THE EFFECTS OF NEUTRON IRRADIATION ON DIMENSIONAL CHANGE IN ADVANCED SILICON CARBIDE COMPOSITES—K. Ozawa, Y. Katoh, L.L. Snead (Oak Ridge National Laboratory), T. Nozawa (Japan Atomic Energy Agency), T. Hinoki (Kyoto University), and A. Hasegawa (Tohoku University)

OBJECTIVE

The objective of this work is investigation of the neutron irradiation effects on the dimensional change of silicon carbide composites reinforced with advanced silicon carbide fibers.

SUMMARY

The dimensional change and elastic modulus of advanced silicon carbide (SiC) fibers reinforced silicon carbide matrix (SiC/SiC) composites included in the HFIR-18J irradiation experiment were measured and the data collected in the past five years were summarized. The excellent dimensional stability of the advanced SiC/SiC composites was confirmed after neutron irradiation to 7.0×10^{25} n/m^2. The stability is superior to composites reinforced with the earlier generation SiC fibers. The swelling of the advanced composites was measured to be ~0.7% for a dose of ~7.0×10^{25} n/m^2 at 800°C (nominal). This corresponds to the swelling behavior of chemically vapor deposited (CVD) SiC.

PROGRESS AND STATUS

Introduction

Silicon carbide (SiC) -based ceramics and composites are considered for applications in various components in fusion systems, due primarily to their superior irradiation performance and thermo-physical, -chemical, and -mechanical properties [1, 2]. Swelling behavior during irradiation is one of the important issues to be considered. Recently, swelling behavior and microstructural development in monolithic SiC, the main constituent of SiC/SiC composites, have been thoroughly studied after systematic ion and neutron irradiation to high dose and very high temperature [3-8]. In contrast, data on the swelling behavior of advanced SiC/SiC composites are quite limited [9]. There is some data available on one of the composites, but it was reinforced with older generation fibers [10-12]. The main objective of this study is to investigate the neutron irradiation effects on dimensional changes in advanced SiC/SiC composites.

Experimental Procedure

Two types of materials were used in this study. One is monolithic SiC, used to generate statistical data in a flexural strength evaluation with specimen dimensions 1×1×24 or 1×1×25 mm. The specimens are made by chemically vapor deposition (CVD) or nano-infiltration and transient eutectic-phase (NITE) process. The other is SiC/SiC composites reinforced with advanced SiC fibers for flexural or tensile property evaluation with specimen dimensions 2×4×25, 2×4×50, 3×1.5×40 or 2×4×40 mm. The composites were processed by chemically vapor infiltration (CVI) or NITE method and reinforced with Tyranno-SA 3rd or Hi-Nicalon Type-S fibers. Neutron irradiation was conducted at Japan Material Testing Reactor (JMTR), JOYO and High Flux Isotope Reactor (HFIR). The specimens were irradiated to 1.0×10^{25} n/m^2 (~1 dpa, E > 0.1 MeV; hereafter 1.0×10^{25} n/m^2 =1 dpa is assumed) at ~1000°C (nominal) for JMTR campaign, to 12 dpa at ~750°C (nominal) for JOYO CMIR-6 campaign, and to 7 dpa at 800 and 1300°C (nominal) for HFIR-18J. Information on materials characterization and neutron irradiation conditions is listed in Tables 1-3, along with the property change results. Further details about material characterization, irradiation condition, and mechanical properties before and after irradiation are given elsewhere for JMTR 00M-95U [13-15], and the HFIR-18J [16] campaign. After neutron irradiation, the length of the specimens was measured by a conventional caliper. Volumetric swelling was determined using the following equation $\Delta V/V = (L_{irrad.}/L_{unirrad.})^3-1$, where $\Delta V/V$, $L_{irrad.}$, and $L_{unirrad.}$ are volumetric swelling, length of the specimen before irradiation, and length after irradiation, respectively. This equation was chosen in order to avoid low accuracy in measuring width and thickness, and hence it assumes that the swelling of the advanced SiC/SiC composites is isotropic. In parallel, dynamic elastic modulus was

determined at room temperature using the impulse excitation of vibration method per ASTM Standard C1259-01.

Results and Discussion

Monolithic SiC

The results of dimensional change and elastic modulus for monolithic CVD and NITE-SiC are listed in Table 1. Figure 1 shows the dependence of volumetric swelling on irradiation temperature. The swelling results for CVD-SiC are consistent with the values reported in the literature, as shown in Fig. 1. The swelling of monolithic NITE-SiC is almost the same or slightly higher than CVD-SiC. Elastic modulus of both CVD- and NITE-SiC was decreased slightly by neutron irradiation to 7dpa at 800 and 1300°C.

