Structural Response Testing of Thermal Barrier Load-Bearing Ceramic Pads

W.E. Black, R.K. Luci, J.L. Pickering
General Atomic Company, P.O. Box 81608, San Diego, California 92138, U.S.A.

G.B. Oland
Nuclear Division, Oak Ridge National Laboratory, P.O. Box Y, Oak Ridge, Tennessee 37830, U.S.A.

1. SUMMARY

A load bearing insulating structure for use in a high temperature gas-cooled reactor (HTGR) was investigated. The structure was composed of dense ceramic materials in the form of circular pads arranged in a stack. Specifically, the test program was structured to investigate the isolation effectiveness of interface materials placed between the ceramic pads to reduce the effectiveness of mechanically induced loads. The tests were conducted at room temperature using tapered loading platens on single ceramic pads. Seventeen alumina specimens, representing two types of material and two thicknesses, were tested. Three interface material thicknesses were introduced using silica cloth and graphite foil. Pre and post test nondestructive examinations were conducted in an effort to identify potential damage-inducing anomalies in the ceramic pads. A total of 62 tests was conducted with all specimens eventually loaded to failure.

2. INTRODUCTION

The reactor core of the HTGR is supported by graphite posts which rest on ceramic insulator pads at the bottom of the core cavity. An assembly of these pads is positioned beneath each post to provide the necessary support and thermal insulation. The pads are surrounded by a nonload-bearing thermal barrier system composed of graphite cover blocks, ceramic fibrous insulation and metallic components. A cross section view of the four-pad assembly and surrounding thermal barrier system is shown in Fig. 1. The pads are separated from each other with a layer of interface material placed between the pads as illustrated. This total arrangement is termed the Class C thermal barrier. The Class C thermal barrier must perform under direct impingement of the core outlet helium which flows normal and parallel to the surface of the bottom head. In conjunction with the liner cooling water system, the ceramic components (as part of the thermal barrier), must act as efficient thermal insulators to reduce the temperature from that of the core outlet helium to approximately 66°C (150°F) at the liner. In addition, the ceramic pads perform a critical core support function.

This test program was undertaken by GA Technologies Inc. (GA) in conjunction with Oak Ridge National Laboratory (ORNL) where the full size pads were tested. The objective of the tests was to determine the ability of the interface material to act as a strain absorbing compliant interlayer. This is required in order that the pads can rotate independently (with respect to each other) under their respective axial thermal gradient condition while under an axially applied mechanical loading condition. This will have the effect of minimizing the thermal stress in the pads and thus help achieve the specified factors of safety.

3. PAD CONFIGURATION

Three types of alumina specimens were evaluated during this program. All three pad configurations were purchased from the Coors Porcelain Company. Grade 995 (designated AD-995 by Coors) was used as the uppermost of the three alumina pads and had a diameter of 216 mm (8.50 in.) with a thickness of 38.1 mm (1.50 in.). The middle pad was made from Grade 85 (designated AD-85 by Coors) and had the same dimensions as the aforementioned upper pad. The lower pad was also made from Grade 85 with the same diameter as the overlying pads, but with a thickness of 76.2 mm (3.00 in.). All of the pads had a central hole, 77.7 mm (3.06 in.) in diameter which served the dual purpose of accommodating a positioning dowel (see Fig. 1) and facilitating the manufacturing process.

4. INTERFACE MATERIALS

Two types of interface materials were investigated: (1) a woven silica fabric (Siltemp 188 CH) which had a thickness of 1.37 mm (0.054 in.) and (2) a graphite tape (Grafoil) having a thickness of 0.254 mm (0.010 in.). In each test either two or four layers of Siltemp or one layer of Grafoil was used per loaded ceramic pad face.

A series of tests on these interface materials was performed, prior to the loading tests on the pads, to investigate their load-displacement response and determine the effective elastic modulus of the layered materials. The results are presented in Table 1.

