# Temperature Dependence of Elastic Modulus of Nuclear Graphite

Eung-Seon Kim*, Sung-Deok Hong
*Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, 305-353*
**Corresponding author: kimes@kaeri.re.kr*

## 1. Introduction

Graphite is used in very high temperature gas-cooled reactors (VHTR) not only as a moderator and reflector but also as a major structural component due to its excellent neutronic, thermal, and mechanical properties. During normal operation and accidents, these graphite components are subjected to various mechanical and thermal stresses [1, 2]. The elastic modulus value is required for the design and stress analysis of the core, and the temperature dependence of elastic modulus must be examined.

In this study, the high temperature elastic modulus of selected nuclear graphites was measured in an argon environment and compared to one another based on the difference in the pore structure.

## 2. Experimental

### *2.1 Materials and Specimen*

In this study, a pyrolytic graphite (pyrographite) manufactured by GE Advanced Materials-Quartz and six grades of nuclear graphite were used: IG-110 and -430 produced by the Toyo Tanso Co, Ltd, Japan, NBG-17, -18, and -25 produced by the SGL Carbon Group, Germany and PCEA produced by the Graftech, USA. The main properties of the materials are summarized in Table 1. For elastic modulus measurement, we used a bar type specimen with the dimension of 50 mm in length, 5 mm in thickness, and 15 mm in width.

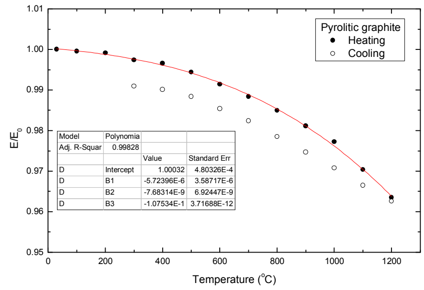
Table I: Typical properties of the graphites

| Grade | Density ($g/cm^3$) | Coke particle size (μm) | Forming method |
|---|---|---|---|
| Pyrolitic graphite | 2.18-2.22 | - | CVD |
| IG-110 | 1.77 | 20 | Isostatic molding |
| IG-430 | 1.82 | 10 | Isostatic molding |
| NBG-17 | 1.84 | Max. 800 | Vibrational molding |
| NBG-18 | 1.85 | Max. 1600 | Vibrational molding |
| NBG-25 | 1.81 | Max. 60 | Isostatic molding |
| PCEA | 1.83 | Max. 360 | Extrusion |

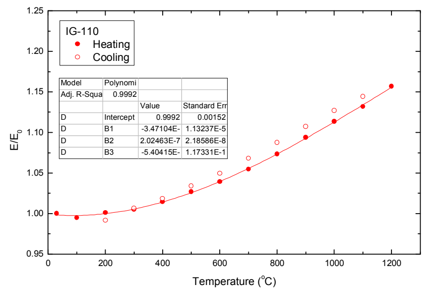
### *2.2 High Temperature Elastic Modulus Measurement*

The elastic modulus was measured at 20 to 1200 °C using a commercialized impulse excitation apparatus (RFDA HTVP 1600, IMCE). After positioning the specimen in two nodes, the furnace was evacuated up to 0.1 mbar and then purged with Ar gas (99.999%). The specimen was heated in an Ar environment at a heating rate of 5 °C/min. The specimen was gently tapped with a small hammer in the anti-node. The vibration signal emitted by the sample is captured using a microphone and sent to the resonant frequency and damping analysis software. The elastic modulus was calculated using the specimen dimensions, weight and measured resonant frequency based on the ASTM C 1259-08 [3].