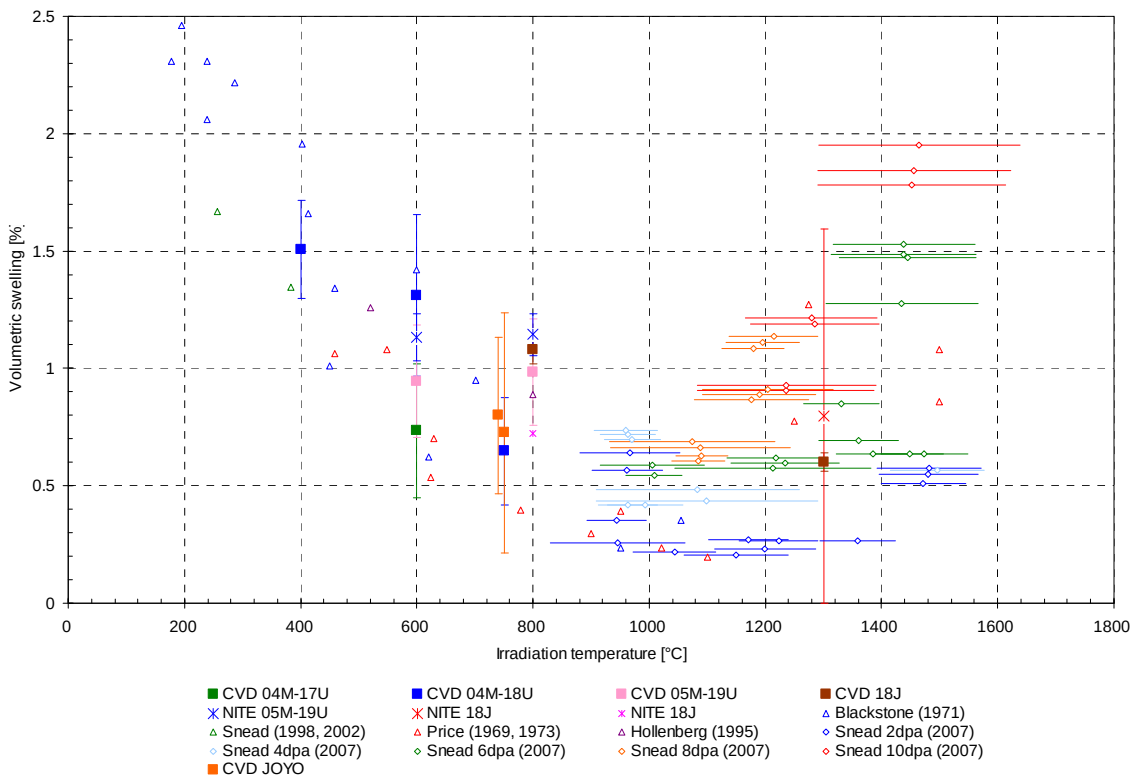

Fig. 1: Temperature dependence of volumetric swelling of monolithic CVD and NITE SiC. The data are from the reports by Blackstone et al. [17], Snead et al. [11, 18], Price [19, 20], Hollenberg et al. [10], Snead et al. [3, 4] , and Katoh et al. [21].

SiC/SiC Composites

Individual results for advanced SiC/SiC composites are listed in Table 1. Average results for each condition are also listed in Table 2. Figures 1, 2 show the volumetric swelling of advanced SiC/SiC composites dependence on dose and irradiation temperature. This confirms the excellent dimensional stability of the advanced SiC/SiC composites during neutron irradiation, compared to the composites reinforced with older generation SiC fibers. For CVI-SiC/SiC composites, 0.2-0.5% swelling after neutron irradiation 1 dpa at 1000°C for JMTR 00M-95U, and ~0.7% swelling after 7 dpa at 800 and 1300°C for HFIR-18J were measured, as shown in Fig. 1. There was no significant difference in swelling detected arising from the difference of fibers used or interphase structure. The swelling of the advanced SiC/SiC

composites irradiated to 7dpa at 800°C (~0.7%) is almost the same as reported by Newsome et al. [9]. The advanced SiC/SiC composites showed similar swelling values as β-SiC after irradiation, as shown in Figs. 2 and 3. This is primarily because both fibers and matrix of advanced SiC/SiC composites are composed of highly crystalline β-SiC. In the intermediate temperature regime, β-SiC swells due to point defect clustering, and the swelling is saturated at a few dpa. This saturation swelling in SiC is significant at irradiation temperatures below ~1000ºC with the volume expansion negatively correlated with temperature (~1.4% at 300ºC, ~0.7% at 800ºC, ~0.3% at 1000°C), as shown in Fig. 1.

A slight decrease (~4%) of elastic modulus was measured in the composites reinforced with Tyranno-SA 3rd fiber, while ~13% decrease was obtained in the Hi-Nicalon Type-S composites.

