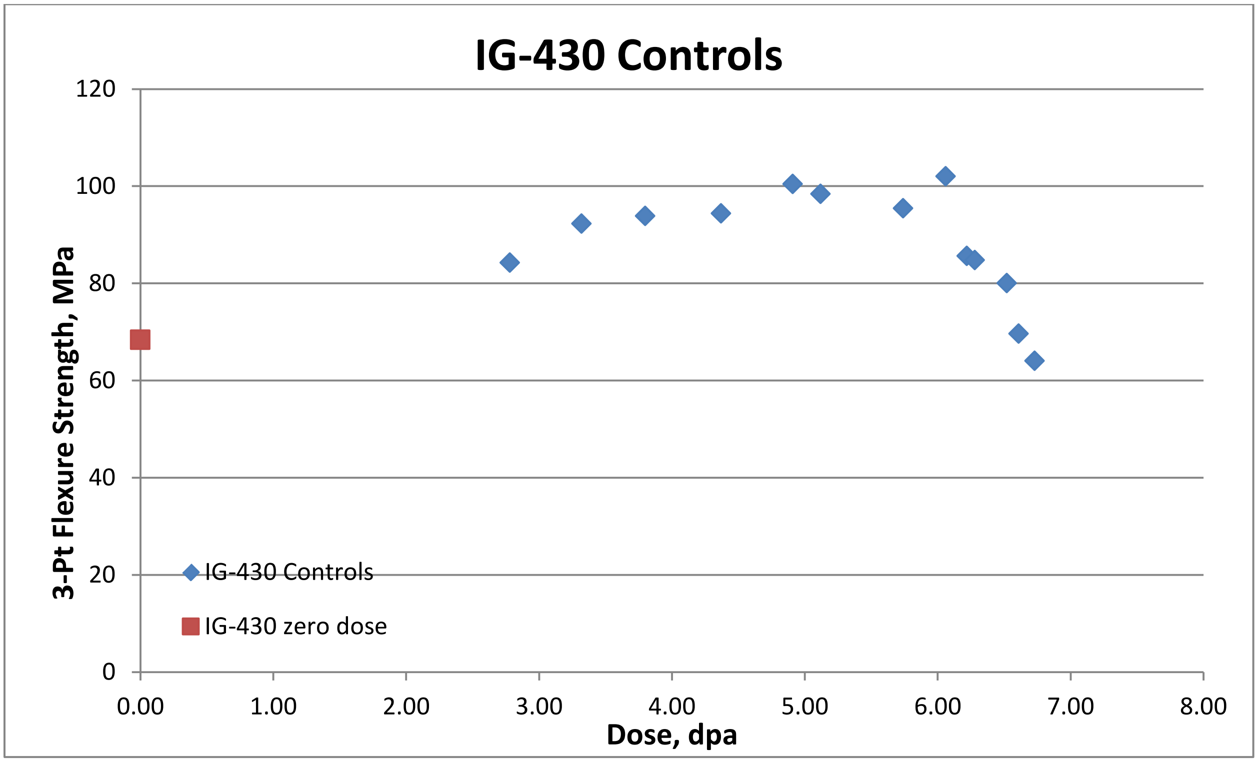

Figure 15 Variation of 3-pt flexure strength with neutron dose for control specimens of IG-430 Graphite

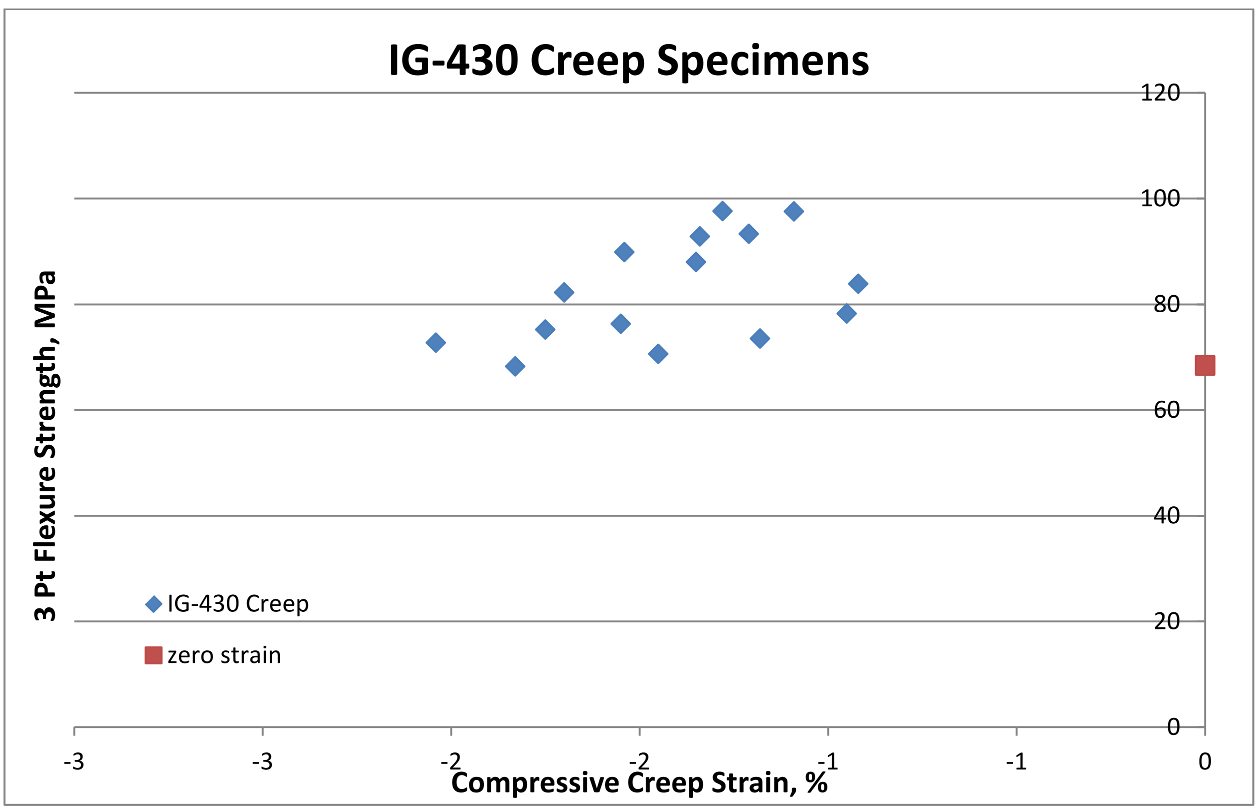

Figure 16 Variation of 3-pt flexure strength with compressive creep strain for creep specimens of IG-430 Graphite

4. Discussion

The mean strengths for the data populations are given in Table 2.

Table 2 Mean Flexure Strengths for the six graphite grades tested here

Mean & St. Dev. Of 3 PT Flex Strength					
		Irradiated		Irradiated & Crept	
Graphite Grade		Mean (MPa)	S.D. (MPa)	Mean (MPa)	S.D. (MPa)
A	NBG-17 (AG)	69.29	3.65	65.89	3.99
A	NBG-17 (WG)	64.65	6.22	64.28	3.99
B	NBG-18 (AG)	78.04	8.50	62.20	4.58
B	NBG-18 (WG)	70.07	6.83	69.63	7.45
C	H-451	42.68	5.52	45.01	6.95
D	PCEA (AG)	55.88	15.51	45.57	0.98
D	PCEA (WG)	70.93	4.35	71.58	6.20
E	IG-110	63.87	3.99	59.79	5.45
F	IG-430	88.10	11.59	82.69	9.99

The data are presented as fractional change in flexural strength [(σ_i/σ_0)-1] in Figure 17 to Figure 22. These data are very scattered. The flexural strength changes (fractional changes) are given for both the creep and control specimens as a function of neutron dose.

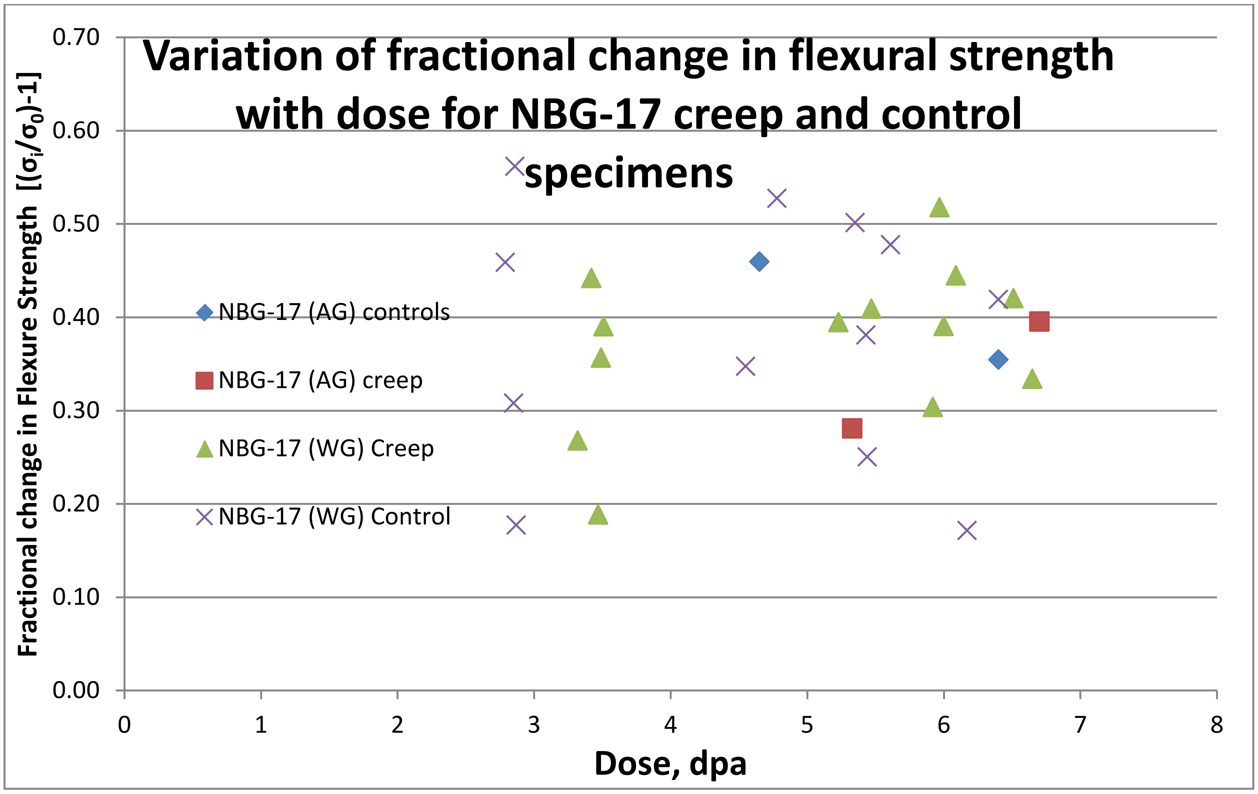

Figure 17 Variation of Fractional Change in Flexural Strength with Neutron Dose for NBG-17