## 3. Results and Discussion




(a)

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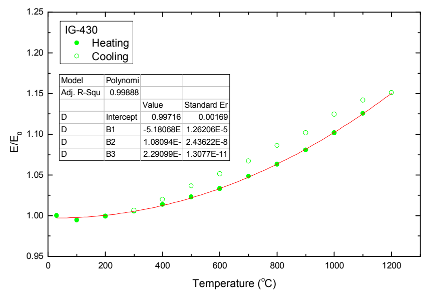
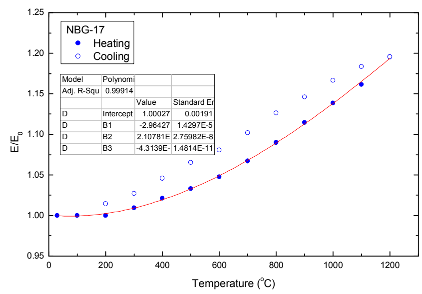
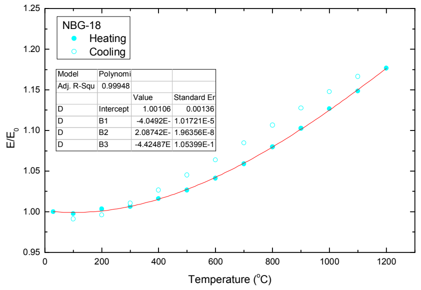


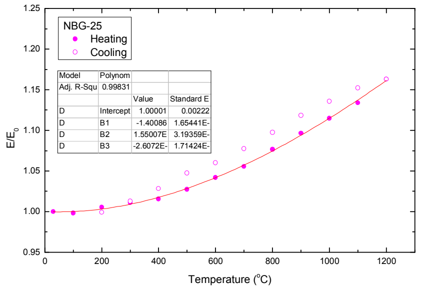

(c)



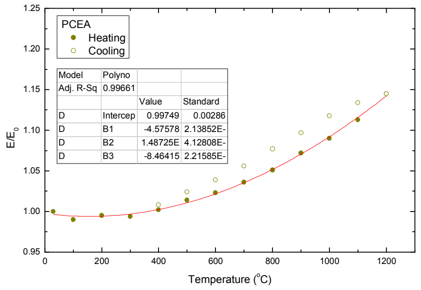

(d)




(e)




(f)




(g)

Fig. 1. Temperature dependence of the elastic modulus: (a) pyrolytic graphite (b) IG-110 (c) IG-430 (d) NBG-17 (e) NBG-18 (f) NBG-25 and (g) PCEA

Fig. 1 shows the dependence of the normalized elastic modulus. The modulus of the pyrolytic graphite decreased with increasing temperature. The fractional decrease of the modulus was less than 4 % at 1200 $^{o}$C. The negative temperature dependence represents the behavior of the crystallite alone on thermodynamic grounds [4]. However, the modulus of the nuclear graphite increased with increasing temperature regardless of the grade. The positive temperature dependence was attributed to the progressive closure of Mrozowski cracks, which are a result from the relief of thermal stress produced by anisotropic shrinkage of graphite crystallites on cooling from graphitization temperatures [5, 6]. Fractional increase of the modulus was much higher in the high density and coarse-grained graphites.

Changes in the elastic modulus during the heating and cooling process were also observed. It is attributed to the fact that thermal stresses are required to open Mrozowski cracks on the cooling process and thus there are more closed cracks than on the heating process, which would result in the higher modulus at a given temperature during the cooling process [4]. It is to be noted that the hysteretic behavior observed during this process is more pronounced for the medium-grained graphites than the fine-grained graphites.

Elastic modulus of the polycrystalline graphite usually depends on its pore volume (bulk density) and the precise variation of elastic modulus with temperature depends on the nature of the graphite, since the extent and distribution of Mrozowski cracks will depend on the thermal history of the graphite as well as the microstructure of the precursor materials. For example, the density of NBG-18 (1.82 g/cm$^3$) is much higher than that of IG-110 (1.78 g/cm$^3$) so that the modulus of NBG-18 was higher than IG-110 at all temperatures. The higher positive temperature dependence and larger hysteresis change of the modulus in NBG-18 than in IG-110 is attributed to higher closed porosity of NBG-18, as reported by Kim et al [7].

## 4. Summary

The elastic modulus of the nuclear graphite increased with increasing temperature regardless of the grade and changes in the elastic modulus during the heating and cooling process were also observed. The higher positive temperature dependence and larger hysteresis change of the modulus in the high density and coarse-grained graphites is attributed to their higher closed porosity.

## ACKNOWLEDGEMENT

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