Phenolic Ball Bearing Retainer Testing for Space/Vacuum Environments

John Renaud*

Abstract

This paper documents testing performed on recently produced lots of phenolic material and a review of historical testing and publications. The results of this testing could be used to update bearing retainer designs and risk mitigation practices for phenolic ball bearing retainers used in space flight applications.

Introduction

Cotton phenolic composite is a common material used for ball bearing retainers in a variety of high-precision applications, including applications used in a vacuum environment such as satellites working in space. The material is porous, allowing oil impregnation, and meets general requirements for space material out-gassing. In addition, the material has long-time heritage use in successful space flight mechanisms and is used extensively for these types of applications.

Phenolic composite material is known to change size due to moisture absorption, typically from humidity in ambient air. However, the space vacuum environment is devoid of humidity and moisture. A retainer fabricated and measured in a typical manufacturing environment shrinks when placed in a vacuum and expands with increases in humidity. If the bearing retainer shrinks sufficiently in the vacuum, along with thermal expansion and contraction, it can create an interference fit on the inner ring of the bearing. This condition can result in excessive bearing drag torque and in extreme case, possible cage failure.

Previous Publications

A commonly referenced publication for the phenolic material property of size change with humidity is Bertrand-and-Sinsheimer's 2002 article, "Humidity-Induced Dimensional Changes in Cotton-Phenolic Ball-Bearing Retainers" [1]. This report was based on testing of phenolic retainers performed by Bertrand of Aerospace Corp and Sinsheimer of TRW (now Northrop Grumman).

In summary, this testing found that a phenolic bearing retainer's size can change between 0.2% and 0.4% with humidity. These results were based on measurements of retainer bores using a tapered arbor. Measurements were taken both immediately upon removal from vacuum and also after multiple days of soaking at 52% and 87% relative humidity (RH) conditions.

Background

All material tested as part of this evaluation was compliant with the requirements of MIL-I-24768/13 [2] "FBE" material, which is the material specification typically used for spaceflight bearing applications. Previously collected, internally generated data (2012) regarding the size change of phenolic bearing retainers with exposure to humidity, largely aligned with published results across multiple size ranges. The data included results from testing two prominent manufacturers of phenolic material for this type of application. This data was used to define size requirements in relation to various humidity conditions, with good results.

However, recent testing of a thin section bearing system operating in a vacuum environment resulted in a torque anomaly that was determined to have been caused by a loss of retainer piloting clearance. This

* Timken Aerospace, Keene, NH

Proceedings of the 46th Aerospace Mechanisms Symposium, Virtual, May 11-13, 2022

prompted a review of more recently produced materials to determine if design offsets needed to be revisited.

Test Details

A test plan was developed to classify the phenolic material for vacuum application using equipment readily available in the bearing production facility. This testing was performed in four steps as shown below. The testing compared the material in the as-machined condition to reference humidity conditions. The area of most concern/risk is the resulting cage piloting clearance when operating in a vacuum condition typical of space flight applications.

Test overview steps:

1. Define how to determine a truly “dry” state for the bearing cage to establish a low temperature bake process that would prevent any unwanted changes to material properties
2. Expose the retainers to ascending steps of humidity using a controlled humidity chamber to determine the size response of the material, and compare to historical testing.
3. Extrapolate the size response model to an assumed full vacuum condition.
4. Vacuum dry the retainers and test directly from the vacuum chamber for minimum size using a go-no go pin check to test the full vacuum state.

Four groups of retainers, 10 samples each, were obtained. Two groups were manufactured at The Timken Company bearing plant from “Manufacturer A” (MFR A) phenolic material, and two groups were produced at JPM of Mississippi using material produced from “Manufacturer B” (MFR B). All retainers were through-hole designs for use in angular contact thin section bearing typical of ABMA Standard 12 thin sections. The retainer groups included one design that was common across historic 2012 and current testing, as well as one alternate design from both material manufacturers for comparison. Figure 1 depicts an image of retainer Design 1 from MFR B material and Table 1 contains an overview of the retainer designs with approximate dimensions.

