ASTRONUCLEAR LABORATORY

WANL-TR-6658

CLASSIFICATION: Unclassified

Author:

P. P. Zemanick

Date:

July 8, 1971

DISTRIBUTION:

Library (2) ←

G. E. Cort

G. J. DeSalvo

J. W. Fisch

D. C. Goldberg

J. D. Holmgren

J. Kenney

G. R. Kilp

W. R. Morris

R. F. Lampe

K. L. Rieke

R. H. Singleton

J. M. Tobin

M. K. Wright

Trip to:

1. Southern Research Institute
Birmingham, Alabama

2. Oak Ridge National Lab
Oak Ridge, Tennessee

Date of Trip:

June 2-4, 1971

PERSONS PRESENT:

WANL

P. P. Zemanick

P. A. Stancampiano

G. J. DeSalvo

J. M. Tobin

R. H. Singleton

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

PURPOSE:

To expand on knowledge of the NERVA fuel structural behavior, structural modeling, and thermal stress testing from sources of known expertise in these areas; namely, Southern Research Institute, the ORNL Applied Mechanics Group, and ORNL Y-12. See complete discussion of purpose in PPZ:2274 and 2288.

SUMMARY:

The trip fulfilled its objective of seeding fresh ideas on NERVA fuel structural analysis and testing.

The high points of the SRI visit were exposure to Pears' theory of graphite behavior and observation of an apparently promising thermal stress test rig. Our discussions with the ORNL Applied Mechanics Group indicated that fracture mechanics (the SNSO favored method) can indeed be applied to the graphite (and probably composite) components on some rational basis. Moreover, the group provided some additional suggestions and cautions on a more sophisticated fuel stress model. This was the first WANL-Y-12 meeting primarily dealing with fuel structural behavior. The discussions with Y-12's Mr. Napier, first, set up an arrangement whereby WANL will be kept abreast of the graphite fuel characteristics, and, secondly, led to a better WANL appreciation for the difficulties of a structural characterization of the coating.

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

June 2 - Southern Research Institute, Birmingham, Ala.

SRI Attendees:

C. Pears
H. Starrett
E. Smily

1. WANL Presentations

Although the WANL visitors came prepared with four informal presentations (see Attachment 1), the schedule allowed only two to be given at SRI; Mr. Stancampiano describing the fuel analytic model and Dr. DeSalvo discussing our present thinking on graphite failure theories.

2. SRI Test Facilities

The first activity was a tour of the SRI mechanical testing facilities with emphasis on the high temperature compressive and tensile testing apparatus and the SRI thermal stress test rig still under construction. One of the uniaxial test rigs had a temperature capability of 7000°R, while the others could test to 6000°R. The thermal stress test rig and its analysis will be discussed later.

3. Pears' Theory of Graphite Behavior

Mr. Pears was asked to present his theory of graphite mechanical behavior (which has attracted the favorable attention of Mr. Helms of SNSO). According to Pears, graphite behaves on the microscopic level in the manner expected of a brittle material. That is, the characteristic flaws are the internal voids which spread abruptly normal to the principal tensile stress direction under sufficient load. However, this rapid flaw propagation does not result directly in a component failure because the moving crack is halted when it encounters another void or crack. The end result is a gradual and permanent relaxation of graphite due to widening of the many distributed internal flaws until the cumulative damage leads to a macroscopic part failure. Such a theory is not inconsistent with the non-linear graphite stress-strain curve which implies permanent set in the material beginning at very low stresses. We were referred to the American Ceramic Society Journal, October, 1967, for photographic evidence of this behavior. (Subsequent review of this article led the undersigned to feel that the article conclusions were largely based on a fairly subjective interpretation of photographs.)

The following strength curve was suggested by Mr. Pears:

The above curve is reminiscent of pioneering work done by Griffith (of fracture mechanics renown) in the 1920's measuring glass tensile strength versus fiber diameter. Mr. Pears concludes that all graphites fail incrementally according to the Griffith theory and can actually be characterized by the same fracture toughness K_{IC} . The difference from one graphite to another would be a difference in the dimension of the characteristic flaw size. While incremental damage follows a brittle fracture mode, overall "failure" might be characterized by a maximum strain or generalized strain theory.

