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20 July 1965

Westinghouse Astronuclear Laboratory

BUCKLING TESTS OF SCALED
GRAPHITE BARREL INNER REFLECTORS

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INFORMATION CATEGORY

Unclassified

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SECTION I

INTRODUCTION

Larger inner reflectors, of high strength graphite, have been considered for use in advanced nuclear rocket designs. These reflectors are too large for one-piece construction from presently available high strength graphites. To permit the use of small stock sizes of high strength graphites, some of the proposed new designs specify that the reflectors be made from cylindrical sectors assembled as stave-type barrels. This report describes buckling tests which were performed on miniature (6 inch diameter) barrels of high strength fine-grained isostatically molded P-03 graphite.⁽¹⁾ This material had an average tensile strength at room temperature of 4865 psi and a compressive strength of 17,945 psi.^(2, 3) By comparison the average tensile strength of the H4LM graphite from which the NRX-A1, NRX-A2, and NRX-A3 inner reflectors were made, had an average tensile strength of only 1926 psi and a compressive strength of only 6445 psi.⁽⁴⁾

The test specimens were geometrically scaled to simulate the proposed full scale inner reflector barrels. Three types of barrels were tested; these included one piece (non-stave) barrels, bonded stave barrels and unbonded stave barrels.

(1) Numbers in brackets refer to notes and references listed in Section 7 of this report.

SECTION 2

TEST OBJECTIVES

These tests were performed to provide data on the relative merits of stave-type barrels compared with one-piece non-stave barrels. They also served to check the calculated critical buckling pressures of high strength P-03⁽¹⁾ graphite barrels. These calculated values were based on classic pressure vessel formulae for one-piece (non-stave) barrels, as derived from analyses of circular tubes subjected to external pressure.⁽⁴⁾ However, due to uncertainties as to the effects of the stave joints on the barrel buckling strengths, the tests were performed to determine experimentally if these formulae were appropriate regardless of the stave joint construction, and if the stave type barrels, so designed, would be capable of withstanding their anticipated external design pressure without buckling.

The effects of both internal and external radial restraints, which restricted the barrels from deforming freely in their weakest buckling modes were also investigated. The manner of applying these restraints is described under Test Description in Section 4. They simulated design concepts under consideration for the full scale inner reflectors.

SECTION 3

TEST RESULTS

The buckling strengths of one piece (non-stave) graphite barrels were compared with both bonded and unbonded stave barrels. The effects of restricting the barrels from buckling with both external and internal radial restraints, as a means of preventing buckling, was also investigated. The external restraints were imposed at the barrel ends and the internal restraints were imposed over almost the entire barrel length as described in Section 4.

Photographs of barrel buckling failures, and the mode shapes of the barrel deflections just before failures are shown in figures 6 through 19. Table I summarizes the test conditions and the pressures at which buckling failures occurred. The external and internal clearances used in these tests were scaled down from contemplated full scale inner reflector clearances.

For each condition of barrel restraint all three types of barrels had similar deflection mode shapes. For the condition with external radial restraints only, the cylinders buckled inwardly as shown in figures 7, 9 and 11. For the condition with both internal and external restraint, each graphite cylinder pressed against the internal plugs except for an outward bulge over a portion of the one-piece and bonded barrel circumferences. This is shown in figures 13 and 14.

Only the bonded stave barrel failed in this test, failing in the area of a 23 mil high bulge (See figure 13). Although the one piece barrel also developed a bulge (See figure 14) it did not fail, indicating that it was more resistant to this type of buckling failure. The unbonded stave barrel did not provide a good comparison in this particular test because it was manufactured somewhat undersized and had less clearance with the internal plug (See table I). As a result it compressed tightly against the internal plug under external pressure conditions and thus it could not possibly buckle (See figure 15).

For the condition of no restraint (internal or external) the unbonded stave barrel was very unstable and the test results were inconsistent. Deflection measurements could not be obtained on the barrel before buckling failure occurred. Consequently only the deflection curves for the one piece barrel and the bonded stave barrel are shown for the unrestrained condition (See figures 17 and 19). Each of these two barrels deformed outwardly almost identically in an elliptical manner before failure.

The test results indicated that stave barrels had 85 to 90 percent of the one-piece (non-stave) barrel buckling strengths. It should be noted, however, that the number of samples was very limited and the buckling tests were not repeated.

SECTION 4

TEST DESCRIPTION

Basically, these tests were simple external pressure tests on scaled-down models of the inner reflector. A conventional hand-operated water pump (0 to 4000 psi rating) was used to supply pressure to the annulus between the graphite test barrels and the inside wall of a steel pressure vessel. Pressure was applied in small increments until the test barrels failed. The applied pressures and the corresponding barrel deflections were recorded at each pressure increment.

Before installation in the test rig, each of the specimens was wrapped in a rubber blanket to overcome the porosity of the graphite material.* A typical test specimen is shown in figure 1 together with a second barrel prepared for testing with the rubber blanket installed. These rubber blankets also sealed the joints between the 36 staves in the stave-type barrel configurations. Typical bonded and unbonded stave barrels (after buckling failures) are shown in figures 8 and 10. Rubber O-rings were used as seals between the test cylinders and the end seal plates (see figure 2). The pressure vessel in which the pressure tests were conducted is shown in figure 3 and the interior parts are shown in figure 4. The interior of the pressure vessel with the top seal assembly removed is shown in figure 5. The rotor in the center of the pressure vessel contains three transducers which were used for measuring the deflections of the inside surfaces of the test barrels in three planes perpendicular to the axis of the rotor. Three linearly variable displacement transducers, three signal conditioning units, three amplifiers and three channels of an oscillograph recorder comprised the deflection recording equipment.