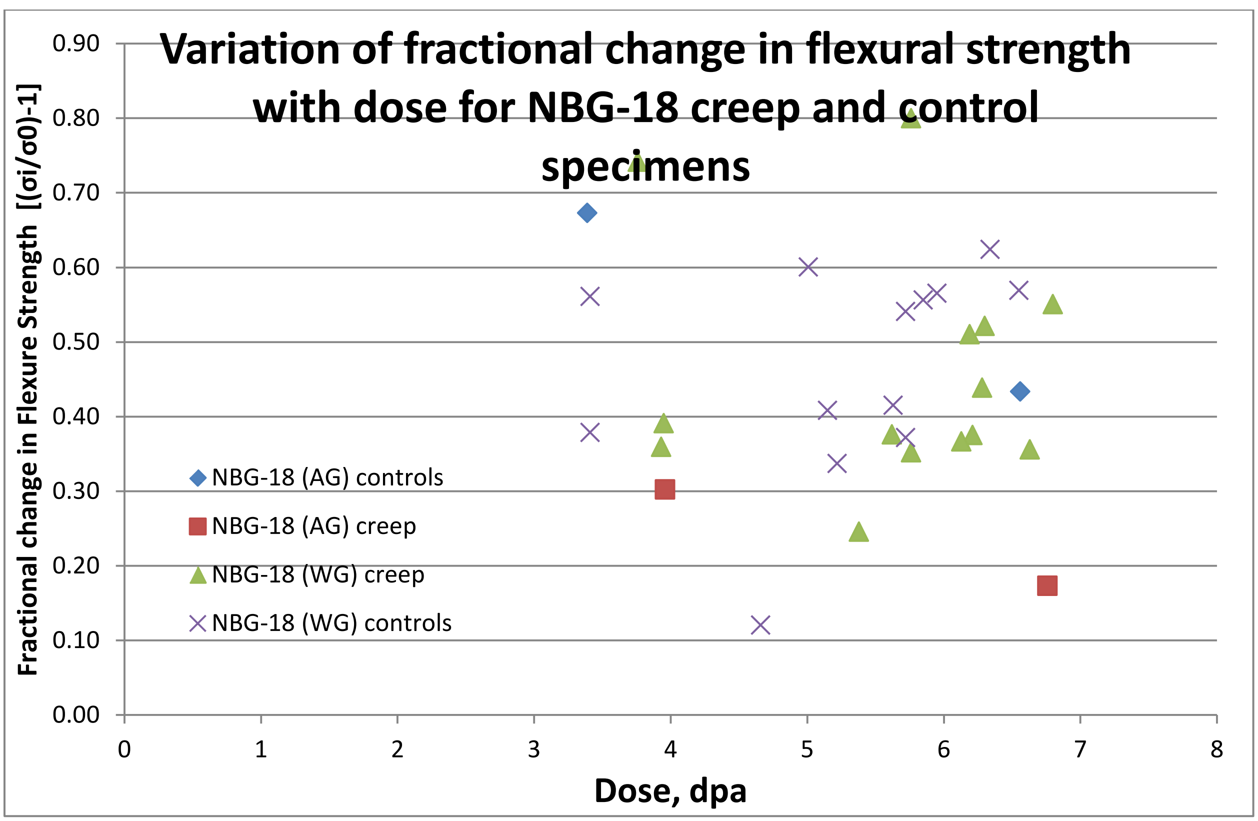

Figure 18 Variation of Fractional Change in Flexural Strength with Neutron Dose for NBG-18

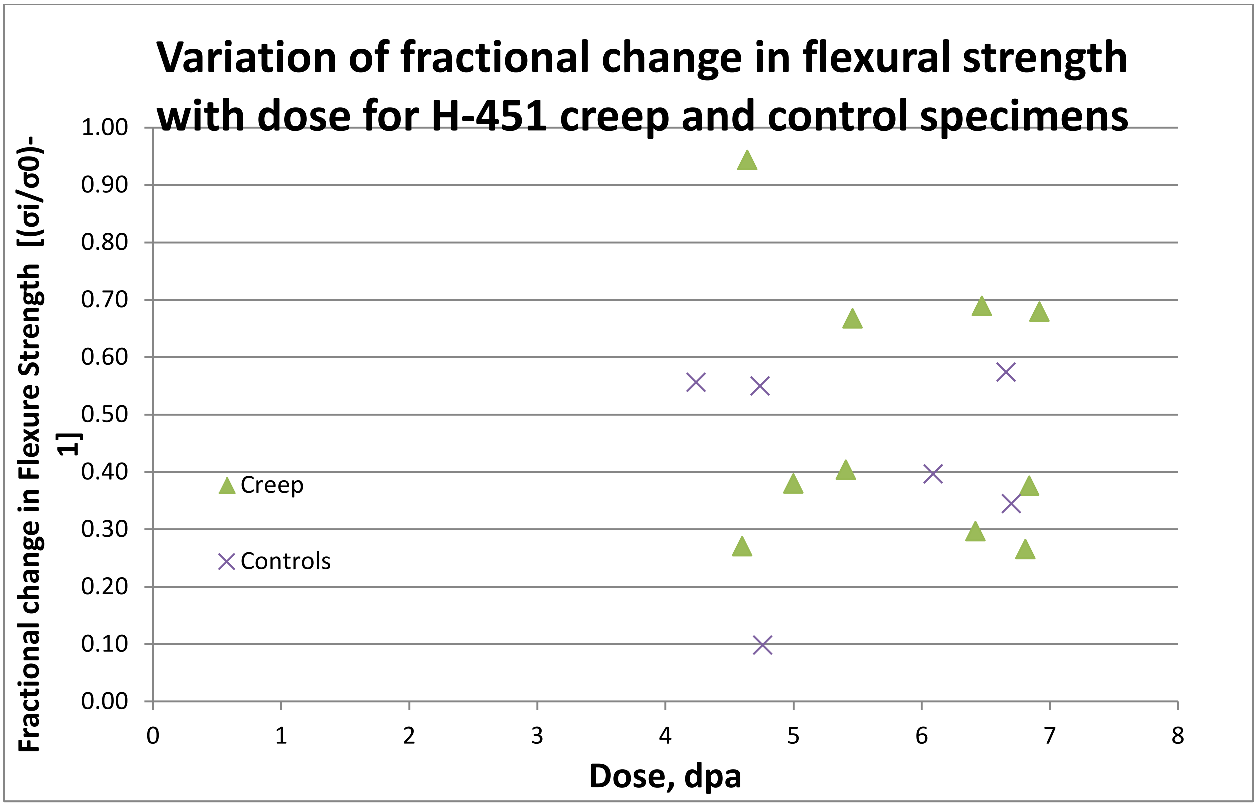

Figure 19 Variation of Fractional Change in Flexural Strength with Neutron Dose for H451

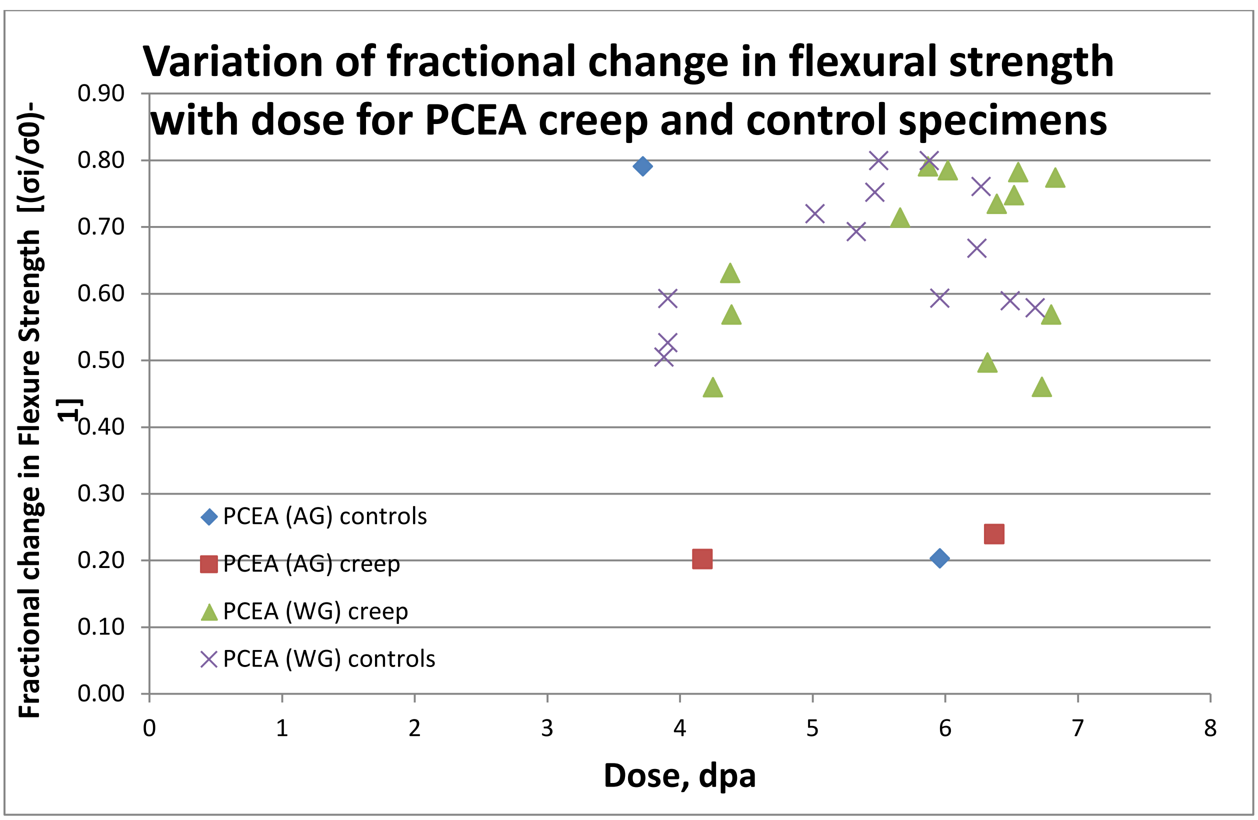

Figure 20 Variation of Fractional Change in Flexural Strength with Neutron Dose for PCEA

