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HIGH-TEMPERATURE PROPERTIES OF NUCLEAR GRAPHITE

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ABSTRACT

The unique combination of physical properties inherent to graphite makes it an attractive material for use as a moderator in high-temperature nuclear reactors (HTR's). High-temperature physical properties of three nuclear grade graphites manufactured by GrafTech International Holdings Inc. (GrafTech) (PCEA, PCIB-SFG, and PPEA) have been determined experimentally and are presented here. Tensile strength, Young's modulus, thermal conductivity, specific resistance, and coefficient of thermal expansion (CTE) data are collected at temperatures from 25 °C to as high as 2000 °C and are found to be consistent with classical graphite behavior.

INTRODUCTION

Graphite was used as the moderator for the first nuclear reactor in 1942 because neutrons can travel a great distance in graphite without being captured, while having multiple collisions with carbon atoms that slow down the neutrons. Graphite's thermal stability in inert atmospheres, ease of machining, relatively low cost, and high purity make it a good moderator for nuclear reactors [1,2].

GrafTech has provided nuclear graphite to the industry for more than sixty years and today leverages more than 125 years of manufacturing expertise to provide a wide product offering to the nuclear graphite industry. GrafTech nuclear graphite is specially produced for the desired strength, isotropy, and purity, using raw materials that are expected to be stable in their chemical composition and readily available in large quantities into the distant future. Three different nuclear graphite grades are presented here: PCEA, PCIB-SFG, and PPEA. These grades differ in both their forming methods and raw material base.

Graphite's unique high-temperature properties also make it well-suited for the future construction of highly-efficient, inherently-stable high-temperature reactors (HTR's). These reactors will operate at temperatures of 1200 °C, and must be mechanically stable up to 2000 °C [3]. Thus, HTR designers must understand the behavior of nuclear-grade graphite at elevated temperatures, in addition to understanding the irradiation effects on graphite.

This paper will highlight some of the strength, thermal, and electrical properties that can be achieved for these grades at high temperatures. These nuclear graphites are undergoing irradiation testing as well*; the data presented here for "as-manufactured" graphite will later be combined with post-irradiation measurements to give HTR designers a complete picture of the high-temperature performance of these three nuclear graphite grades.

HIGH-TEMPERATURE PROPERTIES

The focus of this paper is to present elevated temperature data of standard graphite samples of grades PCEA, PPEA, and PCIB-SFG, as determined by the modified ASTM test methods summarized below in Table 1 [4, 5].

Property	Temp. Range, (°C)	Test notes
Young's Modulus	25-2000	GrafTech design: Modified ASTM C747
CTE	25-100	GrafTech design: PATE
	25-2000	GrafTech design
Specific resistance (SR)	25-2000	GrafTech design: modified ASTM C611
Thermal diffusivity and specific heat	25-900	ASTM C714 (TD) and ASTM C781 (SH)
Tensile strength	25-2000	ASTM C565, C749

TABLE 1. HIGH-TEMPERATURE TESTING METHODS FOR NUCLEAR GRAPHITE GRADES.

High-temperature tensile strength properties are presented in Table 2. Tensile strengths are 4-9% higher in the with-grain (wg) direction than against-grain (ag) at 25 °C, and 1-3% higher at 1600 °C. All three grades tested demonstrated significant improvement in tensile strengths (with-grain) at the higher temperature, with increases ranging from 25-63%.

* Controlled irradiation experiments are currently being performed at NRG Petten as part of the RAPHAEL programme.

	25 °C (MPa, wg/ag)	1600 °C (MPa, wg/ag)	% Increase (wg)
PCEA	23.5 / 21.6	31.5 / 31.2	34%
PCIB	41.8 / 39.9	52.1 / 50.6	25%
PPEA	18.3 / 17.5	29.9 / 29.1	63%

TABLE 2. HIGH-TEMPERATURE TENSILE STRENGTH.

Young's modulus was also determined for the three grades of nuclear graphite, over the temperature range 25-2000 °C. Select results are shown in Table 3. As in the case of tensile strength, moduli are somewhat stronger in the with-grain direction, increasing with temperature for each grade tested. Each value shown in the table is an average of a measurement made during heating and one made during cooling.