Table 1: Retainer design reference used in test

	Bore	OD	Width	Phenolic Material	Measurement Data Sets
Design 1 "3746"	64.3 mm (2.53 in)	67.1 mm (2.64 in)	5.8 mm (0.23 in)	MFR A and B	Historic 2012 data, current testing
Design 2 "2128"	37.3 mm (1.47 in)	39.9 mm (1.57 in)	5.8 mm (0.23 in)	MFR A	Current testing
Design 3 "3240"	55.4 mm (2.18 in)	57.9 mm (2.28 in)	5.8 mm (0.23 in)	MFR B	Current testing

Figure 1: Phenolic bearing retainer Design 1 from MFR B material

Establishing Vacuum Dry Condition

Vacuum drying was done in a ThermoScientific™ vacuum oven in the manufacturing clean room. Retainers were placed in vacuum of at least 28 in-Hg gage pressure. An elevated temperature well below the glass transition temperature of the phenolic resin was used to speed the process and limit other material factors from playing a role in the size testing. Vacuum dry testing was done using both of the current testing "MFR A" samples (Designs 1 and 2) to determine an adequate cycle for preparing samples of the full dry condition to use in later tests.

Mass measurements were taken immediately upon removal from the vacuum at specified time steps between two working days. Fitting a first order function to the mass-over-time data gives a correlation coefficient of 0.985, indicating a good fit. Using this function, it can be determined that both Design 1 and Design 2 retainers, when taken from ambient manufacturing conditions, will lose over 99% of their moisture mass after vacuum drying for 14 hours. This testing was also used to verify the mass condition of fully dried retainers that were vacuum-baked from a different starting point.

After the full dry condition was established various preservation methods were tested to keep parts dry between the vacuum drying process and the measurement process. Storing retainers in the controlled humidity cabinet at 10% (RH) resulted in a mass change with less variability from moisture absorption, equivalent to that obtained when using the best available dry purged packaging process. This 10% RH was used as the minimum humidity state for continuous bore and OD measurements for size modeling.

Measurement of Retainer Bore and OD with Humidity

The next step of testing was to measure and fit a model to the phenolic size change with humidity for each set of retainers. This was done by soaking the retainers at various levels of relative humidity and measuring bore and OD at each condition. An Electro-Tech Systems humidity cabinet utilizing a humidity sensor with a microcontroller (controlling a dry nitrogen supply and a deionized water humidifier) was used to actively control humidity. Retainer bore and OD measurements were taken using a TESA Visio V-300 vision system.