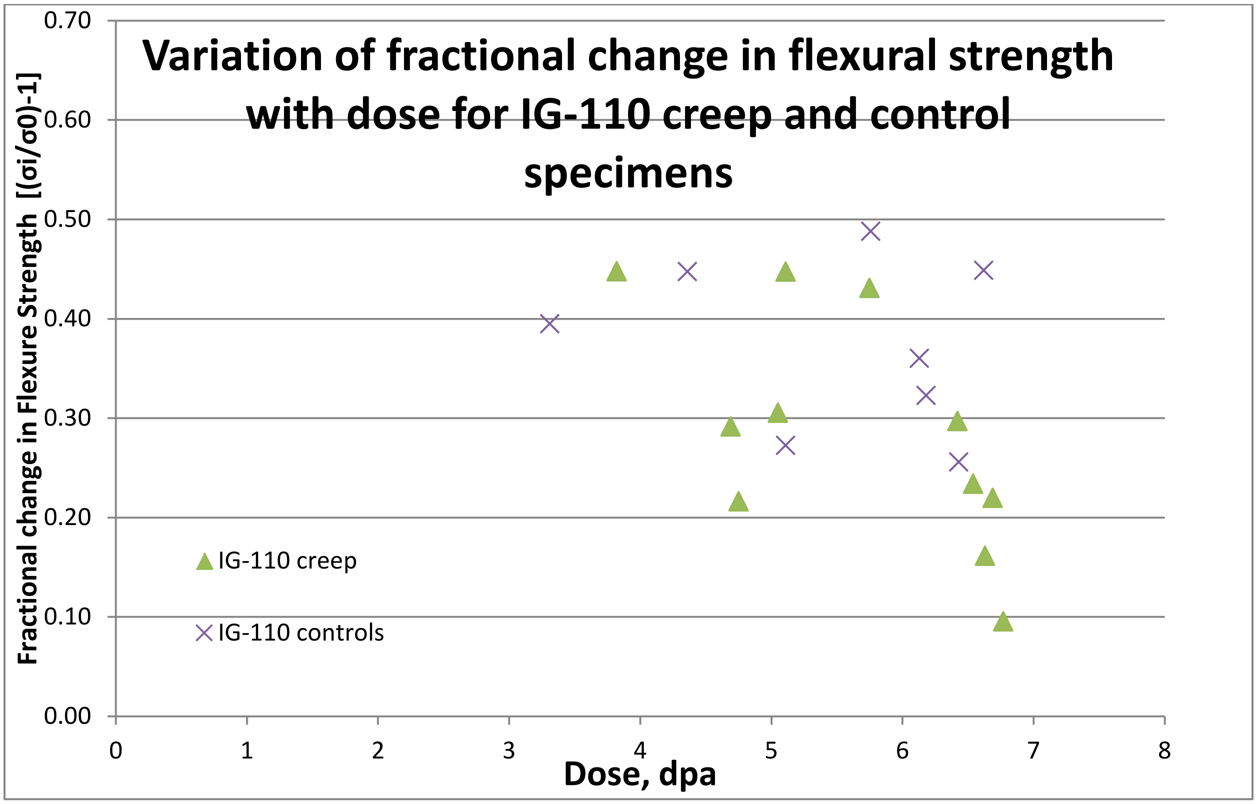

Figure 21 Variation of Fractional Change in Flexural Strength with Neutron Dose for IG-110

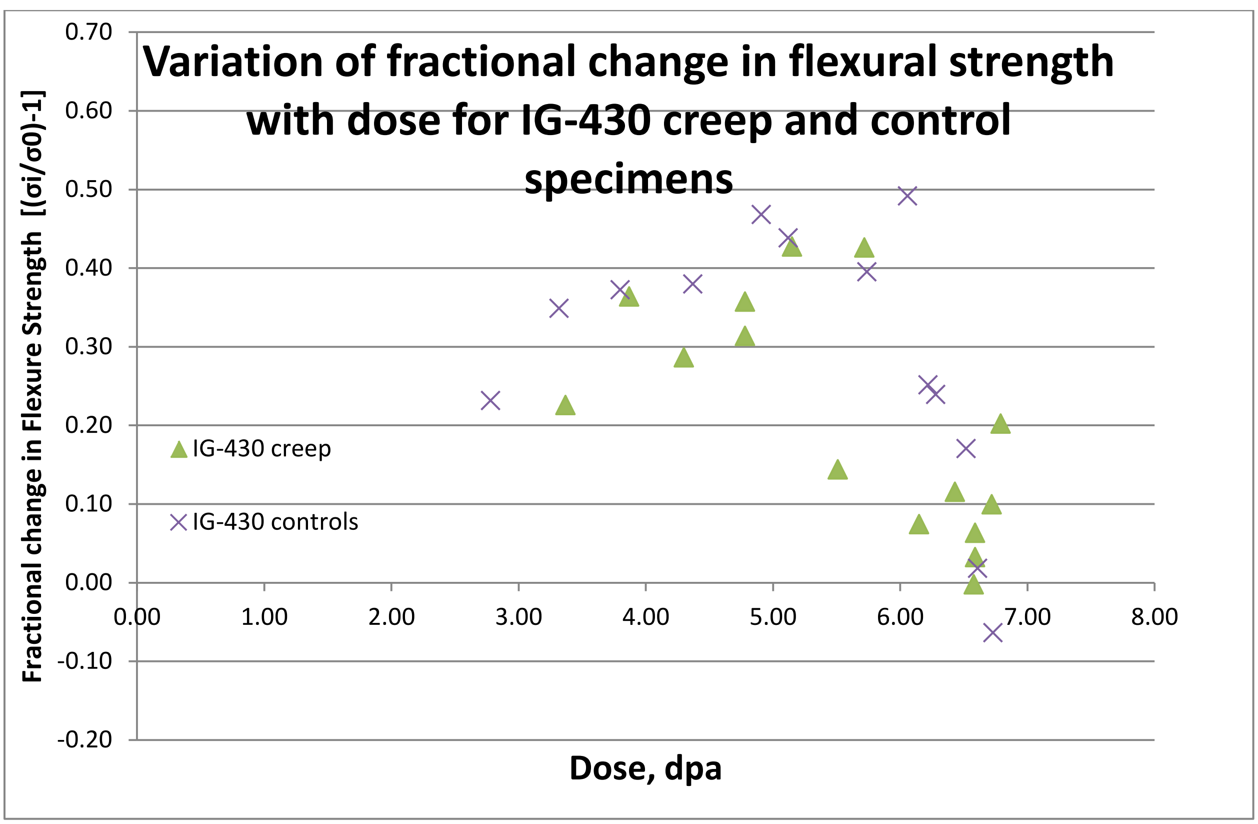

Figure 22 Variation of Fractional Change in Flexural Strength with Neutron Dose for IG-430

The fractional changes as function of neutron dose look very similar for the creep and control specimens. Key questions are thus (i) does strength increase on irradiation and (ii) does creep have an "additional" effect on strength (these questions are given in Table 3). The 3-point flexure test is definitely not the optimum test of strength after irradiation because of the relatively small volume stressed in a flexure test. However, given the problems associated with glued ends [1] there is currently no alternative test. It should be noted that the American Society of Testing and Materials (ASTM) are currently developing a "Brazilian Disc" tensile test whose geometry would allow PIE testing. Some cutting of the AGC specimen would be required, however. The stressed volume of a Brazilian Disc would unfortunately also be relatively small, depending upon the exact geometry, but in the case of the AGC specimens, the Brazilian Disc is seen as an improved test method.

Traditionally [9,10,11,12], the strength increases on irradiation are considered to be the result of two effects. The first is a rapid increase in strength associated with in-crystal point defects formation as a result of irradiation-induced damage acting as dislocation pinning sites. This effect tends to saturate at small doses and remains constant with further dose. This effect is represented by the series 1 line in Figure 23 (ii). The second effect is caused by structural changes that occur in the graphite due to the anisotropic irradiation induced dimensional response of the graphite crystallite. This effect is most clearly manifested in the volume change behavior on irradiation (Figure 23(i)). The decrease of volume, i.e., closure of internal porosity (predominantly aligned Mrozowski [13] and Mrozowski-like cracks) by <c>-axis growth, along with crystal <a>-axis shrinkage decreases the volume and densifies the graphite, thus causing a slow increase in strength which can be expected to reach a maximum at about the volume-change turn-around dose.

