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A Study on Integrity Assessment Methodology for Graphite Structure of the Very High Temperature Reactor

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1. Introduction

The VHTR is a nuclear reactor that uses helium as a coolant and graphite as a reflector, moderator, and fuel compact. Helium has no phase change, because of chemically inert; there is no corrosion problem of the structure and activation of corrosion product.

Graphite has an excellent ability to moderate the neutrons, small neutron absorption cross section, and mechanical and physical performance is great at high temperature. In addition, it has an excellent heat-resistant that can maintain integrity as core structural materials at high temperature. Therefore, when accidents happen, there is no melting down of the core structure. There are various kinds of Graphite, and the physical and chemical properties are different and more research is needed.

2. Methods and Results

2.1 Objectives of study and Graphite properties

The VHTR is currently developed under the conceptual design phase, and it is necessary to perform more case study and progress to improve safety of the VHTR. As seen from the side of safety secured, it is important issues to keep integrity of nuclear fuel materials and reactor components including graphite structure, because VHTR is operating at a high temperature of more than 900℃. Fig.1 is flow chart of study.

Graphite is similar to other brittle materials in that it does not exhibit plastic deformation and shows wide scatter in strength. Graphite shows 'quasi-brittle' behavior nonlinear stress-strain response and large amounts of acoustic emission. Graphite is considerably stronger in compression than in tension. In nuclear-grade graphite, the compression strength is three or four times the tensile strength.

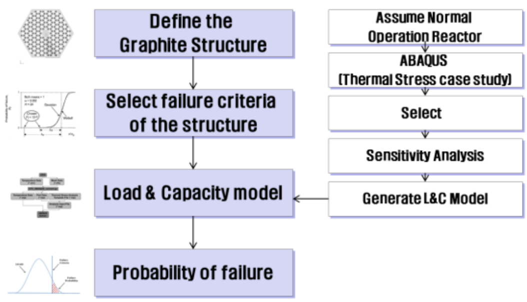


Fig.1. Process of Graphite Structure POF

Tensile fracture occurs when a local concentration of microcracks develop and coalesce to form an unstable macrocrack of critical size. Table I is properties of Graphite that uses for Korean VHTR.

Table I: Graphite Properties

	Symbols	Units	IG-110	Fuel compact	H-451
Density	ρ	g/cm^3	1.78	1.74	1.74
Young's modulus	E	GPa	10.2	6.89	9.6
Poisson's ratio	ν		0.14	0.19	
Compressive Strength	σ_c	MPa	76.9	25.7	60
Tensile Strength	σ_t	MPa	25.3	5.94	13.9
Mean coefficient of thermal expansion	α	K^{-1}	4.06E-06	4.86E-06	4.0E-04

2.2 Methodology for Estimation of Graphite Structure Integrity [1]

The stochastic fracture in engineered materials can be viewed from two models: series systems and parallel systems. Series systems assume that the material is composed of a set of n links connected in series such that the structure fails whenever any of the links fail. In the parallel-system model, the n links are arranged in parallel. When one link fails, load is redistributed to the remaining n−1 links, but the system may still survive. Series system is more adequate to be applied in graphite structure such as graphite block, graphite plug, and fuel compact. Eq.(1) describes a series system where failure of any one element means failure of the whole system.

$$P_s = \prod_{i=1}^{n} (P_s)_i = \prod_{i=1}^{n} [1-(P_s)_i] \cong \prod_{i=1}^{n} exp[-(P_f)_i] = exp\left[-\sum_{i=1}^{n} (P_f)_i\right] \quad (1)$$

2.3 Weibull Distribution

The strength of graphite is always stochastic, probability distribution like normal or weibull can fit experimental data nearly equally well, the latter is more appropriate to show graphite structure failure probability. Weibull distribution equation is as shown below Eq.(3)(4)(5):

$$f(t) = \frac{m}{\theta} t^{m-1} e^{-\left(\frac{t}{\theta}\right)^m} = \left(\frac{m}{\theta}\right)\left(\frac{t}{\theta}\right)^{m-1} e^{-\left(\frac{t}{\theta}\right)^m} \quad (3)$$

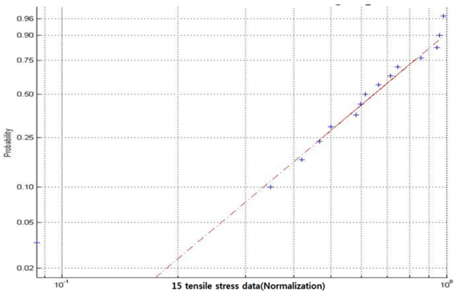
$$F(t) = 1 - e^{\left(\frac{t}{m}\right)^m} \quad (4)$$

$$MTTF = \int_0^\infty R(t)dt = \frac{\Gamma(1/m)}{m(1/\theta)} \quad (5)$$

Graphite block replacement cycle is about 3~5 years. It is not related to MTTF of graphite structure but refueling cycle or diminution of strength of graphite.