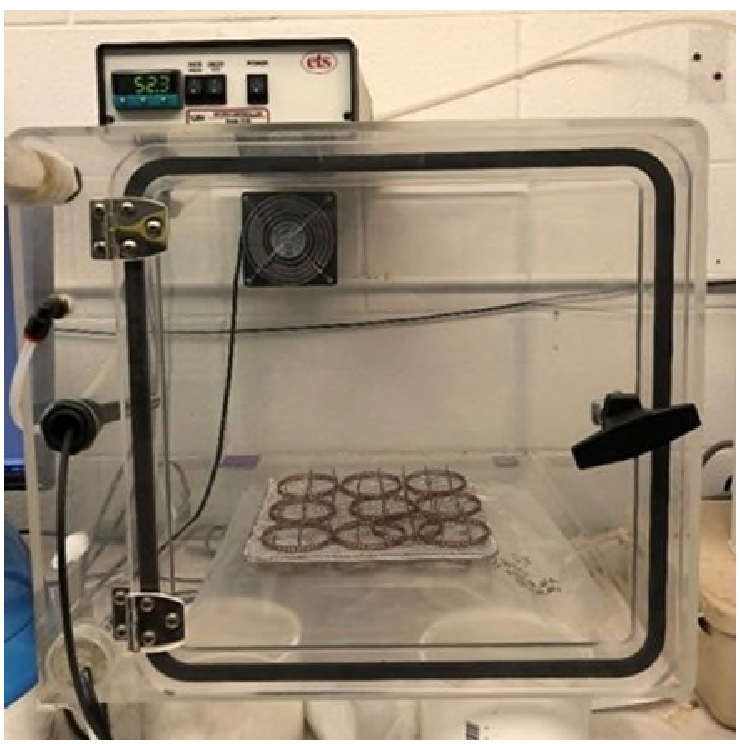

Figure 2: ETS humidity-controlled cabinet

This is a non-contact optical measurement system which fits an average size to hundreds of optical measurements via specific program for each retainer design. All measurements used in this paper including previous data from 2012, and current testing were done using the same humidity cabinet type and the same Visio measurement system. Each retainer was removed independently from the humidity chamber for each measurement taken on current testing. Previous 2012 data being used as a reference comparison, the exact procedure used for this testing was not fully documented at the time of testing. Humidity cabinet and measurement Bore and OD vision system are shown for reference in Figures 2 and 3. Both systems are immediately next to each other on a common work bench to limit time outside of the reference humidity conditions.

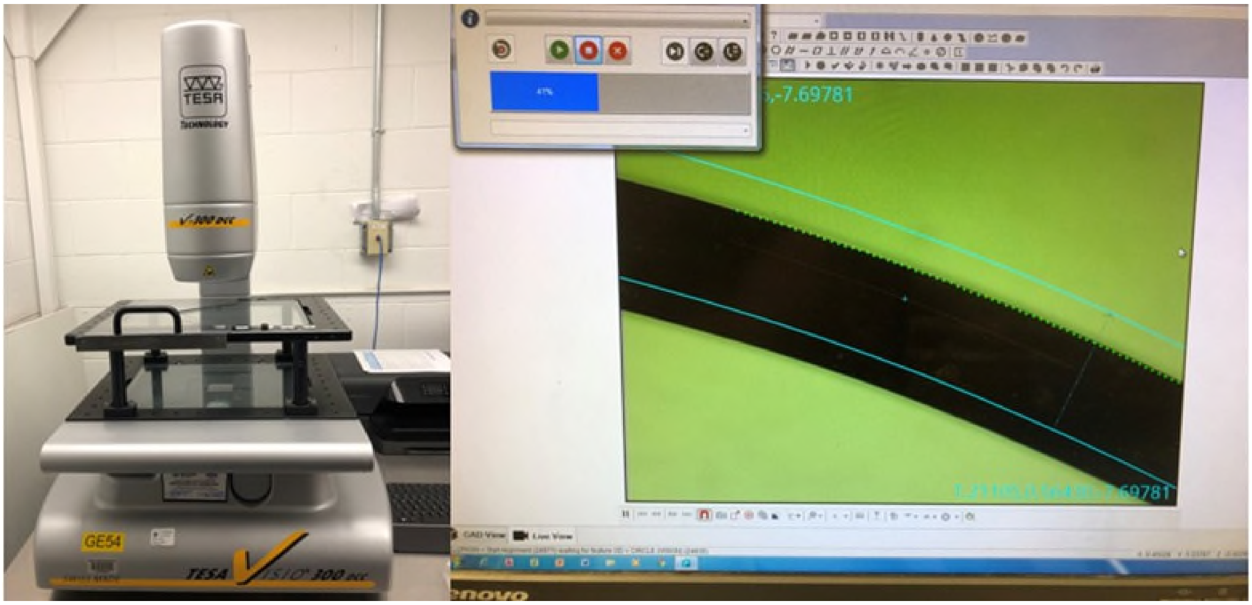

Figure 3: TESA Visio 300 optical vision measurement system

Previous reference data was available for retainer “design 1” using both MFR A and B material from 2012. Bore and OD sizes were available for 20%-40%-60%-80% Relative Humidity. The new retainer samples were all measured after soaking at the minimum set 10% RH condition as well as the same 20% RH steps from previous testing in ascending order to allow for a direct comparison using similar test conditions.

Bore and OD measurements were taken every 24 hours at each humidity step until a matched pairs comparison of the data set did not show a statistically significant change in average growth from the previous day. The humidity chamber was then increased to the next step of humidity and the process was repeated for each humidity step through 80% RH. Size data for each retainer design was normalized for comparison as a percentage size change from a reference condition. The reference condition used was the 40% RH measurement which is the closest data point to a typical “as manufactured” condition.

Bore and OD size change data is shown as Figures 4 and 5 respectively. The data is plotted along with the data collected in 2012 to determine if there was a difference in how the material changes in size with humidity between manufacturers or time of manufacture.