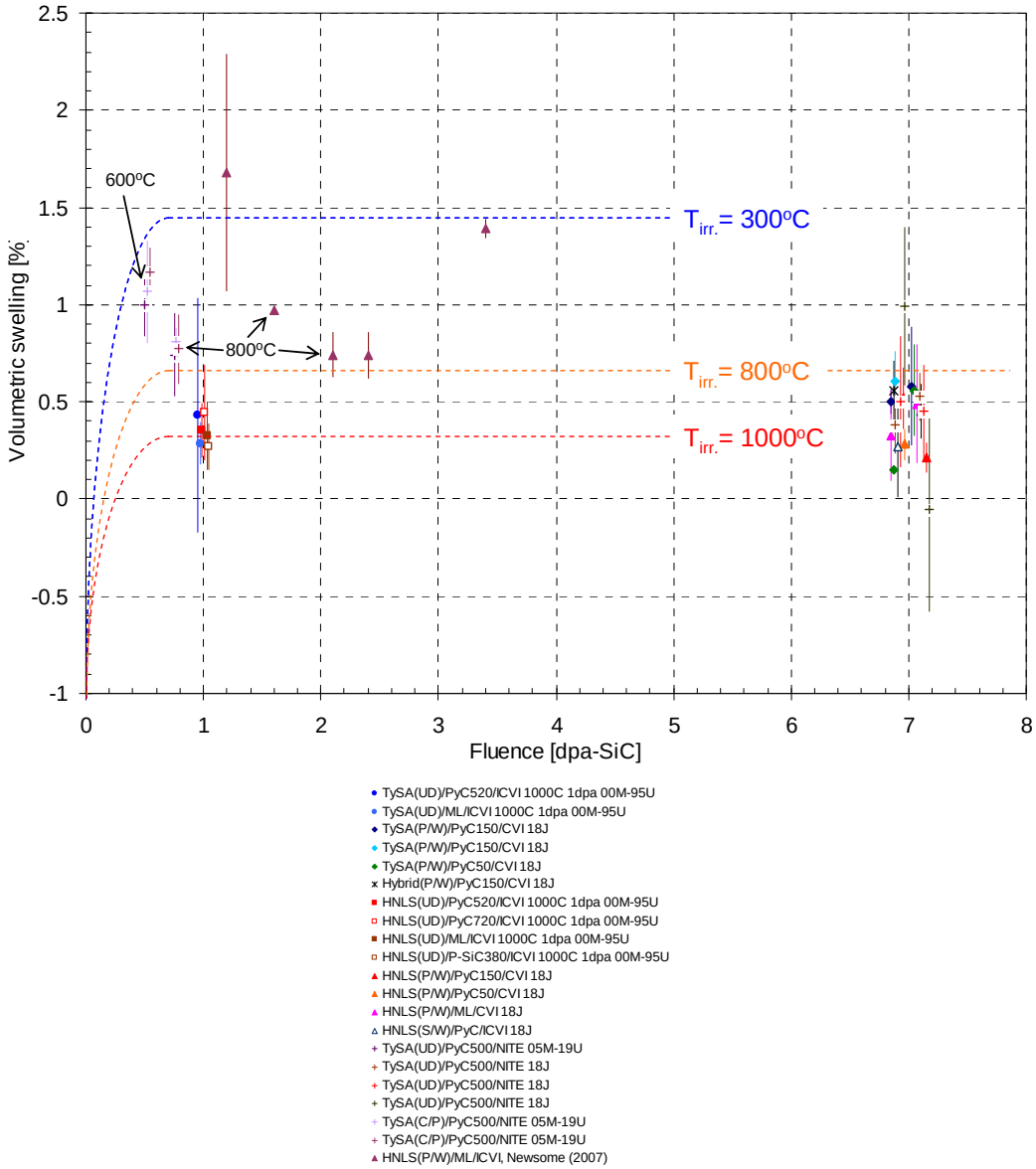

Fig. 2: Dose dependence of swelling of neutron irradiated advanced SiC/SiC composites. The data have been shifted slightly on the Fluence axis for clarity. For comparison, the values in ref. [9] were also plotted.

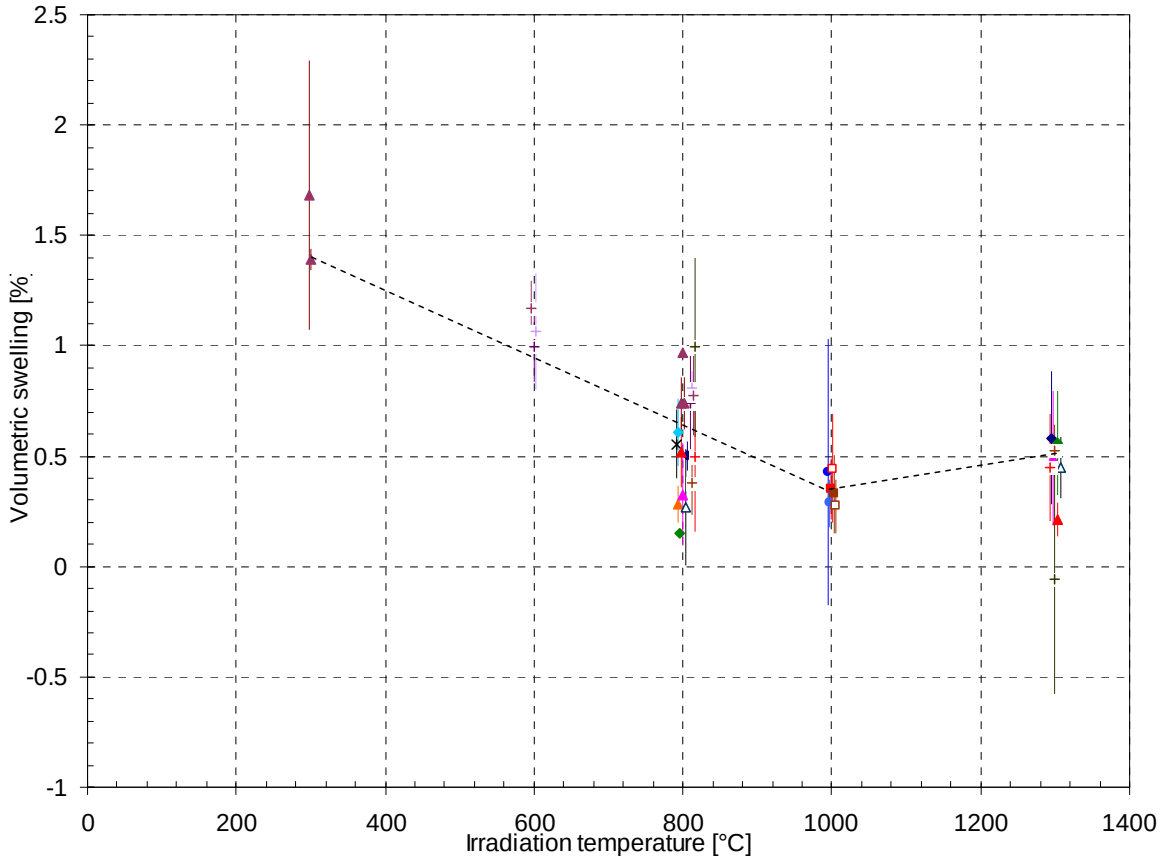

Fig. 3: Temperature dependence of swelling of advanced SiC/SiC composites. The data have been shifted slightly on the Irradiation temperature axis for clarity. For comparison, the values in ref. [9] were also plotted. The legend symbols are the same as used in Fig. 1.