Beyond volume turn-around the strength can be expected to fall to zero with increasing dose. It should be noted that the pores that are closing and causing volume reduction (densification) prior to volume turn-around are not the same pores that cause volume expansion after turn-around. Post turn-around porosity will probably be a mix of Mrozowski [13] like aligned cracks and other voids that have profoundly different shape and orientation and affect the strength differently. In other words, the pre-turnaround strength increase should not be expected to be identical to the post-turnaround behavior. This effect is represented by the series 2 line in Figure 23(ii). The total strength change is the sum of these two effects and is represented by the series 3 line in Figure 23(ii).

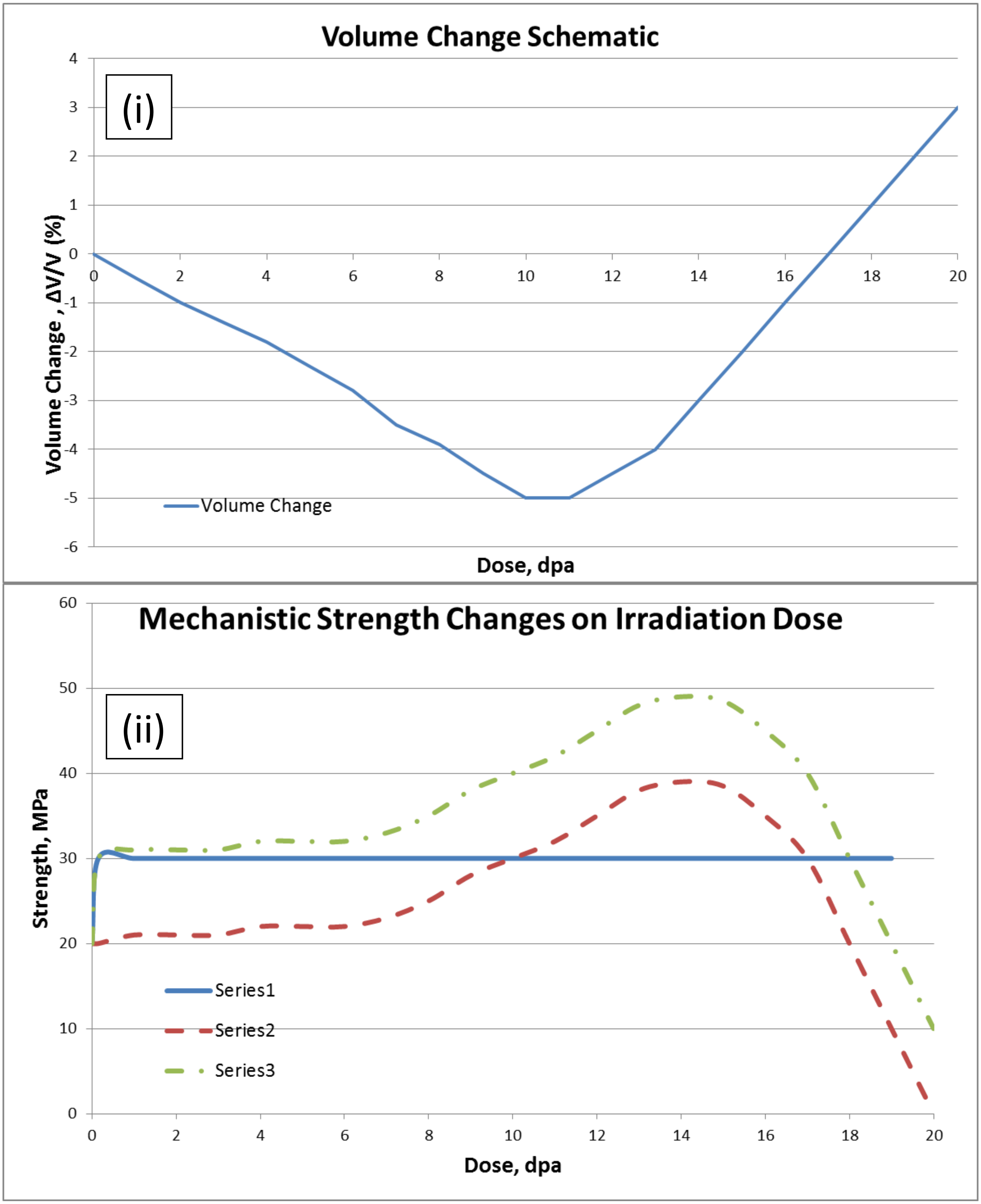

Figure 23 Schematic representations of the anticipated (i) volume changes and (ii) strength changes, on irradiation

Returning to the key questions:-

Table 3 Three key differences that were statistically "t" significance tested

Question/test i	**are irradiated strength of controls > virgin strength for grade**
Question/test ii	**are irradiated strength of creeps > virgin strength for grade**
Question/test iii	**are flexure strengths of the creep and control different**

Taking the three highest doses for the control and creep specimens, calculating the strength mean and standard deviation and performing statistical "t" tests of significance will allow us to answer these key questions with some degree of certainty. Table 4 gives the strength mean and S.D. for each of the three highest dose specimens for the six grades examined here. Statistical "t" testing was performed on the mean strengths to answer the three hypothesis (questions) posed here. The outcomes of statistical "t" testing are given in Table 5.

As expected, "t" test results show clearly that NBG-17, NBG-18, H-451, PCEA and IG-110 all increased their strength after irradiation, i.e., the answer to questions (i) and (ii) was an unequivocal yes. In the case of IG-430, "t" testing revealed that the 3 highest dose control specimen strength were not significantly different from the unirradiated strength, however, the three creep specimens with the highest dose had a statistically significant difference in their strengths compared to the unirradiated strengths. These results show that the control specimens had passed their maximum strength and the strength had begun to reduce as a result of structure (volume) changes, as shown schematically in Figure 23 and actually in Figure 15.

Examination of the volume shrinkage behavior [5] for IG-430 (Figure 24) indicates the control specimens have indeed entered the "turnaround" phase and have clearly begun swelling. The creep specimens, however, show a less pronounced turnaround behavior. As illustrated in Figure 4, the control specimens ran considerably cooler than the creep specimens for IG-430 graphite, and this temperature disparity explains the unconventional behavior of IG-430.

Table 4 Mean and SD of the three highest dose flexure strengths of the creep and control specimens

GRADE		Unirradiated flex strength, MPa	Irradiated Flex Strength Test Statistics				
			controls (3 highest dose)		creep (3 highest dose)		
ID	NAME		flexure strength, MPa	dose, dpa	flexure strength, MPa	dose, dpa	Creep Strain, %
A	NBG-17 (WG)	n=11	69.14	5.61	66.46	6.51	-1.42
			54.81	6.17	67.60	6.09	-1.47
			66.39	6.4	62.42	6.65	-1.62
	MEAN	46.79	63.45	6.06	65.49	6.42	-1.50
	S.D.	3.68	7.60	0.41	2.72	0.29	0.10
B	NBG-18 (WG)	n=10	74.86	5.95	72.76	6.3	-1.2
			77.66	6.34	64.84	6.63	-1.35
			75.03	6.55	74.16	6.8	-1.72
	MEAN	47.82	75.85	6.28	70.59	6.58	-1.42
	S.D.	5.55	1.57	0.30	5.03	0.25	0.27
C	H-451(WG)	n=11	41.98	6.09	50.49	6.92	-2.1
			47.31	6.66	41.36	6.84	-1.89
			40.42	6.7	38.03	6.81	-3.09
	MEAN	30.06	43.24	6.48	43.29	6.86	-2.36
	S.D.	3.73	3.61	0.34	6.45	0.06	0.64
D	PCEA(WG)	n=8	75.25	6.27	75.80	6.83	-2.42
			67.91	6.49	67.03	6.80	-2.04
			67.47	6.68	62.41	6.73	-1.63
	MEAN	42.74	70.21	6.48	68.41	6.79	-2.03
	S.D.	3.84	4.37	0.21	6.80	0.05	0.40
E	IG-110	n=9	67.35	6.62	54.00	6.63	-1.94
			58.39	6.43	50.94	6.77	-2.53
			61.5	6.18	56.71	6.69	-2.76
	MEAN	46.5	62.41	6.41	53.88	6.70	-2.41
	S.D.	2.72	4.55	0.22	2.89	0.07	0.42
F	IG-430	n=11	80.08	6.52	82.25	6.79	-1.70
			69.65	6.61	75.21	6.72	-1.75
			64.04	6.73	72.76	6.59	-2.04
	MEAN	68.43	71.25	6.62	76.74	6.70	-1.83
	S.D.	1.98	8.14	0.11	4.92	0.10	0.18

Table 5 "t" significance test hypotheses outcomes

UNPAIRED t TEST RESULTS						
		statistics parameters				
GRADE	TEST	t	df	SE of difference	P	TWO-TAILED TEST RESULT
A(WG)	i	5.5933	12	2.979	0.0001	Difference is exetremly statistically significant
A(WG)	ii	8.1145	12	2.305	<0.0001	Difference is exetremly statistically significant
A(WG)	iii	0.4377	4	4.66	0.6842	Difference **not** considered statistically significant
B(WG)	i	8.4075	11	3.334	<0.0001	Difference is exetremly statistically significant
B(WG)	ii	5.6715	11	3.521	0.0001	Difference is exetremly statistically significant
B(WG)	iii	1.7290	4	3.042	0.1589	Difference **not** considered statistically significant
C(WG)	i	5.4538	12	2.417	0.0001	Difference is exetremly statistically significant
C(WG)	ii	4.7189	12	2.804	0.0005	Difference is exetremly statistically significant
C(WG)	iii	0.0117	4	4.267	0.9912	Difference **not** considered statistically significant
D(WG)	i	10.2363	9	2.684	<0.0001	Difference is exetremly statistically significant
D(WG)	ii	8.1313	9	3.157	<0.0001	Difference is exetremly statistically significant
D(WG)	iii	0.3857	4	4.667	0.7194	Difference **not** considered statistically significant
E	i	7.5245	10	2.114	<0.0001	Difference is exetremly statistically significant
E	ii	4.0184	10	1.837	0.0024	Difference is very statistically significant
E	iii	2.741	4	3.112	0.0519	Difference **not quite** considered statistically significant
F	i	1.1445	12	2.464	0.2747	Difference **not** considered statstically significant
F	ii	4.7216	12	1.76	0.0005	Difference is exetremly statistically significant
F	iii	0.9997	4	5.491	0.374	Difference **not** considered statistically significant

The third statistical test yielded perhaps the most interesting results. We posed the hypothesis (question III) to be significance tested: Are the creep specimens any different in strength from the control specimens? For the grades (NBG-17, NBG-18, H-451, PCEA, IG-110 and IG-430), the differences in the creep and control means were not considered statistically significant, note the difference was not quite considered statistically significant in the case of IG-110. These significance test (Table 1) results (Table 5) tell us that creep strain has no additional effect on strength. The observed changes up to "volume turnaround" are identical for creep and control specimens and are simply a function of neutron dose. Indeed the volume change behavior for all the grades examined was considered identical [5] (e.g., Figure 25 and Figure 26) with the exception of IG-430 (Figure 24). Prior to "turn-around" creep is considered to be volume conserving, i.e., the volume shrinkage before turn-around is identical for the creep end control specimens. This behavior is clearly seen in the examples shown in Figure 25 and Figure 26.