(While this point of view provides useful insight into the nature of graphite behavior under load, incorporation of these ideas into a macroscopic stress model requires further development and probably unique test data.)

4. SRI Thermal Stress Test Rig

SRI is completing construction of a thermal stress rig which at present is testing the geometry sketched below:

The rig features induction heating of the outer rim of the specimen. Preheating of the specimen to about 3000°R has been done. The preheating is intended to have the point of failure at other than room temperature. The specimen rests on one or three pedestals designed to impose minimum mechanical constraint. All graphites tested have been fractured in the sketched geometry. In a washer configuration (no wide rims), all graphites except ATJ have been broken. When rig construction is complete, temperatures will be measured at three radial locations and displacements will be measured at several radial locations on two diametral lines.

Mr. Smily covered the thermal analysis of the test rig. The big problem in modeling this situation is correct definition of the internal heat generation distribution. The postulated power distribution was fine tuned by iterations between the analytic results and the measured radial temperature distribution. The final thermal analysis is likely to be a fairly good one, but of course, would have to be adjusted to correspond with measurements for each material tested.

Mr. Starrett's stress analysis was based on a two-dimensional finite element model in the plane of the specimen (r, θ). Although this is a simplified model which SRI plans to refine, they claim to predict failures fairly successfully comparing the analytic results with a maximum strain failure criterion.

Mr. Pears volunteered to test a few 1/8 inch thick fuel wafers gratis. We are exploring ways to transmit unfueled 19-hole specimens machined to a non-classified geometry.

When asked what kind of thermal stress test rig he would build given unlimited resources, Mr. Pears responded that he would design a rig which would test long thick-walled cylinders with inductive heating. He estimated two years would be needed for an learn-as-you-go kind of test rig development.

5. Miscellaneous Comments

Mr. Pears shares the Structural Design opinion that a valid thermal stress test requires a reasonable analytic understanding. He drew from his own experiences of ranking tests yielding different preferences among materials as a function of temperature level. A logical block of thermal stress testing effort includes conventional material specimens from which basic properties are measured, an analysis using these properties, and, finally, thermal stress testing proper to compare with the analytic results.

Mr. Pears made a strong pitch for a more comprehensive application of NDT techniques at every stage of a material's history. One motivation would be better characterization of the material from the initial raw stock stage, through properties test specimen fabrication, to final component fabrication. This characterization would do such things as indicating if a truly controlled material, uniform even in the raw material state, was being used in critical

applications, provide statistical data for analysis, and pick up maverick batches early in the game. Beyond the complete characterization, a second motivation is NDT proof testing of the final product, either as a routine quality control device or as a final screening to choose the best pieces and advantageously shift strength distribution curves. Some techniques which he suggested are; sonic velocity attenuation, electrical resistance, open porosity, pulse echo, eddy current, and more radiography. The screening function would, of course, depend on correlating NDT results with such parameters as fracture toughness or failure strain. (This whole idea is consistent with thoughts expressed by the NERVA customer and contractors, especially since the probabilistic design philosophy was introduced, regarding both material characterization and final product proof testing.)

Mr. Pears felt no good biaxial test program has been ever done on graphite and that none was in progress. Testing to date has shown enough scatter to support any biaxial stress theory.

SRI has not been able to break the quarter-inch OD WNCO hollow tubes by thermal stresses. The method attempted was heating to 5000°R followed by submersion in water.

Although he feels the ultimate graphite theory will not be Weibull or conventional fracture mechanics, Mr. Pears thought the Weibull and fracture mechanics investigations being carried on at the ORNL Applied Mechanics Group were worthwhile and would supply useful data.