Table 1: Average values of volumetric swelling and dynamic modulus (E) of monolithic SiC after neutron irradiation.

Reactor	Capsule ID	Specimen ID	Irradiation Temperature [°C]	Fluence [dpa]	Material	# of Tests	Length Before Irrad. [mm]	Length After Irrad. [mm]	Length Change [%]	Vol. Swelling [%]	Std. dev. [%]	Sonic E Before Irrad. [GPa]	Sonic E After Irrad. [GPa]	% Change In E
JMTR	04M-17U	-	600	0.52	CVD	20	23.98	24.04	0.24	0.73	0.29	-	-	-
JMTR	04M-18U	-	400	0.77	CVD	20	23.98	24.10	0.50	1.51	0.21	-	-	-
JMTR	04M-18U	-	600	0.52	CVD	20	23.98	24.09	0.44	1.31	0.35	-	-	-
JMTR	04M-18U	-	750	0.77	CVD	20	23.98	24.04	0.22	0.65	0.23	-	-	-
JMTR	05M-19U	-	600	0.52	CVD	20	23.99	24.06	0.31	0.95	0.24	-	-	-
JMTR	05M-19U	-	800	0.77	CVD	20	23.99	24.06	0.33	0.99	0.23	-	-	-
JMTR	05M-19U	-	600	0.52	NITE	20	24.98	25.08	0.38	1.13	0.10	-	-	-
JMTR	05M-19U	-	800	0.77	NITE	20	24.99	25.08	0.38	1.14	0.09	-	-	-
JOYO	CMIR-6 JNC-54	-	750	12	CVD	18	22.02	22.08	0.24	0.73	0.51			
JOYO	CMIR-6 JNC-61	-	740	3.1	CVD	19	22.02	22.08	0.27	0.80	0.33			
HFIR	18J	R001-R030	800	7	CVD	5	24.86	24.95	0.36	1.08	0.06	-	-	-
HFIR	18J	R061-R090	1300	7	CVD	28	24.86	24.91	0.20	0.60	0.04	-	-	-
HFIR	18J	L061-L090	1300	7	NITE	21	24.98	25.05	0.26	0.80	0.80	-	-	-
HFIR	18J	R1	800	7	CVD	1	25.40	25.42	0.09	0.28	-	448.31	433.73	-3.25
HFIR	18J	R7	800	7	CVD	1	25.41	25.43	0.08	0.24	-	450.06	436.38	-3.04
HFIR	18J	R5	1300	7	CVD	1	-	-	-	-	-	449.35	441.36	-1.78
HFIR	18J	R6	1300	7	CVD	1	-	-	-	-	-	446.20	436.88	-2.09
HFIR	18J	L1	800	7	NITE	1	24.93	24.99	0.24	0.72	-	352.81	336.70	-4.57
HFIR	18J	L3	1300	7	NITE	1	-	-	-	-	-	337.69	319.56	-5.37

Table 2: Length change, volumetric swelling and dynamic modulus of individual advanced SiC/SiC specimens before and after neutron irradiation. Temperatures shown are nominal values. E; elastic modulus, Hybrid; combination of Tyranno-SA 3rd SiC fiber and P-120 carbon fiber ,UD; uni-directional, P/W; plain-woven, S/W; satin-woven, 3D; 3D orthogonal, PyC; pyrolytic carbon, ML; multi-layered, P-SiC; porous SiC, ICVI; isothermal chemically vapor infiltration.

