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# Strength Testing of Hot Gas Filters
# Volume VI

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## 1. INTRODUCTION

The strength of various ceramic hot gas filter materials has been evaluated by four laboratories: Argonne National Laboratory, DuPont Lanxide, Southern Research Institute and Babcock and Wilcox. The filter materials under study include (a) a Nextel™/SiC composite filter (from 3M), (b) PRD-66, an all oxide layered microstructure of alumina, mullite, cordierite and some amorphous material by DuPont Lanxide, (c) a Babcock and Wilcox material consisting of an oxide composite of chopped fibers (Saffil) and continuous Nextel™ fibers, (d-f) monolithic and recrystallized SiC materials and an alumino/aluminosilcate material by IFPM, and (g) a monolithic SiC by the Pall Corporation. Not all four organizations tested each of the materials. PRD-66 was tested by three of the four.

Four tests were used to evaluate properties of the candle filter materials. They included (a) the C-ring test, (b) the O-ring test, (c) the burst test and (d) the axial compression test. Each organization identified above did not perform all four tests.

Reports from the four organizations were provided beginning in September, 1996.[1-4] Only one report was in final form [3]; one report was in draft form [1]; the remainder were technical memoranda or copies of research notebook data with no discussion [2,4].

The objective of the study described here was to (a) provide an evaluation of the test methods used for hot gas filters to determine which is best for hot gas filter evaluation and (b) evaluate the discrepancies in results from tests run at different laboratories. No material ranking was made here, nor requested.

## 2. EVALUATION

The most likely cause of failure of hot gas filters is thermal shock. Large temperature excursions on heating or cooling provide a temperature gradient across the material which gives rise to a large thermally-derived strain and corresponding stress which may exceed the failure stress of the material. Depending on whether the excursion occurs during heating or cooling, failure may originate on the inside or outside surface. Hence, a knowledge of failure-determining properties on the inner surfaces and the outer surfaces is in order.

The C-ring test and the O-ring test are used to evaluate outer surface and inner surface properties, respectively. The rings are loaded in diametral compression and the maximum circumferential stresses are located on the outer and inner mid-section for the C-ring and O-ring, respectively. The disadvantage of both of these tests is that only a small surface area is under maximum stress. For materials which show truly brittle behavior, a large flaw located near the loading axis may not serve as the failure determining flaw in this configuration. The burst test, alternatively, provides a means assessing the inner surface flaw population under uniform pressure. Hence the largest flaw is likely to serve as the failure origin in the brittle solid. Not surprisingly, strength values tend to be lower than those measuring using O-ring test as demonstrated by Singh et al.[1] since a greater volume of material is under uniform stress. The axial compression test should provide uniform compression along the length of the tube for specimens with thick wall sections.

## 2.1. Thin-Walled vs. Thick-Walled Cylinders

In the work by Chambers [2] in both C-ring and O-ring tests, the cylinders are assumed to be thin-walled cylinders. In general, thin-walled cylinders must meet the following thickness criterion:

$$t/2r_i<0.01,$$

where t is the wall thickness and $r_i$ is the inner radius.[5] In all of the tests evaluated here, none meet the thin-walled criterion. For example, PRD-66 rings tested by DuPont Lanxide fall into the category of $t/2r_i=0.15$. Babcock and Wilcox C-rings have $0.07<t/2r_i<0.05$. Using a less conservative definition of thin-walled ring, $r_i/r_o$ should be greater than 0.7.[6] This is indeed the assumption that has been used by DuPont Lanxide [2] in using the formula for strength:

$$\sigma_f = \frac{2\,Pr_a(6r_a - t)}{\pi bt^2(2r_a - t)}$$

where $\sigma_f$ is the maximum stress at fracture, P is the load at failure, b is the sample width, $r_a=(r_o+r_i)/2$, $r_o$ is the outer radius, $r_i$ is the inner radius and t is the ring thickness. Using the most conservative approach of the thick-walled cylinder should than provide reduced stresses in the part by the term $(1+t/2r_o)$.