It appears; therefore, that prior to volume turn-around creep has no additional effect on flexural strength. The observed strength changes (Figure 5 to Figure 16) are as a result of neutron irradiation dose only, up to volume turn-around doses.

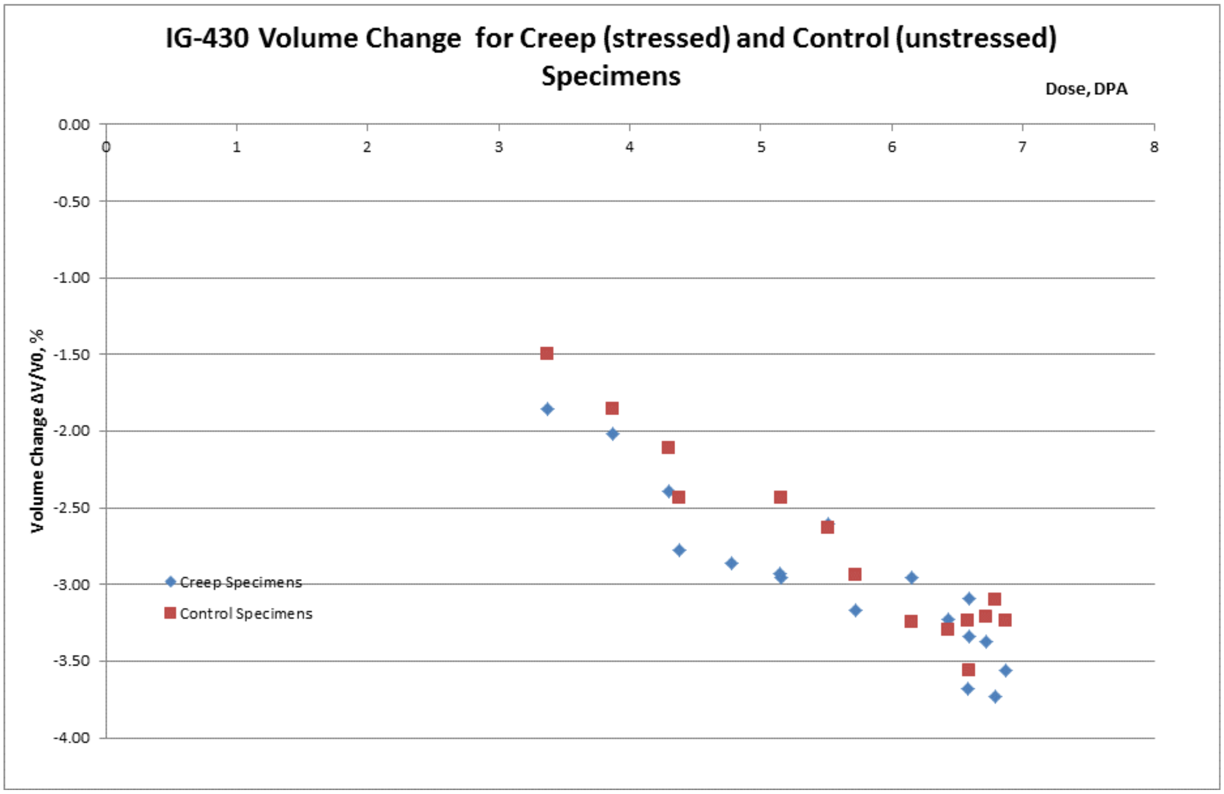

Figure 24 Volume change behavior of IG-430 for control and creep specimens as a function of neutron dose

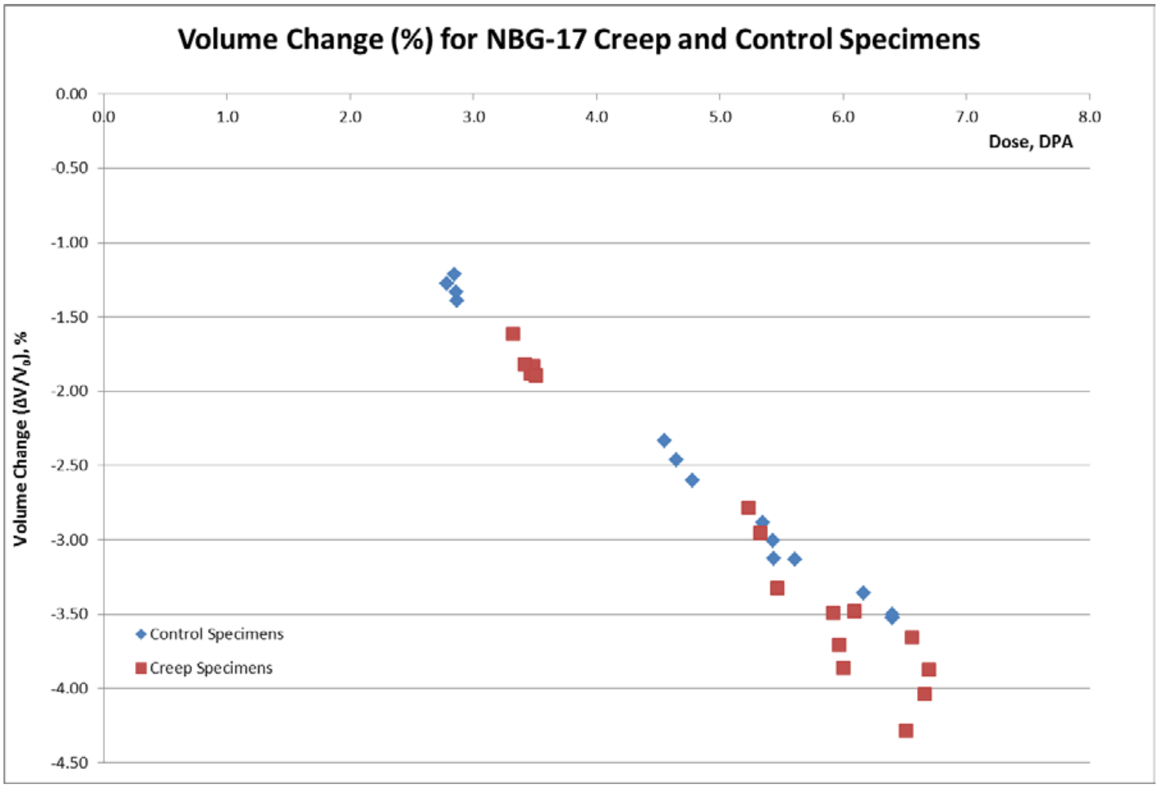

Figure 25 Volume change behavior of NBG-17 for control and creep specimens as a function of neutron dose

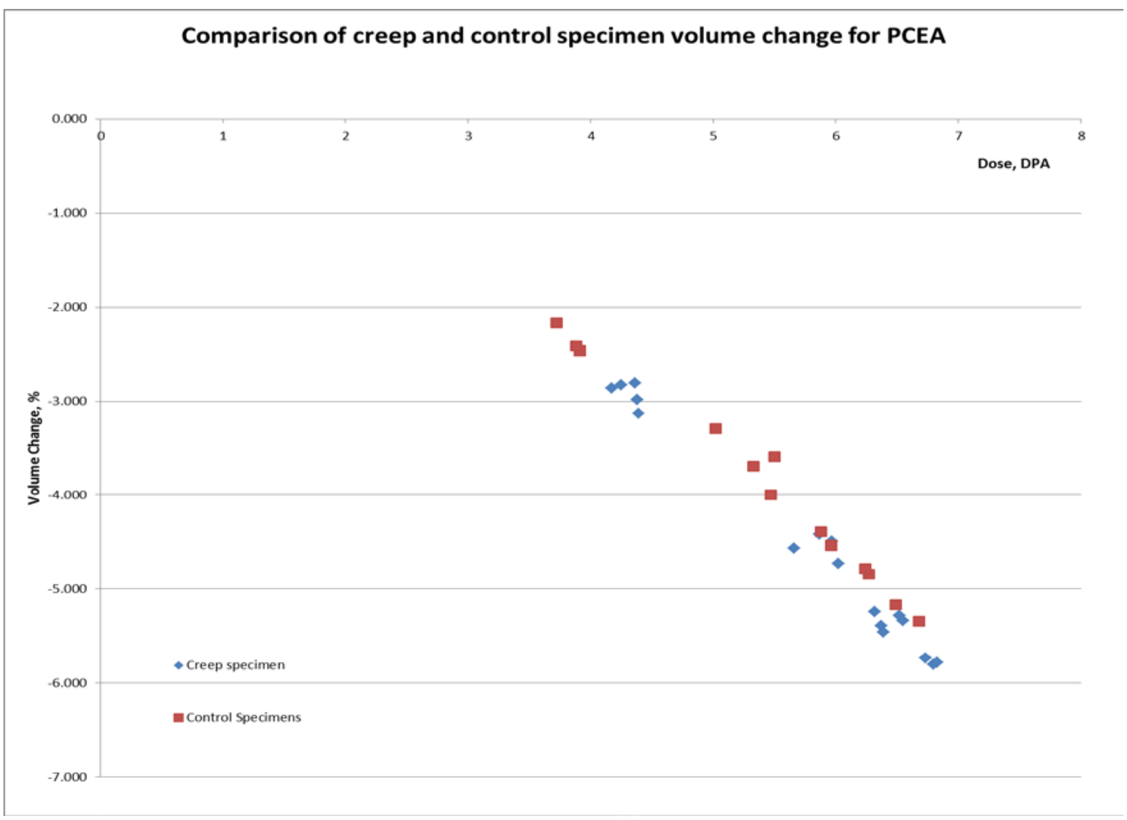

Figure 26 Volume change behavior of PCEA for control and creep specimens as a function of neutron dose