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Length Before Irrad. [mm]	Length After Irrad. [mm]	Length Change [%]	Vol. Swelling [%]	Sonic E Before Irrad. [GPa]	Sonic E After Irrad. [GPa]	% Change In E
JMTR	00M-95U	1000	1	TP23-1	Tyranno-SA 1st	UD	PyC	520	ICVI	24.85	24.98	0.54	1.62	-	-	-
JMTR	00M-95U	1000	1	TP23-2	Tyranno-SA 1st	UD	PyC	520	ICVI	24.99	25.00	0.04	0.12	-	-	-
JMTR	00M-95U	1000	1	TM24-1	Tyranno-SA 1st	UD	ML		ICVI	25.22	25.24	0.09	0.28	-	-	-
JMTR	00M-95U	1000	1	TM24-2	Tyranno-SA 1st	UD	ML		ICVI	24.59	24.61	0.07	0.20	-	-	-
JMTR	00M-95U	1000	1	ST41-2	Hi-Nicalon Type-S	UD	PyC	720	ICVI	25.01	25.04	0.13	0.40	-	-	-
JMTR	00M-95U	1000	1	SM25-2	Hi-Nicalon Type-S	UD	ML		ICVI	25.01	25.02	0.03	0.08	-	-	-
JMTR	00M-95U	1000	1	SS26-1	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	24.64	24.66	0.08	0.24	-	-	-
JMTR	00M-95U	1000	1	SS26-2	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	25.10	25.12	0.09	0.28	-	-	-
JMTR	00M-95U	1000	1	TP17	Tyranno-SA 1st	UD	PyC	520	ICVI	50.06	50.08	0.05	0.14	-	-	-
JMTR	00M-95U	1000	1	TP18	Tyranno-SA 1st	UD	PyC	520	ICVI	50.07	50.15	0.16	0.48	-	-	-
JMTR	00M-95U	1000	1	TP19	Tyranno-SA 1st	UD	PyC	520	ICVI	50.08	50.11	0.07	0.20	-	-	-
JMTR	00M-95U	1000	1	TP20	Tyranno-SA 1st	UD	PyC	520	ICVI	50.10	50.10	0.01	0.02	-	-	-
JMTR	00M-95U	1000	1	TM17	Tyranno-SA 1st	UD	ML		ICVI	50.07	50.11	0.07	0.22	-	-	-
JMTR	00M-95U	1000	1	TM18	Tyranno-SA 1st	UD	ML		ICVI	50.07	50.10	0.06	0.18	-	-	-
JMTR	00M-95U	1000	1	TM19	Tyranno-SA 1st	UD	ML		ICVI	50.08	50.15	0.14	0.42	-	-	-
JMTR	00M-95U	1000	1	TM22	Tyranno-SA 1st	UD	ML		ICVI	50.08	50.15	0.14	0.42	-	-	-
JMTR	00M-95U	1000	1	SP20	Hi-Nicalon Type-S	UD	PyC	520	ICVI	50.05	50.13	0.15	0.45	-	-	-
JMTR	00M-95U	1000	1	SP21	Hi-Nicalon Type-S	UD	PyC	520	ICVI	50.07	50.15	0.16	0.48	-	-	-
JMTR	00M-95U	1000	1	SP23	Hi-Nicalon Type-S	UD	PyC	520	ICVI	50.05	50.10	0.10	0.30	-	-	-
JMTR	00M-95U	1000	1	SP25	Hi-Nicalon Type-S	UD	PyC	520	ICVI	50.11	50.14	0.06	0.18	-	-	-
JMTR	00M-95U	1000	1	ST36	Hi-Nicalon Type-S	UD	PyC	720	ICVI	50.09	50.18	0.19	0.56	-	-	-
JMTR	00M-95U	1000	1	ST37	Hi-Nicalon Type-S	UD	PyC	720	ICVI	50.10	50.12	0.04	0.12	-	-	-
JMTR	00M-95U	1000	1	ST38	Hi-Nicalon Type-S	UD	PyC	720	ICVI	50.09	50.15	0.12	0.36	-	-	-
JMTR	00M-95U	1000	1	ST39	Hi-Nicalon Type-S	UD	PyC	720	ICVI	50.07	50.20	0.26	0.78	-	-	-
JMTR	00M-95U	1000	1	SM21	Hi-Nicalon Type-S	UD	ML		ICVI	50.07	50.14	0.14	0.42	-	-	-
JMTR	00M-95U	1000	1	SM22	Hi-Nicalon Type-S	UD	ML		ICVI	50.07	50.11	0.07	0.22	-	-	-
JMTR	00M-95U	1000	1	SM23	Hi-Nicalon Type-S	UD	ML		ICVI	50.05	50.12	0.13	0.40	-	-	-

Table 2: (Cont'd)

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Length Before Irrad. [mm]	Length After Irrad. [mm]	Length Change [%]	Vol. Swelling [%]	Sonic E Before Irrad. [GPa]	Sonic E After Irrad. [GPa]	% Change In E
JMTR	00M-95U	1000	1	SM24	Hi-Nicalon Type-S	UD	ML		ICVI	50.02	50.11	0.17	0.52	-	-	-
JMTR	00M-95U	1000	1	SS22	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	50.07	50.10	0.06	0.18	-	-	-
JMTR	00M-95U	1000	1	SS23	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	50.04	50.10	0.12	0.36	-	-	-
JMTR	00M-95U	1000	1	SS24	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	50.10	50.18	0.15	0.45	-	-	-
JMTR	00M-95U	1000	1	SS25	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	50.08	50.10	0.04	0.12	-	-	-
HFIR	18J	800	7	T01	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.98	40.04	0.16	0.48	251.01	242.16	-3.53
HFIR	18J	800	7	T02	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.98	40.06	0.20	0.60	273.94	264.40	-3.48
HFIR	18J	800	7	T03	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.98	40.04	0.16	0.48	226.87	218.34	-3.76
HFIR	18J	800	7	T05	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.97	40.04	0.18	0.53	234.73	227.64	-3.02
HFIR	18J	800	7	T06	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.94	40.00	0.14	0.43	268.00	261.20	-2.54
HFIR	18J	1300	7	T15	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.99	40.10	0.27	0.80	259.17	252.87	-2.43
HFIR	18J	1300	7	T16	Tyranno-SA 3rd	P/W	PyC	150	CVI	40.00	40.14	0.35	1.05	250.55	245.42	-2.05
HFIR	18J	1300	7	T27	Tyranno-SA 3rd	P/W	PyC	150	CVI	40.00	40.05	0.13	0.40	244.77	238.07	-2.74
HFIR	18J	1300	7	T28	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.95	40.02	0.17	0.50	256.13	251.46	-1.82
HFIR	18J	1300	7	T29	Tyranno-SA 3rd	P/W	PyC	150	CVI	40.00	40.09	0.23	0.68	266.38	260.15	-2.34
HFIR	18J	1300	7	T30	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.96	40.00	0.09	0.28	243.91	238.29	-2.31
HFIR	18J	800	7	X14	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.99	40.01	0.05	0.15	274.68	272.84	-0.67
HFIR	18J	1300	7	X01	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.97	40.03	0.15	0.45	246.18	242.49	-1.50
HFIR	18J	1300	7	X02	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.95	40.04	0.22	0.65	270.21	266.15	-1.50
HFIR	18J	1300	7	X13	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.94	40.03	0.23	0.68	275.52	270.24	-1.92
HFIR	18J	1300	7	X14	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.99	40.01	0.05	0.15	274.68	272.84	-0.67
HFIR	18J	1300	7	X15	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.94	40.05	0.28	0.83	284.32	281.33	-1.05
HFIR	18J	1300	7	X16	Tyranno-SA 3rd	P/W	PyC	50	CVI	39.98	40.06	0.20	0.60	277.47	273.09	-1.58
HFIR	18J	800	7	F01	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.96	40.02	0.15	0.45	251.57	245.25	-2.51
HFIR	18J	800	7	F02	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.96	40.06	0.25	0.75	253.31	246.84	-2.55
HFIR	18J	800	7	F03	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.97	40.07	0.25	0.75	263.97	254.47	-3.60
HFIR	18J	800	7	F04	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.97	40.05	0.21	0.63	237.00	230.80	-2.61
HFIR	18J	800	7	F05	Tyranno-SA 3rd	P/W	PyC	150	CVI	39.96	40.02	0.15	0.45	226.64	218.35	-3.66
HFIR	18J	800	7	M01	Hi-Nicalon Type-S	P/W	ML		CVI	39.96	40.06	0.24	0.73	241.18	235.82	-2.22

