GSP GRAPHITE FORMING UNDER IRRADIATION

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INTRODUCTION

The main center on development of the components of nuclear reactors cores is the National Science Center "Kharkov institute of Physics and Technology". The significant place in institutes' investigations was occupied with works on creation the constructional materials and nuclear fuel for fast and high-temperature gas cooled reactors BGR, BRIG-300, PAMIR-300, VGR-50, VGM and VG-400. Radiation tests and post-irradiation research confirm intended material-study, technological and design decisions of GSP graphite on the whole.

GSP GRAPHITE / PRODUCTION PROCESS

The production of GSP graphite (GSP is commercial name for pyrocarbon-bound graphite) in NSC KIPT is based on CVI methods the basis of which includes the following operations of the technological process:

- preparation of graphite powder;
- powder mesh on fraction sieving and mixing of various fractions of powder in required proportions;
- forming of billets;
- densifying of billets with pyrocarbon;
- billets treatment up to the required sizes and surface finish;
- heat treatment;
- quality control

GSP GRAPHITE / THERMOGRADIENT METHOD

The thermogradient method provides creation in the preform being treated of the temperature gradient in the direction reverse to the gradient of the carbon-containing gas concentration in the preform. The temperature is decreasing from the central internal regions of the preform to its surface. In the center of the preform a current-leading rod is installed. The space between the shell and central rod is filled with a powder mix of a required composition. In the pyrolysis chamber the central rod, being in the flow of natural gas, is resistively heated to (1000-1500) ^{o}C.

GSP GRAPHITE / PYROCARBON DEPOSITION

Then around the rod a comparatively narrow pyrolysis zone is created (with a temperature from (1000-1500) ^{o}C to 840 ^{o}C) and the powder in this zone is bonded with pyrocarbon. The temperature on a radius in the rest volume of the preform is lower than the above-indicated. There is no pyrocarbon deposition in this volume and the transport pores are not packed with pyrocarbon. These conditions provide a free access of hydrocarbon gas into the pyrolysis zone and a release from this zone of hydrogen being formed due to their interdiffusion in the transport pores.