5. PRE-TEST NON-DESTRUCTIVE EXAMINATION

A pre-test non-destructive examination program was conducted by GA on the Grade 85 and Grade 995 alumina ceramic pads. The tests performed were: fluorescent penetrant for surface flaws, ultrasonics and radiography for internal flaws, and ultrasonic back reflection attenuation "C" scans as a reference for possible detection of internal microscopic damage developed during subsequent compression testing of the pads.

6. TESTING

The expected prototype ceramic pad rotation under the design axial thermal gradient condition results in a relative axial displacement between the inner and outer radius of the pad of approximately 0.076 mm (0.003 in.), if unrestrained. This value is based on a 65°C (150°F) axial temperature drop across a 38 mm (1.50 in.) thick alumina ceramic pad. The axial load from the core, through the core support posts, estimated to be 74.3 kN (16,700 pounds) for normal operative condition dead weight and pressure drop loads and 182.4 kN (41,000 pounds) for Operating Basis Earthquake (OBE) conditions, has a tendency to prevent the thermally induced rotation. The interface material placed between the ceramic pads is intended to provide a certain degree of isolation from the normal loading affects. The degree of isolation developed for each pad is a function of the interface material thickness and modulus characteristics and the amount of rotational difference between the adjacent pads.

A mechanical-load-only (room temperature) test was performed for this preliminary evaluation of the individual pads and for the effectiveness of the interface materials. A rotation was introduced into the pads producing a hoop bending stress distribution simulating that which results from the design axial thermal gradient. (Note, the maximum thermal stress is induced when the pad is constrained, i.e., no rotation). The rotation was imposed on the pad through tapered loading platens as illustrated in Fig. 2. The purpose of the tapered platen loading arrangement was to illustrate the degree of isolation possible with the introduction of different interface materials and/or thicknesses on both sides of the pad.

6.1 Test Facility

Oak Ridge National Laboratory (ORNL) performed the loading tests on the alumina pads. The test fixture was a 1780 kN (400,000 lb) Forney Testing Machine with loading of the specimens accomplished as shown schematically in Fig. 2.

The top and bottom loading platens and conical platens were fabricated from tool steel. The top loading platen consisted of two parts: (1) lower, or top access platen, which was recessed to receive the top conical platen and permit access to the center of the specimen for the displacement measurement apparatus; and (2) upper part of the load cell platen which had a flat top surface for application of load and a bottom surface fabricated to fit into a recess in the upper part of the access platen. The bottom loading platen was recessed to accept the bottom conical platen and was also slotted on the bottom surface to permit instrumentation leads into the center opening for attachment of strain gages and the capacitance transducer. The top and bottom conical platens had an outside diameter of 222 mm (8.75 in.) and an inside diameter of 70 mm (2.75 in.). All flat platens were plane to within 0.0076 mm (0.0003 in.). Dimensions of the conical platens which had loading surface tapers (offsets) from 0.15 mm (0.006 in.) to 0.35 mm (0.014 in.) are presented in Table 2.

Overall, components of the test fixture were fabricated to tolerances such that under the worst case condition load was applied to the specimens with a maximum eccentricity of 1.5 mm 0.060 in.).

6.2 Instrumentation and Data Acquisition

6.2.1 Loading System

Specimens were loaded in compression by a manually controlled hydraulic machine having a 1780 kN (400,000 lb) loading capacity. The magnitude of loading was determined by a low-profile load cell attached to the top head of the testing machine. The load cell transferred load from the testing machine to the specimen load train through a spherical surface to ensure that only a vertical compressive load was applied to the specimen.

6.2.2 Displacement Transducers

Three capacitance-type displacement transducers were utilized to monitor platen-to-platen displacements and pad rotations during testing.

Two of the displacement transducers were mounted at 180° on the test fixture to determine platen-to-platen displacements.

An instrumentation frame was especially designed for this series of tests and consisted of an inner and an outer attachment fixture. The inner fixture was attached at three points at mid-height on the inner circumference of the pad and contained the capacitance gage for determining pad rotation. The outer fixture, which held the target for the capacitance gage, was attached at three points at mid-height on the outer circumference of the pad. Small teflon gage points epoxied to the ceramic pad surface served as seats for the inner and outer attachment fixtures. Pad rotation under loading was measured by the capacitance gage system as relative movement of the specimen neutral axis. Fig. 3 presents a schematic of the instrumentation frame.