June 3-4 - Oak Ridge National Laboratory, Oak Ridge, Tennessee

ORNL Applied Mechanics Group Attendees:

W. Greenstreet	C. Pugh
J. Corum	J. Smith
S. Moore	R. Valochovic
L. Overholser	T. Yahr

ORNL Y-12 Attendees:

J. Napier
A. Caputo

1. WANL Presentations

The WANL presentations were made as indicated on Attachment 1, the June 3 meeting agenda. The Applied Mechanics Group members appreciated the discussions of design engineering applications of their data and showed considerable interest in the presentations. In fact, ORNL questions put the meeting so far behind schedule that Dr. Tobin's talk was abbreviated.

2. ORNL Presentations

Dr. Greenstreet described the history of his group, originally called the Graphite Mechanics Group. The goal was to develop a general design technology for graphite on an international basis. The initial work was done on AGOT graphite used in the Experimental Gas Cooled Reactor. While stress analytic methods have progressed rapidly since that time (5-10 years), complete stress-strain relationships (the constitutive equations) are lacking. Because of funding reductions, only a small percentage of the group's work is on graphite at present, the bulk of the effort being devoted to solid mechanics problems related to the breeder reactor program.

Mr. Valochovic described mechanical properties test work performed on Phoebus fuel elements for LASL. The portion of the talk of greatest interest had to do with the development of subminiature fuel specimens and of techniques to test the small pieces.

Dr. Greenstreet summarized his work on the graphite constitutive equations. This is an impressive piece of work which sets up the framework for planning a graphite properties test program which would supply the necessary constants to formulate the constitutive equations for the particular graphite (or composite material, probably) of interest. (See "Constitutive Equations for Artificial Graphite," Yale Ph.D. dissertation, available in Structural Design.) Cyclic uniaxial measurements were also discussed as related to this theory. (See ORNL-TM-2727, "The Mechanical Behavior of Artificial Graphites as Portrayed by Uniaxial Tests," available in Structural Design.)

Mr. Moore presented his development of plasticity relations for graphite based on pressurized thick wall cylinder tests. The work is of special interest since the biaxial stress state can be tested in this geometry. This is important testing for any material, of extra importance for graphite, because of its anisotropy. Again a graphite of little current interest to NERVA was the object of this study, but the development of the method of approach provides a good starting point for analysis and testing with the material of immediate concern. This same general comment applies to Mr. Pugh's presentation, discussed next.

Mr. Pugh's work attacked the problem of formulating the stress-strain relationships for graphite with time-dependent effects, creep or stress relaxation. He showed good success in preparing the form of the equations, completing a test program to supply necessary constants, then applying the completed equations to other experimental results. The work was done with RVD graphite. (See ORNL-TM-2812, "A Viscoelastic Representation of the Mechanical Behavior of RVD Graphite at Elevated Temperatures," available in Structural Design.)

Mr. Yahr gave a kind of 20-year history of thermal stress testing. He described tests by Crocker (ORNL) in 1949 of tubular geometry, by Carlson (ORNL) of graphite spheres, and by Bond (TRW) of graphite cylinders, all unsuccessful in that thermal stress failures could not be induced. More recent tests described by Yahr are successful in producing fractures but leave something to be desired in terms of specimen thermal and load environment understanding. Some examples are Myers' (McDonnell-Douglas) test of thin discs with a weld arc struck on each side at the disc's center, Pears' (SRI) test described earlier in this trip report, King's (LASL) "ZAP" test with rapid induction heating of the periphery of a disc, Andrae's (LASL) steady state test with a disc and inductive edge heating, and, of course, the ORNL disc test. In this last test, a weld arc is struck at the middle of a disc (although the same test has been recently applied to wafers of the 19-hole fuel geometry, coated and uncoated). By a "staircase method", the required welder power setting to produce failure is used as a measure of a given material's thermal stress resistance. (See ORNL-4467, "Determination of Relative Thermal Rupture Resistance of Graphite," available in Structural Design.) Mr. Yahr showed a surprising amount of confidence in their ability to understand the wafer test. A detailed analysis has been attempted, and this analysis is currently being studied in Structural Design ("Thermal Shock of Graphite Disks," Col. School of Mines Dissertation, Derby).