UNIQUE STRUCTURE OF GSP GRAPHITE



GSP graphite structure

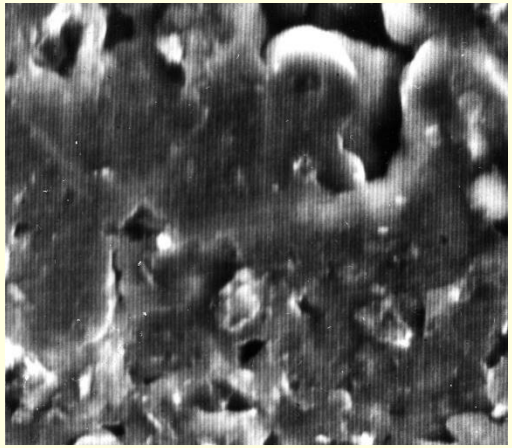
GSP GRAPHITE STRUCTURE



GSP-30



GSP-50



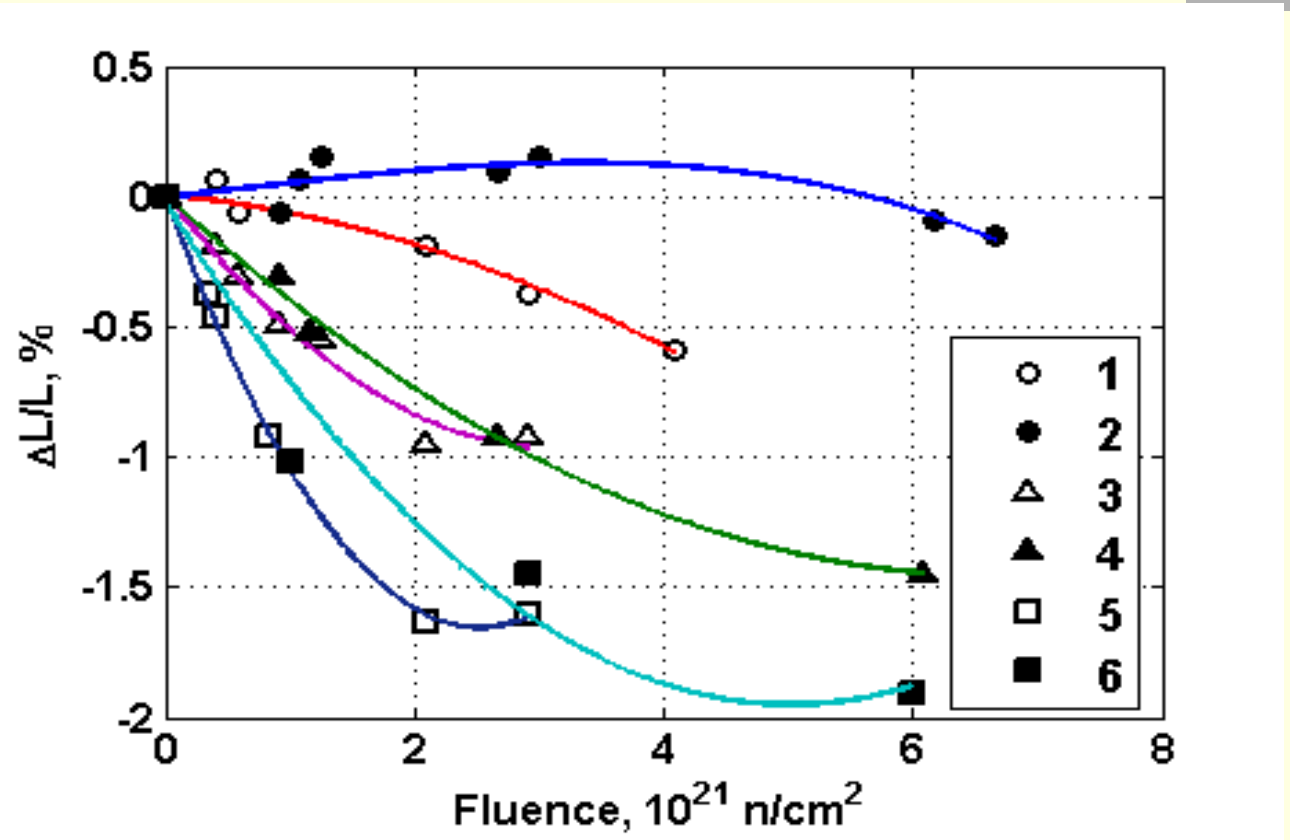
GSP-90

GSP graphite structure, 1200x

SOME PROPERTIES OF GSP GRAPHITE

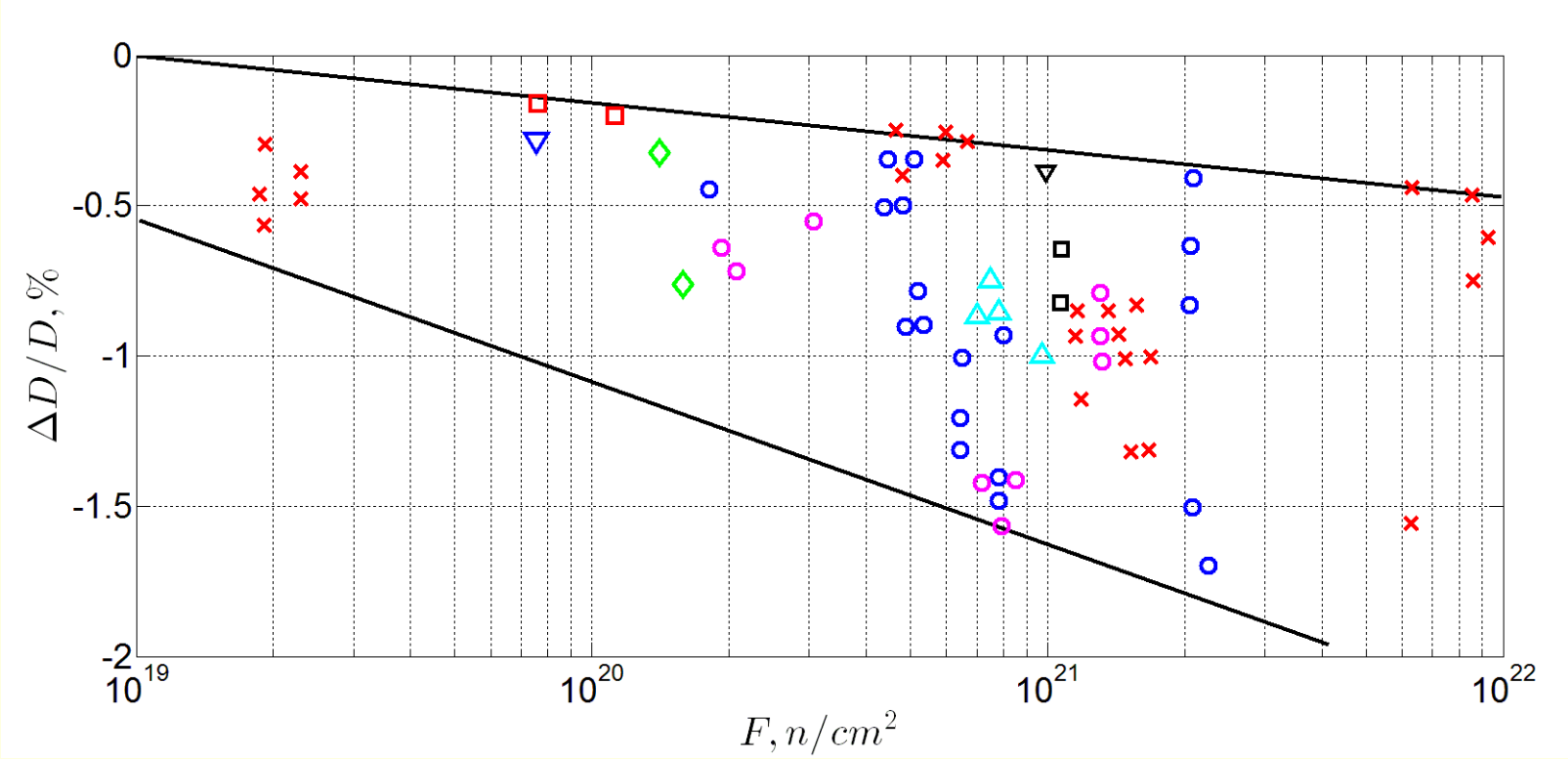
Characteristic	Commercial Graphites	GSP Graphite
Density [Mg/m^3]	1,7-1,88	1,7-1,95
Young's modulus [10^3 MPa]	9-12	9-21
Ultimate strength at 20 ^oC [MPa]:		
in compression	60-120	160-400
in bending	30-70	30-70
in tension	20-40	25-35
Thermal conductivity [W/m·K]:		
at 20 ^oC	90-130	10-80
at 500 ^oC	70-75	10-60
at 1000 ^oC	50-55	15-60
Thermal expansion coefficient [10^{-6} /K]:		
at 20-1000 ^oC	5-8	4-5
at 20-1500 ^oC	8-9	4,5-5,5
Specific electrical resistance at 20 ^oC [$\Omega \cdot mm^2 \cdot m^{-1}$]	11-16	16-35
Friction coefficient (carbon-copper)	-	0,1-0,3
Anisotropy factor	$\leq$1.3	1.03-1.05

GSP GRAPHITE FORMING UNDER IRRADIATION



Relative change of the linear sizes of the ARV and GSP graphite samples, irradiated by the temperature 600 ^{0}C (light points) and 800 ^{0}C (dark points), in dependence of neutrons fluence. O, • - ARV graphite; Δ, ▲ - GSP – 30 graphite; □, ■ - GSP – 50 graphite