6.2.3 Data Acquisition

Load, strain, displacement, and time output during testing were obtained by a data acquisition system which consisted of a minicomputer, signal conditioning equipment, digital clock, digital volt meter, magnetic tape unit, printer, and X-Y recorder. Prior to testing, all transducers were calibrated against reference standards and the calibration results stored on magnetic tape and also printed (a hard copy of magnetic tape). Data scans were obtained periodically during testing, usually at prescribed loading intervals, and the scanned data was stored on magnetic tape and printed.

6.2.4 Acoustic Emission

Approximately one-half of the ceramic pads tested were also monitored by acoustic emission. Three acoustic emission transducers were positioned at 120° intervals on the outer circumference of the pad at mid-height.

6.3 Test Procedure

Specimens were loaded at ~1.1 kN/sec (~250 lb/s), with the maximum rate being 8.9 kN/s (2000 lb/s), until either a limiting load, a limiting strain, or specimen failure occurred. (Several of the specimens were subjected to several load cycles.) Data scans were taken at prescribed loading increments.

7. TEST RESULTS

Seven 38 mm (1.5 in.) thick specimens of AD-995, seven 38 mm (1.5 in.) thick specimens of AD-85 and three 76 mm (3.0 in.) specimens of AD-85 alumina were tested. A total of 62 loading tests was applied to these ceramic pads. Combinations of various platen sets were utilized to determine their affect on the structural response of the pads. All specimens tested were eventually failed by either keeping the maximum applied load at 890 kN (200,000 lb) and changing the interface material or, by increasing the applied loading, using the same interface material configuration. The cracks appeared to initiate at the upper inside corner (highest hoop stress region) and propagate out radially. Specimens failed with at least one audible event followed by as many as two more events. After each of these events there was no noticeable decrease in applied load. No specimens failed violently to produce missile fragments. Either one, two or three pie-shaped segments were produced in the specimens which cracked.

7.1 Interface Material Efficiency

A ratio of the rotation induced into the pad to the loading platen set angle is used to define the efficiency of the interface material configuration used. That is;

$$\text{(interface material)} = \frac{\delta_{i/o}}{\text{Platen set angle}} \times 100 \qquad (1)$$

where: $\delta_{i/o}$ = relative axial displacement between the inner and outer corner of the pad

Platen set angle = average of the upper and lower conical loading platens (Table 2)

The efficiency ' η ' could theoretically be 100 percent for a condition with an infinitely stiff interface material (or the loading platens having direct contact with the ceramic pad). The main intent of this test program, however, was to determine the degree of isolation that could be provided by an interface material. Therefore, an isolation effectiveness term is developed by calculating '$1-\eta$'. An isolation effectiveness of 100 percent would imply that the pad was completely isolated from the loading platen. Figures 4, 5 and 6 illustrate the isolation effectiveness of the three interface material configurations for the three pad geometries tested. The isolation effectiveness is, of course, a function of the applied load, as illustrated. The design loading condition on the thermal barrier system (Fig. 1) can vary from 11300 lb/post for the normal design condition to 65300 lb/post for the faulted condition. The figures illustrate that either a very thick interface material or a very low modulus (E) material would produce an isolation effectiveness of 100%, as would be expected. The test results indicate that the isolation effectiveness for an interface material with stiffness characteristics greater than 2-layers of Siltemp levels off quickly for the 38 mm (1.5 in.) AD-995 pads. The 38 mm (1.5 in.) AD-85 pad results have a higher variability with respect to each loading platen set and also do not show the leveling-off beyond the 2-layer Siltemp stiffness value. The 76 mm (3.0 in.) AD-85 pads were very stiff in comparison to the 38 mm (1.5 in.) pads and the degree of isolation between the 4 and 2-layer Siltemp was relatively small. The 1-layer Grafoil was not tested with the 76 mm (3.0 in.) AD-85 pads.