Table 2: (Cont'd)

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Length Before Irrad. [mm]	Length After Irrad. [mm]	Length Change [%]	Vol. Swelling [%]	Sonic E Before Irrad. [GPa]	Sonic E After Irrad. [GPa]	% Change In E
HFIR	18J	800	7	M02	Hi-Nicalon Type-S	P/W	ML		CVI	39.99	39.99	0.01	0.03	212.55	205.41	-3.36
HFIR	18J	800	7	M03	Hi-Nicalon Type-S	P/W	ML		CVI	39.98	40.01	0.08	0.25	204.26	197.48	-3.32
HFIR	18J	800	7	M04	Hi-Nicalon Type-S	P/W	ML		CVI	39.98	40.03	0.13	0.40	208.33	202.46	-2.82
HFIR	18J	800	7	M05	Hi-Nicalon Type-S	P/W	ML		CVI	39.96	39.99	0.08	0.23	200.15	194.34	-2.91
HFIR	18J	800	7	M06	Hi-Nicalon Type-S	P/W	ML		CVI	39.97	40.01	0.11	0.33	208.13	201.63	-3.12
HFIR	18J	1300	7	M13	Hi-Nicalon Type-S	P/W	ML		CVI	40.00	40.03	0.08	0.25	219.42	215.02	-2.01
HFIR	18J	1300	7	M14	Hi-Nicalon Type-S	P/W	ML		CVI	39.99	40.03	0.10	0.30	214.70	208.91	-2.69
HFIR	18J	1300	7	M15	Hi-Nicalon Type-S	P/W	ML		CVI	40.00	40.03	0.08	0.25	227.69	224.60	-1.36
HFIR	18J	1300	7	M16	Hi-Nicalon Type-S	P/W	ML		CVI	39.95	40.00	0.13	0.38	202.65	200.85	-0.89
HFIR	18J	1300	7	M17	Hi-Nicalon Type-S	P/W	ML		CVI	39.96	40.07	0.28	0.85	206.48	202.27	-2.04
HFIR	18J	1300	7	M18	Hi-Nicalon Type-S	P/W	ML		CVI	39.97	40.09	0.30	0.90	203.09	197.65	-2.68
HFIR	18J	800	7	H01	Hybrid	3D	PyC	150	CVI	39.98	40.06	0.21	0.63	146.72	143.43	-2.24
HFIR	18J	800	7	H02	Hybrid	3D	PyC	150	CVI	40.00	40.05	0.12	0.35	117.02	104.95	-10.31
HFIR	18J	800	7	H03	Hybrid	3D	PyC	150	CVI	40.00	40.07	0.18	0.53	117.41	105.56	-10.09
HFIR	18J	800	7	H04	Hybrid	3D	PyC	150	CVI	40.01	40.07	0.15	0.45	96.77	94.16	-2.70
HFIR	18J	800	7	H05	Hybrid	3D	PyC	150	CVI	39.96	40.07	0.27	0.80	99.75	94.94	-4.82
HFIR	18J	800	7	H06	Hybrid	3D	PyC	150	CVI	39.97	40.05	0.19	0.58	127.12	126.36	-0.60
HFIR	18J	800	7	N01	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.08	0.15	0.45	325.23	323.92	-0.40
HFIR	18J	800	7	N02	Tyranno-SA 3rd	UD	PyC	500	NITE	40.03	40.11	0.19	0.58	336.08	324.58	-3.42
HFIR	18J	800	7	N03	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.05	0.07	0.23	334.54	336.35	0.54
HFIR	18J	800	7	N04	Tyranno-SA 3rd	UD	PyC	500	NITE	40.04	40.07	0.07	0.20	323.58	320.56	-0.93
HFIR	18J	800	7	N05	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.07	0.12	0.38	332.38	337.48	1.53
HFIR	18J	800	7	N06	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.08	0.15	0.45	335.34	340.44	1.52
HFIR	18J	800	7	N15	Tyranno-SA 3rd	UD	PyC	500	NITE	40.04	40.09	0.13	0.40	329.41	326.55	-0.87
HFIR	18J	1300	7	N13	Tyranno-SA 3rd	UD	PyC	500	NITE	40.03	40.09	0.15	0.45	345.83	347.03	0.35
HFIR	18J	1300	7	N14	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.11	0.22	0.65	350.86	350.30	-0.16
HFIR	18J	1300	7	N16	Tyranno-SA 3rd	UD	PyC	500	NITE	40.02	40.10	0.20	0.60	333.34	336.23	0.87
HFIR	18J	800	7	S1	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.95	40.00	0.14	0.41	-	217.41	-
HFIR	18J	800	7	S2	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.99	40.03	0.10	0.30	-	232.62	-