The size changes for both bore and OD appear linear, with a similar rate of change for each measurement set regardless of retainer design. The material is assumed to swell from moisture absorption, resulting in a higher rate of change for the OD compared to the bore, which is reflected in the measured data. The results of the 2012 data indicate both of the phenolic manufacturers’ materials grew at a similar rate. The new test data shows each manufacturer’s material grew at a similar rate between the two designs tested, but MFR A’s size change varied significantly from the 2012 data. The current MFR B material changed at a different rate but was not as significantly different from the 2012 data.

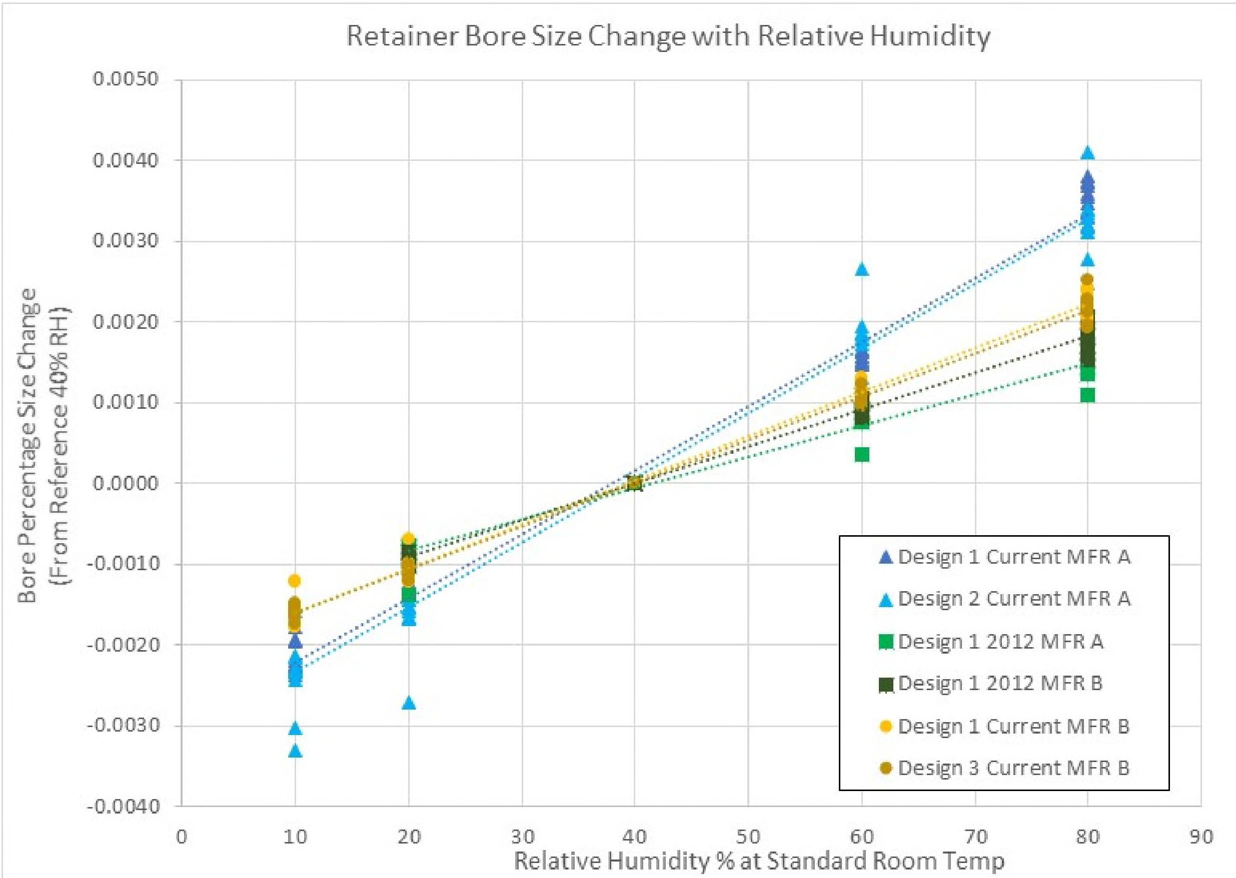