5. Quality Assurance

The described technical work scope and related activities were conducted in accordance with the applicable quality assurance requirements of ASME NQA-1-2008/1a-2009*, Quality Assurance Requirements for Nuclear Facilities*. Work scope at ORNL was performed under the activity-specific requirements of the applicable ORNL nuclear R&D quality assurance plan (QAP) numbered QAP-ORNL-NR&D-01 and entitled *Quality Assurance Plan for Nuclear Research and Development Conducted at the Oak Ridge National Laboratory*. This QAP is based on and compliant with ASME NQA-1-2008/1a-2009.

6. Conclusions

Here we have reported the analysis of 3pt flexure testing of the AGC-1 specimens (162), along with 103 unirradiated specimens to provide reference data. The data are analyzed, in terms of the flexure strength increase with neutron dose and with increasing creep strain.

It is believed that the flexural test is not the optimum test of strength change on irradiation because of the small stressed volume. The preferred test is the glued end tensile test which offers a larger test volume, although this test has been shown to be subject to problems associated with premature failure of the specimen at or near the glue line, and so cannot be easily used. It is strongly recommended that an alternate tensile strength test be developed, preferably with a larger stressed volume than the current flexure test. It should be noted that ASTM is currently developing a test standard for the "Brazilian Disc" tensile test, a geometry that is suitable for AGC specimen testing.

Statistical significance testing has been used to establish flexure strength changes with neutron dose and irradiation compressive creep strain. The flexural strength is seen to increase with neutron dose up turn-around doses (as expected).

There is no statistically significant additional change of flexural strength due to compressive creep strain up to volume turnaround doses. Beyond turn-around doses the flexural strength is observed to reduce.

7. Acknowledgments

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The author wishes to thank Michael McAlister and Ashli Clark for their diligence performing the 3-pt flexure measurements.

8. Tabular Data

The data for each graphite grade are tabulated here in ascending dose, and the creep and control population are separated.

8.1. NBG-17

Table 6 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade NBG-17

NGNP AGC-1 IRRADIATED SPECIMENS PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER						σ_f (MPa)		DOSE	Irr. Temp	SPEC TYPE	CREEP STRAIN	Fractional change $[(\sigma_i/\sigma_0)-1]$
Date	Sample ID	Diameter (mm)	lb(f)	F (N)	GRADE	REDUCED DATA SET		DPA	°C		%	
	AL8-02	12.6303	799.08	3554.308	NBG-17 AG		71.87	4.65	585	Control	0	0.46
	AL6-01	12.5911	734.82	3268.479	NBG-17 AG		66.71	6.4	667	Control	0	0.35
	AL8-01	12.6901	711.33	3163.996	NBG-17 AG		63.07	5.33	655	Creep	-1.42	0.28
	AL6-02	12.6805	773.21	3439.238	NBG-17 AG		68.72	6.7	703	Creep	-1.61	0.40
						mean	67.59					
						SD	3.68					
	AW6-01	12.687	769.20	3421.402	NBG-17 WG		68.26	2.79	472	Control	0	0.46
	AW13-01	12.683	689.04	3064.85	NBG-17 WG		61.20	2.85	470	Control	0	0.31
	AW5-01	12.685	823.08	3661.06	NBG-17 WG		73.07	2.86	470	Control	0	0.56
	AW2-03	12.665	617.46	2746.462	NBG-17 WG		55.08	2.87	468	Control	0	0.18
	AW7-01	12.638	702.33	3123.964	NBG-17 WG		63.05	4.55	587	Control	0	0.35
	AW4-03	12.632	794.96	3535.982	NBG-17 WG		71.47	4.78	582	Control	0	0.53
	AW5-03	12.608	777.01	3456.14	NBG-17 WG		70.24	5.35	597	Control	0	0.50
	AW12-03	12.597	712.81	3170.579	NBG-17 WG		64.62	5.43	594	Control	0	0.38
	AW2-02	12.599	645.64	2871.807	NBG-17 WG		58.50	5.44	592	Control	0	0.25
	AW10-01	12.592	761.76	3388.308	NBG-17 WG		69.14	5.61	617	Control	0	0.48
	AW2-01	12.590	603.71	2685.302	NBG-17 WG		54.81	6.17	650	Control	0	0.17
	AW9-03	12.581	729.55	3245.038	NBG-17 WG		66.39	6.4	678	Control	0	0.42
	AW 6-03	INL	669.93	2979.849	NBG-17 WG		59.32	3.32	594	Creep	-0.69	0.27
	AW1-03	12.706	629.64	2800.639	NBG-17 WG		55.62	3.47	589	Creep	-0.72	0.19
	AW4-02	12.714	719.90	3202.115	NBG-17 WG		63.48	3.49	592	Creep	-0.90	0.36
	AW6-02	12.680	734.17	3265.588	NBG-17 WG		65.26	5.23	656	Creep	-1.05	0.39
	AW12-01	12.727	740.08	3291.876	NBG-17 WG		65.05	3.51	593	Creep	-1.09	0.39
	AW5-02	12.719	766.04	3407.346	NBG-17 WG		67.46	3.42	594	Creep	-1.10	0.44
	AW1-02	12.649	793.21	3528.198	NBG-17 WG		71.02	5.97	668	Creep	-1.13	0.52
	AW4-01	12.671	740.36	3293.121	NBG-17 WG		65.94	5.47	653	Creep	-1.28	0.41
	AW1-01	12.625	738.04	3282.802	NBG-17 WG		66.46	6.51	690	Creep	-1.42	0.42
	AW9-01	12.679	760.41	3382.304	NBG-17 WG		67.60	6.09	677	Creep	-1.47	0.44
	AW7-03	12.687	703.36	3128.545	NBG-17 WG		62.42	6.65	712	Creep	-1.62	0.33
	AW13-02	12.696	689.04	3064.85	NBG-17 WG		61.01	5.92	674	Creep	-1.85	0.30
	AW10-03	12.681	732.11	3256.425	NBG-17 WG		65.06	6	670	Creep	-1.89	0.39
						mean	64.46					
						SD	4.97					

8.2. NBG-18

Table 7 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade NBG-18

NGNP AGC-1 IRRADIATED SPECIMENS PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER						σ_f		DOSE	Irr. Temp	SPEC TYPE	CREEP STRAIN	Fractional change $[(\sigma_i/\sigma_0)-1]$
Date	Sample ID	Diameter (mm)	lb(f)	F (N)	GRADE	REDUCED DATA SET		DPA	°C		%	
	BL7-02	12.671	943.79	4197.978	NBG-18 AG		84.06	3.39	505	Control	0	0.67
	BL6-02	12.573	789.96	3513.742	NBG-18 AG		72.03	6.56	678	Control	0	0.43
	BL7-01	12.724	743.86	3308.689	NBG-18 AG		65.43	3.96	599	Creep	-1.06	0.30
	BL6-03	12.701	666.71	2965.526	NBG-18 AG		58.96	6.76	714	Creep	-2.07	0.17
						mean	70.12					
						SD	10.71					
	BW1-02	12.675	838.85	3731.205	NBG-18 WG		74.65	3.41	504	Control	0	0.56
	BW11-02	12.673	740.55	3293.966	NBG-18 WG		65.93	3.41	505	Control	0	0.38
	BW7-01	12.624	594.9	2646.115	NBG-18 WG		53.58	4.66	585	Control	0	0.12
	BW10-02	12.625	849.99	3780.756	NBG-18 WG		76.54	5.01	585	Control	0	0.60
	BW3-01	12.612	745.65	3316.651	NBG-18 WG		67.35	5.15	582	Control	0	0.41
	BW8-02	12.630	711.03	3162.661	NBG-18 WG		63.94	5.22	599	Control	0	0.34
	BW5-03	12.593	745.85	3317.541	NBG-18 WG		67.68	5.63	617	Control	0	0.42
	BW12-01	12.604	724.92	3224.444	NBG-18 WG		65.60	5.72	613	Control	0	0.37
	BW5-02	12.591	811.67	3610.308	NBG-18 WG		73.69	5.72	611	Control	0	0.54
	BW10-01	12.599	821.52	3654.121	NBG-18 WG		74.43	5.85	638	Control	0	0.56
	BW8-01	12.591	824.57	3667.687	NBG-18 WG		74.86	5.95	658	Control	0	0.57
	BW1-03	12.575	852.28	3790.941	NBG-18 WG		77.66	6.34	664	Control	0	0.62
	BW2-03	12.562	820.88	3651.274	NBG-18 WG		75.03	6.55	675	Control	0	0.57
	BW7-03	12.706	942.73	4193.263	NBG-18 WG		83.28	3.76	603	Creep	-0.62	0.74
	BW12-02	12.706	735.95	3273.506	NBG-18 WG		65.01	3.93	597	Creep	-0.72	0.36
	BW9-03	12.704	752.59	3347.52	NBG-18 WG		66.52	3.95	599	Creep	-0.9	0.39
	BW3-02	12.625	802.19	3568.141	NBG-18 WG		72.23	6.19	671	Creep	-1.19	0.51
	BW7-02	12.665	815.62	3627.878	NBG-18 WG		72.76	6.3	698	Creep	-1.2	0.52
	BW1-01	12.642	723.01	3215.948	NBG-18 WG		64.84	6.63	700	Creep	-1.35	0.36
	BW9-02	12.683	740.84	3295.256	NBG-18 WG		65.81	5.62	668	Creep	-1.37	0.38
	BW2-02	12.662	964.19	4288.717	NBG-18 WG		86.06	5.76	665	Creep	-1.38	0.80
	BW12-03	12.690	729.16	3243.304	NBG-18 WG		64.66	5.76	675	Creep	-1.48	0.35
	BW9-01	12.692	776.20	3452.538	NBG-18 WG		68.79	6.28	686	Creep	-1.49	0.44
	BW5-01	12.693	672.32	2990.479	NBG-18 WG		59.58	5.38	656	Creep	-1.64	0.25
	BW2-01	12.661	830.59	3694.464	NBG-18 WG		74.16	6.8	709	Creep	-1.72	0.55
	BW11-01	12.639	732.89	3259.895	NBG-18 WG		65.77	6.21	674	Creep	-1.8	0.38
	BW3-03	12.690	736.96	3277.998	NBG-18 WG		65.35	6.13	678	Creep	-1.82	0.37
						mean	69.84					
						SD	7.02					