2.4 CAPACITY (IG-110 Experiment Data)

IG-110 is a fine grained, isostatically molded, high strength, isotropic graphite manufactured by the Toyo Tanso Company. IG-110 is graphite that uses in HTTR (Japan). There are not enough experimental data. Joseph p. Strizak [2] had researched 4 different sizes (6.35, 9.53, 15.88, 25.40mm) and plotted it by normal distribution. Graphite is more appropriate to plotted by weibull distribution. Fig 2. is probability of failure of IG-110.



MPa	POF
21	0.08577
24	0.34852
24.5	0.42049
24.8	0.46696
25	0.49904
25.5	0.58175
25.6	0.59851
25.7	0.61527
26	0.66523
26.3	0.71398
26.5	0.74535
27.3	0.856
28.2	0.9412
28.5	0.95954
29	0.9804

Fig 2. Probability of failure of IG-110

2.5 LOAD (Tensile Strength of graphite structure)

Kang [3] performed this research with ABAQUS Code. Analysis model is a 1/12 section of the fuel assembly and graphite structure is divided 10 blocks. Maximum stress (tensile) of graphite block is 4.75MPa, fuel compact is 1.21MPa, and graphite plug is 8.13MPa. Thermal stress calculation results are as shown below:
(left - graphite block / right top – fuel compact / right bottom – graphite plug)

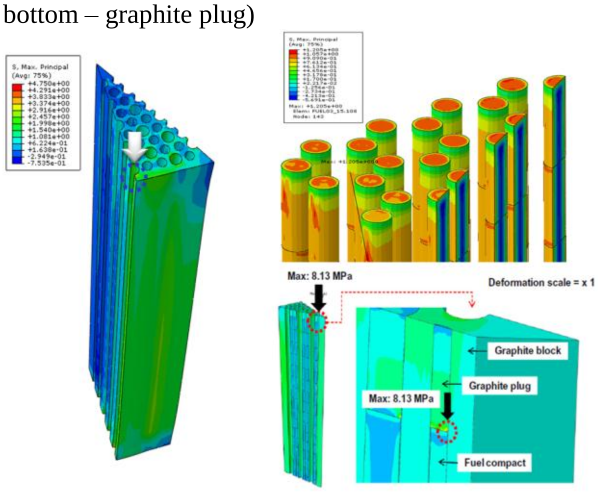


Fig 3. Peak principal stress in the graphite structures

2.6 Results

In this study, load and capacity model was used to obtain probability of graphite structure to estimate graphite structure integrity. Using 15 number of IG-110 experimental data which specimen size is 9.63mm normal distribution, convert to weibull distribution. In addition, from the tensile strength of graphite, divided 10 blocks shows each maximum stress. In this process, Eq(1) was used to estimate POF. Fuel compact was excluded because there is no exact experimental data and has no exact probabilistic criteria. Table Ⅱ, Fig 4. are POF of IG-110 and POF of graphite structure.

Table Ⅱ: POF of Graphite Structure

	Graphite Block		Graphite Plug	
No.	MPa	POF	MPa	POF
1	4.75	2.462E-09	6.2	5.580E-08
2	4.5	1.307E-09	6	3.800E-08
3	4	3.290E-10	5.8	2.555E-08
4	3.98	3.103E-10	6	3.800E-08
5	3.5	6.886E-11	6	3.800E-08
6	3	1.132E-11	6.2	5.580E-08
7	3.4	4.903E-11	6.1	4.612E-08
8	3.3	3.456E-11	7.9	9.534E-07
9	3.3	3.456E-11	6.3	6.730E-08
10	4	3.290E-10	8.13	1.334E-06
Total	4.937E-09		2.652E-06	

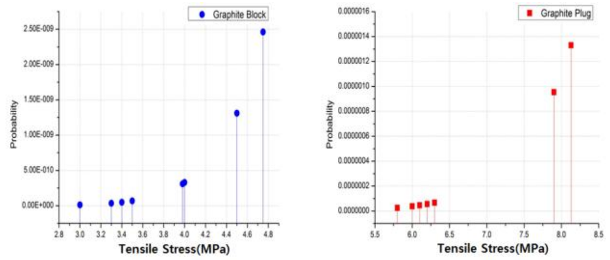


Fig 4. Probability of failure of Graphite structure

3. Conclusions

This article shows how to measure probability of graphite structure. Graphite fracture strength is stochastic, and it should be dealt with a probabilistic methodology because of material properties. The Weibull distribution is appropriate statistical distribution for modeling the stochastic strength response of graphite. MTTF and λ of graphite structure are needed more studies.

ACKNOWLEDGMENTS

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