The isolation effectiveness (Figs. 4, 5 and 6) can be used to estimate the degree of isolation possible from an interface material configuration by knowing its composite height (L), elastic modulus (E), and expected loading. The figures show that for an applied load of 0.111 MN (25,000 lb) and an isolation effectiveness of ~90%, a K/A = E/L value of approximately 400 N/mm^3 (1.5 x 10^6 lb/in^3) is suggested for the 1.5 AD-995 pads, and approximately 200 N/mm^3 (0.75×10^6 lb/in^3) for the 38 mm (1.5 in.) AD-85 pads. The 76 mm (3.0 in.) AD-85 pad results (Fig. 6) indicate that a 90% (and greater) isolation effectiveness under the stipulated loading could be obtained with any of the interface material configurations tested. Although both Siltemp and Grafoil appear to be acceptable interface material candidates, they have not been tested in a thermal/time environment representing the prototype design conditions.

7.2 Nondestructive Examination

The thermal barrier ceramic pads were selected for structural tests based on nondestructive examination (NDE) screening to remove flawed pads. The methods and acceptance limits used were ultrasonics and radiography. One of the aims of the structural test was to determine accept/reject information for nondestructive examinations. To accomplish this the same nondestructive test methods and sensitivity used to screen the pads were used to evaluate half of the pads after test to failure and the other half of the pads after being tested to a prefailure load level. Acoustic emission data were recorded during this preload cycle and again when these pads were tested to failure. The ORNL acoustic emission equipment could not record the continuous acoustic emissions versus load required to develop an index of structural integrity. However, the method used was adequate to determine if the fracture sites were acoustically active at prefailure loads. These data were also adequate to determine if compression testing could be used with acoustic emission instead of thermal loading to develop an index of structural integrity.

8. CONCLUSIONS

The test results indicated that: (1) four layers of silica cloth resulted in the lowest strain and deflection for a given pad and platen configuration; (2) the graphite foil resulted in the largest strain and deflection; (3) the relationship of strain to deflection was proportional to the pad thickness and agreed with analytical predictions; (4) pad failures in the form of cracking generally were initiated from two or three locations at the top (i.e., loaded) surface at the inner radius which was the location of high stress; (5) the alumina pads exhibited crack arrest capability in the high compressive stress region; (6) the use of acoustic emission as a means of performing acceptance tests on production pads was encouraging but will require further evaluation since very little noise was emitted from the pads prior to reaching the threshold of failure; (7) ultrasonic and radiographic NDE methods proved to be effective in identifying the location of anomalies within the pads; and (8) with Siltemp the alumina pads exhibited a factor of safety of 12 for normal operating condition mechanical loads with a conservatively simulated mechanically induced thermal gradient. However, the effects of thermal aging and crack growth were not included in this phase of the test program.

ACKNOWLEDGMENT

The work reported here was sponsored by the San Francisco Operations Office of the U.S. Department of Energy under Contract DE-AT03-76ET35301.

TABLE 1 INTERFACE MATERIAL CHARACTERISTICS

	GRAFOIL(1) 1 - LAYER	SILTEMP 188CH(2) 2 - LAYERS	SILTEMP 188CH(2) 4 - LAYERS
Material Height, L	0.25mm (0.01 inch)(3)	2.08mm (0.818 inch)(4)	4.379mm (0.1724 inch)(4)
Modulus of Elasticity, E(5)	0.2758 kN/mm^2 ($0.04x10^6$psi)	0.6895 kN/mm^2 ($0.1x10^6$psi)	0.6895 kN/mm^2 ($0.1x10^6$psi)
Calculated Spring Constant, AE/L(6)	34.326 MN/mm ($196x10^6$ lb/in)	10.479 MN/mm^2 ($60.x10^6$ lb/in)	4.98 MN/mm^2 ($28.4x10^6$ lb/in)
and E/L (Fig. 5)	1.086 kN/mm^3 ($4x10^6$ lb/in^3)	0.3315 kN/mm^3 ($1.22x10^6$ lb/in)	0.157 kN/mm^2 ($0.58x10^6$ lb/in^3)