Table 2: (Cont'd)

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Length Before Irrad. [mm]	Length After Irrad. [mm]	Length Change [%]	Vol. Swelling [%]	Sonic E Before Irrad. [GPa]	Sonic E After Irrad. [GPa]	% Change In E
HFIR	18J	800	7	S3	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.99	40.00	0.04	0.11	-	219.91	-
HFIR	18J	800	7	S4	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.98	40.07	0.22	0.67	-	224.72	-
HFIR	18J	800	7	S5	Hi-Nicalon Type-S	S/W	PyC		ICVI	40.00	39.99	-0.03	-0.10	-	230.65	-
HFIR	18J	800	7	S6	Hi-Nicalon Type-S	S/W	PyC		ICVI	40.00	40.03	0.08	0.23	-	224.03	-
HFIR	18J	1300	7	S19	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.97	40.04	0.18	0.53	-	291.45	-
HFIR	18J	1300	7	S20	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.89	39.96	0.17	0.51	-	291.02	-
HFIR	18J	1300	7	S21	Hi-Nicalon Type-S	S/W	PyC		ICVI	39.96	39.99	0.08	0.24	-	281.93	-
HFIR	18J	1300	7	S22	Hi-Nicalon Type-S	S/W	PyC		ICVI	40.00	40.07	0.17	0.52	-	268.55	-
HFIR	18J	800	7	A01	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.99	40.03	0.09	0.28	228.29	205.52	-9.97
HFIR	18J	800	7	A02	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.97	40.03	0.15	0.45	202.18	182.76	-9.60
HFIR	18J	800	7	A03	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.96	40.03	0.17	0.50	229.21	206.02	-10.12
HFIR	18J	800	7	A04	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.94	40.04	0.24	0.73	230.11	207.37	-9.89
HFIR	18J	800	7	A05	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.96	40.03	0.18	0.53	239.78	220.57	-8.01
HFIR	18J	800	7	A06	Hi-Nicalon Type-S	P/W	PyC	150	CVI	40.00	40.05	0.12	0.38	219.02	193.18	-11.80
HFIR	18J	800	7	A07	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.98	40.06	0.19	0.58	207.68	188.66	-9.16
HFIR	18J	800	7	A08	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.93	40.03	0.24	0.73	233.81	209.37	-10.45
HFIR	18J	1300	7	A13	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.99	40.00	0.03	0.10	210.55	185.44	-11.92
HFIR	18J	1300	7	A14	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.94	39.98	0.09	0.28	210.90	187.70	-11.00
HFIR	18J	1300	7	A15	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.95	39.98	0.08	0.23	229.53	203.24	-11.45
HFIR	18J	1300	7	A16	Hi-Nicalon Type-S	P/W	PyC	150	CVI	39.98	40.01	0.08	0.25	218.14	190.48	-12.68
HFIR	18J	800	7	E01	Hi-Nicalon Type-S	P/W	PyC	50	CVI	40.01	40.04	0.08	0.25	236.23	221.27	-6.33
HFIR	18J	800	7	E02	Hi-Nicalon Type-S	P/W	PyC	50	CVI	39.95	39.98	0.08	0.23	226.30	210.55	-6.96
HFIR	18J	800	7	E03	Hi-Nicalon Type-S	P/W	PyC	50	CVI	39.97	40.01	0.10	0.30	188.68	181.35	-3.88
HFIR	18J	800	7	E04	Hi-Nicalon Type-S	P/W	PyC	50	CVI	40.00	40.04	0.10	0.30	237.96	217.90	-8.43
HFIR	18J	800	7	E05	Hi-Nicalon Type-S	P/W	PyC	50	CVI	39.95	39.99	0.10	0.30	-	-	-
HFIR	18J	800	7	E06	Hi-Nicalon Type-S	P/W	PyC	50	CVI	40.01	40.03	0.06	0.18	214.71	203.85	-5.06
HFIR	18J	800	7	E07	Hi-Nicalon Type-S	P/W	PyC	50	CVI	39.95	40.01	0.15	0.45	222.35	209.52	-5.77
HFIR	18J	800	7	E08	Hi-Nicalon Type-S	P/W	PyC	50	CVI	40.01	40.04	0.08	0.25	226.26	209.42	-7.44

Table 3: Average values of volumetric swelling and dynamic modulus after neutron irradiation. Temperatures shown are nominal values. E; elastic modulus, Hybrid; combination of Tyranno-SA 3rd SiC fiber and P-120 carbon fiber, UD; uni-directional, P/W; plain-woven, S/W; satin-woven, 3D; 3D orthogonal, PyC; pyrolytic carbon, ML; multi-layered, P-SiC; porous SiC, ICVI; isothermal chemically vapor infiltration.