Figure 4: Bore size change of phenolic samples with humidity

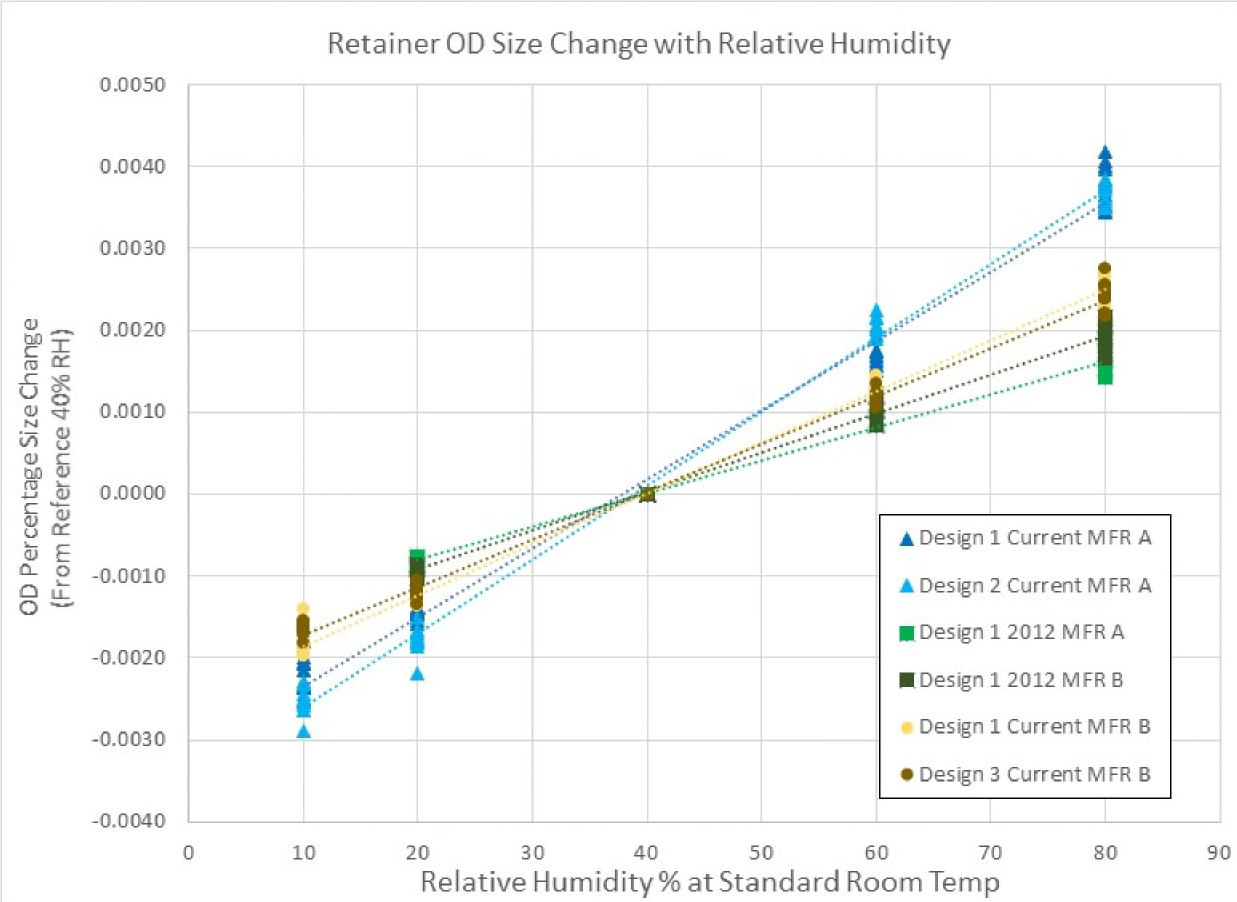

Figure 5: OD size change of phenolic samples with humidity

Data Fitting and Extrapolation

The data from each set appears to follow a linear rate of change. A linear fit can be extrapolated to the design conditions to determine the smallest and largest size the retainer could attain with varying levels of humidity. Linear fits with extrapolation of the expected size changes are listed in Table 2. Included are a fit of each data set as well as combined models for each test set. The size data fits a linear model well, with high correlation coefficients for each individual design and for the combined test data sets.