(1) Manufactured by Union Carbide Corp., New York, NY
(2) Manufactured by Ametek Haveg Div., Wilmington, DE
(3) Nominal thickness
(4) Measured height under a uniform stress state of 0.069 N/mm^2 (10 psi)
(5) Modulus values were developed from the linear portion of the applied stress/displacement curve of the tested configuration. The listed values can only be considered preliminary
(6) Where A, cross sectional area of the ceramic pad = 31613 mm^2 ($49in^2$)

TABLE 2 CONICAL PLATEN DIMENSIONS

Platen Set Number(1)	Thickness at Diameter: Outer Diameter 216 mm	Outer Diameter (8.5 in.)	Inner Diameter 76 mm	Inner Diameter (3.0 in.)	$\Delta_{i/o}$(2)
	mm	(in.)	mm	(in.)	
006 T	25.565	(1.0065)	2.540	(1.0000)	0.0065
006 B	25.32	(0.9970)	2.5438	(1.0015)	0.0045
010 T	25.659	(1.0102)	2.540	(1.0000)	0.0102
010 B	25.387	(0.9995)	2.565	(1.0015)	0.0105
014 T	25.794	(1.0155)	2.5438	(1.0015)	0.0140
014 B	25.43	(1.0010)	2.578	(1.0150)	0.0140

(1) T - top platen, B - bottom platen
(2) Relative axial thickness dimensional change between the inner and outer diameter of the loading platen