8.3. H-451

Table 8 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade H-451

NGNP AGC-1 IRRADIATED SPECIMENS PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER						σ_f (MPa)		DOSE	Irr. Tem	SPEC TYPE	CREEP STRAIN	Fractional change $[(\sigma_i/\sigma_0)-1]$
Date	Sample ID	Diameter (mm)	F lb(f)	F (N)	GRADE	REDUCED DATA SET		DPA	°C		%	
21-10-14	CW13-01	12.623	519.08	2308.868	H-451 (WG)		46.77	4.24	567	Control	0	0.56
21-10-14	CW14-02	12.610	515.47	2292.811	H-451 (WG)		46.58	4.74	582	Control	0	0.55
20-10-14	CW8-03	12.614	365.59	1626.144	H-451 (WG)		33.01	4.76	580	Control	0	0.10
20-10-14	CW10-03	12.558	458.85	2040.965	H-451 (WG)		41.98	6.09	657	Control	0	0.40
20-10-14	CW10-02	12.554	516.51	2297.436	H-451 (WG)		47.31	6.66	681	Control	0	0.57
20-10-14	CW8-02	12.562	442.18	1966.817	H-451 (WG)		40.42	6.7	674	Control	0	0.34
21-10-14	CW13-02	12.670	566.64	2520.415	H-451 (WG)		50.49	6.92	708	Creep	-2.1	0.68
20-10-14	CW9-01	12.662	436.65	1942.219	H-451 (WG)		38.98	6.42	683	Creep	unknown	0.30
21-10-14	CW11-02	12.680	429.61	1910.905	H-451 (WG)		38.18	4.6	628	Creep	-1.19	0.27
20-10-14	CW11-01	12.666	508.91	2263.632	H-451 (WG)			4.91	642	Creep	-1.21	
20-10-14	CW7-03	12.656	472.09	2099.856	H-451 (WG)		42.20	5.41	649	Creep	-1.35	0.40
21-10-14	CW14-01	12.696	659.73	2934.479	H-451 (WG)		58.42	4.64	627	Creep	-1.42	0.94
21-10-14	CW12-02	12.671	465.74	2071.612	H-451 (WG)		41.48	5	641	Creep	-1.79	0.38
20-10-14	CW7-01	12.634	460.35	2047.637	H-451 (WG)		41.36	6.84	706	Creep	-1.89	0.38
21-10-14	CW13-03	12.678	563.61	2506.937	H-451 (WG)		50.12	5.46	653	Creep	-2.25	0.67
20-10-14	CW10-01	12.695	573.40	2550.483	H-451 (WG)		50.78	6.47	697	Creep	-2.61	0.69
20-10-14	CW9-03	12.709	430.82	1916.287	H-451 (WG)		38.03	6.81	712	Creep	-3.09	0.27
						mean	44.13					
						SD	6.36					

8.4. PCEA

Table 9 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade PCEA

NGNP AGC-1 IRRADIATED SPECIMENS PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER									σ_f (MPa)		DOSE	Irr. Temp	SPEC TYPE	CREEP STRAIN	Fractional change $[(\sigma_i/\sigma_0)-1]$
Date	Sample ID	Diameter (mm)		F (N)	Fracture Location	Crosshead Speed		GRADE	REDUCED DATA SET		DPA	°C		%	
21-10-14	DA702	12.658	748.17	3327.86	Middle	.50 mm per min		PCEA (AG)		66.84	3.72	538	Control	0	0.79
21-10-14	DA601	12.546	489.43	2176.985	Middle	.50 mm per min		PCEA (AG)		44.91	5.96	632	Control	0	0.20
21-10-14	DA701	12.675	504.34	2243.304	Middle	.50 mm per min		PCEA (AG)		44.88	4.17	612	Creep	-1.17	0.20
21-10-14	DA602	12.608	511.75	2276.264	Middle	.50 mm per min		PCEA (AG)		46.27	6.37	680	Creep	-1.88	0.24
									mean	50.72					
									SD	10.77					
22-10-14	DW10-02	12.626	714.36	3177.473	Middle	.50 mm per min		PCEA (WG)		64.31	3.88	534	Control	0	0.50
21-10-14	DW2-03	12.634	757.52	3369.449	Middle	.50 mm per min		PCEA (WG)		68.07	3.91	533	Control	0	0.59
21-10-14	DW5-01	12.630	725.15	3225.467	Middle	.50 mm per min		PCEA (WG)		65.23	3.91	534	Control	0	0.53
22-10-14	DW6-01	12.600	811.30	3608.662	Middle	.50 mm per min		PCEA (WG)		73.49	5.02	585	Control	0	0.72
22-10-14	DW9-01	12.589	796.61	3543.321	Middle	.50 mm per min		PCEA (WG)		72.35	5.33	597	Control	0	0.69
21-10-14	DW4-01	12.571	820.60	3650.029	Off Center	.50 mm per min		PCEA (WG)		74.86	5.47	594	Control	0	0.75
22-10-14	DW7-02	12.588	846.49	3765.188	Middle	.50 mm per min		PCEA (WG)		76.90	5.5	618	Control	0	0.80
22-10-14	DW5-03	12.553	839.26	3733.028	Middle	.50 mm per min		PCEA (WG)		76.89	5.88	638	Control	0	0.80
21-10-14	DW2-02	12.546	741.92	3300.06	Middle	.50 mm per min		PCEA (WG)		68.08	5.96	634	Control	0	0.59
22-10-14	DW8-03	12.545	776.51	3453.916	Center then off to side	.50 mm per min		PCEA (WG)		71.27	6.24	670	Control	0	0.67
22-10-14	DW7-01	12.537	818.22	3639.443	Middle	.50 mm per min		PCEA (WG)		75.25	6.27	679	Control	0	0.76
21-10-14	DW2-01	12.525	736.39	3275.463	Middle	.50 mm per min		PCEA (WG)		67.91	6.49	672	Control	0	0.59
21-10-14	DW4-03	12.511	729.21	3243.526	Middle	.50 mm per min		PCEA (WG)		67.47	6.68	674	Control	0	0.58
21-10-14	DW1-03	12.673	929.01	4132.236	Middle	.50 mm per min		PCEA (WG)		82.72	4.36	606	Creep	-0.95	0.94
22-10-14	DW8-02	12.691	703.69	3130.013	Middle	.50 mm per min		PCEA (WG)		62.39	4.25	611	Creep	-1.25	0.46
21-10-14	DW3-03	12.681	784.42	3489.1	Middle	.50 mm per min		PCEA (WG)		69.71	4.38	609	Creep	-1.32	0.63
22-10-14	DW10-01	12.680	754.15	3354.459	Middle	.50 mm per min		PCEA (WG)		67.03	4.39	610	Creep	-1.59	0.57
21-10-14	DW1-01	12.593	687.74	3059.068	Middle	.50 mm per min		PCEA (WG)		62.41	6.73	706	Creep	-1.63	0.46
22-10-14	DW6-03	12.625	829.47	3689.483	Off Center	.50 mm per min		PCEA (WG)		74.69	6.52	714	Creep	-1.66	0.75
21-10-14	DW3-02	12.639	849.98	3780.711	Middle	.50 mm per min		PCEA (WG)		76.29	6.02	670	Creep	-1.75	0.78
22-10-14	DW8-01	12.655	855.80	3806.598	Middle	.50 mm per min		PCEA (WG)		76.53	5.87	674	Creep	-1.85	0.79
22-10-14	DW7-03	12.636	847.97	3771.771	Off Center	.50 mm per min		PCEA (WG)		76.15	6.55	706	Creep	-2.04	0.78
21-10-14	DW3-01	12.614	742.41	3302.24	Middle	.50 mm per min		PCEA (WG)		67.03	6.8	711	Creep	-2.04	0.57
21-10-14	DW1-02	12.643	826.83	3677.74	Middle	.50 mm per min		PCEA (WG)		74.14	6.39	683	Creep	-2.40	0.73
22-10-14	DW9-03	12.634	843.68	3752.689	Middle	.50 mm per min		PCEA (WG)		75.80	6.83	710	Creep	-2.42	0.77
21-10-14	DW5-02	12.670	822.07	3656.567	Middle	.50 mm per min		PCEA (WG)		73.25	5.66	669	Creep	-2.42	0.71
22-10-14	DW11-01	12.654	715.06	3180.587	Middle	.50 mm per min		PCEA (WG)		63.95	6.32	687	Creep	-2.54	0.50
22-10-14	DW6-02	12.637	667.41	2968.64	Off Center	.50 mm per min		PCEA (WG)			5.97	679	Creep		#VALUE!