The underlying purpose of the testing was to determine an adequate phenolic retainer design offset for the as-machined condition when designing for operation in space flight vacuum conditions, assuming 0% relative humidity. This helps to assure the retainers will not shrink onto the inner bearing ring, thereby creating an interference condition in vacuum that could lead to torque increases.

It is not practical to attempt to machine vacuum-dried material to replicate space-like conditions. Vacuum-dried material changes size from moisture absorption at a very fast rate when fully dried at a typical humidity level for manufactured ambient conditions. This has been shown in Manufacturing trials to be less repeatable than machining material at consistent ambient conditions with an offset based on the ambient humidity to account for shrinkage under prolonged vacuum exposure.

Using the combined model of 2012 data, a retainer bore needs to be offset from a reference 40% RH manufactured condition, and the offset would need to account for only a 0.17% reduction in size, on average, to ensure positive clearance of the inner ring at vacuum. The current data for MFR A shows that a 0.32% reduction in size, on average, would have to be incorporated into the design and the reduction would be 0.21%, respectively, for MFR B. The OD size change for a high-humidity condition is also different. Current test data shows that the ODs could vary up to 0.87% over a full theoretical range of humidity, although this is less of a concern for space flight bearing applications.

Table 2: Linear bore/OD size change models for each data set

	Linear Regression			**Extrapolation**	
	Data Set	**Feature % Rate of Change with RH**	**R^2**	**0%-40% RH**	**Total 0%-100% RH**
Bore	Design 1 MFR A 2012	3.88E-05	0.97	-0.0016	0.0039
	Design 1 MFR B 2012	4.53E-05	0.99	-0.0018	0.0045
	Design 1 MFR A Current	7.91E-05	0.99	-0.0032	0.0079
	Design 2 MFR A Current	8.00E-05	0.96	-0.0032	0.0080
	Design 1 MFR B Current	5.17E-05	0.98	-0.0021	0.0052
	Design 3 MFR B Current	5.32E-05	0.99	-0.0021	0.0053
OD	Design 1 MFR A 2012	4.02E-05	0.99	-0.0016	0.0040
	Design 1 MFR B 2012	4.78E-05	0.99	-0.0019	0.0048
	Design 1 MFR A Current	8.43E-05	0.99	-0.0034	0.0084
	Design 2 MFR A Current	9.00E-05	0.99	-0.0036	0.0090
	Design 1 MFR B Current	5.86E-05	0.99	-0.0023	0.0059
	Design 3 MFR B Current	5.73E-05	0.97	-0.0023	0.0057

Combined Data Sets

Bore	Combined MFR A/B 2012	4.22E-05	0.97	-0.0017	0.0042
	Combined MFR A Current	7.96E-05	0.97	-0.0032	0.0080
	Combined MFR B Current	5.37E-05	0.98	-0.0021	0.0054
OD	Combined MFR A/B 2012	4.41E-05	0.98	-0.0018	0.0044
	Combined MFR A Current	8.72E-05	0.99	-0.0035	0.0087
	Combined MFR B Current	5.84E-05	0.99	-0.0023	0.0058

Test Minimum Size Extrapolation

The minimum measured humidity condition was 10% RH. Using the linear models, the minimum size can be extrapolated from the minimum measured condition to the fully dry 0% RH vacuum condition. A verification test was performed to review the linear model for accuracy of the minimum expected vacuum dry bore sizes, which are the main areas of concern for bearing function and the risk being reviewed.

Retainers from the current MFR A group were vacuum-dried and test-fit with a set of available gage pins immediately after removal from the vacuum. This is similar to the method Bertrand used with the tapered arbor immediately out of vacuum. An assortment of gage pins both above and below the expected retainer bore sizes were obtained to assess whether the model was adequate at predicting the vacuum-dried condition. The 0% RH model predicted minimum bore sizes using the “Combined MFR A Current” bore size model from Table 2 applied to each individual retainer’s 40% RH reference condition bore measurement to create a 0% RH bore prediction for the functional evaluation.