Mr. Yahr next summarized the results to date of a program presently underway and sponsored by SNSO to determine the graphite criterion of failure and to make fairly extensive fracture mechanics measurements. This program has been followed fairly closely by WANL and is well documented in Structural Design's library of quarterly progress reports on the work. Only the most recent data were new to us. Two comments are pertinent. First, ORNL has not yet decided on the best graphite failure criterion but will do so by their autumn deadline. Second, Mr. Yahr has made considerable progress with the fracture mechanics work and does have a self-consistent story to tell. However, it is not clear whether the data could not be interpreted differently and applied in the simpler manner following maximum principal stress failure theory, with the same failure prediction success.

Finally, Mr. Corum gave us a quick rundown of computer programs being modified and made available for public use by ORNL under AEC funding. Most of the programs are from the Gulf General Atomics library of SAFE codes. Options include linear viscoelasticity, creep, combined stress or strain failure theory, irradiation swelling, orthotropic properties, etc. It is important to know the capability of these programs and to realize they are publicly available. However, our present computer tools appear to be adequate for near future needs.

When the ORNL people were asked what kind of thermal stress test they would build, given unlimited funds, they voted for their disc test with some relatively small modifications, like testing with a 0.1 inch hole at the disc center, use of a pointed welding electrode rather than a blunt one, and additional instrumentation.

3. Discussions with Mr. Napier

Mr. Napier made many comments indicating problems with the current NERVA coatings. His most significant remarks are repeated here. The CTE of the carbide coating is very sensitive to stoichiometry, so that this important parameter can be expected to change as a function of operating time and of axial location, just as the stoichiometry varies. The lack of a heat treatment to temperature exceeding service temperatures makes for an unstable coat which cracks both circumferentially and longitudinally. The coats exist in microlayers of varying chemistry and hardness; the coat process time is long enough that changes in atmospheric pressure affect carrier gas velocity and influence the coat properties as a function of time into the deposition process. The carbide coat should be in combination with oxygen and nitrogen ($ZrC_xO_yN_z$) and also heat treated beyond operating temperatures for reduced carbon diffusion through the coating and greater all around stability.

Mr. Napier routinely measures from a molded 2" x 3" circular plug on a given graphite CTE, flexural strength, electrical resistance, BAF (x-ray diffraction indicating the degree of isotropy), and sonic modulus. On a 0.1" x 2.0" flex bar he generates a flex displacement versus load curve. Our discussion showed him how useful this flex data could be to us. Previously, it was never documented or transmitted to anyone. Many of the other data do appear in the Y-12 biweekly received by Materials, WNCO, and Structural Design.

The most important item in our discussions with Mr. Napier was transmittal of a request for graphite thermal, mechanical, and corrosion properties. The properties are needed if WANL is to assess the current Y-12 product and offer guidance to the graphite fuel development effort. Attachment 2 is this properties request. Mr. Napier was very receptive to the request, and made short range and long range best effort agreements that will vastly improve our ability to follow the graphite fuel work.

Robert P. Jernigan

Approved by:

Robert P. Jernigan

AGENDA OF WANL-ORNL MEETING

June 3, 1971

A. INTRODUCTION -- W. L. Greenstreet
P. P. Zemanick

B. WANL PRESENTATIONS

1. "Failure Theories for Graphitic Materials and Analysis of Specimens from Central Support Elements"
G. J. DeSalvo
2. "Fuel Materials Testing and Mechanical Behavior of Fuel Materials"
R. H. Singleton
3. "Current Fuel Stress Analytic Model and Thermal Stress Testing Principles"
P. A. Stancampiano
4. "Thermal Stress Test Experience and Recent Fuel Process Experience"
J. M. Tobin

C. ORNL PRESENTATIONS

1. "Objectives of the Graphite Mechanics Program"
W. L. Greenstreet
2. "Mechanical Behavior of Phoebus Fuel Elements"
R. S. Valachovic
3. "A Plasticity Theory for Graphite"
W. L. Greenstreet
4. "Plasticity Analysis of a Pressurized Thick-Walled Graphite Cylinder"
S. E. Moore
5. "Viscoelastic Analysis of the Elevated Temperature Behavior of Graphite"
C. E. Pugh
6. "Thermal Stress Tests"
G. T. Yahr
7. "Graphite Fracture Investigations"
G. T. Yahr
8. "Finite Element Analysis"
J. M. Corum