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Vol. Swelling [%]	Standard dev. [%]	Retention of E [%]	Standard dev.	# of tests
JMTR	00M-95U	1000	1	TP	Tyranno-SA 1st	UD	PyC	520	ICVI	0.43	0.60	-	-	6
JMTR	00M-95U	1000	1	TM	Tyranno-SA 1st	UD	ML		ICVI	0.29	0.11	-	-	6
JMTR	00M-95U	1000	1	SP	Hi-Nicalon Type-S	UD	PyC	520	ICVI	0.35	0.14	-	-	4
JMTR	00M-95U	1000	1	ST	Hi-Nicalon Type-S	UD	PyC	720	ICVI	0.44	0.25	-	-	5
JMTR	00M-95U	1000	1	SM	Hi-Nicalon Type-S	UD	ML		ICVI	0.33	0.18	-	-	5
JMTR	00M-95U	1000	1	SS	Hi-Nicalon Type-S	UD	P-SiC	380	ICVI	0.27	0.12	-	-	6
JMTR	05M-19U	600	0.52	TS06-UD	Tyranno-SA 3rd	UD	PyC	500	NITE	1.00	0.16	-	-	5
JMTR	05M-19U	800	0.77	TS06-UD	Tyranno-SA 3rd	UD	PyC	500	NITE	0.74	0.21	-	-	2
JMTR	05M-19U	600	0.52	TS06-XP	Tyranno-SA 3rd	C/P	PyC	500	NITE	1.07	0.26	-	-	5
JMTR	05M-19U	800	0.77	TS06-XP	Tyranno-SA 3rd	C/P	PyC	500	NITE	0.81	0.07	-	-	4
JMTR	05M-19U	600	0.52	TS06-AN	Tyranno-SA 3rd	C/P	PyC	500	NITE	1.17	0.12	-	-	5
JMTR	05M-19U	800	0.77	TS06-AN	Tyranno-SA 3rd	C/P	PyC	500	NITE	0.77	0.18	-	-	5
HFIR	18J	800	7	T	Tyranno-SA 3rd	P/W	PyC	150	CVI	0.50	0.07	96.73	0.49	5
HFIR	18J	1300	7	T	Tyranno-SA 3rd	P/W	PyC	150	CVI	0.58	0.30	97.75	0.34	5
HFIR	18J	800	7	X	Tyranno-SA 3rd	P/W	PyC	50	CVI	0.15	-	99.33	-	1
HFIR	18J	1300	7	X	Tyranno-SA 3rd	P/W	PyC	50	CVI	0.56	0.23	98.63	0.44	6
HFIR	18J	800	7	F	Tyranno-SA 3rd	P/W	PyC	150	CVI	0.61	0.15	97.01	0.59	5
HFIR	18J	800	7	M	Hi-Nicalon Type-S	P/W	ML		CVI	0.33	0.23	97.04	0.42	6
HFIR	18J	1300	7	M	Hi-Nicalon Type-S	P/W	ML		CVI	0.49	0.31	98.06	0.72	6
HFIR	18J	800	7	H	Hybrid	3D	PyC	150	CVI	0.56	0.16	94.87	4.16	6
HFIR	18J	800	7	N	Tyranno-SA 3rd	UD	PyC	500	NITE	0.38	0.14	99.81	1.87	6
HFIR	18J	1300	7	N	Tyranno-SA 3rd	UD	PyC	500	NITE	0.53	0.12	100.05	0.74	4
HFIR	18J	800	7	S	Hi-Nicalon Type-S	S/W	PyC		ICVI	0.27	0.26	-	-	6
HFIR	18J	1300	7	S	Hi-Nicalon Type-S	S/W	PyC		ICVI	0.45	0.14	-	-	4
HFIR	18J	800	7	N601-3	Tyranno-SA 3rd	UD	PyC	500	NITE	0.50	0.34	98.60	3.28	3
HFIR	18J	1300	7	N604-6	Tyranno-SA 3rd	UD	PyC	500	NITE	0.45	0.24	100.65	1.01	3
HFIR	18J	800	7	A	Hi-Nicalon Type-S	P/W	PyC	150	CVI	0.52	0.16	90.13	1.08	8

Table 3: (Cont'd)

Reactor	Capsule ID	Temp. [°C]	Fluence [x10^25 n/m^2]	Specimen ID	Fiber	Archi-tecture	Inter-phase	Thick-ness [nm]	Matrix	Vol. Swelling [%]	Standard dev. [%]	Retention of E [%]	Standard dev.	# of tests
HFIR	18J	1300	7	A	Hi-Nicalon Type-S	P/W	PyC	150	CVI	0.21	0.08	88.24	0.72	4
HFIR	18J	800	7	E	Hi-Nicalon Type-S	P/W	PyC	50	CVI	0.28	0.08	93.73	1.52	8
HFIR	18J	800	7	K601-4	Tyranno-SA 3rd	UD	PyC	500	NITE	0.99	0.41	98.78	1.80	4
HFIR	18J	1300	7	K611-4	Tyranno-SA 3rd	UD	PyC	500	NITE	-0.06	0.52	100.40	3.35	4

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