Tested retainers were vacuum-baked to a fully dry state validated by comparing the retainer mass to values obtained in test step 1. The retainers were cooled to room temperature 20°C at vacuum overnight for size comparison, and at room temperature aligned with the previous Visio measurement conditions. Retainers were removed from the chamber and immediately tested with the assortment of pins. The pin results listed as “go” indicate the retainer easily fits on the pin with minimal force and slid easily, and would slide off under its own weight.

The second outcome of “tight” indicates the retainer went on the pin but with resistance and would not fall off the pin under its own weight. This result assumes a line-to-line/light interference fit. The third outcome, “no,” indicates the retainer would not slide on the pin because the bore was smaller than the pin size being used. Results of pin checks for MFR A Design 2 retainers are shown in Table 3 with the expected modeled 0% RH size for each numbered retainer. This design was used as the verification example as it had the largest available set of pin sizes near the expected minimum size value.

Table 3: Retainer Design 2, MFR A, vacuum-baked minimum size verification

Retainer Sample	**Test Pin Diameter**						**0% RH Model Prediction**
	37.06 mm (1.459 in)	**37.11 mm (1.461 in)**	**37.16 mm (1.463 in)**	**37.21 mm (1.465 in)**	**37.24 mm (1.466 in)**	**37.31 mm (1.469 in)**	
1	go	go	tight	no	no	no	37.16 mm (1.463 in)
2	go	go	go	no	no	no	37.16 mm (1.463 in)
3	go	go	go	no	no	no	37.13 mm (1.462 in)
4	go	go	go	no	no	no	37.16 mm (1.463 in)
5	go	go	go	tight	no	no	37.16 mm (1.463 in)
6	go	go	go	no	no	no	37.16 mm (1.463 in)
7	go	go	go	no	no	no	37.16 mm (1.463 in)
8	go	go	go	no	no	no	37.13 mm (1.462 in)
9	go	go	go	no	no	no	37.19 mm (1.464 in)
10	go	go	go	no	no	no	37.19 mm (1.464 in)

Pin verification aligned with the predicted model in all but one example. Retainer 5 measured slightly larger than the expected model prediction, fitting tightly on a bore pin 51 µm (0.002 in) larger than the model expectation. Given the variation of the bore change in the data set shown in Figure 4, this is not unexpected. Design 1 of the MFR A material was tested similarly but with less resolution of pin sizes. All predicted minimum sizes followed the model prediction.

The variation in the measured retainer parameters for each completed set of test samples highlights an important factor when using phenolic material for bearing retainers in thin section bearings for use in vacuum. The composite structure of the material, along with the variation between production lots, presents risk if a size variation model is used exclusively. Simple design offsets work for most retainer designs; however, some designs inherently result in a higher risk of loss of retainer piloting clearance. In higher-risk applications such as thin section ball bearings, the most conservative approach when applying phenolic retainers is to perform a functional minimum retainer clearance test in serial production either after a vacuum bake cycle or as part of the lubricant vacuum impregnation process.

Lessons Learned / Conclusions

Historical assumptions for phenolic ball bearing retainer size change due to humidity may not be conservative enough for all retainers using currently available materials. This is of the most significant concern in thin section ball bearing designs commonly used in space flight applications Retainer diameters that are larger in proportion to the bearing retainer clearances represent a higher risk for loss of retainer clearance around the inner bearing ring, and loss of retainer piloting clearance can result in excessive bearing torque.

In high-risk bearing applications utilizing continuous (non-segmented) phenolic bearing retainers, design review for operation at full vacuum is recommended. Functional pin testing immediately following vacuum drying or the vacuum impregnation process can be used as a further risk mitigation method. There is a surprising amount of variation reported in the material's response to humidity. It is unknown if this is the result of changes to the material being supplied to the industry or is characteristic of the typical lot-to-lot variation that comes with the composite manufacturing process.

Acknowledgments

The author would like to thank the Timken Company for support of this work, permission to publish and for providing equipment used in testing. The author thanks JPM of Mississippi for providing the additional test samples that were used to finalize the test set.

Reference

[1] Bertrand, P.A. and Sinsheimer, J.D., "Humidity-Induced Dimensional Changes in Cotton-Phenolic Ball-Bearing Retainers," *ASME Journal of Tribology*, Vol. 124 p. 474-479, July 2002
[2] MIL-I-24768/13