The effects of limiting outward and inward radial deflections on the barrel critical buckling pressures were determined in the following manner. First, the effects of limiting the barrel outward deflection were determined. This was done by seating both ends of the barrels

*Tests without the rubber blanket could not produce a pressure greater than 150 psi due to porosity.

in one-eighth inch deep wells which had been machined in the end seal plates. (See figures 2 and 4). These wells were slightly larger in diameter than the test barrels with the diameter clearances scaled down to 0.016 inches to simulate contemplated full scale inner reflector clearances. To determine the effects of limiting inward radial deflections, two aluminum plugs 0.80 inches smaller in diameter than the enclosing barrels were installed therein. They were then free to move radially within the limits of the enclosing wall. One of the radial displacement transducers was mounted in the rotor and extended radially in the space between the plugs. This allowed measurement of the deflections of the inside walls of the graphite barrels. The bottom plug installed within a failed barrel is shown in figure 12. The diametral clearance between the plugs and the barrel inside walls simulated contemplated design clearances between the reactor core and the inner reflector. For the unrestrained barrel configuration both the plugs and the well walls were removed allowing the barrels to buckle without any radial restraint. All of the clearance conditions are shown in table I. Since no simulation of the inner reflector axial loads was planned, no axial loads were applied to the barrels during the test.

TABLE 1

BARREL PRESSURE TEST RESULTS

TYPE OF SPECIMEN	EXTERNAL RESTRAINT AGAINST BUCKLING (on diameter)	INTERNAL RESTRAINT AGAINST BUCKLING (on diameter)	CRITICAL BUCKLING PRESSURE (psi)
One-piece (non-stave)	0.016 inches	None	575
Bonded Stave	0.016 inches	None	525
Unbonded Stave	0.016 inches	None	505
One-piece (non-stave)	0.016 inches	0.080 inches	1000+*
Bonded Stave	0.016 inches	0.080 inches	850
Unbonded Stave	0.033 inches	0.063 inches	1000+*
One-piece (non-stave)	None	None	215
Bonded Stave	None	None	185
Unbonded Stave	None	None	20 to 80**

*Maximum Test Pressure (No failure occurred in these two cases)

**Results were inconsistent.

SECTION 5

CONCLUSIONS

- 1) The results of the pressure tests on the miniature barrels demonstrated the suitability of the stave type barrel construction for fabrication of graphite inner reflectors.
- 2) Classic external buckling pressure calculations, used for the design of one piece barrels, appear to be suitable for stave type barrel designs.
- 3) Stave type barrels tested in this program were 85 to 90 percent of the strength of the one piece barrels, but the number of samples tested was too limited to establish quantitative design data on this strength differential.
- 4) With both external and internal radial restraints in use in the tests, the buckling strengths of the radially unrestrained barrels more than quadrupled.
- 5) The one piece (non-stave) barrels and the bonded stave barrels exhibited almost identical buckling characteristics when subjected to equivalent test parameters of radial restraint and pressure.
- 6) Due to buckling instability, it appears impractical to use unbonded stave-type barrels for inner reflectors without radial restraint built into the design.
- 7) Row PO-3 barrels of the size used for the experiments had excessive porosity requiring a special sealing member. It is considered that this sealing member had negligible effects on buckling characteristics.

SECTION 6

RECOMMENDATIONS

The test series did not provide sufficient data to permit the establishment of good scaling factors for use in future graphite barrel programs. Further comparative testing of scale model barrels with larger or full scale barrels of the same design and material is recommended. Sufficient comparisons would then establish a high level of confidence in the scaling parameters so that small barrels could be used for design evaluation and qualification testing. Additional small scaled barrel tests would be of considerable value to the program because they could be completed quickly and at considerably lower cost than full sized barrel tests.

Porosity sealing should also be investigated to verify if large cylinders will also require special sealing to be used in a reactor environment. Bonding techniques for both the small and the large test cylinders will have to be improved to insure a homogeneous low porosity bond throughout all joints.

SECTION 7

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3. V. Kachur, Properties of P-03 Graphite, WANL-TME-1031 of January 1965
4. W. Pollack, Evaluation of NRX-A2 Tile Inner Reflector Properties, WANL-TME-765, May 8, 1965
5. S. Timoshenko, Strength of Materials, Parts I and II, D. Von Nostrand Company, New York, N.Y.

Figure 1 Test Specimens With and Without Rubber Blanket and O-Rings

Figure 2 Test Graphite Barrel Seated in Bottom Seal Plate

Figure 3 Assembled Pressure Vessel Test Rig

Figure 4 Transducer Rotor, Top Seal Plate, Spacer Plate and Top Retainer Plates

Figure 5 Test Rig Interior on First Bonded Stave Barrel Test

Figure 6 One Piece Barrel (0.016 inch external restraint) Failure at 575 psi

Figure 8 Bonded Stave Barrel (0.016 inch external restraint) Failure at 525 psi

Figure 10 Unbonded Stave Barrel (0.016 inch external restraint) Failure at 505 psi

Figure 12 Bonded Stave Barrel (0.016 inch external restraint) (0.080 inch internal restraint) Failure at 850 psi

FIGURE 14
MID-PLANE DEFLECTIONS AT 1000 PSI
(FULL SCALE)
ONE PIECE NON-STAVE BARREL # 2
EXTERNAL RESTRAINT (0.016 INCH)
INTERNAL RESTRAINT (0.080 INCH)
(NO FAILURE)

Figure 16 One Piece Barrel (no radial restraints) Failure at 215 psi

Figure 18 Bonded Stave Barrel (no radial restraints) Failure at 185 psi