	25 °C (GPa, wg/ag)	1000 °C (GPa, wg/ag)	2000 °C (GPa, wg/ag)
PCEA	11.8 / 11.3	13.5 / 12.8	16.5 / 15.9
PCIB	12.8 / 11.7	15.1 / 13.7	17.3 / 15.8
PPEA	10.8 / 10.4	12.2 / 11.9	16.3 / 15.6

TABLE 3. HIGH-TEMPERATURE YOUNG'S MODULUS

Thermal conductivity values were measured for PCEA, PCIB, and PPEA over the temperature range of 25-900 °C. The data, shown in Fig. 1, illustrate that thermal conductivity decreases by roughly 50% over this temperature range for each grade tested.

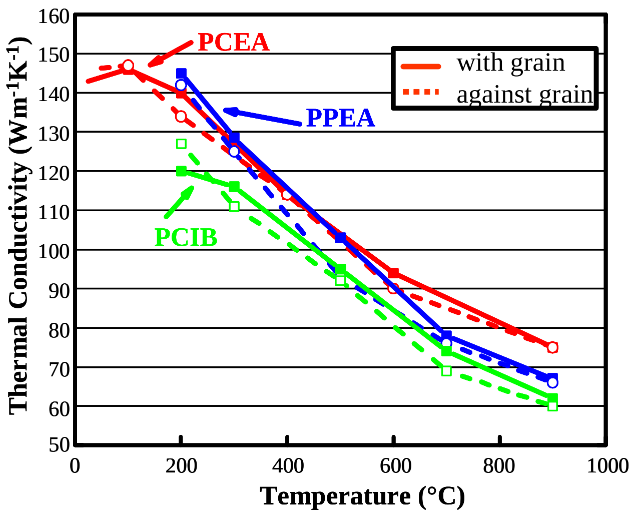

FIG. 1 HIGH-TEMPERATURE THERMAL CONDUCTIVITY.

The specific resistance of the nuclear graphite grades was also measured, over the temperature range 25-2000 °C (Table 4). The against-grain resistances were generally higher than with-grain values, up to 8% greater. For all three grades, resistances reached a minimum between 500-1000 °C and increased steadily all the way up to 2000 °C.

CTE measurements were recorded over the temperature range of 25-2000 °C (Fig. 2). All three grades showed a steady increase of with-grain CTE over the entire temperature range, between 65-75%. The behavior of these materials is consistent with calculations made from predictive models [6].

	25 °C (μΩ-m, wg/ag)	1000 °C (μΩ-m, wg/ag)	2000 °C (μΩ-m, wg/ag)
PCEA	7.7 / 7.9	6.6 / 6.6	8.5 / 8.4
PCIB	10.4 / 11.1	7.8 / 8.2	9.5 / 9.9
PPEA	8.8 / 9.2	6.8 / 7.4	8.6 / 9.1

TABLE 4. HIGH-TEMPERATURE SPECIFIC RESISTANCE.

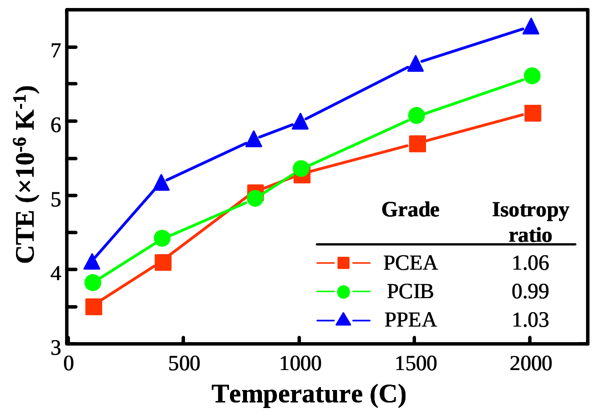

FIG. 2 HIGH-TEMPERATURE WITH-GRAIN CTE. ISOTROPY RATIO IS AG/WG VALUE FOR RT-2000 °C.

CONCLUSIONS

High-temperature test results of these three nuclear graphite grades confirm classical predictions of how temperature affects strength, electrical, and thermal properties:

- Mechanical properties like tensile strength and Young's modulus increase with temperature.
- Thermal conductivity decreases by approximately 50% as temperature is increased from RT to 900 °C.
- Specific resistance reaches a minimum between 500-1000 °C and increases at higher temperatures.
- CTE increases 65-75% upon heating from RT to 900 °C, following established predictive models.

This data is part of the extensive characterization effort by academic, government, and industrial partners needed to complete the design of a modern HTR.

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