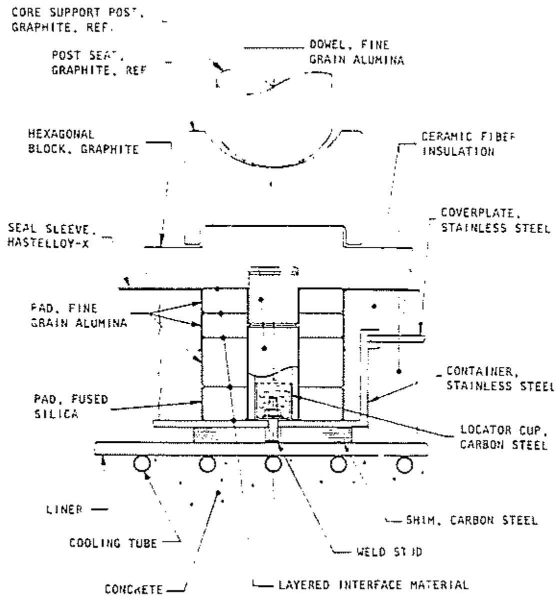

FIG. 1 CERAMIC THERMAL BARRIER SUPPORT STRUCTURE AND INSULATION SYSTEM

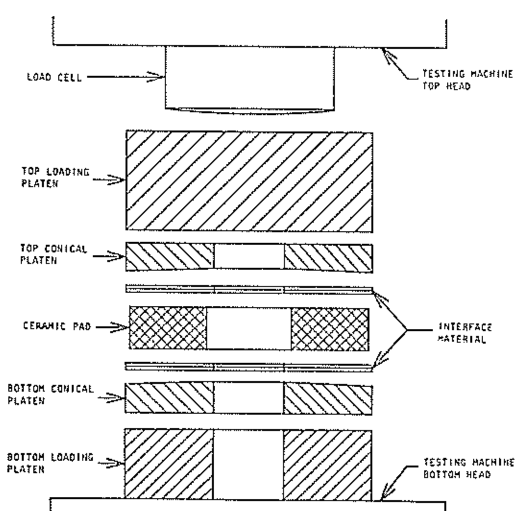

FIG. 2 SCHEMATIC OF TEST FIXTURE USED TO APPLY REPRESENTATIVE LOADINGS TO CERAMIC PADS

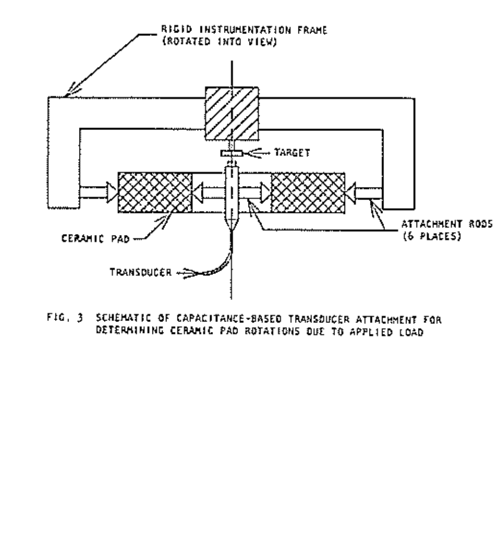

FIG. 3 SCHEMATIC OF CAPACITANCE-BASED TRANSDUCER ATTACHMENT FOR DETERMINING CERAMIC PAD ROTATIONS DUE TO APPLIED LOAD

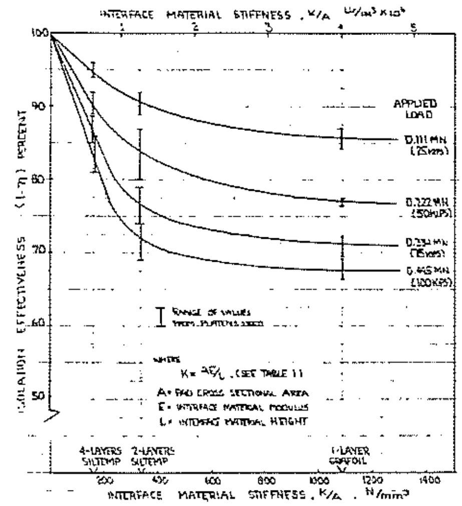

FIG. 4 ISOLATION EFFECTIVENESS VS INTERFACE MATERIAL STIFFNESS FOR 76mm GRADE 995 ALUMINA

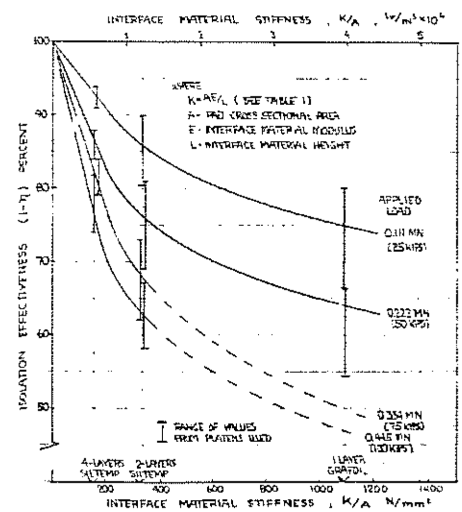

FIG. 5 ISOLATION EFFECTIVENESS VS INTERFACE MATERIAL STIFFNESS FOR 38mm GRADE 95 ALUMINA

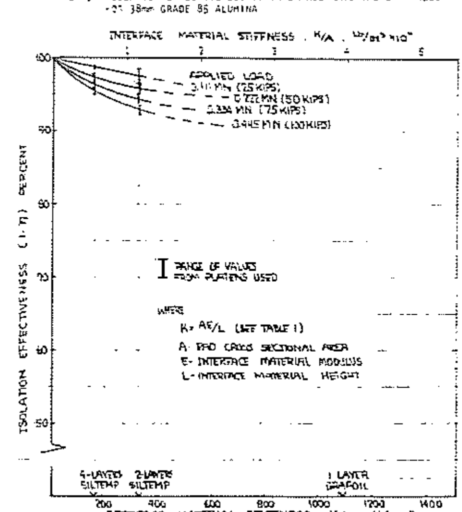

FIG. 6 ISOLATION EFFECTIVENESS VS INTERFACE MATERIAL STIFFNESS FOR 76mm GRADE 95 ALUMINA