REACTOR TEST RESULTS (GSP GRAPHITE)



Dimensional changes of absorbing (x) and fuel (the other points) elements versus the neutron fluence at irradiation temperatures of 400…1500 ºC for absorbing elements and for fuel elements:

∇- 500 ºC, ▼- 600 ºC, □ - 750 ºC, ■ - 800 ºC, ◊ - 1100 ºC,

∇○ - 1200 ºC, ●- 1250 ºC, △ - 1400 ºC, ▲ - 1500 ºC

RADIATION-VACANCY GRAPHITE FORMING MODEL

The change of pore relative volume of *isotropic reactor graphite* as a result of influence of high temperatures and intense neutron flux can be determined by the following expression:

$$\frac{\Delta V_{\Sigma}(\tau)}{V_{\Sigma}(0)} = \frac{\left(n(\tau) - n(0)\right)}{n(0)} = \left(1 + X_i\right)\left(\exp(-\tau) - 1 + \tau\frac{X_i}{1 + X_i}\right)$$

The change in relative pore volume of *unisotropic reactor graphite* as a result of exposure to high temperatures and intense neutron flux can be determined by the following expression:

$$\frac{\Delta V_{\Sigma}(\tau)}{V_{\Sigma}(0)} = \frac{\left(\sqrt{n(\tau)} - \sqrt{n(0)}\right)}{\sqrt{n(0)}} = \frac{\left(n(\tau) - n(0)\right)}{\left(\sqrt{n(\tau)} + \sqrt{n(0)}\right)\sqrt{n(0)}} =$$

$$= \left(1 + X_a\right)\frac{\left(\exp(-\tau) - 1 + \tau\frac{X_a}{1 + X_a}\right)}{1 + \sqrt{\left(\exp(-\tau)\left(1 + X_a\right) + \tau X_a - X_a\right)}}$$

RADIATION FORMING OF REACTOR GRAPHITE

In the virtual space of the formation of a new phase can be viewed as the result of mutual transitions of carbon atoms from one phase (the atoms in the crystal lattice sites or in the interstices) to another phase (the pores formed by the accumulation of vacancies). In the isotropic graphite moving of carbon atoms is isotropic due to the isotropy of the internal stresses. In the anisotropic graphite broken carbon atoms will move in inhomogeneous force field, which is characterized by a variety of internal longitudinal and transverse mechanical stress of the sample. Finally, the carbon atoms will be displaced preferably into the region of equal internal pressure. In this regard, pores will reflect the structure of the internal stresses in the sample and will be take the form of an ellipsoid of revolution [1].

With increasing of neutron fluence more $2 \cdot 10^{26}$ n/m^2 necessary to take into account the increasing by quantity of formation of lattice defects (vacancies) of reactor graphite. Displaced atoms of carbon are clustered in small groups on 5-10 atoms [2].

[1] Kane J., Karthik C., Butt D.P., Windes W.E., Ubic R. Microstructural characterization and pore structure analysis of nuclear graphite. Journal of Nuclear Materials. 2011. - V. 415. - P. 189–197.

[2] Burchell T. Neutron Irradiation Damage in Graphite and Its Effects on Properties. Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN, 37831-6088, USA. Text from the screen, electronic resource: http://web.ornl.gov/~webworks/cppr/y2001/pres/114924.pdf

RADIATION FORMING OF GRAPHITE / VERIFICATION I

We obtain the expression for the radiation forming of ***isotropic graphite*** :

$$n_i^+(\tau) = n_i(0)(1+X_i)\left((\exp(-\tau)-1)\left(1-\frac{2d\cdot X_i}{1+X_i}\right)+\frac{\tau X_i+1}{1+X_i}+\frac{d\cdot X_i}{1+X_i}\tau(\tau-2)\right)$$

In Fig.3 shows the dependence for values Xi = 1,3 d·Xi = 177,87 [2].