D. Open Discussion

Att. 1

TABLE I

GRAPHITE FUEL AND SUPPORT ELEMENTS*
STRUCTURAL PROPERTIES REQUIRED

		<u>RT</u>	<u>4000°R</u>
1.	Longitudinal Tensile (Uncoated)		
	a. Stress Versus Strain to Fracture	(3) ⁺	(3)
	b. Stress Versus Strain to Fracture After Sixty (60) Cycles at 1200 μ in./in. Strain	—	(2)
2.	Flexure (Uncoated)	(5)	(5)
	(Coated)	(5)	(5)
3.	Across Flats Crush (Uncoated)	(5)	(5)
	(Coated)	(5)	(5)
4.	Thermal Conductivity (Uncoated)	(5)	(5)
	(Coated)	(5)	(5)
5.	Longitudinal CTE (Uncoated)	(3) $\frac{\Delta L}{L}$ Curve RT to 4500°R	
	<div style="border: 1px solid black; width: 100px; height: 15px; display: inline-block;"></div>		
	Transverse CTE (Uncoated)	(3) $\frac{\Delta L}{L}$ Curve RT to 4500°R	
6.	CTE of Coating	(3) $\frac{\Delta L}{L}$ Curve RT to 4500°R	
7.	Stress Versus Strain of Coating to Fracture	(3)	(3)

* If support elements are not available, tests should be repeated for unfueled material extruded in the 19-hole configuration.

+ Suggested minimum number of tests at each temperature.

TABLE I (Continued)

STRUCTURAL PROPERTIES REQUIRED

8. 10 Hour Longitudinal Compressive Creep Strain for Coated Graphite Support Element* - Uncorroded

Conditions:

	<u>2600°R</u>	<u>3800°R</u>	<u>4200°R</u>	<u>4600°R</u>
1000 psi	(2)	(2)	(2)	(2)
3000 psi	(2)	(2)	(2)	(2)
5000 psi	(2)	(2)	(2)	(2)

NOTE: Repeat 3000 psi and 4200°R test for two (2) specimens subjected to corrosive weight loss. Record weight loss.

9. TRANSVERSE AND LONG. FRACTURE TOUGHNESS K_I RT 4500°R
(5) (5)

* If support elements are not available tests should be conducted for unfueled extruded material in the 19-hole configuration.

TABLE II
PROCESS PARAMETERS REQUIRED

1. Coating Thickness Versus Station
2. Bore Coat Deposition Temperature Versus Station & time at temperature
3. O.D. Coat Deposition Temperature Versus Station & time at temperature
4. Bore Coat Ambient Crack Count (Frequency) Versus Station
5. Cooldown Temperature Versus Time in Deposition Furnace

TABLE III

THERMAL AND CORROSION DATA NEEDED ON GRAPHITE ELEMENTS

1. Corrosion test results at D.09, A.07, and/or E.02 conditions in WANL furnace, with ten minute cycles
 - 1.1 Standard furnace parameters power, flow, temperatures, pressure, voltage probe results, etc.
 - 1.2 Post-test measurements on element(s) tested;
 - Incremental ΔW - gm/inch (consistent data treatment with WNCO)
 - Pinholes, breaks, etc.
 - Met. study results on representative elements (for example, see DRM 51780, 2-1-71 on WNCO composites)
 - 1.3 HREC, if available Pre and Post
2. For corrosion tested elements, standard NDT, and processing information;
 - Coating thickness, process parameters
 - Leak rate (whole body)
 - Matrix "pedigree" - raw materials used - designation of extrusion process used to identify "sister" matrices
 - Air impedance, channel diameters
 - S/N's and disposition of sister elements, if any
3. Property data in addition to that supplied to structural:

Longitudinal electrical resistivity as a function of temperature, coated and uncoated

Suggest three samples at four temperature levels to $\sim 4000^{\circ}\text{R}$ for each element family.