8.5. IG-110

Table 10 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade IG-110

NGNP AGC-1

IRRADIATED SPECIMENS

PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER

Date	Sample ID	Diameter (mm)	F (lbs)	F (N)	Fracture Location	Crosshead Speed	GRADE	σ_f REDUCED DATA SET	DOSE DPA	Irr. Temp °C	SPEC TYPE	CREEP STRAIN %	Fractional change $[(\sigma_i/\sigma_0)-1]$
27-10-14	EW9-02	12.622	719.74	3201.404	Center then off to side	.50 mm per min	IG-110	64.86	3.31	507	Control	0.00	0.39
22-10-14	EW2-03	12.606	743.89	3308.823	Middle	.50 mm per min	IG-110	67.29	4.36	562	Control	0.00	0.45
27-10-14	EW10-01	12.564	647.62	2880.614	Center then off to side	.50 mm per min	IG-110	59.17	5.11	582	Control	0.00	0.27
22-10-14	EW5-03	12.545	753.79	3352.858	Center then off to side	.50 mm per min	IG-110	69.18	5.76	613	Control	0.00	0.49
27-10-14	EW8-01	12.527	685.99	3051.284	Center then off to side	.50 mm per min	IG-110	63.24	6.13	671	Control	0.00	0.36
22-10-14	EW5-02	12.534	668.25	2972.376	Center then off to side	.50 mm per min	IG-110	61.50	6.18	653	Control	0.00	0.32
27-10-14	EW10-03	12.519	632.25	2812.248	Center then off to side	.50 mm per min	IG-110	58.39	6.43	678	Control	0.00	0.26
27-10-14	EW9-01	12.515	728.51	3240.412	Center then off to side	.50 mm per min	IG-110	67.35	6.62	681	Control	0.00	0.45
22-10-14	EW2-02	12.664	633.78	2819.053	Center then off to side	.50 mm per min	IG-110	56.55	4.75	621	Creep	-1.21	0.22
27-10-14	EW8-03	12.668	755.08	3358.596	Center then off to side	.50 mm per min	IG-110	67.31	3.82	601	Creep	-1.31	0.45
22-10-14	EW2-01	12.649	751.62	3343.206	Middle	.50 mm per min	IG-110	67.29	5.11	635	Creep	-1.32	0.45
27-10-14	EW7-01	12.630	670.45	2982.162	Center then off to side	.50 mm per min	IG-110	60.30	6.42	708	Creep	-1.82	0.30
22-10-14	EW4-01	12.677	675.22	3003.379	Center then off to side	.50 mm per min	IG-110	60.05	4.69	628	Creep	-1.92	0.29
27-10-14	EW6-03	12.623	599.37	2665.998	Middle	.50 mm per min	IG-110	54.00	6.63	713	Creep	-1.94	0.16
22-10-14	EW5-01	12.638	626.31	2785.827	Broke to side at hole	.50 mm per min	IG-110		6.24	674	Creep	-2.12	
22-10-14	EW6-01	12.683	683.27	3039.185	Center then off to side	.50 mm per min	IG-110	60.69	5.05	642	Creep	-2.17	0.31
27-10-14	EW9-03	12.661	745.23	3314.783	Center then off to side	.50 mm per min	IG-110	66.53	5.75	666	Creep	-2.31	0.43
27-10-14	EW8-02	12.655	569.78	2534.381	Center then off to side	.50 mm per min	IG-110	50.94	6.77	712	Creep	-2.53	0.10
27-10-14	EW10-02	12.666	636.00	2828.928	Center then off to side	.50 mm per min	IG-110	56.71	6.69	713	Creep	-2.76	0.22
22-10-14	EW4-02	12.655	641.64	2854.015	Center then off to side	.50 mm per min	IG-110	57.36	6.54	693	Creep	-2.78	0.23

8.6. IG-430

Table 11 Variation of 3-pt. flexure strength with neutron dose in the not-crept and crept condition for grade IG-430

NGNP AGC-1 IRRADIATED SPECIMENS PERFORMED BY ASHLI CLARK AND MICHAEL MCALISTER								σ_f	DOSE	Irr. Temp	SPEC TYPE	CREEP STRAIN	Fractional change $[(\sigma_i/\sigma_0)-1]$
Date	Sample ID	Diameter (mm)	F (lbs)	F (N)	Fracture Location	Crosshead Speed	GRADE	REDUCED DATA SET	DPA	°C		%	
28-10-14	FW4-01	12.648	940.82	4184.767	Center then off to side	.50 mm per min	IG-430	84.25	2.78	472	Control	0.00	0.23
30-10-14	FW7-03	12.649	1030.62	4584.198	Center then off to side	.50 mm per min	IG-430	92.27	3.32	508	Control	0.00	0.35
30-10-14	FW7-02	12.638	1045.78	4651.629	Middle	.50 mm per min	IG-430	93.89	3.80	537	Control	0.00	0.37
28-10-14	FW3-03	12.600	1042.19	4635.661	Center then off to side	.50 mm per min	IG-430	94.41	4.37	564	Control	0.00	0.38
30-10-14	FW9-01	12.603	1109.52	4935.145	Center then off to side	.50 mm per min	IG-430	100.43	4.91	587	Control	0.00	0.47
28-10-14	FW2-01	12.568	1078.05	4795.166	Center then off to side	.50 mm per min	IG-430	98.41	5.12	580	Control	0.00	0.44
30-10-14	FW5-03	12.567	1045.35	4649.717	Center then off to side	.50 mm per min	IG-430	95.44	5.74	639	Control	0.00	0.39
30-10-14	FW10-02	12.572	1119.04	4977.49	Center then off to side	.50 mm per min	IG-430	102.05	6.06	656	Control	0.00	0.49
28-10-14	FW3-02	12.550	934.03	4154.565	Center then off to side	.50 mm per min	IG-430	85.62	6.22	653	Control	0.00	0.25
30-10-14	FW7-01	12.561	927.42	4125.164	Center then off to side	.50 mm per min	IG-430	84.80	6.28	670	Control	0.00	0.24
30-10-14	FW10-01	12.574	878.54	3907.746	Center then off to side	.50 mm per min	IG-430	80.08	6.52	678	Control	0.00	0.17
28-10-14	FW1-03	12.563	762.16	3390.088	Center then off to side	.50 mm per min	IG-430	69.65	6.61	672	Control	0.00	0.02
30-10-14	FW11-03	12.554	699.31	3110.531	Center then off to side	.50 mm per min	IG-430	64.04	6.73	677	Control	0.00	-0.06
30-10-14	FW12-01	12.697	947.40	4214.035	Center then off to side	.50 mm per min	IG-430	83.86	3.37	593	Creep	-0.92	0.23
30-10-14	FW8-02	12.658	875.97	3896.315	Center then off to side	.50 mm per min	IG-430	78.26	5.51	669	Creep	-0.95	0.14
30-10-14	FW13-01	12.647	1089.25	4844.984	Center then off to side	.50 mm per min	IG-430	97.57	5.72	662	Creep	-1.09	0.43
28-10-14	FW4-02	12.651	821.27	3653.009	Center then off to side	.50 mm per min	IG-430	73.50	6.15	688	Creep	-1.18	0.07
28-10-14	FW5-02	12.708	1056.85	4700.869	Center then off to side	.50 mm per min	IG-430	93.31	3.87	602	Creep	-1.21	0.36
28-10-14	FW2-03	12.641	1088.52	4841.737	Center then off to side	.50 mm per min	IG-430	97.65	5.15	639	Creep	-1.28	0.43
28-10-14	FW3-01	12.651	1037.60	4615.245	Center then off to side	.50 mm per min	IG-430	92.86	4.78	625	Creep	-1.34	0.36
28-10-14	FW5-01	12.685	991.54	4410.37	Center then off to side	.50 mm per min	IG-430	88.02	4.30	612	Creep	-1.35	0.29
30-10-14	FW8-01	12.656	790.05	3514.142	Center then off to side	.50 mm per min	IG-430	70.62	6.59	716	Creep	-1.45	0.03
30-10-14	FW11-01	12.679	729.94	3246.773	Broke to side at hole	.50 mm per min	IG-430		5.14	639	Creep	-1.54	
30-10-14	FW11-02	12.686	1012.55	4503.822	Center then off to side	.50 mm per min	IG-430	89.87	4.78	626	Creep	-1.54	0.31
30-10-14	FW9-03	12.663	855.27	3804.241	Center then off to side	.50 mm per min	IG-430	76.32	6.43	697	Creep	-1.55	0.12
27-10-14	FW1-01	12.618	911.83	4055.82	Center then off to side	.50 mm per min	IG-430	82.25	6.79	708	Creep	-1.70	0.20
30-10-14	FW9-02	12.670	844.22	3755.091	Center then off to side	.50 mm per min	IG-430	75.21	6.72	714	Creep	-1.75	0.10
28-10-14	FW2-02	12.636	760.03	3380.613	Center then off to side	.50 mm per min	IG-430	68.26	6.58	693	Creep	-1.83	0.00
28-10-14	FW4-03	12.683	819.21	3643.846	Center then off to side	.50 mm per min	IG-430	72.76	6.59	707	Creep	-2.04	0.06
30-10-14	FW10-03	12.692	566.23	2518.591	Broke to side at hole	.50 mm per min	IG-430		6.87	708	Creep	-2.56	

9. Distribution

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Tim Burchell	Mark Carroll	William Corwin
Anne Campbell	Judy Mount	Tom O'Connor
Cristian Contescu	Larry Hull	Carl Sink
Yutai Katoh	Travis Mitchell	
Nidia Gallego	David Petti	
Mark Vance	David Swank	
Wei Ju Ren	William Windes	

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