We obtain the expression for the radiation forming of ***unisotropic graphite*** :

$$n_a^+(\tau) = n_a(0)(1+X_a)\left((\exp(-\tau)-1)\left(1-\frac{2d_1X_a}{1+X_a}\right)+\frac{\tau X_a+1}{1+X_a}+\frac{d_1X_a}{1+X_a}\tau(\tau-2)\right)$$

In Fig.4 shows the dependence for values X_a = 4,0 $d_1 \cdot X_a$ = 30,2 [2].

RADIATION FORMING OF GRAPHITE / VERIFICATION II

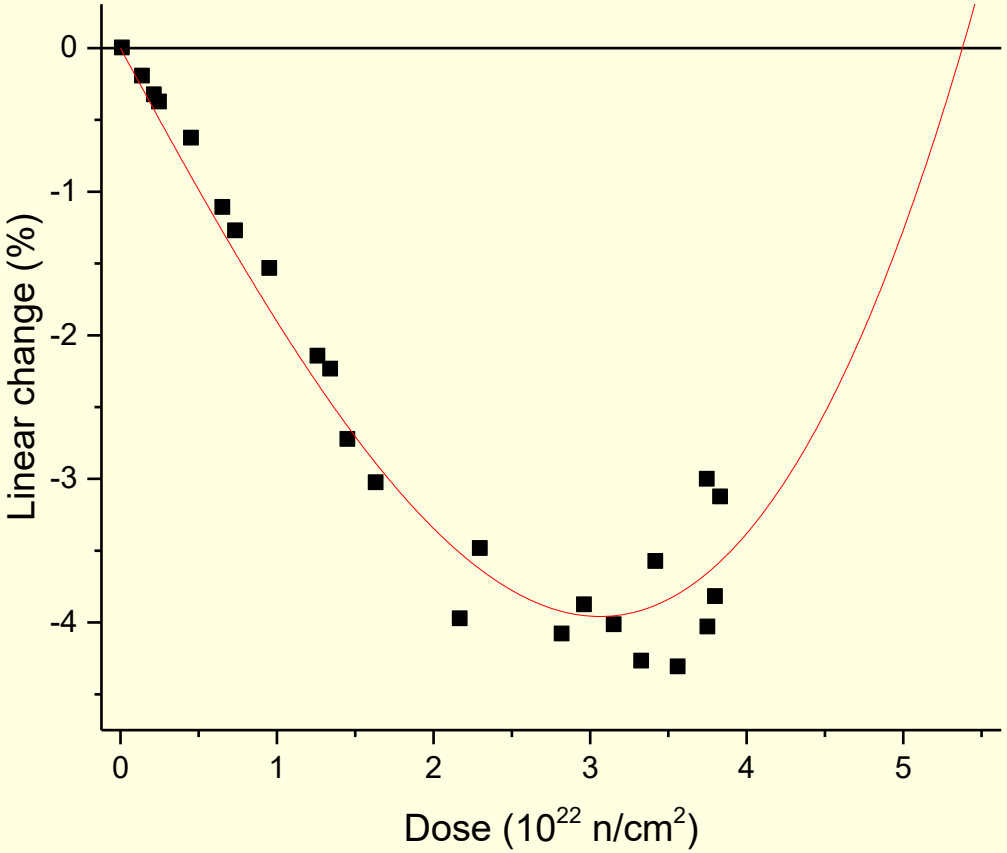


Fig.3. Dimensional change behavior of H-451 graphite (parallel) at an irradiation temperature of 600°C [2]