In the case where the O-rings are considered to be thick-walled cylinders, as done be Singh et al. from Argonne National Laboratory [1], the following formula is used :

$$\sigma_f = \frac{PK}{\pi r_o b}$$

where P is the fracture load, K is a function of the inner and outer diameters and has been numerically determined by Ripperger and Davis [7] $r_o$ is the outer radius of the specimen and b is the sample width. Using the formulatoin above, Singh et al. measure strengths of approximately 1100 psi. This value is considerable higher than that measured by Chambers (approximately 400 psi). As is noted in the report by Jeff Chambers of DuPont Lanxide[2], the discrepancies are likely due to evaluation of the data since failure loads at both laboratories average 40 lbs. Following the thick-walled model in Reference 7, for 40 pound loads, I come to the conclusion that failure stresses should be of the order of 750 psi, rather than the 1100 psi reported by Singh et al. In any event this thick-walled cylinder model used by virtue of a more conservative definition of a thin-walled cylinder results in a larger computed strength. A more detailed report of Singh et al.'s calculations is warrented.

This formulation assumes that the material is homogeneous, which is not true for all of the materials tested. For example, the 3M ceramic composite was a three-layer material consisting of a continuous fiber reinforced inner layer, a middle filtration layer and a coarsely woven outer layer. Structures such as these require that the stress analysis for a thin or thick-walled cylinder must be adapted to accommodate the radial change in elastic properties. This has been treated by Singh et al. [1] and for other materials where cavitation alters the modulus during testing, by Chuang et al. [8].

## 2.2 O-ring Tests vs. C-Ring Tests

It was noted by Chambers [2] that O-ring tests were preferred because there was less variability in the data. It is no surprise that Chambers sees different values for C-Ring and O-Ring tests since different surfaces are evaluated. It is far less likely a consequence of the test than of the material, and its processing. It is commonly observed that the internal surface of a ceramic cylinder has a different porosity, surface finish, microstructure than the external surface if the internal surface is in contact with different materials during processing, e.g. a mandrel vs. a free surface. Such details were not afforded in the reports received. But the variability in the C-ring data is just as telling as the lack of variability in the O-ring data. The C-ring data provided by Babcock and Wilcox also shows much variability, up to ± 18%. These data cannot be compared to others since they were acquired at temperatures of 1600°F.

## 2.3. Burst Tests

Comparison between O-ring or C-ring tests and burst tests are limited. In the Singh et al. study, the average burst strength of was approximately 30% of the O-ring test results. This reduction in strength is believed to be due to larger area (volume) subjected to higher stresses compared to the O-ring tests. Probabilistic methods which include Weibull statistics allow for treatment of different volumes and stress distributions. [See, for example, reference 9] Spain and Starrett [3] performed burst tests on a variety of hot gas filters and find, for example, that PRD-66 demonstrate strengths of 760 psi. It should be noted that this value is significantly higher than the O-ring strength (approximately 400 psi) determined by DuPont Lanxide using the thin-walled cylinder model, and is consistent with the Singh et al. observtions.

# 3. CONCLUSIONS

Although burst tests, without a doubt, provide a better means of assessing inner surface flaw populations in the entire component, they are unlikely to provide useful information concerning out surface flaw populations. A combination of C-ring and O-ring tests could be coupled to provide a useful description of external surface vs. internal surface sources of failure. Such information is necessary for designing for thermal excursions on heating or cooling which may lead to thermal shock failure.

Treating the hot gas filters as thin-walled cylinders is not entirely appropriate and is the cause of discrepancy in calculated strength results. A further feature of the filter materials which should be included in these materials has to do with the inhomogeneity of the filters themselves. For example, layered cylinders, as those produced by 3M must be treated as inhomogeneous bodies, as shown in the analysis of Singh et al.[1], or alternatively, by Chuang [8].

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