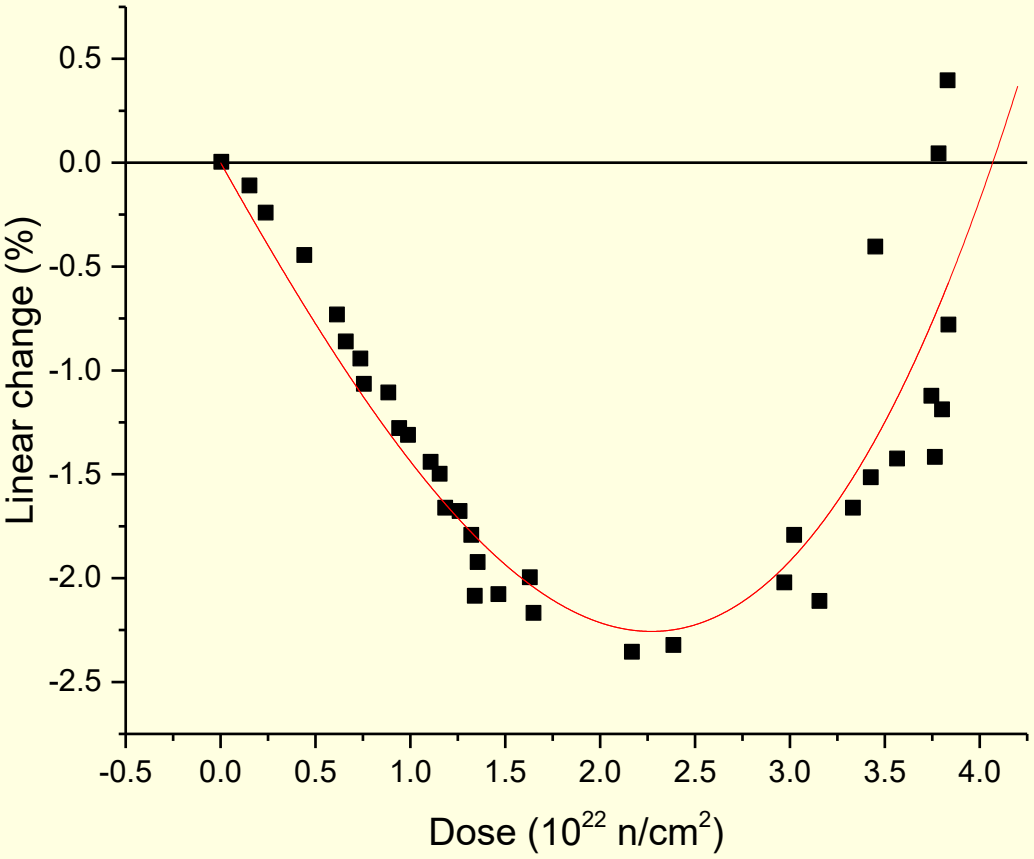
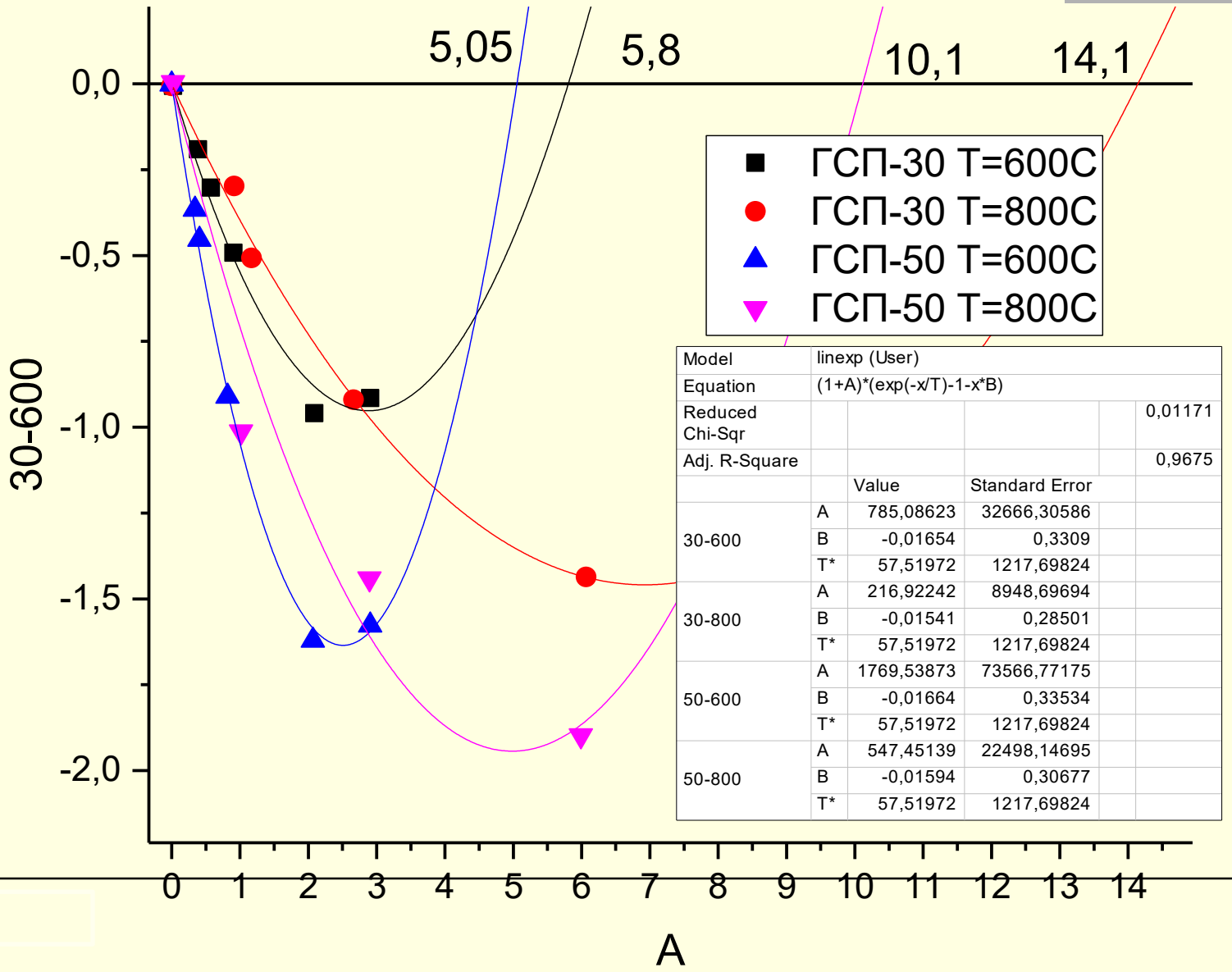


Fig.4. Dimensional change behavior of H-451 graphite (perpendicular) at an irradiation temperature of 600°C [2]

GSP GRAPHITE FORMING / FORECAST



Model	linexp (User)			
Equation	(1+A)*(exp(-x/T)-1-x*B)			
Reduced Chi-Sqr				0,01171
Adj. R-Square				0,9675
		Value	Standard Error	
30-600	A	785,08623	32666,30586	
	B	-0,01654	0,3309	
	T*	57,51972	1217,69824	
30-800	A	216,92242	8948,69694	
	B	-0,01541	0,28501	
	T*	57,51972	1217,69824	
50-600	A	1769,53873	73566,77175	
	B	-0,01664	0,33534	
	T*	57,51972	1217,69824	
50-800	A	547,45139	22498,14695	
	B	-0,01594	0,30677	
	T*	57,51972	1217,69824	

MAIN PROPERTIES OF GRAPHITE

- Under neutron irradiation GSP graphite, manufactured by the gas-phase technology, undergo the isotropic shrinkage slightly dependent on the irradiation temperature and neutron fluence (above $1 \cdot 10^{22}$ n/cm^2) and did not reveal any degradation of properties;
- Regarding the absolute values, the strength characteristics of irradiated GSP graphite remain high and much exceed those of the best sorts of reactor graphite;
- Presented forecast for GSP graphite forming at high temperatures and irradiation fluences, which makes possible to correctly plan the conditions of the reactor tests.
- By now GSP graphite, manufactured by the gas-phase technology, can be recommended for the use as thermally stressed elements of HTGR core

Thank you very much for your attention!

